

Climate Projections of salt-wedge intrusions in a Po river branch (Northern Adriatic Sea)

Giorgia Verri¹, Sahameddin Mahmoudi Kurdistani¹, Nadia Pinardi², Giovanni Coppini³,
and Dario Conte¹

¹CMCC Foundation

²University of Bologna

³CMCC

November 21, 2022

Abstract

Estuaries are the transitional systems between the riverine freshwaters and the ocean salt water. Increasing salt-wedge intrusions are mentioned as one of the major impacts of climate change in coastal areas. We propose a new methodology to predict salt wedge intrusions with an intermediate complexity model, so-called Estuarine Box Model (EBM), that allows to use hydrology and ocean climate scenarios to predict salt wedge intrusions. We apply this methodology to the Goro branch of the Po river flowing into the Northern Adriatic Sea. A 30 years' period (1982-2011) is used to train and test the EBM that is then used to project the salt wedge in the (2021-2050) time period under the RCP8.5 emission scenario. The numerical results show that in the (2021-2050) period, the Po di Goro salt wedge intrusion length will increase by 15% on an annual basis (up to 50% in summertime) and the outflowing salinity will increase 9% on annual basis (up to 35% in summer). Finally, a statistical estimation of the extreme values of salt wedge and outflowing salinity shows return periods of 10 years for extremes twice the present mean values. It means that a 16 Km of salt-wedge intrusion, and outgoing salinity about 28 psu are highly expected as an extreme event with 10 years return period

1 **Climate Projections of salt-wedge intrusions in a Po river branch (Northern Adriatic**
2 **Sea)**

3 **Sahameddin M. Kurdistani,¹ Giorgia Verri,^{1*} Nadia Pinardi,² Giovanni Coppini,¹ Dario**
4 **Conte¹**

5 ¹Centro Euro-Mediterraneo sui Cambiamenti Climatici, CMCC, Lecce 73100, Italy.

6 ²Alma Mater Studiorum - Università di Bologna, Department of Physics and Astronomy,
7 Bologna 40126, Italy

8

9 Corresponding author: Giorgia Verri (giorgia.verri@cmcc.it)

10

11 **Key Points:**

- 12 • Climate projections for a salt-wedge estuary show a strong seasonality in the foreseen
13 increase of both the salt wedge intrusion length and the outflowing salinity
- 14 • A two-layer estuary box model is provided to work as an impact tool for coastal
15 environmental projections

16 Abstract

17 Estuaries are the transitional systems between the riverine freshwaters and the ocean salt
18 water. Increasing salt-wedge intrusions are mentioned as one of the major impacts of
19 climate change in coastal areas. We propose a new methodology to predict salt wedge
20 intrusions with an intermediate complexity model, so-called Estuarine Box Model
21 (EBM), that allows to use hydrology and ocean climate scenarios to predict salt wedge
22 intrusions. We apply this methodology to the Goro branch of the Po river flowing into the
23 Northern Adriatic Sea. A 30 years' period (1982-2011) is used to train and test the EBM
24 that is then used to project the salt wedge in the (2021-2050) time period under the
25 RCP8.5 emission scenario. The numerical results show that in the (2021-2050) period,
26 the Po di Goro salt wedge intrusion length will increase by 15% on an annual basis (up to
27 50% in summertime) and the outflowing salinity will increase 9% on annual basis (up to
28 35% in summer). Finally, a statistical estimation of the extreme values of salt wedge and
29 outflowing salinity shows return periods of 10 years for extremes twice the present mean
30 values. It means that a 16 Km of salt-wedge intrusion, and outgoing salinity about 28 psu
31 are highly expected as an extreme event with 10 years return period

32

33 Plain Language Summary

34 Salt wedge climate projections for one branch of the Po river Delta show a seasonality in
35 the increase of the salt wedge intrusion length up to 50% in summer time considering the
36 RCP8.5 climate scenario

37

38 1 Introduction

39 River salt-wedge intrusions are important threats to the quality of inland waters (1).
40 Regionally downscaled climate change scenarios do not properly consider the river salt-
41 wedge intrusions because their grid spacing cannot represent the estuary geometry and
42 they do not involve a proper river-seawater coupling. If we want to gain insight on the
43 trends of salt wedge intrusions along the river estuaries, we need to couple regional
44 climate models with intermediate complexity models that can represent the estuarine
45 overturning circulation and mixing processes as a result of the competition between the
46 upstream riverine freshwater discharge and the ocean waters at the river mouths.

47 Recent literature on salt-wedge intrusion (SWI) projections has considered the changes in
48 the upstream river flow and the sea level rise (SLR) under different climate change
49 scenarios (2, 3). The overall result is that the river discharge changes are expected to
50 affect the SWI more than the SLR. A source of uncertainty is represented by the use of
51 global or at most regional scale SLR (4) without considering the coastal effects probably
52 because no regional downscaled scenario reaches the resolution required to resolve the
53 local SLR (5, 6).

54 An additional challenge is the computational resources required to perform long term
55 numerical experiments with very high-resolution hydrology and ocean models to resolve
56 the estuary geometry. For this reason, the SWI response to climate change has been
57 evaluated by means of synthetic experiments and/or annual mean experiments with

58 upstream river runoff and ocean water inflow averaged over multidecadal time windows
59 representing the present and future climate (2, 3). There is a need to have an impact
60 model tool, capable to run many decades, with inputs from the hydrological changes
61 upstream the estuary and the ocean salt water changes at the estuary mouth.

62 In the past 10 years, other studies have simulated the temporal variability of the SWI
63 length. (7) provided an empirical estimate of this length scale in river-dominated
64 estuaries and the EBM presented in (8) followed this formulation. The current study uses
65 a novel, intermediate complexity model, the so-called CMCC EBM model (9, 10), which
66 solves the estuarine water exchange by two conservation equations for volume and salt
67 averaged over the diurnal tidal cycle. The EBM has been applied to the Goro branch of
68 the Po river which is a river-dominated estuary and flows into the micro-tidal Adriatic
69 Sea (Fig. 1).

