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Identification and Characterization of Surface Water Intakes on the Chesapeake Bay

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Abstract

Even though surface water intakes in coastal regions are increasingly threatened by saltwater intrusion and river salinization, there are no comprehensive databases of these intakes. Here, using information from state agencies, we identified and characterized in a consistent manner the surface water intakes on the Chesapeake Bay, a large, coastal plain estuary of the Mid-Atlantic region of the United States, for the period 2016–2020. We identified 291 intakes in six use types: 156 irrigation and agriculture; 76 industrial, commercial, and manufacturing; 28 municipal; 19 fossil power; 10 mining; and 2 nuclear power. The nuclear and fossil power intakes accounted for 67.2% and 28.6%, respectively, of the water volume withdrawn (348 m^3 s^{-1}); most of the remainder was due to industrial, commercial, and manufacturing (2.5%) and municipal (1.5%), with very small contributions from irrigation and agriculture (0.1%) and mining (0.04%). There are intakes across a wide salinity (S) range, but many occur in the low-salinity waters threatened by saltwater intrusion —specifically tidal fresh ($S < 0.5$ g kg^{-1}) and oligohaline (0.5 g kg^{-1} $< S <$ 5 g kg^{-1}) , which have, respectively, 37% and 21% of the intakes and 11% and 28% of the water withdrawal. Our findings suggest a large potential threat of salt contamination to surface water intakes in tidal waters and the need for national databases identifying and characterizing these intakes to facilitate adaptation planning.

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Abstract

Even though surface water intakes in coastal regions are increasingly threatened by saltwater intrusion and river salinization, there are no comprehensive databases of these intakes. Here, using information from state agencies, we identified and characterized in a consistent manner the surface water intakes on the Chesapeake Bay, a large, coastal plain estuary of the Mid-Atlantic region of the United States, for the period 2016–2020. We identified 291 intakes in six use types: 156 irrigation and agriculture; 76 industrial, commercial, and manufacturing; 28 municipal; 19 fossil power; 10 mining; and 2 nuclear power. The nuclear and fossil power intakes accounted for 67.2% and 28.6%, respectively, of the water volume withdrawn (348 $m^3 s^{-1}$); most of the remainder was due to industrial, commercial, and manufacturing (2.5%) and municipal (1.5%), with very small contributions from irrigation and agriculture (0.1%) and mining (0.04%). There are intakes across a wide salinity (S) range, but many occur in the low-salinity waters threatened by saltwater intrusion—specifically tidal fresh ($S < 0.5$ g kg^{-1}) and oligohaline (0.5 g $kg^{-1} < S < 5$ g kg^{-1}) , which have, respectively, 37% and 21% of the intakes and 11% and 28% of the water withdrawal. Our findings suggest a large potential threat of salt contamination to surface water intakes in tidal waters and the need for national databases identifying and characterizing these intakes to facilitate adaptation planning.

1 Introduction

In coastal regions, surface water intakes for drinking, agriculture, industry, power generation and many other uses are being threatened by salt contamination via two primary mechanisms: saltwater intrusion (the landward movement of seawater) and the salinization of rivers feeding coastal waters (Kaushal et al., 2025; Li et al., 2025). Saltwater intrusion is driven by a variety of factors (Tully et al., 2019), including increases in mean sea level (e.g., from ocean thermal expansion and melting of ice caps), peak sea level (e.g., from tides and storms), drought, human water use, and hydrological connectivity (e.g., shipping channels and drainage ditches). River salinization also has multiple drivers, including increased application of road deicers and enhanced weathering from human development of the landscape and climate change (Kaushal et al., 2018).

To quantify and adapt to the impacts of salt contamination on surface water intakes in tidal waters, these intakes must be identified and characterized in terms of use, withdrawal rate, and salinity. However, in the United States, the main national database of surface water intakes (Dieter et al., 2018) does not distinguish between tidal and non-tidal waters, making it difficult to determine which intakes are at risk of salt contamination. Cognizant of this lack of information, the state of Maryland has prioritized research to “identify currently vulnerable water users” and “map the locations of intake pipes (surface water appropriation permits) relative to the current freshwater–saltwater transition zone” (Maryland Department of Planning, 2024). Here, using information from Maryland and Virginia state agencies, we identified and characterized in a consistent manner the surface water intakes on the Chesapeake Bay, a large, coastal plain estuary of the Mid-Atlantic region of the United States for the period 2016–2020.

2 Methodology

Surface-water intake data for Maryland and Virginia were provided by the Water Supply Program of the Maryland Department of the Environment (MDE) and the Office of Water Supply of the Virginia Department of Environmental Quality (VADEQ). Here, surface water is the qualifier used to contrast with groundwater; the intakes may, in fact, be located at the middle depths of a water body or close to the bottom. Though the tidal boundary of the Chesapeake Bay extends into Delaware and the District of Columbia, we did not consider intakes in these areas as it is likely that contributions from these regions are very small (see Discussion).

The MDE and VADEQ datasets are statewide, with 895 intakes in Maryland and 1515 intakes in Virginia, and include information on each intake's location, use, and withdrawal rate. However, the datasets differ in their characteristics in three main ways. First, while the VADEQ dataset provides latitude and longitude for each intake, the MDE dataset only provides addresses or brief geographical descriptions, sometimes with an accompanying stream name. Additional location information in the MDE dataset is the county, whether the intakes are in freshwater or saltwater, and, for most intakes, whether they are in tidal or nontidal waters. Second, the datasets differ in the number of use types: 9 for VADEQ and 23 for MDE. For comparison, the United States Geological Survey (USGS) employs eight use types in their national categorization of water intakes (Dieter et al., 2018). Third, water withdrawal rates are described by VADEQ as annual reported values from 2016 to 2020 and by MDE as permitted values of annual and daily withdrawal rates for all intakes and monthly reported withdrawal rates from 1979 to 2023 for some of the intakes. In order to create a single surface-water intake dataset for the Chesapeake Bay that describes location, use, withdrawal rate, and salinity in a consistent manner, the two datasets were homogenized in two major steps: (1) identification of the tidal intakes and (2) characterization of those intakes in terms of salinity, use type, and withdrawal rate.

