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Research papers

Groundwater pumping causes salinization of coastal streams due to baseflow depletion: Analytical framework and application to Savannah River, GA

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A R T I C L E I N F O

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A B S T R A C T

Groundwater-surface water interactions and associated water management issues are complicated by the risk of salinization along coastlines. Groundwater pumping can be a driving factor of streamflow depletion and allow for increased stream saltwater intrusion. In this study, we develop an analytical framework combining two analytical approaches to calculate the length of saltwater intrusion at high slack water and the stream depletion rate due to groundwater pumping. We test this framework using data from the Savannah River in southeastern U.S and use it to explore saltwater intrusion in the surface water system. The analytical approach produces an accurate estimate of the position of the salt front at approximately 56 km inland. Current pumping rates decrease streamflow by less than 1%, resulting in an increase in the saltwater intrusion length of 100 m. Increased groundwater pumping scenarios, however, show a risk of extending the saltwater intrusion length up to 4 km inland. In these cases, effects from pumping-induced saltwater intrusion would equal or exceed the impacts of sea-level rise or geomorphic change. Salinity is a critical factor in the ecological balance of this estuarine ecosystem and this analytical approach allows for investigation of hypothetical groundwater development in the region. We show, for the first time, the direct link between groundwater pumping and coastal stream salinity that should be an important management consideration all along developed coastlines.

1. Introduction

In coastal areas, where nearly half of the world population lives, water resources are continually threatened by natural and anthropogenic stressors (Michael et al., 2017). Both surface and subsurface water reservoirs are at risk of salinization due to saltwater intrusion. In estuaries, increased salinization may cause adverse impacts on freshwater resources and ecological function. This is particularly true under the increasing pressure of climate change and sea-level rise.

The mouth of coastal streams is a transition zone between saline seawater and terrestrial freshwater, and the location of this interface is dictated by the balance between streamflow, meteorological conditions, and tidal forcing (Conrads et al., 2006; Ross et al., 2015). In general, during periods of high streamflow, seawater is prevented from intruding upstream, and the freshwater-saltwater interface (salinity of 0.5 ppt) is located relatively close to the ocean. During periods of low streamflow, high-salinity water moves upstream, shifting the freshwater-saltwater interface and potentially compromising freshwater resources and ecosystems.

The balance between the terrestrial flow system and ocean forcing is complicated by multiple processes–natural and human-induced–that occur across various time scales. These processes include, but are not limited to, storms, tides, seasonal climatic fluctuations, groundwater pumping, and interannual variability. The freshwater-saltwater interface in coastal streams is controlled by a delicate balance between these often opposing and simultaneous forces. For example, coastal storms can temporarily increase the salinity in surficial water reservoirs through elevated sea level, wind, waves, and storm surge that collectively push

Abbreviations: HWS, high water slack; SWI, saltwater intrusion; LSR, Lower Savannah River.

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the freshwater-saltwater interface inland (Huang et al., 2014). Simultaneously, extreme high runoff events from coastal storm precipitation may increase freshwater discharge, which can potentially push the transition zone seaward and reduce the overall stream salinity (Hagy et al., 2000; Lerczak et al., 2009; Tian, 2019). Furthermore, spring-neap tidal cycles are a major control on the vertical and horizontal distributions of salinity in estuaries (Ji, 2008). High tidal range leads to strong vertical mixing and little stratification, whereas low tides create poorly mixed (highly stratified) salt wedges in the stream (Simpson et al., 1990). Depending on the dominant force, water in tidally mixed estuaries can change from completely fresh to saline within a tidal cycle, whereas salinity in larger estuaries, more controlled by seasonal freshwater inflows, may show little fluctuation (Ji, 2008).

Previous studies have shown that in coastal streams, seasonal variations in saltwater intrusion are primarily controlled by sea-surface level (Hong and Shen, 2012), whereas longer-term, interannual variability is largely dominated by river flow (Tian, 2019). Modeling studies have demonstrated that long-term sea-level rise causes shifts in estuarine salinity circulation, tidal impacts, and maximum extent of intrusion (e.g. Bhuiyan and Dutta, 2012; Hilton et al., 2008; Hong and Shen, 2012). However, the natural variability in local climatology and river runoff may obscure these weak trends and make them undetectable without extensive data or modeling (Wiseman et al., 1990). Although fast processes like storm surges cause greater variation, long-term slow processes magnify the effects of the fast processes. This is of particular importance when considering the complexity of groundwater-surface interactions in coastal systems.

Groundwater interacts with surface water through infiltration and exfiltration and can significantly alter stream discharge. The groundwater contribution to streamflow, termed baseflow, may be reduced by natural (e.g. low precipitation and recharge) or anthropogenic (e.g. pumping) groundwater depletion. The streamflow is almost entirely baseflow during times of minimal rainfall (Priest, 2004). Thus, for certain estuaries, estimates of groundwater discharge rates might be important for a complete understanding of the coastal hydrologic system (Hagy et al., 2000).

Groundwater withdrawals have been cited as a driving factor of streamflow depletion in a wide variety of aquifers, including coastal plains. For example, the cumulative response to groundwater pumping in the Northern Atlantic coastal plain contributed to greater than a 20% reduction in streamflow (Masterson et al., 2016). The Ganges River, India, has seen large-scale river dry out over the past five decades, triggered by a 59% reduction in baseflow from irrigation withdrawals (Mukherjee et al., 2018). Similarly, Li et al. (2020) calculated the streamflow depletion from groundwater pumping in two watersheds in Canada, and showed that, depending on the site specific hydrogeology and the well location, the volume of water pumped could cause an equivalent decrease in stream volume. In gaining streams it is not necessary for a well to reverse flow gradients below the stream to reduce baseflow. Streamflow depletion occurs when the well simply captures some of the baseflow discharge before it reaches the stream (Chen and Yin, 2001; Wilson, 1993). It is thus clear that regardless of the level of complexity, groundwater withdrawal inevitably results in depleted streamflow (Barlow et al., 2018).

Numerous studies have used different forms of field-based and statistical analysis (e.g. Barlow et al., 2014; Killian et al., 2019), numerical models (e.g. Griebling and Neupauer, 2013; Leake and Pool, 2010), and analytical models (e.g. Barlow and Leake, 2012; Hunt, 1999; Li et al., 2020; Zipper et al., 2019b) to demonstrate the linkages between groundwater levels and streamflow. The field-based analysis requires extensive surface water and groundwater measurements. Numerical models are process-based representations of the flow and can be prohibitively complex, requiring time, expertise, and computational power to perform a site-specific analysis. Compared to numerical models, analytical models provide a simpler approach to calculate streamflow depletion for different hydrogeologic conditions.

Analytical solutions show that streamflow reduction due to groundwater depletion is mainly controlled by the aquifer transmissivity and storativity, by the streambed resistance to seepage, and by the proximity of pumping wells to the stream (Hunt, 1999). Numerical simulations of real-world settings showed that analytical models perform better in relatively simple hydrogeological settings, while in more complex systems the errors are large (Li et al., 2020; Zipper et al., 2019b). Overall the dynamics and trends predicted by the analytical solutions hold for both settings. Therefore, analytical approaches appropriately demonstrate links between groundwater pumping and streamflow depletion in most watersheds where the aquifer is connected to the surficial system (Barlow and Leake, 2012; Hunt, 1999; Killian et al., 2019; Li et al., 2020; Mukherjee et al., 2018; Zipper et al., 2018, Zipper et al., 2019b).

