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Drought and salinity intrusion in the Lower Chao Phraya River: variability analysis and modeling mitigation approaches

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Abstract: Saltwater intrusion in the Lower Chao Phraya River (LCPYR) is a significant national concern for Thailand, requiring a thorough understanding and a development of effective prediction systems for current and future management. This study investigates the key drivers influencing saltwater intrusion in the LCPYR. Cross-wavelet analysis was applied to examine the interactions between tidal forces, drought conditions represented by the rolling standardized discharge anomaly (RSDA) and rolling standardized precipitation anomaly (RSPA), and salinity levels. The results reveal that saltwater intrusion in the LCPYR is controlled by two interacting mechanisms: a drought-dependent mechanism and a drought-relaxation mechanism. The drought-dependent process, driven by regional hydro-climatic variability and quantified using the Rolling Standardized Discharge Anomaly (RSDA), dominates sub-annual to annual salinity fluctuations. Extreme salinity peaks are primarily modulated by non-tidal sea-level anomalies, underscoring the crucial influence of sea-level oscillations. In turn, the drought-relaxation mechanism, captured by the Rolling Standardized Precipitation Anomaly (RSPA), reflects transient wet periods that can temporarily reduce salinity levels, at times weakening the usual correlation between salinity and hydrological drought severity. The numerical model demonstrates high accuracy in simulating both hydrodynamic and salinity behaviors, validating the cross-wavelet analysis and offering a reliable approach for modeling salinity in this complex estuarine system. We revise and suggest strategies to mitigate the salinity intrusion for emergent drought periods (e.g. optimal redistribution of the diverting freshwater) and proactive/long-term solutions e.g. using impacts of tributary rivers-urban runoff and developing a robust prediction system. These findings offer essential insights to guide management strategies and the development of prediction tools for the LCPYR and surrounding regions.

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Table S1 Different inflow rates (Q_u, m^3/s) used in the scenario-based study for the extreme salinity event in early 2020, and differences in percentage of mean salinity from the baseline scenario.

Scenarios	1st 7 day	1st 15 days	2nd 15 days	% Difference
RM6_S2	157	151	102	49.0
CPY_S1	126	117	134	9.9
CPY_S2	126	119	138	11.9
CPY_S4	136	136	110	32.6
CPY_S5	146	146	120	44.2
Cnst_S1	130	130	130	29.1
Comb1	190	182	90	59.7
Comb2	190	182	75	55.5
Comb3	180	142	112	52.6
rBaseline	140	135	111	30.9

Table S2 As in Table S1, but for the total volume (in million cubic meters or MCM) of freshwater.

Scenarios	1st 7 days	1st 15 days	2nd 15 days	% Difference
RM6_S2	89	194	139	49.0
CPY_S1	65	154	181	9.9
CPY_S2	67	154	181	11.9
CPY_S4	79	174	149	32.6
CPY_S5	85	187	162	44.2
Cnst_S1	78	167	167	29.1
Comb1	113	231	124	59.7
Comb2	113	228	96	55.5
Comb3	104	182	153	52.6
rBaseline	81	173	147	30.9