2.1 Intake identification

Figure 1 is a flowchart of the steps taken to identify the tidal intakes; each of the steps is described in detail in this subsection. Most of the steps involve finding the latitude and longitude of the Maryland intakes and then determining if those intakes are tidal. Of the 895 Maryland intakes, 301 were designated as “Tidal” or “N/A.” Three entries were missing a location, so only 298 intakes were considered further. We then applied a series of filters to those intakes using information about the county, the address, salinity, the distance to shoreline, and the stream name to eliminate the non-tidal intakes.

The county filter uses the county associated with each intake: the 40 Maryland intakes that are not within the 18 counties sharing a border with the Chesapeake Bay were removed, leaving 255 intakes.

Location descriptions within the MDE dataset range from exact (addresses) to exceptionally vague (e.g., “any point within the state of Maryland with public access to the water body”). An address filter was applied that split the intakes into two categories: those with an address (212 intakes, distinguished by the address string ending in “Maryland”) and those without an address (43 intakes). For the intakes with an address, an automated programming interface (API) script was implemented using the Python programming language, powered by the Google Maps platform and its corresponding API. The script first imports the Google Maps library for address validation and geocoding and the Pandas library for data manipulation. The script then loads an API key acquired from the Google Developer Program, reads the input file containing the addresses into a Pandas data frame, and finally applies the Google Maps geocoding function to convert each address to its respective longitude and latitude.

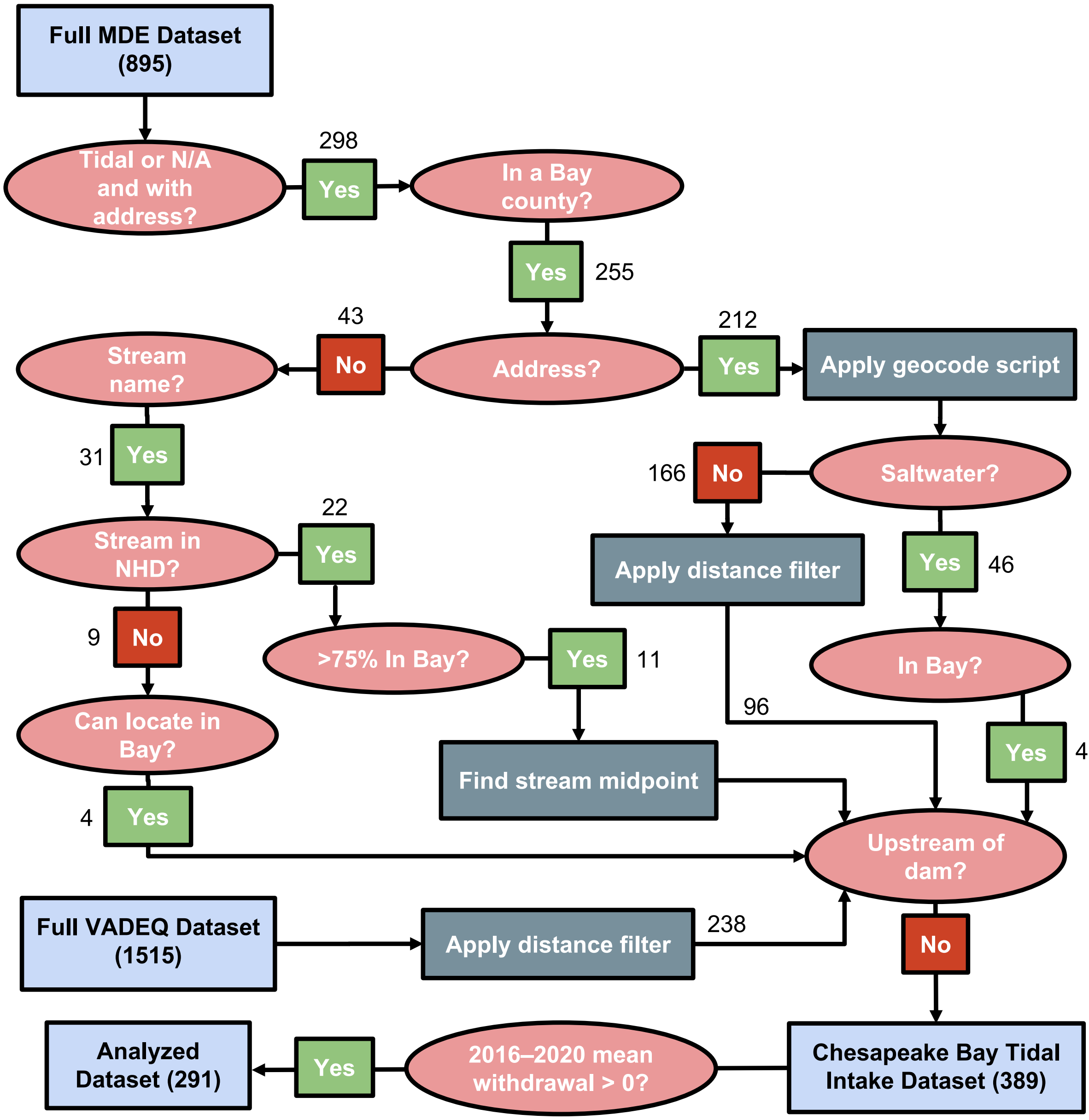

Fig. 1. Flowchart for determining tidal intakes in Maryland and Virginia. Number of intakes retained is indicated for each step.

Of the 212 Maryland intakes with an address, there were 46 designated as saltwater, which were kept in the final database, except for the 4 on the Atlantic coast. For the remaining 166 intakes, we applied a distance filter that removed any intakes beyond a specified distance from the Chesapeake Bay shoreline, the coordinates of which were provided by the Chesapeake Bay Program (2025b). To determine the threshold distance for the intake to be considered tidal, we took the 127 intakes designated as tidal by MDE and found the distance to the Bay shoreline (**Figure 2**). We chose 3 km as the threshold, as only 8.8% of the intakes (16 of them) were beyond this distance. The distance filter removed 70 intakes, placing 96 into the final database. Thus, the county, address, salinity, and distance filters placed 138 intakes into the final database.

