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IMPACT OF WIND, TIDAL VARIATIONS, WAVE FIELD AND DENSITY GRADIENT ON THE SEAWATER EXCHANGE TROUGH FLUSHING CULVERTS IN MARINAS

Ivana Bartolić, Goran Lončar, Damjan Bujak, Silvija Klapčić, Ivan Mišura

The paper presents the results of in-situ measurements and 3D numerical model of seawater circulation in the marine waters, whose main breakwater contains a constructed culvert. The in-situ measurements were carried out in the marina aquatorium of the city of Opatija (Croatia) and include: seawater current measurements, sea temperature and salinity, culvert discharge measurement, wave spectra parameters, atmospheric elements - wind speeds and directions and precipitation intensity. The presented results show that wind, wave field and freshwater sources have important contribution to the seawater exchange in the marina and that the maximum seawater exchange is achieved by constructing culvert axis to the middle sea level.

KEY WORDS: flushing culverts, marina, Adriatic Sea, numerical model

VPLYV VETRA, VARIÁCIE PRÍLIVOV, ZACHYTÁVANIE VĹN A ZVYŠOVANIE HUSTOTY MORSKEJ VODY CEZ PREPLACHOVACIE KANÁLY V PRÍSTAVOCH. Práca prezentuje výsledky lokálnych meraní a 3D numerický model cirkulácie morskej vody v morských vodách, ktorých hlavný vlnolam obsahuje konštruované kanály. Merania sa uskutočnili v aquatóriu prístavu mesta Opatija (Chorvátsko) a zahŕňali: meranie prúdu morskej vody, teplotu a slanosť mora, meranie výtoku podzemných vôd, parametre vlnových spektier, atmosférické prvky – rýchlosť a smer vetra a intenzita zrážok. Predložené výsledky ukazujú, že vietor, vlny a sladkovodné zdroje významne prispievajú k výmene morskej vody v prístave a že maximálna výmena morskej vody sa dosahuje pri konštrukcii osi kanálov na stredovú hladinu mora.

KĽÚČOVÉ SLOVÁ: preplachovacie kanály, prístav, Jadranské more, numerický model

Introduction

According to the legal definition, nautical tourism is defined as navigation and staying in nautical ports by tourists for rest and recreation. Croatia is very suitable for the nautical tourist development because of the large number of islands and indented coast. Due to above mentioned, the Croatian coast is protected from direct impact of open sea waves, which allows for the construction of smaller ports. In a wider context, the functionality of marinas/ harbours/ ports is achieved by building costal structures which reduce the intensity of waves in sheltered sea areas. Since breakwater construction is the costliest element in the construction of a marina, the goal is to reduce its size by choosing a partially or completely naturally sheltered area. Breakwater price increases progressively with sea depth and therefore it is economical to consider locations with depths of less than 10 m. In Croatia, the largest number of marinas and harbours are protected by gravity breakwaters. Because of this, seawater within a marina is separated from the surrounding seawater and natural circulation is prevented. The negative consequence of decreased water circulation in a marina and water exchange with surrounding sea body can be reduced by construction of flushing culverts in the body of the breakwater. Their purpose is to improve exchange of seawater between a marina and the surrounding water body.

Seawater exchange between a marina and the surrounding sea is generally the result of natural factors such as tidal variability, wind conditions, wave climate and water density gradients (Fisher et al., 1979; Schwartz, 1989; Nece, 1984; Falconer, 1991). One or

more of mentioned factors, depending on geographical location, may dominate the flushing process in a marina. If the concentration of pollutants rises above the critical level, the result is unsatisfactory water quality characterized by a reduction of dissolved oxygen and eutrophication. Flushing characteristics of a marina depend on the structural parameters such as the geometry, entrance dimensions, depth and bottom slope (Nece, 1984; Falconer, 1991; CEM, 2002). As mentioned, seawater exchange can be improved with the use of flushing culverts (pipes or rectangular openings in the body of the breakwater) which is the most cost-effective engineering solution. Application of flushing culverts is justified in areas with small variations of tides (such as the Adriatic and the Aegean Sea), where the difference of tide variations is not enough for good flushing in ports (Ozhan et al., 1992) or in semi-closed and closed bays where tidal circulation is poor (Weston Solutions, 2013). For this reasons, researches associated with flushing culverts come mostly from the countries with similar oceanographic conditions, from Greece and Turkey in the Aegean Sea (Ozhan et al., 1992; Stamou et al., 2001, 2004; Tsoukala et al., 2003, 2005, 2009, 2010; Fountoulis et al., 2005; Stagonas et al., 2009; Balas et al. 2010). These works partially show physical processes in marinas with flushing culverts, focused on an analysis of the flushing culverts efficiency in terms of the flow generated by the direct wind or tide action. Wind – induced flow through the flushing culverts is not analysed, except in the area of determining the coefficient of transmission, and the wave agitation of the marina basin. The effect of tidal variations is generally recognized as insufficient for the flushing process.
The paper presents the results of in-situ measurements and 3D numerical model of seawater circulation in the marina waters whose main breakwater contains a constructed culvert. The in-situ measurements were carried out in the marina aquatorium of the city of Opatija (Croatia) during one month of winter period. The in-situ measurements included seawater current measurements, sea temperature and salinity, culvert discharge measurement, wave spectra parameters, atmospheric elements – wind speeds and directions and precipitation intensity. The impact of tidal variations, wave intensity and directions, precipitation intensity on discharge trough culverts was analysed. The 3D numerical model of seawater exchange was parametrised according to in-situ measurements, and the comparison of measured and simulated results is shown. Impact on culvert inflow and outflow is analysed.

