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Spatial Distribution of Suspended Solids During Short-Term High River Discharge in the Bay of Koper, Northern Adriatic Sea

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Abstract

The Bay of Koper located in the Gulf of Trieste (northern Adriatic Sea) is subject to a variety of anthropogenic influences; pollutants from inland are transported to the sea by local rivers. The impact of high river discharge on suspended solids distribution was assessed by analysing the results of an extensive measurement campaign conducted during two episodes of river flooding. The spatial analysis indicated the area influenced by fresh water and the distribution of inorganic suspended solids (ISS). The results were used to calibrate the PCFLOW3D model and to simulate two episodes. Statistical analyses confirmed significant agreement between the measurements and short-term simulations in the bay. The results suggest the methods and the model used in this study are appropriate for studying suspended solids processes in coastal areas.

Keywords: River plume, spatial distribution, inorganic suspended solids, PCFLOW3D model, Bay of Koper, northern Adriatic Sea.

Introduction

In estuarine and coastal environments of the Gulf of Trieste, river inflows significantly impact thermohaline properties, as well as the transport and distribution of fluvial suspended solids (Faganeli & Turk, 1989; Covelli *et al.*, 2007). The freshwater impact on salinity is mostly noted through density currents in the sea surface layer, while the suspended solids affect turbidity in the water column. High turbidity is considered a stress factor for benthic organisms (Orpin *et al.*, 2004). Furthermore, the suspended matter brought into the sea, can, when settled to the bottom, destabilize the substrate and bury the benthos (Wolanski, 2007). Numerous authors (Stone & Droppo, 1994; Covelli *et al.*, 2007) have identified suspended solids as the transport mechanism for nutrients and pollutants through adsorption and flocculation. The river Rižana is the main source of fluvial water and sediment for the Bay of Koper (Faganeli and Turk, 1989), the easternmost part of the Gulf of Trieste in the northern Adriatic Sea (Ogorelec *et al.*, 1987). Pollutants from industry and the densely inhabited inland area are also transported by the river Badaševica (Lipej *et al.*, 2006). The selected study site is subject to high anthropogenic pressure (Orlando Bonaca *et al.*, 2008), visible in the heavily modified coast and river estuary (Ogorelec *et al.*, 1987). In recent reports on monitoring water quality and pollution from inland conducted by the Marine Biology Station – National Institute of Biology (MBS – NIB) within the programme of the Barcelona Convention (Turk *et al.*, 2011; Turk *et al.*, 2012; Turk *et al.*, 2013; Turk *et al.*, 2014), the Rižana river was mentioned as an important source of inland pollutants.

Due to the highly variable discharge (and impact) of the Rižana river, water quality monitoring at a single sampling site on a monthly basis performed by MBP – NIB (Turk *et al.*, 2011; Turk *et al.*, 2012; Turk *et al.*, 2013; Turk *et al.*, 2014) is insufficient for evaluating the influence of the river inflow in such a wide-open bay. On the other hand, uncertain weather forecasts and river discharge rate oscillation as well as the sea conditions during river floods limit the possibilities of extended measurements campaigns in conditions with the highest sediment inflow. Recently, a two-year campaign of extended spatial surveys was performed in the Bay of Koper (Soczka Mandac *et al.*, 2014), which revealed the spatio-temporal influence of the Rižana and Badaševica rivers at various discharge rates. Total suspended solids distribution and deposition rate were addressed (Soczka Mandac & Faganeli, 2015). Unfortunately, even such an extended measurement strategy did not satisfy the need for information at the studied site, particularly during events of short duration (river plumes).

Sediment transport modelling in the wider area was addressed by using Princeton Ocean Model (POM)-based models in the Adriatic Sea (Wang *et al.*, 2007) and in the

Gulf of Trieste (Malačič & Petelin, 2006). In the Bay of Koper these processes were simulated using various models (Malačič *et al.*, 2009; Malačič *et al.*, 2010; Žagar *et al.*, 2012); however, none of the models was adequately calibrated or validated using measured data from the entire modelling domain. Furthermore, the impact of wind and navigation on resuspension was studied, but none of the previous studies in the Bay of Koper included the influence of the rivers Rižana and Badaševica, which undoubtedly affected the obtained results. Previous numerical modelling of particle bound pollutants in the area was limited to mercury pollution caused by the Soča/Isonzo River inflow (Rajar *et al*., 2000; Žagar *et al*., 1999) and mostly performed in relatively coarse resolution within the modelling studies of the Gulf of Trieste (Rajar *et al*., 2000). Data from recent measurements (Soczka Mandac *et al.*, 2014; Soczka Mandac & Faganeli, 2015) should, however, represent a satisfactory and representative source for calibration and evaluation of the model PCFLOW3D, which has been used in several previous modelling studies within the Mediterranean Sea (Rajar *et al*., 2004b; Žagar *et al*., 2007 and the references therein). Such a procedure is fundamental for development of adequate modelling tools that can be used for simulation of episodic events (e.g., high river discharges). Therefore, the main aims of the present study were:

1. Spatial analysis of inorganic suspended solid concentrations within two episodes of high river discharge.
2. Calibration and validation of the PCFLOW3D model by comparing the results to an extended set of in situ measured data.
3. Analysis of spatial distribution of inorganic suspended solids (ISS) during high river discharge events simulated by the sediment transport module of the PCFLOW3D model.

Materials and Methods

Site description

The Bay of Koper (BoK) is a wide open bay with an average depth of 16 m, covering about 35 km^2 (Ogorelec *et al.*, 1987). The depth decreases linearly from 23 m at the western open boundary to 1 m in the coastal zone. Three dredged canals (average depth 16 m) intended for maritime traffic connect the open part of the bay to the port basins. Circulation is mainly forced by tide (range of ±0.6 m) and wind, in particular the easterly Bora wind (Malačič *et al.*, 2014). The mouth of the Rižana river is located at the east side of the bay in the second port basin (port of Koper), while the first port basin (the southernmost of the three basins) is situated in the vicinity of the town of Koper (Fig. 1).