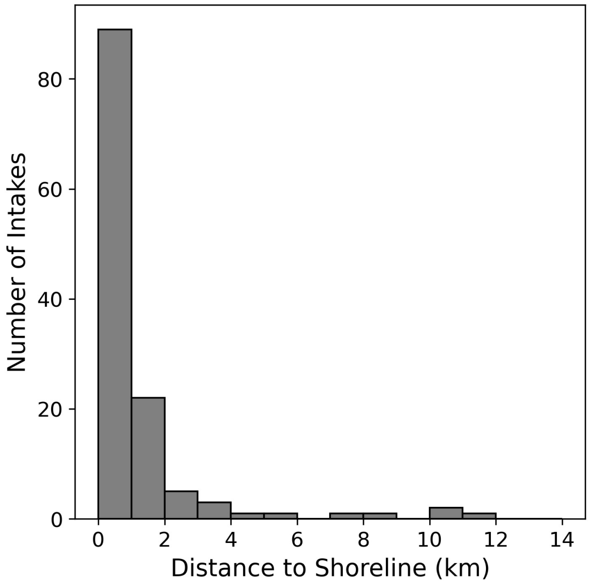

Fig. 2. Histogram of distance to shoreline of intakes in Maryland designated by the Maryland Department of the Environment as tidal.

We applied a stream filter, consisting of several steps, to the 43 intakes that passed the county filter but did not have an address. 31 of these intakes specified a stream name, which we used to estimate the location; the other 12 intakes were discarded. 22 of the 31 intakes had a stream name identified by the National Hydrography Dataset (United States Geological Survey, 2019), which provided the coordinates of the stream. We kept the associated intake if more than 75% of the stream was inside the Bay as defined by the Bay shoreline (Chesapeake Bay Program, 2025b); the 11 intakes that passed this test were kept and the remaining 11 were discarded. The latitude and longitude of the intake was estimated to be the midpoint of the stream. Of the remaining nine intakes, via internet searches, three were found to be associated with streams that were completely outside of the Bay and six with streams that were completely inside of the Bay, again using the definition of the Bay shoreline (Chesapeake Bay Program, 2025b). The intakes associated with streams completely outside of the Bay were discarded. Of the six intakes associated with streams completely inside of the Bay, there were four stream names associated with them, with three intakes having the stream name “Chesapeake Bay.” We discarded two of these intakes because of the ambiguity of the stream name but one of the intakes was designated to lie within North Beach, MD, which has a specific location and hence was retained. This left four of the six intakes to keep, and their latitude and longitude were found by hand by entering the stream name and the county or the town name (for the North Beach intake) into Google Maps. In summary, of the 31 intakes with no address but with a stream name in Bay counties, 15 were kept.

Ultimately, 153 tidal intakes on the Chesapeake Bay were found in the MDE dataset. We then applied the 3 km distance filter to the 1515 intakes in Virginia, which resulted in 238 tidal intakes in Virginia. As a final check, we eliminated intakes upstream of dams, which are clearly non-tidal. Using the National Inventory of Dams (United States Army Corps of Engineers, 2025), we found all of the dams that were inside of the Bay as defined by the Bay shoreline (Chesapeake Bay Program, 2025b). In principle, no dams should be within this boundary, but we nevertheless found 16 such instances, with 2 being associated with intakes (both in Virginia). These intakes were removed, leaving a total of 389 intakes in the Chesapeake Bay dataset.

2.2 Intake characterization: Salinity, use type, and withdrawal rate

The MDE dataset provides, for each intake, a classification of "freshwater" or "saltwater," and the VADEQ dataset provides no salinity information. To associate salinity to each intake consistently, we used an irregular high-resolution gridded product of the 1985–2018 average salinity from the Chesapeake Bay Program (2025a). This product is made up of polygons of different shapes and sizes. For each intake, we found the closest polygon edge and assigned the salinity of that polygon to the intake. We analyzed results using the conventional (The Venice System, 1958) salinity (S) classes found in the Chesapeake Bay: tidal fresh ($S < 0.5$ g kg^{-1}), oligohaline (0.5 g kg^{-1} $< S <$ 5 g kg^{-1}), mesohaline (5 g kg^{-1} $< S <$ 18 g kg^{-1}), and polyhaline (18 g kg^{-1} $< S <$ 30 g kg^{-1}).

We mapped the 23 use types in the MDE dataset onto the 9 use types in the VADEQ dataset and further collapsed VADEQ's agriculture and irrigation use types into one and manufacturing, commercial, and industrial into another, leaving us with a total of 6 use types (**Table 1**). For most of the MDE use types, the mapping was straightforward. Assistance was provided by VADEQ, who clarified that drinking water intakes were included in the municipal use type and that the agriculture use type includes all non-irrigation uses, including aquaculture. The six use types have some similarity to the eight use types employed by the USGS (Dieter et al., 2018): public supply, domestic, irrigation, livestock, aquaculture, industrial, mining, and thermoelectric power.

We computed the 2016–2020 average of the reported withdrawal rates (in units of m^3 s^{-1}) where available, which was for all of the Virginia tidal intakes and 103 of the 153 Maryland tidal intakes. For the remaining 50 tidal intakes in Maryland, we estimated the reported withdrawal rate using an equation relating the permitted (P) to reported (R) rates. That equation was created as follows. Because the permitted rates span 6 orders of magnitude, from about 10^{-4} to 10^{2} m^3 s^{-1}, we applied a base-10 log transformation to the reported and permitted rates; we did not include the 24 intakes with zero reported withdrawals to avoid singularities when taking the log. We then used least squares to fit the line $\log_{10} R = a + b\log_{10} P$ to the data (**Figure 3**), where a = 0.961 and b = –0.794. Finally, the reported withdrawal rate for the 50 intakes was computed from $R = 10^{a}P^{b}$.

Table 1. Homogenization of use types across Maryland and Virginia.

