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Simulation of pollutants spreading from a sewage outfall in the Rijeka Bay

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Abstract

Results from a 3D numerical simulation of wind-induced currents and pollution spreading from a sewage outfall are described. The goal was to predict seawater sanitary quality in the Rijeka Bay, Adriatic Sea. A sea motion model was coupled with a model of transport and chemical reactions of fecal coliforms (FC), fecal streptococci (FS) and dissolved oxygen. The selected simulation period of 36 hours following wastewater discharge was found to be sufficient for a significant extinction of bacteria. The simulation was carried out for eight wind directions and two intensities (moderate and high). Mesh convergence was obtained. Two mesh sizes were coupled: coarse, for the whole Bay, and fine, for the northern part of the Bay, close to the sewage discharge of the Rijeka city.

For all considered wind directions, the pollution plume with a concentration higher than 100 FC and 100 FS per 100 ml of seawater is conveyed mostly parallel to the coast in either north-west or south-east directions. The plume does not rise to the surface but stays at the depth of 10 to 20 meters. This is a consequence of the hydrodynamics of the Rijeka Bay: the *bora* wind carries the surface water layer out of the Bay through the Middle and Great Gates, while cold water enters the Bay from the layer below the thermocline. During the southern wind (*jugo*), the situation is reversed: warmer surface water enters the Bay through either the Middle Gate or the Great Gate, while cold seawater exits through the bottom layer, accumulating warmer seawater in the Bay.

The conclusion is that the Rijeka city sewage discharge Delta is well-designed, and the microorganism concentration is well within the suggested regulatory range. The discharge site is far enough from the coast, where local streamlines are mostly parallel to the coast, hence the elevated pollution concentration does not come close to swimming and recreational areas. Even if the discharge increases by 50%, which is unlikely in the near future, the pollution at beaches will stay within regulatory boundaries.

Keywords: Numerical simulation; MIKE 3; ROMS; ALADIN; fecal coliforms; fecal streptococci; Rijeka Bay.

Introduction

The knowledge of the atmospheric influence on water movement in semi-enclosed bays is used, among other factors, to analyze pollution from city sewage outfall discharge, pollution caused by ship accidents, oil spills and heat accumulation focusing primarily on recreational waters, beaches and protected infrastructure, such as aquaculture. Semi-enclosed basins are more vulnerable than open seas due to existing coastal pollution sources because of possibly slower water exchange rate with the open sea.

Marine pollution modeling techniques have been extensively studied since 1960 (Fisher *et al.*, 1979). Specialized modeling methods have been used to simulate pollutant dispersion from offshore outfall, including empirical and analytical methods, particle tracking method and numerical solutions for solving the advection-diffusion equations.

A thorough overview of other studies and their main findings on the topic of effluent dynamics, hydrodynamic simulation and the influence of currents and winds is given by Zhao *et al*., 2011. The paper reviews modeling techniques associated with simulation of wastewater dispersion discharged from offshore outfalls based on type of method and the physical process of ocean discharge, such as near-field and far-field modeling. The advantages and limitations of the major mathematical methods are analyzed, as well as their functionality and the availability of modeling software.

The identification of flow mechanisms in characteristic layers of sea water begins with measurements of sea currents and state variables such as temperature and salinity (Degobbis *et al.,* 1978; Ilić *et al.,* 1979). In the

Rijeka Bay (Fig. 1), a part of the northern Adriatic Sea, there are two periods of the year in which the difference in the direction and intensity of the sea currents is clearly expressed: a shorter, summer period and a longer, winter period (Ilić, *et al.*, 1978). In the winter period, the direction of the current is cyclonic, and in the summer it is anticyclonic (Legović & Sekulić, 1979; Orlić & Kuzmić, 1980). June and October may be considered as transitional periods between the two seasons.

Based on current measurements, the exchange of water between the Rijeka Bay and the northern Adriatic Sea was computed by Legović (1982). He found that the exchange time varies seasonally and identified only two seasons: summer and winter. During summer, the exchange takes a clockwise direction with the bulk of the flow in the surface layer above the thermocline. During winter, the exchange rate is counterclockwise, and it is two to three times stronger than during summer season. The resulting exchange time can vary as often as eleven times during the course of a year, from one week to eleven weeks. It is the shortest during mid-winter season and the longest during early summer season, as the same water crosses the Rijeka Bay three times.

However, the exchange rate of the existing water masses is not the same for the whole Bay (Jeftić *et al.*, 1980). The exchange rate in the northern and northwestern parts is slower than in the southern and southeastern parts of the Bay.

High ecological vulnerability of the Rijeka Bay is due to its geospatial characteristics as a semi-enclosed basin, existence of mariculture in its eastern part and fishing grounds throughout the Bay, but mostly in its eastern part (Degobbis *et al.*, 1978).

In our previous work (Ivić, *et al.*, 2017), a simulated one winter month of the sea surface current field in the Rijeka Bay was analyzed using Lagrangian coherent structures (LCSs) to assess the diffusion and chaotic advection of a passive pollutant (dye). LCSs were extracted by the Finite-Time Lyapunov Exponents (FTLE), hypergraphs, Lagrangian advection alone and advection-diffusion methods. The results showed relatively complex nonstationary flow dynamics. Areas with discontinuities in the FTLE fields were found along north-south and northeast-southwest directions, and they moved eastward.

Similarly, the hypergraphs method showed areas of attraction and areas of mixing that can be observed along mentioned stripes that stretch in the north-south and northeast-southwest directions. The inserted Gaussian pollutant moved in the same direction (northeast-southwest) with lateral diffusion, proportional to the turbulent diffusion coefficient.

The goal of our previous work (Mrša Haber *et al.*, 2018) was a quantification of wind influence on the dynamics of the Rijeka Bay sea motion, which is important for surface dispersion of the city sewage. We compared the effect of the *jugo* and *bora* winds to a calm period. The resulting simulations showed that the *bora* wind conveys surface water layer out of the Bay through the Middle Gate and Great Gate, while deep cold water enters the Bay through the same gates. During the southeastern wind (*jug*o) the situation was reverse: warmer surface sea water entered the Bay through the Middle Gate and Great Gate, while colder bottom sea water exited the Bay through the Middle Gate and Great Gate, accumulating warmer sea water in the Bay. In the case of no wind, the surface current vectors (at 0.5 m depth) were disordered and did not follow any particular pattern (starting from 16 July 2008 at 18:00) while the movement at 12 m, 24 m, 36 m, 48 m and 60 m showed a dominant flow from the western coast (of the island Krk) toward the eastern coast of the Istrian peninsula (cyclonal).

The dominant source of pollution within the coastal zone of the cities are sewage discharges, which contain microorganisms, some of which are pathogenic. Although these organisms are relatively short-lived in the sea, their presence indicates microbiological contamination resulting from untreated or partially treated municipal wastewaters (Steel & McGhee, 1979). The total coliforms, fecal coliforms (FC), fecal streptococci (FS), i.e., human-animal bacteria, are used as indicators of microbial pollution of the coastal sea. Coliform bacteria are pri-

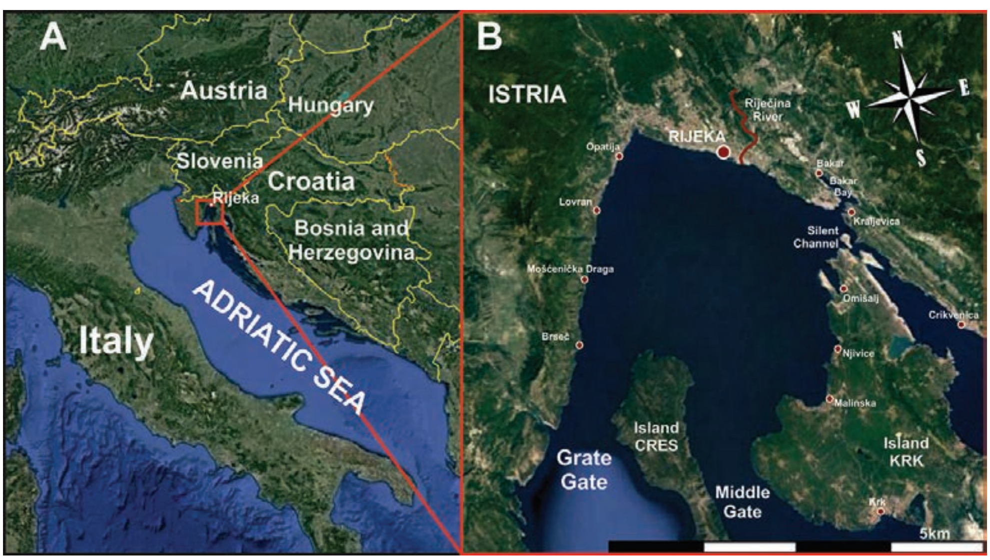

Fig. 1: (A) Adriatic Sea; (B) Rijeka Bay.

marily non-pathogenic, normally occurring in the lower intestinal tract of humans and warm-blooded animals and are responsible for proper food digestion. They enter the wastewater, and through a sewage outfall are transported into the natural waters. If the bacteria are present, they will also come along with coliform bacteria in waste and natural water, posing a danger to human health. Characterization of these bacteria is done by routine laboratory methods (membrane filtration, DPH 2014). Based on the number of bacteria, microbiological or sanitary quality of the sea is defined (OG, 2008).