The Rižana is a small river with a variable mean flow rate of 4 m^3 s^{-1}. The river estuary is highly stratified with a short mean fresh water replacement time of less than 1 day (Faganeli & Turk, 1989). A discharge from Koper's municipal waste water treatment plant is located ~400

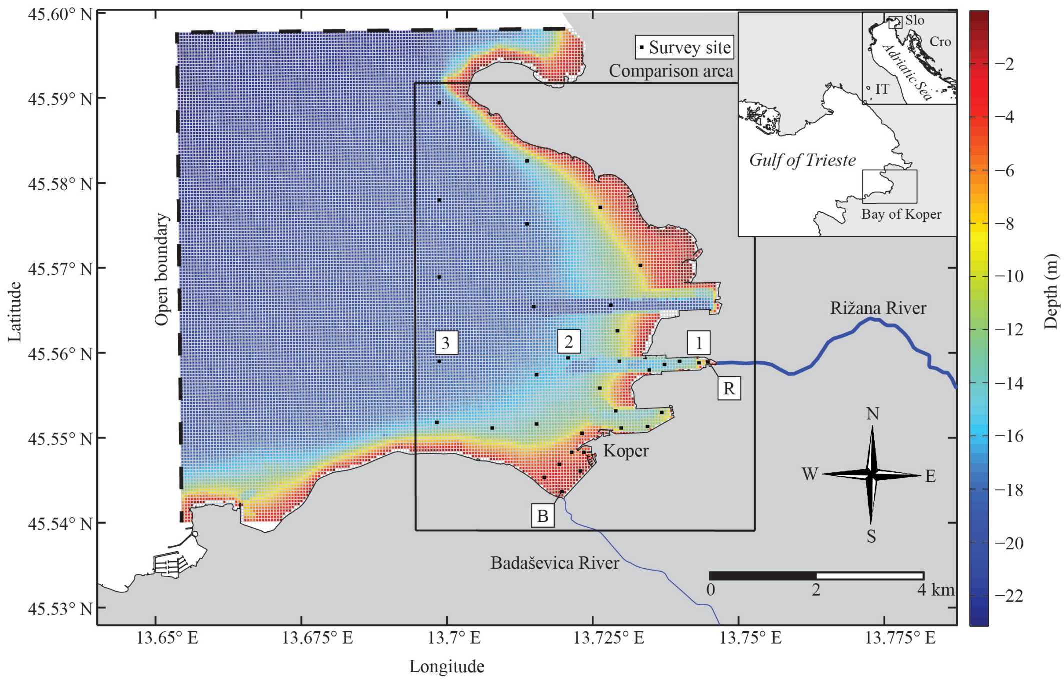

Fig. 1: Bay of Koper situated in the Gulf of Trieste (northern Adriatic Sea). The PCFLOW3D model grid in 40×40 m resolution with the related bathymetry. The rectangle depicts the area with three comparison profiles P1, P2 and P3. The dashed lines indicate the open boundaries.

m west, upriver, from the mouth. Spatial distribution of fluvial water and particulate suspended matter (turbidity) in the BoK is affected by various factors, primarily by wind (meteorological) and river discharge rate (hydrological), as well as maritime traffic (Ogorelec *et al.*, 1987; Malačič *et al.*, 2014). The Slovenian Environment Agency (ARSO) records the hydrological and meteorological data. The flow rate of Rižana river has been monitored since 1966 at the gauge station Kubed (located 13 km upstream from the river mouth), and that of the river Badaševica at Šalara (located 3.2 km upstream from the river mouth) (ARSO, 2014a). Other freshwater inputs to the BoK are storm water runoffs located around the bay, which were not included in the study. The meteorological data was measured in the port zone (at height 2 m) by the ARSO meteorological station (ARSO, 2014b).

In Situ measurements and sampling

Twenty-eight campaigns were performed at 34 sites in the BoK (Fig. 1) between June 2011 and June 2013 in monthly intervals during periods of low maritime traffic (Soczka Mandac *et al*., 2014). The water column was profiled using a conductivity, temperature and depth (CTD) probe (Hydrolab datasonde model 4a) with an optical turbidity sensor (ISO 7027 compliant), which measures the light back scatters at a wave length of 860 nm ±10 nm. The probe was lowered manually from the water surface to the sea bed, recording temperature, conductivity and turbidity at the rate of 1 Hz. All variables were averaged vertically in 0.5 m intervals.

Water samples for total suspended solids (TSS) were collected at the surface (0.5 m deep) at 19 sampling sites in the bay and at sites near the Rižana and Badaševica river mouths using 10 l Niskin samplers. The water samples (1 l) were immediately stored in polyethylene bottles at 5 °C and filtered within four hours. One litre of water sample was filtered through a pre-weighed 47 mm diameter Whatman GF/F glass-fibre filter with approximately 0.7 μm pores pre-ignited at 480 ºC for 3 hours. The filters with particles were washed several times with MiliQ water to remove salt and dried at 60 ºC in an oven (Aurodent typ 830 nf). They were freeze-dried and the net weight (TSS) was recorded. For suspended organic matter (SOM) analysis, the filters were successively ignited in an oven (Aurodent typ 830 nf) at 480 °C for 4 h and weighed. The difference between TSS and residue following ignition was noted as SOM. Inorganic suspended solids (ISS) described in equation (1) represent the difference between TSS and SOM. The acquired regression model between NTU and TSS is described in detail in Soczka Mandac & Faganeli (2015); the relation (Eq. 1) was obtained from measurements and sampling campaigns conducted during low and high river discharge at numerous sampling sites within the Bay of Koper.

$$ISS = 0.87 \times NTU + 0.12$$

In the horizontal plane the DIVA (Data-interpolating Variational Analysis) interpolation (Troupin *et al.*, 2012) was used to provide spatial grid maps of variables at the sea surface and estimated error in a grid of 560×403 cells with ~10×10 m cell resolution. The average error calculated from the obtained maps, was estimated at ~20%, which was found to be acceptable with regard to the distance between the measurement sites and to the adopted interpolation method (Soczka Mandac & Faganeli, 2015). The highest discrepancies were evident in the third basin (the northernmost part of the port, Fig. 1), where measurements were omitted due to restricted access.

The PCFLOW3D model

The PCFLOW3D model and its modules have been described in numerous publications. The model was used for computation of circulation, transport of dissolved and particulate pollutants, and basic mercury transformations in the northern Adriatic Sea, the entire Mediterranean and Minamata Bay (Četina, 1992; Rajar & Četina, 1997; Četina *et al.*, 2000; Rajar *et al.*, 2000; Rajar *et al.*, 2004; Kovšca, 2007; Žagar *et al.*, 2007). Simulations of sediment re-suspension, transport and deposition were also carried out using the model (Žagar, 1999; Rajar *et al.*, 2000). A study of circulation and environmental conditions in the Bay of Koper and the port of Koper (Malačič *et al.*, 2009; Malačič *et al.*, 2010; Žagar *et al.*, 2012, Žagar *et al*., 2014) employed the PCFLOW3D and ECOMSED models to simulate the sediment resuspension due to the Bora wind and navigation in the vicinity of the port.

