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Modelling river-sea continuum: the case of the Danube Delta

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Abstract. Understanding water transport and circulation in coastal seas and transitional environments is among the key topics of oceanographic and climate research, as well as recognizing the role of the land-sea interface. The Danube Delta represents a natural laboratory for river-sea hydrodynamic modelling due to its complex morphology and being subjected to several natural and anthropogenic stressors. In this work, we present the results of the SHYFEM finite element hydrodynamic model application to the whole river-sea continuum of the Danube Delta region. The model was run for several years to characterize: 1) the water discharge distribution among the river branches, 2) the general hydrodynamic characteristics of the coastal region of freshwater influence, 3) the transport time scale of the Razelm Sinoie Lagoon System, and 4) the processes driving the river-lagoon-sea interconnections. The unique numerical description of the transport and mixing in the different water bodies of the Delta (river branches, channels, lagoons and coastal sea) may be used to provide the scientific basis to assess the impact of human activities and to design efficient management choices. Indeed, we used the modelling framework to evaluate the effect of reconnection (restoration) measures in the Razelm Sinoie Lagoon System designed to improve hydrological connectivity.

1 Introduction

Coastal environments at the river-sea interface, like estuaries and deltas, are critical components of coastal ecosystems due to their importance in supporting biodiversity and providing ecosystem services such as nutrient cycling, carbon sequestration, and habitat for marine life (Newton et al., 2023, and references therein). However, these regions are highly sensitive to both natural events (e.g., storms, sea-level rise, droughts) and anthropogenic pressures (e.g., damming, land reclamation, pollution). As such, modelling these environments is essential for understanding their dynamics, predicting their responses to environmental change, and guiding sustainable management practices.

Modelling these coastal transitional water systems is challenging due to their complex morphology made of different components such as river network, coastal lakes, lagoons, creeks, marshes. These different water compartments are generally interconnected and thus influencing each other. In this context, unstructured ocean models, like SCHISM (Zhang et al., 2016), SHYFEM (Umgiesser et al., 2022), FESOM-C (Androsov et al., 2019), Delft3D (D-Flow, 2023), TELEMAC (Telemac-Mascaret, 2022), ADCIRC (Zhang and Yu, 2024), FVCOM (Chen et al., 2003), SLIM (Vallaeys et al., 2018) have proven to be powerful tools for simulating complex hydrodynamics in shallow estuarine and deltaic environments. These models help assess the effects of climate change (Ferrarin et al., 2014; Pein et al., 2023), human interventions (Ferrarin et al., 2013; Thanh et al., 2020), and natural variability on the structure and functioning of coastal systems (Maicu et al., 2018; Zhu et al., 2020; Feizabadi et al.,

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

2024). Models used in estuarine and delta research typically integrate hydrodynamics, sediment transport, water quality, and ecological processes. However, the higher the complexity of the processes to be investigated, the higher is the amount of data needed for the model implementation and testing.

In this study, we implemented the SHYFEM (System of HydrodYnamic Finite Element Modules; Umgiesser et al., 2022) model to the entire Danube Delta region consisting of about 500 km of the river network, the Razelm - Sinoie lagoon system and part of the prodelta coastal sea. This manuscript focuses on the investigation of hydrodynamics in the river-lagoon-sea system and the hydrological connectivity among the different water bodies (river branches, channels, lagoons, coastal sea). In particular, we apply the model to quantify water discharge distribution among the river branches, the dynamics of the coastal sea in front of the multi-mouth delta, the renewal capacity of the Razelm Sinoie Lagoon System and the processes regulating the exchange among the different water environments forming the Danube Delta. Moreover, a few *what-if* scenarios were simulated to explore the potential impacts of different lagoon-sea reconnection solutions.

1.1 The Danube Delta

The Danube Delta is the final part of the Danube River's journey of almost 2900 km, crossing 10 countries and draining a hydrographic basin of over 800,000 km^2 from 19 states towards its connection with the Black Sea (e.g., Panin, 1998). The Danube Delta plain begins at the first bifurcation of the Danube, called Ceatal Izmail (Fig. 1). Here, the Danube River divides into two distributaries: the northern one, Chilia, and the southern one, Tulcea. The Tulcea distributary divides again at Ceatal, 17 km farther downstream, into two other branches, Sulina and Sf. Gheorghe. The fluvial delta plain covers 4000 km^2 and the marine one covers 1800 km^2. The Romanian part of the Danube Delta, including here the attached Razelm Sinoie Lagoon System, was declared in 1991 a Biosphere Reserve (UNESCO "Man and the Biosphere" Programme) and has been ever since a Nature Reserve.

The Razelm Sinoie Lagoon System (hereinafter RSLS) extends on about 1000 km^2 and is located in the southern part of the Danube Delta Biosphere Reserve. The lagoon system has been significantly affected by human interventions since the end of the 19th Century (Panin, 1996, 1998, 1999; Giosan et al., 2006; Vespremeanu-Stroe et al., 2013; Constantinescu et al., 2023). Dredging works to connect the Razelm lagoon to the Sf. Gheorghe arm of the Danube via the Dunavăţ and Dranov canals, ended up at the beginning of the 20th century. Thus, more freshwater discharged to the lagoon system. During the 1950s, management plans were made to decrease the salinity in the lagoon system, with the purpose to increase the freshwater fish culture productivity. Between 1960 and 1990, the lagoon has been used mainly for irrigations and, secondly, for fish breeding. In 1973, the Portiţ Inlet (near the reconnection option named A Fig. 1) of the Razelm Lagoon was completely closed by a system of breakwaters and groins. Consequently, the coastal erosion increased in intensity south of the former inlet, due to the hard coastal defence structure (Spătaru, 1990; Vespremeanu-Stroe et al., 2007). After the closure of the Portiţ inlet in the Razelm lagoon has been transformed into freshwater lakes, due to the permanent connection with the Danube River via Dranov and Dunavăţ Canals. The inlet of Gura Buhazului (near the reconnection option named C Fig. 1) in the southern part of the Sinoie Lagoon was clogged more than 3 decades ago (late 1980s - early 1990s). The permanent circulation between the Sinoie Lagoon and the Black Sea has been restored by the beginning of the years 2000, being controlled by the Periboina and Edighiol

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

inlets. The Periboina inlet has become clogged around 2017, with an intermittent connection with the sea during spring and autumn months up to the year 2021. Anyway, a major hydrotechnical project is underway as part of the Masterplan for the Protection against Erosion of the Romanian Littoral - project that would secure a permanent water exchange for the Periboina Inlet.

The Danube River in its lower part has an average water discharge of 6500 m^3 s^{-1} and values ranging from 2000 to 16000 m^3 s^{-1}. The two major wind regimes characterizing the study area are from north-east, being the most intense, and south-south-west, that can drive alongshore sediment transport (Dan et al., 2009).

2 Methods

2.1 The modelling system

In this study, we used the System of HydrodYnamic Finite Element Modules (SHYFEM, Umgiesser et al., 2022) model to simulate the 3D hydrodynamics in the river-sea continuum of the whole Danube Delta region. SHYFEM is an open-source unstructured ocean model for simulating hydrodynamics and transport processes at very high resolution. The model solves the primitive equations written in z-coordinate system and using a finite element numerical method and semi-implicit time stepping. The model has been already applied to simulate the hydrodynamics in the Mediterranean Sea (Ferrarin et al., 2018), in the Adriatic Sea (Bellafiore et al., 2018; Ferrarin et al., 2019), in the Black Sea (Bajo et al., 2014; Bellafiore et al., in review) and in several coastal systems (Ferrarin et al., 2021; Umgiesser et al., 2022).

SHYFEM is here used to reproduce the 3D hydrodynamics of the Danube Delta under the influence of river discharge, heat and momentum fluxes at the water surface, salinity and sea temperature gradients and open sea forcing (sea level oscillations and currents). Moreover, the concurrence of intense atmospheric forcing, direct morphological interventions within the delta territory and freshwater inflows lead the Danube Delta to be characterized by a wide range of different transport phenomena. Therefore, to investigate water mixing and renewal, the numerical model has been used to estimate the transport time scale, which is a fundamental parameter for understanding chemical and ecological dynamics in lagoon environments (Cucco et al., 2009). In this study, the water renewal time (hereinafter WRT) was computed by simulating the transport and diffusion of a Eulerian conservative tracer released uniformly throughout the entire lagoon system with a concentration corresponding to 1, while a concentration of zero was imposed on the seaward and freshwater boundaries. The local WRT is considered as the time required in each water parcel for the tracer concentration to fall to 0. The reader may refer to Cucco et al. (2009) and Umgiesser et al. (2022) for a more comprehensive description of the WRT computation.

The SHYFEM model was applied to a domain that comprises the river network of the Danube Delta from Isaccea (100 km upstream from the river mouths, in the vicinity of the delta apex at Ceatal Izmail) to the sea (from north to south the Chilia, Sulina and Sf. Gheorghe branches), the Razelm Sinoie Lagoon System, the nearby prodelta and shelf area (290x100 km) and the narrow canals and inlets connecting the different water compartments (Dunavăţ, Dranov, Canal 2, Canal 5, Edighiol and Periboina) (Fig. 1). The application of a triangular unstructured grid in the hydrodynamic model has the advantage of describing accurately complicated bathymetry and irregular boundaries in the river and shallow water areas. It can also solve

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

the combined offshore-coastal interactions and small-scale river-sea dynamics in the same discrete domain by subdividing the basin into triangles varying in form and size. The numerical domain is composed of about 48.000 triangular elements having horizontal resolution varying from about 4 km in the open sea to a few metres in the river branches and the connecting channels. Vertically, the model runs in the z layer configuration, with 68 layers of increasing thickness, from 1 m in the topmost layers, to 50 m in the deepest ones (below 500 m).

