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Global Perspective

The Emerging Global Threat of Salt Contamination of Water Supplies in Tidal Rivers

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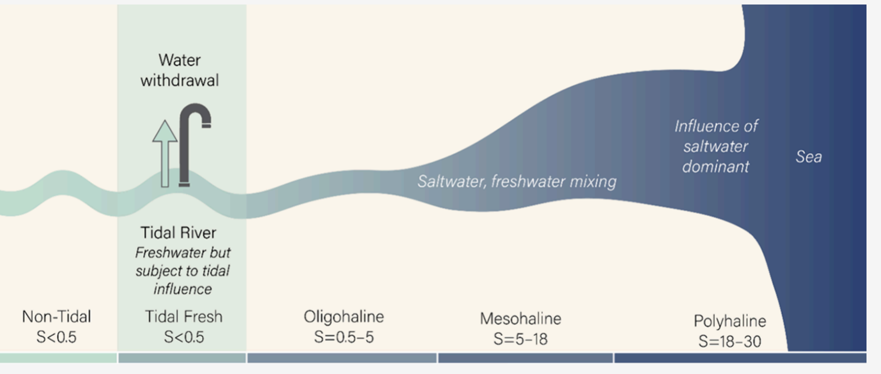

ABSTRACT: Salt contamination of water supplies in tidal rivers is a global problem, but it has received little attention beyond site-specific studies. Drought, sea-level rise, navigation channel dredging, and watershed land-use change increase the risk of salinization and threaten drinking water supplies, agricultural irrigation, and infrastructure (via corrosion). The emerging issue of salt contamination of water supplies in tidal rivers and its diverse impacts highlight the critical need for interdisciplinary research that must integrate knowledge from oceanography, hydrology, and water resource management. Here we elucidate oceanic and hydrological processes regulating saltwater intrusion into estuaries and tidal rivers as well as watershed processes driving enhanced chemical weathering and export of watershed salts into rivers. By synthesizing studies around the world, we discuss how sea-level rise, prolonged drought, and increasingly extreme weather events in a changing climate are driving more frequent saltwater intrusion events that threaten water security globally. We propose a convergent research agenda toward the development of a decision support tool for salinity management. Specifically we recommend making ion-specific measurements and developing hydrological–hydrodynamic models to simulate the transport of major salt ions. These models can then be combined with artificial intelligence algorithms and enhanced monitoring to explore management strategies with stakeholders.

KEYWORDS: *Tidal rivers, saltwater intrusion, freshwater salinization, water supplies, climate change*

1. THE EMERGING GLOBAL ISSUE

About two-thirds of the global drinking water supply comes from surface waters, including tidal rivers. The World Health Organization recommends that drinking water should not contain more than 250 mg L^{-1} of chloride, and that high sodium levels (>20 mg L^{-1}) in drinking water are linked to hypertensive disorders and developmental delays in children.[1−4] Since seawater contains about 19,400 mg L^{-1} of chloride and 10,670 mg L^{-1} of sodium, saltwater intrusion poses a major threat to public health. Salt contamination of drinking water intakes in tidal rivers has made headlines worldwide in recent years. For example, the United States (US) Army Corps of Engineers had to barge freshwater to water treatment facilities in New Orleans to decrease the salinity to levels safe for drinking in fall 2023.[5] A temporary emergency barrier was placed on the West False River in the Sacramento−San Joaquin Delta in June 2021 to slow saltwater intrusion from the ocean.[6] Salt contamination of drinking water also occurred in the Chao Phraya River in 2020, where residents in Bangkok, Thailand, were urged to conserve water.[7] The 2022 summer drought in Europe led to record low flows in the Rhine River and triggered emergency water conservation measures in The Netherlands.[8] These events expose a void in understanding the salt contamination of water supplies in tidal rivers.

