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Research article

Increased operational costs of electricity generation in the Delaware River and Estuary from salinity increases due to sea-level rise and a deepened channel

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ABSTRACT

Like many estuaries in the world, salinity levels in the Delaware River and Estuary are expected to increase due to a deepened navigational channel and sea-level rise. This study estimated operational cost increases resulting from increased ambient salinity likely to be incurred at PSEG-Hope Creek, an evaporatively cooled electricity generating station. To estimate cost increases, a linked physical-economic model was developed to generate daily forecasts of salinity and the resulting changes in facility's cooling water treatment and pumping requirements. Salinity increases under potential future bathymetric configurations were simulated using a hydrodynamic model. On an equivalent annual basis (discounted at 5%), average cost increases were \$0.4M per year, or approximately 0.1% of estimated total annual operating costs for the facility. Methods developed here could be employed at other facilities anticipating future salinity increases. Results inform cost-benefit analyses for dredging projects and contribute to estimates of the indirect costs to society from carbon emissions through sea-level rise. Future research refinements can focus on modeling changes in suspended sediment concentrations and estimating their impacts on operational costs.

1. Introduction

For facilities that withdraw and utilize water from naturally brackish estuarine waters, total operational costs partially depend upon the characteristics of the water, which in turn depend upon environmental conditions. This study investigates how ambient salinity and the operational costs for one facility along the Delaware Estuary are altered by the anthropogenic factors of sea-level rise and a deepened navigational channel from dredging.

1.1. The Delaware Estuary

The Delaware Estuary is a funnel-shaped waterbody located in the US Mid-Atlantic, bordering Pennsylvania, New Jersey, and Delaware (Fig. 1). The watershed spans approximately 35,000 square kilometers, including the cities of Philadelphia, PA and Wilmington, DE (Bryant and Pennock, 1988; Partnership for the Delaware Estuary, 2012). Combined, the Delaware River and Estuary have the fifth highest water withdrawal volumes of any river system in the United States (USEPA, 2014). Facilities withdrawing water along the Delaware River and Estuary include petrochemical and manufacturing, oil refineries, municipal water systems, and electricity generating stations.

Salinity in the estuary decreases travelling upstream from the mouth of Delaware Bay (i.e., River KM 0). The salinity distribution in the estuary varies spatially and temporally, depending upon river flow, tides, sea level, and bottom topography, among other factors. Prior research has reported salinity variations and trends in the Delaware River and Estuary (Wong, 1995).

Salinity in the estuary is typically highest in the summer/fall, and lowest in winter/spring, while river discharge exhibits the opposite pattern (Ross et al., 2015). Compared to many estuaries, the Delaware exhibits a weak response to changes in discharge, as both tidal salt flux due to lateral processes and steady salt flux in the channel increase with discharge (Aristizábal and Chant, 2015; Garvine et al., 1992). The median and historic maximum locations of the salt front are located at River KM 115 and 164, respectively (Delaware River Basin

