Dynamics of the saltwater wedge in the lowermost Mississippi River during the 2022 low flow season

Brendan Yuill, Hydrologist, U.S. Army Corps of Engineers, New Orleans, LA, e-mail Brendan.yuill@usace.army.mil
Gary L. Brown, Research Hydraulic Engineer, U.S. Army Corps of Engineers ERDC, Vicksburg, MS, e-mail Gary.L.Brown@erdc.dren.mil
Eden Krolopp, Hydrologic Technician, U.S. Army Corps of Engineers, New Orleans, LA, e-Eden.h.krolopp @usace.army.mil
Hailey Laurent, Civil Engineer, U.S. Army Corps of Engineers, New Orleans, LA, e-mail Hailey.m.Laurent@usace.army.mil
David Ramirez, LMR&T Branch Chief, U.S. Army Corps of Engineers, New Orleans, LA, e-mail David.A.Ramirez@usace.army.mil

Abstract

During periods of low discharge (< 8500 m^3/s based on historical assumptions), saline water from the Gulf of Mexico intrudes into the channel of the Lowermost Mississippi River (LMR). The density of the marine Gulf water relative to the fresh river water allows the marine water to overcome the momentum of the river discharge and flow upstream tens of river miles. While this behavior is typical of many low-slope, coastal rivers world-wide, it poses a management problem as the saline water introduces water quality issues to municipal and industrial water in-takes located along the LMR. As the U.S. Army Corps of Engineers (USACE) maintains river depths below natural bed levels within the navigation channel of the LWR to benefit deep-draft shipping, the USACE mission includes mitigating the derogatory effects of the saltwater intrusion (referred to as a saltwater 'wedge') promoted by channel dredging. The mitigation efforts include forecasting the leading 'toe' of the wedge as it progresses upstream and by building a sill (i.e., a submarine dam constructed of sandy bed sediment) to arrest the upstream movement of the wedge if the location nears critical infrastructure. In this study, we present observations of the saltwater wedge dynamics during the 'record-breaking' low flow 2022 season as well as results from numerical modeling tools in development to aid forecasting wedge behavior.

Our field observations show how the saline Gulf water preferentially advances up-channel by filling channel bed areas of low elevation and how the location of the toe can linger in deep pools while moving swiftly over more shallow reaches. Because of the dependence on river bathymetry, the rate at which the wedge advances upstream is highly variable for a given river discharge. Our modeling confirms the importance of river bathymetry as well as the sensitivity of wedge behavior to relative discharge and marine water level. While current forecasting methods reliant primarily on river discharge have successfully identified river conditions when sill construction was required, methods that incorporate the effects of river bathymetry will add improved precision to future saltwater wedge management decisions and reduce uncertainty related to the timing of sill construction.

Introduction

It is common for low-slope, coastal rivers to experience saltwater intrusion from the marine basins into which they flow during periods of low river discharge (Figure 1) (McAnally and Pritchard, 1997). Marine water typically has a salinity of 28-32 ppt and fresh river water typically has a salinity of near zero. This salinity differential generates a relative density differential between marine water and river water of approximately 3%. During most river discharges, the momentum of the river flow is of sufficient magnitude to prevent the relatively dense marine water from intruding into the river channel. However, during periods when the downstream river momentum is significantly reduced, such as during extreme high tides, high wind and marine surge events, or periods of low river discharge, the density differential may generate flows of saline water upstream through the river channel (Balloffet and Borah, 1985; Rattray and Mitsuda, 1974; Xue et al., 2009). These saline flows occur within the bottom of the flow column, where downstream river flow velocities are smallest and due to the relative negative buoyancy of the saline water. The density difference induces a significant damping of the turbulent exchange of momentum and salt mass between the fresh and salt water (B. Henderson-Sellers. 1982). This, in turn, induces a strongly stratified condition, preserving the differential momentum between the upstream and downstream flows. The low slope of many deep, coastal rivers, such as the Mississippi River, makes the rivers particularly prone to saltwater intrusion as long reaches of the channel bed are below sea-level (~500 km for the Miss. Riv.), and therefore, potentially accessible to density-driven saltwater flows (McAnally and Pritchard, 1997; Soileau et al., 1990).

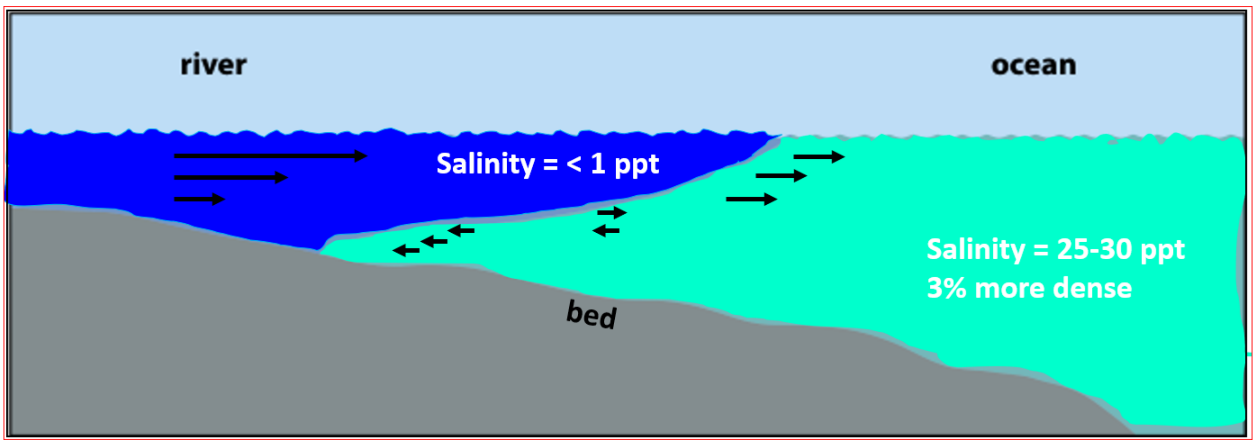

***Figure 1**: Diagram of ocean/marine saltwater intrusion into a river channel (longitudinal view). Arrow length represents relative flow velocity.*