Material and methods

In-situ measurements

The in-situ measurement has been carried out in the aquatory of ACI Marina Opatija (45°19'/14°17,7', Fig 1.). Marina is open all year round. The number of berths in the marina is 290 and the number of marina's disponible places for the seating of the boats on land: 35.
Detailed bathymetry soundings were carried out in the area of the marina, as a basis for the establishment of sea circulation numerical model of the port basin. Physical oceanography parameters were monitored at several oceanographic sites (Fig. 2), and the obtained data sets were used for the initiation of the model and boundary conditions and for the verification of the sea circulation model results. Currents were monitored continuously in the periods 15 February 2017 – 23 March 2017 by means of two Acoustic Doppler Current Profilers (ADCP at position 4 and 5) (Fig. 2). The sea temperature (T) and salinity (S) were measured throughout the vertical sea column at two CTD (conductivity, temperature, depth) stations in the marine area (positions 1 and 4, see fig. 2), at the beginning and at the end of the measurement period in which the currents were measured. The sea surface elevation (Fig. 3) was recorded with a 10-minutes resolution at the ADCP station 4 located in the vicinity of marina entrance (Fig. 2).

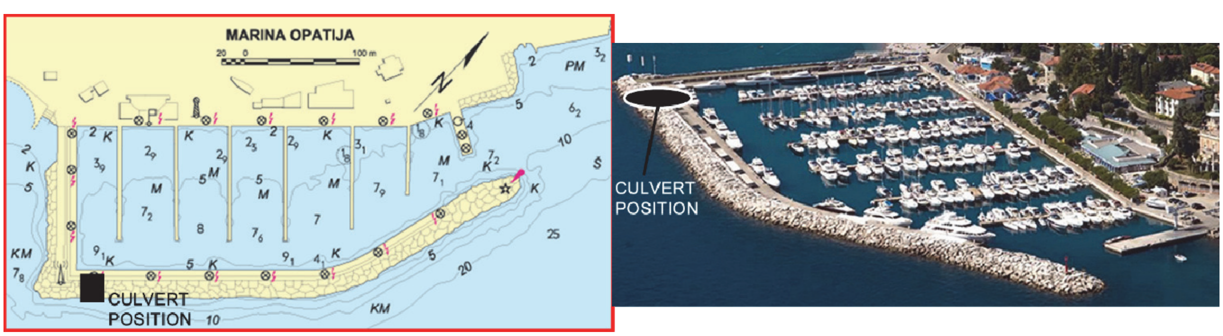

Fig. 1. Situation map and figure of ACI marina Opatija.
Obr. 1. Mapa polohy a obrázok ACI prístavu Opatija.

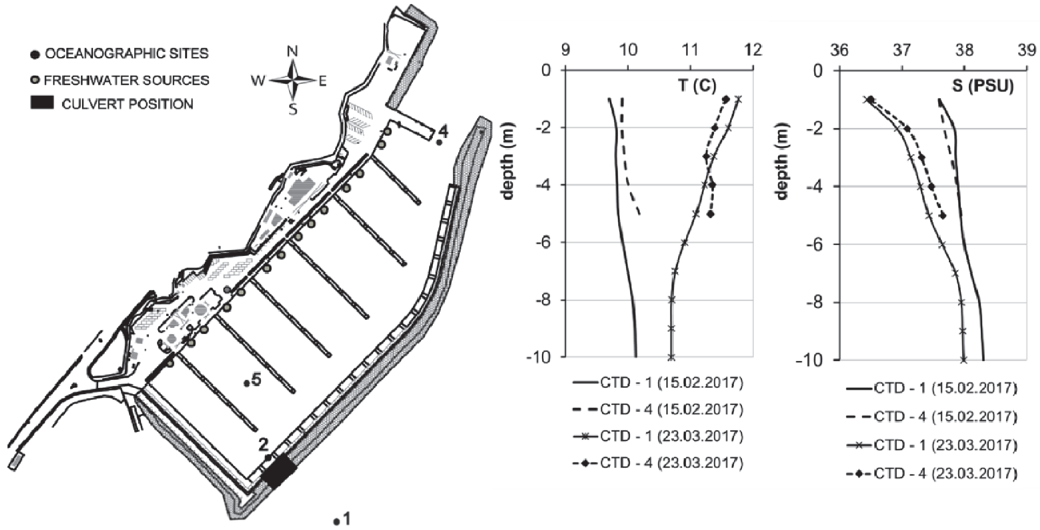

Fig. 2. The positions of oceanographic sites (1, 4, 5 – CTD measurements, 4, 5 – sea current measurements, 1 – wave parameters measurements, 2 – PCM measurements), measured sea temperatures/salinity vertical distribution at CTD measurement positions (1, 4 and 5).

Obr. 2. Pozície oceánografických miest (1, 4, 5 – CTD merania, 4, 5 – merania morských prúdov, 1 – merania vlnových parametrov, 2 – PCM merania), merané teploty mora/vertikálna distribúcia slanosti v miestach merania CTD (1, 4 a 5).

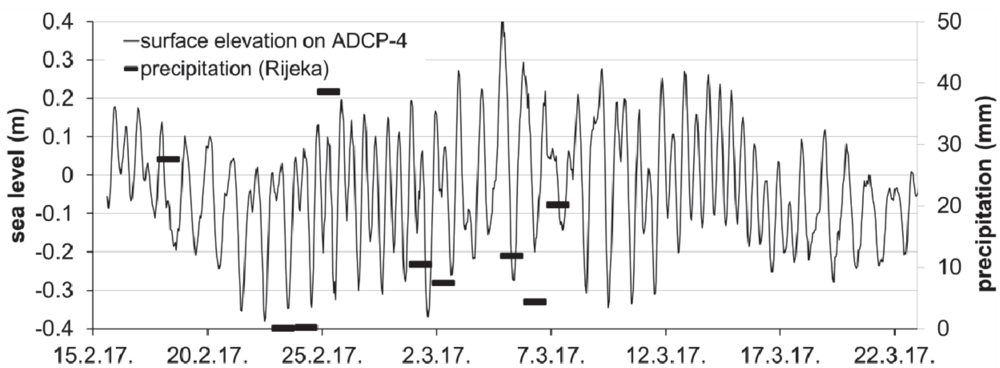

Fig. 3. Surface elevation time series according to the record at ADCP station 4 and daily precipitation at meteorological station situated near the marina (Rijeka $\varphi = 45^0 20'$, $\lambda = 14^0 27'$).