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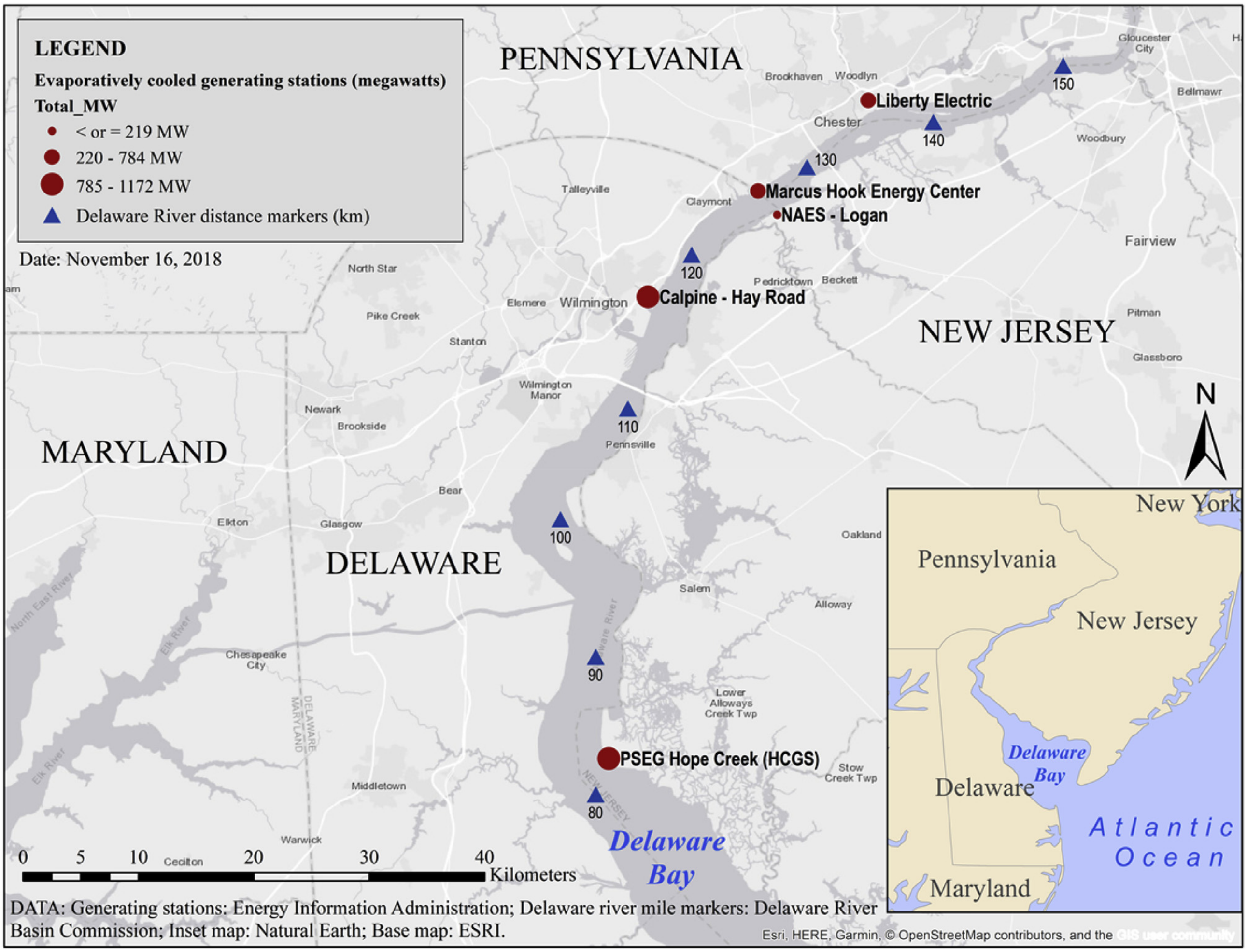

DATA: Generating stations: Energy Information Administration; Delaware river mile markers: Delaware River Basin Commission; Inset map: Natural Earth; Base map: ESRI.

Fig. 1. The study area showing middle and upper sections of the Delaware River and Estuary with evaporatively cooled generating stations.

Commission, n.d.).

Sea levels at a nearby monitoring station have risen an average 3.54 mm/yr between 1956 and 2016 (NOAA, 2016). Higher sea levels result in greater seawater forcing in the upstream direction and increased average salinities in the estuary.

In 2010, the US Army Corps of Engineers began deepening the Delaware main channel from 12.2 m to 13.7 m, partially in response to a recently expanded Panama Canal (USACE, 2011). As of November 2018, the Delaware deepening project was nearly complete (USACE, 2017). Because estuarine circulation and associated landward salt flux increase nonlinearly with water depth, the extent of salinity intrusion is also anticipated to increase with a deepened channel (Hansen and Rattray, 1965; MacCready and Geyer, 2010).

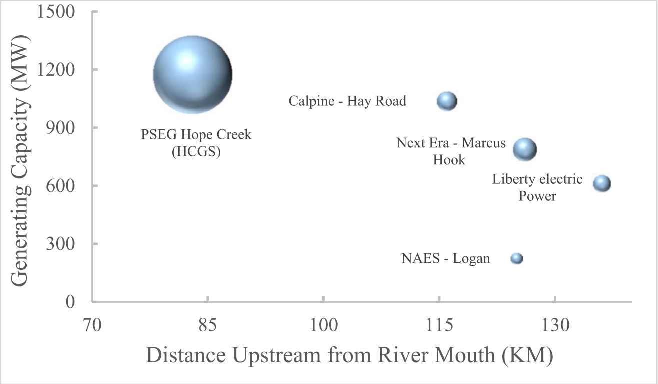

Fig. 2. Evaporatively cooled generating facilities in the Delaware River and Estuary. Bubble size represents the relative rate of water withdrawals, where PSEG Hope Creek is 50 million gallons per day (US EIA, 2018).