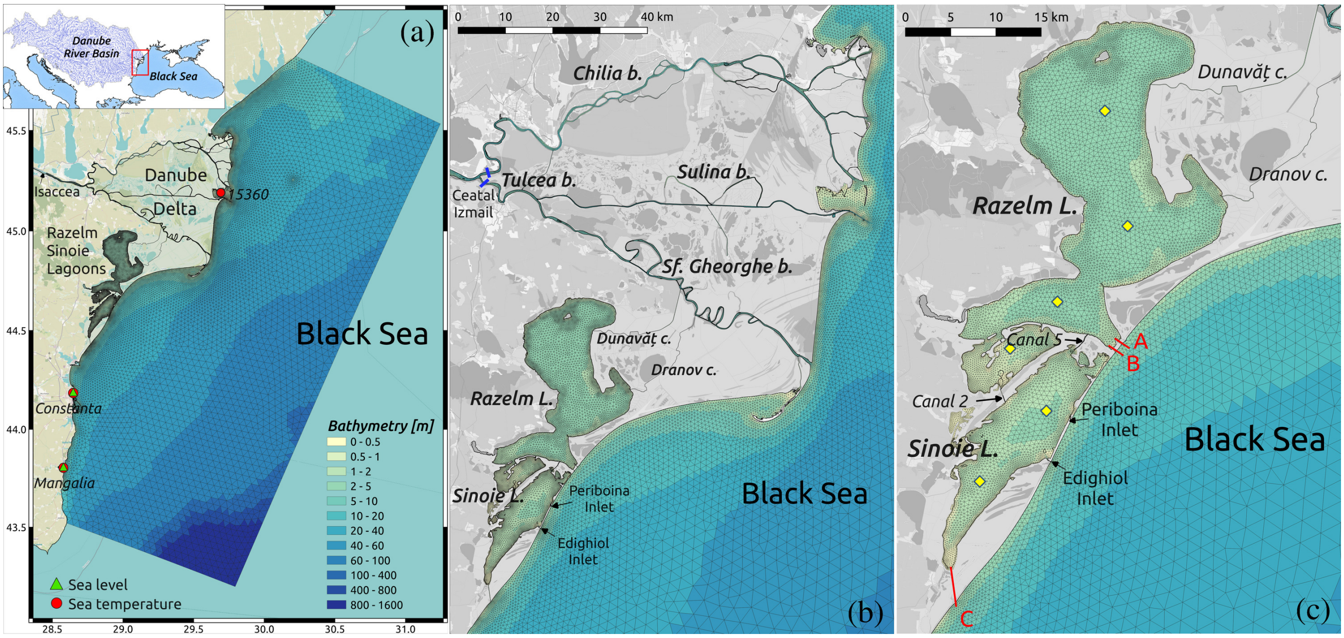

Figure 1. (a) Unstructured numerical grid and bathymetry of the hydrodynamic model of the Danube Delta and Black Sea shelf with the red dots and the green triangles marking the sea temperature and sea level monitoring stations, respectively; (b) zoom of the grid over the Danube Delta with the blue bars near Ceatal Izmail indicating the river discharge monitoring stations; (c) zoom of the grid over the Razelm Sinoie Lagoon Systems with the red bars illustrating the considered reconnection solutions and the yellow diamonds marking the satellite SST control points. Background: ©OpenStreetMap contributors 2024; distributed under the Open Data Commons Open Database License (ODbL) v1.0.

The model bathymetry is obtained by a bilinear interpolation on the numerical grid of the following available datasets (all referred to the Marea Neagra Sulina vertical datum):

- the 2022 European Marine Observation and Data Network dataset (EMODnet Bathymetry Consortium, 2022) for the shelf sea;
- the 2024 dataset for the Razelm Sinoie Lagoon System;
- three separate datasets for the main river branches: the 2023 dataset for Chilia; the 2019 dataset for Sulina; the 2016-2017 dataset for Sf. Gheorghe.

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

2.2 Numerical experiments

To reproduce the past sea conditions over the period 2015-2020, the simulations were forced by 3-hourly wind, mean sea level pressure, air temperature, relative humidity, incident solar radiation, total precipitation and cloud cover fields from Copernicus European Regional ReAnalysis (CERRA; Schimanke et al., 2021) made available via the Copernicus Climate Change Service (https://doi.org/10.24381/cds.622a565a). CERRA has a horizontal resolution of 5.5 km and is forced by the global ERA5 reanalysis (Hersbach et al., 2020). The SHYFEM hydrodynamic model was forced at the lateral boundary of the Black Sea with the sea level, current velocity, sea temperature and salinity from the Black Sea Physics Reanalysis made available via the E.U. Copernicus Marine Service Information (Lima et al., 2020, https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004, accessed on 14-Jun-2024). Daily observed water river discharges at Isaccea were provided by the National Institute of Hydrology and Water Management of Romania and imposed as a boundary condition for the Danube River. Water temperature at the Danube River boundary was taken from the daily results of the wflow catchment model implemented over the Danube River basin (Bellafiore et al., in review).

The maximum allowable time step in the simulation was set to 60 s, and the model adopts automatic sub-stepping over time to enforce numerical stability with respect to advection and diffusion. The wind drag coefficient was set to 2.5 10^{-3}. Bottom friction is computed following the Strickler formulation (Umgiesser et al., 2004) with the friction parameter considered homogeneous over the whole domain and set equal to 32 $m^{1/3}$ s^{-1}. Vertical diffusivities are calculated by the $k-e$ turbulence closure model.

Being aware that the RSLS is suffering from poor water renewal and stagnation (Dinu et al., 2015), the model was used to investigate the potential effects on WRT and salinization of different reconnection solutions designed with local stakeholders to improve the river-lagoon-sea exchange. The *what-if* scenarios considered in this study consisted of opening a 1.5 m depth and 70 m wide channel to connect the Razelm Lagoon (red bars marked A and B in Fig. 1c) and the Sinoie Lagoon (red bar marked C in Fig. 1c) with the Black Sea. These reconnection solutions are located in the vicinity of previous inlets now either closed by humans (Portiţa; solutions A and B) or now clogged (Gura Buhazului inlet, active till the beginning of the 1990s; solution C).

2.3 The validation dataset

The monitored parameters used in the validation procedures are grouped into the following three categories:

- In-situ river discharge: daily values are provided by the National Institute of Hydrology and Water Management of Romania for two river sections near Ceatal Izmail where the Danube River splits into the Chilia and Tulcea branches (blue bars in Fig. 1b). The Tulcea branch downstream splits into the Sulina and Sf. Gheorghe arms, but no observations were available for these branches.

- In-situ sea level: hourly values were retrieved from the in-situ ocean thematic centre of the Copernicus Marine Service (https://marineinsitu.eu/dashboard/) for stations Constanta and Mangalia (green triangles in Fig. 1a).

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

– In-situ sea temperature: daily values were retrieved from the in-situ ocean thematic centre of the Copernicus Marine Service (https://marineinsitu.eu/dashboard/) for BS_TS_MO stations 15360, 15480 (Constanta) and 15499 (Mangalia) (red dots in Fig. 1a).

– Satellite Sea Surface Temperature (SST): Level 2 data derived from the Landsat-8 Thermal Infrared Sensor (TIRS) extracted over six locations within the Razelm Sinoie Lagoon to cover the spatial variability in the lagoons (yellow diamonds in Fig. 1c). The SST data are generated through the application of an atmospheric correction algorithm to the Top-Of-Atmosphere thermal radiance values from the TIRS bands (B10 and B11). This algorithm accounts for atmospheric effects such as water vapor and aerosol interference and applies a split-window technique to estimate surface temperatures with high accuracy (Barsi et al., 2003). The data, provided by the United States Geological Survey (USGS), were accessed via the Google Earth Engine platform using the LANDSAT/LC08/C02/T1_L2 dataset. To ensure data quality and reliability, scenes with cloud cover below 1% were selected, effectively minimizing the impact of atmospheric interference. For each location, SST values were extracted using a 1x1 pixel window, corresponding to the nearest pixel to the specified coordinates. A total of 37 time frames providing 135 valid SST observations were selected in the period from 2015 to 2020.

3 Results

3.1 Model validation

In this work, we consider the root mean square error (RMSE), the difference between the mean of simulation results and observations (BIAS), the Pearson cross-correlation coefficient between model results and observations (CC) and the slope of the linear regression best-fit line (SLOPE) as the metrics for measuring the accuracy of the numerical results of the reference simulation in representing the river discharge, sea level and sea temperature variability.

As shown in Fig. 2a, the Danube River discharge at Isaccea (the upstream river boundary in the model domain) in the period 2015-2019 varies from 2000 to 14000 m^3 s^{-1} with an average value of about 6000 m^3 s^{-1}. Figures 2b and 2c represent the scatter plots of observed and simulated river discharge through the Chilia and Tulcea river branches at Ceatal Izmail. The model well represents the total water discharge distribution in the Chilia and Tulcea branches. It is worth noting that the model tends to underestimate (overestimate) the peak discharge values in the Chilia (Tulcea) arm, as revealed also by a slope of the linear regression best-fit line of 0.89 (1.11). Since in flood events there is a possible enlargement of the river section, including floodplains, probably a lack of information on the altimetric quotes around the river can justify this small inconsistency. The model has a RMSE of about 160 m^3 s^{-1} in both distributaries.

We report in Figure 3, the time series of the modelled daily sea levels compared with the observations for 2017 at the coastal stations Constanta and Mangalia located along the Romanian coast (green triangles in Fig. 1a). The model can reproduce the long-term sea level variability as well as the major fluctuations associated with intense meteorological events (storm surges) in the range of 1-10 days. The model is slightly underestimating sea levels in some periods (e.g., Constanta in July-August and

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

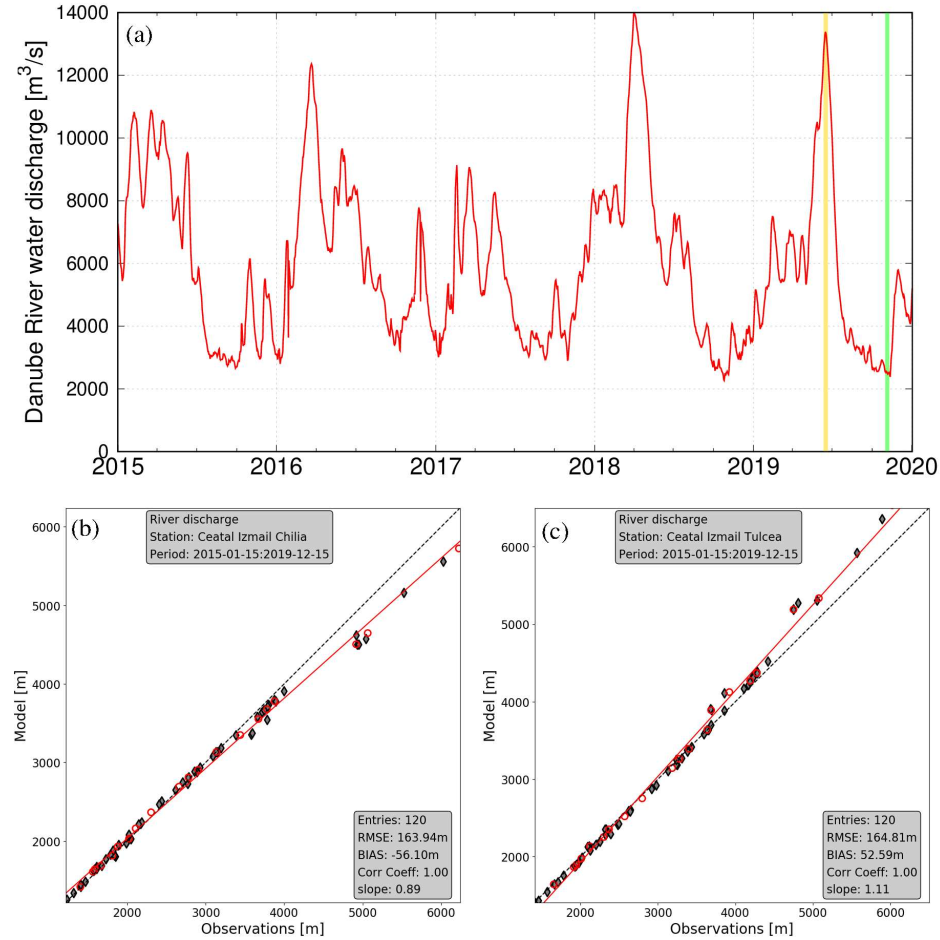

Figure 2. Danube River water discharge timeseries (a) and scatter plots of observed and modelled river discharge in the Chilia (b) and Tulcea (c) river branches. The gold and green bars in panel (a) indicate the flood and drought conditions considered in Figs. 6b and 6c.