Obr. 3. Časové rady nadmorskej výšky podľa záznamu na stanici ADCP 4 a denné zrážky na meteorologickej stanici nachádzajúcej sa v blízkosti prístavu (Rijeka $\varphi = 45^0 20'$, $\lambda = 14^0 27'$).

Data on wind speeds and directions are obtained from the anemometer situated on the roof of the marina authority building at the 10 m above the ground (Fig. 4). Wave spectra parameters (significant wave height H_S, peak period T_P and incident wave direction, Fig 4.) with hourly resolution were obtained using the ADCP at station 1 (Fig. 2). The PCM device (station 2, Fig 2.) was located at the entrance of one culvert pipe, and used for culvert discharge measurement with a 10-minutes resolution (Fig. 5). Precipitation (Fig 3.) was obtained by means of measurements at the local meteorological station situated near the marina (Rijeka station, $\varphi = 45^0 20'$, $\lambda = 14^0 27'$).

Current culvert position provides most intense seawater exchange for the incident wave direction range 90^0 (E) – 180^0 (S). Table 1 shows relevant situations, adopting the following criteria: $H_S \geq 0.3$ m; $T_P \geq 2.8$s; incident direction range 90^0 – 180^0, for the deep water point in front of the marina Opatija breakwater (site 1). 8 situations are recognised in total. The start point of each relevant situation, its duration, corresponding average significant wave height and peak period as well as maximum significant wave height are also listed in table 1. Relevant situations are also indicated in figure 5.

Data shown in figure 5 and listed in table 1 indicate that wave direction range 104^0 – 170^0 causes increased inflow trough culvert Q_{PCM} ($+Q_{PCM}$ means inflow - entering outer seawater into the marina aquatorium). Discharge intensity and culvert inflow/outflow depend on the sea surface level. The lower the surface level, the grater the inflow. For the situation 28.2 13:00, sea surface level is -0.22 m and $Q_{PCM} = 0.089$ m^3/s, while in case of high surface levels (4.3. 20:00, sea surface level +0.38m) and the greatest significant wave height and periods ($H_S = 1.1$m, $T_P = 5.2$s, incident wave direction 162^0) discharge is Q_{PCM} = -0.012 m^3/s. ENE wind generates wind field direction parallel to breakwater with lower significant wave heights and periods (situation 7.3. and 10.3., Fig. 4), wherein culvert inflow is absent. NE wind effect is just the opposite. Surface elevation in SW part of marina, where culvert is constructed, is rising, and due to surface elevation difference greater outflow appears (see situation 10.3. 10:00, Fig. 5).

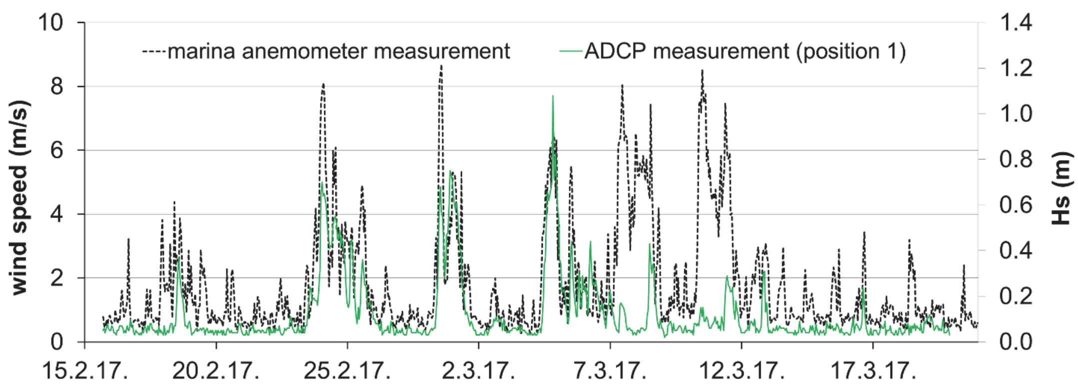

Fig. 4. Time series of wind speed (recorded on the roof of the marina authority building at the 10 m above the ground, hourly averages) and significant wave height (measured at position 1, hourly averages) for period 15 February 2017 – 23 March 2017.
Obr. 4. Časové rady rýchlosti vetra (zaznamenané na streche administratívnej budovy prístavu vo výške 10 m nad zemou, hodinové priemery) a významná výška vlny (meraná na pozícii 1, hodinové priemery) za obdobie od 15. februára 2017 do 23. marca 2017.

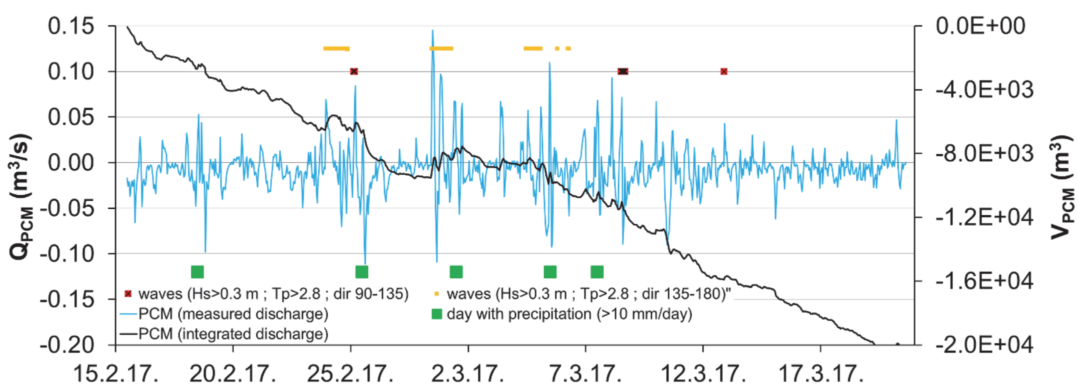

Fig. 5. Time series of measured and integrated culvert discharges from PCM device, situations with significant wave height $H_S \geq 0.3$ m , peak period $T_P \geq$ 2.8s and incident wave direction range $90^0 – 180^0$ situations with precipitation intensity > 10 mm/day.
Obr. 5. Časové rady meraných a integrovaných výtokov z PCM zariadenia, situácie s významnou výškou vlny $H_S \geq 0,3$ m;najvyššia perióda $T_P \geq 2,8$ s a smerovanie vĺn v rozsahu $90^0 – 180^0$ s intenzitou zrážok > 10 mm/deň.