70 The main aim of this study is to show how to predict climate change impacts on SWI and
71 outflowing estuarine-water salinity with an intermediate complexity model, a new salt
72 intrusion impact model, encompassing the main estuarine dynamics processes.

73 The question asked is: is the salt-wedge changing in the future climate scenarios and
74 why? To what degree the estuarine dynamics is dominated by changes in the upstream
75 river discharge?

76 In section 2 we describe the modeling strategy and the forcing data used to perform the
77 climate experiments. Section 3 presents the results on the salt-wedge intrusion scenario
78 and the changes in outflowing salinity. Moreover, a statistical estimation of the extreme
79 values is provided. Conclusions are in section 4. Finally we briefly describe the CMCC
80 EBM model in Appendix A and the Bootstrap method used for the statistical analysis in
81 Appendix B.

82

83 **2 Methodology**

84 **2.1 Modeling Strategy**

85 The use of intermediate complexity models in climate change coastal impact studies is
86 important because the earth system climate models do not consider the complex coastal
87 geometry and the very local processes while mitigation and adaptation plan actions
88 concentrate on very localized areas of high social and economic impact. This is the case
89 of estuarine areas where the freshwaters meet the saltwater and eventually give rise to
90 SWI phenomena and river plumes on the offshore area of the estuary that might affect
91 primary, secondary and tertiary marine production (11, 12) in addition to groundwater
92 salt contamination. The more recent earth system models are still not able to properly
93 couple model components at the land-sea interface (13, 4, 5, 6) and in order to study the
94 interactions between river waters and the sea it is necessary to use intermediate
95 complexity models such as the Estuarine Box Model of this study.

96 The two unknowns of our study are the SWI length and the salinity of the outflowing
97 waters: the first has obvious implications for the salinization of inland waters already

98 mentioned and the second affects the coastal circulation and dynamics off the river
99 mouths, i.e. the river plume, as well as the large-scale circulation (14).

100 **2.2 River forcing: historical data and climate projections**

101 The scenario of the Po discharge has been predicted by (15) using a hydrological model
102 forced by a regional atmospheric model (16) nested in a global earth system climate
103 model (17). (15) computed the RCP8.5 scenario projections for the Po at Pontelagoscuro
104 (Fig.1) which is located right upstream of the Po delta river branches. For the historical
105 (1982 – 2011) period, the Po river discharge was taken from observations at
106 Pontelagoscuro hydrometer station. Figure 2a depicts daily discharge values observed
107 during the (1982 – 2011) period having a time mean discharge of 1482 m³/s while Fig. 2b
108 shows the predicted discharge for Po at Pontelagoscuro for the scenario period (2021–
109 2050) amounting to 1205 m³/s. Thus the mean annual discharge of the Po river is
110 reduced in the future period by approximately 23% with respect to the present conditions.
111 We estimate the Goro branch of the Po river receives about 13% of the discharge at
112 Pontelagoscuro (10) so in all our calculations we will use the upstream Po di Goro
113 discharge value as the Po discharge at Pontelagoscuro scaled by 0.13.

114 **2.3 Ocean forcing: historical data and climate projections**

115 The EBM considers a two-layer flow in the estuary averaged over the estuarine
116 horizontal areas. The lower layer inflowing salinity, S_{ll} , and volume flux, Q_{ll} , for both the
117 past state and the future scenario period were taken from the ocean component of a
118 regional climate model (18). The Q_{ll} shows an average value of 3.3 m³/s in the historical
119 period while 3.1 m³/s for the scenario period, corresponding to a decrease of about 6%.
120 The S_{ll} values show mean values of 35.3 psu for the historical period and 35.6 psu for the
121 scenario period indicating a 1% increase.

122 The volume flux due to the flood tides Q_{tidef} is taken from the OTPS astronomical tidal
123 model in its regional configuration over the Mediterranean Sea with 1/30-degree
124 horizontal resolution (19). The mean tidal flow, extracted during the diurnal flood tide
125 phases and averaged over 30 years, amounts to 18.6 m³/s for the historical period and
126 18.7 m³/s for the scenario period, given the short period considered for astronomical
127 parameters to change. Thus all the ocean lateral boundary conditions here considered
128 change relatively little with respect to the river discharge and this strongly affect the salt-
129 wedge projections.

130

131 **3 Results**

132 **3.1 Salt-wedge intrusion projections**

133 Using the CMCC-EBM model, the SWI length L_x and the outflowing upper layer salinity
134 S_{ul} have been computed for both historical and scenario periods. Figure 3 shows the
135 values of L_x for the historical period (1982-2011) with the long-term average value of L_x

136 = 8.1 Km. For the scenario period (2021– 2050) L_x increases by 1.2 km, i.e. a 15%
 137 increase over the present condition values.

138 Similarly, the outflowing upper layer salinity is higher as shown in Figure 4(a, b) where
 139 the salinity at the river mouth will increase of 1.1 psu in the mid-term scenario with
 140 respect to the present climate (corresponding to a 9% increase on annual basis).

141 The comparison of the seasonal daily mean values over the two 30 years' periods for L_x
 142 and S_{ul} is shown in Fig. 5(a, b). The (2021-2050) projections show a larger increase of L_x
 143 during summer, arriving to a 40% increase in the July-August period with respect to
 144 present conditions. For the outflowing upper layer salinity, we see an increase from 20
 145 to 25 psu during the summer months. In the (2020-2050) period we expect the salinity at
 146 river mouth will rise up to 35% in summer while a decrease is foreseen over November-
 147 January.

148 In conclusions we argue that the river discharge is the driver of SWI length and the
 149 salinity changes at the river mouth, neglecting the local SLR trends at the river mouth
 150 that are not available for this region. The other forcing changes, such as the inflowing
 151 lower layer salinity and volume flux are negligible with respect to upstream discharge
 152 changes. Nevertheless, even knowing the changes upstream and downstream of the river,
 153 it will be impossible to calculate the exact changes in SWI length without the CMCC-
 154 EBM which encompasses all the necessary physical processes.