In the case of coastal watersheds, reduction in streamflow is expected to induce an inland migration of the salt front. This mechanism has been shown and discussed extensively in several studies, including field observations (e.g. Lamar, 1940; Yobbi and Knochenmus, 1989a,b), numerical simulations (Conrads et al., 2006; Nobi and Gupta, 1997), and analytical solutions (Cai et al., 2015; Yobbi and Knochenmus, 1989a,b). For example, in the Red River, Vietnam, field observations and numerical modeling suggest that adding reservoirs upstream and increasing stream discharge reduces the salinity in the river across the watershed (Hien et al., 2020). In the Richmond River estuary system, Australia, periods of low freshwater flow (e.g. droughts, excess pumping) induce larger tidal excursions and an overall increase in the stream salinity throughout the estuary (Pierson et al., 2001).

The studies mentioned above establish separately two links in coastal hydrogeological systems: (1) groundwater depletion - streamflow reduction, and (2) streamflow reduction - surface water salinization. However, the overarching link between groundwater pumping and coastal stream salinization (Fig. 1) has, to our knowledge, only been explored in one study (Nobi and Gupta, 1997). Numerical modeling of an integrated aquifer-stream system in coastal Bangladesh showed that an increase of 30% in groundwater pumping could increase the salinity of the river and push the salt front inland across the simulated watershed (Nobi and Gupta, 1997). The timing of the sensitivity of river salinity to groundwater depletion has yet to be explored.

It is likely that the overarching link between pumping and salinization has been relatively understudied because of (1) the complexity of the multiple interacting processes occurring over a range of time scales and (2) the potential time lag between cause and effect for groundwater system changes. It is difficult to distinguish long-term trends that create small changes over long periods from fast processes that create large changes over short periods. To differentiate between salinization cause and effect, high resolution and long-term field monitoring may be required. Yet, even in the *best* data trends may be indistinguishable. Analytical models offer a practical solution and can produce theoretical estimates of streamflow depletion and salinization. Similar approaches have been used to characterize subsurface seawater intrusion processes due to pumping for over 100 years.

The goals of this study are to (1) observe the long-term controls on stream salinization and (2) illustrate the potential impact of groundwater pumping on stream salinity using the Lower Savannah River, GA as an example. A significant number of studies have been conducted to identify the dominant factor in controlling saltwater intrusion in estuaries, but no studies look at groundwater-surface water interactions. Our hypothesis is that pumping-induced groundwater depletion could be significant to saltwater intrusion despite being undetectable in most short-term data. In this study, we constrain the extent of saltwater intrusion in the Lower Savannah River, GA with analytical models for groundwater pumping and saltwater intrusion. The Savannah River is the location of multiple stream gages, extensive estuary surveying, and tidal monitoring that are rarely available at coastal streams, allowing for the initial testing of our analytical model. We use observed trends in groundwater pumping, stream discharge, and stream salinity to determine potential extents of

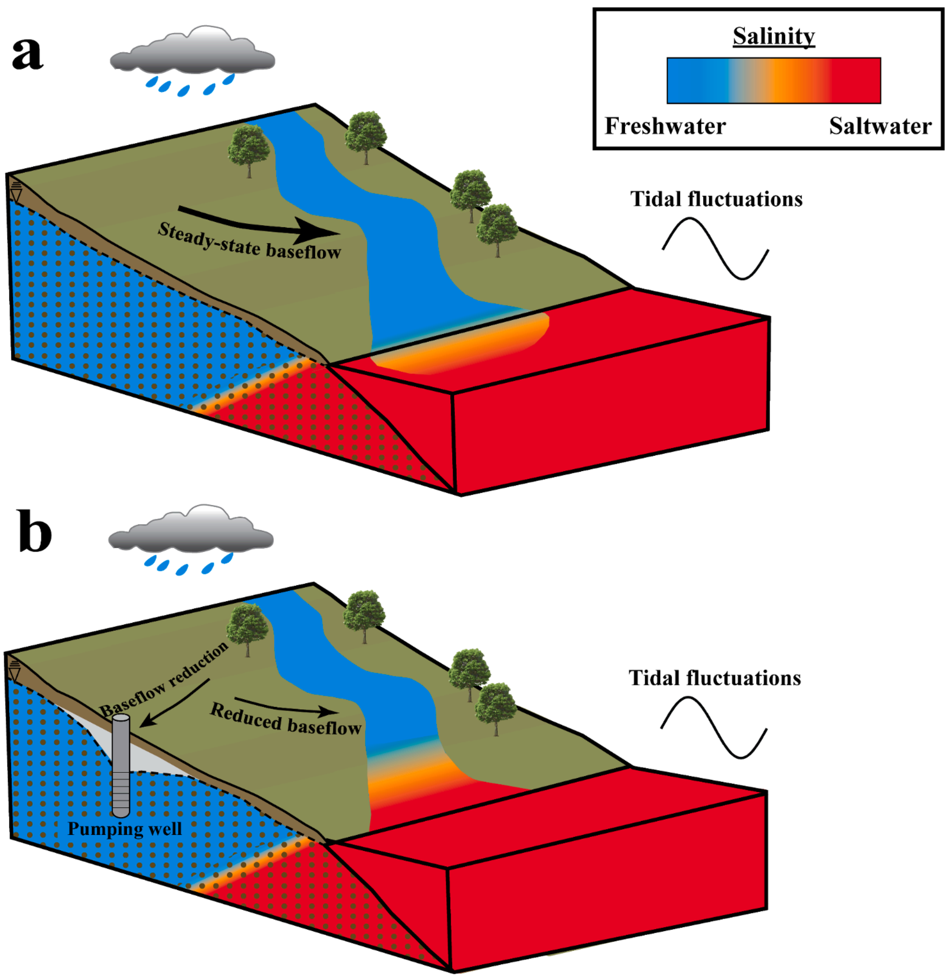

Fig. 1. A conceptual diagram showing coastal stream dynamics before (a) and after (b) groundwater pumping. The saltwater-freshwater interface is a balance of river discharge and ocean forcing (tides, waves, sea level) that can be shifted inland due to reduced baseflow from nearby pumping.

impact with increased pumping and discuss the opportunity that this analytical approach provides for estimating salinization due to groundwater-stream interactions in streams lacking high quality, longitudinal measurements.

2. Analytical framework for streamflow depletion and salinization

2.1. Pumping and streamflow depletion model

To assess the impact of groundwater pumping on streamflow, the Glover model was used to calculate the relative stream discharge reduction as a function of pumping rate (Glover and Balmer, 1954). This model calculates the depletion with time in a single stream and includes the following assumptions: (1) the stream and the general groundwater flow direction are perpendicular; (2) the streambed has the same hydraulic conductivity of the aquifer; (3) the aquifer that feeds the stream is infinite in the horizontal dimension, homogeneous and isotropic, and (4) the groundwater flow is horizontal. Additional details about model assumptions can be found in Jenkins (1968).The Glover equation for a given well relates the volumetric streamflow depletion at a given segment (Q_a) to the pumping rate (Q_w) using the following complementary error function (*erfc*):

$$\frac{Q_a}{Q_w} = erfc\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \tag{1}$$

where d is the distance between the well and the stream, t is time since pumping, and S and T are the aquifer storativity and transmissivity, respectively. It is important to note that in steady state, the entire pumped volume is accounted for by streamflow depletion, meaning that $\frac{Q_a}{Q_w} = 1$(which can be seen in Equation (1) with $t \rightarrow \infty$). Changes in groundwater recharge rates from precipitation is ignored.