Mangalia in March). The statistical analysis revealed that RMSE and CC in Constanta and Mangalia are 3.4 cm and 0.64, and 7.8 cm and 0.55, respectively. It must be noted that the performances of the coastal model in reproducing sea levels are directly dependent by the open boundary conditions, therefore any discrepancy at the basin scale in the Black Sea Physics Reanalysis dataset is propagated to the coast and needs to be considered.

As presented in Figure 4 (illustrated for the year 2019 at stations 15360 and Mangalia), the numerical model captures correctly the seasonal variability as well as the short-term fluctuations of the sea temperature in the investigated area. The statistical analysis of the simulated sea temperatures revealed that RMSE is between 1.5 and 1.7 °C and the CC is always above 0.97 (Table 1).

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

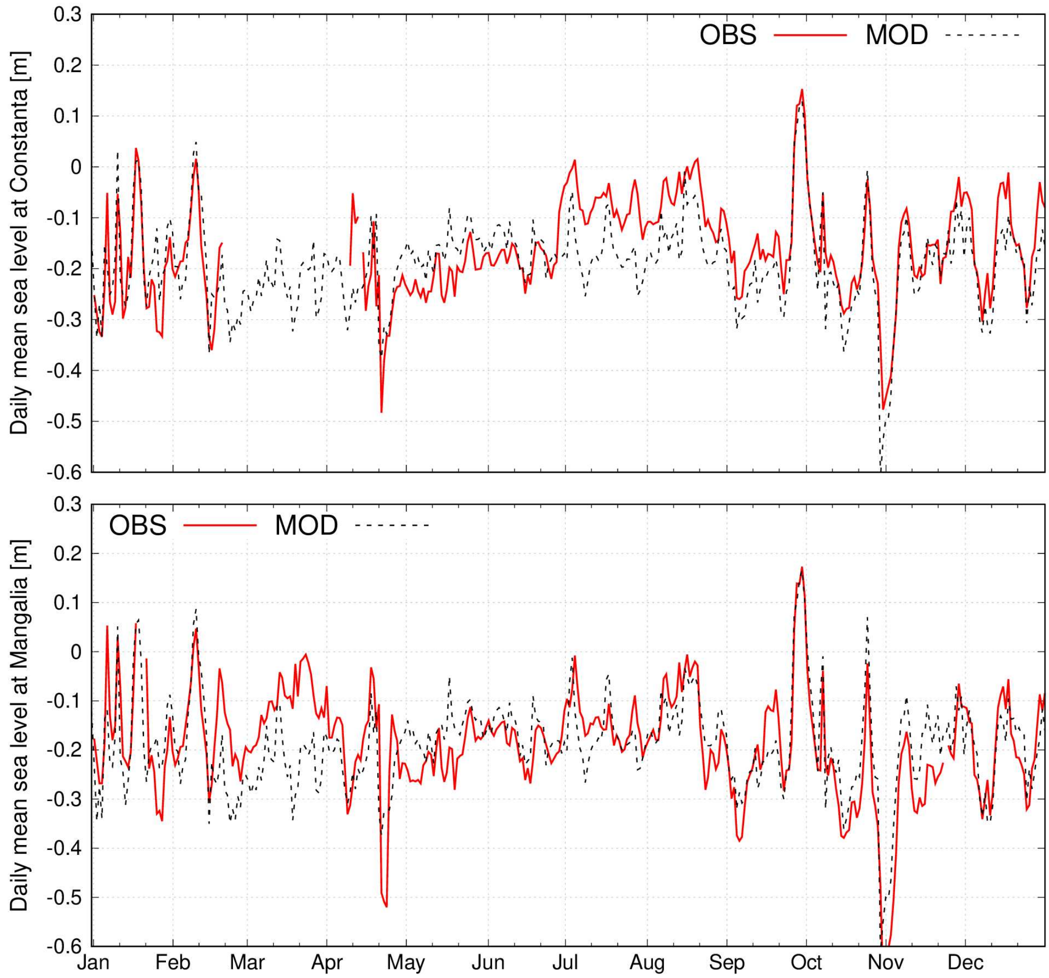

Figure 3. Observed (red line) and simulated (black dashed line) sea levels at Constanta (top panel) and Mangalia (bottom panel) for year 2017.

Table 1. Statistical analysis (in terms of centered RMSE, BIAS and R) of simulated sea temperature at the monitoring stations.

Station	**RMSE (°C)**	**BIAS (°C)**	**CC**
15360	1.7	0.2	0.98
Constanta	1.6	-0.4	0.97
Mangalia	1.5	-0.2	0.97

Satellite derived data demonstrate that sea surface temperature in RSLS strongly varies over the year with values ranging from 0 °C in winter to almost 30 °C in summer. Spatially SST in the lagoons has a moderate variance with difference usually lower than 1.5 °C. To assess the performance of the model we extracted from the simulation results daily averaged water

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

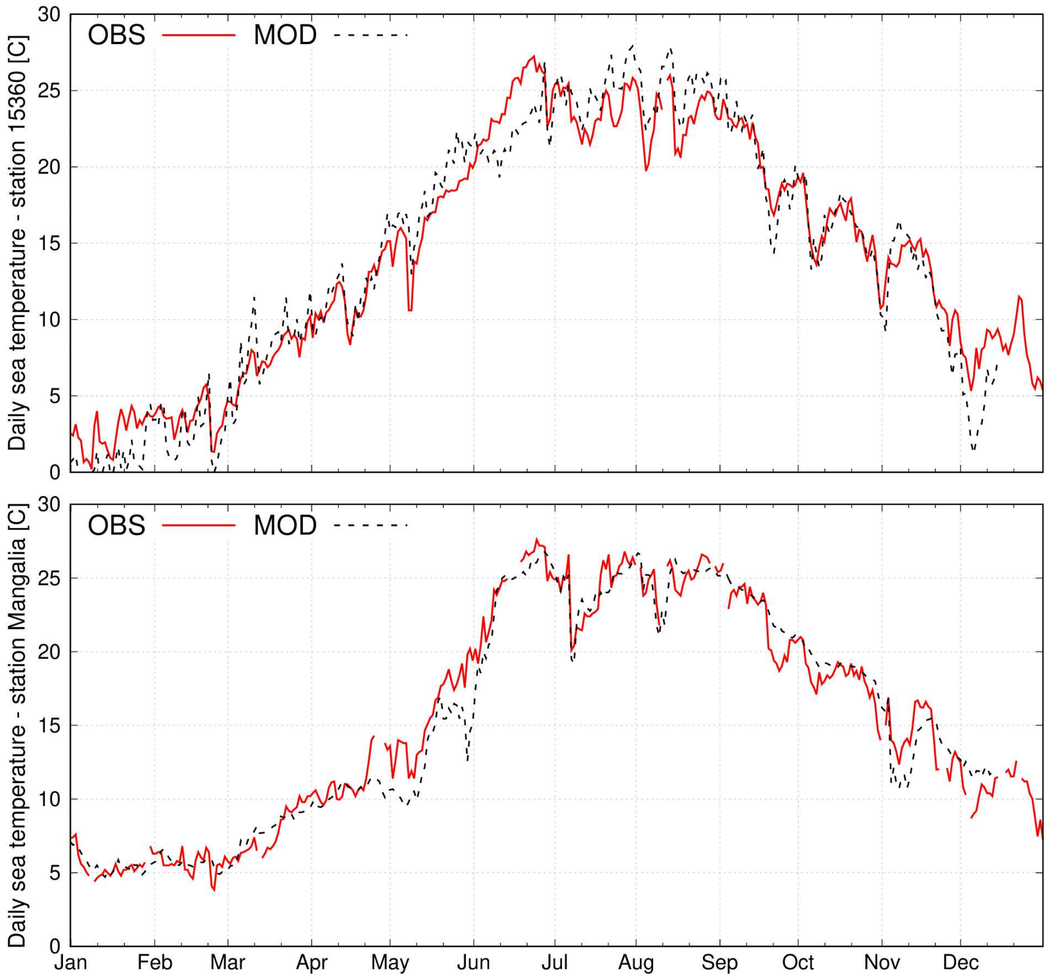

Figure 4. Observed (red line) and simulated (black dashed line) daily sea temperatures at station 15360 (top panel) and Mangalia (bottom panel) for year 2019.

temperature values in the surface layer at the location and timing of the satellite SST data. The statistical comparison between model results and observations (RMSE = 1°C, BIAS = 0.3°C, CC = 0.97, slope = 0.99) demonstrated that SHYFEM can represent well both the spatial and temporal variability revealed by satellite data.

3.2 Water division in the river network of the delta

The Danube Delta River network is formed of hundreds of natural and artificial channels, streams, and lakes. The numerical model could not resolve such a high morphological complexity and was designed to represents the more relevant water courses. It can therefore be used to estimate the water discharge distribution among the different river branches. Here, the water fluxes were extracted for several river sections and averaged over the simulation period (2015-2019) to estimate the relative load

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

(in %) of each branch with respect to the total Danube River discharge (imposed at the open boundary of Isaccea). We point out that the model estimate of the water division into the multiple branches of the delta is very sensitive to the accuracy of the morphological and bathymetric datasets used to create the numerical grid, which - as mentioned in section 3.1 - has been validated only for the upper part of the delta river network. Moreover, the river discharge division among branches can vary in different flow regimes. The average water division values are reported in Fig. 5.