The PCFLOW3D model is a non-steady state 3D hydrodynamic baroclinic z-coordinate numerical model. It consists of hydrodynamic, transport-dispersion, sediment-transport and biogeochemical modules and can be used for simulations of circulation, transport and dispersion of dissolved and particle bound pollutants, and mercury transformation simulations in an aquatic environment. A detailed description of the structure and functionality of the PCFLOW3D model is given in the literature (Rajar & Četina, 1997; Četina et al., 2000; Žagar et al., 2007). In the present study we adopted the Smagorinsky turbulence models in both horizontal and vertical directions, as described in Kovšca (2007). The equations for horizontal and vertical coefficients of turbulent viscosity (and turbulent diffusion, taking into account an appropriate Prandtl-Schmidt number) are as follows:

$$N_h = C_{smaH}\Delta x\Delta y\left(\left(\frac{\partial u}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right)^{\frac{1}{2}}$$

$$N_{v,x} = C_{smaV}\Delta x\Delta z\left(\left(\frac{\partial u}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial z}\right)^2\right)^{\frac{1}{2}}$$

$$N_{v,y} = C_{smaV}\Delta y\Delta z\left(\left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial z}\right)^2\right)^{\frac{1}{2}}$$

The topography and bathymetry of the BoK (Fig. 1) were described using a rectangular 183×158 grid with 40×40 m resolution in the horizontal plane, while in the vertical direction the domain was divided into 22 layers with equal thicknesses of 1 m. The influence of tide was not taken into account; all simulations of sediment transport were performed in 24-hour intervals, which correspond approximately to a full diurnal tidal cycle. We adopted the clamped open-boundary condition (OBC) at both open boundaries.

Model input data

In the present study the PCFLOW3D model simulations were performed using seasonal and peak river inputs of the Rižana and Badaševica rivers and calibrated for two high river discharge events. Furthermore, the results were validated according to seasonal salinity and turbidity data obtained from previous studies at the site (Soczka Mandac *et al.*, 2014; Soczka Mandac & Faganeli, 2015). Evaporation, precipitation and other freshwater inputs were neglected either due to short duration of simulations or the lack of representative data. The input data is presented in Table 1.

Short-term simulations (24 h) were performed for two events with relatively high river discharge (8th June 2011 and 21st March 2013). The daily mean river discharges Rižana – Q_r and Badaševica – Q_b (Hydrological data in Table 1) were calculated from data measured by the Slovenian Environment Agency at stations Kubed 2 (Rižana – Q_R) and Šalara (Badaševica – Q_B) (ARSO, 2014a), and used in the simulations. Wind speed and direction (ARSO, 2014b) in the performed simulations were averaged over 24-hour intervals (meteorological data in Table 1) and used as constant in time and uniformly distributed over the bay. Measured riverine temperature (T), salinity (S) and turbidity data (concentration of TSS - inorganic) from sampling sites R and B (Fig. 1 and Table 1) were also used in simulations.

During the first event, Rižana river discharge rate (Fig. 2A) showed a rapid increase of river discharge with a peak Q_R = 31.1 m^3 s^{-1} between 8th and 9th June 2011, which occurred during the survey campaign. The estimated daily mean river discharge was 21.5 m^3 s^{-1} and the mean river discharge during the survey was (30 m^3 s^{-1}), slightly below the maximum. During the survey period, the Badaševica river mean discharge was Q_b =1.6 m^3 s^{-1} with 2.2 m^3 s^{-1} peak before the start of the survey

Table 1. Meteorological and hydrological input data for the PCFLOW3D model

	W_v	W_d	Q_r	Q_b	ISS_r	ISS_b	T_r	T_b	S_r	S_b
date	(m s^{-1})	(°)	(m^3 s^{-1})	(m^3 s^{-1})	(mg l^{-1})	(mg l^{-1})	(°C)	(°C)		
8th June 2011	1.72	188	21.5	1.4	60	20	19.3	19.4	14	14
21st March 2013	1.45	221	18.9	1	30	0.5	9	9	14	14

Data source: ARSO and Harpha Sea, d.o.o. Koper.

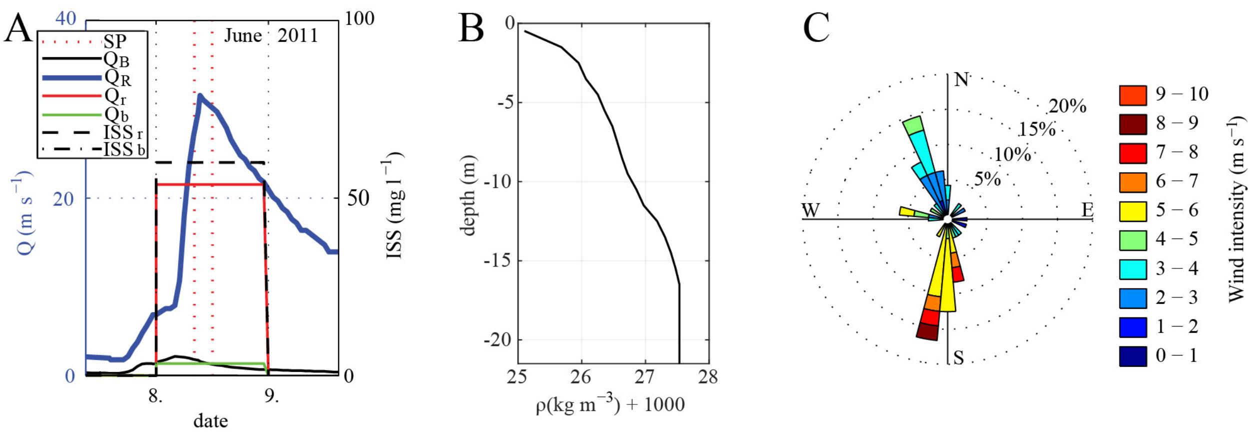

Fig. 2: Rižana and Badaševica river hourly (Q_R and Q_B) and daily mean (Q_r and Q_b) discharge with related inflow concentrations of ISS (ISS_r and ISS_b) (a). Density profile (b) and wind direction and velocity applied (average wind velocity of 1.7 m s^{-1} 188°) during the high-discharge event 8th June 2011 (c) (ARSO, 2014a).