The percentage of streamflow depletion (Q_a) relative to the total streamflow (Q_f) is $Q_a/Q_f \times 100$. Because the depletion component in this model is solely from groundwater contribution, Q_a can be considered equivalent to the proportion of baseflow. This calculated relative depletion is used as input in the saltwater intrusion model, explained in the following section.

2.2. Stream saltwater intrusion model

An analytical model developed by Savenije (2015, 1993, 1989, 2012) for alluvial estuaries was applied to predict salinization based on stream discharge data. Hypothetical freshwater discharge values (linked to decreased baseflow during low flow periods) were used to estimate shifts in the saltwater-freshwater interface.

According to Savenije (2012), the salinity distribution can be calculated based on estuary geometry and tidal and hydrologic boundary conditions (see Fig. S1 for an estuary diagram). The saltwater intrusion length [L] is the distance from the estuary mouth to the point where water salinity equals the river water salinity. It is described as

$$L_i = a ln(\frac{1}{\beta_i} - 1) \tag{2}$$

where a is the convergence length of the cross-sectional area [L]. Estuaries are generally 'funnel' or 'trumpet' shaped, with a width that tapers upstream in an approximately exponential fashion. The length scale of this exponential function is represented by the convergence length. The dispersion reduction rate (β_i) is equal to

$$\beta_i = -\frac{KaQ_f}{D_{0i}A_0} \tag{3}$$

The subscript i refers to the boundary conditions at High Water Slack (HWS), Low Water Slack (LWS), or the Tidal Average (TA). At HWS the intrusion is at its maximum and the tidal discharge is zero. This condition, which is generally the condition of most interest to planners concerned with saltwater intrusion, is the focus of this analysis. In Eq. (3), the K is the unitless Van der Burgh's coefficient (Van der Burgh, 1972), calculated following methods described in Savenije (1993). The parameter Q_f [L^3T^{-1}] is the freshwater river discharge, A_0 [L^2] is the tidal averaged cross-sectional area at the mouth, and D_{0i} [L^2T^{-1}] is the tidal average dispersion coefficient (a proxy for salinity dilution) at the mouth of the estuary.

Savenije (1993) solved the expression for the dispersion at the mouth and the saltwater intrusion length at HWS using

$$\frac{D_0^{HWS}}{v_0E_0} = 1400\frac{h_0}{a}N_R^{0.5} \tag{4}$$

where h_0 is the depth at the estuary mouth or constant tidal average stream depth [L], E_0 is the tidal excursion at the estuary mouth [L], v_0 is the tidal velocity amplitude at the estuary mouth [LT^{-1}], and N_R is the Estuarine Richardson number. Derivations and additional parameter information can be found in Savenije (2012) and Section S9.2.

For pumping scenarios, river discharge (Q_f) was reduced by the estimate of stream depletion from groundwater pumping near the river (Section 2.1). Various hypothetical streamflow depletion scenarios were also evaluated, including different pumping rates and well distances.

3. Case Study: Savannah River

3.1. Study site

The Savannah River originates at the confluence of the Tugaloo and Seneca Rivers and forms much of the state border between Georgia and South Carolina. The Lower Savannah River (LSR) watershed encompasses approximately 27,500 km^2 and ultimately discharges to the Atlantic Ocean near the city of Savannah, Georgia (Fig. 2). The river is a major water supply for both Georgia and South Carolina and the location of extensive freshwater tidal marshes, including the Savannah National Wildlife Refuge. This estuarine system is highly sensitive to saltwater intrusion so the salinity of the lower Savannah River has been closely monitored in response to streamflow and tidal action since the 1930s (Lamar, 1940). Development impacts on saltwater intrusion, including channel deepening for navigational purposes, tidal gate construction, and the addition of a new channel, have also been considered (Conrads et al., 2006; Mendelsohn et al., 2000). Potential increases in spatiotemporal extent of saline reaches due to a shifting of the freshwater/saltwater interface would have detrimental effects on water resource and ecosystem stability.

3.1.1. Stream hydrology and salinity

The LSR watershed provides water to the City of Savannah and surrounding municipalities for drinking and other uses. Land use in the watershed consists of urban development in the city of Savannah, wetlands surrounding the river, and a mix of forest, pasture, and cropland farther upstream (Provost et al., 2006; Wickham et al., 2021). In the

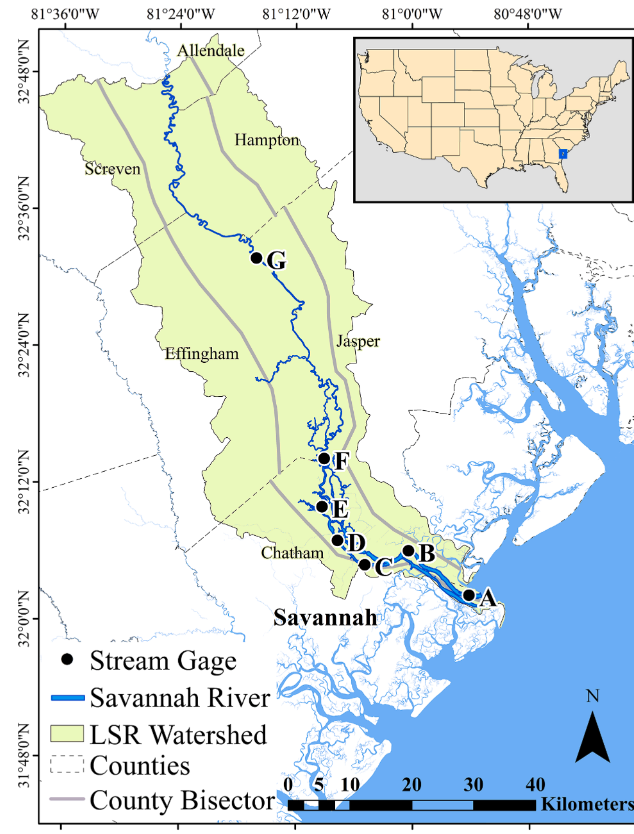

Fig. 2. Map of Lower Savannah River (LSR) watershed. *Gray lines* mark bisecting county lines. Details for stream gage identifiers are provided in Table 1.

coastal region, the system is characterized by a large estuary system that introduces multiple tributaries and meandering channels and includes the Savannah National Wildlife Refuge, which is home to ecosystems and wildlife that could be vulnerable to changes in salinity. The estuary is characterized by semi-diurnal tides with tidal amplitudes of approximately 5–6 ft during neap tides and 8 ft during spring tides. Historically, streamflows on the Savannah River range from 115 to 1415 m^3/s (Conrads et al., 2006) and are regulated by Lake J. Strom Thurmond Dam near Augusta, GA. The modifications to the 33 km of the lower river for the Savannah Harbor have greatly altered the natural river system. The channel has been deepened from 4 to 4.5 m to about 13 m over the last several decades, which is believed to have affected the movement of saltwater upstream (Conrads et al., 2006). Channel dredging and deepening was facilitated by controlled flows at a tide gate installed on the Back River below Route US 17 (Conrads et al., 2006). While this was effective in dredging the main channel, it pushed the freshwater-saltwater interface inland to its current position beyond river kilometer 40 (Conrads et al., 2010, Conrads et al., 2006).