Saltwater intrusion has been well studied in coastal rivers world-wide (e.g., An et al., 2005; Bellafiore et a'., 2021; Miller, 2021; Mulrennan, et al., 1998; Veerapa et al., 2019; Wang et al., 2012). The majority of these studies focused on frequent drivers of intrusion, such as tidal or ocean current cycles with fixed durations, which limit the time and distance over which the intrusion may occur. Low-river discharge driving intrusion has been less well documented because of its historical infrequency, which is often dependent on relatively infrequent regional drought conditions. Low river discharge may last for months and has the potential to cause relatively severe intrusion, in terms of duration and extent. While significant saltwater intrusion has been documented within the Mississippi River at approximately 10-year recurrence intervals (e.g., 1988, 1998, 2012, 2022), climate change is expected to alter the frequency and severity of drought conditions within the Mississippi River watershed making the future recurrence interval of significant intrusion events uncertain.

In this study we document field observations of saltwater intrusion during the 2022 low discharge period within the lowermost Mississippi River (LMR) (Figure 2). The intrusion event generated a 'saltwater wedge' type density current that extended over 100 km (62 miles) upstream of the river terminus at the Head of Passes (HOP). This study uses the term, 'saltwater wedge' to refer to a coherent water mass within a river channel with salinities greater than 9 ppt as per U.S. Army Corps of Engineers (USACE) convention. As the saltwater wedge progressed upstream, it threatened the intake of industrial and municipal water supplies reliant on access to fresh LMR water. To arrest the upstream progression of the saltwater wedge below critical river infrastructure (i.e., water intakes for the City of New Orleans, LA), the USACE builds a submarine sill out of dredged riverbed sand (Fagerburg and Alexander, 1994). The sill is designed to act as a dam, impounding the salt water on the downstream side. Sill dimensions are determined to specifically mitigate saltwater intrusion promoted by channel deepening, related to USACE maintenance dredging of the LMR navigation channel, beyond the likely extent of the intrusion under natural conditions. While sill construction has proven effective, it is costly and takes a significant period of time to plan and construct (~3 weeks). Therefore, efficient sill engineering and management requires the ability to forecast the likely extent and progression velocity of the saltwater wedge. To that end, we introduce a suite of forecasting tools and test their performance relative to the observed saltwater wedge dynamics. We explore the utility of reduced complexity predictive numerical models. Past studies of saltwater intrusion have indicated that saltwater wedge dynamics are influenced by a range of fluvial, meteorological, and oceanographic processes. As our interest lies primarily wedge dynamics in response to low river discharge, we hypothesize that useful forecasts may be generated from metrics river discharge magnitude and river bathymetry alone.

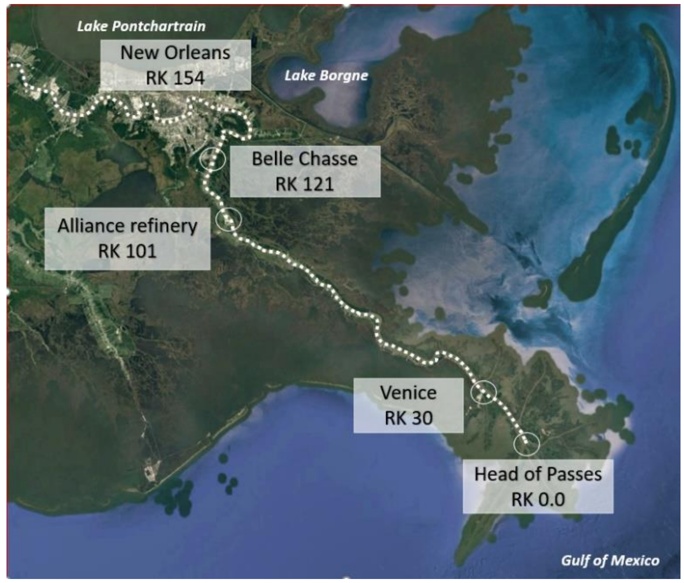

Figure 2: Map of the LMR channel (white dashed line) and the location of key infrastructure susceptible to damage from saltwater intrusion relative to Head of Passes measured by river kilometer (RK).

Methods

To enhance our understanding of the dynamics of the LMR saltwater, we utilized collection of observed riverine salinity measurements and numerical modeling methods.

Measurements of saltwater intrusion

To measure saltwater intrusion into the LMR channel, we utilized vessel-based salinity probe SonTek CastAway-CTD casts, which recorded at-a-station (i.e., discrete point) salinity concentration values along a vertical depth profile. Casts recorded salinity values at approximately 0.3 m (1 foot) intervals and captured the salinity profile from the water surface to 1-2 meters above the riverbed.

During the 2022 low discharge event, the frequency of data collection trips ranged from once per week to three times per week, with the frequency increasing as the upstream-most extent of the saltwater wedge (referred herein as the saltwater wedge 'toe') moved upstream. During each data collection trip, the location of the casts were selected to identify the present position of the toe. During two trips (Oct. 17th, Nov. 28th), additional casts were collected to map the saltwater wedge ceiling (i.e., minimum depth to which significant saltwater extended) along the channel reach downstream of the toe.

Numerical modeling

As of the low river discharge event of 2022, the USACE predicted saltwater wedge behavior based on linear relationships derived from past observations of river discharge magnitude, discharge duration, and previous toe location. While this method has historically successfully identified the timing at which the saltwater sill should be built to safe-guard critical infrastructure, it cannot resolve the effect of river bathymetry (e.g., deep pools vs. shallow reaches) or other influential processes. Previous predictions of toe location relative to observed values typically had errors on the order of +/- 8 km (10 miles), which, if compounded over time, could lead to unnecessary or delayed sill construction in the future. To reduce the errors related to predicting wedge dynamics and improve forecasting the toe location, the USACE is currently developing numerical models that resolve a more robust range of processes that influence saltwater wedge behavior.