The microbiological state of the sea at a particular location may vary considerably, depending on the meteorological conditions and hydrographic characteristics of the sea (wind, sea temperature, salinity, cloud cover, sea current, waves, etc.) and the way wastewater is discharged (discrete versus continuous discharge, daily and seasonal variations in the amount of wastewater) (Perović, 2003).

By entering into the sea, the concentration of indicator and pathogenic organisms is abruptly reduced due to physical (solar radiation, temperature), chemical (salinity, heavy metals, pH, xenobiotics, antibiotics and biotoxins) and biological (predation, parasitism) influences (Šolić & Krstulović, 1992; Šolić & Krstulović, 1997). Therefore, to determine the quality of the coastal sea, it is necessary to know the ecological and hydrodynamic processes.

Within the first phase of the Water Pollution Prevention Project in the coastal area (Andročec *et al.*, 2009), measurements of biological, chemical and physical variables were performed at several measuring stations in the Rijeka Bay. Following a numerical analysis using the MIKE 3 FM model in the Bay, the project concluded that the model may be accepted as verified but that the flow field dynamics analysis should be done in the subdomain of Rijeka Bay close to the submarine sewage outfall using a more detailed resolution. This is the scope of the present paper.

An overview of state-of-the-art published results in sewage spreading modeling has been published already, and we included the reference. The overview of results on the Rijeka Bay has not been published so far; hence, it is included in the paper. As for novelties and scientific contributions, the paper gives new insight into the sewage outfall pollution in the Rijeka Bay, its dynamics, diffusion and dispersion, its extent and influence on people's health and recreation. The paper is very important as an example that may be followed in other coastal areas.

Materials and Methods

The area of study

A three-dimensional simulation of wind-induced flow patterns was performed using the hydrostatic version of the MIKE 3 model. Hydrodynamic Reynolds-Averaged Navier-Stokes equations were solved on regular grids of square cells. The Rijeka Bay domain was covered by a finite differences grid with a 232 m by 165 m horizontal and 2 m vertical resolution. The time step was 20 seconds.

The modeled area covers the Rijeka Bay, located between the east coast of the Istrian peninsula, the north coast of the Rijeka city and the islands of Krk and Cres (Fig. 1). The area is about 500 km^2, and its volume is about 27 km^3. The average depth is 60 meters (Jeftić, 1982).

Prevailing winds blow from northeast (45°) and southeast (135°). The mean annual air temperature is 13 °C, with an absolute maximum of 36 °C and a minimum of -12 °C. The annual precipitation is about 1400 mm with the maximum in autumn and winter. The surface seawater temperature varies from 10.4 °C in the winter to 26.6 °C in the summer time. The bottom seawater temperature reaches its maximum of about 15 °C in October (Legović & Sekulić, 1979).

Models

To simulate the transport of substances from the source to the coastal sea, two approaches related to scale have been identified: near field and far field (Legović, 1997). If the source is a submarine outfall, in the near field one considers an area of up to 5 km around the discharge.

When the analysis is semi-analytical (Brooks approach), the total dilution is obtained as a multiplication of initial dilution, dispersion of wastewater in the sea and bacterial decomposition rate (Metcalf & Eddy, 1979).

In the MIKE 3 numerical models, factors such as bed friction, eddy viscosity, flood and dry, major rivers inflow, and water outflow through the Rijeka Bay, wind stress and atmospheric pressure at the sea level, precipitation, evaporation and the Coriolis force were included (Sharbaty, 2012).

The far field model consists of continuity, momentum, temperature, salinity and density equations with a turbulent closure scheme. The density does not depend on pressure, just on temperature and salinity. The following boundary conditions were adopted: sea height, salinity and temperature fields calculated on open boundaries using the Regional Ocean Modelling System (ROMS) (Shchepetkin & McWilliams, 2005) simulation on a larger domain of the Adriatic Sea, taken from Andročec *et al.,* (2009). No slip condition was set on coastal boundaries. Besides the sea level, the forcing of the sea flow was also made by momentum, heat and water fluxes at the air-sea interface. These were calculated using surface wind, air humidity and temperature extracted from the ALADIN atmospheric simulation model (ALADIN 1997; Tudor *et al.,* 2013) with an 8 km space and 3 hour time resolution.

The Navier Stokes equations (continuity and momentum equations) describe the water dynamics in the MIKE 3 model. The local continuity equation is given by:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

where x, y and z are Cartesian coordinates; u, v and w are the corresponding fluid velocity components; and *S* is a discharge due to point sources.

Two horizontal momentum equations for the x and y components are:

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(v_t\frac{\partial u}{\partial z}\right)+u_s S$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^{\eta}\frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right)+v_s S$$

where t is the time; η is the surface elevation measured from the still water position; d is the still water depth; $h=\eta+d$ is the total water depth; $f=2\Omega\sin\varphi$ is the Coriolis parameter (Ω is the angular rate of revolution and φ the geographic latitude); g is the gravitational acceleration; ρ is the density of water; ν_t is the vertical turbulent (or eddy) viscosity; p_a is the atmospheric pressure; ρ_0 is the reference density of water; S is the magnitude of the discharge due to point sources; and (u_s, v_s) is the velocity at which water is discharged into the ambient water (Moharir, *et al.*, 2014; Warren & Bach, 1992). These two equations represent Newton's second axiom: the change in velocity is proportional to the resultant force. The horizontal stress terms are described using a gradient-stress relation, which is simplified to

$$F_u=\frac{\partial}{\partial x}\left(2A\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)$$

$$F_v=\frac{\partial}{\partial x}\left(A\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial y}\left(2A\frac{\partial v}{\partial y}\right)$$

where A is the horizontal eddy viscosity.

For the turbulence closure, the eddy viscosity concept was used: the Smagorinsky (1963) approach in the horizontal and *k-ε* model in the vertical directions, separately. The Smagorinsky (1963) approach, in which the sub-grid scale transports are represented by an effective eddy viscosity to a characteristic length scale, was adopted to calculate the horizontal eddy viscosity. The sub-grid scale eddy viscosity (A) was calculated as follows:

$$A=c_s^2 l^2\sqrt{2S_{ij}S_{ij}}$$

Here, c_s is a constant and l is the characteristic length scale. The deformation rate is given by

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)(i,j=1,2)$$

In the *k-ε* model the eddy viscosity is derived from turbulence parameters k and ε as follows:

$$v_t=c_\mu\frac{k^2}{\varepsilon}$$

where k is the turbulent kinetic energy per unit mass (TKE); ε is the dissipation of the TKE; and C_μ is an empirical constant.

Temperature (T) and salinity (s) are modeled by general advection-diffusion equations:

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z}=F_T+\frac{\partial}{\partial z}\left(D_v\frac{\partial T}{\partial z}\right)+H+T$$

$$\frac{\partial s}{\partial t}+\frac{\partial us}{\partial x}+\frac{\partial vs}{\partial y}+\frac{\partial ws}{\partial z}=F_s+\frac{\partial}{\partial z}\left(D_v\frac{\partial s}{\partial z}\right)+s_s S$$

where D_v is the vertical turbulent (eddy) diffusion coefficient. H is a source term due to heat exchange with the atmosphere. T_s and S are the temperature and the salinity of the source. F_T and F_S are the horizontal diffusion terms defined by:

$$F_T=\left[\frac{\partial}{\partial x}\left(D_h\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_h\frac{\partial}{\partial y}\right)\right]T$$

$$F_S=\left[\frac{\partial}{\partial x}\left(D_h\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_h\frac{\partial}{\partial y}\right)\right]s$$

where D_h is the horizontal diffusion coefficient.