Baseflow in the LSR watershed is approximately 62–70% of total streamflow and the proportion increases during drought periods (Priest and Clarke, 2003). Baseflow is mostly discharged from the surficial aquifer, but a small portion originates from the Floridan system aquifers farther upstream (Provost et al., 2006). Topographically higher portions of the watershed have a greater baseflow contribution to streamflow (Priest and Clarke, 2003). Priest (2004) determined that significant pumping of confined aquifers near the coast may increase inter-aquifer leakage. This induced leakage from the surficial aquifer to deeper aquifers could reduce discharge as baseflow. Thus groundwater-stream interactions are connected to the surficial aquifer as well as deeper aquifers that are actively pumped, despite confining or semiconfining conditions.

3.1.2. Hydrogeology and groundwater use

The flat topography of the Lower Savannah River basin is underlain by the lower Coastal Plain aquifer system, which consists primarily of a surficial aquifer and the confined Floridan aquifer below (Fig. 3). The surficial aquifer is approximately 65 ft of alluvial sands, underlain by a confining unit that encompasses the discontinuous Brunswick aquifer (Provost et al., 2006). The Floridan aquifer includes both an upper and lower unit that both dip toward the southeast (Priest, 2004; Provost et al., 2006). Paleochannel fill cutting through the confining units has been observed offshore as the Upper Floridan aquifer subcrops in the Atlantic Ocean (Cherry, 2006; Falls et al., 2005; Provost et al., 2006; Williams and Kuniansky, 2015). The sub-cropping of confined aquifer units farther inland, as well as the incision of confining units filled by paleo Savannah River channel alluvium, allow for interaction between the Floridan and deeper aquifers and streams (Conrads et al., 2006). In the flatter estuarine topography, Floridan aquifer-stream exchange is only likely with longer intermediate and regional groundwater flow paths (Priest, 2004).

In the lower Coastal Plain, with the exception of the unconfined surficial aquifers, groundwater levels are largely unaffected by climatic factors and fluctuate due to groundwater pumping (Conrads et al., 2006). Groundwater withdrawals associated with pumping near the city of Savannah produce pronounced drawdowns in groundwater levels that may lead to similar drawdowns in adjacent aquifers due to inter-aquifer leakage (Priest, 2004). Since the late 1800s, the Upper Floridan aquifer has served as the primary source of water for the region (Conrads et al., 2006). Increasing groundwater pumping during the last century has led to subsurface saltwater intrusion. This prompted development of the shallower surficial and Brunswick aquifers as a water source. To date, the shallower aquifers are mostly used as only a source of irrigation water (Priest, 2004).

3.2. Observational analysis of stream and groundwater variations

Streamflow, stream salinity, and groundwater level data were obtained from the U.S. Geological Survey (USGS) National Water Information System (Table S1). South Carolina and Georgia 2015 county-level groundwater pumping rates were determined by USGS reports (Dieter et al., 2018) (Table S2).

Stream gage trends in salinity, flow, and baseflow were characterized over short (~1 tidal cycle) and long-term (seasonal and multi-year) periods. Using the EcoHydRology R package (Fuka et al., 2013), a hydrograph separation to define baseflow, upstream of the tidal influence, was completed at site G using the Lyne and Hollick (1979) method (alpha = 0.925), which uses a recursive digital filter that separates the low frequency baseflow from the higher frequencies present in the time series (Lyne and Hollick, 1979; Nathan and McMahon, 1990). Annual baseflow indices (i.e. baseflow percentage of total discharge) were determined from all available data. Summer baseflow indices were calculated for the months of June through August.

At each stream gage, Pearson correlation coefficients between salinity and flow (discharge or gage height) were used to assess the direct relationship between flow and salinity. Negative coefficients were generally expected (i.e. as discharge decreases, salinity increases) despite complications from tidal signals and temporal lags. A 38-hour low-pass filter is used to assess non-tidal trends (Table S6). Two positive correlations were observed for gages that only had gage height measurements rather than discharge. The gage height peak occurs before the discharge peak because discharge is affected by both the gage height and the flow velocity.

3.3. Pumping and streamflow depletion model Inputs

Inputs and source data for the Glover solution are shown in Table 1. Pumping rates were derived from county-wide 2015 average groundwater pumping withdrawals (Mgal/d) in all use categories (public supply, domestic, irrigation, thermoelectric power, industrial, mining, livestock, and aquaculture water-use) for the counties intersecting the LSR watershed (Dieter et al., 2018) (Fig. 2). Majority of domestic groundwater withdrawals came from the Floridan aquifer system and irrigation withdrawals from the surficial aquifer (Painter, 2019). Since the county boundaries are beyond the boundary of the watershed, scale factors for each county were determined using the ratio of the county

Table 1
Parameters for Glover stream depletion model.

Description	Parameter	Units	Value	Explanation and Source
Storativity	S	–	0.3	Lohman, 1972; Provost et al., 2006; Smith, 1994
Distance between well and stream	d	m	6289	The mean of the following for each county that intersects the LSR. $d = \frac{A_{LSR_i}}{2h_{LSR_i}}$, where A_{LSRi} = county area within LSR watershed, h_{LSRi} = length parallel to river of county within LSR watershed
Transmissivity	T	m^2/day	1000	Provost et al., 2006
Time since pumping began	t	days	50 × 365.25	50 years of pumping
Well pumping rate	Qw	m^3/day	88,542	$Q_w = \sum_{i=1}^{n} \frac{A_{LSR_i}}{A_i} Q_i$ where Q_i is the USGS 2015 county pumping rate (Dieter et al., 2018) and A_i is the total area of each county.

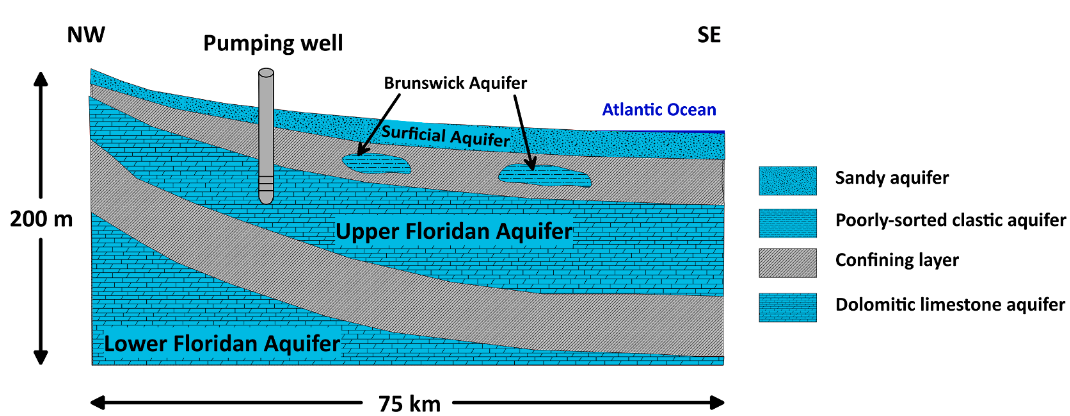

Fig. 3. Hydrogeologic cross section beneath the Savannah River.

area located within the watershed (henceforth referred to as within-watershed area) and the total county area. Total county withdrawals, in Mgal/day, were multiplied by the county scale factor to establish a within-watershed, county-specific pumping rate.