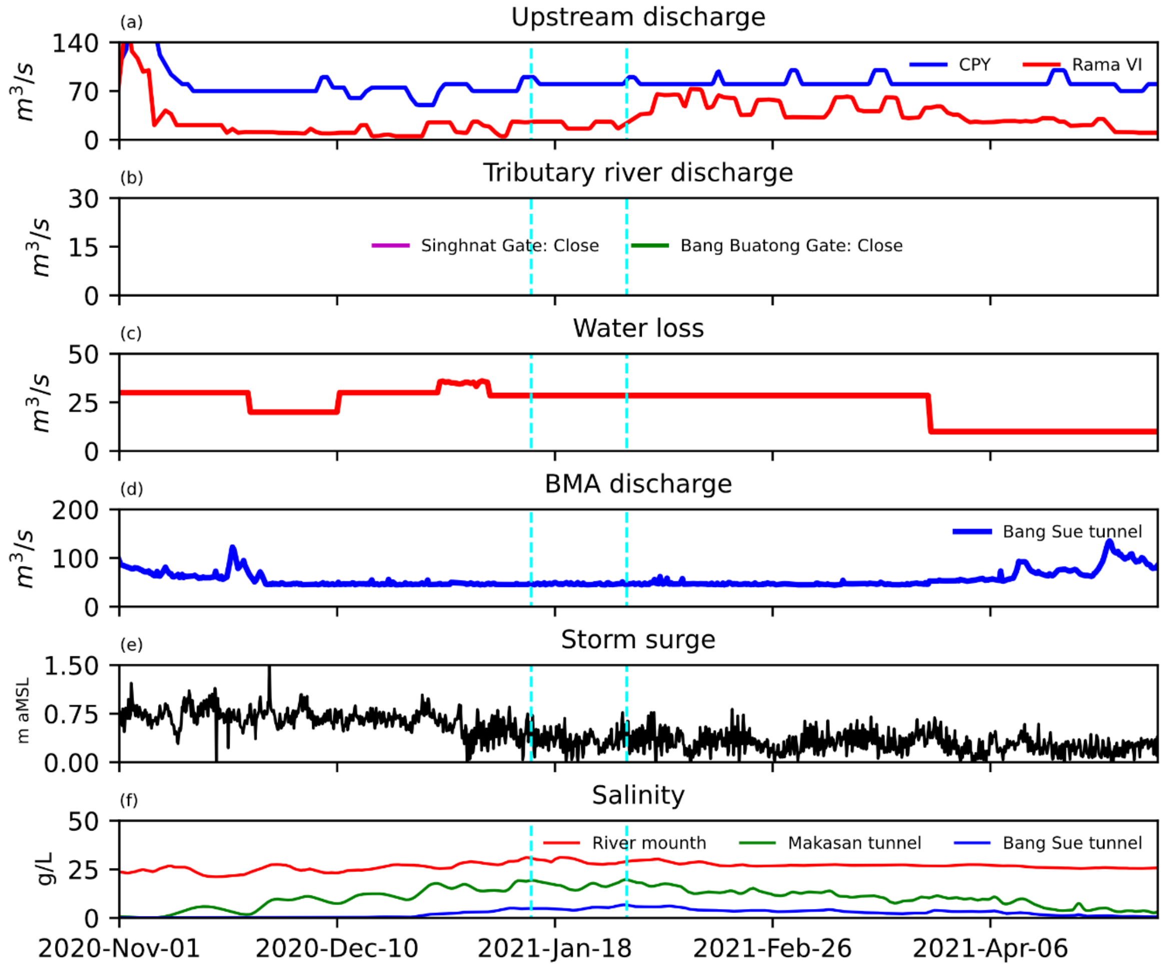

Fig. S1. Collected forcing data for modeling hydrodynamics and salinity in the LCPYR, as in Fig. 4 in the main manuscript, but covering the period from November 2020 to May 2021: (a) the upstream discharge (m3/s) from the Chap Phraya (CPY) Dam (BC7) and Rama VI (BC5) Dam; (b) the diverting discharge water (m3/s) from the Singhnat (BC9) and Bang Buatong (BC10) gates, closed during the study period; (c) the water loss (m3/s) at Bang Kaew station (BC6) due primarily to agricultural withdrawals; (d) the Bangkok Metropolitan Administration (BMA) discharge (m3/s) at the Bang Sue tunnel (BC3); and (e) the storm surge (m above average mean sea level or aMSL); and (f) the salinity level (g/L). Vertical dashed cyan lines indicate extreme salinity events in early 2021.