The boundary conditions are defined by the given 2D velocity and temperature fields at open boundaries with zero velocities at the sea bottom, 1D sea level and pressure on the free surface.

To integrate the equations, the method of finite differences was used on three horizontal nested numerical meshes: coarse mesh (165 m by 232 m), medium mesh (55 m by 77 m) and, for the area close to the coast and the submarine outfall, fine mesh (18.3 m by 25.8 m). The vertical mesh size was 2 m for all meshes. The time step was 20s. The numerical integration method is described in DHI (2008).

A simulation period of 36 hours was used following the discharge of the pollution plume. The period was considered to be sufficient for a significant extinction of bacteria. For the wind spectra typical for the Rijeka Bay, and for two intensities, moderate and high, the forcing of sea flow with real boundary and initial conditions was taken from meteorological predictions and measurements. The wind shear was calculated assuming a balance between the wind shear and the water shear at the surface (DHI, 2008).

The mesh convergence was obtained with the conclusion that it was sufficient to work with two mesh sizes: coarse, for the whole Bay, and medium, for the north part of the Bay, close to the sewage discharge and the Rijeka city. The medium mesh was about three times smaller in step size: 55 m in the equatorial and 77.33 m in the meridional directions.

The medium mesh is nested in the coarse mesh and covers only the northern part of the Rijeka Bay (Fig. 2). The simulations were forced with water inflow through the sea boundaries: the Middle and the Great Gates, the selected wind, heat flux and humidity at the sea surface. The small opening between the northern coast and the Krk island (Silent channel, Fig.1) was not treated as an open boundary due to a very small water exchange.

At the open boundaries, the sea level, salinity and temperature fields were obtained by running the ROMS (Shchepetkin & McWilliams, 2005) and were taken from Andročec *et al.,* 2009.

The Delta sewage outfall

The dominant pollution source in the Bay consists of a sewage discharge called Delta, i.e., release from the

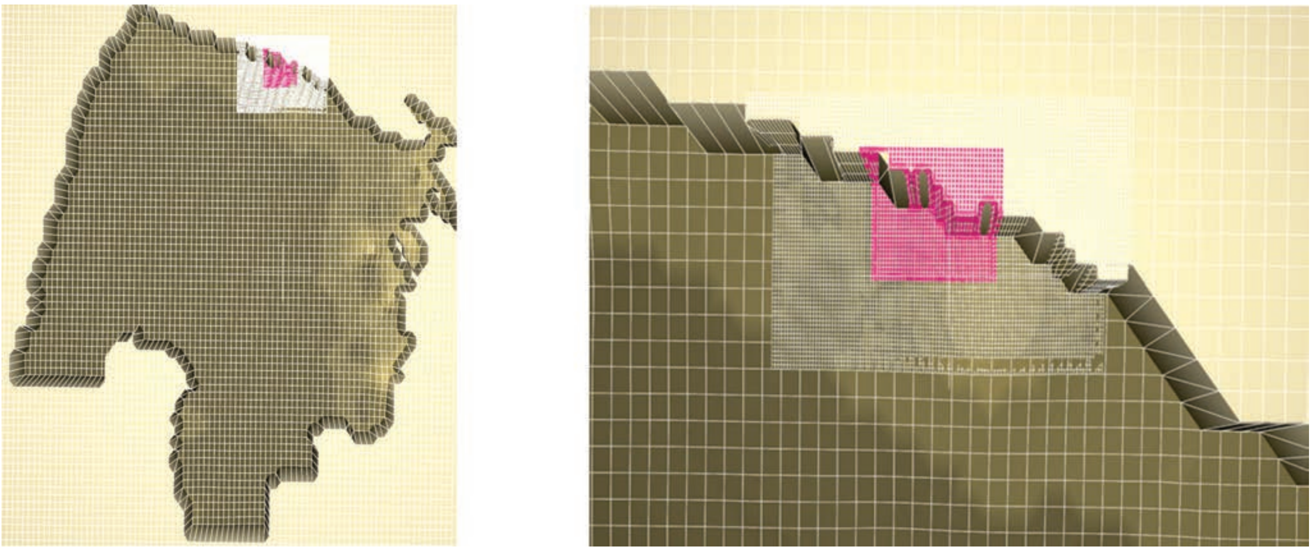

Fig. 2: The Rijeka Bay area covered by the three numerical meshes: coarse (gray), medium (white) and fine (pink). Left: the whole domain. Right: a detail of the domain around the sewage discharge point. The black dot represents the submarine outfall.

submarine outfall. The wastewaters of the Rijeka city are brought to the Delta site, where they are purified using coarse and fine grids and aerated sandbags. Then, the wastewater is discharged from the dive pool into the submarine outfall of the following characteristics:

- the length of the submarine pipeline is 500 m, 48 m of which is the diffuser length;
- the diameter of the underwater pipeline is 1100 mm while the diffuser has the diameter of 700 mm;
- the depth at the end of the discharge is 40.2 m, while the discharge head is raised from the sea floor for 2 m.

The input data of the pollution spreading simulation are the intensity of the source and the concentration of FC and FS. The inflow during a typical day without precipitation varies from 214 ls^{-1} to 370 ls^{-1}. The concentration of FC at the discharge is 5 million $(100\ ml)^{-1}$ and the concentration of FS is about 10 times smaller, i.e., 500 000 $(100\ ml)^{-1}$.

Wastewater from the Rijeka city enters the Delta sewage outfall and is released to the bottom of the Bay at 46 m below the surface. Depending on the composition of wastewater and the oceanographic conditions of the coastal sea, the pollution cloud is carried out through the domain volume.

The distance from the discharge to the closest boundaries of the coastal water intended for swimming and recreation is 1600 m towards east and 2900 m towards west. The submarine discharge of the Delta outfall drains up to 34500 m^3 of wastewater per day. Since this is by far the largest discharge of municipal wastewater in the Rijeka Bay, assessing its impact on sea quality is of great importance.

The seawater criteria for bathing and recreation have been enacted since 2008 by the Regulation on the Quality of Bathing Seawater (OG, 2008). According to the regulation, the microbiological quality indicators are intestinal enterococci and Escherichia coli.

Since in the two key monitoring campaigns FC and FS were measured as prescribed by the previous Regulation on Standards of Water Quality (OG, 1996), we used these data for verification. The regulation prescribes limit values in the amount of 100 bacteria per 100 ml of seawater. Since the parameters of both regulations are correlated, and the values of the older regulation correspond to the values of the newer regulation, meeting the requirements of the 1996 Regulation means meeting the requirements of the 2008 Regulation.

The seawater velocity field, salinity, temperature, microbial pollution (FC and FS as indicators of sanitary water quality) and dissolved oxygen (DO) in coastal area and whole of the Rijeka Bay are given as results of numerical simulations.

Numerical simulations of Rijeka Bay seawater hydrodynamics with submarine sewage (Delta outfall) pollution dispersion were performed using the MIKE 3 software for a variety of typical wind directions and intensities during the time period of 36 hours. The 90% extinction period for FC is 2.2 hours close to the sea surface (due to higher sunlight intensity) and 76.4 hours below the thermocline (Šolić & Krstulović, 1992).

The finest mesh covers the part close to the coast of the Rijeka city and the submarine outfall. The time step was 20 seconds. It was not necessary to further reduce the size of the mesh to the fourth level because the convergence was achieved with the second and third levels of the mesh resolution.

Results and Discussion

Figures 3 and 4 show that the FC concentration isosurface of 100 bacteria per 100 ml sea water is almost the same shape as the rough mesh (white edges), finer mesh (black edges) and the finest mesh (red edges). It was therefore concluded that it would be sufficient to work only with two meshes: coarse for the whole Bay and finer near the submarine outfall.