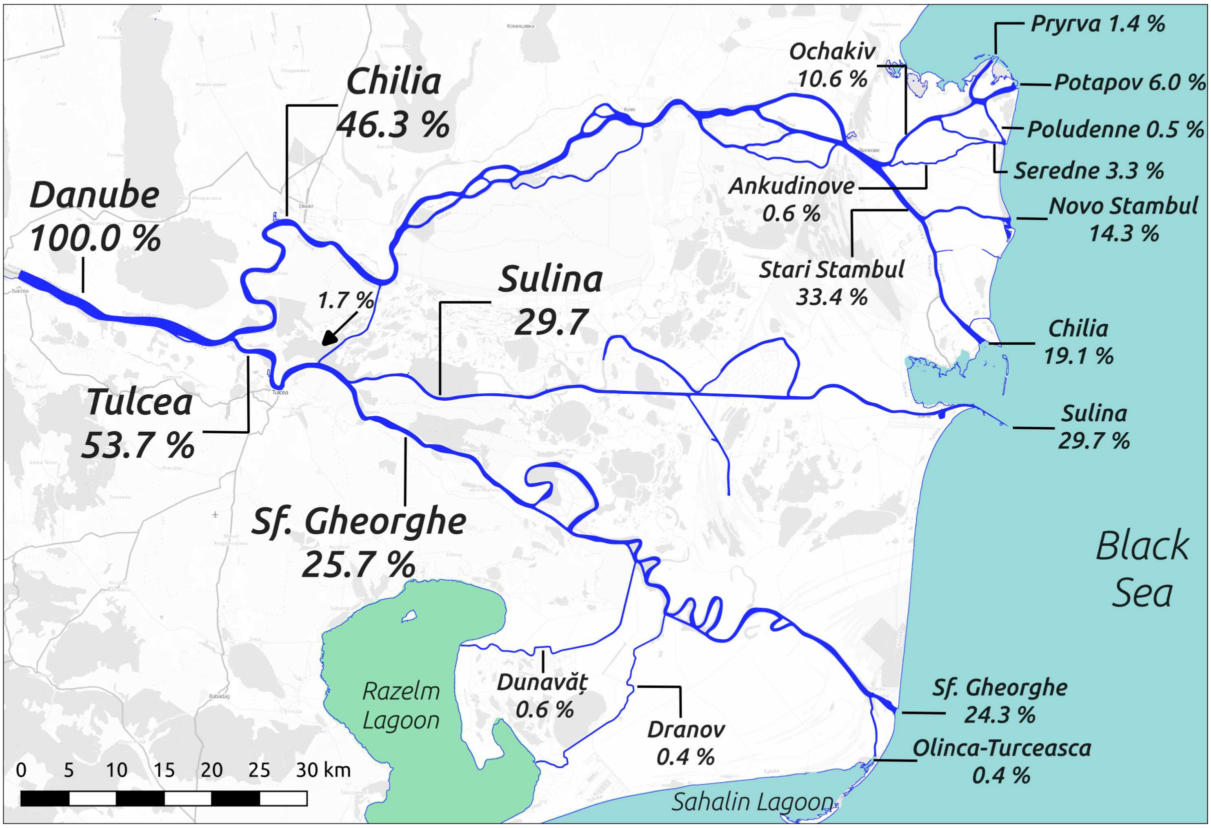

Figure 5. Modelled average water diversion within the Lower Danube River downstream of Isaccea. Background: ©OpenStreetMap contributors 2024; distributed under the Open Data Commons Open Database License (ODbL) v1.0.

The Danube discharge firstly subdivides into the Chilia and Tulcea branches, which have an average fraction of 46.3 and 53.7 %, respectively, this well reproducing the observed distribution. The Chilia branch in the northern part of the delta is characterized by a complex network of secondary arms that depart and rejoin to the main channel. 20 km from the sea, Chilia bifurcates into the Ochakiv (also known as Ochakov) channel (10.6 %), that downstream originates four mouths, and the Stari Stambul Vechi (33.4 %) channel, which splits into Novo Stambul (14.3 %) and Chilia (19.1 %) outflows. The 18 km long Tulcea distributary bifurcates into the Sulina branch, carrying almost 29.7 % of the Danube waters to the sea, and the Sf. Gheorghe (25.7 %) branch flowing through the southern part of the delta. A small fraction of the Sf. Gheorghe discharge is captured by the Dunavăţ (0.6 %) and Dranov (0.4 %) canals that flow down into the Razelm Lagoon. Just before flowing into

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

the Black Sea, the Sf. Gheorghe branch separates in the Olinca-Turceasca channel (0.4 %), flowing into the Sahalin Lagoon (0.4 %), and the main mouth (24.3 %).

3.3 Spatial and temporal variability of coastal dynamics

The dynamics in coastal areas at the river-sea interface is generally determined by the mixing processes induced by the interaction of the river plume and coastal currents, mainly driven by the open sea circulation and wind (Garvine, 1995; Fong and Geyer, 2002; Bellafiore et al., 2019). Similarly, in front of the Danube Delta, the general coastal circulation (determined averaging the values over the whole simulated period) reflects these processes with the several branches of the multiple-mouth delta forming separated freshwater plumes (Fig. 6a). The region of freshwater influence (ROFI; Simpson et al., 1993) extends on average for about 15 km offshore the river mouths. A low-intensity (< 10 cm s^{-1}) southward current characterize the shelf area which is also influenced by the long-shore dynamics induced by the rivers flowing along the northwestern Black Sea coast (Southern Bug, Dniestr and Dniepr; Bellafiore et al., in review). A well-defined recirculation structure can be identified south of the 5 km long artificial jetty of the Sulina mouth. The lagoon system is on average characterized by very low currents (in the order of a few cm s^{-1}) and salinity ranging from 1 to 4 g L^{-1}, with the Sinoie Lagoon being saltier than the Razelm lagoon due to the inflow of marine waters through the Edighiol and Periboina inlets.

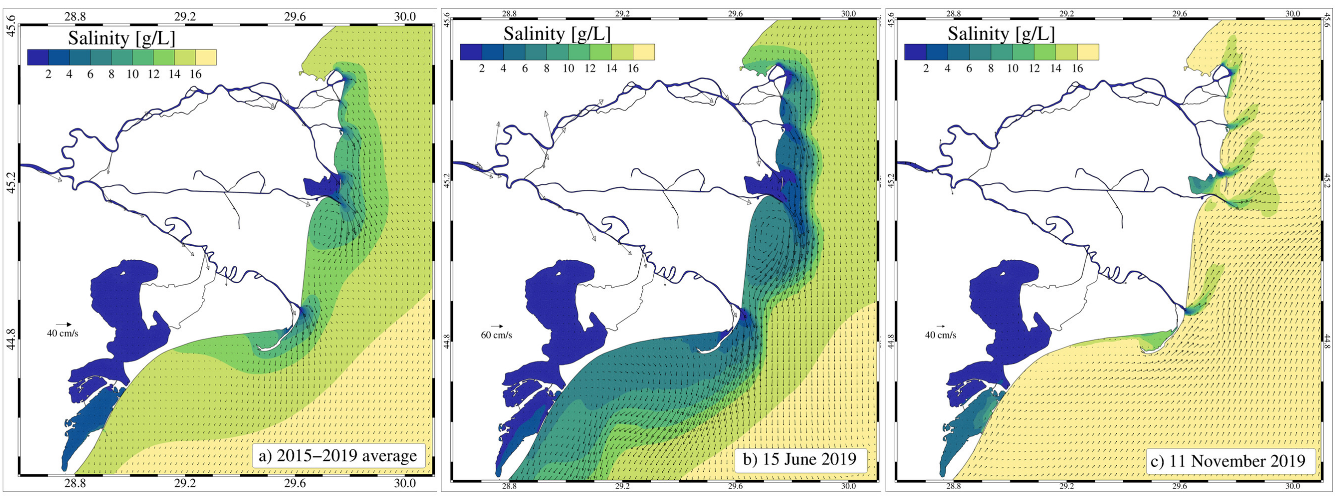

Figure 6. Surface salinity and current velocity maps: a) average values over the 2015-2019 period; b) instant values on 15 June 2019; c) instant values on 11 November 2019.

The hydrodynamics of the whole area is strongly variable in time and space depending on Danube River discharge and other forcing (e.g., wind, heat fluxes, long-shore currents). Indeed, such a variability is illustrated in Figs. 6b and 6c presenting examples of the dynamics (in terms of current velocity and salinity) in the investigated area during summer (16 June 2019) calm weather with peak river discharge (13000 m^3 s^{-1}) and autumn (11 November 2019) windy (northerly) with low river discharge (2400 m^3 s^{-1}) autumn conditions, respectively.

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

The high freshwater input during peak Danube River flow extends ROFI far offshore and to the south determining a reduction in salinity over a large portion of the coastal area and the enhancement of the southward surface coastal currents up to 60 cm s^{-1} (Fig. 6b). On the contrary, during low river discharge, the surface coastal dynamics is mainly driven by the wind. The autumn event present in Fig. 6c is characterized a general northward surface transport of saline waters with the ROFI limited to river plumes extending north-eastward for a few km from the river mouths.

A season analysis was performed to compute the standard deviation (hereinafter STD, considered here as a metric of the temporal variability) of the multi-year model results over the whole domain and for each of the four seasons (winter=DJF, spring=MAM, summer=JJA, fall=SON). The surface current variability is higher in winter (Fig. 7a) and spring (Fig. 7b) with STD values above 50 cm s^{-1} in a coastal strip extending from the Sulina mouth down to the end of the Sahalin spit. During summer (Fig. 7c) and fall (Fig. 7d) the highest current velocity variability is found south of the Sf. Gheorghe mouth. The highest variability in the surface salinity is found during spring (Fig. 7f) and summer (Fig. 7g) months with STD values above 3 g L^{-1} characterizing large areas in front of each river mouth and a large coastal band south of the delta. The freshwater input from the multiple mouths show a similar pattern in winter (Fig. 7e) and fall (Fig. 7h) but with lower STD values. These findings are highly correlated with the variability of the Danube River discharge, that usually peaks in spring or early summer while drought conditions are generally found in autumn (Fig. 2a), and the winds (either northerly and southerly), that are generally stronger in winter and autumn (Bajo et al., 2014).