Table 1. **Start point for each relevant situation (adopted criteria $H_S \geq 0.3$ m ; $T_P \geq 2.8$; incidental direction range $90^0 - 180^0$), its duration, corresponding average significant wave height, peak period, maximum significant wave height, as well as incident direction for deepwater points in front of the marina Opatija breakwater**

Tabuľka 1. **Počiatočný bod pre každú relevantnú situáciu (prijaté kritériá HS ≥ 0,3 m; TP ≥ 2,8; náhodné smerové rozpätie $90^0 - 180^0$), jej trvanie, zodpovedajúca priemerná významná výška vlny, najvyššia perióda, maximálna významná výška vlny ako aj smer dopadu pre hlbokomorské body pred vlnolamami prístavu v Opatiji**

		deep water conditions				
	situation onset	duration	$H_{S\text{-}AV}$	$T_{P\text{-}AV}$	$H_{S\text{-}MAX}$	dir_{AV}
		(h)	(m)	(s)	(m)	(^{0})
1	23.2.17. 22:00	23	0.50	3.6	0.70	**164**
2	25.2.17. 2:00	3	0.42	3.5	0.45	107
3	28.2.17. 11:00	21	0.54	3.9	0.75	**159**
4	4.3.17. 11:00	15	0.63	4.6	1.08	**150**
5	5.3.17. 11:00	2	0.41	2.8	0.44	104
6	6.3.17. 5:00	3	0.36	5.2	0.44	**170**
7	8.3.17. 11:00	5	0.35	3.0	0.43	113
8	12.3.17. 20:00	1	0.31	2.8	0.31	115

Precipitation effect is important, especially in the form of freshwater sources along the marina coastline, and much less when falling directly on the sea surface of marina aquatorium (Fig. 2). The intensity of fresh water sources is not known, but visual inspection has determined its activation in precipitation days. It has also been noted that freshwater source intensity correlates with precipitation intensity. This phenomenon is a consequence of the characteristic karstic geological condition with the occurrence of spring (surface) and subsurface sources in the observed area. Figure 5 shows that PCM device has registered culverts outflow in the days with precipitation intensity P > 10mm/day. The most intense precipitation during in-situ measurements is registered on 25.2.2017 (38.6 mm/day, Fig. 3) when PCM device has registered maximum culvert outflow Q_{PCM} = -0.112 m^3/s.

Numerical modelling – sea circulation and exchange

Numerical model solutions for the domain (Fig. 7) were computed using the Mike 3fm numerical model (www.dhigroup.com). This is based on a flexible mesh approach, and its hydrodynamic module solves the 3D RANS equations using the Boussinesq and hydrostatic approximations. The model uses a free surface, and vertical model discretization is carried out using the standard sigma coordinate approach (Song at al., 1994). Governing equations are solved within a finite volume frame, based on a single cell division and continuum discretization with non-overlapping elements (Sleigh, 1998). An unstructured mesh is used in the horizontal but a sigma-structured one in the vertical. An approximate Riemann solver (Roe, 1981) is used to calculate convective terms, enabling computation in cases of discontinuous solutions with steep gradients. For time integration, the model uses a semi-implicit approach – explicitly in the horizontal and implicitly in the vertical. The Smagorinsky scheme (Smagorinsky, 1993) and k-ε models (Rodi, 1987) are used for turbulence closure formulation in the horizontal and vertical directions, respectively.

Simulations with the model were run using the following parameter values: minimum time step of external mode Δt=0.1s, maximum time step of internal mode Δt=30s with a critical threshold CFL of 0.8. Dispersion coefficients (Prandtl's number) for the scalar T, S fields were defined with proportionality factor 0.09 in the vertical and 0.85 in the horizontal with respect to the scaled eddy viscosity. The proportionality factors for the dispersion coefficients of turbulent kinetic energy *(TKE)* and dissipation (ε) were used with the values 1 for the *TKE* and 1.3 for ε in the horizontal and vertical directions. Roughness and Smagorinsky coefficients were set as spatially and temporally constant values of 0.01 and 0.2, respectively. The value of 0.0013 (Wu, 1994) was used for the wind friction coefficient.

Figure 7 shows the finite element model grid used in the Mike 3fm model simulations. Variable grid spacing between numerical nodes ranging from 2 m to 5 m were used in the horizontal, and 9 sigma layers were used in the vertical. At defined culvert position series of 8 circular pipes, 1 m diameter and 10 m total length, was set. The pipe inlet and outlet are at the depth of -1.0 m from the mean sea level (which is set to 0.0 m).

Surface elevation are variable during the numerical simulations and surface elevation time series data are obtained based on the measured sea dynamics at the position of ADCP 4 (Fig. 3). At the open boundaries of numerical model (culvert and marina entrance) the sea temperature and salinity fields were used, obtained with CTD measurements at stations 1 and 4 (Fig. 2) on 15 February 2017 and 23 March 2017. The initial conditions are expressed by current velocity values set to 0 m/s for all three directions, to all numeric cells. The initial conditions for the scalar fields of sea temperature and salinity in the vertical direction have been considered on the basis of the measured values at CTD station 4 (Fig. 2), and a homogeneous distribution of sea temperature and salinity in the horizontal direction.

According to above mentioned comments on the indirect precipitation impact of freshwater surface sources, in numerical model, 15 freshwater sources were set along the marina coastline (Fig. 2, 7). Freshwater inflow is parametrised with constant temperature value of 10^0 C and salinity of 0 PSU. Source inflow dynamics depends on precipitation occurrence (Fig. 2), whereby the proportionality coefficient 0.0003 was used (for one source $Q_{\mathrm{SOURCE}} = 0.0003*P$).