The sea surface current field was used for the period starting from 16 July 2008 at 18:00 and ending 18 July 2008 at 6:00. This time period was chosen because of

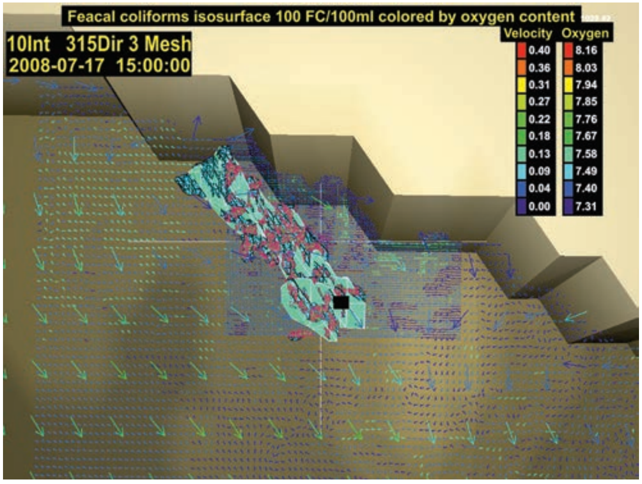

Fig. 3: Current vectors and FC plume concentration of 100 bacteria per 100 ml sea water colored by DO concentration on the three different meshes: coarse (white edges), finer (black edges) and the finest (red edges) for 315° wind direction and 10 ms-1 wind intensity. The black square represents the submarine outfall.

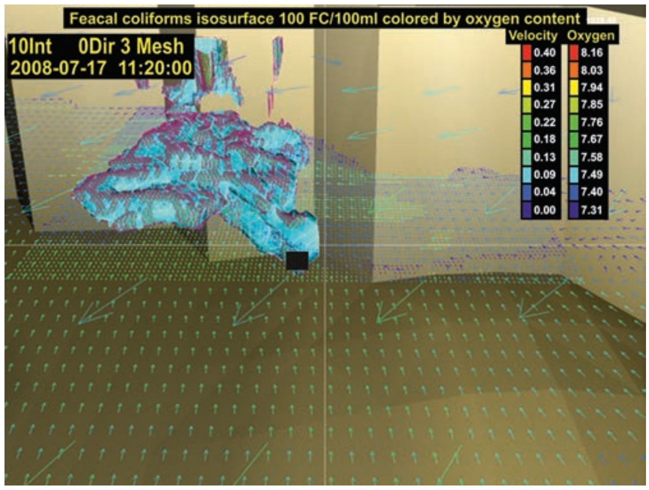

Fig.4: Current vectors and FC plume concentration of 100 bacteria per 100 ml sea water colored by DO concentration on the three different meshes: coarse (white edges), finer (black edges) and the finest (red edges) for 135° wind direction and 10 ms^{-1} wind intensity. The black square represents the submarine outfall.

available meteorological and hydrographic data.

The simulation was forced by interpolation of measured data on heat flow, humidity, wind direction and intensity at the water surface. Atmospheric forcing was obtained from ALADIN (Tudor *et al.*, 2013) with an 8 km spatial resolution and 3 h temporal resolution (which is regularly employed for meteorological modeling of atmospheric flow).

At the open boundaries, the Great and Middle Gates, the boundary conditions were: 1D sea levels and 2D current, salinity and temperature fields obtained by running the ROMS software for a larger north Adriatic Sea area. The two-dimensional DO concentrations were interpolated from measurement at nearby oceanographic sites.

Besides other parameters, the sewage outflow pollution is characterized by fecal coliform (FC) and fecal streptococci (FS) concentrations, which were taken from measurements (RL 2006, RL 2008). At the sewage outflow diffusor, the concentration varies during the day, but it is under 10^7 FC/100 ml and 10^6 FS/100 ml, respectively.

The sewage outflow pollution is characterized by two zones: near field and far field. In the near field zone the plume momentum is higher than the surrounding sea water fluid. In the far field zone the plume is practically passive with a momentum equal to that of the surrounding sea water. The pollution concentration for the beginning of the far field zone was calculated using measured data. After that, the passive advection by surrounding sea water and diffusion were simulated. The Cormix software (Akar & Jirka, 1994, 1995) was used to calculate the dilution (the ratio of pollution concentrations at the sewage outflow and at the end of near field zone). The calculated dilution amounted to 68.3.

Simulations were performed for the set of eight wind directions: N (0°), NE (45°), E (90°), SE (135°), S (180°), SW (225°), W (270°) and NW (315°); each for three constant wind intensities: 10 ms^{-1} (moderate winds), 30 ms^{-1} (hurricane winds) and the case of no wind.

In the following text we analyze the Rijeka Bay water dynamics for the most common winds, sirocco (*jugo*) and *bora*, and the influence of those winds on sewage plume path and spreading. The simulation results for the other six mentioned wind directions are given in a supplementary file as figures and video clips. The isosurface concentration of 100 FC per 100 ml, which is the limit value for the sea level of category 2 intended for bathing, was chosen to assess the impact of the sewage from the Rijeka city on the pollution of nearby beaches.

Water dynamics and pollution movement simulation analysis for the sirocco wind (135 °)

The current vectors at different depths – 0 m, 12 m, 24 m, 36 m, 48 m and 60 m – and at the moment of 16.5 hours after the forcing started, originate from a simulation using a coarse grid. The dominant current is the surface current from the direction of the Middle Gate (between the islands of Krk and Cres), which turns around the northern tip of the island of Cres, where it forms a local vortex, and exits through the Great Gate. The velocities in the remaining part of the Bay are much smaller.

This pattern is repeated for other depths, with lower velocities at a greater depth. Along the northern coast, including the location near the Rijeka city, velocities are small at all depths, and their direction is generally parallel to the coast, northwest to southeast and *vice versa*.

The following set of six figures shows an enlarged part of the flow close to the northern edge of the Bay near the Rijeka city and the Delta sewage outfall for two different meshes: coarse and fine and during the three-hour intervals.

Fig. 5 to Fig. 10 present simulation results for every 3 hours starting from the beginning of wind blowing until 33 hours after the start. Based on the time development

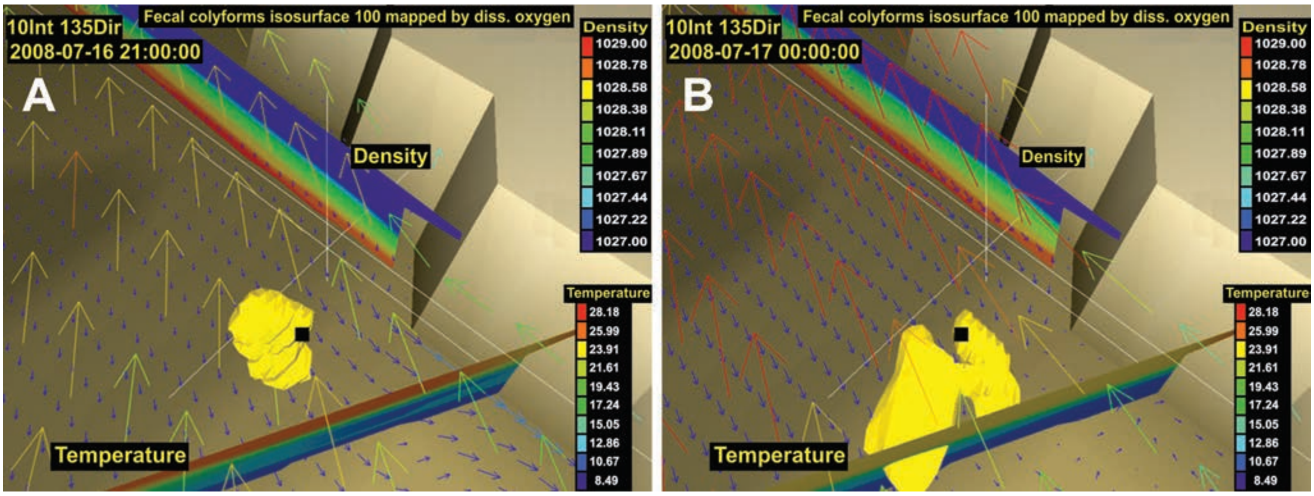

Fig. 5: Current vectors and the FC plume concentration of 100 bacteria per 100 ml sea water colored by DO concentration on three different meshes: coarse (white edges), finer (black edges) and the finest (red edges) for 0° wind direction and 10 ms^{-1} wind intensity. The black square represents the submarine outfall.