Two reduced-complexity modeling approaches were investigated for this study. The first approach included development of a two-dimensional (20 vertical layers, one cell wide) Delft3D model (D3D model). The D3D model simulated per unit-width hydro- and salinity dynamics down the thalweg of the LMR between river kilometer (RK) 312 (river mile [RM] 194) to RK -30 (RM -19; at the terminus of Southwest Pass) above the Head of Passes. The computational grid was 11645 cells long, with a mean cell length of 30 m. The model had a single, time-varying water-level boundary condition at the 'downstream side' and a total discharge boundary condition at the 'upstream side'. USACE New Orleans district previously developed a full complexity three-dimensional Delft3D model that resolved the influence of spatially variable Gulf water levels, temperature, and salinity as well as the LMR distributary channels and wind (Ayres, 2015). The diffusivity parameterization calibrated in the full complexity model was maintained in the reduced complexity D3D model.

The second reduced complexity modeling approach was developed by the USACE Coastal and Hydraulics Laboratory (CHL). This approach utilized a 1-dimensional (cross-sectionally averaged), 2-layer hydrodynamic and salt transport model that resolves two discrete flow layers with layer averaged quantities. It includes a simplified exchange of salt mass and momentum between the layers based on the physics of stratified flows expressed in terms of the layer averaged quantities. (CHL model). The model effectively calculates the velocity profile of freshwater discharge headed downstream and the flow of saline water upstream along the channel bed.

For this study, model scenarios focused on exploring the impact of river discharge on saltwater wedge behavior, with and without sill constructed at RK 102 (river mile [RM] 63.7). Scenarios simulated steady, relatively-low magnitude discharge (2831-8495 m^3/s; 100,000-300,000 ft^3/s) for 30 days and the 2022 low-discharge event (utilizing observed flow and water level values at the model boundaries for the period between August and November 2022). The downstream water level boundary condition for steady flow scenarios assumed a harmonic diurnal tide of +/- 0.1 m with 14-day lunar tidal cycle with an amplitude of +/- 0.2 m unless otherwise specified.

Previous studies of LMR saltwater intrusion suggest that the saltwater formation required discharges less than 8495 m^3/s; for reference, the annual low discharge for the LMR typically occurs in early October and is on the order of 8500 m^3/s.

RESULTS AND DISCUSSION

Observed saltwater wedge dynamics

The measured progression of the upstream limit of the saltwater wedge (i.e., the toe) between mid-September and November 2022 is shown in Figure 3; data for the last major low-discharge event (2012) is shown for comparison. As the daily-averaged discharge dropped from 7000 to 4000 m^3/s between late September and mid-October, the toe moved from RK 52 to 102, where further upstream flow was arrested by the construction of the sill. The progression velocity of the toe during this period was approximately 2 km/day, which matched the velocity of the progression velocity in 2012. For a two-week period in late October 2022, significant saline water overtopped the sill and the toe moved an additional 5-6 RK upstream. This saline water stayed relatively deep within the flow column (<3 m above bed) upstream of the sill. By mid-November, the toe of the saltwater wedge was retreating downstream, likely as a result of the gradually increasing river discharge. As observed in Figure 3, the daily tides heavily influenced discharge within the LMR, with high tide reducing discharge by up to 50% relative to low tide.

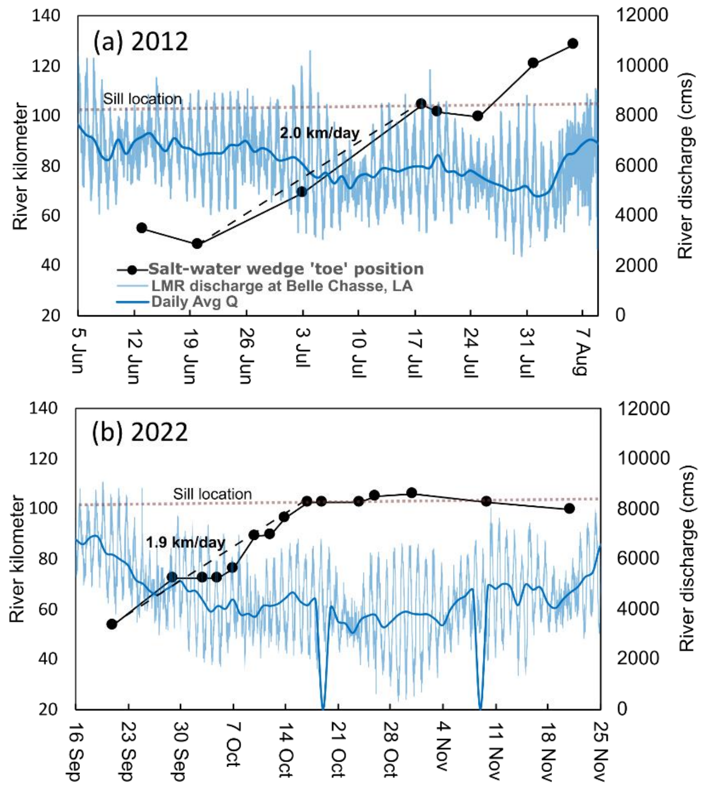

Figure 3: Saltwater wedge toe position for 2012 and 2022 by river kilometer. LMR discharge is shown for reference.

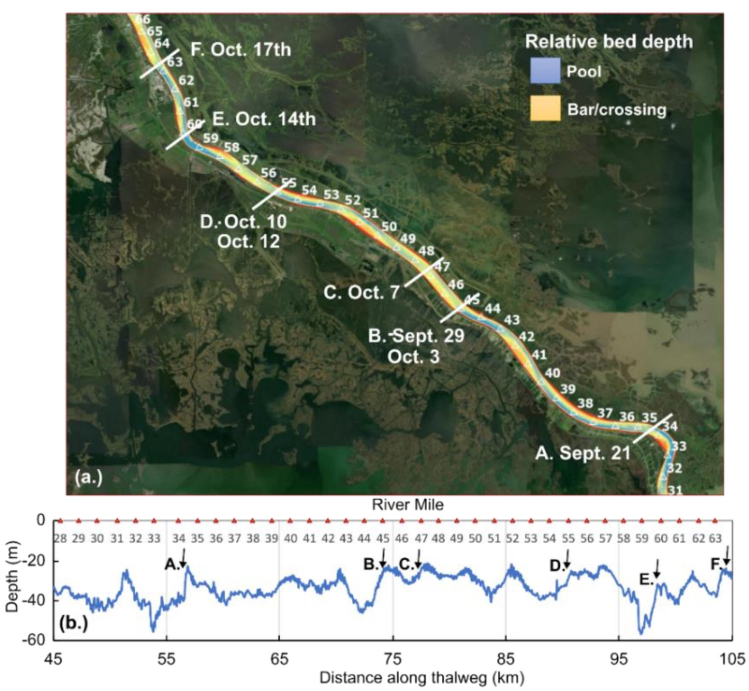

Figure 4: (a) Planform map of the observed toe position and (b) relative to the thalweg elevation. Both maps plot data by river mile for reference. USACE typically cites stationing by river mile.