To determine the hypothetical well distance from the stream, lines were drawn parallel to the river bisecting the within-watershed area of each county (Fig. 2). The within-watershed area was divided by the length of these lines and multiplied by 0.5 to find a central location for each well. The sum of all the pumping rates and average of the well distances were calculated as Q_w and d, respectively, of a single hypothetical well. Therefore, we assume the within-watershed central location for each county is representative of a random location and the pumping rate represents the average pumping withdrawals for the county. In addition to this base case scenario, Q_w and d were independently varied to test the sensitivity of the single-well approach.

Inputs to Eqs. (2)–(4) were determined for the northern channel of the Savannah River based on Eq. (1), USGS gage data, LiDAR digital elevation models (Office for Coastal Management, 2021), NHD stream polygons (U.S. Geological Survey, National Geospatial Program, 2021), and NOAA bathymetry (NOAA National Centers for Environmental Information, 2016) (Table 2). By characterizing the estuary geometry on solely the northern main channel, this study assumes that a negligible amount of discharge leaves the watershed through the southern channel due to its shallow depth. The deeper northern channel leads to a greater saltwater intrusion extent (i.e. greater channel depth and channel convergence is associated with greater inland tidal extent). Furthermore, Zhang et al. (2011) showed that the analytical solution for individual branches in a multi-channel stream or river was as effective in estimating saltwater intrusion as combining the branches as a weighted average. Because the main channel convergence length was calculated to be greater than the combined main channel and south channel, the estuary geometry of the main channel controls the maximum extent of saltwater intrusion.

In funnel-shaped estuaries, common to the North Atlantic Coastal Plain, the width convergence length (b) was found to be roughly equal to the convergence length (a) (Savenije, 2012). Because of the similarities of the Savannah River in estuary and channel geometry and depositional environment to other funnel-shaped estuaries where $a \sim b$, the channel width is used to approximate the convergence length (Fig. S2).

To test the robustness of the analytical saltwater intrusion length estimate, parameters in Table 2 were independently varied and compared to the overall intrusion length. A 10% uncertainty (independent of parameter unit) is considered to depict relative control of each parameter.

4. Results

4.1. Observed discharge-salinity relationships

Freshwater discharge from the Savannah River measured at site G, approximately 103 km upstream from the estuary mouth, varies between 110 and 1637 m3/s. Low flows typically occur during late summer (Fig. S3). Over the past 20 years, baseflow has accounted for an average of 80% of the total flow (Table S3). Seasonal differences in baseflow result in higher proportions of groundwater in streamflow during the summer (Table S3). At the river mouth, tidal forcing causes an oscillation between 1000 and −1000 m^3/s, where the negative designates flow moving inland. The tidal range is approximately 3.6 m and 1.5 m during spring and neap cycles, respectively.

Correlations between discharge and salinity are complex and mirror tidal ebbs and flows in the lower Savannah River (Fig. 4). Discharge is greatest, in both the upstream (negative value) and downstream (positive value) direction, when the tides are rising and falling, respectively. At high tide and low tide, stream discharge is zero. The maximum and minimum salinities occur when discharge is zero. Pairwise correlations of collocated, simultaneous measurements of salinity and discharge do not show strong negative relationships (e.g. lower discharge related to higher salinity) because both the peak and trough of the salinity signal occur during slack water.

Gage data along the Savannah River show saltwater intrusion at high spring tide reaching distances greater than 51 km inland (Fig. 5). Linear trendlines show a decrease in salinity of 0.7 ppt/km (Fig. 5). Assuming a saltwater-freshwater gradient (~0.7 ppt/km), the maximum saltwater intrusion length in the Savannah River is between 51 and 58 km inland.

4.2. Results of analytical modeling of streamflow-salinity relationships

Using Eqn. (2) and the parameters listed in Table 2, the high slack water saltwater intrusion is calculated to be approximately 56 km in the Savannah River (Fig. 6). This is a close match to gage salinity

Table 2
Parameters for analytical saltwater intrusion length model.

Description	Parameter	Units	Northern Channel Value	Explanation and Source
Channel width at mouth	B_0	m	795	Channel width determined from NHD stream polygons.
Convergence length of the cross-sectional area	a	m	33,333	$a = b$ Savenije, 2012
Convergence width	b	m	33,333	Convergence width, was obtained by calibration of $B = B_0 exp(-\frac{x}{b})$, where B [L] is the cross-sectional width at location x (km) from the mouth. Channel width was determined from NHD stream polygons. See Fig. S2. (Nguyen et al., 2008)
Van der Burgh's coefficient	K	–	0.502	$K = 0.16x10^{-6}\frac{{h_0}^{0.69}g^{1.12}T^{2.24}}{{H_0}^{0.59}b^{1.10}{B_0}^{0.13}}(0 < K < 1)$ (Savenije, 1993)
Initial river discharge	Q_f	m^3/s	224	Average summer (Jun, Jul, Aug) discharge from upstream gage A from 1999 to 2020.
Tidal averaged cross-sectional area at the mouth	A_0	m^2	6241	Average stream discharge divided by velocity at mouth gage A.
Tidal average depth at estuary mouth	h_0	m	8.5	Average depth across mouth from NOAA bathymetry
Tidal range at estuary mouth	H_0	m	3.35	Tidal range at spring tide as measured from gage A at mouth.
Tidal velocity amplitude at the estuary mouth	v_0	m/s	1.2	Average daily maximum - minimum water velocity at gage A near mouth.
Time length of tidal cycle	T	s	44,280	12.3 hrs
Tidal excursion at the estuary mouth	E_0	m	16,914	$E_0 = \frac{v_0 T}{\pi}$ Savenije, 2012
Estuarine Richardson number	N_R	–	0.1326	$N_R = \frac{\Delta\rho}{\rho}\frac{gh_0}{{v_0}^2}\frac{Q_f T}{A_0 E_0}$, where $\Delta\rho = 25$ kg/m^3, $\rho = 1025$ kg/m^3, and $g = 9.81$ m/s^2 Savenije, 2012
Dispersion length	D_0	m^2/s	2638.3	

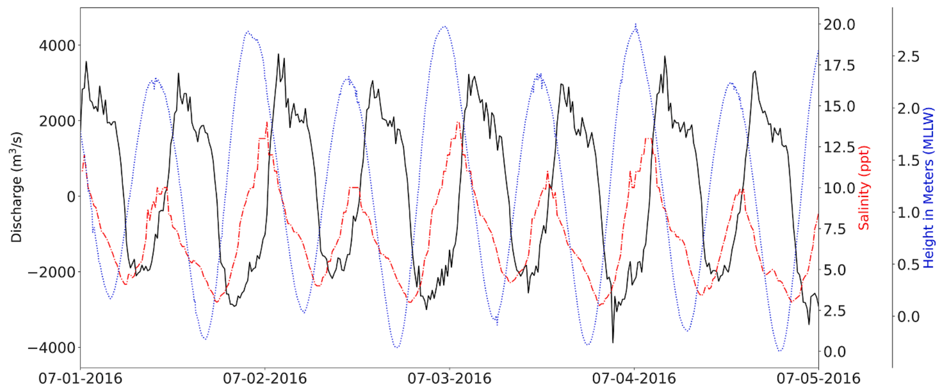

Fig. 4. Discharge and salinity at gage C, 23 km upstream from the mouth, from July 1–5, 2016. Tide level as measured at the coast is shown in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