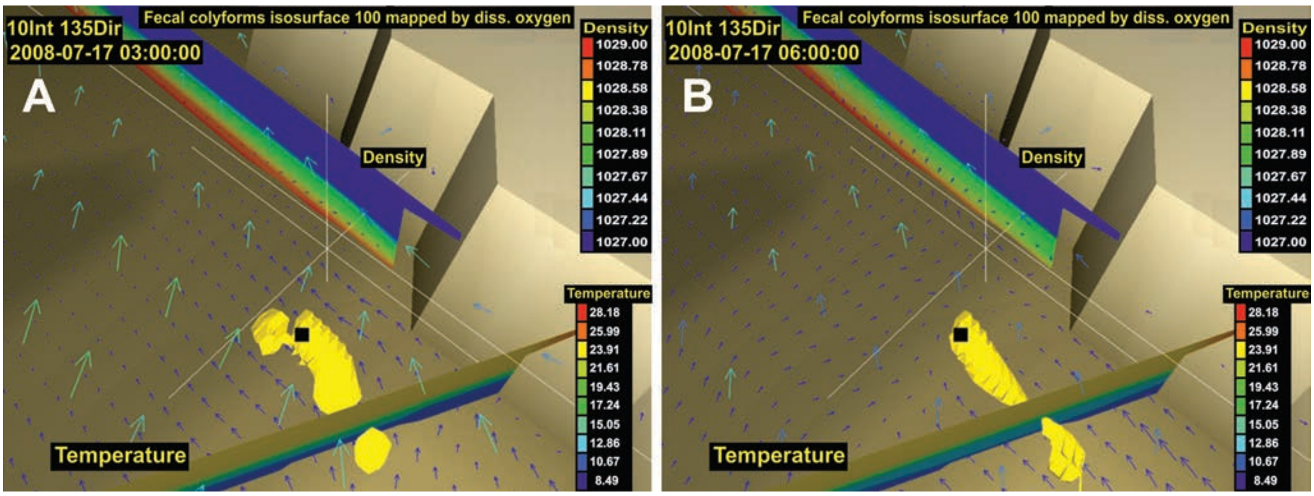

Fig. 6: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 0th (A) and 3rd (B) hours for wind intensity of 10 ms^{-1} from the direction of 135° is colored yellow.

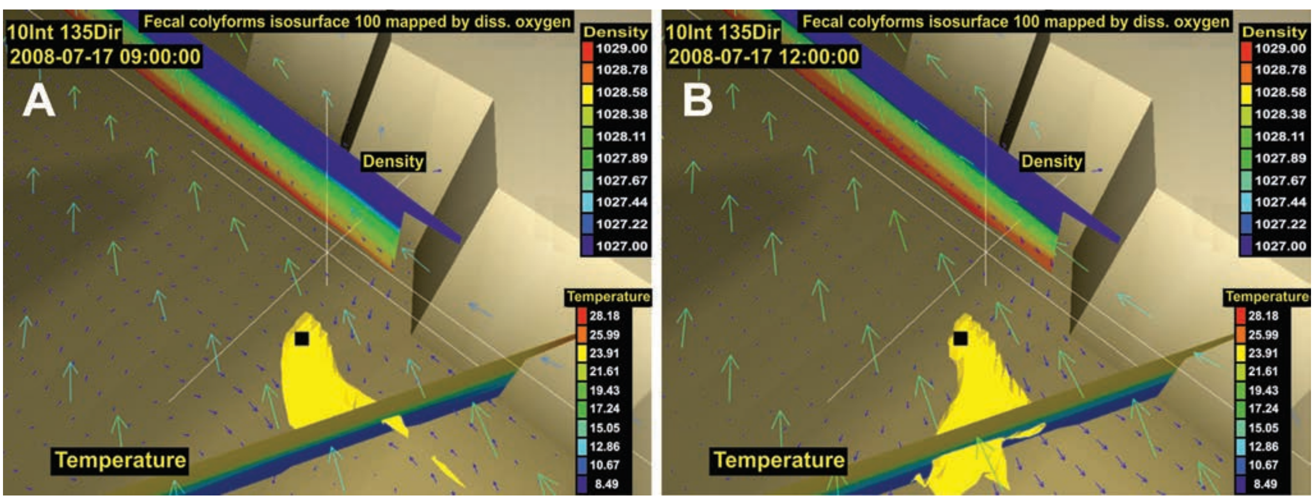

Fig. 7*:* Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 6th (A) and 9th (B) hours for wind intensity of 10 ms^{-1} from the direction of 135° is colored yellow.

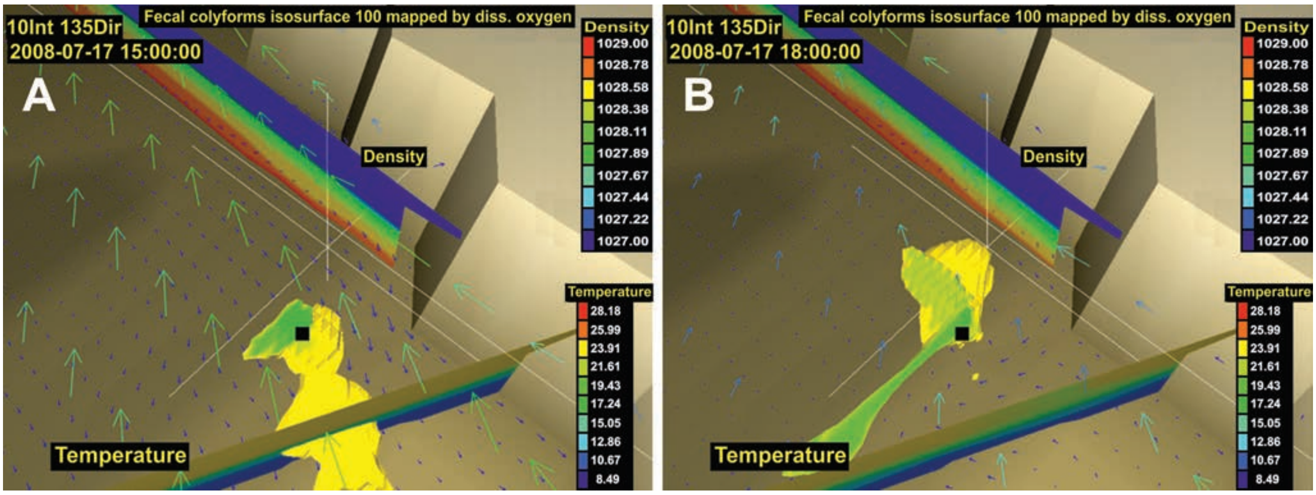

Fig. 8: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of $\geq$ 100 FC(100 ml)$^{-1}$ at 12th (A) and 15th (B) hours for wind intensity of 10 ms^{-1} from the direction of 135° is colored yellow.

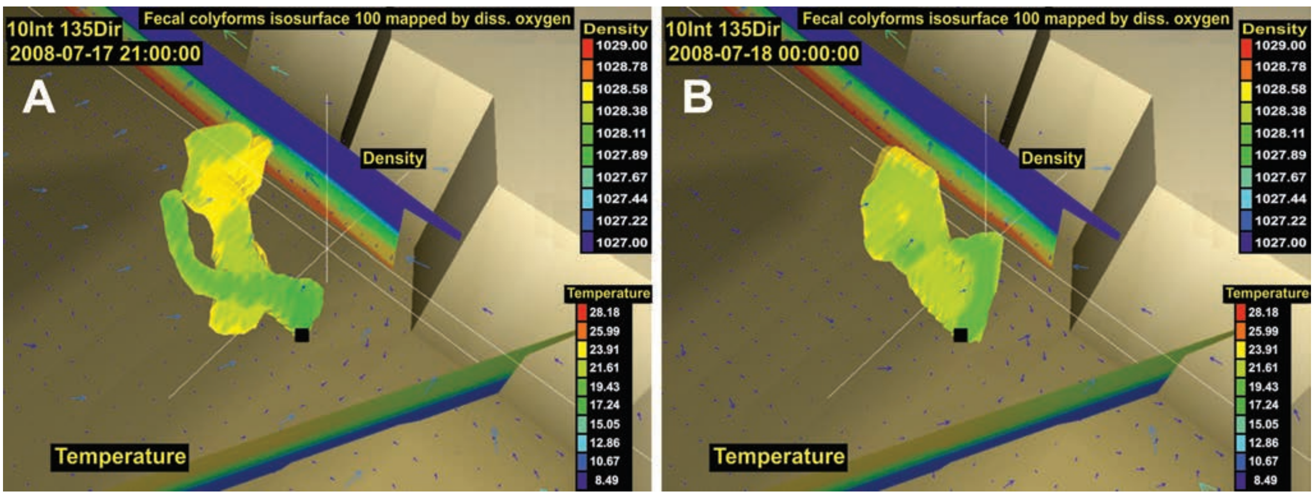

Fig. 9: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of $\geq$ 100 FC(100 ml)$^{-1}$ at 18th (A) and 21st (B) hours for wind intensity of 10 ms^{-1} from the direction of 135° is colored in yellow.