The location of the toe was typically found in the upstream margins of deep pools (Figure 4). This tendency suggests that the toe moved quicker through shallow reaches and lingered in deeper reaches.

Figure 5 illustrates the longitudinal depth profile of the one and nine ppt isohalines down the thalweg of the LMR for periods when (a.) the wedge was near its peak extension (LMR discharge = 4248 m^3/s; 150,000 ft^3/s) and (b.) when the wedge was in regression (discharge = 7079 m^3/s; 250,000 ft^3/s). During peak extension, the 9 ppt isohaline did not rise much higher than the elevation peaks within the thalweg bed for the uppermost 10-15 km length and gradually rose to a depth of 10 m at approximately 20 km above HOP. During the recession, the 9 ppt isohaline had translated downstream and dropped significantly in depth. The upstream margins of the 9 ppt isohaline shown in Figure 4.b is at the same approximate elevation as the elevation peaks of the proximal thalweg. The distance between the one and nine ppt isohalines show the degree of vertical mixing between the water volume in the saltwater wedge and the freshwater higher within the flow column.

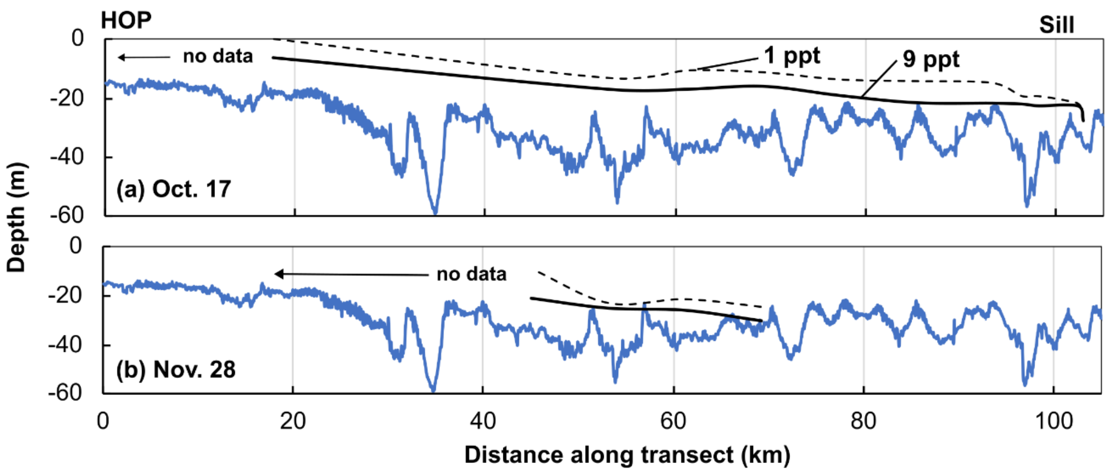

Figure 5: The longitudinal depth profile showing the 1 and 9 ppt isohalines relative to the thalweg elevation. The isohalines do not extend to HOP due to lack of observational data.

Numerical modeling of the saltwater wedge dynamics

Model predictions relative to observed measurements

The reduced complexity D3D model predicted formation of the saltwater wedge and its progression to the sill at RK 102 at a velocity on the order of that observed (2.0 km/day). The model calculated that the wedge started to significantly move upstream of HOP during the high tide periods (promoting lower river discharges) in the week following September 5th, 2022 (Figure 6). Linear interpolation of the observational measurements beginning September 21st at RK 54 suggests that the saltwater wedge started to extend upstream of the HOP around August 25th. Similarly, the model predicted that the wedge reached the sill at RM 102 around October 24, while observations show that the wedge likely reached the sill by October 17th. Typically, the calculated location of the toe location was biased minus 7-10 days or minus 15-30 kilometers. Considering the number of environmental variables that have been shown to influence saltwater intrusion, the simple D3D model, which calculates saltwater dynamics based on discharge and downstream water-level alone, calculated relatively realistic saltwater wedge toe locations and progression velocities.

Figure 7 illustrates the vertical profile of the saltwater wedge predicted by the D3D model for mid-October 2022. The model replicated the observed tendency for marine saline water to seep, upstream along the bottom of the channel with the fresh river water flowing downstream higher in the water column. The model predicted more diffuse salinity gradients within the LMR channel than that observed, which may explain why the modeled wedge ceiling extended higher into the water column and why lower salinities (< 9 ppt) extend much further upstream than that observed. Currently, the model calculates flow viscosity and constituent diffusivity using a k-epsilon turbulence model, which was found to generate realistic salinity gradients in a more complex three-dimensional Delft3D model (Ayers, 2015) of the same approximate domain extent. Future D3D model improvements will seek to dampen the mixing relative to that predicted by the current turbulence model.