155

156 3.2 Extreme values estimation

157 In addition to the projection of mean changes with respect to the present climate, it is
 158 important to define the probability of extreme events in terms of return periods. The Peak
 159 Over Threshold (POT) (20) method has been used to generate the input dataset of the
 160 extreme values of SWI lengths and outflowing upper layer salinity. One of the key
 161 choices in the POT method is to decide a threshold value. For the extreme values, the
 162 threshold has been considered as the minimum value of the yearly maximum values
 163 during the historical period (1982-2011) which produces the threshold values of 12 Km
 164 for L_x and 23 psu for S_{ul} .

165 Literature shows that the PDF of positive definite atmospheric and ocean variables are
 166 skewed and heavy-tailed (21, 22). Figure 6(a, b) shows that the frequencies of occurrence
 167 of the daily values of L_x and S_{ul} follow a Weibull probability density function PDF (23)
 168 for both parameters. The *Bootstrap percentile method* (24,25,26) has been applied to
 169 compute the confidence intervals of the parameters β and σ as the “shape” and “scale”
 170 parameters of the Weibull PDF for the data of L_x and S_{ul} . Details are in the Appendix B.

171 The probability curves of the extreme values of the L_x and S_{ul} as function of their return
 172 periods T along with the upper and lower 95% confidence intervals are shown in Fig. 7a
 173 and Fig. 7b respectively. The return period is by definition $T = \frac{1}{1 - P_{x \leq x_{max}}}$ where $P_{x \leq x_{max}}$

174 is the Weibull cumulative distribution function representing the probability that the
 175 variable x (L_x and S_{ul} in this work) is less than or equal to the selected threshold x_{max} .

176 The salt wedge values of 16 km and 20 km registered during the historical period (when
 177 the mean SWI length is found to be equal to 8.1 km) are expected with 10 and 100 years
 178 return periods respectively. Red points in Fig. 7a are the projected values of L_x by EBM
 179 model for the scenario period (2021-2050). In the projections L_x values of 20 km will
 180 have a shorter return period of about 60 years.

181 Moreover, the river mouth salinity values of 28 psu and 34 psu registered during the
 182 historical period (when the mean outflowing salinity at river mouth is found to be equal
 183 to 12.9 psu) are also expected to occur with 10 and 100 years return periods (Fig. 7b).
 184 Red points in Fig. 7b are the projected values of S_{ul} by EBM model for the scenario
 185 period (2021-2050) and the 34 psu values will have a shorter return period of about 50
 186 years. showing reliable predictions inside the upper-lower 95% confidence intervals for
 187 all the return periods.

188 Overall the hazard estimation shorter short return periods of the extreme values of
 189 outflowing salinity and SWI length: return periods of 10 years (high occurrence
 190 probability) are found for extremes twice the present mean values. Moreover, the EBM
 191 projections show even shorter return periods with respect to the extreme values of L_x and
 192 S_{ul} computed during the historical period.

193

194 **4 Conclusions**

195 An intermediate complexity estuarine box model, so-called CMCC-EBM, has been used
 196 for the first time as an impact model to study SWI and outflowing salinity in rivers for
 197 present and future climate conditions. The CMCC-EBM couples the hydrology and the
 198 shelf ocean waters from general circulation models. In this way the simulations we
 199 carried out include the 2way feedback between riverine and marine waters by solving the
 200 estuarine water exchange mechanism.

201 This study shows that, for a river-dominated estuary flowing into a micro-tidal sea, the
 202 river discharge reduction is the main factor affecting the increase of the salt-wedge length
 203 and the river outflowing salinity. The numerical findings for the Po di Goro river branch
 204 depict an average lengthening of the SWI in the (2021-2050) period equal to 1.2 km
 205 (meaning a 15% increase) and an increase of the river outflowing salinity of 1.1 psu
 206 (corresponding to a 9% increase). This increase has a large seasonal cycle, the projections
 207 showing a sharp increase in summer time for the SWI length and the salinity up to 40-
 208 50% of the present state values.

209 The extreme values of SWI and outflowing salinity computed during the historical period
 210 are found to have relatively short return periods of about 10 years (high occurrence
 211 probability) for extremes twice the present mean values. SWI maximum values such as

212 20 km, have return periods of 100 years for the historical period and about 60 years in the
213 projected climate.

214 Overall the projected changes in the SWI length of the Po di Goro branch provide a
215 valuable piece of information for adaptation policies since it is already clear that this
216 region is facing increasing salinization of inland waters. Furthermore, it is known that a
217 change of several psu in river outflowing salinity has the potential of changing the ocean
218 circulation and dynamics from coastal to large scales (14). For all these reasons above,
219 the CMCC-EBM intermediate complexity model used here could be a valuable impact
220 tool for coastal environmental projections and impact studies.

221

222 **Appendix A: The Estuarine Box Model**

223 The CMCC EBM (9, 10), (<http://www.estuaryboxmodel.org>) is based on the assumption
224 of a two-layer flow dynamics in the estuary. The continuity equation and the salinity
225 advection-diffusion equation are integrated in each layer and across the horizontal
226 dimensions of the estuary, its length and width (see Fig. A1). This produces conservation
227 equations for the volume flux and the salt flux supposed to be uniform in each layer. The
228 two resulting equations are:

$$229 \quad \mathbf{Q}_{ul} = \mathbf{Q}_{river} + \mathbf{Q}_{ll} + H L_y \mathbf{u}_{tidef} \quad (1)$$

$$230 \quad \mathbf{S}_{ul} = S_{ul} \mathbf{Q}_{ul} + \bar{S} H L_y \mathbf{u}_{tidef} + K_{SH} H L_y \frac{\bar{S}}{L_x} \quad (2)$$

231 where H , L_y , L_x the estuary depth, width and length respectively. The subscripts "ul" and
232 "ll" refer to the upper and lower estuary layers respectively, \mathbf{u}_{tidef} is the barotropic
233 velocity corresponding to the flood tide phase, \bar{S} is the depth averaged ocean salinity and
234 $K_{SH} = C_k L_y u_{tidef}$, the horizontal eddy diffusivity where C_k is the non-dimensional eddy
235 diffusivity coefficient representative of the estuary stratification and described in (10) by
236 a parametric equation using the dimensional analysis. The lateral ocean input fields at the

237 estuary mouth are: Q_{ll} , S_{ll} , \bar{S} and \mathbf{u}_{tidedf} . The river volume flux Q_{river} has to be provided at
 238 the estuary head, i.e. at the last section along the river network moving in the

239 downstream direction where the salinity is still equal to zero on multi-year average
 240 conditions.