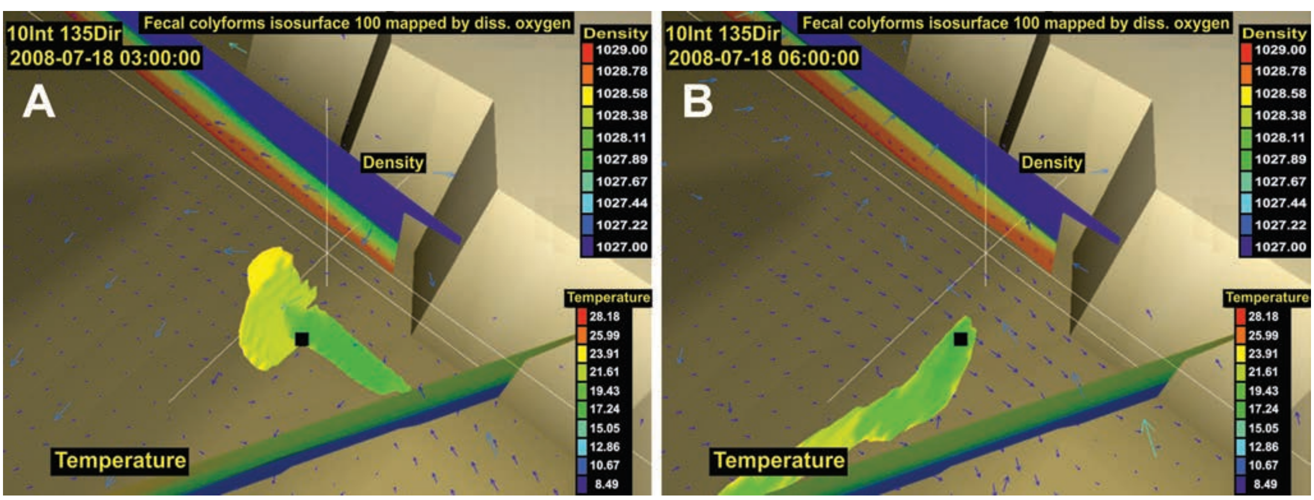

Fig. 10: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of $\geq$ 100 FC(100 ml)$^{-1}$ at 24th (A) and 27th (B) hours for wind intensity of 10 ms^{-1} from the direction of 135° is colored yellow.

of the flow and the motion of the pollution plume, it can be concluded that for the sirocco wind the surface field is mostly parallel to the coast. The pollution moves eastward, hence the direction of motion is caused by the deflection of the dominant current from the Middle Gate to the Great Gate. At a higher depth, pollution movement often has the same or almost the same direction. Sometimes it has an opposite direction from movement at the surface, but in all cases it is characterized by a much smaller current intensity.

The FC isosurface concentration of 100 bacteria per 100 ml is parallel to the coast, due to the current direction. It may be concluded that it does not reach the coast and it does not emerge on the surface but remains at a depth of about 30 m. This has also been confirmed by measurement campaigns (RL 2006, RL 2008).

Water dynamics and pollution movement simulation analysis for the bora wind (45 °)

The current vectors at different depths of 0 m, 12 m, 24 m, 36 m, 48 m and 60 m, and at the moment of 16.5 hours after the forcing started, originate from the simulation using a coarse grid.

The dominant surface current direction at 0 m and 12 m is oriented from north-east at the north coast of the Bay toward Middle and Great Gates, hence the seawater from the entire surface layer flows through both gates out of the Bay.

The direction of water movement in the lower layer is opposite to the upper layer, hence at the depths of 24 m, 36 m, 48 m and 60 m water enters into the Bay through the Middle Gate and the Gate Gate. It then flows along the northern coast of the Bay, including the Rijeka city and the Delta discharge. Velocities are small at all depths and are mostly parallel to the coast, i.e., south-east to north-west.

Fig. 11 to Fig. 16 show an enlarged vector field in the

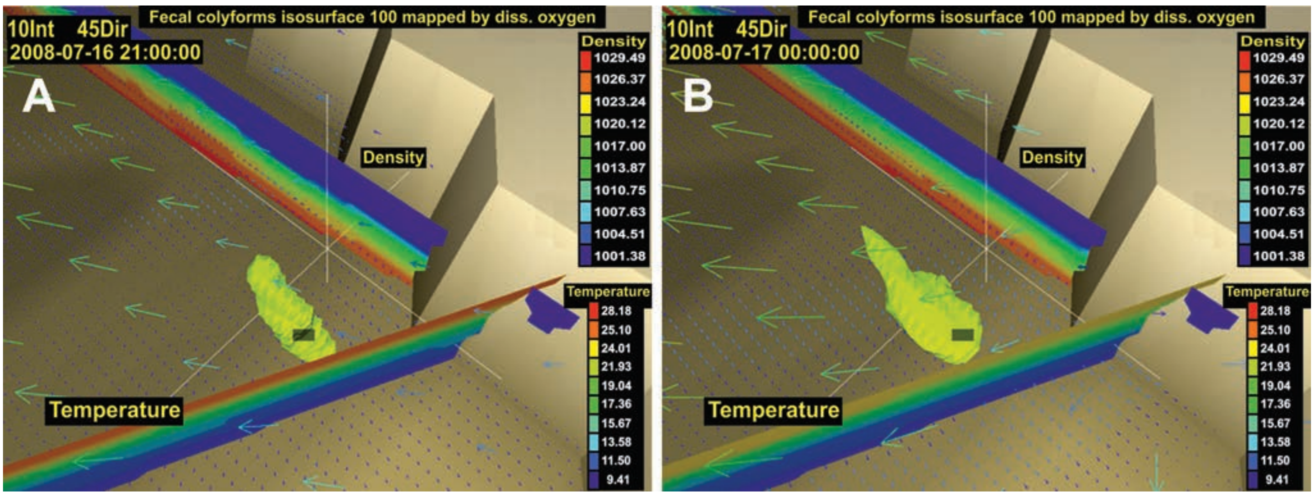

Fig. 11: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 30th (A) and 33rd (B) hours for wind intensity of 10 ms^{-1} from the direction of 135° is colored yellow.

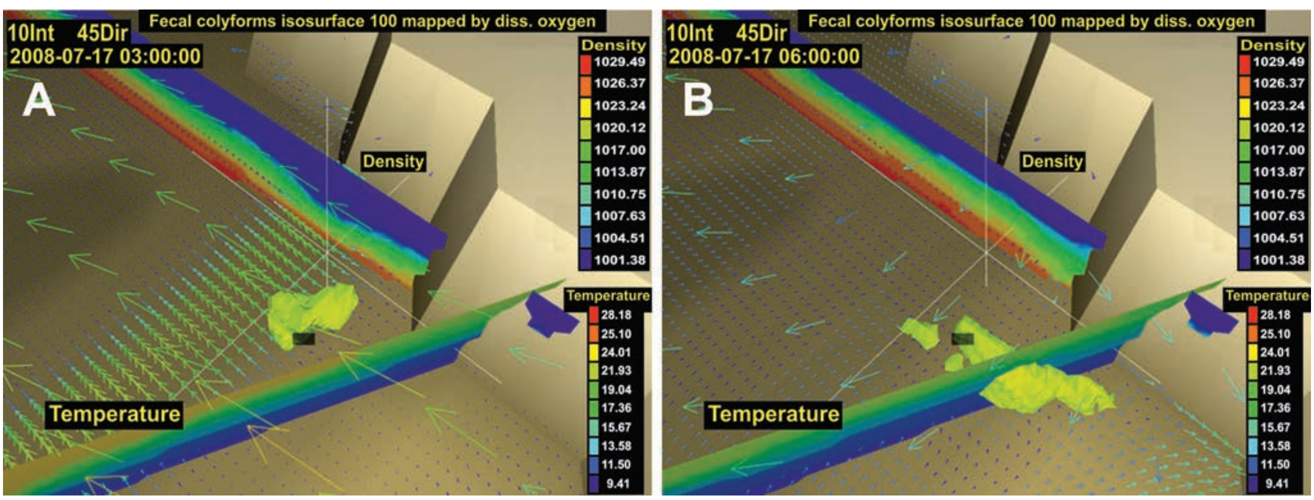

Fig. 12: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 0th (A) and 3rd (B) hours for wind intensity of 10 m s^{-1} from the direction of 45° is colored yellow.