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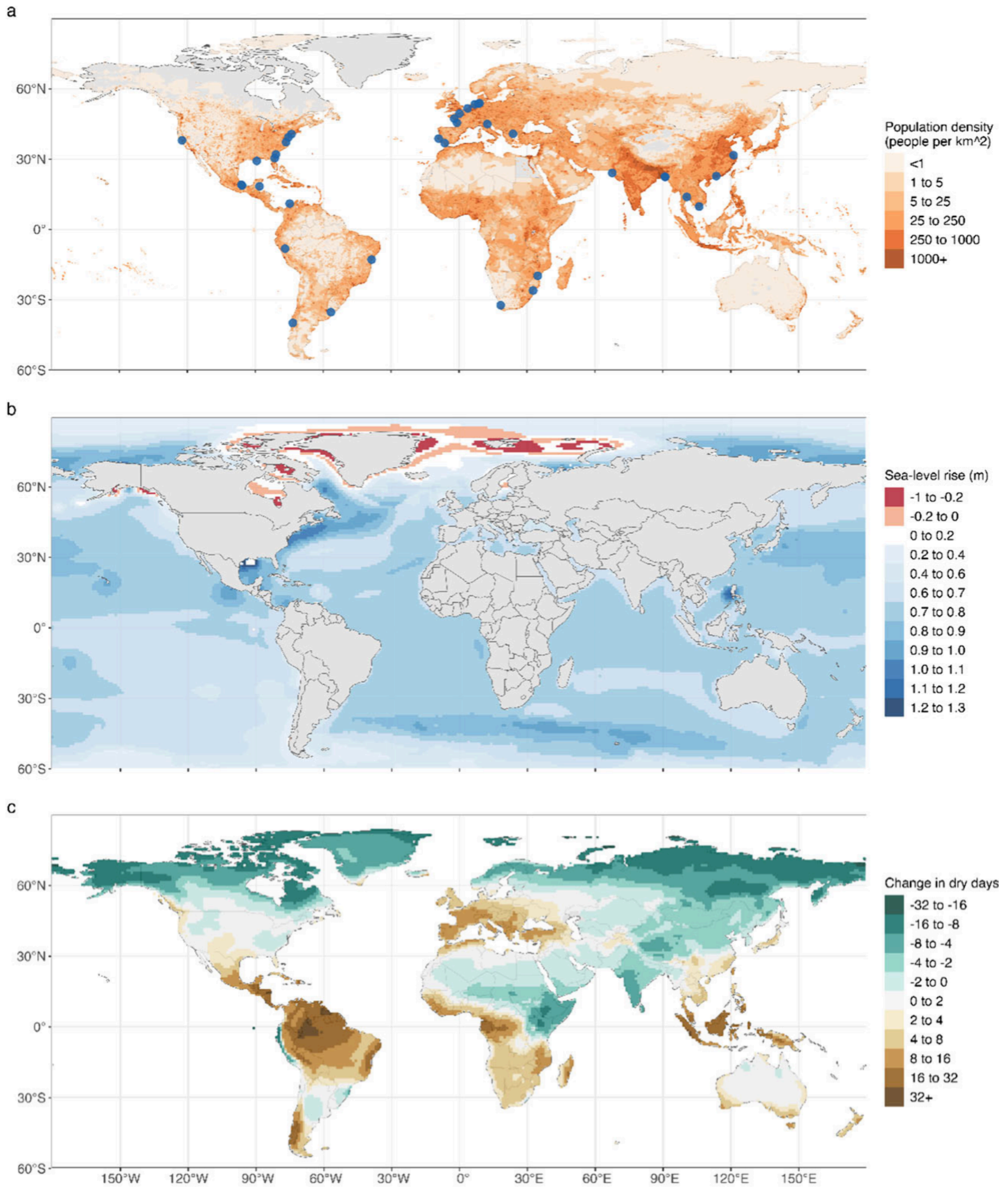

Figure 1. (a) Global map of population density (color) and locations of the tidal rivers with reported saltwater contamination issues (blue dots). Global maps of the projected (b) median regional relative sea-level change and (c) seasonal mean relative changes (%) in the number of dry days (i.e., days with less than 1 mm of rain) from 1995−2014 to 2100 averaged across available Coupled Model Intercomparison Project Phase 6 (CMIP6) models in the high emission SSP5-8.5 scenario. The sea-level projection is from ref 111 and the dry days projection is from ref 135.