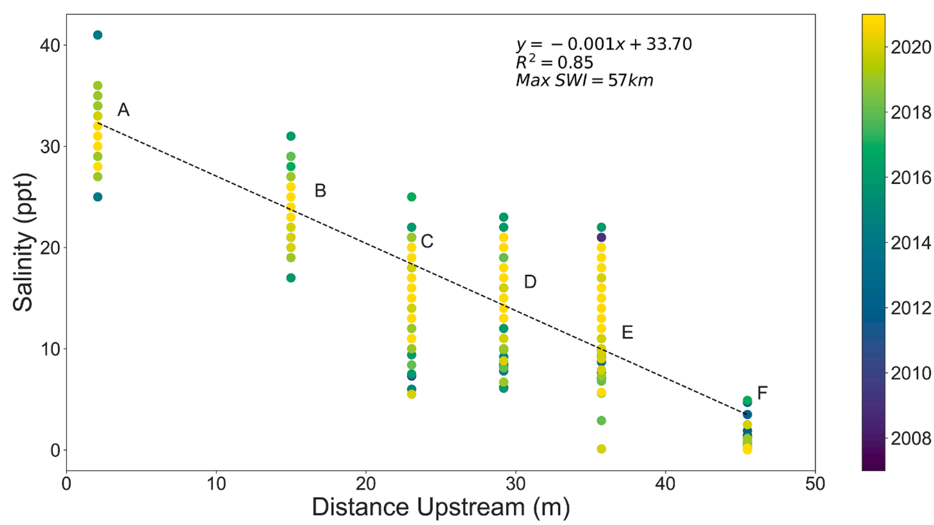

Fig. 5. Observed monthly maximum salinity at gages along the Savannah River between 2008 and 2020. *Dashed line* marks linear trendline from mean of all observations at each station. See Fig. 2 for locations of A-F.

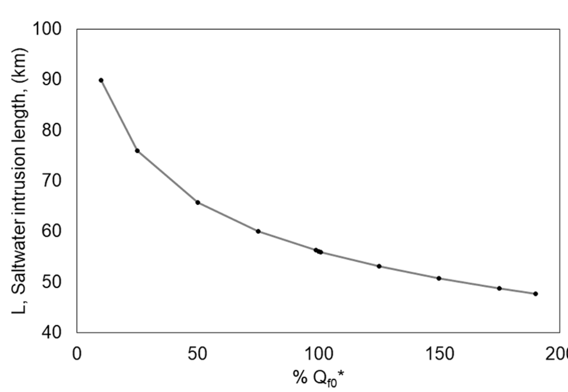

Fig. 6. Saltwater intrusion length with various freshwater discharge rates relative to Q_{f0} (224 m^3/s).

observations (Fig. 5). The model estimate was most sensitive to variations in tidal depth (h_0), convergence width (a), and convergence length (b) (Fig. 7). Convergence length has the most influence on intrusion length, while also being a particularly difficult parameter to estimate (this study assumes $b = a$ due to the funnel-shaped estuary).

The saltwater intrusion length is inversely related to the discharge – the lower the discharge, the greater the intrusion length. The saltwater intrusion length generally changes at a rate of $-14.3/Q_f$ (m^3/s) where the negative indicates the upstream movement of the intrusion as freshwater discharge (Q_f) decreases (Table S4). A hypothetical 25% decrease in freshwater flow will lead to 4 km (7.1%) increase in saltwater intrusion length, while a 25% increase in freshwater flow will lead to a 3 km (5.3%) decrease in saltwater intrusion length (Fig. 6).

The Glover model demonstrates a non-linear relationship between streamflow depletion and pumping characteristics (e.g. location, time, and rate). Using model inputs from Table 1 and the total within-watershed pumping withdrawals ("base scenario"), pumping at a rate of 88,542 m^3/day at a central within-watershed county location causes a <1% reduction in streamflow, or a ~ 100 m upstream shift in the salt front (Fig. 8). The depletion was 0.26% and 0.39% of total freshwater discharge after 50 and 500 years of pumping, respectively. Chatham county, where the city of Savannah is located, reports groundwater pumping rates much higher than neighboring counties. These pumping rates increase the average streamflow depletion estimate for the region. If all counties extracted groundwater at the Chatham county pumping rates, then the streamflow depletion in the Savannah river would be greater than 1% (Fig. 8).

In the Glover model, pumping rate and well-to-stream distance had an impact on stream depletion timing and volume (Fig. 6 & S4, Table 4 & S4). Well-to-stream distance had a larger impact than pumping rate on timing to depletion effects. Under the base scenario, there was a 210-day time lag between the model start time and a 1 m^3/day depletion volume.