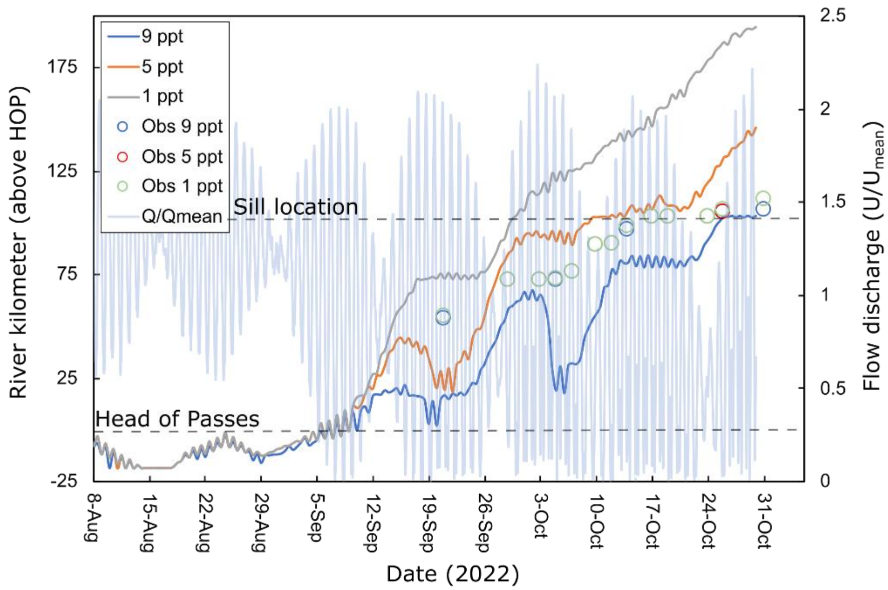

Figure 6: Modeled and observed upstream extent of the 1,5,9 (toe) isohalines. Modeled discharge recorded in the middle of the model domain is shown for reference.

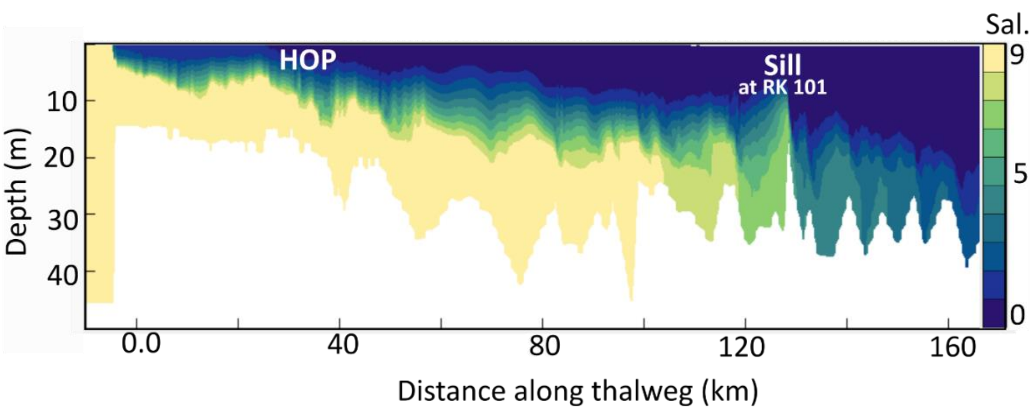

Figure 7: Modeled longitudinal depth profile of the saltwater intrusion for October 17th, 2022. River flow is from right to left. The approximate location of HOP and the sill are shown for reference; the distance along the thalweg on the x-axis is offset from the river kilometer stationing based on distance from HOP.

The modeled influence of river discharge and sill construction on saltwater wedge behavior

Our study employed the D3D model to simulate scenarios designed to isolate the impact of river discharge, sill construction, and marine water level on saltwater wedge behavior. Figure 8(a) shows the calculated toe position (9 ppt isohaline) with and without sill construction for a 30-day period with a steady discharge of 3398 m3/s (125,000 ft^3/s). The upstream extent of the 5 ppt isohaline is also shown to illustrate how the model predicted saline-fresh water mixing upstream of the toe. The sill arrested upstream advancement of the toe for ~7 days relative to advancement without sill construction. The relative advancement of the 5 ppt isohaline was arrested by ~2 days. The model predicted that the effectiveness of the sill at slowing wedge progression was highly sensitive to river discharge. Figure 8(b) shows that increasing the steady discharge to 4248 m3/s (150,000 ft^3/s) delayed the advancement of the wedge toe by >10 days (the toe did not pass the sill location over the simulation period), while decreasing the discharge to 2832 m^3/s (100,000 ft^3/s) reduced the delay to ~5 days.

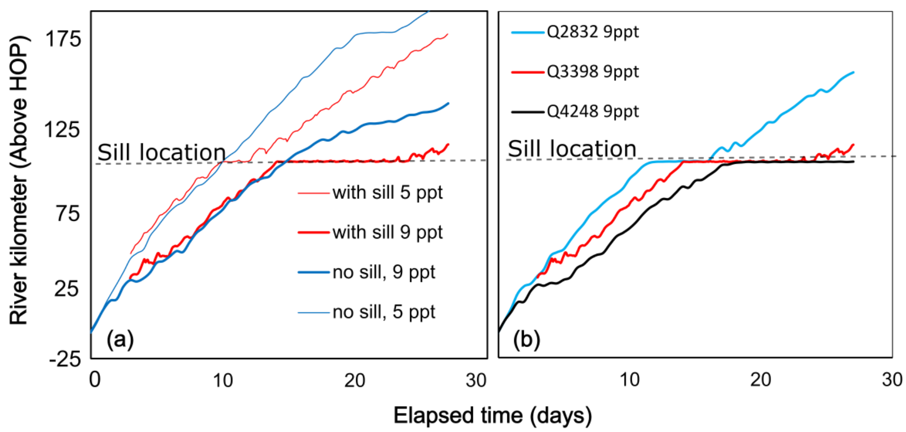

Figure 8: (a) Modeled maximum upstream extent of the 5 and 9 ppt isohalines with and without sill construct; (b) Modeled maximum upstream extent of the 9 ppt isohalines (i.e., wedge toe) at three steady river discharges.