Saltwater intrusion is a global problem affecting many countries[9] (Figure 1a). Several rivers in Africa are affected, including the Pungue River between Zimbabwe and Mozambique and the Incomati River in southeast Africa.[10] In Europe, saltwater intrusion concerns range from the Mediterranean to the Atlantic and North Sea coasts, including the Po River Delta in Italy,[11] the Garonne, Loire and Seine Rivers in France,[12] the Rhine River in The Netherlands, and the Elbe, Weser and Ems estuaries in Germany.[13] Many of Asia's megacities are vulnerable to salt contamination of water

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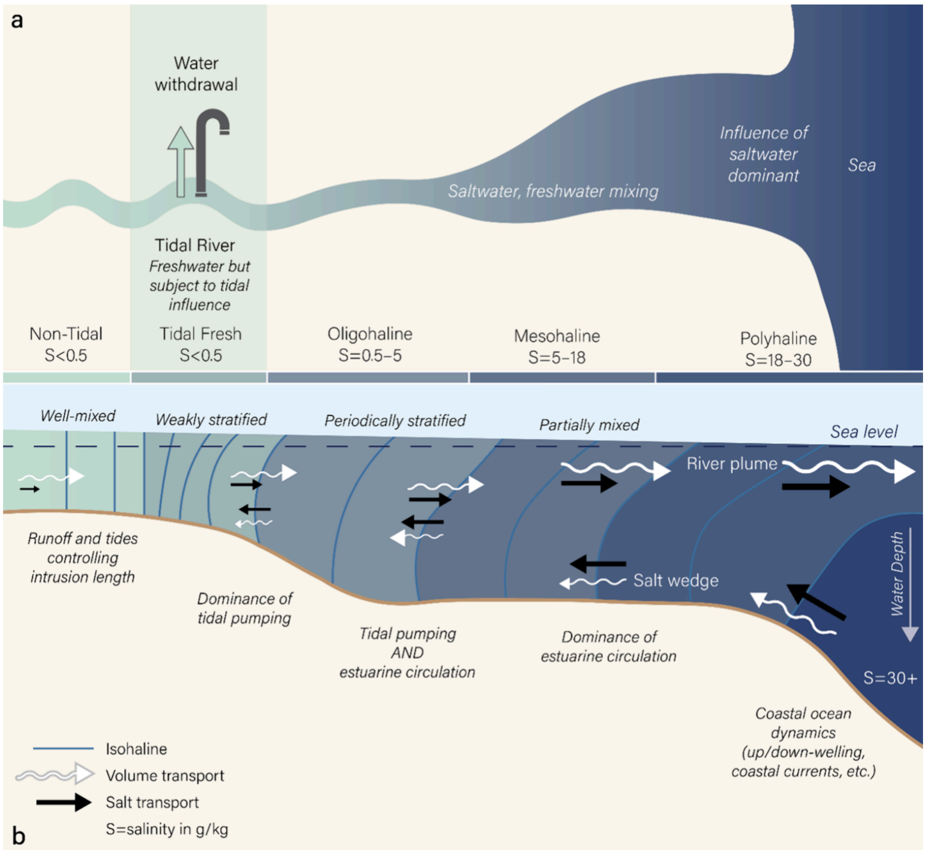

Figure 2. (a) A schematic plan view of an estuary showing different salinity (in units of g kg^{-1}) subregions including the tidal river where many drinking water intakes are located. (b) A schematic along-channel section view of the typical volume and salt transport regimes in an estuary. Blue lines show isohalines, and colors show salinity. The white arrows indicate volume transports, while the black arrows indicate salt transports. The dotted line shows the position of the mean sea level. Note that for corresponding pairs of arrows, incoming and outgoing salt transports are almost identical, while outgoing volume transports are substantially larger than the incoming volume transports due to the river runoff.

supplies, including Shanghai on the Changjiang River,[14] Zhuhai and Zhongshan on the Pearl River[15] and several cities on the Ganges-Brahmaputra-Meghna Delta.[16] In South America, saltwater intrusion affects the Valdivia River in Chile,[17] the São Francisco River in Brazil and the Magdalena River in Colombia.[18] In North America, saltwater intrusion affects rivers that drain into all three coasts, including the Delaware River (Figure S1 in the Supporting Information), the Hudson River (Figure S2),[19] Sacramento–San Joaquin Delta–San Francisco Bay,[6] the Mississippi River, and the Papaloapan River. Saltwater intrusion into tidal rivers is occurring not only in semiarid and Mediterranean-type climate regions, which are exposed to annually recurrent drought periods,[20,21] but also in precipitation-rich temperate climates that may experience flash droughts.[22–24] Equally serious to the problem of oceanic saltwater intrusion is freshwater salinization, the rise in salinity in the "fresh" end member of tidal rivers, owing to various anthropogenic activities within watersheds.[25,26] Despite widespread reports of drinking water supplies being threatened by saltwater contamination, there is no global synthesis of the commonalities faced by these coastal systems.