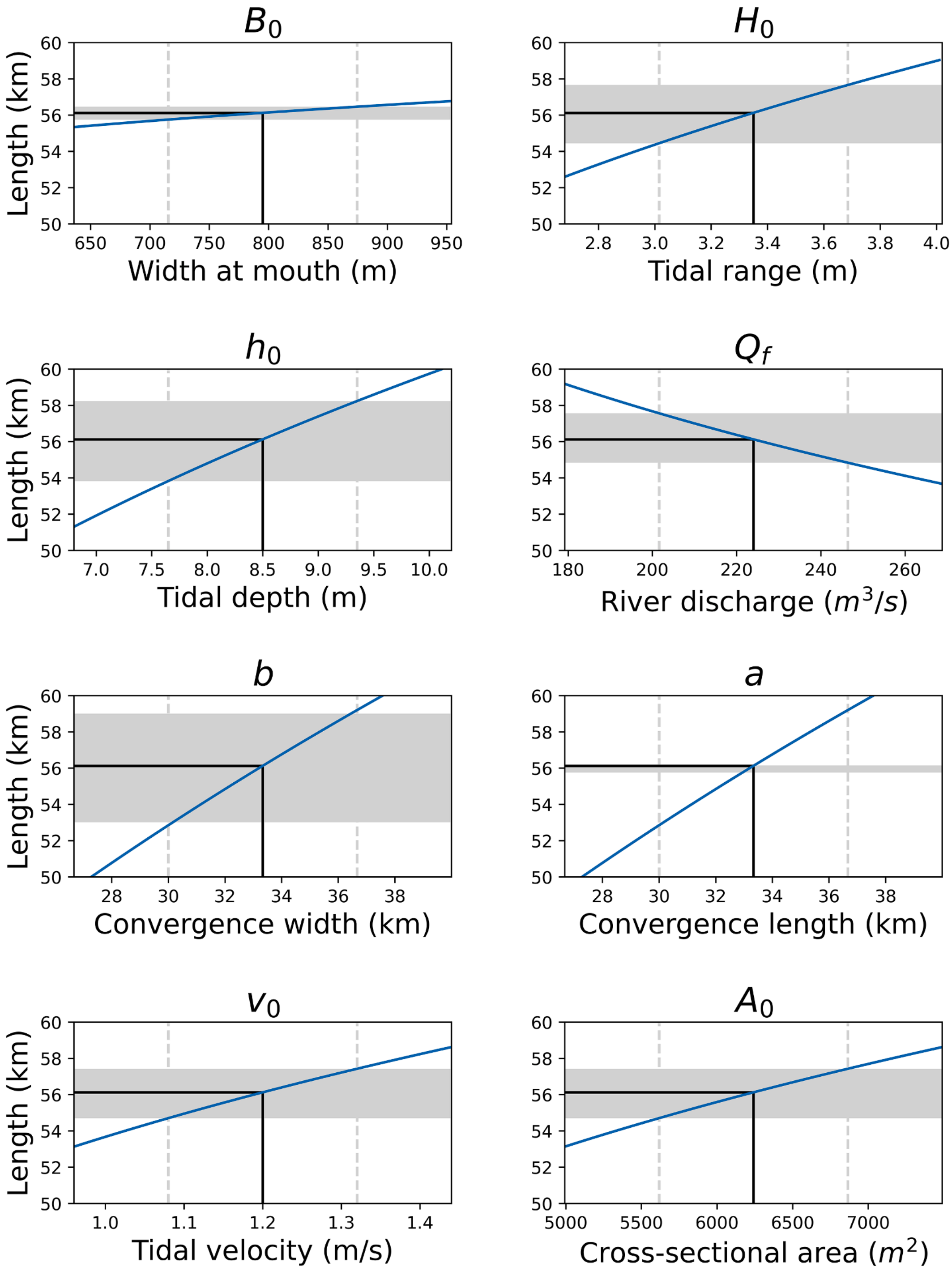

Fig. 7. Sensitivity of the intrusion length to input parameters. *Dashed lines* show ± 10% of x-axis parameters. Resulting range of intrusion length (km) is shown with *gray* shading.

5. Discussion

5.1. Impact of pumping regimes on saltwater intrusion

Regional studies have shown decades of subsurface saltwater intrusion from groundwater pumping and surface salinization due to stream alteration near Savannah (Conrads et al., 2006; Priest, 2004; Provost et al., 2006). Efforts to mitigate saltwater intrusion have led to shifts in water conservation priorities, decreases in groundwater pumping, and river dredging studies (Conrads et al., 2006; Provost et al., 2006). Based on analytical models, current pumping rates will lead to small increases in saltwater intrusion in the Savannah River. Current pumping in the Savannah watershed is a small portion of the overall flow in the river thus limiting the impact of pumping on saltwater intrusion by less than 1% (~100 m upstream).

Although findings indicate that reported groundwater pumping rates have little direct impact on streamflows, a consistent increase of 100 m saltwater intrusion could have an important effect on the coastal system. These long-term slow salinization processes increase the risk of detrimental effects of the fast salinization events, such as storm-surge, tidal highs, and drought. For example, during extended periods of drought, the increased demands on irrigation may lead to higher pumping rates

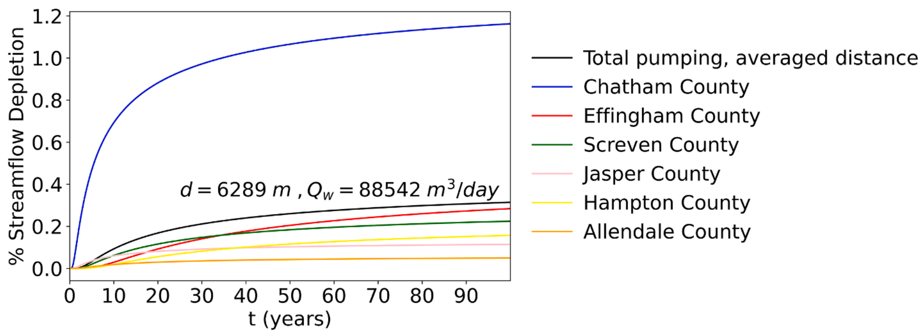

Fig. 8. Percent streamflow depletion due to nearby pumping over time based on rates reported by each county. *Black line* represents a single well at 6289 m from the stream with a total pumping rate of 88542 m^3/day (Table 2). Other lines use the given county values for d and Q_w and assume 6 wells (for the 6 counties) extract groundwater at that rate (Table S1). Note that the values on the vertical are percentage, such that a value of 1 means that $Q_a/Q_f = 0.01$. County locations are shown in Fig. 2.

and more streamflow depletion. During these droughts, baseflow accounts for a higher proportion of the stream. Because the water level in the local flow system may be substantially decreased, exfiltration comes from the intermediate and regional flow systems, and deeper aquifers where pumping drawdowns are greater (Faye and Mayer, 1990). The model predicts that the lowest recorded streamflows in the Savannah River (115 m^3/s) could allow saltwater intrusion extending up to 65 km inland. While annually baseflow accounts for roughly 80% of total Savannah River streamflow, baseflow accounts for up to 90% of total streamflow during the summer and a reduction in baseflow during this time would have a greater impact on overall stream quantity and quality (Table S3). Inversely, if relative contribution of baseflow decreases due climatic shifts (e.g. increase in stormwater from increased precipitation), pumping-induced depletion may become negligible.

While current pumping rates suggest minimal impact on the saltwater front in the Savannah River, it is likely to have a much greater effect under higher pumping regimes and in smaller watersheds. If the city of Savannah were to double their pumping, the salt front could move ~ 200 m inland (which is equivalent to 0.8% streamflow depletion). In some watersheds, however, irrigation wells can decrease streamflow by 10 to 25% (Burt et al., 2002; Killian et al., 2019). For example, in a watershed in North Carolina, close to the area studied here, increased agricultural water needs have led to a 10% decrease in flow (Zipper et al., 2019a). In the Savannah River, the depletion potential (Fienen et al., 2017), a term referring to the potential reduction in streamflow from pumping, may even exceed 10% streamflow depletion during the irrigation season. Estimates of streamflow depletion in this study are much lower due to the yearly average approach. For example, reports of total irrigation groundwater withdrawals for LSR watershed counties in South Carolina account for approximately 60% of annual usage from June to September (Monroe, 2018). Considering this seasonal distribution of irrigation pumping, which concentrates most of the pumping during the growing season, using the county-specific mean as a constant underestimates the pumping rate for the summer months. Additional studies on the time lag between increased summer pumping and streamflow depletion are necessary to determine if these seasonal fluctuations lead to lasting saltwater intrusion impacts.

Assuming other coastal streams experience similar (or greater) levels of streamflow depletion, groundwater pumping may have induced undocumented stream salinization in the past and may increase risk of saltwater intrusion in the future. Near-stream groundwater management will be essential to reduce saltwater intrusion impacts in regions with highly connected groundwater-surface water resources. The combined data analysis and analytical modeling approach demonstrated in this study may be applied to other coastal systems, even those with limited data, to better understand the management implications. Longitudinal field studies and numerical models may help unravel hydrologic feedbacks and site-specific heterogeneity in the groundwater pumping and stream salinity relationship.

5.2. Ecological impacts of increased pumping

With increased groundwater pumping and streamflow depletion, salt will extend 100 s to 1000 s m upstream through the Savannah National Wildlife Refuge (Fig. 6). This protected region is the location of a large portion of the tidal freshwater marshes left in southeastern states. The conditions for tidal freshwater and oligohaline marshes exist for only a few kilometers along the Savannah River, placing a great importance on the conservation of this reach (Lindgren, 2010). Salinity is the main designation between the marsh vegetation assemblages and distributions (Latham et al., 1991). Ecological shifts in response to a saltwater intrusion are expected to be extreme as salt-tolerant vegetation communities (e.g. *Scirpus validus*) become dominant in altered freshwater oligohaline marsh communities (Welch and Kitchens, 2007). Already, over half of the tidal freshwater marshes has been lost in the refuge due to upstream transgression of the salinity gradient (Griess, 2011). The northern part of the refuge consists mostly of bottomland hardwoods and cypress–gum swamp that may be periodically flooded (Dodd and Barichivich, 2017; Garman and Nielsen, 1992; Griess, 2011). These regions contain small channels and an extensive number of woodland pools and creeks important for declining populations of amphibians (Dodd and Barichivich, 2017). Forest dieback and saltwater intrusion could cause irreversible damage to this wildlife refuge ecosystem.