1.2. Electricity generating stations on the Delaware

Twelve large electricity generating stations withdraw water from the lower Delaware River and Delaware Estuary, representing a combined generating capacity of over 8000 MW (MW), equivalent to the average electricity draw of six million US homes (US EIA, 2017). These facilities include two large nuclear stations and numerous smaller fossil fuel-fired stations. In 2017, these 12 stations withdrew over 3200 million gallons per day (MGD) or approximately 140 m^3/s, mostly for cooling purposes (US EIA, 2018). Evaporatively cooled stations (Fig. 2) were responsible for less than 2% of the total volume of water withdraws, yet they generated approximately half of the total electricity (US EIA, 2018). Continual evaporation and circulation of cooling water within an evaporatively cooled system decreases the volume of water withdrawals but increases the sensitivity of the cooling system to changes in water composition (Ting and Suptic, n.d.; Zhang and Dzombak, 2010).

Of the evaporatively cooled stations in the estuary, PSEG's 1,161MW nuclear powered Hope Creek Generating Station (HCGS) has the greatest power capacity, capacity factor, and water volume requirements (DRBC, 2013). HCGS withdraws approximately 50 MGD (US EIA, 2018) and has an average capacity factor exceeding 90% (Nuclear Energy Institute, 2017). HCGS is also the most seaward of the evaporatively cooled stations (River KM 83), located in the stretch of the estuary where salinity increases from SLR are expected to be the most pronounced (Hull and Titus, 1986; Ross et al., 2015) and where a significant signal of SLR on salinity increase has been detected in the historical record (Ross et al., 2015).

1.3. Cooling water systems

Cooling water is essential to most thermo-electric generating station designs. Cooling water condenses the working fluid to help maintain a large pressure difference across the turbine. This pressure difference drives the turbine's operation. Without sufficiently cool water or sufficient flow of cooling water at the low-pressure side of the turbine, 'backpressure' would build, resulting in lower power cycle efficiency and/or reduced electricity generation.

Water-cooled systems use either once-through or evaporative cooling. Briefly, once-through systems extract cooling water from a waterbody and pass it across a heat-exchanger before releasing it directly back. For these systems, the waterbody is the primary recipient of waste heat. Once-through systems in brackish environments typically require limited chemical treatment, often consisting of only occasional chlorine pulses (Nickel Development Institute, 1994; Zhang and Dzombak, 2010). Due to ecological concerns, a shift away from once-through cooling began in the 1970s (US EIA, 2014), although many such stations still operate with decades of remaining operational life.

Evaporative cooling systems, on the other hand, consist of a heat exchanger, one or more evaporative towers, and pumps to circulate water within the system. The atmosphere is the primary recipient of waste heat through the latent heat of evaporation. As pure water evaporates, dissolved solids (i.e., salts) concentrate in the recirculating water. The level to which dissolved solids concentrate in this manner is controlled by facility operators through a flushing process called "blowdown." Due to the greater surface areas and water residence time-relative to once through systems—evaporatively cooled systems are typically coupled with more intensive chemical treatments to limit corrosion, scaling, and fouling in the cooling towers and the condenser. (Maulbetsch and Difilippo, 2008; Zhang and Dzombak, 2010). While costly, these chemical treatments increase can increase the effectiveness of the cooling system thereby increasing power cycle efficiency and reducing overall station costs when implemented properly. Walker et al. (2012), for example, explores a methodology for assessing cost-impacts of fouling in cooling systems.

Prior studies have investigated the marginal costs for constructing a new evaporatively cooled systems using brackish or saline water (Maulbetsch and Difilippo, 2008) and for operating with treated municipal wastewater relative to freshwater for cooling purposes (Barker and Stillwell, 2016; Walker et al., 2013). Another study investigated the impact of sea-level rise on the increased flooding probabilities of electricity generating station, finding that sea-level rise will place the majority of current electricity generating capacity in Delaware and New Jersey at risk of major flooding events by the end of the century (Bierkandt et al., 2015). We are aware of no study that estimates cost increases for an existing facility facing future salinity increases, however.