Pipe culvert is implemented in a model as an external explicit routine based on the difference of sea levels in the marina aquatorium and the outer side of the marina at the culvert position. Culvert is defined in the model as a connected sink-source function inside the marina. Depending on the sea level, the model takes into account the difference between the free surface flow and under-pressure flow, based on the Manning equation. The local inflow loss coefficient ζ_{IN} at the culvert entrance is variable and depends on the conditions of the wave field (H_s, T_p, and incident direction) and sea levels for the wave situations.

For the eight situations from table 1, calibration of the inflow loss coefficient ζ_{IN} at the culvert entrance was done. Model domain shown in figure 7 was used. At the open boundary (marina entrance) sea surface level measured by ADCP 4 device was used (figure 3), as a boundary condition at the culvert position superposetion of registered surface elevation from ADCP 4 and levels obtained by applying the JONSWAP spectrum with features H_s and T_P shown in table 1. For the minimum wave period of each wave spectrum, the value T_{MIN} = 1.8 s was adopted. Data time resolution is 0.2 s, thus providing a minimum of 9 points for the description of the shortest waveform with T_{MIN} = 1.8 s.

Figure 8 shows time series sequence of sea surface levels for the situation 4 (H_S = 0.63 m, T_P = 4.6 s).

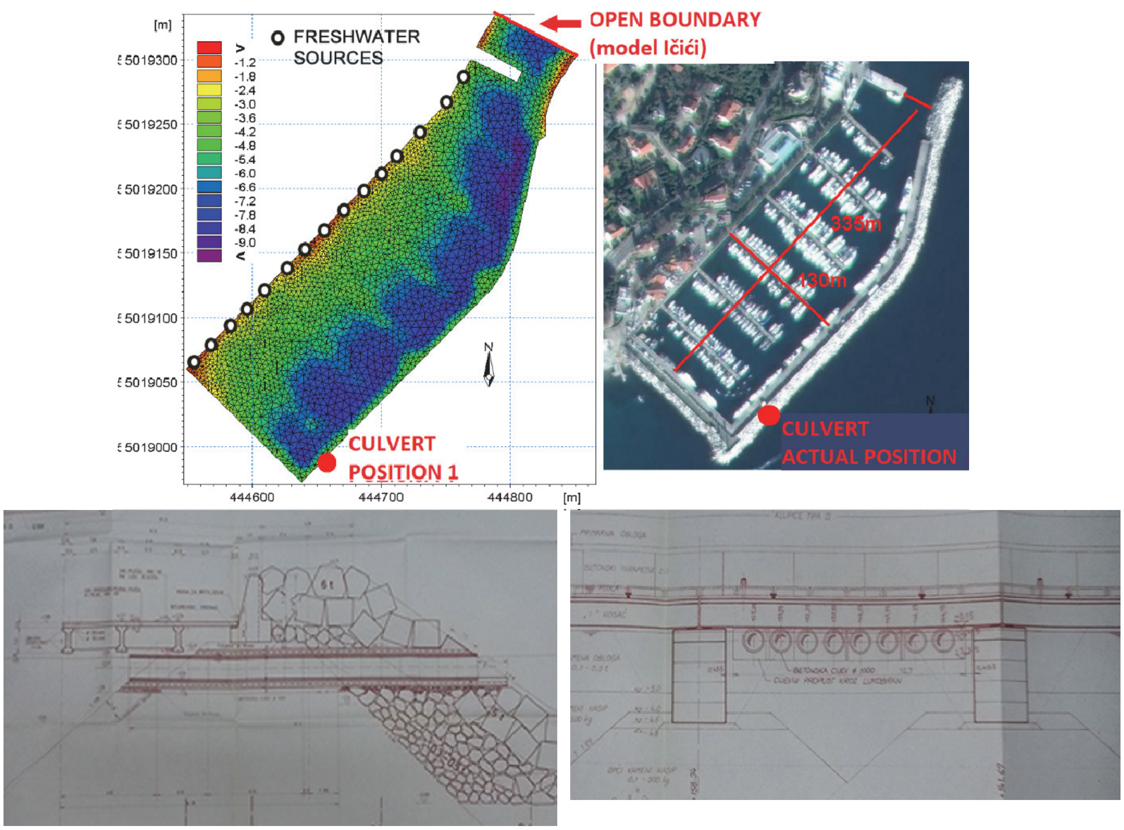

Fig. 6. Spatial domain of sea circulation model and discretization with triangular cells (above), cross section (below left) and side view at position of pipe culverts (below right).
Obr. 6. Priestorová doména modelu morskej cirkulácie a diskretizácia s trojuholníkovými bunkami (hore), prierezom (vľavo dole) a bočným pohľadom pozície rúrkových priepustov (vpravo dole).

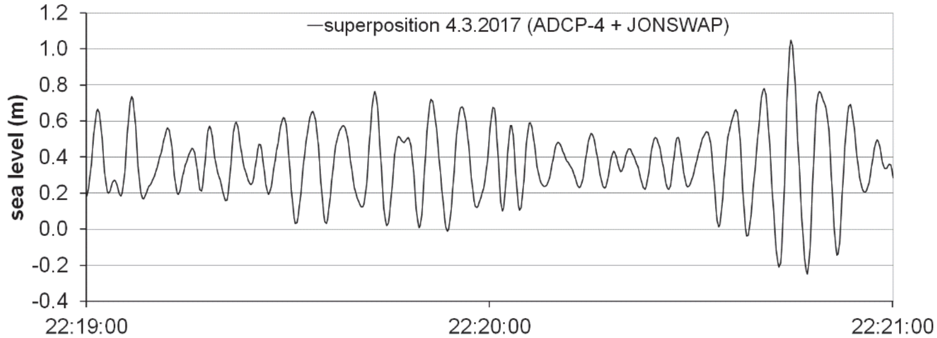

Fig. 7. Time series sequence of sea surface levels (sitaution 4 from table 1; H_S = 0.63m, T_P = 4.6 s) which is used for boundary condition on the open boundary at the culvert position.
Obr. 7. Sekvencia časových radov hladiny mora (bod 4 z tabuľky 1, HS = 0,63 m, TP = 4,6 s), ktorý sa používa pre hraničné podmienky na otvorenej hranici v pozícii priepustnosti.