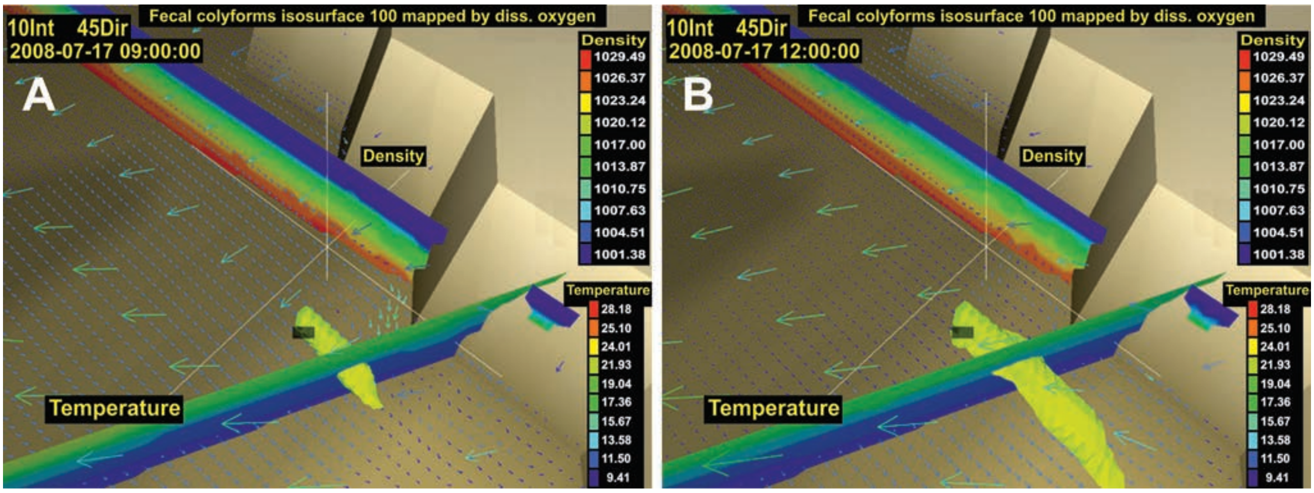

Fig. 13: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 6th (A) and 9th (B) hours for wind intensity of 10 ms^{-1} from the direction of 45° is colored yellow.

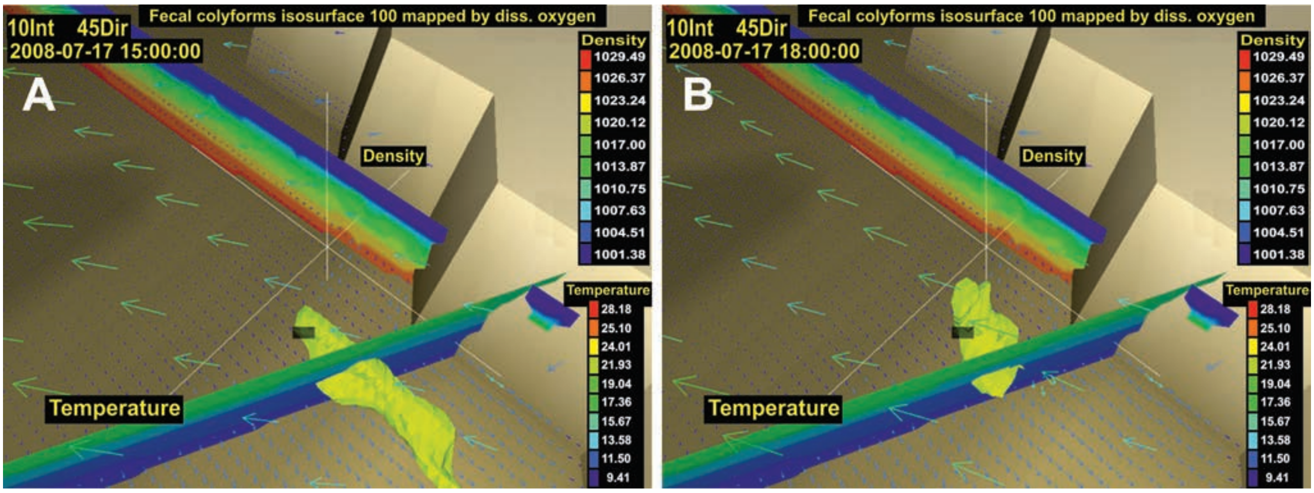

Fig. 14: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 15th (A) and 18th (B) hours for wind intensity of 10 ms^{-1} from the direction of 45° is colored yellow.

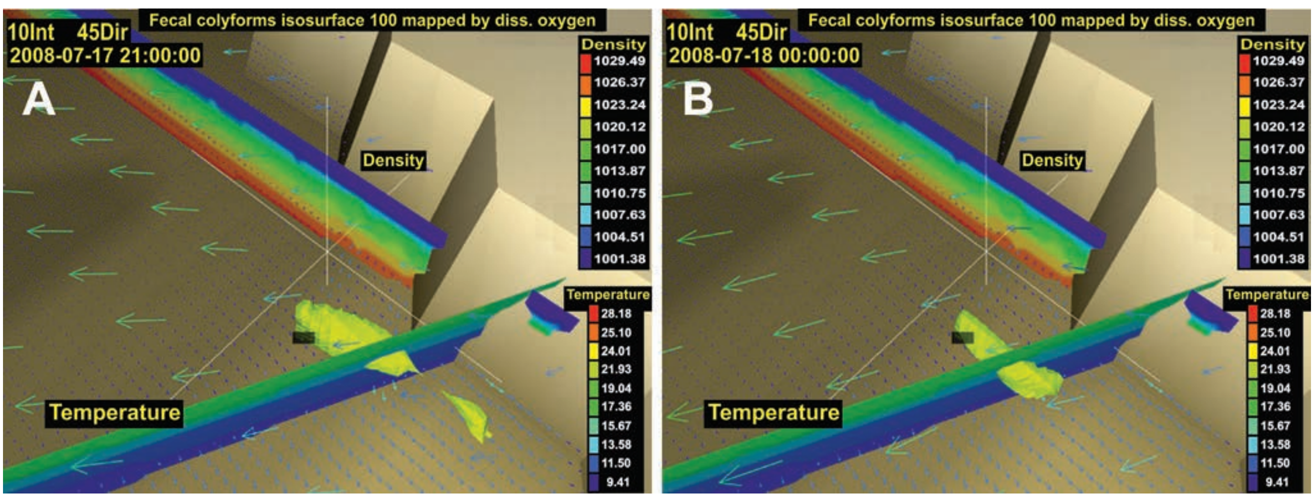

Fig. 15: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100 FC(100 ml)$^{-1}$ at 21st (A) and 24th (B) hours for wind intensity of 10 ms^{-1} from the direction of 45° is colored yellow.