The risk of salt contamination extends to uses other than drinking water, including thermoelectric power, agricultural irrigation, industrial production, mining, and aquaculture.[27] Salt contamination of irrigation water damages conventional agricultural crops (e.g., corn and beans) and forces farmers to grow salt-tolerant crops (e.g., cotton and grain sorghum) that are less profitable.[28] High salinity can be detrimental or even fatal to many freshwater finfish species while favoring salt-tolerant invasive species.[29] High chloride concentration promotes galvanic corrosion of lead-bearing materials[30,31] and pitting corrosion of copper.[32] Along water distribution systems, elevated chloride concentration can increase mobilization of lead from pipes into drinking water.[33] Critical transportation infrastructure, such as steel-reinforced concrete bridges, may also suffer from corrosion after an initiation period, in which the steel reinforcement becomes more vulnerable when the oxide layer is removed due to chloride exposure.[34]

2. A MULTIDIMENSIONAL AND MULTIDISCIPLINARY PROBLEM

A tidal river, located in the upper part of an estuary, is influenced by both river flows from land and tides from the ocean (Figure 2a). It is a vital but understudied nexus between hydrology and oceanography.[35,36] Saltwater contamination of tidal rivers is a multidimensional and multidisciplinary problem involving physical and biogeochemical processes across the watershed–river–estuary–ocean continuum.

2.1. Oceanic Saltwater Intrusion into Estuaries. Although the river flow transports water including salt seaward, other processes transport salt in the up-estuary direction. The two most important of those processes are estuarine circulation and tidal pumping (Figure 2b). Estuarine circulation is a bidirectional residual circulation with a near-bottom, up-estuary-directed current of increased salinity and a near-surface, down-estuary-directed current of fresher water, resulting in a vertically integrated up-estuary salt transport.[37] Estuarine circulation[38,39] is primarily due to the density gradient between salt and fresh water,[40] but it may also be influenced by tidal straining,[41,42] lateral circulation,[43] and estuarine convergence.[44] Tidal pumping is the vertically integrated temporal covariance of vertically averaged horizontal velocity and salinity, meaning that higher salinity during flood tide and lower salinity during ebb tide result in up-estuary salt transport.[45] Generally, in relatively deep estuaries with weaker tides, estuarine circulation dominates, and in shallow estuaries with strong tides, tidal pumping dominates. In partially mixed estuaries, both processes may be of comparable magnitude.[46]

Since the down-estuary transport scales with the river flow, saltwater intrusion extends farther landward during droughts and shifts seaward during high flows. Effects of variations in tidal amplitude with the spring−neap cycle depend on the dominant salt transport mechanism, with estuarine circulation generally decreasing during periods with stronger tidal mixing, while tidal pumping increases with tidal amplitude. Thus, water depth, tidal amplitude, and river flows are the major processes influencing saltwater intrusion.[47−49] Additionally, differences in saltwater intrusion length between estuaries are influenced by differences in morphology such as channel area or depth, curvature, channel−shoal geometry, branching, sills, constrictions, convergence, and much more.[50,51]

2.2. Oceanic and Estuarine Processes Influencing Saltwater Intrusion. The influences of river flow, tidal amplitude, and estuarine bathymetry on saltwater intrusion can be estimated from scaling based on the salt transport equation.[40,52] In some estuaries like the Hudson River, the saltwater intrusion length L has been observed to scale as $Q^{-1/3}$, where Q is the river flow,[53,54] but L is much less sensitive to river flow in other estuaries, such as the Delaware Bay[55−57] and San Francisco Bay.[52] In the Delaware Bay, both channel bathymetry and spring−neap variations in mixing contribute to the weak dependence of L on Q,[57,58] while in the San Francisco Bay it has been attributed to influences of stratification on mixing and the along-channel variation in bathymetry.[52,59,60] In partially mixed estuaries, L scales inversely with the tidal velocity U_t as strong vertical mixing limits the landward saltwater intrusion. In relatively shallow, well-mixed estuaries where tidal pumping dominates, however, $L \sim Q^{-1}U_t$.[60] These differing sensitivities of L to Q and U_t highlight the challenge in predicting saltwater intrusion.