5.3. Model evaluation and limitations

The analytical stream salinity model matches data for the Savannah River well. The model predicts the inland extent of saltwater intrusion at high slack water to be 56 km (Fig. 6), which is consistent with reports of saltwater detected more than 40 km upstream with tidal water-level signals reaching 64 km upstream (Bossart, 2002; Conrads et al., 2006; Pearlstine et al., 1993). This calculation assumes the system has reached steady state, and disregards any time delays between stream discharge and salinity. Although this would lead to an overprediction, the limitations in the Glover model may underpredict the impact of current pumping rates on the Savannah.

When assessing the performance of analytical models, it is important to consider the simplifying assumptions that they include. For streamflow depletion, the Glover solution assumes a homogeneous, isotropic subsurface in direct connection with a stream of constant flow (Glover and Balmer, 1954). The hydrogeological setting of the lower Coastal Plain does not meet these idealized conditions. For example, transmissivity is a large component of this model and the transmissivity of the surficial aquifer is highly variable (Provost et al., 2006). However, we expect that our estimates of streamflow depletion may be underestimated mostly due to nonlinearities in the Glover solution. Our calculations assume that pumping rates are evenly distributed across each adjacent county. Based on that, the sum of pumping rates is modeled as a single well located in the middle between the river and the boundary of the watershed. For the adopted parameters (Table 1), the relationship between the stream-to-well distance and the depletion indeed approached linearity rapidly (Fig. S5), which supports this simplified approach. However, for certain hydrologic regimes, it is possible that this relationship is non-linear (blue curve in Fig. S5), and wells located closer to the river are highly impactful and distant ones are negligible. This simplification is hard to resolve without further information on specific pumping rates and site-specific hydrologic conditions (Zipper et al., 2021). In cases where the impact of wells decays with distance faster than linearity, modeling a single well located halfway between the river and the watershed boundary likely underestimates streamflow depletion due to greater development along the river. A future analysis of unevenly distributed pumping rates may illustrate the importance of pumping distances.

For saltwater intrusion, each parameter used in the analytical approach has uncertainty and the model parameters can coevolve. For example, streamflow (Q_f) will impact channel geometry (e.g. depth, mouth shape) and tidal and hydrologic boundary conditions (e.g. velocity). This can lead to compounding effects of streamflow reduction and sea-level rise. The approach used here assumes no delay in reaching the maximum saltwater intrusion length at equilibrium. However, estuary systems react differently to increases versus decreases in freshwater discharge. An increase in discharge propagates as a mass wave very quickly through the system, however decreased discharge is gradual since fresh and saline water must mix in the channel. The estimation for the maximum saltwater intrusion extent to pumping may never be reached if higher pulses of freshwater discharge (i.e. during wet winter seasons) prevent the system from reaching equilibrium.

5.4. Contribution of pumping vs other saltwater intrusion factors

The relationship between coastal stream salinity and freshwater discharge is controlled by processes that take place simultaneously over a wide range of timescales ranging from short-term storm events to long term sea-level rise and precipitation changes. The discussion on coastal stream salinization revolves mostly around sea-level rise or channel alteration. In this analysis, these factors are important controls. For example, sea level is predicted to rise approximately 39 cm along the South Carolina and Georgia coastlines by the year 2100 (Church et al., 2013). There is also indication that the tidal amplitude has exhibited long-term change (e.g. Müller (2011) suggested a 2% increase per century), but the impact on saltwater intrusion is not well understood. Calculations show that a 10% increase in tidal depth (associated with sea level rise) or a 10% increase in tidal amplitude may extend saltwater intrusion by another $\sim$ 2 km (Fig. 7). Meanwhile a slight shift in convergence width due to geomorphological alteration could push the freshwater-saltwater interface significantly (up to 3 km).

6. Conclusions

We show, for the first time, the direct link between groundwater pumping and coastal stream salinity. In the Savannah River, pumping-induced streamflow depletion is currently limited and leads to little salinization compared to storm surge, channel dredging, and sea level rise. Increases in groundwater pumping, however, could increase this impact, equaling or exceeding the impacts of sea-level rise or geomorphic change, and ultimately altering the distribution and health of the coastal ecosystems. Salinity is a critical factor in the ecological balance and this study allows for investigation of hypothetical development in the region. The impacts of groundwater pumping on coastal stream salinity is an important management consideration for developed coastlines.

The combined Glover and Savenije models give an estimate for the position of the salt front consistent with observations (Glover and Balmer, 1954; Savenije, 2012). The initial testing of the validity of this method would have been difficult without the multiple stream gages, extensive estuary surveying, and tidal monitoring that are rarely available. Since there are few coastal watersheds like the Savannah River with high quality, longitudinal measurements of both stream and groundwater resources, this analytical approach provides a means of estimating salinization due to groundwater-stream interactions. The parameters required for the models can be inferred from regional hydrogeology, satellite imagery, and basic tidal curves. An extensive application of the approach would identify vulnerable coastal systems in need of careful groundwater management.

The complexities of groundwater-surface water interactions are not well understood in regions experiencing increased water use, land-use change, and climate change. Along coastlines, management of these interconnected water resources is complicated by the risk of salinization. By assessing the potential impact of groundwater pumping on near-coast streamflow, future studies concerned with stream salinization should include impacts of groundwater pumping in addition to discussions of sea level rise, channel alteration, and reduced precipitation. Reliable estimates of streamflow depletion are essential for effective water management in coastal plains.

7. Plain text summary

The location of the freshwater-saltwater interface in coastal streams is a balance between upstream river flows and downstream tidal forcing. During periods of high streamflow, seawater is prevented from intruding upstream, and the freshwater-saltwater interface is located relatively close to the ocean. During periods of low streamflow, high salinity water moves upstream, shifting the saltwater-freshwater interface. Coastal stream salinization may be caused by rising sea levels, increasing storm intensity, and prolonged drought, but changes in groundwater use may also play a role. We assess the impact of groundwater pumping on the salinity of Savannah River, GA. Stream measurements show that salinity reaches 51–58 km inland during high tide and low freshwater stream discharge conditions. Using two mathematical models (one for stream saltwater intrusion and one for streamflow depletion from pumping), we determine that reported groundwater pumping rates only decrease streamflow by 1%, resulting in an increase in the saltwater intrusion length of 100 m. However, increased groundwater pumping could increase saltwater intrusion by 4 km. This would have devastating impacts for freshwater ecosystems and coastal water resources. Overall, we present a new analytical framework that can help determine vulnerable coastal systems and opportunities to better water management.

CRediT authorship contribution statement

Chelsea N. Peters: Conceptualization, Methodology, Writing – original draft, Visualization, Supervision, Project administration, Investigation, Formal analysis, Validation, Software. **Charles Kimsal:** Investigation, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Ryan S. Frederiks:** Writing – original draft, Data curation, Investigation, Formal analysis, Validation, Software, Conceptualization. **Anner Paldor:** Writing – original draft, Visualization, Investigation, Formal analysis, Validation, Software, Conceptualization. **Rachel McQuiggan:** Writing – review & editing, Data curation, Investigation, Formal analysis, Validation, Software, Conceptualization. **Holly A. Michael:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2021.127238.

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