For an existing evaporatively cooled system, given various technical and regulatory constraints, costs are minimized by optimizing recirculating water chemistry. Allowing salinity to concentrate to high levels within the cooling system reduces the need for makeup water and associated pumping and treatment costs. On the other hand, higher salinities accelerate the processes of corrosion, fouling, and/or scaling along the surfaces of the cooling tower and the condenser, thereby decreasing thermal performance (Ibrahim and Attia, 2015; Keister, 2008; Maulbetsch and Difilippo, 2008).

Higher salinity in the cooling system also increases particulate emissions associated with "drift," the small quantity of liquid-state emissions entrained in the evaporation plume. Drift contains solutes at the same concentration as the circulating water and is frequently regulated under air quality permits for particulate matter.

From an economic perspective, nuclear stations comprise baseload generation, meaning that they tend to generate electricity nearly continuously with low marginal operating costs. Consequently, cost increases at HCGS due to increases in treatment and pumping requirements approximate a reduction in social welfare. In comparison to a scenario without SLR and channel deepening, more societal resources are required to provide each additional unit of electricity. All else equal, this implies fewer resources available for other desired goods and services in the economy.

2. Materials and methods

Future salinity forecasts were created by combining historic salinity variability, a modest historic trend of decreasing salinity, and estimates of future salinity increases from SLR and deepened channel. The resulting salinity regimes were used to inform changes in daily water throughput in a salinity-constrained cooling tower at HCGS. Increased water throughput was monetized by applying a volumetric cost for pumping and treatment to all incremental makeup water. The summation of discounted costs over baseline conditions—absent SLR and a deepened channel—represent present value of social costs. A Monte Carlo analysis was performed over each forecast to assess results over a range of input values. The presumption in this analysis is that operators respond to increased salinity by increasing blowdown and incurring greater pumping and treatment costs that result.

2.1. Baseline forecast

Daily salinity data were derived from specific conductivity measurements at the USGS station at Reedy Island, DE (USGS, 2017) during the period from June 4, 1976 to February 28, 2010, just prior to channel deepening operations began. Conductivity data were converted into salinity following industry standards (Schemel, 2001).

From 34 years of historic daily salinities, a salinity distribution was created for each calendar month. These 12 distributions were sampled probabilistically within each month to build a forecast of daily salinities into the future.

Because the Reedy Island station is 5 km upstream from HCGS and samples higher in the water column, an adjustment was necessary to account for the higher salinity that would be present at HCGS' intake. A 3-D hydrodynamic model of the estuary using the Regional Ocean Modeling System (ROMS) was used to evaluate concurrent salinity at Reedy Island and Hope Creek locations over a range of discharge conditions. Development and validation of this circulation model have been described in prior work (Chen et al., 2018, 2016). Based on the model results, a linear relationship ($1.1830\,x + 1.5853$) was derived to estimate salinity at Hope Creek from observed salinities at Reedy Island. The salinity estimates resulting from the linear transformation ranged from 0.1 psu to 19 psu with a mean of 7.0 psu, similar to previous reports for HCGS (Nickel Development Institute, 1994; PSEG Nuclear, 2010). Salinity exhibited a modest but statistically significant decrease over time, averaging 0.087 psu/yr, explained in other studies by increases in regional precipitation and greater river discharge (Najjar et al., 2013; Ross et al., 2015). This trend is captured for the duration of the analysis by incorporating iterative decreases in baseline salinity forecasts at the beginning of each model year. Because the future magnitude of this trend is uncertain, dependent on both future precipitation and river basin management trajectories, this factor was modeled in the Monte Carlo simulation between zero and twice the recently observed rate of decrease (-0.0174 psu/yr) across model iterations.

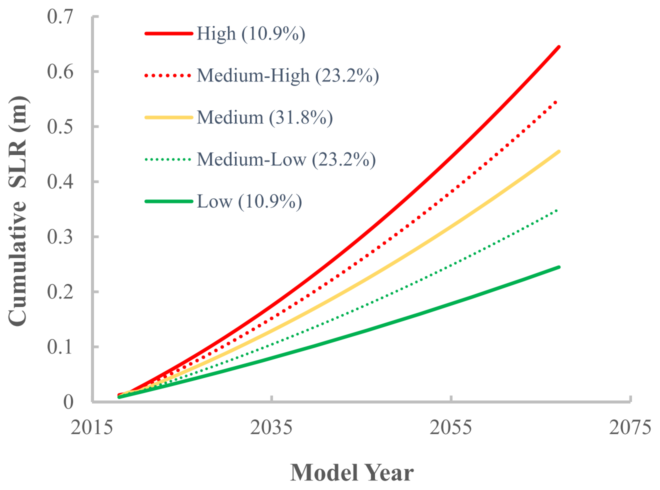

Fig. 3. The five sea-level rise paths and their assigned probabilities in model simulations based on Callahan et al. (2017). Dashed lines represent paths created through interpolation.