The D3D model results show that increased water level fluctuations (such as that driven by tidal cycles) reduced the velocity of the wedge progression and its upstream extent over the simulation duration. In our scenarios, periods of low tidal water levels temporarily increased river discharge and slowed wedge progression; the coinciding periods of high tidal water levels temporarily decreased river discharge but that decreased discharge did not generate an equally offsetting increase in wedge progression velocity. Figure 9 shows the toe progression for scenarios that fluctuated daily water levels at the downstream boundary by 0.2 (+/- 0.1 m oscillations), 0.4 (+/- 0.2 m oscillations), and 0.6 m (+/- 0.3 m oscillations) as well as without fluctuations (mean-sea level). Figure 9 also shows the toe progression for the scenario with observed downstream water levels (as measured at the Southwest Pass East jetty gage). The scenarios shown in Figure 9 used the same observed discharge inputs at the upstream boundary. For these scenarios, the wedge began its upstream progression at the same time, but the toe reached the sill by Oct. 10th for the +/- 0.1 m fluctuation scenario and never extended beyond approximately RK 25 for the +/- 0.2 and 0.3 m fluctuation scenarios.

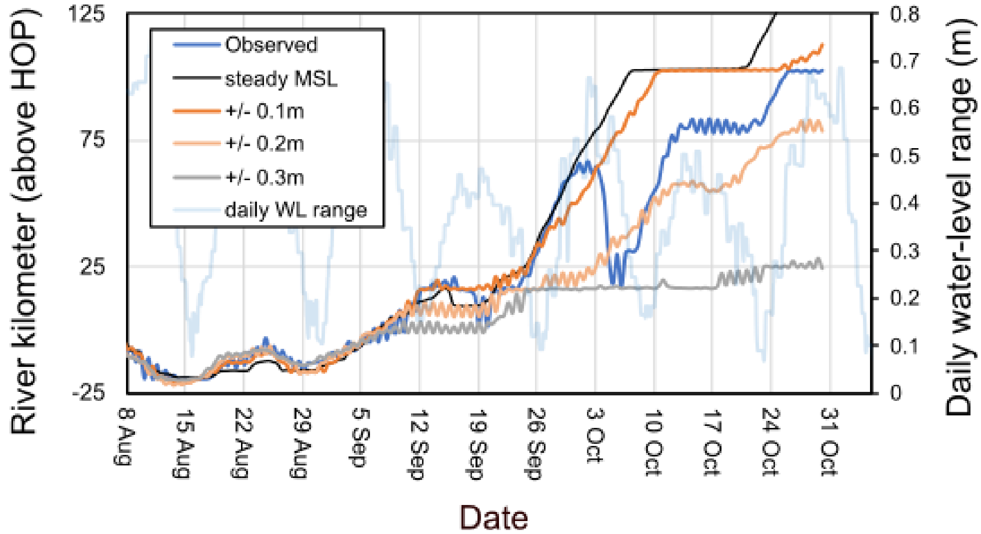

Figure 9: Modeled toe progression for scenarios with variable downstream boundary water levels. The observed water-level range for each day of the simulation period is shown for reference.

Simulation of wedge recession

There has been little observational study of the dynamics of the saltwater wedge during the recession period as the toe moves downstream. During wedge recession, uncertainties related to the threat of contact between saltwater and infrastructure declines which reduces the need monitor river salinities. Interpretation of the sparse historical observational data available, suggest that a higher (x 2) discharge was required to push the wedge toe downstream than that was required to drive the initial upstream progression.

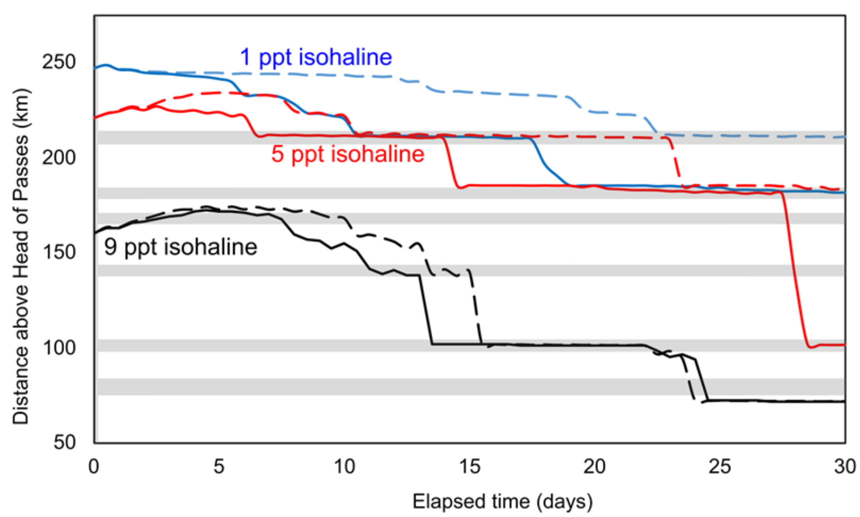

Figure 10: Modeled maximum upstream extent of the 1,5,and 9 ppt isohalines during toe recession induced by a steady 6773 m3/s (240,000 ft3/s) [solid line] and a 8987 m3/s (317,000 ft3/s) [dashed line] river discharge. The horizontal gray lines show the location of pools deeper than 38 m on the y-axis.

The D3D model calculated that wedge recession was more sporadic than the initial progression (Figure 10 and Figure 11). The model results show that, as the wedge toe receded downstream, the toe position lingered in deep pools for extended periods and traveled over shallower reaches over much shorter time periods. Figure 11. shows the wedge extent at three-day intervals for recession driven by a steady 6773 m^3/s (240,000 ft^3/s) discharge. As the toe was pushed downstream by the river discharge, the ceiling of the wedge throughout the entire river channel was progressively eroded downward into the deep pools until it was completed dissipated.