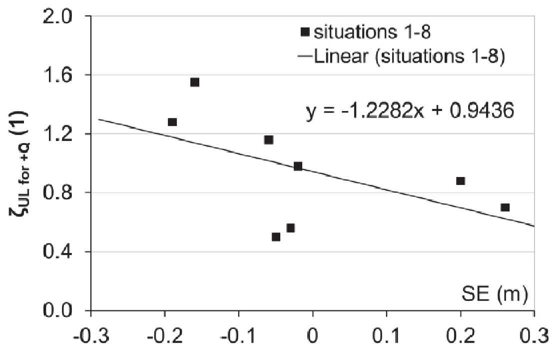

Fig. 8. Ratio of the adopted inflow loss coefficient values $\zeta_{IN\ for\ +Q}$ and mean sea surface levels for the analysed wave situations with the interpolated trend-line.
Obr. 8. Pomer prijatých hodnôt koeficientu straty prítoku $\zeta_{IN\ for\ +Q}$ a priemerných hladín mora pre analyzované vlnové situácie s interpolovanou trendovou čiarou.

For sea temperature and salinity boundary conditions, values measured on 15.2.2017 and 23.3.2017 were used, using the linear interpolation for the period of each simulation according to the situation in Table 1. The inflow loss coefficient ζ_{IN} values varied until the same integral flow rate on the model was obtained, the same as measured by the PCM device at the end of the particular situation period. (Table 1). Ratio of adopted values of the inflow loss coefficient ζ_{IN} and mean sea surface levels for the analysed situations with the interpolated trend-line are given in figure 9. In the rest of the period the constant loss coefficient values were used (for the inflow ζ_{IN}=0.5, for the outflow ζ_{OUT}=1.0, Manning coefficient n= 0.013 s/m$^{1/3}$).

Results and discussion

Numerical analyses of sea currents and water mass exchanges between the marina and the surrounding maritime zone were carried out. A comparison of the measured and modelled hourly average current speeds at the positions of ADCP-4, ADCP-5 is shown in Figure 9 and 10. At the position of the ADCP-5 in the surface and bottom layer modelled current speeds are higher than measured as at the position of ADCP-4 measured values are higher than modelled values.

A comparison of the measured and modelled hourly integrated culvert discharge, marked wave field situations ($H_S \geq$ 0.3 m; $T_P \geq$ 2.8s; incident direction range 90^0 – 180^0 and incident direction range 135^0 – 180^0) and days with registered precipitation are shown in Figure 11. Impact of the wave field is taken into account using external explicit routine and precipitation as freshwater sources along the marina coastline (explained in section 2.2).

Modelled values of integrated culvert discharge are similar to those obtained from the measurement (Fig. 11).

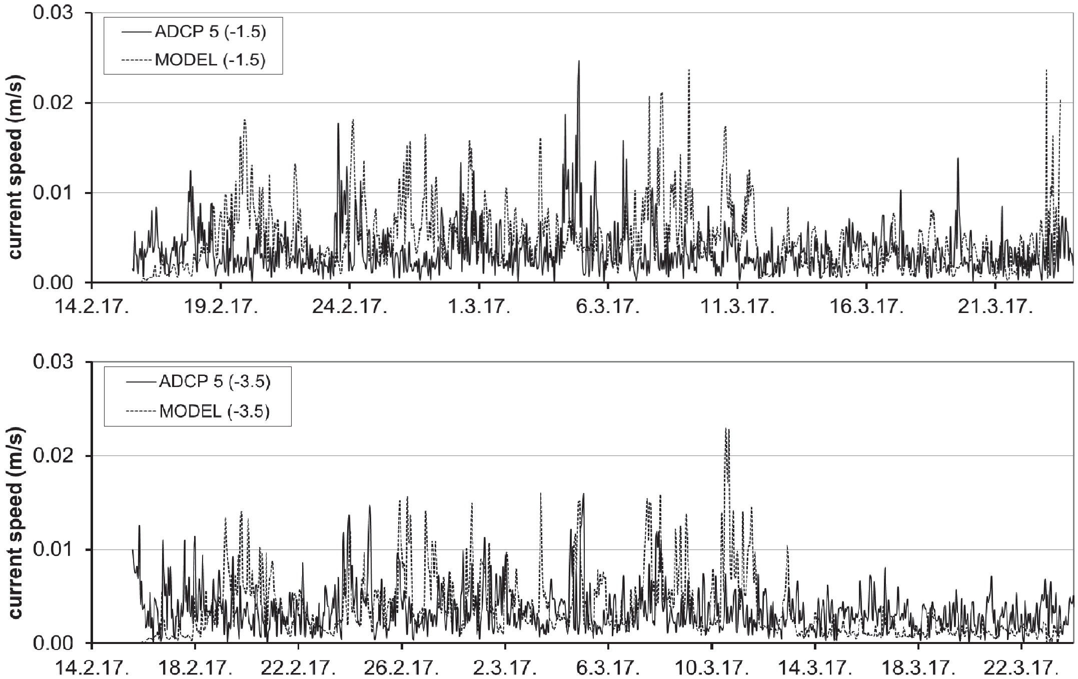

Fig. 9. Comparation of the measured and modelled hourly averaged current speeds at the positions of ADCP measurement site 5 for depth of -1.5 m (up) and -6.0 m (down).
Obr. 9. Porovnanie nameraných a modelovaných priemerných hodinových prúdových rýchlostí v ADCP mieste merania 5 pre hĺbku -1,5 m (hore) a -6,0 m (dole).