2.2. Anthropogenic-1 forecast

An alternative salinity forecast (Anthropogenic-1) was created by adjusting the Baseline forecast upwards to account for the marginal salinity impacts from SLR and a deepened channel. Salinity increases from SLR required estimation of both the magnitude of SLR in each future year, as well as the sensitivity of salinity at this location to each increment of rise. Five SLR projections, (Low, Medium-Low, Medium, Medium-High and High) corresponding to between approximately 0.24 m and 0.63 m of rise by 2067 relative to 2018 levels, were created based on the 2017 Delaware Sea Level Rise Technical Committee Report (Callahan et al., 2017) (Fig. 3). Callahan et al. (2017) provide three SLR scenarios and their respective probabilities for the state of Delaware based upon the work of Kopp et al. (2014) within the RCP 8.5 “business as usual” framework. We created two additional intermediate SLR cases through interpolation of the original three for more granular results.

The 3-D hydrodynamic model of the estuary was used to characterize the response of the salinity field to changes in water depth due to dredging or SLR. To incorporate the dependence of the salinity response to discharge, the model was run to equilibrium for constant river discharge cases of 100, 300, 600, and 1000 m^3/s. Three versions of model bathymetry were compared: a baseline case with a 12.2 m (40 ft) navigation channel, a dredged case with a 13.7 m (45 ft) navigation channel, and SLR case with the 12.2 m navigational channel plus a uniform increase in depth of 0.18 m, equal to the SLR over a 50yr period given a constant current trend of 3.54mm/yr. The salinity increase from SLR relative to the baseline is expressed as a sensitivity (i.e., salinity increase per meter of SLR), and the salinity increases from the 0.18 m SLR model case were used to scale the other levels of future SLR. This approach simplifies potential nonlinearities in the response of the salinity intrusion to the full range of SLR scenarios and the combination of dredging with SLR, but within the constraints of running a feasible number of hydrodynamic model cases, this approach provides scaling for the sensitivity of the estuary to the different deepening factors.

This hydrodynamic modeling also did not incorporate potential morphological feedbacks between the deepening and sediment transport processes that might mitigate the increase in estuary depth with SLR, nor did it evaluate inundation of land with SLR.

For each bathymetry case, modeled salinity at the HCGS intake was evaluated to develop relationships between salinity and river discharge. In all cases, salinity decreased as discharge increased, consistent with previous observations and modeling of the Delaware (Aristizábal and Chant, 2015; Garvine et al., 1992).

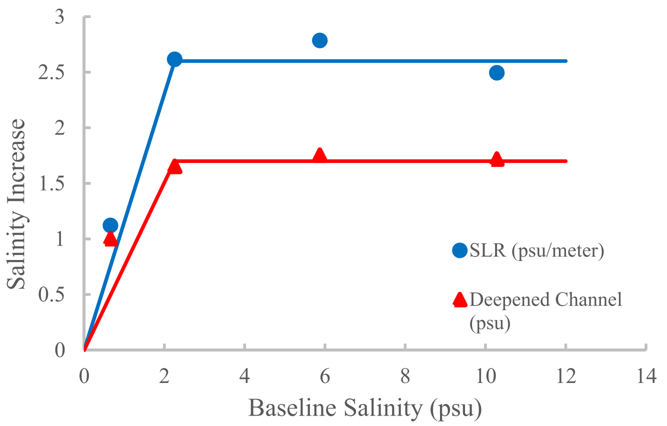

Fig. 4. Salinity increase over baseline due to SLR and a deepened channel for HCGS. Dots indicate ROMS results and lines represent approximations used in this analysis to inform future salinity increases.

In the model case with 0.18 m SLR, salinity at the HCGS intake increased by 2.6 psu/m of SLR in normal and low flow conditions and increased by a smaller magnitude in high flow conditions (Fig. 4). For a channel deepened from 12.2 m to 13.7 m, the hydrodynamic model indicated a salinity increase of 1.7 psu (or 1.1 psu/m of deepening) in normal and low flow conditions, and less of an increase in high flow conditions (Fig. 4). Refer to Table 1 for additional detail. Salinity increase due to SLR was implemented in annual increments according to the simulated SLR schedules, whereas salinity increase from channel deepening was implemented in full upon the first model year.