Saltwater intrusion is highly sensitive to water depth H, as suggested in the scaling $L \sim H^2$ from theory.[40] Both sea-level rise and channel dredging can increase saltwater intrusion and tidal range.[61−64] In most industrialized estuaries, dredging dominates other processes that increase the water depth. Channel deepening has been shown to increase saltwater intrusion and modify tidal amplitude in a number of estuaries worldwide.[63,65−67] Even in wide estuaries where deepening of a narrow channel will only modestly increase channel cross-sectional area, the impact on salt flux is still significant because landward salt flux is focused in the deep channel.[68,57]

Saltwater intrusion is also influenced by coastal sea-level oscillations and the direct forcing of the wind on the estuary.[69,70] Both the local and remote wind forcing drive a barotropic adjustment that produces transient landward salt fluxes reversing the river flow.[53,57,71,72] Increases in saltwater intrusion with the passage of storm events can temporarily threaten water supplies, as seen in the Changjiang River[73] and Delaware River.[74]

Increased offshore ocean salinity enhances the density contrast between river and oceanic water and, therefore, intensifies the estuarine circulation and saltwater intrusion. For example, the bottom salinity in the Chesapeake Bay covaries with the salinity in the Mid-Atlantic Bight on decadal time scales.[75−77] Also, episodic events, such as upwelling and downwelling, can change the salinity of the inflowing oceanic water. An extreme example is the Western Baltic Sea, where the salinity outside the estuary can increase from 10 to 20 g kg^{-1} within a few hours.[78,79] River plumes could also interact and thus change the salinity of the inflow waters.[80]

2.3. Hydrological Processes Influencing Freshwater Availability and Delivery. Transport of water and solutes such as salts in the watershed occurs through multiple hydrological pathways: surface runoff, soil percolation, subsurface lateral flow, groundwater flow, and river flow.[81] The connectivity among these pathways is critical for understanding water transport in the watershed. Groundwater sustains about half of the river flow on average and is dominant during low-flow periods.[82] Drought conditions can propagate across the hydrological pathways. A decline of precipitation beyond normal conditions reduces watershed soil moisture, which may, in turn, lead to reduced river flow through lower groundwater levels and decreases in groundwater contribution to the river flow. This drought cascade has led to the identification of different drought types:[83,84] meteorological drought measured using precipitation, agricultural drought based on soil moisture, and hydrological drought measured using river flow or low-flow indicators.

The hydrological cycle is highly sensitive to the temperature. Warming increases evaporative demand and vegetation water use and, in cold climates, can lead to shifts in the partitioning between rain and snow.[85] Increasing the level of evapotranspiration (surface evaporation and plant transpiration) can lead to soil drying. Besides reductions in soil moisture, drying is associated with reduced groundwater levels and baseflow, and the proportion of groundwater contributing to river flow.[85] Changes in the partitioning of rain and snow can increase the early spring river flow at the expense of summer river flow. Rain-on-snow flooding events can result in freshwater pulses.

2.4. Freshwater Salinization and Secondary Effects on Water Quality and Ecosystems. Besides oceanic saltwater intrusion, salinity in the "fresh" end member of tidal rivers has increased due to numerous anthropogenic activities within watersheds, such as human-accelerated weathering, road salts for deicing, irrigation, and fertilizers.[25,86−88] Urbanization and agricultural land use led to human-accelerated weathering of concrete impervious surfaces,[89] which increases pH and concentrations of base cations.[89,90] Due to the increased use of weathering agents and easily weathered substrates, the concentrations and loads of chemical weathering products such as alkaline salts and carbonates are increasing in rivers.[89,91−94] For example, there have been increasing long-term trends in alkalinity and calcium concentration in approximately 2/3 of the major rivers draining the US East Coast[92] and the seasonal impacts of salinization extend to tidal waters.[95] It is also recognized that multiple ions (Ca^{2+}, HCO_3^-, Mg^{2+}, and K^+) contribute to freshwater salinization.[89,94,96−98]

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Freshwater salinization can lead to secondary effects, exacerbating hypoxia, mobilizing contaminants and affecting the distribution and abundance of species.[90,99−101] Salinization can mobilize a wide variety of contaminants, including nutrients, metals, radionuclides, and arsenic.[90,102] Pulses in salinity may trigger the release of many heavy metals from sediments and soils to streams and rivers that can persist for days and weeks.[89,97] In addition, saltwater intrusion has been shown to enhance mobilization of phosphorus, arsenic, and other contaminants in groundwater.[90] Recent research showed that salinization effects on contaminant mobilization extend to tidal rivers.[103]

2.5. Geographic Distribution and Use Types of Water Intakes. To assess the societal impacts of salinization, we need to identify and characterize the water intakes along tidal rivers. In the US, water intakes have been characterized in terms of use (public supply, irrigation, aquaculture, mining, domestic, livestock, industrial, and thermoelectric power), source (surface water or groundwater), salinity, amount of water withdrawn, and fraction of the withdrawal that is consumptive.[27] As a first approximation of the uses of tidal rivers, we considered all surface freshwater withdrawals in the US in 2015, 96% of which were in four use types: thermoelectric power (48%), irrigation (31%), public supply (12%), and industrial (6%). For the thermoelectric power and industrial use types, saline water is also withdrawn. Therefore, the biggest impacts on human water use of tidal rivers are expected to be on irrigation and public supply.