VADEQ use types	MDE use types
Fossil power	Fossil fueled power generation
Industrial, commercial, and manufacturing	Industrial (undefined) Industrial heating and cooling water Industrial wash and separation processes Commercial (undefined) Hydrostatic testing and fire protection
Irrigation and agriculture	Crop irrigation Golf course irrigation Lawn & park irrigation Nursery irrigation Sod farm irrigation Small intermittent irrigation Irrigation (undefined) Aquaculture
Mining	Mining operations
Municipal	Government run water supply Recreational drinking/sanitary Institutional drinking/sanitary Commercial drinking/sanitary Environmental enhancement Laboratories Wildlife ponds and recreational
Nuclear power	Nuclear power generation

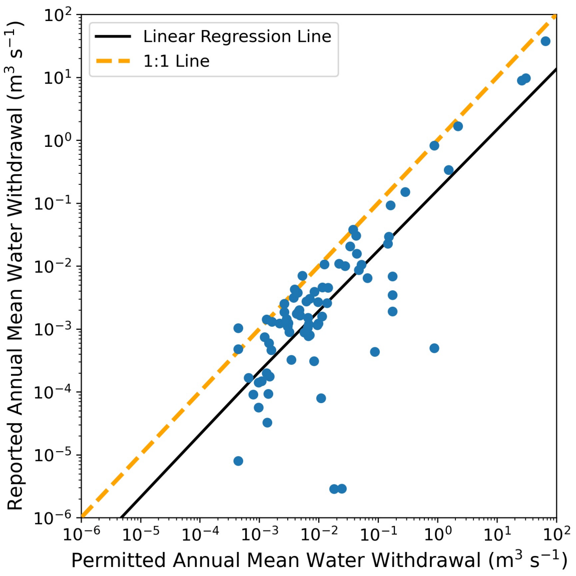

Fig. 3. Relationship between permitted (*P*) and reported (*R*) tidal water withdrawal rates in Maryland. Linear regression equation is $\log R = -0.794 + 0.961 \log P$, $N = 79$, $r^2 = 0.82$.

3 Results

Unless otherwise specified, withdrawal rates always refer to the 2016–2020 average. The withdrawal rate was non-zero for 291 intakes and we limit our analysis to these intakes (**Figure 1**), the locations of which are shown in the context of the four salinity classes in **Figure 4**. Intakes are well distributed throughout the Bay. The total water withdrawal from the Chesapeake Bay (summed over the 291 intakes) is 348 $m^3 s^{-1}$ or, in units commonly used in US water resources analyses (e.g., Dieter et al., 2018), 7.9 billion gallons per day.

Most (54%) of the intakes are in the irrigation and agriculture use type (**Figure 5a, Table 2**), with industrial, commercial, and manufacturing being the second most populous use type (26%). However, when the use types are ranked by the withdrawal rate, power generation dominates (**Figure 5b, Table 3**). Remarkably, the two nuclear power plants in the dataset—Calvert Cliffs Nuclear Power Plant, Unit 2 (Lusby, MD) and Surry Power Station, Unit 2 (Surry, VA)—account for 67% of the water withdrawn. Of the remaining 33%, nearly all of it (29%) is due to the 19 fossil power plants, followed by industrial, commercial, and manufacturing uses (2.4%) and municipal uses (1.5%), with very small contributions from irrigation and agriculture (0.1%) and mining (0.04%).

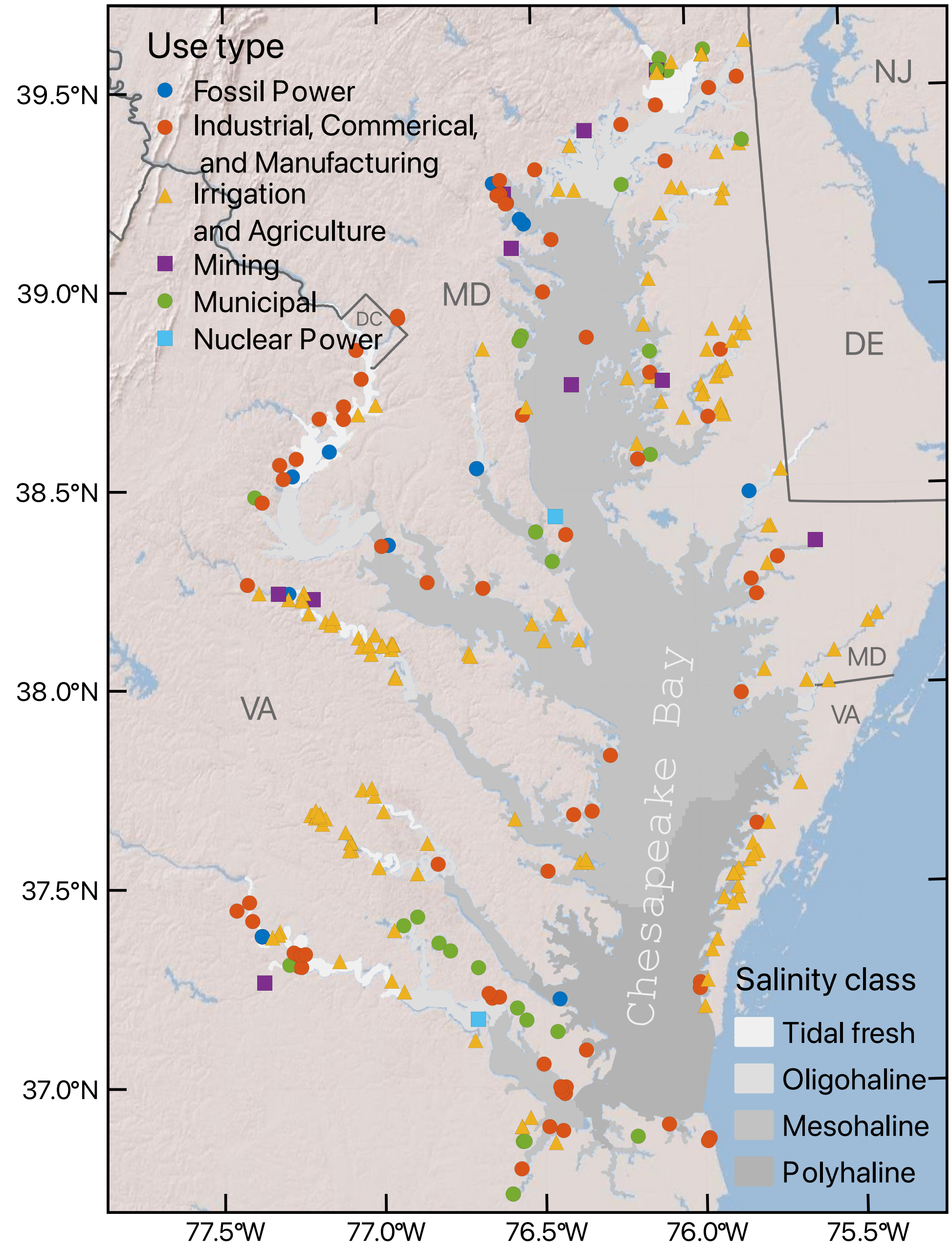

Fig. 4. Locations and use types of the 291 surface water intakes on the Chesapeake Bay (2016–2020) mapped on the four salinity classes based on the mean surface salinity for 1985–2018.