(Fig. 2A). The Badaševica daily mean discharge was 1.4 $m^3\ s^{-1}$ (Fig. 2A) and the evaluated ISS inputs of Rižana (ISS_R) and Badaševica (ISS_B) were 60 mg l^{-1} and 20 mg l^{-1} (Table 1), respectively. The density profile (Fig. 2B) shows the water column stratification obtained from the T and S (Table 2) used as input values in the model. During the survey (4 h) the mean wind force was 5.3 m s^{-1} and mean direction 256°. Slightly different wind direction (188°) and speed (6 m s^{-1}) were used as input values for the model (Table 1 and Fig. 2C). During the episode of 21st March 2013, the maximum Rižana river discharge was Q_R= 26 $m^3\ s^{-1}$, lower than the June 2011 episode. The river discharge dynamics were also different; Fig. 3A shows a decreasing river discharge rate (Q_R) before and after the measurement campaign. In the model we used the daily mean rates Q_r = 18.9 $m^3\ s^{-1}$ and Q_b = 1 $m^3\ s^{-1}$ provided by ARSO (2014a) (Fig. 3A). During the survey, the wind velocity reached 3 m s^{-1} with direction 218°, while the daily mean wind velocity was 1.5 m s^{-1} with direction 221° (Fig. 3C). Strong stratification was present in the top 3 m of the water column (Fig. 3B).

Particle grain size parameters for the sediment transport module were acquired on 21st March 2013 from a water sample taken at the mouth of the Rižana River, when the TSS mass on the filter was sufficient to perform the grain size analysis. The mean particle diameter D_{50} = 6.8 µm and the diameters D_{16} = 1.9 µm; D_{84} = 37.4 µm and D_{90} = 70 µm were used in performed simulations. The density of dry sediment taken into account was 2760 kg m^{-3}, and the adopted average porosity in the top sediment layer was 0.5.

High stratification with a pronounced pycnocline ($\Delta\rho$= 2.5 kg m^{-3}) is evident in the surface layers (0.5 to 4.5 m). The initial temperature (T) and salinity (S) data for individual layers were obtained from horizontally averaged data in the vertical profiles of spatial measurements on the selected days (Table 2); thus, different but uniform distribution of salinity and temperature in the model layers were used as the initial data.

Table 2. Vertical profiles of temperature (T) and salinity (S) in each layer.

Date	8th June 2011		21st March 2013	
Depth (m)	T (°C)	S	T (°C)	S
0.5	20.34	35.58	10.26	29.77
1.5	19.76	36.12	10.11	36.03
2.5	19.31	36.32	10.01	37.02
3.5	18.99	36.36	9.93	37.24
4.5	18.61	36.48	9.80	37.41
5.5	18.38	36.54	9.69	37.50
6.5	18.04	36.59	9.62	37.57
7.5	17.76	36.6	9.58	37.63
8.5	17.49	36.61	9.56	37.68
9.5	17.19	36.63	9.56	37.71
10.5	16.71	36.66	9.56	37.76
11.5	16.39	36.71	9.56	37.80
12.5	15.78	36.80	9.56	37.84
13.5	15.58	36.90	9.55	37.90
14.5	15.20	36.91	9.52	37.95
15.5	14.94	36.93	9.51	37.96
16.5	14.74	36.95	9.51	38.00
17.5	14.74	36.95	9.51	38.06
18.5	14.74	36.95	9.56	38.12
19.5	14.74	36.95	9.56	38.12
20.5	14.74	36.95	9.56	38.12
21.5	14.74	36.95	9.56	38.12

Data source: Harpha Sea, d.o.o. Koper.

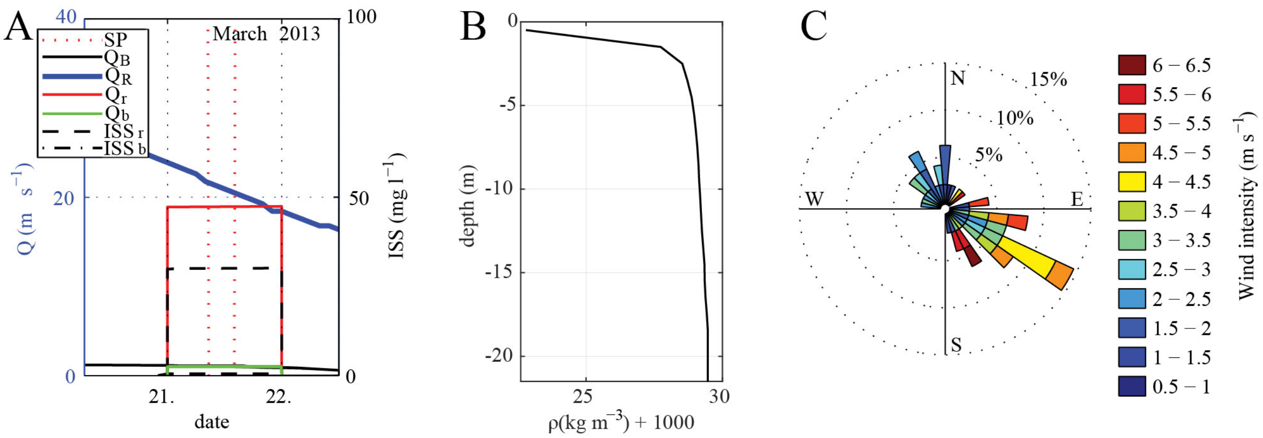

Fig. 3: Rižana and Badaševica river hourly (Q_R and Q_B) and daily mean (Q_r and Q_b) discharge with related inflow concentrations of ISS (ISS_r and ISS_b) (a). Density profile (b) and wind direction and velocity applied (average wind velocity of 1.5 m s^{-1} 221°) during the high-discharge event 21st June 2013 (c) (ARSO, 2014a).