None of the above water intake characterizations determine equivocally the tidal character of the water. As part of an ongoing study to identify water intakes on the Chesapeake Bay, we contacted water agencies within the two states that cover most of the Bay shoreline: Maryland and Virginia. The Maryland database contained 895 intakes, 130 of which were identified as tidal. Of those intakes, the use types were mainly agricultural irrigation (53%). The Virginia data set did not distinguish between tidal and nontidal intakes. The length of the Maryland shoreline is 6% of that of the contiguous US,[104] so if Maryland is typical, then there may be as many as 2000 tidal water intakes in the US.

Figure 1a shows where saltwater intrusion into tidal rivers has impacted or is expected to impact irrigation and public water supply around the world. Some notable examples of impacts on irrigation from saltwater intrusion are the Ganges−Brahmaputra delta in Bangladesh,[105] the Changjiang River in China,[106] the Shatt-Al Arab River in Iraq,[107] the Bay of Fundy in Canada,[108] and South Kalimantan in Indonesia.[109]

2.6. Critical Need for Interdisciplinary Research. Currently, three research communities are working on different aspects of salt contamination in tidal rivers. Estuarine oceanographers have focused on salt transport in the mesohaline region of an estuary, whereas saltwater intrusion into the tidal river region may be controlled by different physical processes (Figure 2). Hydrologists are mostly concerned with the occurrence of floods and droughts, and they have long ignored tides and their interactions with river networks. Biogeochemists studying freshwater salinization have mostly focused on nontidal rivers. To address the issue of salt contamination of water supplies in tidal rivers, convergent research that integrates these communities is needed.

3. CLIMATE CHANGE AS A MAJOR DRIVER OF SALTWATER INTRUSION

The frequent reports of salt contamination of water supplies in recent years point to climate change as a major driver of saltwater intrusion into tidal rivers. Although the underlying mechanisms are not yet well understood, recent research has highlighted the role of several processes, including accelerated relative sea-level rise, changing drought and river flow regimes, and extreme weather events.

3.1. Impacts of Sea-Level Rise and Changing Ocean Circulation. Sea level rose ∼0.2 m during the 20th century[110] and is projected to increase ∼1 m by the end of the 21st century,[111] but there are large regional variations in the sea-level rise rate due to Earth's uneven gravity field, glacial isostatic adjustment and ocean dynamics (Figure 1b).[112] Sea-level rise increases saltwater intrusion into estuaries. Analysis of historical data in the Chesapeake and Delaware Bays showed a clear connection between sea-level rise and estuarine salinity increases.[76,113] In the San Francisco Bay and the James River the effects of sea-level rise were found to be stronger during periods of low river flow.[114,115] Climate change increases the risk of extreme saltwater intrusion across European estuaries, including the Loire, Scheldt, Rhine−Meuse, Elbe, and Humber estuaries.[116] In Asia sea-level rise is a major factor enhancing saltwater intrusion into the Changjiang, Pearl, Mekong, Gorai, and Ganges Rivers.[117,118] A recent study of 18 estuaries worldwide suggests that future climate change would increase estuarine salt intrusion mainly through sea-level rise rather than through reduced river flow.[119] The effects of sea-level rise may be cast as an increase in the mean water depth of the estuary. Both salt flux and saltwater intrusion length increase with the depth to the second or third power, depending on the details of how mixing is modified by the increased water depth.[120,121]

It is important to note that many estuaries are capable of rapid morphological change such that the mean depth of an estuary may increase more slowly, or not at all, with sea-level rise due to sediment accumulation. The estuarine circulation that drives landward salt flux also promotes trapping of fine sediment from both riverine and marine sources.[122] Near-bottom residual currents transport sediment landward into the estuary, and the strong feedback among channel cross-sectional area, tidal currents, bed shear stress, and sediment erosion and deposition results in estuaries maintaining morphological equilibrium depths.[123] Given sufficient sediment supply, estuaries tend to accrete vertically at rates similar to the relative sea-level rise.[124,125] Consequently, the response of saltwater intrusion may be muted relative to the nonlinear scaling $L \sim H^2$.