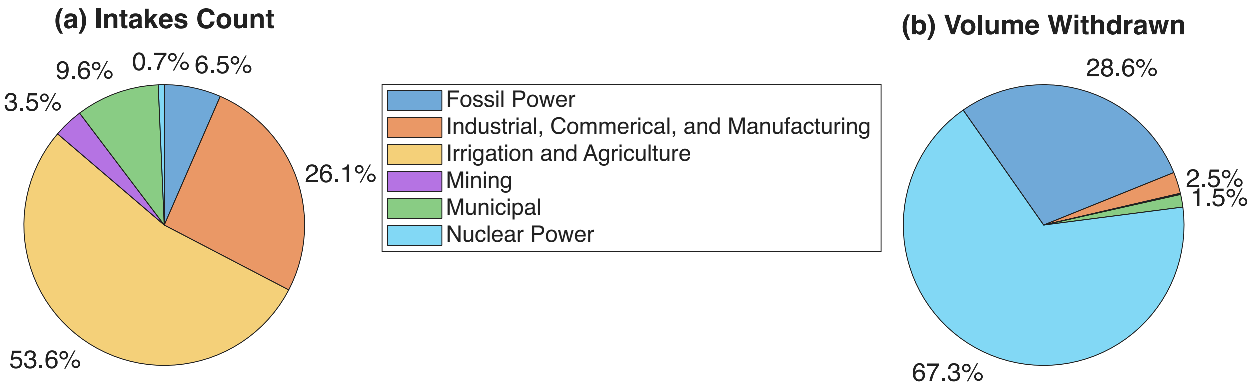

Fig. 5. Percent of (a) intakes (b) water volume withdrawn by each of the six use types in the Chesapeake Bay (2016–2020). Percentage of volume withdrawn by Industrial, Commercial, and Manufacturing and Mining is not shown, as they total ~0.1%

Table 2. Number of intakes by use type and salinity class.

	Tidal fresh	**Oligo-haline**	**Meso-haline**	**Poly-haline**	**Total**
Fossil	10	3	5	1	19
Ind., com. & man.	21	11	40	4	76
Irrigation and agriculture	66	38	33	19	156
Mining	4	1	5	0	10
Municipal	6	7	14	1	28
Nuclear	0	1	1	0	2
Total	107	61	98	25	291

Table 3. Water withdrawn ($m^3\ s^{-1}$) by use type and salinity class.

	Tidal fresh	Oligo-haline	Meso-haline	Poly-haline	Total
Fossil	29.8	9.67	48.6	11.5	99.6
Ind., com. & man.	7.33	0.00533	1.22	0.0237	8.58
Irrigation and agriculture	0.172	0.0892	0.0664	0.0264	0.354
Mining	0.0701	0.000185	0.0563	0	0.127
Municipal	1.08	1.14	2.06	0.784	5.06
Nuclear	0	87.2	147	0	234
Total	38.5	98.1	199	12.3	348

Figure 6 provides detailed information about withdrawal rate statistics, including the number of intakes in decadal (factor-of-10) withdrawal rate bins for the six individual use types and all use types together, as well as mean and median withdrawal rates for each of the use types. The withdrawal rate varies dramatically across the 291 intakes, from the lowest at $1.14 \times 10^{-6}\ m^3\ s^{-1}$ for an irrigation and agriculture intake, to the highest at $147\ m^3\ s^{-1}$ for a nuclear power intake, a range of more than eight orders of magnitude. Even within a use type, the range in the mean withdrawal rate is large, between three and six orders of magnitude for all use types except nuclear power. The mean withdrawal rate per intake for each use type varies considerably across the use types, with low withdrawal rates for irrigation and agriculture ($0.0023\ m^3\ s^{-1}$) and mining ($0.013\ m^3\ s^{-1}$), moderate withdrawal rates for industrial, commercial, and manufacturing uses ($0.11\ m^3\ s^{-1}$) and municipal uses ($0.18\ m^3\ s^{-1}$), and high withdrawal rates for fossil power ($5.2\ m^3\ s^{-1}$) and nuclear power ($117\ m^3\ s^{-1}$). Median withdrawal rates were similarly organized, except for the industrial, manufacturing, and commercial use type, which had the lowest value. Except for

nuclear power, medians were lower than means, indicating distributions skewed towards lower values.