241 The estuary length in CMCC-EBM is considered to represent the Salt-Wedge Intrusion
 242 (SWI) length which changes dynamically following a parametric equation developed by
 243 (10) for the Goro branch of the Po river:

$$244 \quad L_x = 10 H F_r^{-0.3} \left(\frac{\rho_{ll}}{\rho_0}\right)^{40} \left(\frac{H}{h}\right)^{-4.6} \left(\frac{Q_{tidedf}}{Q_{river}}\right)^{0.3} \left(\frac{Q_{ll}}{Q_{river}}\right)^{-0.01} \quad (3)$$

245 where F_r is the river Froude number, F_r is the tidal Froude number, $Q_{tidedf} = L_y H \mathbf{u}_{tidedf}$,
 246 $\rho_0 = 1000 \text{ kgm}^{-3}$ is the river freshwater density, $\rho_{ll} = \rho_0 (1 + k_s S_{ll})$ with the haline contraction
 247 coefficient taken to be constant and equal to $k_s = 7.7 \cdot 10^{-4} \text{ psu}^{-1}$ (10).

248 These three equations will give estimates **of** the outflowing volume flux Q_{ul} , the salinity
 249 S_{ul} and the SWI length L_x which we propose as an impact model to be interfaced with the
 250 climate projected input fields for Q_{river} and Q_{ll} , S_{ll} , \bar{S} and \mathbf{u}_{tidedf} .

251

252 **Appendix B: The confidence levels of the extreme values**

253 As it has been explained in the main body of the paper, the Peak Over Threshold (POT)
 254 method has been employed to define the probability of extreme events observed during
 255 the historical range in terms of their return periods. The POT datasets of the extreme
 256 values of SWI lengths and outflowing salinity are the historical daily values which
 257 exceed a threshold defined as the minimum value of the yearly maximum values, i.e.
 258 12km and 23psu respectively.

259 Figure 6(a, b) shows that the frequencies of occurrence of the POT daily values of both L_x
 260 and S_{ul} follow a Weibull probability density function PDF (25).

261 The *Bootstrap percentile method* (26) has been applied to compute the confidence
 262 intervals of the “shape” and “scale” parameters of the Weibull distribution for extreme L_x
 263 and S_{ul} shown in Figure 7.

264 The Bootstrap method (24, 25) is a resampling technique to perform statistical inference
 265 directly from the data. The bootstrap is typically computed with a randomized algorithm.

266 The practitioner randomly generates B new datasets (i.e. the Bootstrap samples) by
267 drawing randomly from the original dataset consisting of N values (i.e. the first guess).

268 The first guess of Bootstrap percentile is represented by the POT daily values of L_x and
269 S_{ul} respectively. The number of resampling is chosen $B = 1000$.

270 Considering β and σ as the “shape” and “scale” parameters of the first guess, β_j^* and σ_j^*
271 are the “shape” and “scale” parameters of the Bootstrap samples ($j = 1$ to 1000). The
272 Bootstrap percentile method determines the standardized variable $\mathbf{z}_{\beta_j}^* = \frac{\beta}{\beta_j^*}$ and $\mathbf{z}_{\sigma_j}^* = \frac{\sigma}{\sigma_j^*}$.

273 In this way, the appropriate limiting values of the standardized parameters may be
274 directly read from the list of their B estimates ranked in descending order of magnitude (j
275 from 1 to 1000).

276 Following Meeker et al. (2017) (26), in order to identify the bounding values of β and σ
277 corresponding to the 95% confidence interval, we compute $B^*(\alpha/2) = 1000 * (0.05/2) = 25$
278 which means that in the ranked values of $\mathbf{z}_{\beta_j}^*$ and $\mathbf{z}_{\sigma_j}^*$ the 25th value is the upper percentile
279 value, i.e. $\mathbf{z}_{\beta_{upper}}^*$ and $\mathbf{z}_{\sigma_{upper}}^*$ respectively. Similarly, $B^*(1-(\alpha/2)) = 1000 (1 - (0.05/2)) =$
280 975 means that the 975th value is the lower percentile value $\mathbf{z}_{\beta_{lower}}^*$ and $\mathbf{z}_{\sigma_{lower}}^*$
281 respectively.

282 The upper and lower values di β and σ corresponding to the 95% confidence interval are
283 then computed from the upper level and lower values of \mathbf{z}_{β}^* and \mathbf{z}_{σ}^* as it follows:

$$284 \quad [\beta_{lower}, \beta_{upper}] = [\mathbf{z}_{\beta_{lower}}^* * \beta, \mathbf{z}_{\beta_{upper}}^* * \beta]$$

$$285 \quad (5)$$

$$286 \quad [\sigma_{lower}, \sigma_{upper}] = [\mathbf{z}_{\sigma_{lower}}^* * \sigma, \mathbf{z}_{\sigma_{upper}}^* * \sigma] \quad (6)$$

287 Finding these upper and lower values of the Weibull distribution parameters, makes it
288 possible to have the probability curves of the prediction of the extreme values of L_x and
289 S_{ul} shown in Fig. 7a and Fig. 7b along with the 95% confidence intervals.

290

291 Acknowledgments

292 The authors are grateful to the Regional Agency for Prevention, Environment and Energy
293 of Emilia-Romagna (Arpae) for providing the salinity observations at the Manufatto
294 gauge and the Po river runoff data at the Pontelagoscuero station.