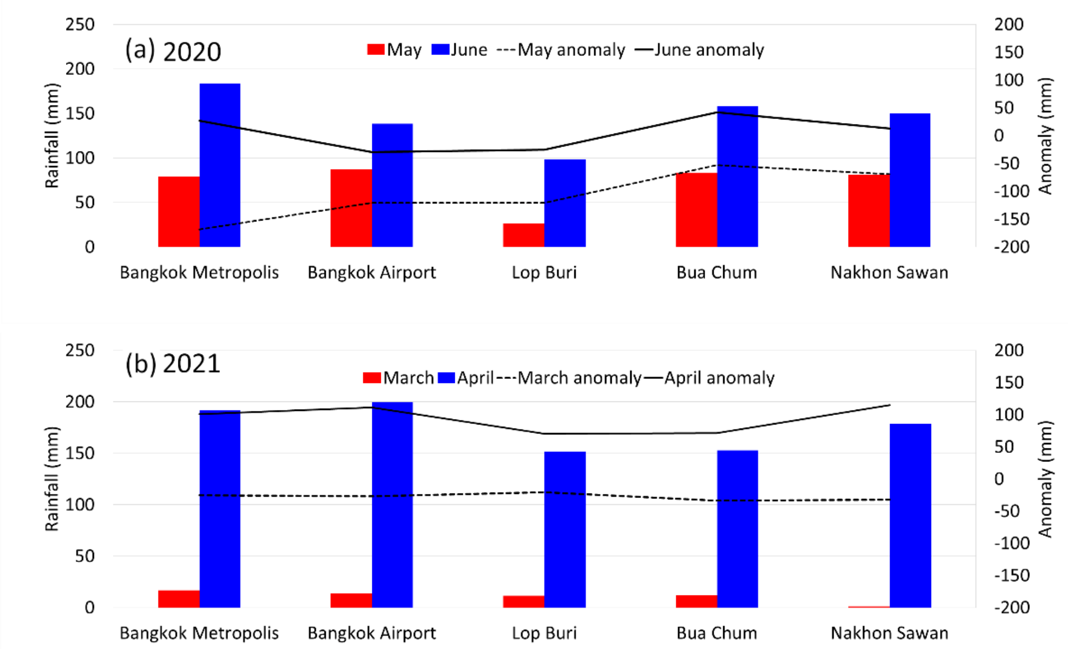

Fig. S2. Variation of monthly rainfall and its anomalies compared to climatological means at multiple locations along the LCPYR: (a) May (red) and June (blue) 2020, and (b) March (red) and April (blue) 2021. For 2020, the dashed line represents May rainfall anomalies, and the solid line represents June anomalies. For 2021, the dashed line represents March anomalies, and the solid line represents April anomalies.

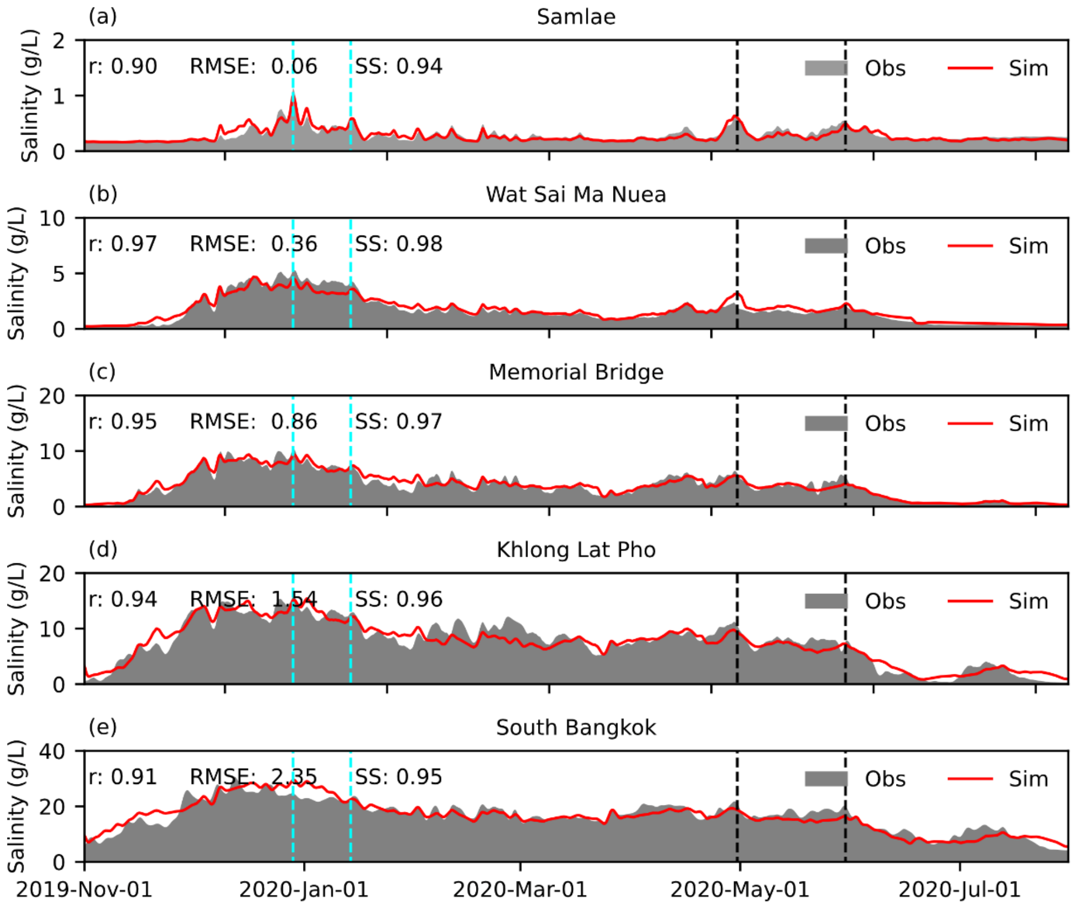

Fig. S3. Comparisons of the salinity trends (24-hour low-pass filtered data) between the observed data (filled gray areas) and the model results (red lines) for the period from November 2019 to July 2020 at various stations: (a) Sam Lae (S5), (b) Wat Sai Ma Nuea (S4), (c) Memorial Bridge (S3), (d) Khlong Lat Pho, and (e) South Bangkok (S1). The locations of the stations are shown in Fig. 1 of the main manuscript. Note that the y-axis ranges are not the same in each panel. Peak salinity events during the winter and summer seasons are marked by vertical dashed cyan and black lines, respectively.