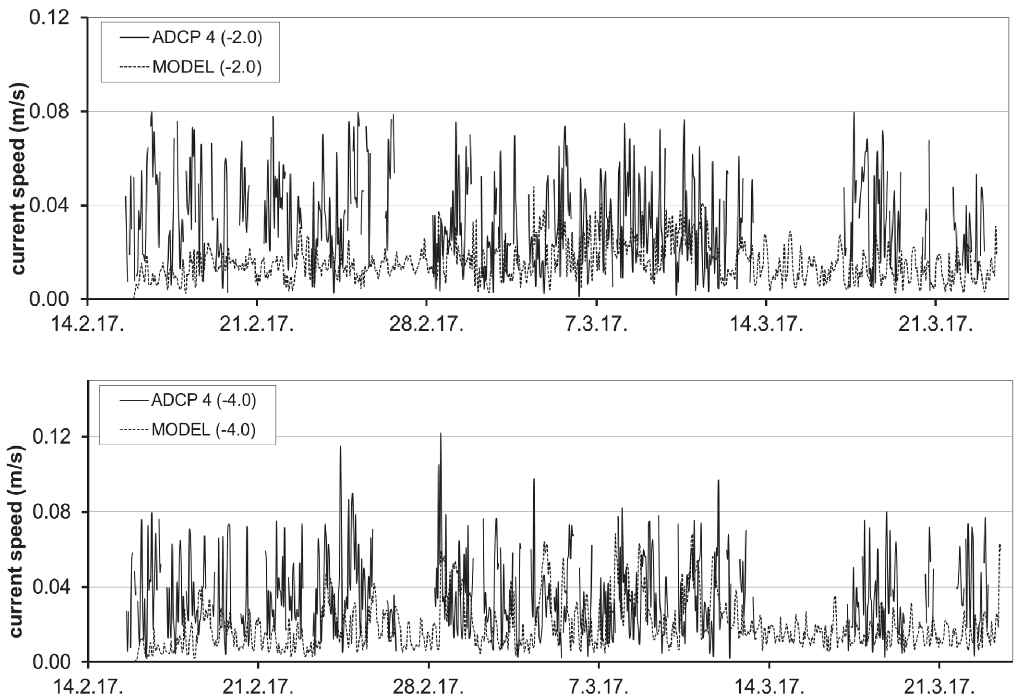

Fig. 10. Comparation of the measured and modelled hourly averaged current speeds at the positions of ADCP measurement site 4 for depth of -2.0 m (up) and -4.0 m (down).
Obr. 10. Porovnanie nameraných a modelovaných priemerných hodinových prúdových rýchlostí v ADCP mieste merania 4 pre hĺbku -2 m (hore) a -4,0 m (dole).

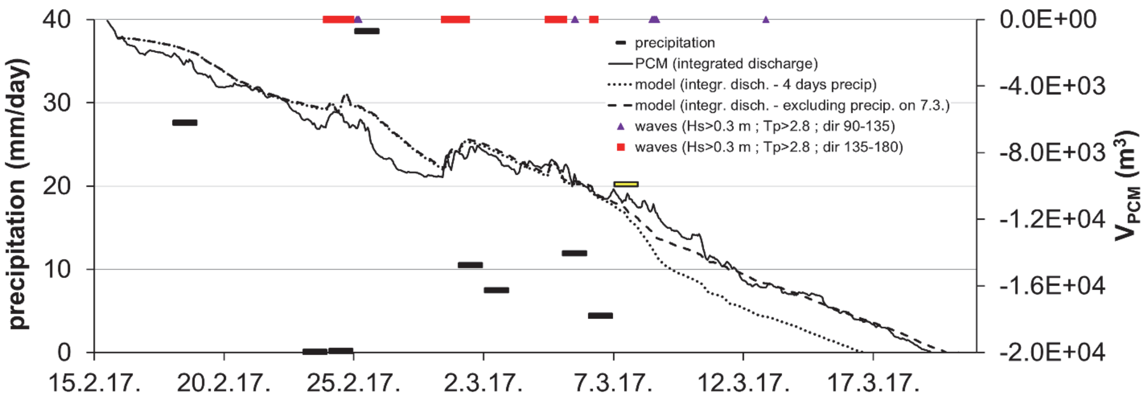

Fig. 11. Comparation of the measured (PCM (integrated discharge) and modelled integrated culvert discharges (model (integr. disch. – excluding precip. on 7.3.); model (integr. disch. – 4 days precip.).
Obr. 11. Porovnanie meraných (PCM (integrovaný odtok) a modelovaných integrovaných odtokových kanálov (model integrovaný – bez zrážok 7.3.), model (integrovaný odtok – 4-dňová zrážka).

Same as integrated culvert discharge from PCM, modelled values for the situations of the wave field, incident direction range 90^0 – 135^0 show inflow trough culverts the same as for incident direction range 135^0 – 180^0 for which inflow is even more dominant. Precipitation impact of the freshwater surface sources has the dominant influence on the culvert outflow. Sources inflow dynamics depends on precipitation occurrence, whereby the proportionality coefficient 0.0003 was used (for one source $Q_{SOURCE} = 0.0003*P$). In the first case, the value of freshwater source discharge is set on the day of registered precipitation and the modelled culvert outflow value shows discrepancies between modelled and measured discharges. Considering that the area and time of the river basin concentration involved in the runoff (influencing the freshwater source discharge) is not known, in the second case it is assumed that the flow lasts for a longer period after rainfall (source discharge sum is the same amount as in the first case). Second case, shown in figure 11 (model – integr. discharge – 4 days precip.), shows similarity of measured and modelled integrated discharge until the day 07.03.2017, when the last significant precipitation in analysed period was registered. Modelled integrated discharge values for the third case (model integr. disch. excluding precip. on 7.3. – Fig. 11) doesn't take into account source discharges affected by the precipitation measured on 7.3. (P=20.2 mm - Fig. 3). As mentioned before, precipitation was not measured at the marina location but at the local meteorological station situated near the marina (Rijeka station). Therefore, last measured precipitation in analysed period at Rijeka station was assumed as a local rainstorm which hasn't affected basin area which is connected with freshwater sources. Third case (model integr. disch. excluding precip. on 7.3.) shows the best similarity of integrated measured and modelled culvert discharges.