Saltwater intrusion could also be driven by rising coastal sea levels due to changing ocean circulation or warming. The accelerated sea-level rise along the US east coast north of Cape Hatteras during 1950−2009 was attributed to the weakening of Atlantic Meridional Overturning Circulation and the Gulf Stream,[126,127] whereas the rapid sea-level rise in the US southeast and Gulf coast in recent years was thought to be either associated with stereodynamic effects due to warming of coastal currents[128] or amplified by internal climate variability in the tropical North Atlantic.[129] Significant correlation has been found between El Niño−Southern Oscillation and extreme sea levels across the Pacific,[130] including the west coast of South and North America[131,132] and the South China Sea.[133]

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3.2. Impacts of Changing Hydrological Cycle and Competing Water Uses. Hydroclimatic shifts, such as increased drought severity, affect all of the continents (Figure 1c). The Mediterranean Sea region, southeastern Africa, parts of Central and South America, and Indonesia could experience significant increases in the number of dry days per year by the end of this century.[134,135] Climate model projections indicate that drought risk will increase, with changes varying across regions, seasons, and drought characteristics (e.g., drought onset, severity, and duration).[136,137] In high northern latitudes and high-elevation areas of the midlatitudes, climate projections show a consistent decline in river flow, an indicator of hydrological drought, in the summer months due to warming impacts on precipitation and changes in snow dynamics (snowpack melts earlier in the season).[138] In other regions, river flow declines are closely associated with decreased precipitation patterns, such as those in regions with Mediterranean climates.

Coastal water supplies are threatened by compounding stressors, including the challenge of balancing competing needs for freshwater resources. Coastal population growth increases needs not only for water supplies but also for energy, infrastructure, and urban space. For example, maintaining supplies for increasing water needs (municipal, agricultural, etc.) might require shifts to groundwater aquifers or to desalination, both of which have a higher energy burden than surface water supplies.

3.3. Impacts of Increasing Climate Extremes. Although saltwater intrusion is affected by long-term trends in river flow and water depth, salinity spikes at water intakes typically occur over a short period and may be affected by a flash drought or short-term sea-level variability, such as from storm surge.[139] Extreme sea levels may occur more frequently due to secular sea-level rise and an increase in intensity or frequency of storms.[111,140] Despite an overall decline in the number of tropical cyclones,[141] several findings suggest conditions that would increase the variability of coastal sea level[142] (and, by inference, salinity), including increases in major hurricanes[143−145] and the number of landfalling tropical cyclones.[146]

Variability in river flow is also likely to increase from daily to interannual time scales due to increases in heavy precipitation[135] and extreme drought. At temperate latitudes, river flow is highest during the winter and spring and lowest during the summer and fall, but climate change is expected to increase winter and spring precipitation, with an increasing fraction of that precipitation as liquid.[135] While summer and fall precipitation projections are more variable, warming will increase evapotranspiration, which will reduce river flow and enhance saltwater intrusion. Hence, we can expect the amplitude of the annual cycle in river flow to increase in the future.

4. RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

The above synthesis reveals a critical need for convergent interdisciplinary research that must be integrated across oceanography, hydrology, and water resource management. We identify several key topics requiring immediate attention and propose a research agenda for developing a decision support tool to manage salt contamination of water supplies in tidal rivers, as outlined below.

4.1. Ion-Specific Measurements. The relative proportions of dissolved salts differ between seawater and nontidal riverine water.[147] Consequently, specific conductivity meters cannot be used to infer the salinity of tidal rivers.[148] Major ions, such as sodium and calcium, can vary by an order of magnitude among rivers.[149,25] To characterize salt contamination in tidal rivers, we need to measure concentrations of major salt ions and enhance monitoring. These measurements will expand our limited understanding of the sources, transport, and fate of major salt ions over watersheds and in tidal rivers. Some salt ions, such as Na^+ and Cl^-, behave conservatively, whereas other salt ions, such as Ca^{2+} and Mg^{2+}, may experience changes in solubility. Other ions, such as carbonates, have been increasing in rivers[93,149] but may be influenced by biological generation and biological uptake.[150] In addition, the combined use of conductivity and pH measurements may be useful as proxies in predicting the behavior of nonconservative ions or shifts in ion sources with changing hydrology.[97]