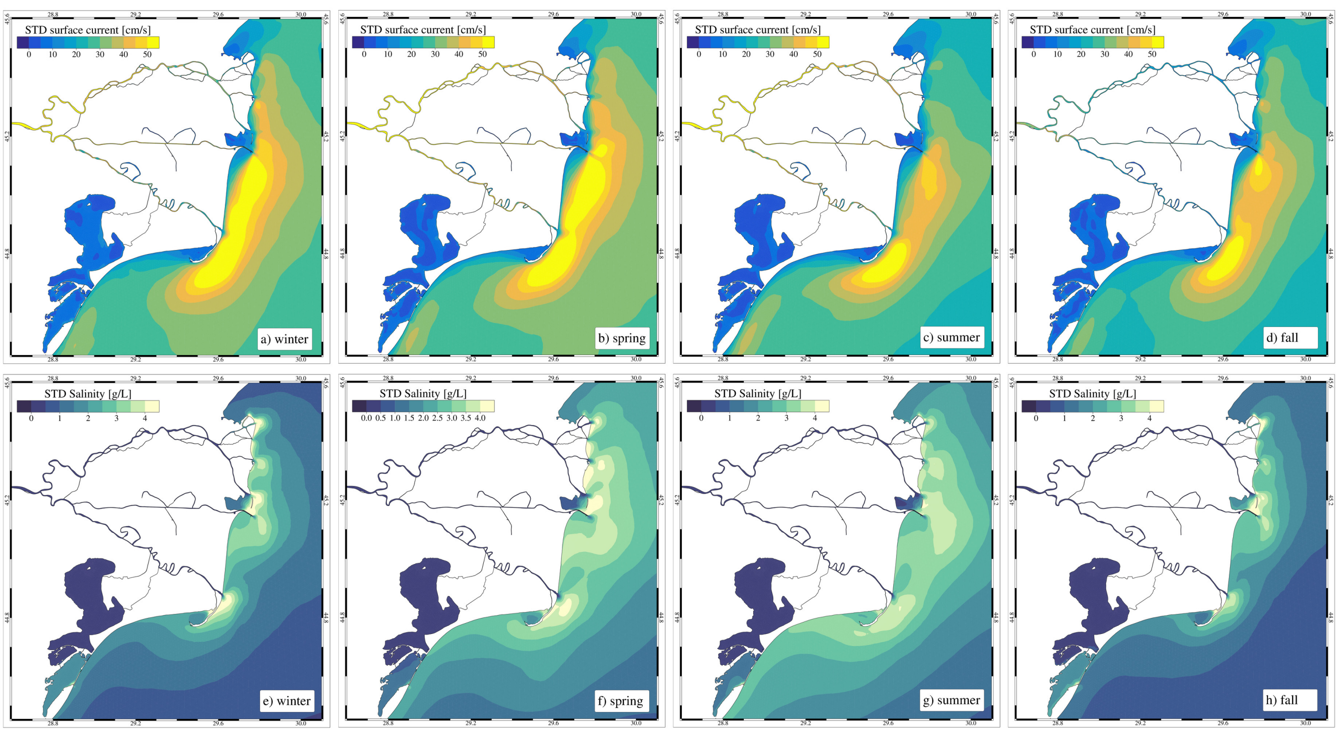

Figure 7. Seasonal standard deviation of surface currents (panels a, b, c and d) and surface salinity (panels e, f, g, and h).

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

3.4 River-lagoon-sea connectivity

The Razelm Sinoie Lagoon System is a choked water body receiving Danube freshwater from the Dunavăţ and Dranov canals and exchanging waters with the Black Sea via the Edighiol and Periboina inlets (Dinu et al., 2015). Here water fluxes and water renewal times are used as metrics for investigating the water exchange, mixing and the time a water particle spend into the lagoon system.

The RSLS has a water volume of about 1300 millions m^3 and receive on average 40 and 22 $m^3\ s^{-1}$ from the Dunavăţ and Dranov canals, respectively. This surplus of water entering the lagoons is mainly discharged into the Black Sea through the Edighiol and Periboina inlets, accounting for a net outflow of 42 $m^3\ s^{-1}$. Evaporation over the lagoon system overpasses precipitation resulting in a net loss of 20 $m^3\ s^{-1}$. Moreover, when the Black Sea level is higher than the lagoon water level an inflow of marine waters entering RSLS occurs, estimated to be 16 $m^3\ s^{-1}$ on average (with peak values of 210 $m^3\ s^{-1}$). The lagoons receive a total water flux of 78 $m^3\ s^{-1}$ from the sea and the river. Therefore, the basin-wide water flushing time (WFT), defined as the theoretical time necessary to replace the complete volume of the water body with new water and assuming a hypothetical fully mixed basin (Umgiesser et al., 2014), corresponds to 193 days.

The flushing time estimate was used to determine the duration of the water renewal time simulations. In this work, we performed five one-year-long replicas of WRT starting the simulations at the beginning of each year. The dispersion and dilution of the tracer initially released into the lagoons (see section 2.1) are determined by the inflow of new water and internal mixing processes that in the shallow lagoon system are mainly induced by the wind. The spatio-temporal average WRT is 241 days (minimum = 194 days in 2015; maximum = 333 days in 2018; standard deviation = 63 days) for the RSLS, thus revealing a mixing efficiency (determined as the ratio between WFT and WRT can be interpreted as an index of the mixing behaviour of the basin) of 0.8 corresponding to a well-mixed water system (Umgiesser et al., 2014).

The spatial and temporal variability of river, ocean and meteorological conditions affects the river-lagoon-sea fluxes as well as the internal mixing in the lagoons, and consequently the WRT computation. Indeed, a marked west-to-east WRT gradient (from 50 to more than 300 days) is evident in the RSLS, with the Razelm Lagoon having lower values than the Sinoie Lagoon (Fig. 8a). This is because the new (fresh) waters enter the Razelm Lagoon from the Dunavăţ and Dranov canals and are subsequently mixed and transported to the Sinoie Lagoon. The input of marine waters through the Edighiol and Periboina inlets has a limited effect on the local WRT, which resulted mostly influenced by the outflow of tracer. Salinity has a limited variability over the RSLS, with values ranging from 1 to 5 g L^{-1} and where the higher values are found in area of the Sinoie Lagoon near the Edighiol and Periboina inlets (Fig. 8b).

3.5 Assessment of lagoon-sea reconnection solutions

As illustrated in previous section, the RSLS is a large and shallow water body separated from the sea by narrow sandy barriers and with limited renewal capacity. In the past, the lagoons were connected to the sea via several inlets, while nowadays only the Periboina and Edighiol connections are active. Restoring the lagoon-sea water exchange via dredging of a new 1.5 m depth channels is therefore under consideration by local communities and authorities, as part of the activities developed

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Preprint. Discussion started: 24 February 2025

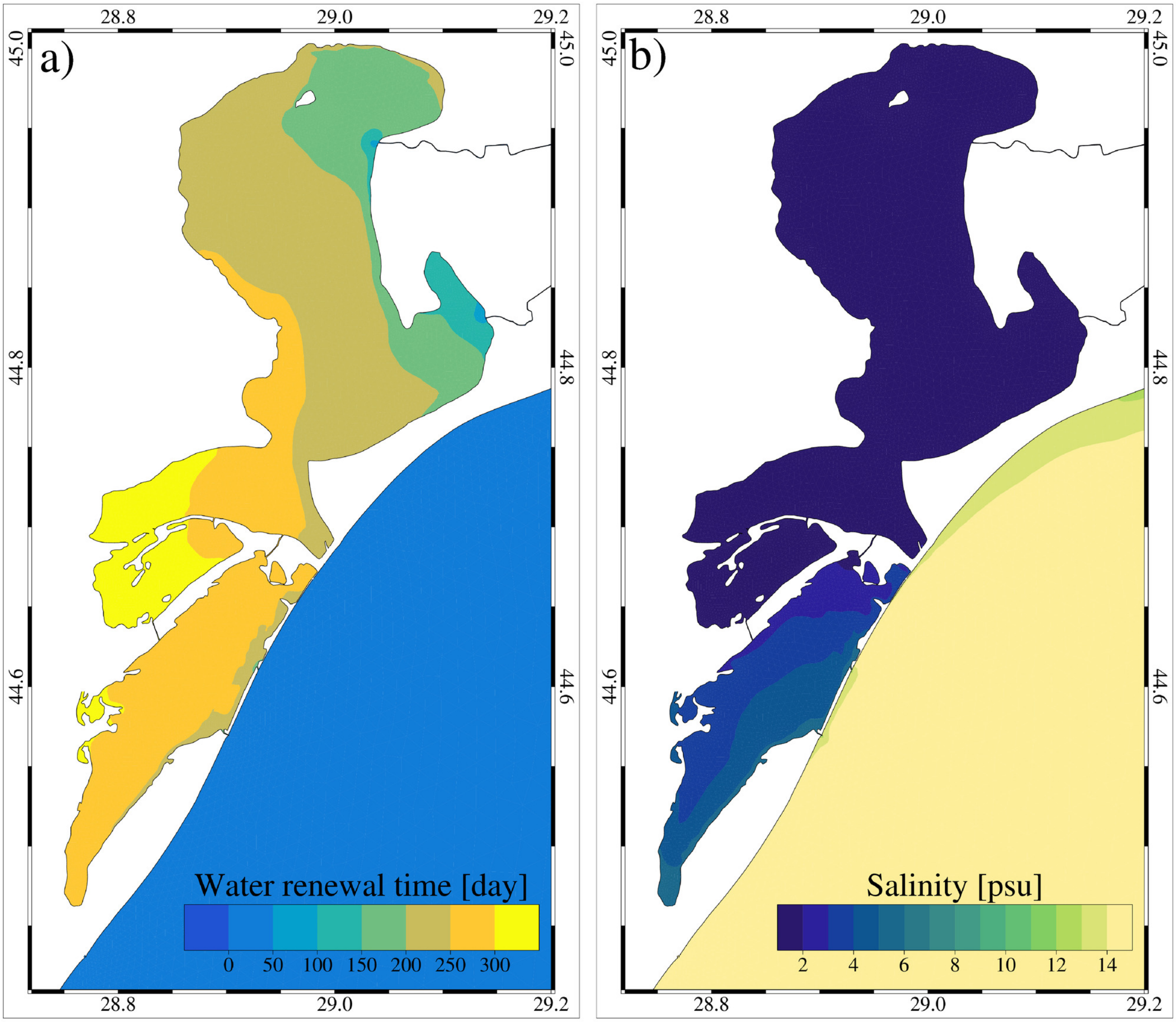

Figure 8. Average water renewal time (panel a) and salinity (panel b) over the Razelm Sinoie Lagoon System.

270 under the framework of the Horizon Europe Project DANUBE4all (https://www.danube4allproject.eu/). In this study, we use the modelling framework to evaluate the effects of several reconnection solutions (Fig. 1c) on the river-lagoon-sea exchange, water renewal time and salinization.