Conclusion

Contribution of flushing culverts on seawater exchange in the marina basin using in-situ measurement and numerical modelling of sea circulation was carried out. Impact of wind field, tidal variations and wave field on discharge trough pipe culverts was analysed. Wave direction range 104^0 – 170^0 causes increased inflow trough culvert. ENE wind generates wind field direction parallel to breakwater with lower significant wave heights and periods wherein culvert inflow is absent. NE wind effect is just opposite. Surface elevation in SW part of marina, where culvert is constructed, is rising and due to surface elevation difference greater outflow appears. Precipitation effect is important in the form of freshwater sources along the marina coastline. Maximum culvert outflow was registered on the days with most intense precipitation. Discharge intensity and culvert inflow/outflow also depend on sea surface level. The lower the surface level, the grater the inflow. According to the above mentioned, the maximum seawater exchange is achieved by constructing culvert axis to the middle sea level.

The 3D numerical circulation model was parametrised according to in-situ measurements. Pipe culvert is implemented in a model as an external explicit routine based on the difference of sea levels in the marina aquatorium and the outer side of the marina at the culvert position. Culvert is defined in the model as

a connected sink-source function inside the marina. The local inflow loss coefficient ζ_{IN} at the culvert entrance is variable and depends on the conditions of the wave field (H_s, T_p, and incident direction) and sea levels for the wave situations. For the eight situations for the incident wave direction range 90^0 (E) – 180^0 (S), and $H_S \geq 0.3$ m; $T_P \geq$ 2.8s calibration of the inflow loss coefficient ζ_{IN} at the culvert entrance was done. In the rest of the period, the constant loss coefficient values were used (for the inflow ζ_{IN}=0.5, for the outflow ζ_{OUT}=1.0, Manning coefficient n= 0.013 s/m$^{1/3}$). Precipitation impact, as the freshwater surface sources, has the dominant influence on the culvert outflow. Sources inflow dynamics depends on precipitation occurrence, whereby the proportionality coefficient 0.0003 was used (for one source Q_{SOURCE} = 0.0003*P). The greatest similarity of measured and modelled discharge values is achieved by prolongation precipitation duration (freshwater sources discharge) on 4 days and excluding last significant registered precipitation which is assumed as local rainstorm at meteorological station Rijeka.
Results obtained that wind has the important impact on culvert discharge. Incident wave direction range 90^0 (E) – 180^0 (S) increase culvert inflow as freshwater sources increase culvert outflow. The maximum seawater exchange is achieved by constructing culvert axis to the middle sea level.

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VPLYV VETRA, VARIÁCIE PRÍLIVOV, ZACHYTÁVANIE VĹN A ZVYŠOVANIE HUSTOTY MORSKEJ VODY CEZ PREPLACHOVACIE KANÁLY V PRÍSTAVOCH

Príspevok preplachovacích kanálov na výmenu morskej vody v prístavoch bol vykonaný pomocou merania in-situ a numerického modelovania morského obehu. V práci boli analyzované vplyvy vetra, zmeny prílivu a zachytávanie vĺn na odtokových potrubiach. Rozsah smeru vlny 104° – 170° spôsobuje zvýšenú priepustnosť žľabu. ENE vietor generuje smer vetra, ktorý je rovnobežný s vlnolamami s nižšou významnou výškou vlny a obdobia, v ktorých chýba prítok odtoku. NE veterný efekt je práve opačný. V severo-východnej časti prístavu, kde je potrubie konštruované, stúpa nadmorská výška a vzhľadom k výškovému rozdielu sa objavuje väčší odtok. Účinok zrážok je dôležitý vo forme sladkovodných zdrojov pozdĺž pobrežia prístavu. Maximálny odtok v potrubí bol zaznamenaný v dňoch s najintenzívnejšími zrážkami. Intenzita výtoku a prítok/odtok cez potrubie závisia aj od úrovne hladiny mora. Čím nižšia je hladina, tým väčší prítok. Podľa vyššie uvedeného sa maximálna výmena morskej vody dosiahne vtedy, keď sa os priepustov vybuduje do strednej hladiny mora.

3D model numerickej cirkulácie bol parametrizovaný podľa meraní in-situ. Potrubie je v modeli implementované ako explicitná vonkajšia rutina založená na rozdieloch hladín mora v aquatóriu prístavu a na vonkajšej strane prístavu v polohe výpustov. Priepust je v modeli definovaný ako funkcia pripojeného ponorného zdroja vo vnútri prístavu. Koeficient straty miestneho prítoku ζ_{IN} na vstupe do priepustu je variabilný a závisí od podmienok vlnového poľa (H_s, T_p a smeru dopadu) a hladiny mora pre vlnové situácie. Pre osem situácií pre rozsah dopadu vlny 90° (E) – 180° (S) a $H_S \geq 0{,}3$ m; $T_P \geq 2{,}8$ s bola spravená kalibrácia koeficientu straty prítoku ζ_{IN} pri vstupe do priechodu. V ostatnom období sa použili hodnoty koeficientu konštantnej straty (pre prítok $\zeta_{IN} = 0{,}5$; pre odtok $\zeta_{OUT} = 1{,}0$; Manningov koeficient n = 0,013 s.m$^{-1/3}$). Zrážky, ako sladkovodné povrchové zdroje, majú dominantný vplyv na odtok potrubia. Dynamika prítoku závisí od výskytu zrážok, pričom sa použil koeficient proporcionality 0,0003 (pre jeden zdroj $Q_{\mathrm{SOURCE}} = 0{,}0003 * \mathrm{P}$). Najväčšia podobnosť nameraných a modelovaných hodnôt výtoku sa dosahuje pri predĺžení trvania zrážok (výtoky sladkovodných zdrojov) na 4 dni a s výnimkou posledných významných zaznamenaných zrážok, ktorá sa považujú za lokálnu búrka na meteorologickej stanici Rijeka.

Z výsledkov vyplýva, že vietor má dôležitý vplyv na vypúšťanie potrubia. Rozsah dopadu smeru vlny 90° (E) – 180° (S) zvyšuje prítok priepustov, pretože sladkovodné zdroje zvyšujú odtok potrubia. Maximálna výmena morskej vody sa dosiahne vtedy, keď sa os potrubia skonštruuje na strednú hladinu mora.

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