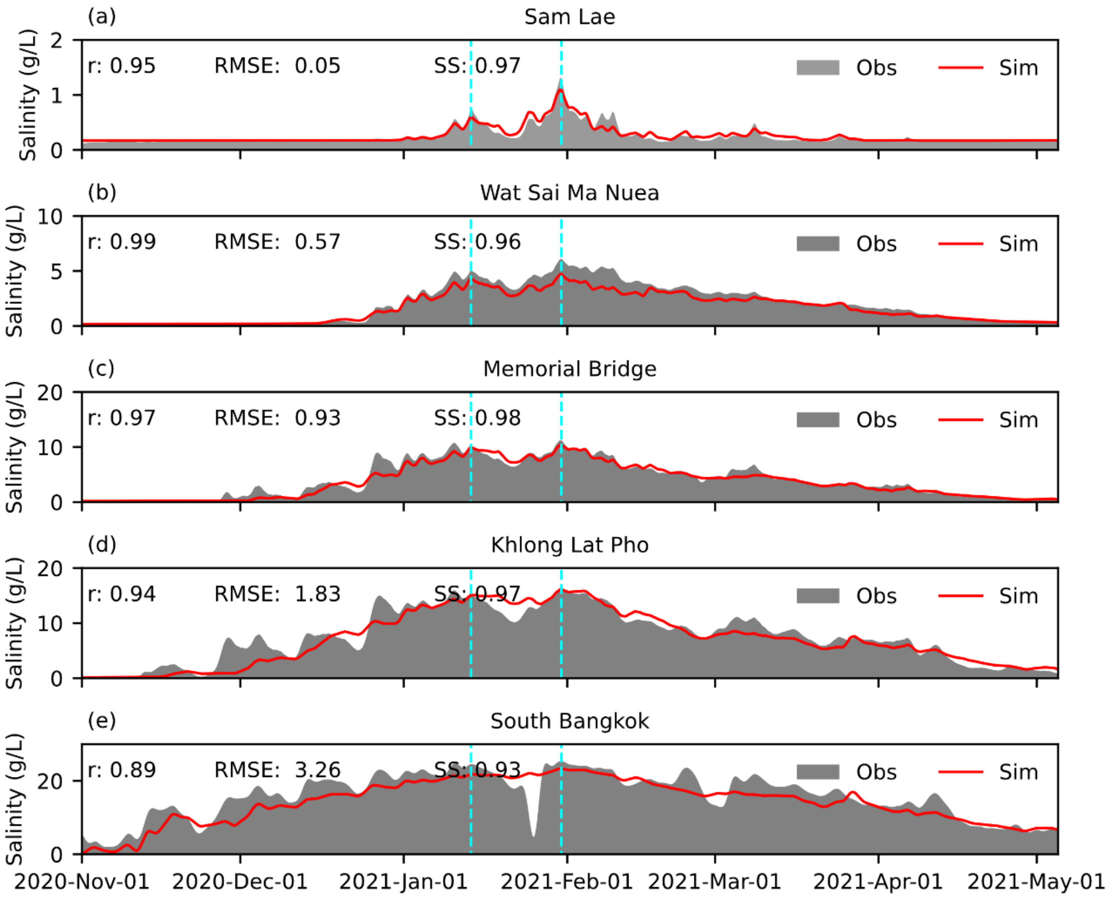

Fig. S4. As in Fig. S3, but for the period from November 2020 to May 2021.