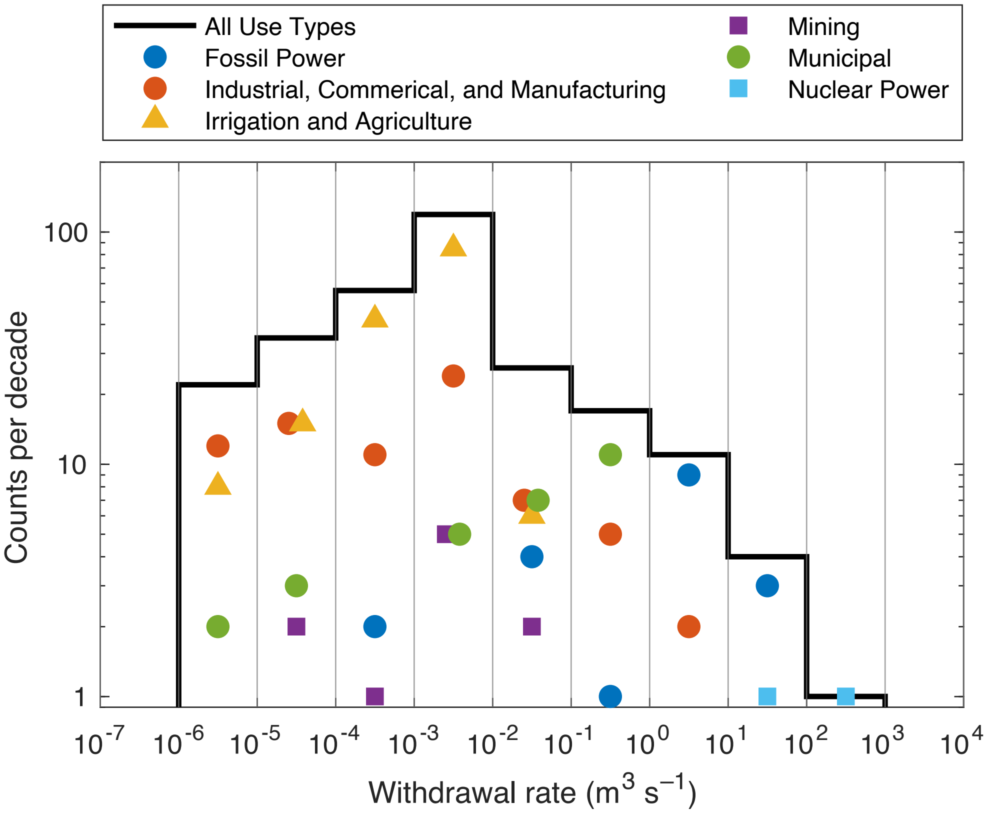

Fig. 6. Histogram of the number of intakes as a function of the 2016–2020 mean withdrawal. Shown are the six individual use types (symbols) as well as all of them together (solid line). Also shown above the histogram are the means and median withdrawal rate for each use type.

There are intakes across a wide salinity range (**Figure 7a, Table 2**), but the largest fractions are in tidal fresh (37%) and mesohaline (34%) waters, followed by oligohaline (21%) and polyhaline (9%) waters. Thus, more than half of the intakes are in the low-salinity (tidal fresh and oligohaline) classes, where increases in salinity are expected to have the largest impacts on intakes. The distribution of withdrawals across salinity classes differs from that of intakes in that there is much less water withdrawn from the tidal fresh and polyhaline classes, 11% and 4% of the total, respectively, than the number of intakes would suggest (**Figure 7b**). More than half (57%) of the water withdrawn is mesohaline and 28% is oligohaline. Thus, low-salinity (tidal fresh and oligohaline) water withdrawal is 39% of the total.

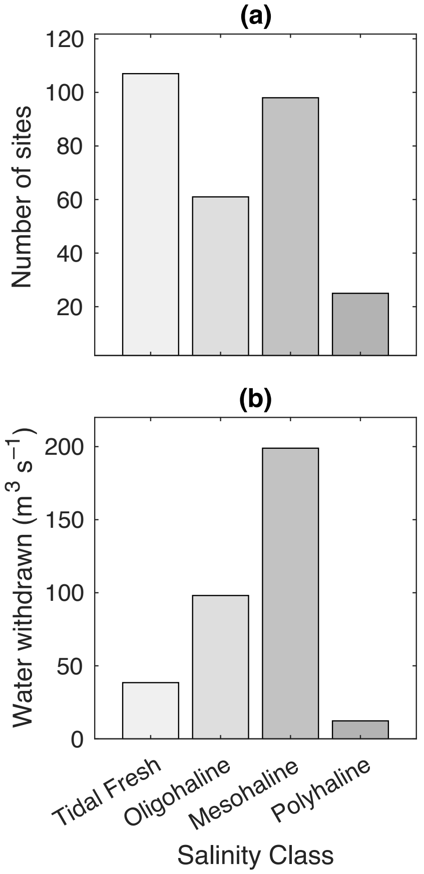

Fig. 7. (a) Number of surface water intakes and (b) volume of water withdrawn by salinity class.

Table 2 shows that the number of irrigation and agriculture intakes decreases with salinity class from tidal fresh (66) to polyhaline (19); a similar pattern is seen for volume of water withdrawn (**Table 3**). Such a pattern is expected, given that many agricultural crops are harmed by increases in salinity (Grieve et al., 2012). For the other use types, the number of intakes or volume withdrawn does not vary monotonically with salinity class. However, the tidal fresh and mesohaline are the two most common salinity classes for fossil power, industrial, commercial, and manufacturing uses, and mining, in terms of both number of intakes and volume withdrawn.

Somewhat unexpectedly, the municipal use type has more intakes in and more water withdrawn from mesohaline waters compared to tidal fresh waters. The two nuclear power plants are split between the oligohaline and mesohaline salinity classes, with 69% more water withdrawn at the mesohaline site.

The irrigation and agriculture use type dominates the number of intakes in the low-salinity classes, tidal fresh and oligohaline, at 61.7 and 62.3% of intakes, respectively. However, power generation (fossil and nuclear combined) withdraws most of the water in these salinity classes: 77% from tidal fresh and 98.8% from oligohaline waters.

In almost all aspects, the results are not sensitive to the method of estimating the reported water withdrawals for the 50 unreported intakes in Maryland (**Section 2.2**). To estimate the error associated with ignoring the 24 intakes with zero reported rates in the regression, we set the lower- and upper-bound estimates for the 50 intakes to zero and to the permitted values, respectively. The total water withdrawal across all use types and for each individual use type differed by less than 1% between the lower- and upper-bound estimates, except for the lowest withdrawal rate category, mining, in which case the upper-bound estimate (0.38 $m^3\ s^{-1}$) was 5 times the lower bound estimate (0.08 $m^3\ s^{-1}$).

4 Discussion

We have identified and characterized 291 intakes on the Chesapeake Bay that were active (withdrawal rate > 0) during the 2016–2020 period. We found that most of the intakes are used for agriculture and irrigation, most of the water withdrawn is for power generation, and the intakes are distributed across the full range of salinity. We now place our findings into a larger regional context, speculate on the vulnerability of the intakes to long-term changes in salinity, discuss the impact that the intakes may have on the Chesapeake Bay itself, and finally argue for coordination of tidal water intake databases at the national level.

4.1 Comparison to state- and national-level analyses

We contextualize our findings by comparing them to the US state- and national-level analyses of water use by Dieter et al. (2018), who categorize water withdrawals in 2015 by two source types (surface water and groundwater), two salinity classes, and eight use types. Regarding source, only a small fraction, 4.5% for Maryland and 4.4% for Virginia, is groundwater, which contrasts with the national level, for which 26% of the source is groundwater.