2.3. Anthropogenic-2 forecast

A second forecast (Anthropogenic-2) was created in which salinity increases over the Baseline forecast were informed by a previous study of salinity increases in the DE Estuary (Johnson, 2010). This study, prepared for the US Army Corps of Engineers, estimated salinity increases at HCGS from SLR of 4.9 psu/m, and increases from a deepened channel of 0.2 psu (or 0.13 psu/m of deepening). These estimates were inferred from the graphical outputs 40(b) and 100(b) that were specific to the HCGS location in Johnson (2010). In these figures, salinity increases from SLR and a deepened channel were weakly related to baseline salinity. Therefore, for Anthropogenic-2, one salinity sensitivity is applied for all flow conditions. Values for salinity increases for both Anthropogenic-1 and Anthropogenic-2 are displayed in Table 1.

2.4. Operating costs

To determine cost increases at HCGS, the cooling system was modeled as continually adjusting cycles of concentration (COC) through differential rates of blowdown to maintain the maximum designed salinity for recirculating water. HCGS was reported to have a maximum recirculating water salinity of 33.6 psu based on air quality regulations

Table 1
Salinity increase from SLR and Deepened Channel from Anthropogenic-1 and Anthropogenic-2, where S_b is salinity under Baseline.

	Anthropogenic-1		Anthropogenic-2
	Salinity increase if $S_b > 2.3$ psu	Salinity increase if $S_b < 2.3$ psu	Salinity increase for all S_b
SLR (psu/m)	2.6	$S_b \times (1.13)$	4.9
Deepened Channel (psu)	1.7	$S_b \times (0.74)$	0.2

Table 2
Overview of model inputs.

Variable	Values	Distribution in Monte Carlo	Notes
Background salinity trend (psu/yr)	0–0.0174	Uniform	Historic 34-yr mean served as the midpoint (USGS, 2017)
SLR Path	Low, Medium-Low, Medium, Medium-High, High	Low:10.9% Medium-Low: 23.2% Medium: 31.8% Medium-High: 23.2% High: 10.9%	See Fig. 4–, (Callahan et al., 2017)
Remaining Life of HCGS (years)	30, 50	Uniform	(Schwitters et al., 2013; Voosen, 2009)
Tr: Treatment Rate ($/kgal)	0.12–1.00	Triangular	(Freedman and Wolfe, 2007; Wolfe et al., 2009)
Pr: Pumping Rate ($/kgal)	0.02	Constant	See supplemental discussion
E: Evaporation rate (gallons per minute)	11,300–13,600	Constant within season	PSEG Nuclear (2010)
S^a: Ambient Salinity (psu)	0.1–18	Probabilistic draws from within month observations	USGS (2017)
S^m: Salinity maximum in cooling system (psu)	33.6	Constant	(Sargent and Lundy, 2006)
Discount Rate (%)	2, 5	–	Calculated separately

limiting particulate emissions from drift at this facility to approximately 42lbs/hr (Sargent and Lundy, 2006). In this mode of operation, fouling and corrosion rates are not likely to be altered from baseline conditions because the salinity of recirculating water is independent of ambient salinity. Operating cost increases at HCGS from elevated salinity were determined by differencing the Baseline pumping and treatment costs from those costs under scenarios Anthropogenic 1 and 2. The method of calculating these costs, including the identification of relevant parameters (Table 2), is provided in the Supplement.

2.5. *Study horizon*

According to industry statements, HCGS is currently licensed to operate until 2047, 30 years from the present, with the possibility of additional 20-year renewal (PSEG Nuclear, 2010). A 20-year extension would allow for a 50-year reactor life from the present, totaling 80 years, considered to be an upper limit on the age of an existing reactor (Schwitters et al., 2013; Voosen, 2009). It was assumed that a new nuclear facility would not be constructed at this location after the existing facility was decommissioned. Therefore, the remaining facility lifetime was specified with equal probabilities as either 30 years or 50 years.