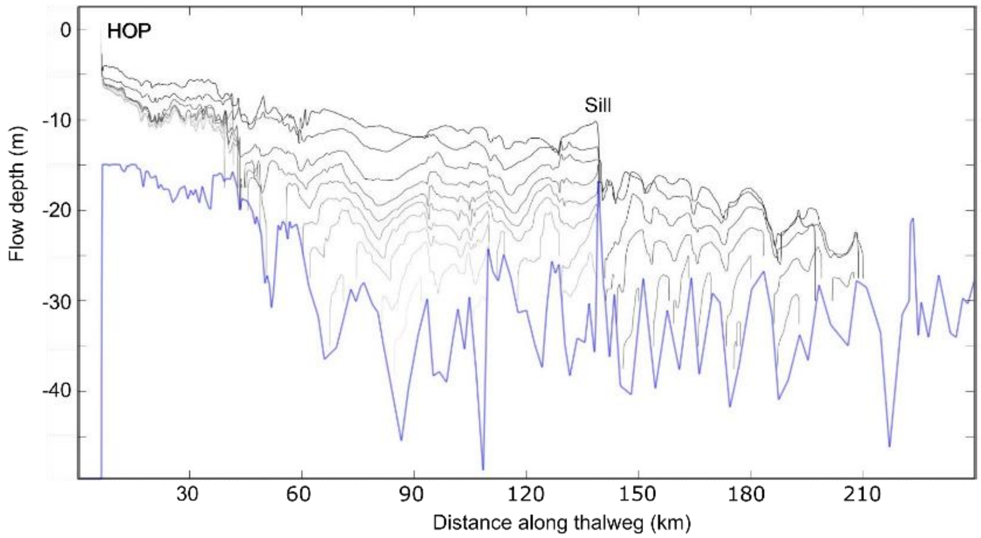

Figure 11: Modeled maximum upstream extent of the 9 ppt isohaline (toe) at three-day intervals. The darker line represents the initial isohaline at the onset of recession and the lightest line represents the isohaline at the conclusion of the 30-day simulation.

CHL Model results

Note that the 1d, 2-layer CHL Model is a developmental model, and was not calibrated or validated for this effort. The results were of interest primarily as a means of qualitatively investigating the hypothesis that much of the basic behavior of the salt wedge can be attributed to river discharge and bathymetry.

The results of the CHL model were similar to the wedge behavior patterns calculated by the D3D model. The modeled simulations assumed constant river discharge and the downstream water level was set as mean sea level. The relatively low interfacial eddy viscosities and diffusivity values utilized by the CHL model generated highly stratified flow. The model calculated that the salt wedge progressed upstream by sequentially filling and overtopping pools in the channel bed, which kept the wedge ceiling low in the flow column relative to the D3D model and more aligned with the observed wedge extent (Figure 12).

Similar to the D3D model, the CHL model predicted that the salt wedge progression was hindered at river discharges exceeding 6773 m^3/s, and that the wedge could not bypass the sill at that discharge. The CHL model predicted that sill construction stalled the upstream progression of the wedge for ~4 days at a steady 3398 m^3/s (120,000 ft^3/s) discharge. For the same steady discharge, the D3D model predicted a longer stall (7 days) and a smaller intrusion distance over a 30-day period (~ -100 km).

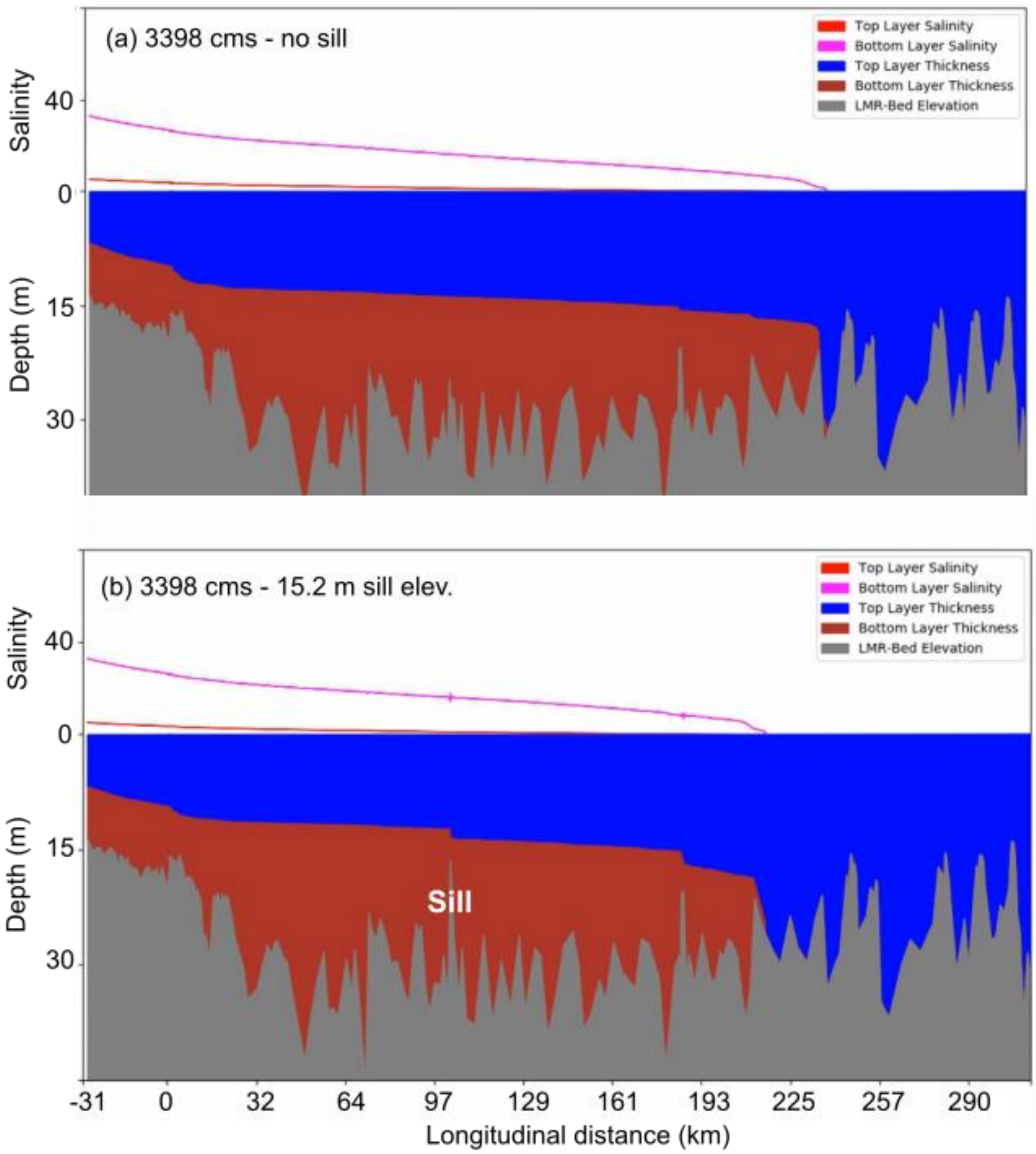

Figure 12: CHL model predictions of the saltwater wedge profile with (a) no sill at RK 101 and (b) with the sill constructed.