295 This research was funded by the OPERANDUM project and the EU Copernicus Marine
296 Environment Monitoring Service projects of the Mediterranean Sea Monitoring and
297 Forecasting (n. 74-351 CMEMS-MFC-MED-N). OPERANDUM project has received
298 funding from the European Union’s Horizon 2020 research and innovation program
299 under grant agreement No. 776848.

300

301 **Open Research**

302 The CMCC EBM is free and open software under the terms of the LGPL license,
 303 distributed from its web page (<http://www.estuaryboxmodel.org>) where a Test Case on
 304 Po di Goro estuary with the model inputs and outputs are accessible and interoperable.
 305 The data archiving of CMCC EBM historical simulations and future projections here
 306 discussed is underway on the webpage; in the meantime, the EBM input data and results
 307 are included as supplementary material.

308 The observational datasets used in this study for the calibration and validation of the
 309 CMCC EBM are publicly available. The observations of salinity at the Po di Goro mouth
 310 (Manufatto gauge) and the Po river runoff at the Pontelagoscuro station are findable
 311 through the Arpae repository and accessible at the Arpae webapp
 312 (<https://simc.arpae.it/dext3r>).
 313

314 **References**

- 315 1. T.R. Green, “Linking Climate Change and Groundwater” in Integrated Groundwater
 316 Management: Concepts, Approaches and Challenges. (Springer International Publishing,
 317 2016), pp. 97-141.
- 318 2. A. Tsz Yeung Leung, J. Stronach, J. Matthieu, Modelling Behaviour of the Salt Wedge in
 319 the Fraser River and Its Relationship with Climate and Man-Made Changes. *Journal of*
 320 *Marine Science and Engineering*. **6**(4), 130: 1-29 (2018).
- 321 3. D. Bellafore, C. Ferrarin, F. Maicu, G. Manfe, G. Lorenzetti, G. Umgiesser, L. Zaggia,
 322 A.V. Levinson, Saltwater intrusion in a Mediterranean delta under a changing climate.
 323 *Journal of Geophysical Research: Oceans*. **126**(2), (2021).
- 324 4. Adloff, F., Jordà, G., Somot, S., Sevault, F., Arsouze, T., Meyssignac, B., ... & Planton,
 325 S.. Improving sea level simulation in Mediterranean regional climate models. *Climate*
 326 *dynamics*, **51**(3), 1167-1178, (2018)
- 327 5. Somot, S., Ruti, P., Ahrens, B., Coppola, E., Jordà, G., Sannino, G., & Solmon, F.
 328 Editorial for the Med-CORDEX special issue. *Climate Dynamics*, **51**(3), 771-777,
 329 (2018).
- 330 6. Torresan, S., Gallina, V., Gualdi, S., Bellafore, D., Umgiesser, G., Carniel, S., ... Critto,
 331 A. Assessment of climate change impacts in the North Adriatic coastal area. Part I: a
 332 multi-model chain for the definition of climate change hazard scenarios. *Water*, **11**(6),
 333 1157, (2019).
- 334 7. P. MacCready, W. R. Geyer, Advances in Estuarine Physics. *Annu. Rev. Marine. Sci.*
 335 **2**(1), 35-58 (2010).
- 336 8. Q. Sun, M. M. Whitney, F. O. Bryan, Y. H. Tseng, A box model for representing
 337 estuarine physical processes in Earth system models. *Ocean Modelling*, **112**, 139-153
 338 (2017).
- 339 9. G. Verri, N. Pinardi, F. Bryan, Y. Tseng, G. Coppini, E. Clementi, A box model to
 340 represent estuarine dynamics in mesoscale resolution ocean models. *Ocean Modeling*.
 341 **148**, 1-14 (2020).

- 342 10. G. Verri, S.M. Kurdistani, G. Coppini, A. Valentini, Recent advances of a box model to
343 represent the estuarine dynamics: time-variable estuary length and eddy diffusivity.
344 *Journal of Advances in Modeling Earth Systems (JAMES)*. **13**(4), 1-16 (2021).
- 345 11. K. Watanabe, A. Kasai, E.S. Antonio, K. Suzuki, M. Ueno, Y. Yamashita, Influence of
346 salt-wedge intrusion on ecological processes at lower trophic levels in the Yura Estuary,
347 Japan. *Estuarine, Coastal and Shelf Science*. **139**, 67-77 (2014).
- 348 12. N.C. James, L. van Niekerk, A.K. Whitfield, W.M. Potts, A. Götz, A.W. Paterson,
349 Effects of climate change on South African estuaries and associated fish species. *Climate*
350 *Research*. **57**, 233-248 (2013).
- 351 13. M. Claussen, L. Mysak, A. Weaver, Earth system models of intermediate complexity:
352 closing the gap in the spectrum of climate system models. *Climate Dynamics*. **18**, 579-
353 586 (2002).
- 354 14. G. Verri, N. Pinardi, P. Oddo, S.A. Ciliberti, G. Coppini, River runoff influences on the
355 Central Mediterranean Overturning Circulation. *Climate Dynamics*. **50**(5-6), 1675–1703
356 (2018).
- 357 15. R. Vezzoli, P. Mercogliano, S. Pecora, A. Zollo, C. Cacciamani, Hydrological simulation
358 of Po River (North Italy) discharge under climate change scenarios using the RCM
359 COSMO-CLM. *Science of the Total Environment*. **521**(2), 346-358 (2015).
- 360 16. E. Bucchignani, M. Montesarchio, A. Zollo, P. Mercogliano, Regional climate
361 simulations with COSMO-CLM over the Mediterranean area. *Advances in Climate*
362 *Science*. 338-351 (2014).
- 363 17. E. Scoccimarro, S. Gualdi, A. Bellucci, A. Sanna, P.G. Fogli, E. Manzini, M. Vichi, P.
364 Oddo, A. Navarra, Effects of Tropical Cyclones on Ocean Heat Transport in a High-
365 Resolution Coupled General Circulation Model. *Journal of Climate*. **24**(6), 4368-4384
366 (2011).
- 367 18. L. Cavicchia, S. Gualdi, A. Sanna, P. Oddo, The regional ocean-atmosphere coupled
368 model COSMO-NEMO MFS. *CMCC Research Paper*. Issue RP0254, (2015).
- 369 19. D. Egbert, S.Y. Erofeeva, Efficient inverse modeling of barotropic ocean tides. *Journal of*
370 *Atmospheric and Oceanic Technology*. **19**(2), 183-204 (2002).
- 371 20. M.R. Leadbetter, On a basis for 'Peaks over Threshold' modeling. *Statistics and*
372 *Probability Letters*. **12**, 357-362 (1991).
- 373 21. A.A. Sepp Neves, N. inardi, A. Navarra, F. Trotta, A General Methodology for Beached
374 Oil Spill Hazard Mapping. *Frontiers in Marine Science*. **7**, 1-10 (2020).
- 375 22. P.D. Sardeshmukh, G.P. Compo, Need for Caution in Interpreting Extreme Weather
376 Statistics. *Journal of Climate*. **28**, 9166-9187 (2015).
- 377 23. W. Weibull, A Statistical Distribution Function of Wide Applicability. *ASME Journal of*
378 *Applied Mechanics* - Transactions of the American Society of Mechanical Engineers.,
379 293-297 (1951).
- 380 24. B. Efron, Bootstrap Method: Another Look at the Jackknife. *The annals of Statistics*. **9**,
381 1-26 (1979).
- 382 25. B. Efron, R.J. Tibshirani, "An Introduction to the Bootstrap" (Chapman and Hall, 1994),
383 pp. 1-436.
- 384 26. W.Q. Meeker, G.J. Hahn, L.A. Escobar, "Statistical Intervals" (JOHN WILEY and
385 SONS, 2017), pp. 1-578.
- 386 27. G.I. Barenblatt, "Dimensional analysis" (CRC Press, 1987).
- 387