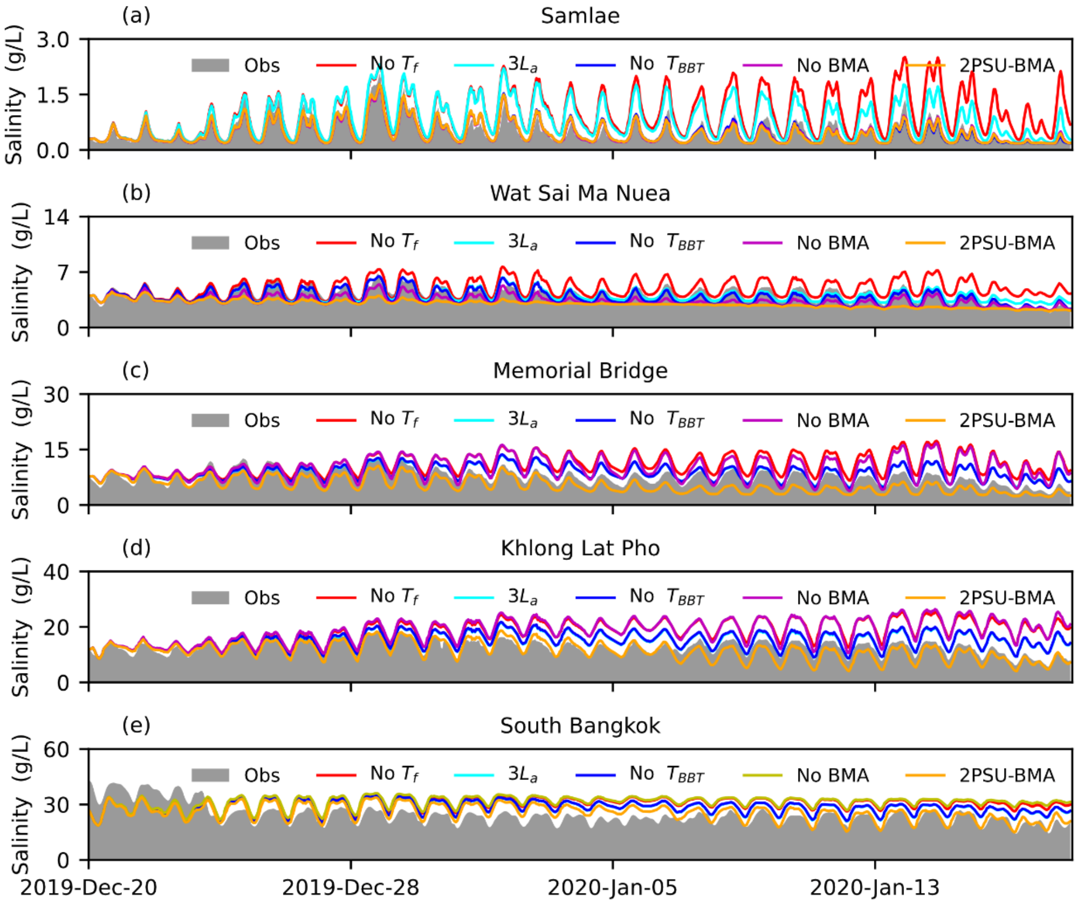

Fig. S5 Comparisons between the observed salinity (filled gray areas) and the simulated salinity from different boundary condition (BC) scenarios, as shown in Table 8 of the main manuscript. The observations and the simulation period are from December 20, 2019, to January 19, 2020.

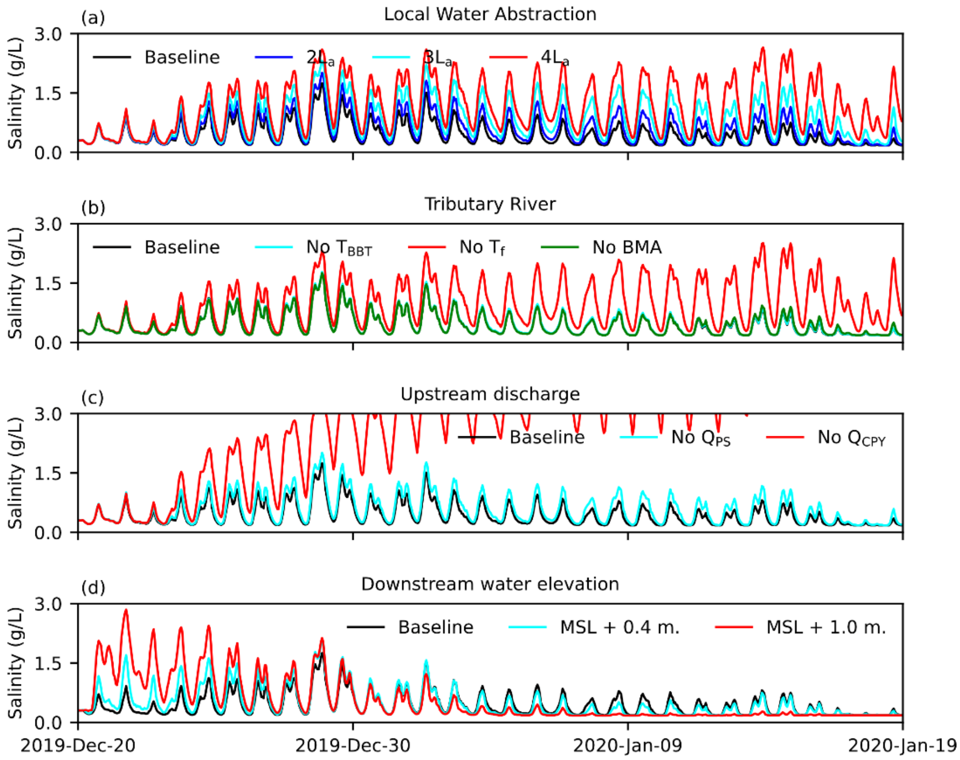

Fig. S6. Salinity responses at Sam Lae station to different perturbation approaches: (a) water abstraction locations, (b) reservoir regulations, (c) side flows and diversion water, and (d) non-tidal sea level conditions, based on an extreme event in late 2019 through early 2020.