2.6. *Monte Carlo analysis*

To account for uncertainty over input values, the model described above was run within a Monte Carlo framework consisting of 100,000 simulations. Within each Monte Carlo iteration, with the exception of daily salinity, one value was chosen for each variable and retained. The items varied between model runs were daily historic salinity, the magnitude of background salinity decrease, the treatment rate of the makeup water, the remaining station lifetime, and predicted SLR scenario. Model inputs are presented in Table 2.

3. Results

3.1. *Baseline costs*

The present value of Baseline costs averaged $121M and $78M at discount rates of 2% and 5%, respectively. The highest and lowest estimates at each discount rate spanned nearly and order of magnitude. For example, at the 2% rate, the present value of costs ranged between $25 and $254M, and $17M to $152M at the at 5% rate (Fig. 5). This wide variation was attributable primarily to the eight-fold range in the specified treatment rate of the makeup water, *Tr*. The largest values in each distribution plateaued at lower levels of probability density than the remainder of the distribution. These lower plateaus corresponded with the draws of a high Tr and a long (50yr) station life. The plateau for the 5% discount rate scenario was less pronounced than that for the 2% scenario because years 31–50 were more heavily discounted. The wide range and substantial impact of the treatment rate for makeup water tended to flatten the remainder of the distributions.

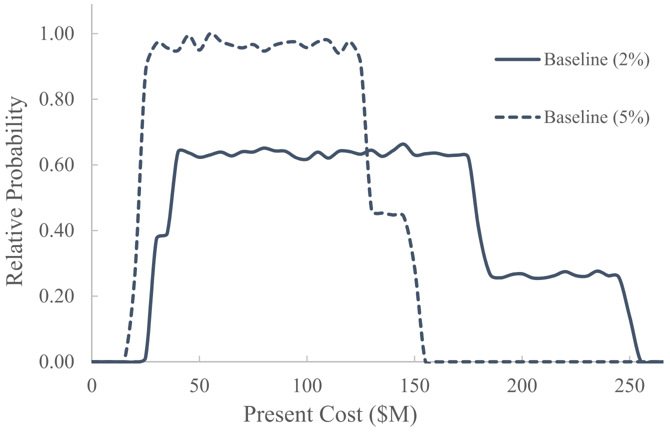

Fig. 5. Distribution of present costs estimated for the Baseline forecast at 2% and 5% discount rates.

3.2. *Anthropogenic-1 Costs*

In the Anthropogenic-1 scenario, the estimated present value of cost increases over the Baseline scenario averaged $12.1M and $7.2M at discount rates of 2% and 5%, respectively. The range of these cost increases were $2.0M to $32.7M at the 2% rate, and $1.4M to $17.1M at the 5% rate. Probability densities for these cost increases are displayed in Fig. 6.

3.3. *Anthropogenic-2 Costs*

In the Anthropogenic-2 scenario, the estimated present value of cost increases over the Baseline Scenario averaged $4.3M and $2.2M at discount rates of 2% and 5%, respectively. The ranges of these cost increases were $0.5M to $14.9M at 2%, and $0.3M to $6.7M at 5% (Fig. 6). Average cost increases from Anthropogenic-2 are approximately one-third as large as those estimated under Anthropogenic-1. The smaller cost increases relative to Anthropogenic-1 can be explained by the substantially lower estimates of salinity increases from channel deepening, partially offset by higher estimates of salinity sensitivity to

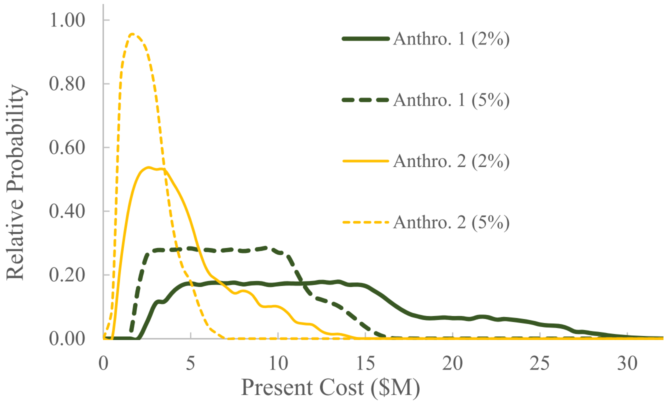

Fig. 6. Distribution of cost increases over Baseline for the Anthropogenic-1 and Anthropogenic-2 scenarios at 2% and 5% discount rates.

SLR.