388

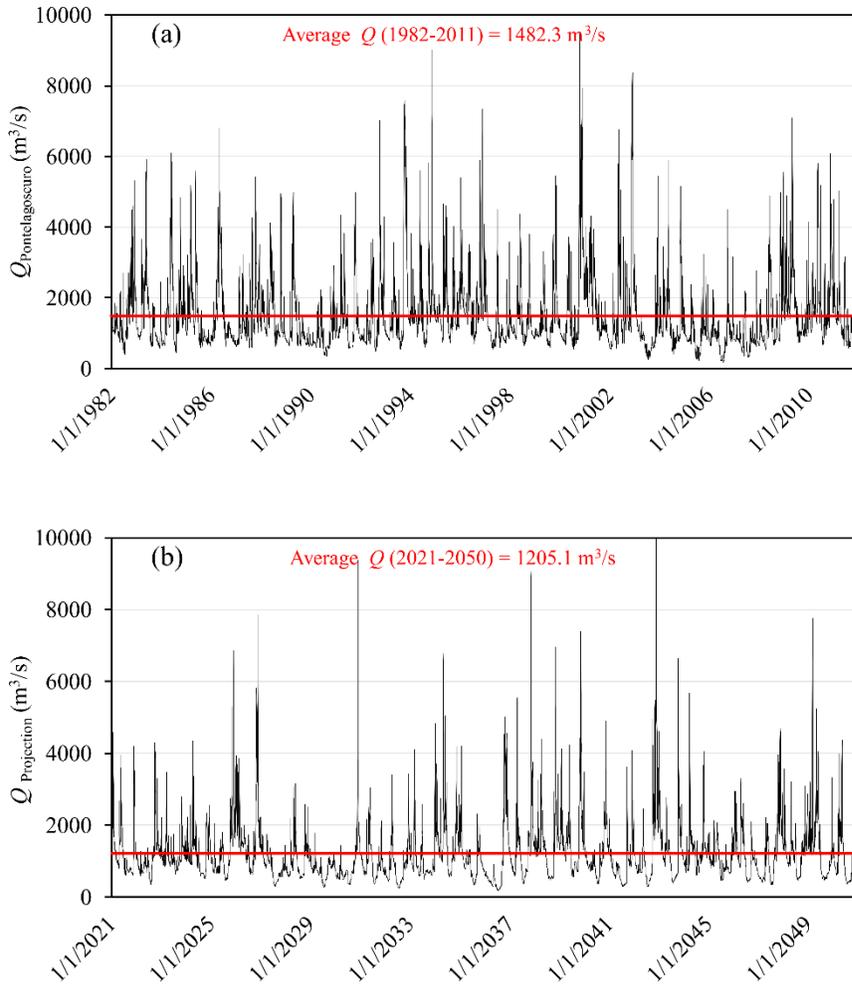
389 **Figures**



390

391 **Fig. 1. The Goro branch of the Po river.** It has a river-dominated estuary and flows into the
392 micro-tidal Adriatic Sea.