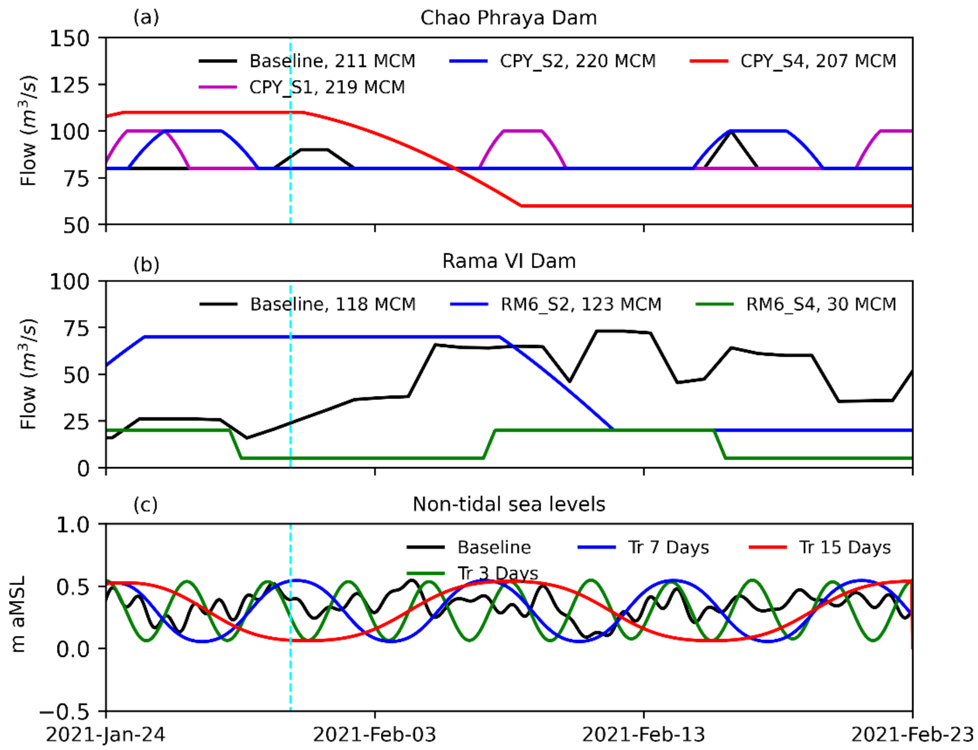

Fig. S7. Corresponding discharges and non-tidal sea level characteristics used for the scenario-based study. The vertical dashed cyan line marks the peak salinity on 30, January 2020: (a-b) The discharge flow rates (m^3/s) at the Chao Phraya (CPY) Dams and the Rama VI Dam, respectively; (c) non-tidal sea levels (m above mean sea level or aMSL). The scenario names and locations of perturbed boundary conditions are as listed in Table 8 of the main manuscript.