3.4. *Relative contribution of factors*

In Anthropogenic-1, a deepened channel accounted for approximately 85% of the cost increase, while SLR accounted for the remainder. A deepened channel resulted in the majority of the cost increases because of its large, immediate impact on salinity compared with an initially small increase from SLR, followed by progressive salinity increases that were increasingly discounted.

4. Discussion

This research pursued three objectives: (i) to identify electricity generating stations in the Delaware River and Estuary most at risk from future salinity increase from SLR and a deepened channel; (ii) to model the magnitude of salinity increases from these factors; and (iii) to estimate the adaptations and associated social costs at the most vulnerable station. A method was developed to estimate the costs at evaporatively cooled facilities that face elevated salinities. While this paper focused on a single facility on the estuary, the method could be applied to other evaporatively cooled facilities subject to future salinity increases. Dozens of such stations exist worldwide (Eftekharzadeh et al., 2003; Maulbetsch and Difilippo, 2008), including the nearby Chalk Point and Possum Point generating stations in Maryland and Virginia. Results could also inform more complete cost-benefit analyses on channel deepening and help to refine estimates of the social cost of carbon through the impacts of SLR.

Cost increases were estimated through a novel method and are subject to several limitations. First, this analysis assumed that the cooling system would operate at maximum salinity as determined by air pollution permit compliance. In certain cases, however, the economic salinity maximum may be lower than the regulatory salinity maximum. In such cases, estimates of cost increases using the method described here may be overstated. This study did not investigate other factors related to climate change, such as shifts in ambient water temperature or turbidity patterns that could also impact cooling station operation and deserve further attention.

Further, this study omitted the social costs associated with the increased impingement and entrainment of aquatic organisms due to greater water throughput necessitated by higher volumes of makeup water. For a detailed discussion of social costs from impingement and entrainment of aquatic organisms, see US EPA (2014).

At the outset of this research, cost increases were expected to be large due to the scale of channel deepening in the Delaware River and Estuary. The estimates presented in the current study, however, suggested only modest impacts relative to operational costs. HCGS generates approximately 10.6 million MWh per year (US EIA, 2018). Assuming average production costs of $27 per MWh (Lazard, 2018), yearly production costs total $286M. Converted to equivalent annual costs, Baseline conditions represented just $4.0M or 1.4% of annual facility operating costs. The additional costs imposed by elevated salinity under Anthropogenic-1 conditions represent an incremental $0.4M, or 0.1% of annual operating costs.

5. Conclusions

The results of this work lead to several general conclusions. First, the salinity increases calculated from ROMS diverged meaningfully from previous work. These divergent results may be explained by differences in model resolution and the ranges of river discharge investigated, among other factors. A third study estimated salinity sensitivity to SLR at this location of 3.3 psu/m, intermediate in magnitude to the two values modeled here (Ross et al., 2015). To the extent regulatory bodies like Delaware River Basin Commission rely on existing models for planning, they may be substantially underestimating the future salinity intrusion resulting from a deepened channel.

Second, a recently updated cost-benefit analysis conducted for the Delaware channel deepening project estimated annual net benefits of the project of $13.7M (USACE, 2017). However, only a limited set of costs and benefits were included in that analysis, with no quantification of impacts from salinity changes. Using the 5% discount rate for comparability, the 85% share of costs from a deepened channel estimated in the Anthropogenic 1 forecast would offset approximately $0.3M, or 2% of expected annual benefits from dredging. At the upper end of findings for the Anthropogenic 1 forecast, $0.9M or 7% of net benefits would be offset. Including other indirect social costs from a deepened channel, for example changes in wetland carbon sequestration (Carr et al., 2018) or increased risk of salt intrusion at Philadelphia area water intakes, could further reduce the estimated net benefits of the Delaware channel deepening project.

Finally, estimates of salinity changes and associated cost increases could improve the capabilities of HCGS or the regional electric grid to forecast future market conditions. Small changes to operating conditions at HCGS could cascade into much larger social costs if they accelerate retirement schedules due to diminished profitability. Of course, factors affecting larger wholesale energy market are likely to be more influential on the profitability of baseload generating stations. Nevertheless, the premature loss of HCGS's annual production of 10.6M MWh of predictable, low-carbon electricity could impose substantial social costs through higher levels of pollution and the increased generating costs of any fossil fuel powered electricity generation that increases production to compensate (Berkman and Murphy, 2017).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.04.056.

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