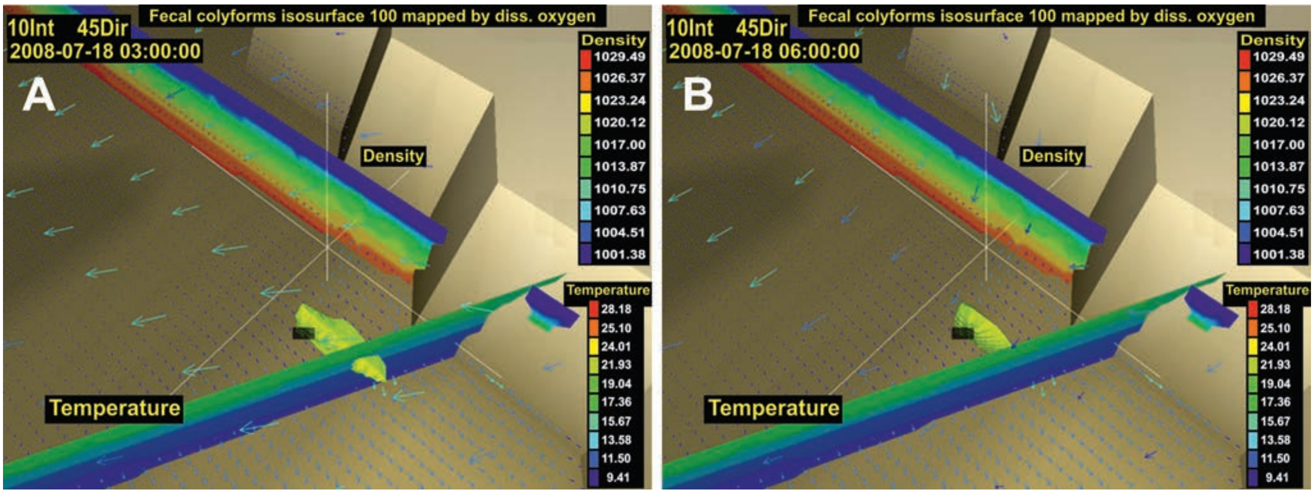

Fig. 16: Current vectors on the surface (coarse mesh) and at a depth of 30 m (finer mesh). Vertical profile of density (parallel to the coast) and temperature (orthogonal to the coast) close to the outfall. Isosurface of ≥ 100FC(100 ml)$^{-1}$ at 27th (A) and 30th (B) hours for wind intensity of 10 ms^{-1} from the direction of 45° is colored yellow.

northern part of the Rijeka Bay along the Rijeka city and the Delta sewage outfall area with two different grids: coarse and fine. The surface velocity field is given on a coarse grid and at a depth of 30 m on a fine grid.

In addition to the current field, which shows the trend of flow at a given instant, the vertical cross-section of the seawater density field through the Delta discharge parallel to the coast is also shown, as well as the vertical cross section of the temperature in the north-south direction.

A pollution plume with FC concentration of ≥100 bacteria per 100 ml is colored yellow on the figures numbered from 11 to 16. The figures show concentrations in 3 h intervals from 0 h to 36 h.

Following the development of flow and the movement of pollution, we may conclude that for this wind, representing a storm, local velocity vector field on the surface, which is mostly perpendicular to the coast, has the northeast-southwest direction. The direction of this movement is caused by the wind, and at greater depths it is north-west to south-east oriented, parallel to the coast and perpendicular to the direction of surface current, but of lower intensity.

The isosurface of FC concentration of 100 bacteria per 100 ml is parallel to the coast in the direction of the current in the layer bellow the thermocline. It may be concluded that the isosurface does not reach the coast and it does not emerge on the surface but remains at depths of about 20 m.

From the vertical temperature distribution, it may be concluded that the sea water leaves the Bay by way of the surface currents. Deep and cold waters are brought to the surface and cool the surface layer relatively quickly (in the first six hours) along the northern coast. This confirms the general impression of swimmers that the *bora* wind cools the sea. The cold water below the thermocline is brought to the surface, but this occurs very close to the coast, leaving the plume, which is located further away from the coast, practically intact.

Discussion

According to the conclusions of the first phase of the Water Pollution Prevention Project in the Croatian coastal area (Andročec *et al.*, 2009), the flow field dynamics analysis should be done in the subdomain of Rijeka close to the submarine sewage outfall using a more detailed mesh resolution, and this is the scope of the present paper. The mesh convergence is achieved using three different meshes with a threefold decrease in mesh size between each two. In Fringer *et al.*, 2019, almost all of the current coastal models are compared, and it is stated that coastal and model applications are highly dependent on resolving bathymetric, coastline and forcing variability, features that can be highly site specific, and therefore our 3D approach is in line with the current trends in the scientific analysis of coastal water and pollution movements presenting a complete 3D analysis for the whole Bay domain instead of depth-averaged models.

The analysis of the distribution and extent of pollution for the given sewage outflow discharge characteristics (the inflow concentrations of $FC = 5 \cdot 10^6\, cells\,(100\, ml)^{-1}$ and $FS = 5 \cdot 10^5\, cells\,(100)^{-1}$ and the discharge of Q = 0.3 m^{3}s^{-1}, obtained from *in situ* measurements) for two dominant winds, *sirocco* (135°) and *bora* (45°) of 10m/s velocity, shows that the isosurface of FC concentration of 100 bacteria per 100 ml is parallel to the coast in the direction of currents in the layer below the thermocline. Hence, we conclude that it does not reach the coast and it does not emerge on the surface but remains at depths of about 20 to 30 m. This has also been confirmed by measurements (RL, 2006; RL, 2008).

For all other analyzed winds in three additional intensities and eight directions, the simulation results are given elsewhere (Mrša Haber, 2016). However, the results do not indicate a change to the above conclusion.

Conclusions

The numerical simulation using the MIKE 3 software was performed for a period of 36 hours and for typical wind directions and intensities. The simulation was forced by wind, humidity and heat exchange at sea surface, which were calculated using the ALADIN software for meteorological modeling with a spatial resolution of 8 km and time resolution of 3 hours. On the open boundaries, surface elevations, temperature and salinity fields were set, as calculated using the ROMS software.

The initial and boundary values of DO concentrations were obtained from the measurements at the nearby oceanographic stations.

The sewage inflow concentrations of $FC = 5 \cdot 10^6 \, cells (100 \, ml)^{-1}$ and $FS = 5 \cdot 10^5 \, cells (100)^{-1}$ and the discharge of Q= 0.3 $m^3 s^{-1}$ were obtained from measurements. The dispersion of the sewage is characterized by two zones: near field and far field zone. The Cormix software was used to calculate the dilution (the ratio of pollution concentrations at the sewage outflow and at the end of the near field zone). The dilution amounted to 68.3. In the far field, the passive dispersion by surrounding sea water movement and diffusion were simulated using MIKE 3.

For two wind directions, N (0°) and SE (135°), and wind intensities of 10 ms^{-1}, the current field at the surface and at 30 m depth as well as the appearance and movement of the pollution was simulated. The concentration isosurface of 100 FC per 100 ml was calculated to assess the impact of the submarine outfall on the pollution of beaches, since this is the limit value for the sea water quality category 2 intended for bathing.

For each direction and intensity of wind, the surface seawater flow of the whole Bay is given in the attached video clips, with a vertical profile of seawater density in the discharge area and three vertical temperature profiles in the north-south and east-west directions, in order to obtain the simulation of 36 hours of constant wind.

The figures and attached films show an enlarged view of the area around the sewage outfall, in order to better assess the dynamics of the pollution motion and critical approach to the coast and the beaches.

For the considered wind directions, the plume with the pollution concentration higher than 100 fecal coliforms and 100 fecal streptococci per 100 ml of water is conveyed parallel to the coast in the north-west or south-east direction with the maximal horizontal extent of 1000 m and plume width of 200 m. It does not rise to the surface but stays at 10 to 20 meters below the surface. This is the result of seawater motion in the Bay: the *bora* wind conveys surface seawater out of the Bay through the Middle and Great Gates, while deep cold seawater enters the Bay. During the sirocco wind (*jugo*), the situation is reversed: warmer surface seawater enters the Bay through the Middle Gate or Great Gate, while colder bottom seawater exits the Bay, accumulating warmer water in the Bay.

The conclusion is that the Delta sewage discharge is well-designed and constructed so that the pollution is within regulatory given boundaries. This is due to the fact that the discharge location is far enough (500 m) from the coast, where local currents are mostly parallel to the coast and the pollution concentration does not come close to swimming and recreational areas. Simulations show that even if the discharge is increased by 50%, the pollution concentration will remain within regulatory boundaries.

The importance of the results transcends the Rijeka Bay because it shows that using a combination of four software packages – ROMS run on a larger area to provide for currents on open boundaries, ALADIN to provide for wind forcing, CORMIX to estimate initial dilution and MIKE3 to perform simulations – it is possible to estimate pollution dispersion and use the results for construction of submarine outfall as well as test whether the existing outfall is safe to use. Since monitoring is obligatory for every existing outfall, monitoring results must be used to validate simulation results.

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