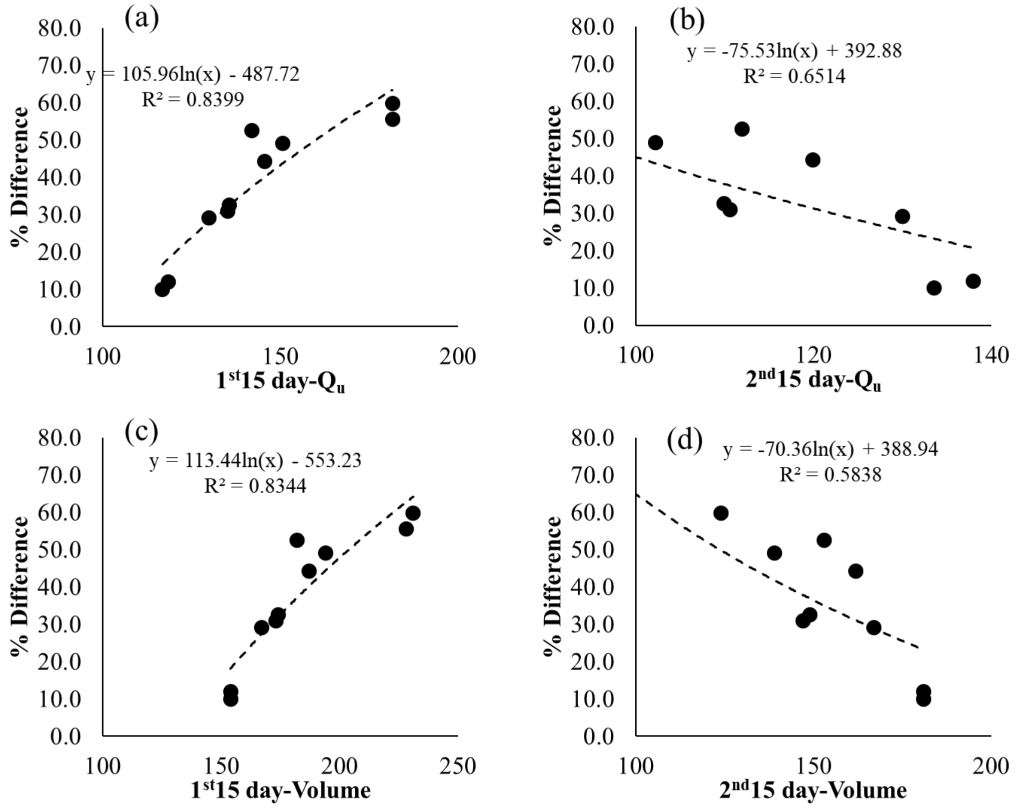

Fig. S8. Relationship between the first and second 15 days inflow (Q_n), total volume of freshwater, and difference percentage from the baseline scenario. The black dashed lines show the best-fit lines for the datapoints; the best-fit equations and the coefficients of determination (R^2) are also shown.