Model calibration and validation

The main goal of the performed simulations was to obtain spatial distribution of riverine suspended solids concentrations after the short flood-events (24 h). We used the quasi-steady state approach, which has been applied in similar simulations (Četina *et al.*, 2000; Žagar *et al.*, 2001; Žagar *et al.*, 2007). The model was calibrated at two river discharge rates, on 8th June 2011 and 21st March 2013, when the discharges of the Rižana reached 21.5 $m^3 s^{-1}$ and 18.9 $m^3 s^{-1}$, respectively. The ISS concentrations at the river mouth on 8th June 2011 and on 21st March 2013 were 60 mg l^{-1} and 30 mg l^{-1}. Due to the lack of data on the composition of the treatment plant effluent and (mostly organic) suspended material from this source, only the inorganic part of the total suspended solids was considered as riverine discharged suspended matter.

The hydrodynamic and sediment transport simulations were calibrated using measured data from the first event (June 2011) by varying the dimensionless vertical diffusivity coefficient in the Smagorinsky turbulence closure scheme in the range $0.005 < C_{smaV} < 1$. Acceptable stability of simulations and agreement with measurements were achieved using $C_{smaV} = 0.1$, which was used in all further simulations. Using the calibrated model we performed simulations of high river discharge events and with seasonally averaged input data. An additional comparison between simulations and measurements during high-discharge events was performed in the three profiles in the BoK (Fig. 1).

Beside visual comparison of the simulated and measured results we applied the standard statistics: r and R^2, RMSE and standard deviation, as well as Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) and Percent bias (PBIAS, Gupta *et al.*, 1999) were calculated.

Results

8th June 2011 episode

Surface velocity fields in the simulation of high river discharge (Fig. 4B) clearly reveal the impact of river inflow on surface currents. The inflow-driven currents are evident within the second port basin, near the basin's mouth. They are less prominent but still visible at the Badaševica river mouth. These currents are not significantly affected by relatively weak wind forcing (average wind speed <2 m s^{-1}). Velocity profile (Fig. 5) shows the currents along the water column in the profile P2 with a distinct Ekman's spiral. Similar current velocity profiles were observed in all performed simulations.

Horizontal distribution of measured ISS is plume shaped (Fig. 4A) with minimum concentrations ~5 mg l^{-1} in the western part of the BoK and the maximum ~90 mg l^{-1} at the Rižana river mouth. High ISS concentrations were observed in the second basin of the port of Koper with strong gradient towards the entrance of the basin, ~35 mg l^{-1} km^{-1}.

Simulated ISS concentrations were generally lower compared to the *in-situ* measurement (PBIAS = 6.9), with relatively good general agreement (r = 0.90, R^2 = 0.80, NSE = 0.81) as shown in Fig. 4C. The simulated ISS concentrations near the Rižana river mouth are significantly lower compared to measurements with maximum deviation -43.7 mg l^{-1} in this zone (Fig. 4C). Agreement in the vast majority of individual cells in the surface layer was, however, within the range between -10 and 5 (mg l^{-1}), with about 50% values with less than 5 mg l^{-1} discrepancy (Fig. 4D).

Salinity and ISS in profiles display relatively good visual and statistical agreement (Table 3 and Fig. 6), with

Table 3. Statistics in the profiles (Fig. 6) on 8th June 2011; ΔMIN and ΔMAX depict minimum and maximum discrepancy, respectively.

Parameter	P3 Sal	P2 Sal	P1 Sal	P3 ISS	P2 ISS	P1 ISS
r	0.91	0.99	0.99	0.54	0.97	0.97
R^2	0.74	0.97	0.98	0.23	0.93	0.89
ΔMIN	-0.32	-0.40	-0.57	0.12	-0.29	0.00
ΔMAX	0.31	0.76	2.25	0.20	4.68	33.05
RMSE	0.17	0.26	0.78	0.13	1.32	12.69
STD	0.14	0.26	0.82	0.02	1.12	9.42
NSE	0.68	0.96	0.98	0.84	0.92	0.63
PBIAS	28%	14%	15%	27%	36%	64%

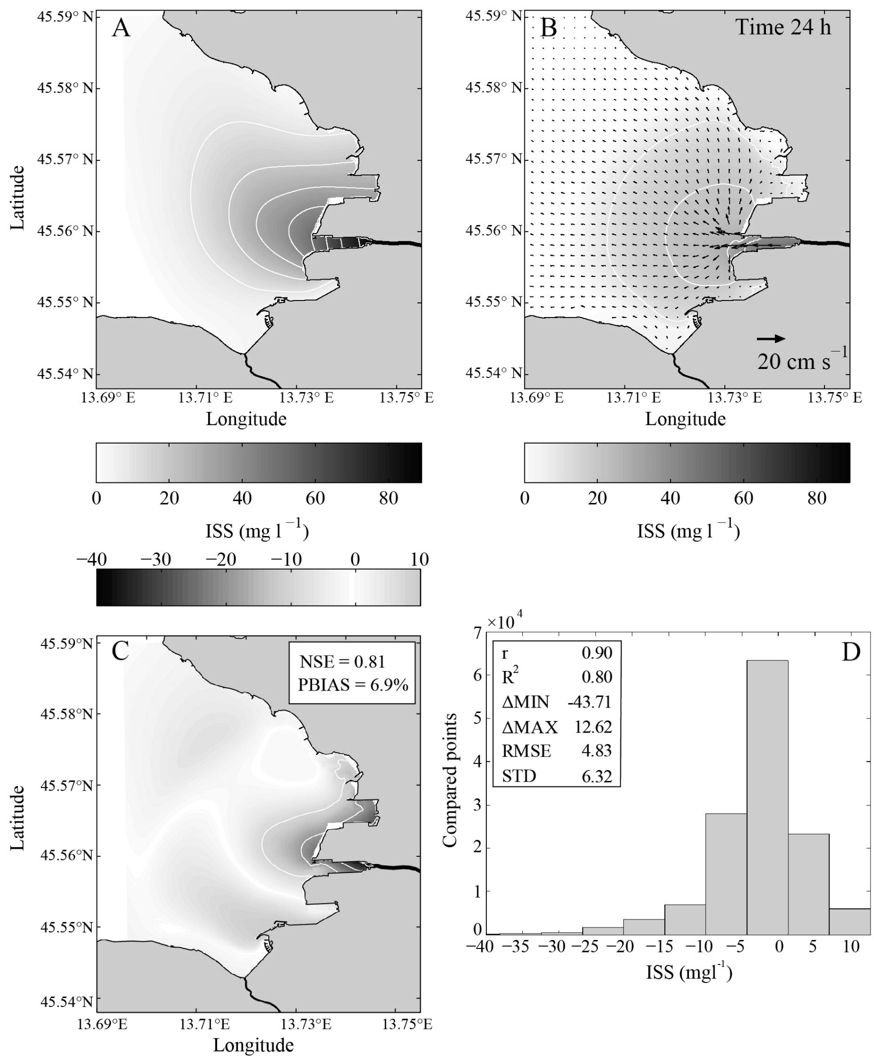

Fig. 4: ISS distribution in the surface layer on 8th June 2011: measurements (a) and model simulation – average velocities and ISS distribution (b). Spatial map of discrepancies between model and measurements (c) and ranging of cells with regard to discrepancies (d); ΔMIN and ΔMAX depict minimum and maximum discrepancy, respectively.