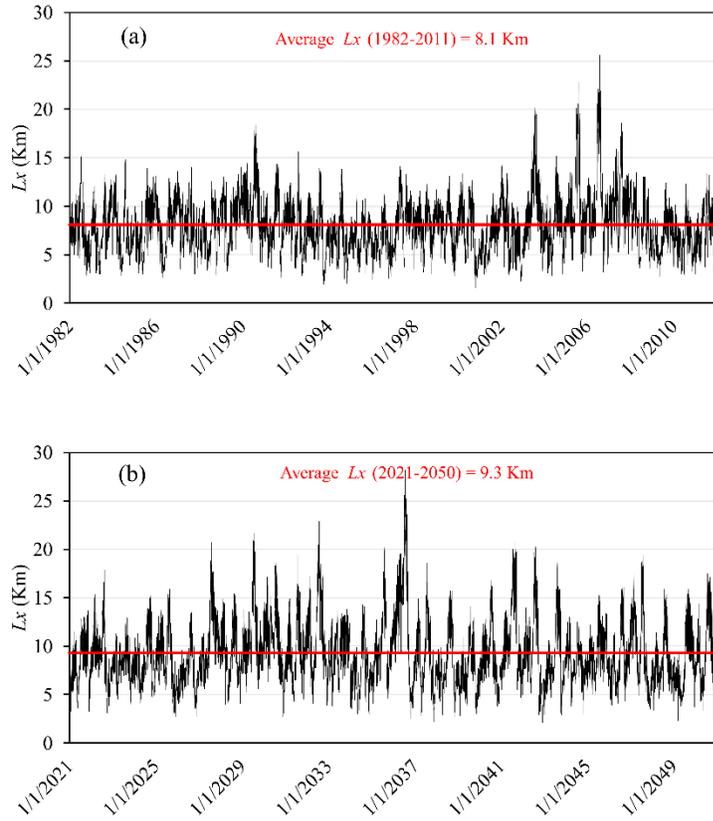
393



394

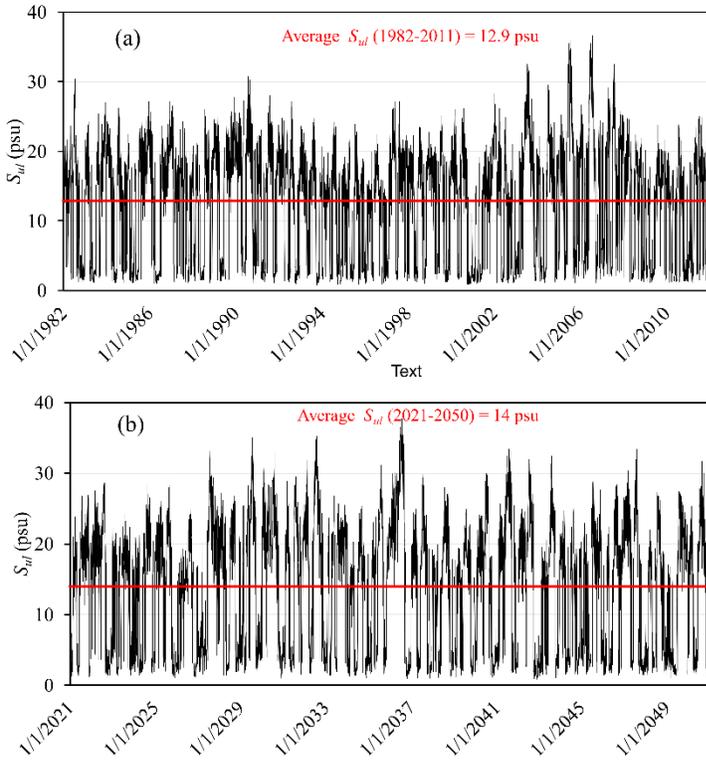
395 **Fig. 2. Pontelagoscuro hydrometry station. (A)** observed discharge values during (1982 –
 396 2011), **(B)** predicted discharge values for the scenario period (2021–2050).

397



398

399 **Fig. 3. Salt-wedge intrusion (EBM model).** (A) historical period (1982-2011), (B) scenario
 400 period (2021–2050).
 401

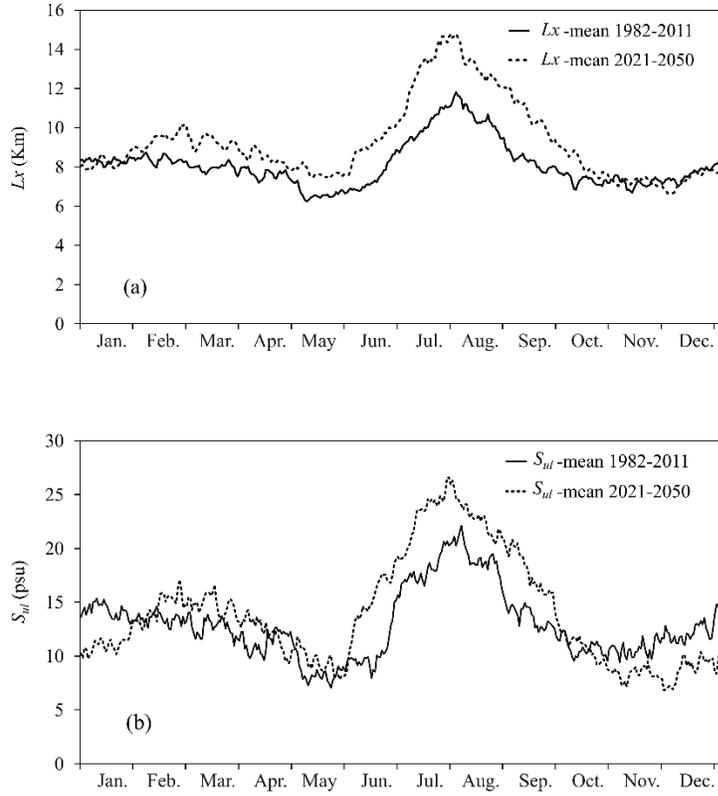


402

403 **Fig. 4. Outflowing salinity (EBM model).** (A) historical period (1982-2011), (B) scenario
 404 period (2021–2050).