The numerical model results of the different simulations were processed to estimate the lagoon-sea water exchange through the inlets (the two existing and the newly designed) and the values are reported in Table 2. The hindcast simulation presented

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

Table 2. Average water fluxes (in m^3 s^{-1}) between the lagoons and the sea via the Edighiol and Periboina inlets and the new inlets (positive values indicate inflow into the lagoons while negative values indicate outflow from the lagoon to the sea).

Scenario	Edighiol and Periboina inlets			New inlet			Total flow		
	Net	Outflow	Inflow	Net	Outflow	Inflow	Net	Outflow	Inflow
REF	-42	-58	16	-	-	-	-42	-58	16
A	-21	-43	22	-23	-49	26	-44	-92	48
B	-20	-42	22	-23	-51	28	-43	-93	50
C	-24	-45	21	-19	-28	9	-43	-73	30

in previous sections is here considered the reference run (hereinafter REF) and used as a basis for comparison for the *what-if* scenarios.

Opening a new inlet has a significant effect on the lagoon hydrodynamics altering the water budget of the basin and the fluxes through the existing Edighiol and Periboina inlets, which generally resulted to be enhanced towards the lagoon and reduced towards the sea. The net flow between the lagoons and the sea is not significant altered (about 40 m^3 s^{-1}), being mostly determined by the river inflow into the lagoon. However, opening a new inlet increases up to four times the total inflow of marine waters into the lagoon with the respect of the reference simulation, with the solutions planned for the Razelm Lagoon (A and B) having a higher effect on the fluxes than the ones designed in the Sinoie Lagoon (C).

Because of these changes in the lagoon-sea fluxes, the water renewal capacity and the salinity increase (lower water renewal time values). The average WRTs decrease to 191, 190 and 230 days in scenarios A, B and C, respectively. The spatial distributions of WRT illustrated in Fig. 9 clearly reflect the changes in the lagoon-sea fluxes. Therefore, solutions A (Fig. 9a) and B (Fig. 9b), are the ones determining a more significant decrease in the water renewal times (> 50 days with respect to the REF simulation), especially in the southern part of the Razelm Lagoon and in the Sinoie Lagoon. Solution C (Fig. 9c) has a moderate effect on WRTs, which is anyway limited to the Sinoie Lagoon.

The augmented inflow of marine waters through the existing and the new inlets determines a general increase in salinity in the southern part of the lagoons. The highest salinity changes with respect to the REF simulation (Fig. 8b) are found in scenarios A (Fig. 9d) and B (Fig. 9e) in the Sinoie Lagoon where the average salinity increases to more than 5 g L^{-1}. As for the water renewal times, solution C (Fig. 9f) has a limited effect on salinity.

To investigate more into details the opening effects on the salinity, we extracted from the simulation results the timeseries in two control stations in the Razelm and Sinoie lagoons identified with red dots in Fig. 9e (Fig. 10). Solutions A and B have very similar effects on salinity which in the southern part of the fluctuates between 2 and 8 g L^{-1}, and between 6 and 16 g L^{-1} in the Razelm and Sinoie lagoons, respectively. Lastly, solution C has an almost negligible (< 1 g L^{-1}) effect on salinity in both lagoons.

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Preprint. Discussion started: 24 February 2025

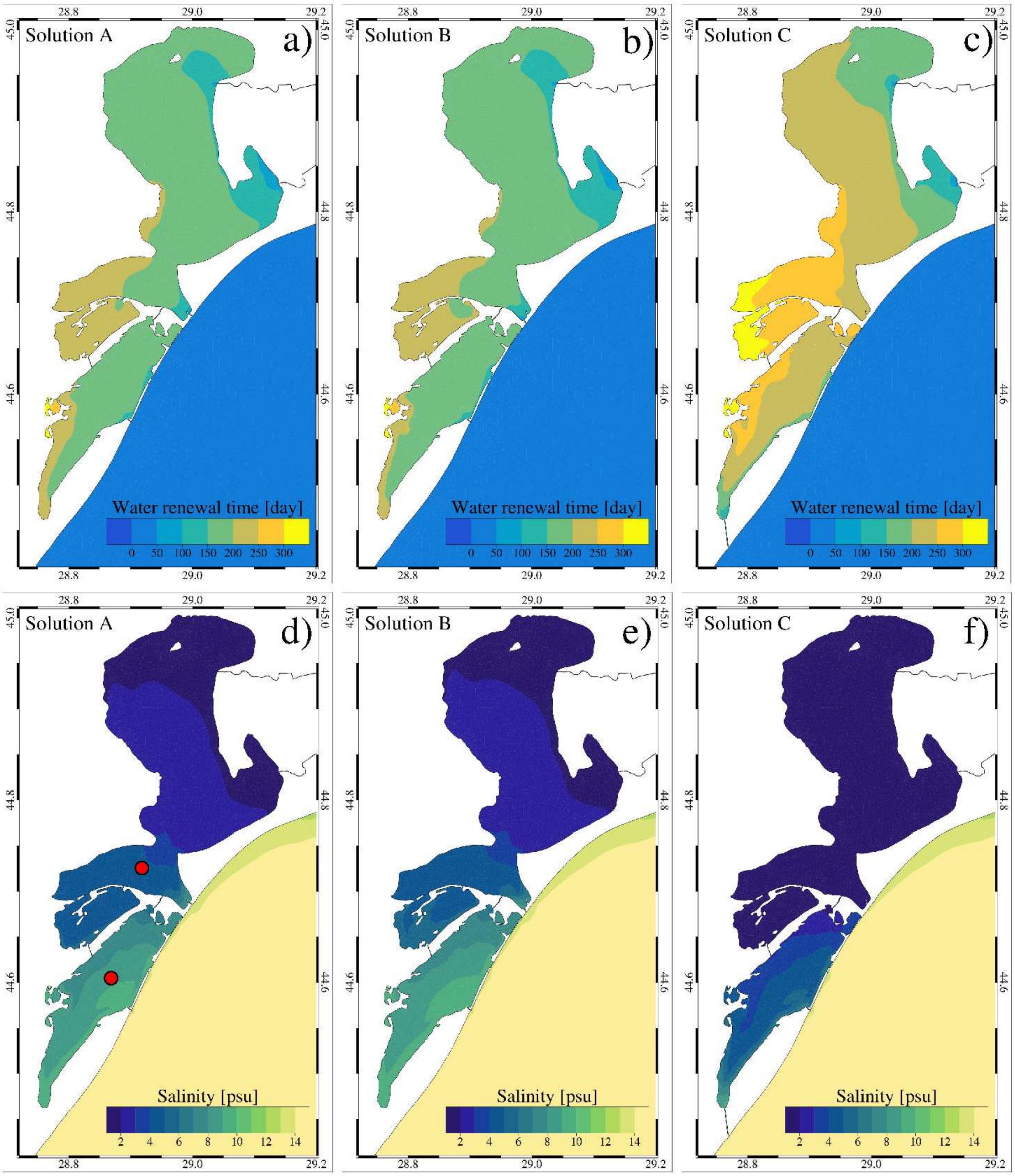

Figure 9. Average WRT (panels a, b, c) and salinity (d, e, f) for the considered open free-flow *what-if* scenarios. The red dots in panel e indicate the location of the two control points where the salinity timeseries were extracted (Figure 10).

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Preprint. Discussion started: 24 February 2025

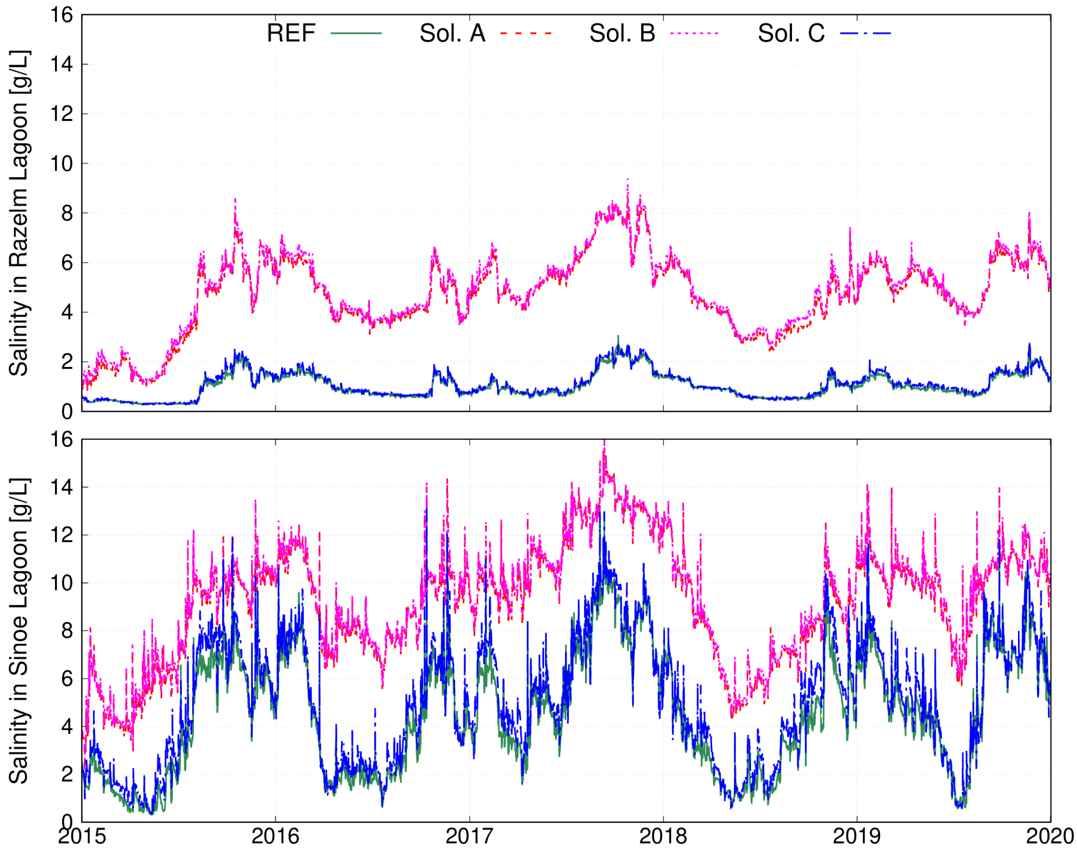

Figure 10. Timeseries of modelled salinity extracted in the control points in the Razelm (top panel) and Sinoie (bottom panel).

4 Discussion

The Danube Delta, as many other coastal systems at the river-sea interface, is composed by several interconnected water bodies (river branches, coastal lakes, lagoons, shelf sea) having different physicochemical characteristics and influencing each other. The exchanges of water among these water bodies are regulated by barotropic and baroclinic processes driven by the forcing acting on the area (upstream river discharge, wind, heat fluxes, open sea conditions). We focus the discuss on the bidirectional interactions and related driving processes separately for the different water compartments. The implication of the reconnection solutions on the connectivity between the different water bodies is finally discussed.