4.2. Development of Ion-Specific Hydrological–Hydrodynamic Models. Coupled hydrological and hydrodynamic models are used to predict compound flooding[151,152] and can be extended to predict salt transport. Given the salt composition difference between riverine water and seawater, we need hydrodynamic models that track not only the salinity but also the concentrations of individual salt ions. The salinity module recently incorporated into the Soil and Water Assessment Tool (SWAT) has demonstrated the capability to simulate salt transport in all major hydrologic pathways at the watershed scale and capture important solution reaction chemistry.[81] The SWAT+ salt module simulates eight major salt ions (Na^+, Cl^-, Mg^{2+}, K^+, Ca^{2+}, CO_3^{2-}, HCO_3^-, and SO_4^{2-}), which fortunately includes the top seven (all but CO_3^{2-}) ions in seawater by weight. Some of these ions (e.g., Na^+) are conservative and can be modeled as passive tracers. Other ions (e.g., Ca^{2+}) are nonconservative, but recent progress in carbonate chemistry modeling could help predict these ions.[153−157] The standard seawater equation of state also needs to be modified for calculating water density in tidal rivers.[158]

4.3. Salinity Management Strategies Informed by Mechanistic Models and AI Algorithms. Climate adaptation and water plans reveal many different implementations of salinity management strategies, ranging in expense and complexity.[159] For drinking water systems, desalination may seem like an obvious strategy, but it requires large up front capital expenditures[160] and is expensive to operate and maintain.[161] Managing flow releases from reservoirs may protect coastal water users from increasing salinity at a relatively lower cost. This method has been in use in the Delaware River and Hudson River basins and elsewhere.[19,162]

Climate adaptations, such as reservoir releases, are often supported by optimization methods and used to tailor releases to short- and long-term projections of regional hydroclimatic conditions.[163] These operations are affected by a "cascade of uncertainties"[164] that significantly affect our ability to quantify the expected effectiveness of adaptive responses.[165] Several methods have been advanced to support dynamically adaptive planning and operations.[166] State-of-the-art reservoir operation methods utilize tools from closed-loop control and multiobjective optimization to design operational policies that meet multiple goals by responding to dynamic conditions.[167,163] These approaches have recently evolved to the use of multiobjective reinforcement learning, a type of machine

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learning where Artificial Intelligence (AI) agents learn to make decisions by receiving rewards or penalties for their actions. The goal is to train adaptive policies that can meet diverse and conflicting operational goals, by exposing them to a wide range of dynamic conditions.[165,168,169] As such, these policies can be trained to also consider salinity mitigation goals in tidal rivers with inland reservoirs,[170] taking into account seasonal variability and long-term changes in hydroclimatic conditions so that dynamic salinity dilution needs can be met.

Key Messages:

1. Prolonged drought and rapid sea-level rise in a changing climate create a vulnerable combination that increases saltwater intrusion into tidal rivers.
2. Local anthropogenic activities, such as channel deepening in estuaries and human-accelerated chemical weathering in the watershed, may have had a larger impact on salinity in the past and may continue to affect saltwater intrusion.
3. To investigate salinization and its impacts in tidal rivers, we need to make ion-specific measurements and develop ion-specific hydrological–hydrodynamic models.
4. We need to integrate mechanistic models with AI algorithms to develop adaptive salinity management strategies.

4.4. Developing a Decision Support Tool Using a Human-Centered Design. By integrating ion-specific hydrological−oceanographic models with AI-based optimization algorithms, we recommend the development of a decision support tool for predicting and managing salt contamination of water supplies in tidal rivers, as illustrated in Figure S3. The model predictions must be evaluated against enhanced real-time monitoring of conditions in tidal rivers, including ion-specific measurements. There is a wide range of stakeholders and potential users, ranging from regulators and water resource managers at local, state, federal, and intergovernmental agencies to stakeholders from the public water supply, agricultural, industrial, power generation, and environmental sectors. They may have different goals, such as short-term management strategies (e.g., reservoir releases) and long-term planning decisions (adaptative policy pathways). To develop a decision support system that can meet user needs, it is important to apply human-centered design and engage with stakeholders during all phases of software development.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.5c00505.

Sample time series of conductivity at tidal rivers and a schematic diagram for a salinity management decision support system. (PDF)

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Notes

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