Conclusions

This study documents a robust time series of field observations and results of reduced-complexity modeling of saltwater intrusion during the 2022 low discharge event of the LMR. The field observations provide insight on the saltwater wedge behavior during the wedge progression. During much of the progression, the wedge moved upstream at a mean velocity of 2 km per day. The wedge toe did not progress at a steady velocity; it progressed much slower in pools than over shallower reaches and was preferentially located in the upstream margins of a pool during periodic surveys.

Reduced complexity numerical models that calculated riverine saltwater dynamics based on river discharge and marine water level predicted relatively realistic saltwater wedge behavior, including required conditions for wedge formation, wedge progression velocity, and wedge extent. While the models predicted that river discharge below 4248 m^3/s (150,000 ft^3/s) were generally sufficient to generate significant saltwater intrusion, the wedge progression velocity and extent were sensitive to the different discharges that were tested. The influence of the typical tidal cycle on marine water levels (+/- 0.1 to 0.3 m) was also found to have an influential effect on wedge behavior. The D3D and CHL models predicted that sill construction would provide a significant delay in wedge progression (countering the increase rate of progression promoted by USACE maintenance dredging of the LMR navigation channel) during river discharges 3398 m^3/s (120,000 ft^3/s) and above.

Current forecasting methods used to predict saltwater intrusion in the LMR rely on empirical relationships based on historical measurements of river discharge magnitude, duration, and at-a-station salinity measurements. The models presented in this study are relatively simple; however, they provide a means to integrate the effects of temporally variable river discharge, marine water level, and bathymetry into the forecast. The effect of river bathymetric, in particular, appears to be an influential predictor of wedge progression velocity and toe location that historically was not considered in forecasts.

References

An, Q., Wu, Y., Taylor, S. and Zhao, B., 2009. Influence of the Three Gorges Project on saltwater intrusion in the Yangtze River Estuary. Environmental geology, 56(8), pp.1679-1686.

Ayres, S.K., 2015. A simulation of the Mississippi river salt wedge estuary using a three-dimensional cartesian z coordinate model (Doctoral dissertation, university of New Orleans).

Balloffet, A. and Borah, D.K., 1985. Lower Mississippi salinity analysis. Journal of Hydraulic Engineering, 111(2), pp.300-315.

Bellafiore, D., Ferrarin, C., Maicu, F., Manfè, G., Lorenzetti, G., Umgiesser, G., Zaggia, L. and Levinson, A.V., 2021. Saltwater intrusion in a Mediterranean delta under a changing climate. Journal of Geophysical Research: Oceans, 126(2), p.e2020JC016437.

Fagerburg, T.L. and Alexander, M.P., 1994. Underwater sill construction for mitigating salt wedge migration on the lower Mississippi river. Army Engineer Waterways Experiment Station Vicksburg MS Hydraulics Lab.

He, W., Zhang, J., Yu, X., Chen, S. and Luo, J., 2018. Effect of runoff variability and sea level on saltwater intrusion: a case study of Nandu River Estuary, China. Water Resources Research, 54(12), pp.9919-9934.

Henderson-Sellers, B. 1982. A simple formula for vertical eddy diffusion coefficients under conditions of nonneutral stability J. Geophys. Res., Oceans, 87 (C8), pp. 5860-5864, 10.1029/JC087iC08p05860

McAnally, W.H. and Pritchard, D.W., 1997. Salinity control in Mississippi River under drought flows. Journal of waterway, port, coastal, and ocean engineering, 123(1), pp.34-40.

Miller, R.L., 2021. Forcing uncertainty and salinity response to dredging in a tidal freshwater river. International Journal of River Basin Management, pp.1-9.

Mulrennan, M.E. and Woodroffe, C.D., 1998. Saltwater intrusion into the coastal plains of the Lower Mary River, Northern Territory, Australia. Journal of Environmental Management, 54(3), pp.169-188. -slr

Rattray Jr, M. and Mitsuda, E., 1974. Theoretical analysis of conditions in a salt wedge. Estuarine and coastal marine science, 2(4), pp.375-394.

Soileau, C.W., Garrett, B.J., Thibodeaux, B.J. and Magoon, O.T., 1990. Drought induced saltwater intrusion on the Mississippi River. Coastal & Inland Water Quality, pp.223-234.

Xue, P., Chen, C., Ding, P., Beardsley, R.C., Lin, H., Ge, J. and Kong, Y., 2009. Saltwater intrusion into the Changjiang River: A model-guided mechanism study. Journal of Geophysical Research: Oceans, 114(C2).Meyer-Peter, E. and Müller, R. 1948. "Formulas for bed-load transport," Proc. 2nd Meeting of the IAHR, Stockholm, Sweden, pp 39–64

Veerapaga, N., Azhikodan, G., Shintani, T., Iwamoto, N. and Yokoyama, K., 2019. A three-dimensional environmental hydrodynamic model, Fantom-Refined: Validation and application for saltwater intrusion in a meso-macrotidal estuary. Ocean Modelling, 141, p.101425.-river

Wang, B., Zhu, J., Wu, H., Yu, F. and Song, X., 2012. Dynamics of saltwater intrusion in the Modaomen Waterway of the Pearl River Estuary. Science China Earth Sciences, 55(11), pp.1901-1918.-sea level rise

Yuan, R., Zhu, J. and Wang, B., 2015. Impact of sea-level rise on saltwater intrusion in the Pearl River Estuary. Journal of Coastal Research, 31(2), pp.477-487.