Danube River to Black Sea. As presented in sections 3.2 and 3.3 the Danube flows into the Black Sea via several mouths having different dimension and discharge. Clearly, freshwater determines a stratified water column along the coast with a complex coastal circulation pattern, which is generally characterized by a southward long-shore current and recirculation cells located south of the river mouths (Fig. 6a). However, the wind plays a crucial role in determining the direction of the coastal circulation and vertical mixing processes (Figs. 6b and 6c). A deeper analysis of the model results revealed complex vertical

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

dynamics in the coastal areas in front of the delta. The sea surface temperature highlighted the presence of small scale near-shore water bulges located between the river mouths and having thermo-haline characteristics different from the surrounding areas (Fig. 11). Similar patterns were found by Bellafiore et al. (2019) in front of the Po River Delta. The vertical alongshore sea temperature transect presented in Fig. 11c (Fig. 11d) indicate that warmer (colder) marine waters are transported from the deep layers to the coast enhancing mixing of open sea and riverine waters. The presented analysis indicate that these peculiar structures are generated by upwelling processes induced by the action of river outflow and southerly winds blowing along the coastline. A clear indication that upwelling - and not horizontal advection - is occurring in these areas is that their surface temperature is different (warmer or colder depending on the season) than the offshore waters.

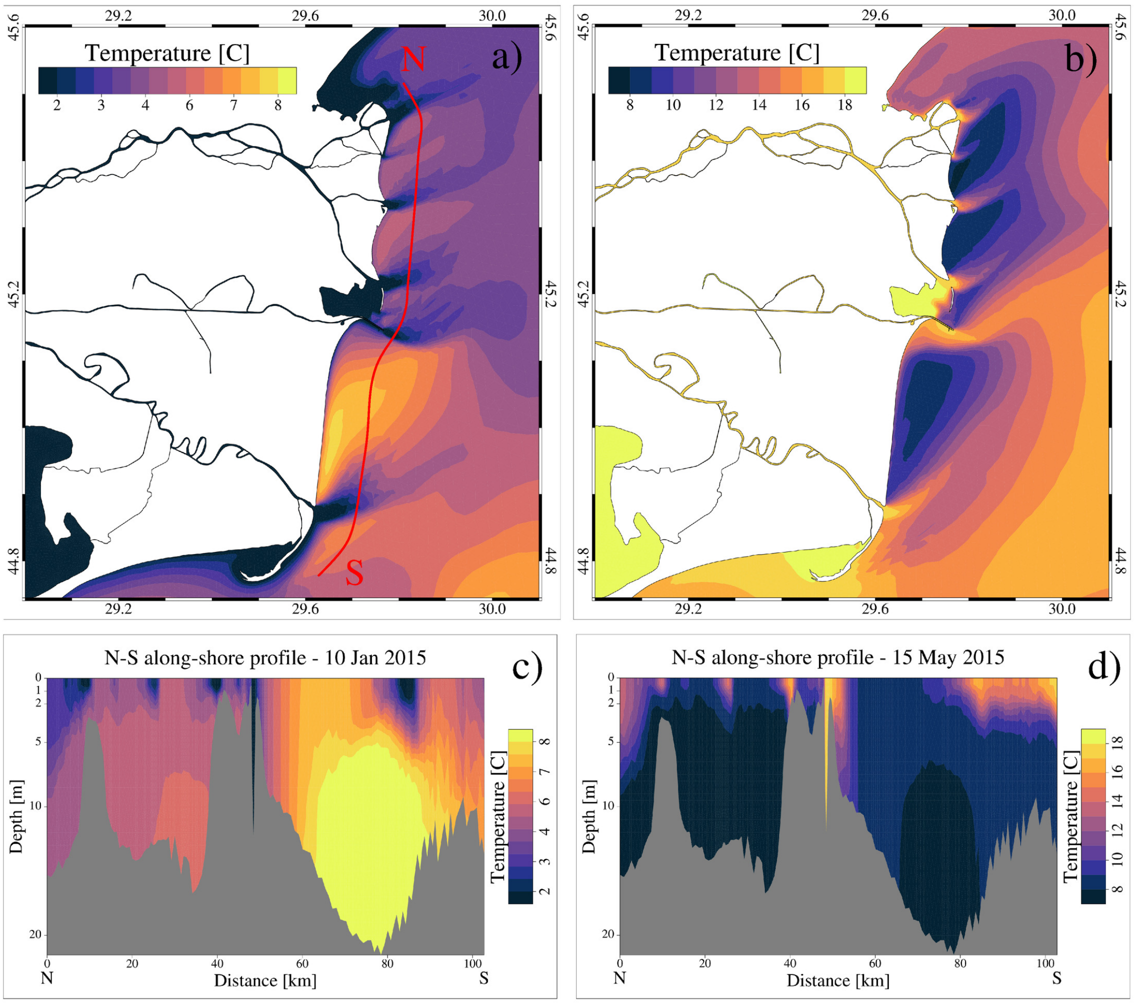

Figure 11. Map of sea surface temperature and north-to-south alongshore transect of sea temperature for the 10 January 2015 (a and c) and 15 May 2015 (b and d). The transect location is indicated with a red line in panel a.

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Preprint. Discussion started: 24 February 2025

Black Sea to Danube River. In addition to the river influence on the Black Sea coastal dynamics, during drought periods marine waters can intrude along the river branches altering their water physicochemical properties. Such a phenomenon, known as saltwater intrusion (SWI), is well documented in several coastal systems at the river-sea interface, such as delta and estuaries (Shen et al., 2018; Tian, 2019; Bellafiore et al., 2021). The near-bottom value of 2 g L^{-1} is chosen as a marker of SWI (Bellafiore et al., 2021). As illustrated in Figure 12 presenting the maximum bottom salinity over the simulated period, in the Danube Delta marine waters enter up to 20 km upstream from the mouth in the Chilia (mostly from the Chilia secondary delta branches) and Sulina branches, and up to 7 km upstream from the Sf. Gheorghe mouth. Saltwater intrusion is determined by an estuarine type of dynamic in the lower part of the branches with freshwater flowing on the surface layers and the salt wedge intruding along the riverbed. It is important to point out that saltwater intrusion is one of the major threats in coastal area affecting freshwater supplies for agriculture and human use, and ecology in coastal wetlands. The situation is predicted to worsen in the near future due to sea level rise (van de Wal et al., 2024) and decreasing summer runoff (Probst and Mauser, 2023).

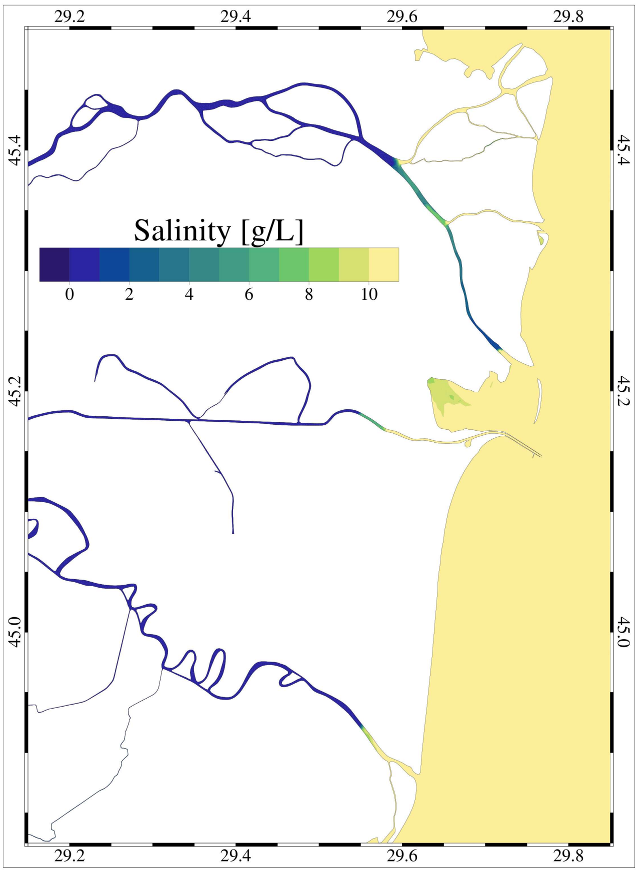

Figure 12. Maximum bottom salinity computed from the model results over the 2015-2019 period.

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

Danube River to RSLS to Black Sea. The Razelm Sinoie Lagoon System is a transitional coastal environment connected to the Danube River and the Black Sea. Due to the input of freshwater from the Dunavăţ and Dranov canals, there exists on average over the 2015-2020 period a water level gradient from the Razelm Lagoon (about 30 cm), the Sinoie Lagoon (about 26 cm) and the coastal sea (about 23 cm) (green line in Fig. 13). Consequently, the long-term net water transport is mainly barotropic and directed from the river to the Razelm Lagoon, then to the Sinoie Lagoon and finally to the open sea. The water level jumps between the two lagoons and between the Sinoie Lagoon and the open sea indicate that the flow through the narrow and shallow canals (Canal 2, Canal 5, Edighiol and Periboina inlets) connecting the different water bodies resulted to be hydraulically limited. The internal average north-to south sea level gradient found into both lagoons is determined by the dominant north-easterly wind regime.

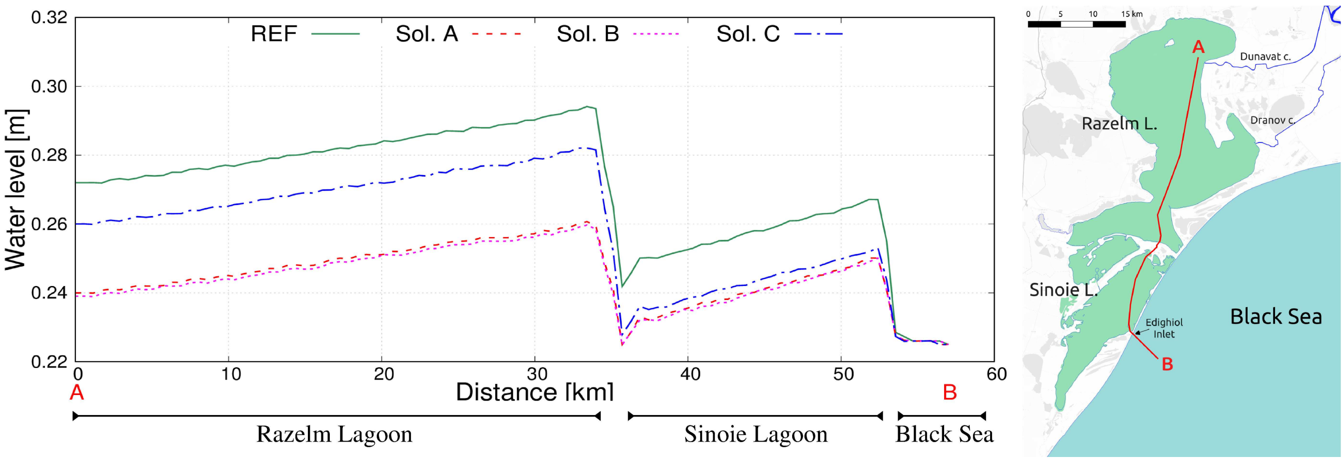

Figure 13. Average water level values along a transect crossing the Razelm Sinoie lagoon systems. Background: ©OpenStreetMap contributors 2024; distributed under the Open Data Commons Open Database License (ODbL) v1.0.