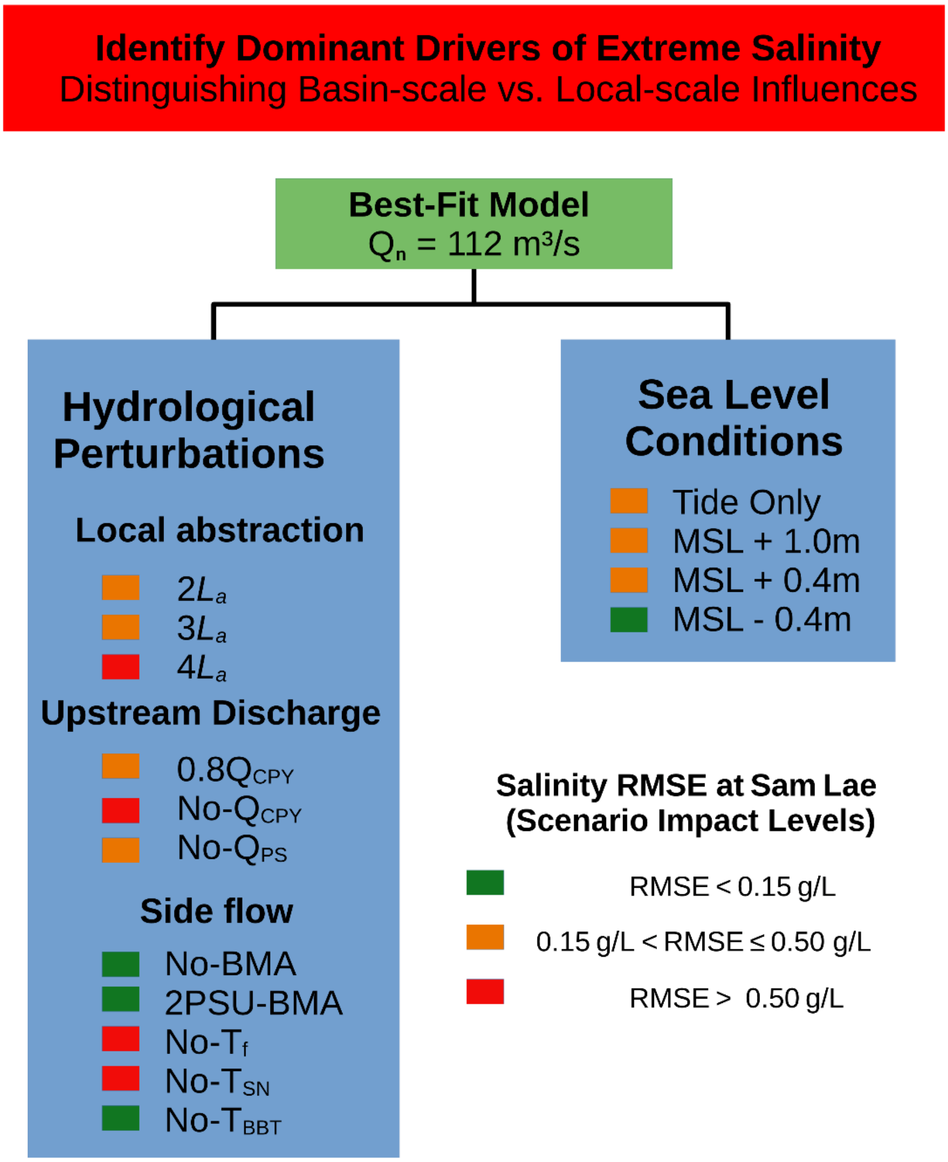

Figure S9 Sensitivity-analysis framework used to isolate the dominant drivers of extreme salinity in the Lower Chao Phraya River (LCPYR). The calibrated best-fit model (green box; net discharge $Q_n = 112$ m³ /s) serves as the baseline. Two perturbation families are explored: (i) hydrological forcings: local abstractions, upstream discharges, and side-flow modifications and (ii) sea-level conditions (blue panels). Each individual perturbation is color-coded by its root-mean-square error (RMSE) at Sam Lae relative to observations: green (RMSE ≤ 0.15 g/ L, minor), orange (0.15 < RMSE ≤ 0.50 g/ L, moderate), and red (RMSE > 0.50 g/ L, severe). The schematic highlights which basin-scale (sea-level) and local-scale (hydrological) factors most strongly influence model skill during the early-2020 extreme-salinity event; numerical RMSE values are listed in Table 2.

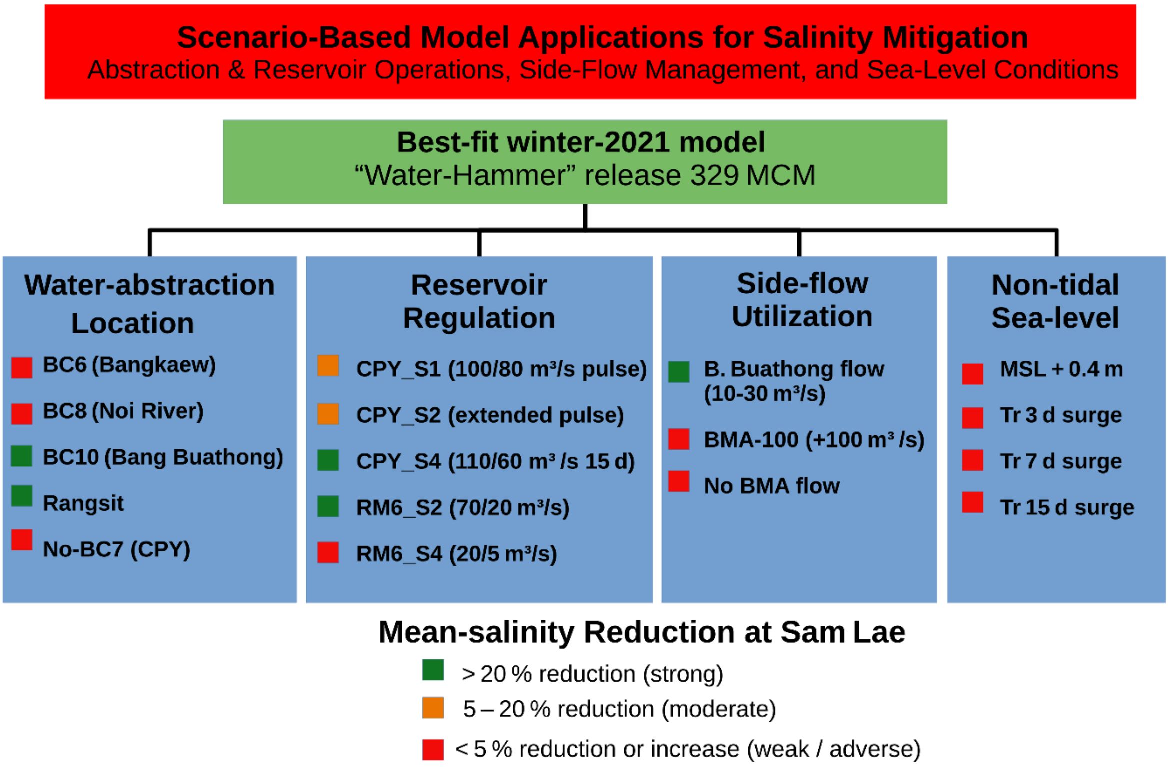

Fig. S10. Scenario-based framework for salinity-mitigation experiments applied to the Lower Chao Phraya River (LCPYR).The calibrated best-fit winter-2021 model (green box) serves as the reference simulation, from which four groups of perturbation scenarios are branched: (i) water-abstraction location, (ii) reservoir regulation, (iii) side-flow utilization, and (iv) non-tidal sea-level conditions (blue panels). Within each group, individual scenarios are colour-coded according to their mean-salinity reduction at Sam Lae relative to the baseline: green (> 20 % reduction; strong mitigation), orange (5–20 % reduction; moderate), and red (< 5 % reduction or increase; weak/adverse). Scenario abbreviations follow Table 3; mean-salinity responses are derived from the time series presented in Fig. 8.