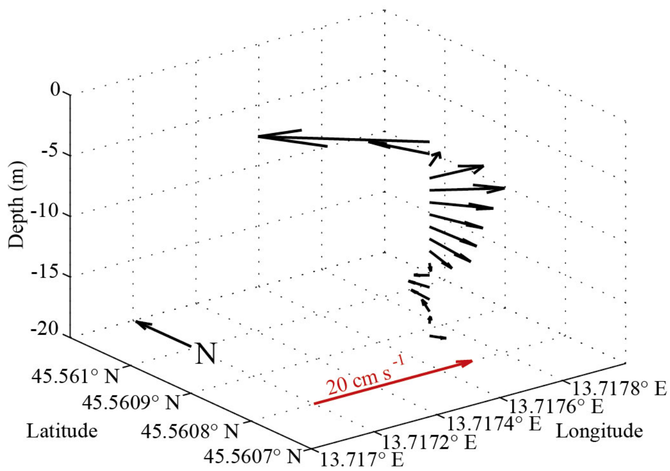

Fig. 5: Velocity profile at comparison site 2 after a 24-hour simulation on 8th June 2011.

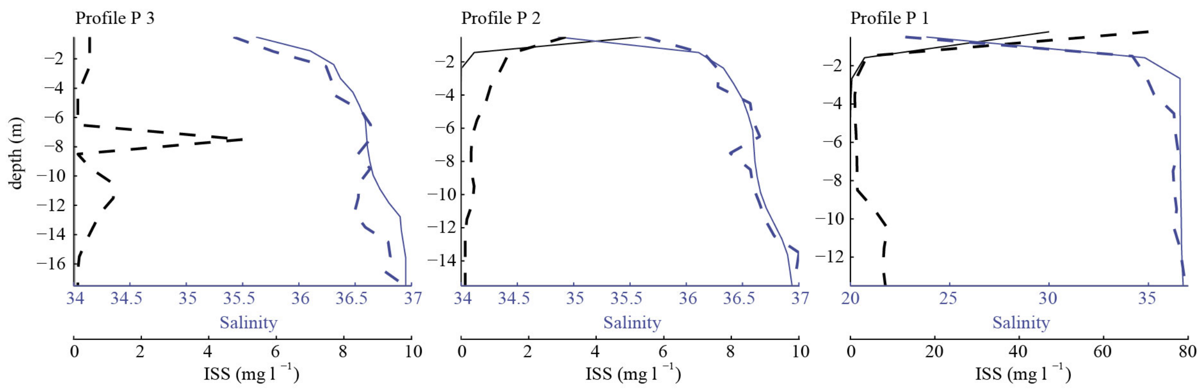

Fig. 6: Salinity and ISS profiles after 24-hour simulation at the comparison sites (P1- right, P2-center and P3-left); the event on 8th June 2011.