Dieter et al. (2018) distinguish only between fresh and saline water, where the boundary between the two is a dissolved solids concentration of 1 g L^{-1} (very close S = 1 g kg^{-1}); further, this distinction is only made for the mining, industrial, and thermoelectric power use types (the five other use types, which are public supply, domestic, irrigation, livestock, and aquaculture, are assumed to withdraw only fresh water). Maryland and Virginia differ substantially in the salinity of water withdrawals (**Table 4**). For all surface waters, the fraction of withdrawals that are fresh is rather small in Maryland (15%) and large in Virginia (63%). As expected, these fractions decrease for tidal waters, quite substantially for Maryland (to 0.1%) and markedly for Virginia (to 28%), showing that most of the freshwater withdrawals from the Chesapeake Bay are in Virginia. For the Bay as whole, the fraction of withdrawals that are fresh is 11%. Note that the results would only change slightly (by 1 m^3 s^{-1} for the whole Bay) had we used S = 0.5 g kg^{-1} as the boundary between fresh and saline water. The contrast with the US as a whole, where most (84%) of the surface water withdrawals are fresh, is dramatic.

To facilitate the comparison with Dieter et al. (2018) in terms of use types, we combined our fossil power and nuclear power use types to compare to their thermoelectric power use type;

their irrigation, livestock, and aquaculture use types to compare to our irrigation and agriculture use type; and their public and domestic supply use types to compare to our municipal use type. Thermoelectric power dominates the surface water withdrawals across the states of Maryland and Virginia (86%), lower than what we found for the Chesapeake Bay as a whole (96%), with the main difference due to the municipal use type, which is responsible for 10% of surface withdrawals across Maryland and Virginia, compared to 1.5% for the Bay. Industry contributes similarly and modestly across the two states (2.8%) as it does for the Bay (2.5%). Smaller contributions in the two states come from irrigation and agriculture (1.6%) and mining (0.2%), which is mimicked by the Bay but at even lower levels (0.1% and 0.04%, respectively). For the US as a whole, thermoelectric power is responsible for 56% of surface water withdrawals, with the remainder mainly due to irrigation and agriculture (29%) and municipal (10%), and relatively minor contributions from industry (5%) and mining (0.5%).

Table 4. Surface water withdrawal estimates by salinity and region ($m^3\ s^{-1}$). Note that 1 $m^3\ s^{-1}$ = 22.8 million gallons per day. The estimates for all surface waters come from Dieter et al. (2018) and correspond to the year 2015. The estimates for tidal waters are based on this study and correspond to the average over the years 2016–2020.

		Fresh **($S < 1$ g kg^{-1})**	**Saline** **($S > 1$ g kg^{-1})**	**Total**
All surface waters	**MD**	41	232	273
	VA	177	105	282
	MD + VA	218	337	555
	US	8670	1690	10380
Tidal waters	**MD**	0.2	206	207
	VA	39.3	102	141
	MD + VA	39.5	308	348

The contribution of Washington, DC to surface water withdrawals from the Chesapeake Bay is small. Dieter et al. (2018) estimate a total surface withdrawal rate of 0.002 $m^3 s^{-1}$, all for irrigation. Unfortunately, we are not able to determine the contributions of surface water withdrawals from Delaware at this time, but we suspect that they are small, given the small area involved, mostly in the southwest corner of the state (**Figure 4**).

4.2 Vulnerability of intakes to salinity change

Many water uses are sensitive to the salinity of the source water, with an increase in salinity generally associated with a decline in water quality. Here we briefly consider impacts on drinking water, crops, and thermoelectric power. The salinity of drinking water is generally not regulated, but a common threshold in many countries is a chloride concentration of 250 mg L^{-1} (Lassiter, 2021), which corresponds to a salinity of 0.45 g kg^{-1}, using the ratio of chlorine to total dissolved salts in seawater (Talley et al., 2011). Hence, rather modest increases in salinity in the Chesapeake Bay, such as those forecasted under some projections of streamflow (e.g., Muhling et al., 2017) and sea-level (e.g., Rice et al., 2012), could significantly compromise the quality of the 6 tidal fresh municipal intakes on the Bay, which collectively withdraw 1 $m^3 s^{-1}$ (**Tables 2 and 3**).

Grieve et al. (2012) tabulated the electrical conductivity of soil water at which negative impacts on plants begin to be seen. We converted these thresholds to salinity by multiplying by 0.5 g kg^{-1} (mSiemens $cm^{-1})^{-1}$, based on the relationship of Schemel (2001) for specific conductivity (the electrical conductivity of the water sample brought to a temperature of 25 ºC). The threshold salinity ranges from 0.2 to 5.7 (median 3.1) g kg^{-1} ($N = 20$) for fiber, grains, and special crops; 0.8 to 4.0 (median 1.3) g kg^{-1} ($N = 31$) for grasses and forage crops; 0.5 to 3.5 (median 0.9) g kg^{-1} ($N = 32$) for vegetable and root crops; and 0.6 to 4.4 (median 0.8) g kg^{-1} ($N =$

10) for woody crops. As with drinking water, many of the thresholds for crops are lower than some projected increases in salinity for the Chesapeake Bay, which suggests that crops irrigated from the numerous (as many as 66) intakes in tidal fresh and oligohaline waters (totaling 0.17 m^3 s^{-1}) may be at risk (**Tables 2 and 3**).

Harto et al. (2014) reviewed the impact of source-water salinity on the construction and operation of thermoelectric power plants. Fresh water is preferred for at least two reasons. First, saltwater cooling towers are 35–50% more costly than their freshwater counterparts due to the more expensive construction materials needed to resist the higher corrosivity of saltwater. Second, saltwater is less efficient than freshwater at cooling due to the decline in vapor pressure with salinity; the impact is about a 1% decline in efficiency for every 10 g kg^{-1} increase in salinity. While long-term salinity increases are unlikely to significantly affect cooling efficiency, corrosion at fossil power plants designed for low-salinity water may be a concern. Specifically, the 10 plants that collectively withdraw 30 m^3 s^{-1} from tidal fresh waters (**Tables 2 and 3**) may be affected.

Impacts of salinity on use types other than drinking water, agriculture, and thermoelectric power are less well known, though we suspect that any intakes in tidal fresh waters may be negatively impacted by projected increases in salinity. For the remaining two use types (mining and industry, commercial, and manufacturing), there are 70 intakes that withdraw 7.5 m^3 s^{-1} (**Tables 2 and 3**). Summarizing, across all use types except nuclear power, there are numerous (a total of 107, withdrawing 38.5 m^3 s^{-1}, **Tables 2 and 3**), that may be at risk of salt contamination.