However, the water level gradients are variable in time depending of the freshwater inflow, the coastal sea level and the wind action over the system. Such a dynamic is well illustrated in Figure 14 reporting for the year 2018 the daily values of Danube River discharge, the sea-lagoon (Sinoie) water level difference, and the water and salt fluxes through the Edighiol and Periboina inlets. The water level in the Sinoie Lagoon is generally higher than in the coastal area particularly during flood river conditions (e.g., from March to May 2018). However, the model results show high temporal variability induced by the wind action over the lagoons and the coastal sea. It must be noted that the water flux is not linearly dependent on the water level gradients confirming that the flow through the Edighiol and Periboina inlets resulted to be hydraulically controlled (ad example at the beginning of March). A two-layers flow in the Edighiol inlet may occur when the lagoon-sea water level gradient is small (in the order of a few of cm).

Black Sea to RSLS. While the water flow from the river to the lagoons is unidirectional, a bidirectional flow characterizes the water exchange between the lagoons and the Black Sea. The inflow of marine waters into the lagoon occurs in concomitance of positive sea-to-lagoon water level gradients. Salinity flux peak values into the lagoons occurs during inflow of marine waters

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

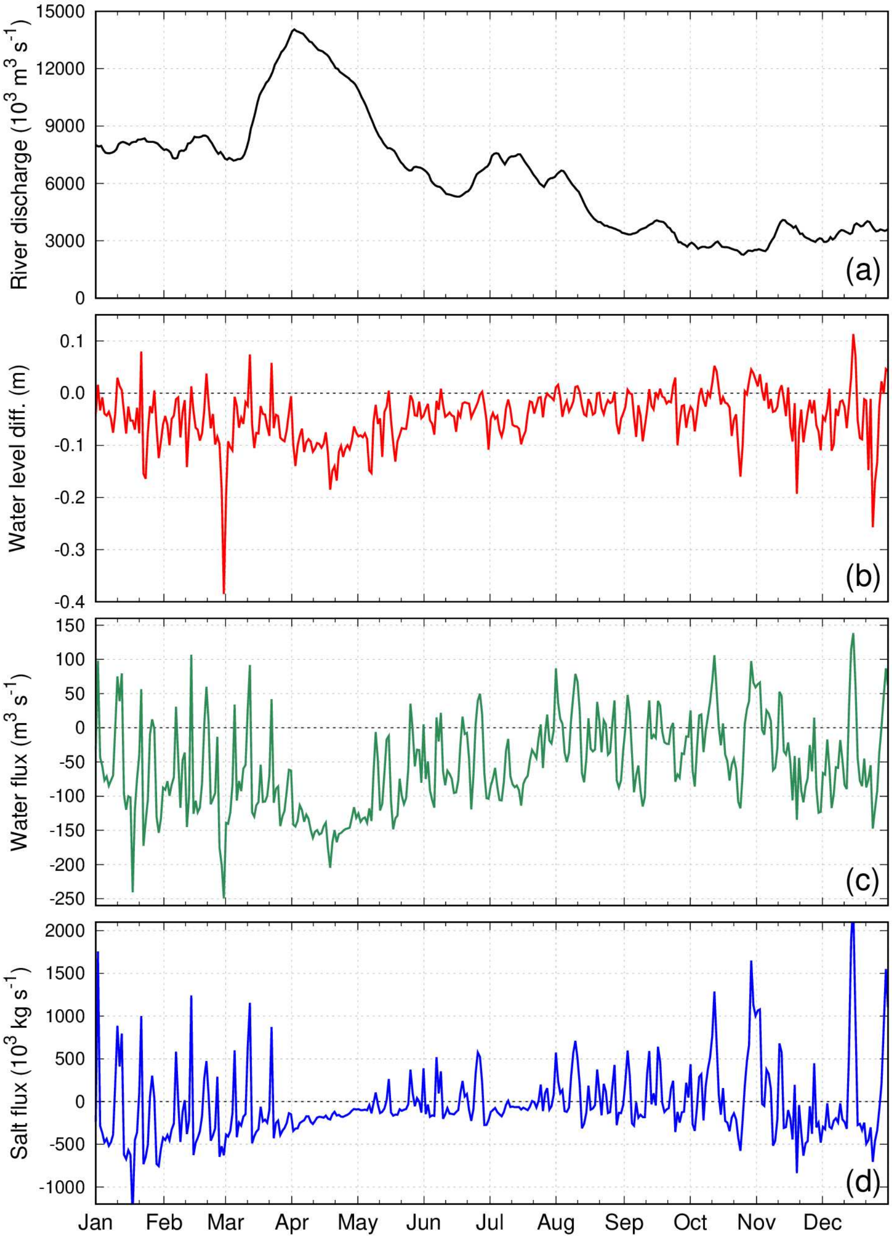

Figure 14. Daily values for the year 2018 of Danube River discharge (a), sea-lagoon water level difference (b), sea-lagoon water fluxes (c) and sea-lagoon salt fluxes (d). Positive values of water and salt fluxes indicate inflow into the lagoons while negative values indicate outflow from the lagoon to the sea. systems.

and are mostly found during autumn and winter drought and windy conditions (Fig. 14d). As a result, salinization events of the lagoon environments are sporadic and have a general duration of a few days. The salt content entering the Edighiol and Periboina inlets is advected and diluted in the Sinoie Lagoon and sporadically reaches the Razelm basin (Fig. 8a).

Implications of the lagoon-sea reconnection solutions. The results presented in section 3.5 indicate that a local change in the morphology of the coastal lagoons may alter the general hydrodynamics of the whole system. The Razelm and Sinoie lagoons are interconnected via two narrow and shallow channels and in the present state the net flow of water is from the Razelm basin, which receives Danube River waters, to the Sinoie basin, which is linked to the Black Sea. Connecting the Razelm Lagoon with the Black Sea with solutions A and B do not only allow the inflow of marine waters but also changes the water level of the two basins (lines red and magenta in Fig. 13) decreasing the water exchange between the two lagoons and the outflow via the existing inlets (Table 2). At the same time, the lower water level inside the lagoons favours the barotropic inflow of marine waters resulting in higher salinity and lower water renewal times in both basins (Figs. 9 and 10). On the contrary, solution C (blue line in Fig. 13) affect water levels in the Sinoie Lagoon and the fluxes with the Black Sea but have a limited impact on the Razelm basin.

5 Concluding remarks and perspectives

This work presents the first cross-scale hydrodynamic model implementation over the whole Danube Delta for representing the river-sea continuum. To address land-sea, river-lagoon-sea and coastal-offshore interactions, the SHYFEM numerical model was applied to a domain comprising the lower river network, the coastal lagoons and part of the shelf sea. A multi-year hindcast simulation was performed by adopting observed Danube River discharge and reanalysis data for the meteorological fields and the Black Sea boundary conditions as forcing.

The model validation showed that the processes controlling hydrodynamics and the fluxes among the different water compartments of the Danube Delta were correctly taken into account and represented. The simulation results allowed to quantify the riverine discharge distribution among major branches (Chilia, Sulina and Sf. Gheorghe) and distributaries of the lower river network, thus characterizing the relative relevance of the nine river mouths. At the same time, the detailed description of the freshwater discharge into the Black Sea permitted to investigate the spatial and temporal variability of the main oceanographic parameters and identify main processes and drivers. The model results clearly show that such a detailed representation of the river-sea continuum of the multi-mouth delta is fundamental for correctly describing the region of freshwater influence, which resulted to be shaped by the several river inputs and along-shore winds. Moreover, we investigated the hydrodynamics of the Razelm Sinoie Lagoon System, looking in particular at the processes determining their flushing and renewal capacity. The average water renewal time of this choked coastal environment connected to both the Danube River and the Black Sea is estimated in 241 ± 63 days.

We demonstrated that this modelling system is a powerful tool that can efficiently be used to evaluate the potential impacts of human interventions in the coastal environment. In this study we considered four lagoon-sea reconnection measures designed for improving the renewal capacity of the two lagoons. The model will be next used to explore several other river-lagoon-sea reconnection solutions to help local authorities and communities managing connectivity and salinization in the lagoon

https://doi.org/10.5194/egusphere-2025-606
Preprint. Discussion started: 24 February 2025

environment. An operational version of the Danube Delta model will be also developed for providing forecasts to support decision-making and improving awareness and preparedness to weather-related risks. The simulated *what-if* scenarios and the forecasting system will constitute the core of the first digital twin of the Danube Delta.

Code and data availability. The community SHYFEM hydrodynamic model is open source (GNU General Public License as published by the Free Software Foundation) and freely available through GitHub at https://github.com/georgu/shyfemcm-ismar.

This study has been conducted using the following public available datasets: the Black Sea Physics Reanalysis (https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004); the Copernicus European Regional ReAnalysis (https://doi.org/10.24381/cds.622a565a); the 2022 European Marine Observation and Data Network bathymetry (https://doi.org/10.12770/ff3aff8a-cff1-44a3-a2c8-1910bf109f85); in situ sea level and sea temperature data (https://marineinsitu.eu/dashboard/). The following datasets are not public available and can be requested to the mentioned authorities: the National Institute of Hydrology and Water Management of Romania for the Danube River discharge data; Deltares (NL) for the Danube River temperature data; the University of Stirling (UK) for satellite sea surface temperature data; GeoEcoMar (RO) for the 2024 Razelm Sinoie Lagoons, the 2019 Sulina branch and the 2016-2017 Sf. Gheorghe branch bathymetric datasets.

Author contributions. CF conceived the idea of the study with the support of AS. ID and CF collected the bathymetric and validation data sets. AS designed the reconnection solution to improve river-lagoon-sea hydrological connectivity. CF and APH performed the numerical simulations and analysed the results. All authors discussed, reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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