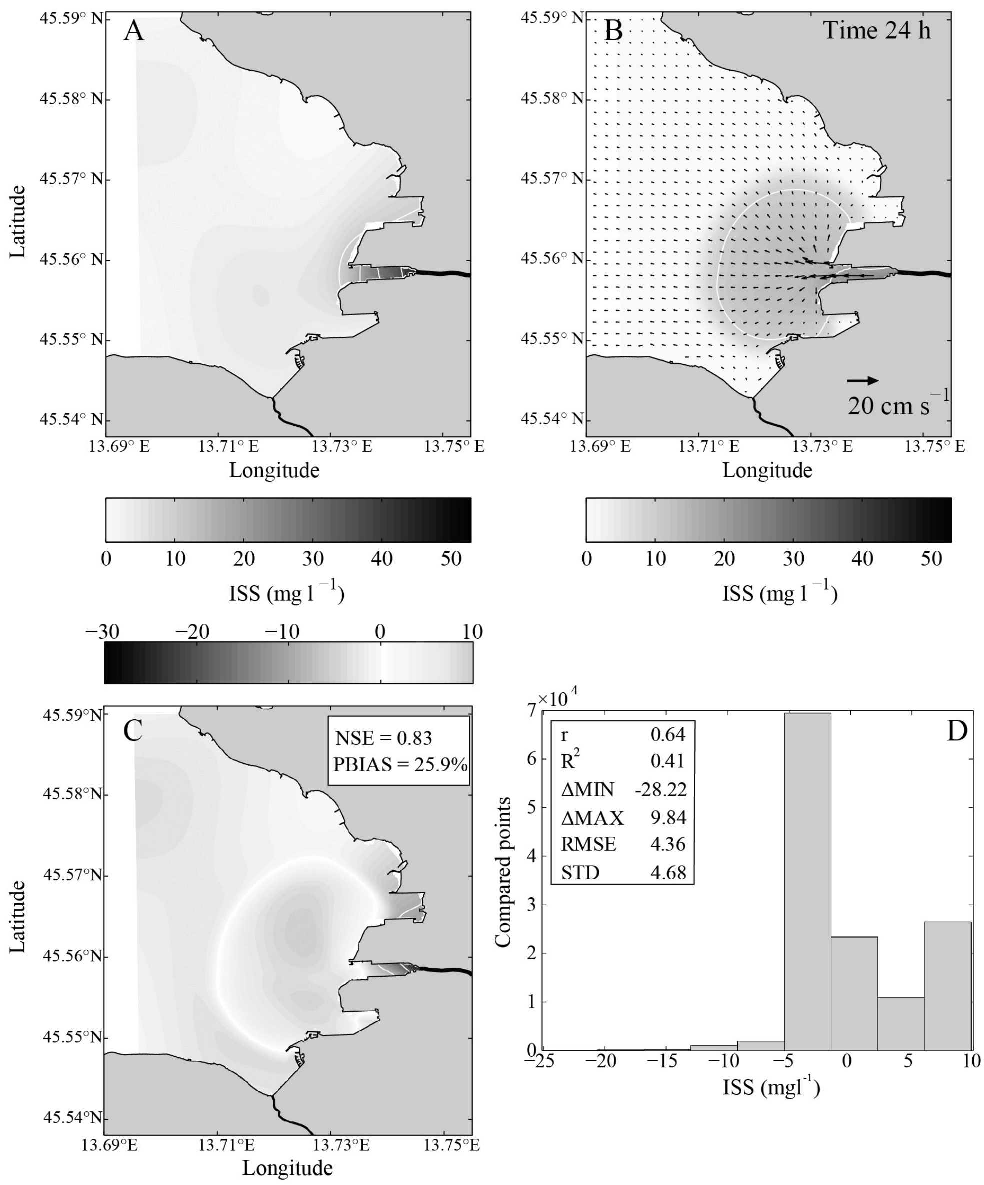

Fig. 7: ISS distribution in the surface layer on 21st June 2013: measurements (a) and model simulation – average velocities and ISS distribution (b). Spatial map of discrepancies between model and measurements (c) and ranging of cells with regard to discrepancies (d); ΔMIN and ΔMAX depict minimum and maximum discrepancy, respectively.

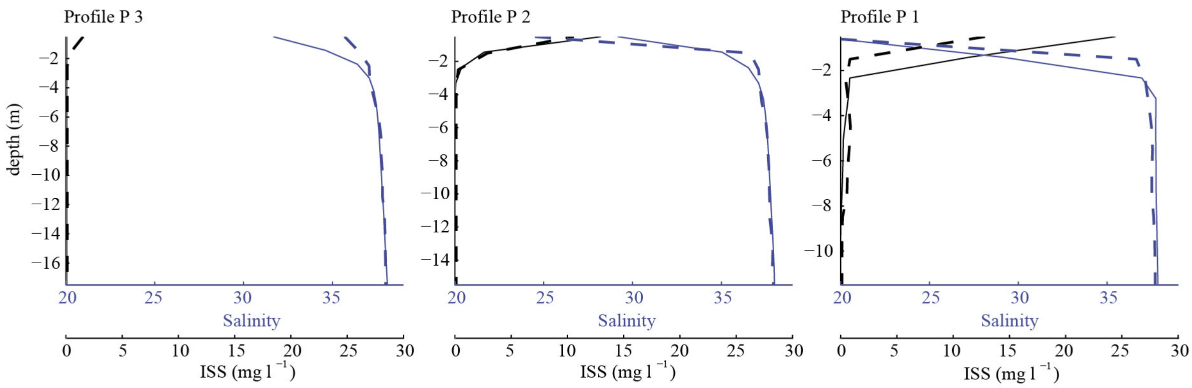

Fig. 8: Salinity and ISS profiles after 24-hour simulation at comparison sites (P1- right, P2-center and P3-left); the event on 21st June 2013.

low r = 0.54 and R^2 = 0.23 in P3 but acceptable NSE and PBIAS values in all profiles. Maximum ISS difference (33 mg l^{-1}) was observed in the surface layer near the river mouth in the profile P1. Increased ISS concentrations below 8 m in P1 and the peak in the 6-8 m layer in P3 are most probably an aftermath of another event (e.g., maritime traffic) that increased turbulence at that depth. At P2 the agreement of ISS at the surface is excellent (ΔISS < 0.3 mg l^{-1}) with the mean difference along the water column ~0.8 mg l^{-1}. Good agreement of salinity was also found in P2 (Fig. 6, Table 3).

21st March 2013 episode

The spatial analysis of ISS distribution (Fig. 7A) shows lower concentrations (<10 mg l^{-1}) in the open part of the BoK. Again, higher ISS concentrations (~50 mg l^{-1}) were measured in the second basin of the port. These were expected, due to a prolonged precipitation period before the survey campaign. The model results (Fig. 7B) show lower concentrations in the port basin and relatively higher at the entrance of the second basin. ISS distribution is plume shaped in comparison to the measurements limited within the region of fresh water influence. Comparison of ISS in individual cells (Fig. 7D) again reveals an underestimation of concentrations (PBIAS > 0) with the majority of cells' discrepancy ranging between -5 and 0 mg l^{-1}, and the rest mostly within 0 and 10 mg l^{-1}. Maximum discrepancies (~-30 mg l^{-1}) were found in the second basin near the river mouth and in the north-eastern part (third basin) of the port (-13 mg l^{-1}, Fig. 7C). About 10 mg l^{-1} higher concentrations in comparison to measurements were observed in the central part of the simulated river plume. The NSE = 0.83 and PBIAS ~ 26% values together with lower r = 0.64 and R^2 = 0.41 reveal somewhat lower, but still acceptable, agreement of the modelling results. Better agreement between the salinity and ISS distribution was, however, observed in profiles (Fig. 8, Table 4). The mean salinity difference was ΔSal = 1.2 and ΔSal = 5.4 was observed throughout the water column and in the surface layer. The agreement in ISS concentrations was excellent (r = 0.99 and R^2 = 0.97), particularly in P2 (ΔISS = 0.2 mg l^{-1}). The maximum observed difference was 1.34 mg l^{-1} in the surface layer.

Table 4. Statistics in the profiles (Fig. 8) on 21st March 2013; ΔMIN and ΔMAX depict minimum and maximum discrepancy, respectively.

Parameter	P3 Sal	P2 Sal	P1 Sal	P3 ISS	P2 ISS	P1 ISS
r	0.96	0.97	0.92	/	0.99	0.92
R^2	0.59	0.48	0.85	/	0.99	0.85
ΔMIN	-0.05	-5.38	-0.86	0.12	-1.34	-11.48
ΔMAX	4.00	1.38	7.35	1.53	0.44	0.55
RMSE	1.05	1.44	2.35	/	0.35	3.65
STD	1.00	1.47	2.42	0.34	0.36	3.59
NSE	0.21	0.81	0.84	/	0.98	0.61
PBIAS	55%	67%	43%	/	4.6%	30%

Discussion

As mentioned in *Materials and Methods*, the third port basin was restricted and unavailable for taking measurements. There, the DIVA interpolation method showed the largest discrepancies, due to the increased distance between measurement locations (Soczka Mandac and Faganeli, 2005). Higher discrepancies in this part of the port were observed in simulations of both events. The major error evaluated in the third port basin exceeded 25% due to limited measurements in this zone. The observed differences to the model results in this part (Fig. 4C and 7C) were also relatively high (~20 mg l^{-1}); this could be connected to the DIVA extrapolations' higher concentrations near the NE coast. Nonetheless, as suggested by Soczka Mandac & Faganeli (2015), the results were found to be acceptable for application in studies connected to sediment transport in the Bay of Koper.