While we have framed the characterization of the intakes and the projected salinity change using long-term averages, changes in salinity variability should be kept in mind. Just as the most extreme impacts of a warming climate may be associated with short-lived increases in temperature and precipitation, salinization events—salt waves—may be the main mode of negative impacts from salt contamination. Salinity variability may increase particularly at short time scales due to projected increases in tidal range (Ross et al., 2017) and storm surge (Gori et al., 2022).

4.3 Impacts on the Chesapeake Bay

Water withdrawals from the Chesapeake Bay are substantial when compared to the amount of freshwater entering the Bay from rivers. The latter is estimated regularly by the USGS using streamflow measurements from the Susquehanna, Potomac, and James Rivers, as well as water diversion estimates upstream of the gauges on the latter two (Bue, 1968). The average for 2016–2020 is 2604 m^3 s^{-1}, making the total water withdrawal from the Chesapeake Bay during this time (348 m^3 s^{-1}) 13% of the river input. Dieter et al. (2018) estimate consumptive water use, which is water withdrawal that is not readily available for another use (due, for example, to evaporation or incorporation into crops), for thermoelectric power and agriculture. Thermoelectric power plants in Maryland and Virginia were estimated to consume 1.0% and 1.1%, respectively, of water withdrawals in 2015. Maryland Power Plant Research Program (2024) estimates an even smaller consumptive fraction, 0.54%, for the Calvert Cliffs Nuclear Power Plant. The agricultural consumptive water use fractions were estimated to be 89% and 85% for Maryland and Virginia, respectively. Given the dominance of thermoelectric power in water withdrawals from the Chesapeake Bay (97% of the total), it is clear that consumptive water use is quite small, at most about 3 m^3 s^{-1}, or 0.1% of the freshwater input to the Bay from rivers.

The main impacts of water withdrawals on the Chesapeake Bay are likely ecological. Once-through (i.e., open-loop) cooling systems, which dominate the thermoelectric plants on the Chesapeake Bay, withdraw a large volume of water, raising its temperature by as much 10 ºC before discharging the water back to the source body (Nuclear Regulatory Commission, 1996). Impacts are generally considered in several categories (Heck, 1987): (1) impingement, which is the trapping of organisms on screens at the intake, (2) entrainment, which is the passage of smaller organisms, mainly plankton, including fish eggs and larvae, through the cooling system, (3) warming of the surrounding waters, (4) scouring of the seabed from the high velocity of the discharge, and (5) contamination.

Numerous studies of these impacts have been conducted in the Chesapeake Bay, particularly on the Calvert Cliffs Nuclear Power Plant, due to the large volume of water withdrawn (147 $m^3\ s^{-1}$ for 2016–2020). Impingement affects a large number of fish, with Calvert Cliffs alone responsible for the impingement of 1.3 million fish per year from 1975 to 1995, 27% of which are killed, though this mortality is dwarfed by the other sources of mortality, such as commercial fish landings (Ringger, 2000). Entrainment impacts on phytoplankton and zooplankton at Calvert Cliffs, estimated by comparing intake water with discharge water, are substantial across a number of metrics (individual counts, chlorophyll, and productivity), though the effects on surrounding waters seem to be minimal (Sellner et al., 1987). Entrainment of fish larvae, such as that of the bay anchovy, can be substantial and also impact higher-trophic levels, as studies in the Patuxent River Estuary have shown (Polgar et al., 1988; Summers, 1989). Warming of surrounding waters is measurable and even detectable from satellite (Ding & Elmore, 2015) but seems to be limited to a rather small area due to rapid mixing. Similarly, scouring of the seabed has mainly localized impacts. Benthic macrofauna studies around several power plants in the Bay confirm the localized impacts of warming and scouring (Jordan & Sutton, 1984; Loi & Wilson, 1979). Finally, early concerns about contamination from metals and radionuclides were either resolved by plant modifications or deemed to be insignificant (Abbe, 1987). In summary, while power plants in the Chesapeake Bay certainly have a measurable impact on the ecology, the effects seem to be localized and sufficiently small compared to other impacts (e.g., commercial fishing) and when balanced against societal need for energy (Richkus & McLean, 2000).

4.4 The need for a national database of surface tidal water intakes

Because river basins and estuaries cross state and national boundaries, water resource management must be conducted at the national and international levels as well as at local (e.g., municipal and state) levels. While local expertise is critical for identification and characterization of water intakes, robust intercomparisons across space and time require consistent criteria. As such, the USGS, in the development of national reports, leverages local expertise while providing guidelines for producing state-level datasets that can be used at the national level (Bradley, 2017). Specifically, these guidelines specify eight use types, two source types (surface water and ground water), and two salinity categories. We support these guidelines and further recommend that some metric for tidal influence be included so that the threat of saltwater intrusion can be assessed for intakes in tidal fresh waters. Along these lines, a national database of the tidal coastline, perhaps provided by the National Oceanographic and Atmospheric Administration, would be extremely helpful.

5 Conclusion

We combined and homogenized databases from Maryland and Virginia to develop a single database for surface water intakes on the Chesapeake Bay, which organizes the intakes by six use types, mean salinity, and volume of water withdrawn (mean over 2016–2020). Our main findings are as follows:

- There are 291 active intakes on the Chesapeake Bay, most of which (54%) are for irrigation and agriculture; however, most of the water withdrawn (96%) is for power generation.

- All salinity categories are represented in the database, with a large number (58% of the intakes and 39% of the withdrawal volume) in the tidal fresh and oligohaline salinity classes, which are considered vulnerable to salt contamination.
- The total amount of water withdrawn is equal to 13% of the freshwater input to the Bay by rivers, though most (99%) is returned to the Bay.

Development of similar databases for other estuaries across the US and other nations is critical for adaptation planning in the face of threats that are unique to coastal waters, such as salt contamination of tidal fresh and oligohaline waters. We encourage national and international coordination efforts so that we can most effectively manage these global threats, which will only increase over the coming decades as the climate continues to warm and coastal regions continue to be developed.

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Data Availability Statement

The intakes database is provided in the file Chesapeake_Bay_Tidal_Surface_Intakes.xlsx, which will be made available upon publication of this article in Penn State's research repository, ScholarSphere. While the intakes are shown on the map in Figure 4, locations are removed from the file for the security of the sites.

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