405

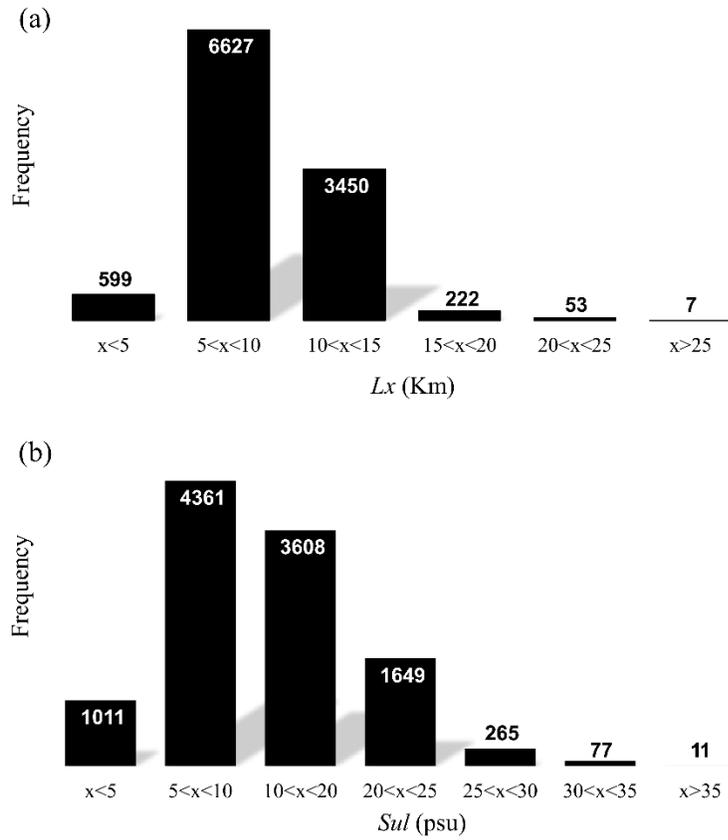
406



407

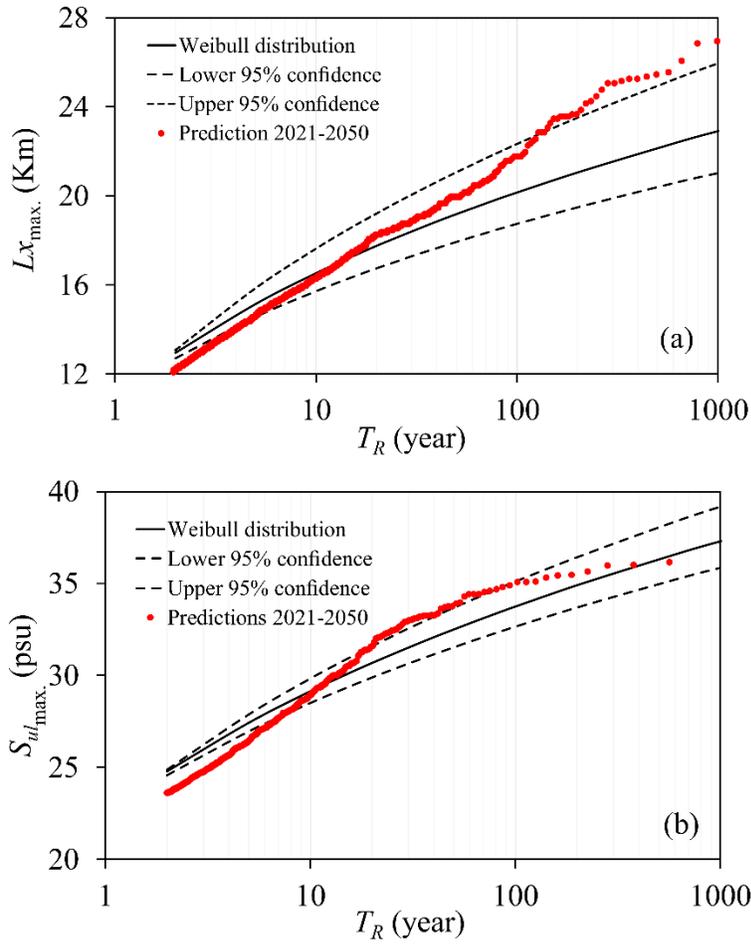
408 **Fig. 5. Seasonal cycle of daily mean values (EBM model). (A) Salt-wedge intrusion, (B)**
 409 **Outflowing salinity.**

410



411

412 **Fig. 6. Frequencies of occurrence of daily values. (A) Salt-wedge intrusion, (B) Outflowing**
 413 **salinity.**



414

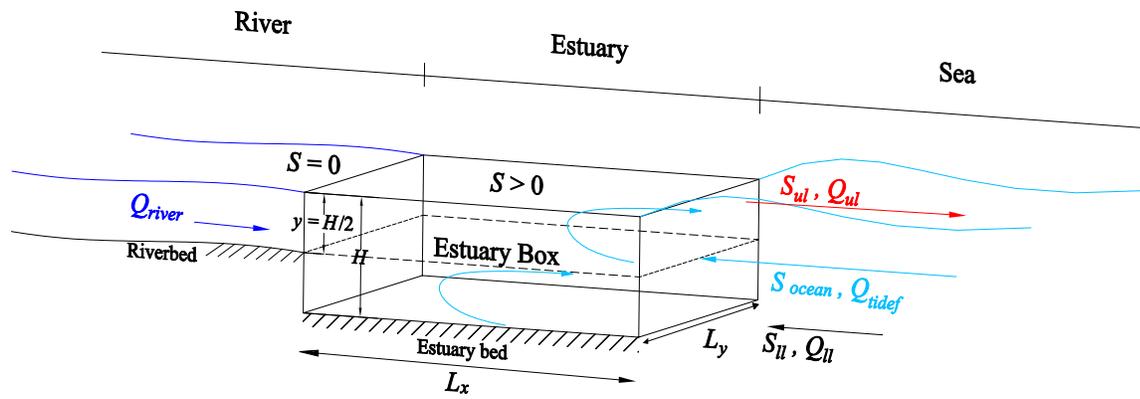
415 **Fig. 7. Probability curves with upper-lower 95% confidence intervals. (A)** Compared with
 416 the predicted values of L_x for the scenario period (2021-2050), **(B)** Compared with the predicted
 417 values of the outflowing salinity for the scenario period (2021-2050).

418

419

420

421



422

423 **Fig. A1 Sketch of the CMCC EBM model.** Black arrows stand for input variables coming from
 424 coupled models or observational datasets, red arrows indicate the unknowns solved by the EBM.
 425 The pairs of blue arrows represent the tidal mixing. The model source code is open and free and
 426 it is available here: <http://www.estuaryboxmodel.org>