Concentrations of nearly cohesive suspended sediment are difficult to measure; particularly in high-discharge and coincident heavy weather conditions. Fewer measurements were performed at high river discharges, which suggests lower reliability of Eq. (1) in such conditions and a part of the discrepancies may stem from measurements and the applied interpolation method. The spatial analysis of measurements exhibited similar patterns of ISS distribution during both high-discharge events. Maximum ISS concentrations were measured within proximity of the river mouth and in the port basin. Significantly lower concentrations were identified in the open part of the bay, which suggest both dilution and settling/accumulation of ISS in the port basin. Some further discrepancies might have originated from the inflow of treated waters and (mainly organic) suspended matter from the municipal treatment plant.

Using any single-fraction sediment transport model results in the settling of a large part of ISS at the outflow to the sea, where the transport capacity decreases due to lower flow velocities. Furthermore, neither the variation of settling velocity due to flocculation nor the colloidal fraction, which tends to remain in suspension, can be simulated with single-fraction models. This is most likely the reason for poor agreement between simulations and measurements in the vicinity of the river mouth. Most probably from this also accounts for the higher ISS concentrations compared to the model that were found in the western part of the bay; a single-fraction model is not capable of simulating transport of small-size particles by the currents. Similar ISS distribution observed at the surface in both simulations suggests the application of an improved (multi-fraction) sediment transport model - in order to assess the distribution of finer fractions and at a greater distance from the river mouth with more accuracy. Qualitatively, the plume-shaped distribution of the ISS concentrations was expected and also observed and described in previous studies (Soczka Mandac & Faganeli, 2015). Furthermore, the vertical gradient of salinity in the major part of the water column was in reasonably good agreement with measurements, except for the uppermost layer. Nonetheless, the observed discrepancies of all parameters in the surface layer may be a consequence of the dynamics of water masses stemming from previous meteorological events, which cannot be taken into account in short-term simulations. Evaluation of the model using the statistical analyses in the surface layer revealed acceptable model efficiency (NSE > 0.8) and the aforementioned underestimation of ISS concentrations (PBIAS > 0). Figs 4C and 7C depict the area with the highest discrepancies in the vicinity of the river mouth while the number of cells with underestimated ISS is visible from Fig.s 4D and 7D. In their vast majority, the underestimation by the model is less than 5 mg l^{-1}.

Qualitatively, the trend of the simulated salinity and ISS in profiles fits the measurements at all sites in both examples. Quantitative agreement within a factor of 2, considering the intricate processes within the study site, is encouraging for a simplified sediment transport model performing short-term simulations. Statistically, five of the six profiles show acceptable agreement between measurements and simulations (NSE > 0). Underestimation of modelled ISS is, however, obvious: all PBIAS values are positive but decreasing with the distance from the river mouth. This again confirms the previously observed deficiency of the applied model for assessing fine sediment fractions, which remain in suspension for a longer time.

In previous studies of suspended sediment inflow involving rivers the PCFLOW3D results were either evaluated qualitatively (Rajar *et al*., 2000), or just the influence of hydrodynamics driven by different wind pattern was presented (Ramšak *et al*., 2013). Never before have the results been compared to a large set of measured data, and in this study we present the first quantitative analysis of the sediment transport module of the PCFLOW3D model. Taking into account all aforementioned prepositions and the complex behaviour of nearly cohesive sediments, we assume the agreement of the obtained results to be reasonably good.

The other studies on sediment transport available for the Adriatic Sea are either not connected to river inflows (Wang *et al*., 2007), or performed in different spatial and temporal scales (Harris *et al*., 2008). Furthermore, none of these studies reports a comparison with in-situ measurements. Research on sediment transport in a similar spatial scale was performed with the combined modelling tool ROMS – CSTMS (Regional modelling ocean system – Community sediment transport modelling system on Waipaoa Shelf, New Zealand (Moriarty *et al.,* 2014). The authors applied a multi-fraction sediment transport model and collected a significantly larger amount of input, calibration and validation data for a one-year period, which was also the interval of their simulation. Nonetheless, even this extremely comprehensive study is predominantly dedicated to morphology alterations due to erosion and sedimentation processes and does not report on distribution of suspended solids during short-term flood events. With regard to scale and quantity of measured data used in model calibration and validation, the present study represents a novelty in sediment transport modelling in the Adriatic area. Moreover, to our best knowledge modelling studies carried out on short term events with the aim of determining distribution of suspended solids in the water column have not yet been performed.

Conclusions

The spatial analysis of the two episodes showed high concentrations of ISS in the port basin near the river mouth and plume shaped patterns of distribution in the open part of the bay. The finding of this study depicts the impact of river discharge in the heavily modified coastal environment on the distribution of ISS concentration.

Relatively good visual and statistical correlations were found between measurements and modelling results. Agreement in salinity provides the basis for determination of the region of fresh water influence. Simulations of the ISS distribution compared to the measured turbidity confirmed the connection between high turbidity and low salinity.

Further research is needed to address the discrepancies of numerical modelling in the selected area of the Bay of Koper that can be attributed to several influences that affect the studied bay: impact of the open boundary, mass and heat fluxes at the interfaces, resuspension of sediment due to maritime traffic, and runoff of treated wastewater, being a few of them. Additional measurements and improvements of the model are therefore needed. In order to perform simulations with greater accuracy, initialization of the model is needed to provide relevant initial conditions throughout the computational domain. Furthermore, nesting of the Bay of Koper into coarser grid models of larger domains is necessary to provide better boundary conditions. Finally, a refined model grid and real time computations would enable the use of real time environmental monitoring data and enhanced model results.

Nevertheless, the results of this study confirm the potential of the applied methods and modelling approach for simulating inflow and transport of particulates and particle-bound pollutants in the costal sea.

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