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THE INFLUENCE OF THE NATURAL GENERATORS ON DISCHARGE THROUGH THE FLUSHING CULVERTS

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ABSTRACT

With growing anthropogenic activity at the coast, the seawater quality is under threat. Manmade semi-enclosed basins like harbours and marinas are focal points where the pressure is the greatest, due to its reduced ability of seawater exchange with the external seawater and therefore undesirable pollution accumulation. Flushing culverts imbedded inside breakwaters provide a viable cost-effective solution in order to improve the seawater exchange, most commonly used in small tidal range areas. With the intention of evaluating the contribution of flushing culverts to water exchange, field measurements have been conducted in ACI marina Opatija, Croatia during summer and winter periods. The influence of freshwater sources present during winter, tidal oscillations and wind action are being analysed in this paper. Wind energy has been utilized as a reference value for wind action impact on the flow through the flushing culvert. It has been observed that in addition to a greater wind velocity, a smaller angle between the direction of the wind and the direction of the flushing culvert provides greater seawater exchange through the flushing culvert.

KEWORDS: water renewal, flushing culvert, wind, breakwater

1 INTRODUCTION

Coastal water quality is under tremendous pressure due to growing anthropogenic activity that takes place at the shoreline. The growing human population on Earth is expected to rise to as much as 11.1 billion people by the year 2100. Additionally, the percentage of people living at the sea shore is also expected to further rise from the existing 60% to 75% by the year 2025 (Airoldi and Beck, 2007; United Nations, Department of Economic and Social Affairs, 2017). With the growth of population and urban areas near the shore, rising anthropogenic activities could pose a critical issue for the marine environment. Manmade infrastructure like harbours and marinas, scattered along the shoreline often provide a focal point where the water quality is under biggest threat from anthropogenic activities (Di Franco *et al.*, 2011). Urban areas utilize ports as gateways for trade of goods, therefore during high cargo traffic and manipulation unanticipated accidents could occur. Water quality degradation in harbours as a result of unforeseen events is conditioned by the type of goods handed over. Extremely volatile goods that are frequently transported like oil could have an enormous impact on the environment, if not handled appropriately (Peris-Mora *et al.*, 2005). Near densely populated areas, additional potentially harmful pollutants could be present. Heavy metals like copper have continually entered to the marine environment as a compound in ship paint and are now buried in the sediment near shipyards, waiting to be resuspended by dreading or river flood waters (Singh and Turner, 2009; Rezayi *et al.*, 2013). Harmful bacteria like E. coli could also enter the coastal waters through the sewage and as a result could be especially dangerous in the vicinity of tourist resorts where visitors are swimming near the shoreline (Bedri *et al.*, 2016). Degraded and stagnate seawater often possess a reduced amount of dissolved oxygen, which favours the development of harmful algal blooms and subsequently may further endanger the marine ecosystem (Gaitanis *et al.*, 2009; Tsoukala *et al.*, 2010). In an effort to counter the negative effects of unacceptably high pollution, pollution concentrations should be continually monitored at sensitive coastal locations.

If an optimal water renewal rate of semi enclosed basins is maintained and potential causes of pollution are controlled, detrimental effects on water quality within a harbour can be avoided (Schwartz and Imberger, 1988). Water renewal in semi enclosed basins has demonstrated to be a crucial influence controlling the chemical and biological behaviour of the marine ecosystem (Ferreira *et al.*, 2005; Borja *et al.*, 2009). The water exchange of a manmade or naturally enclosed basin is influenced by natural flow inducers (e.g. tidal oscillations, wind, waves, external currents, inner freshwater discharge, etc.). Understanding the relationship between flow inducers, harbour design guidelines and seawater renewal makes it possible to utilize hydrodynamic action in order to eliminate any harmful substance introduced into an enclosed basin (Fischer *et al.*, 1979).

Previous scientific articles offer various descriptions and empirical methods to calculate the seawater renewal efficiency of a particular basin, based either on hydrodynamic or morphological characteristics. Most seawater renewal predication approaches are essentially constructed around tidal oscillations as the leading generator of water exchange inside enclosed basins (R. E. Nece and Asce, 1984; Sanford, Boicourt and Rives, 1992; DiLorenzo *et al.*, 1994), permitting the differentiation of the tidal influence on harbour seawater exchange largely upon the latitudes difference. The water renewal effectiveness is also influenced by structural features such as the plan form geometry of a port, inlet width, water depth, bed slope, etc. which is well examined (B. R. E. Nece and Asce, 1984; Falconer and Guoping Yu., 1991; US Army Corps of Engineers, 2002). In areas where tidal oscillations are significantly smaller like the Mediterranean Sea, the water renewal is also reduced considerably. In these areas, it is common to use flushing culverts (pipes or rectangular openings in a breakwater body) in order to improve the ability of water exchange of the seawater inside the port (Tsoukala and Moutzouris, 2009; Bujak, Carević and Mostečak, 2017; Lončar *et al.*, 2017).

Perhaps the second most dominant instrument of sea water renewal in semi enclosed basins is wind action. Investigations using numerical models, developed to analyse the Venice lagoon seawater circulation, display a valuable improvement of seawater renewal (in two inlet basins) with the occurrence of a local sea level rise (sea surface slope) within the basin generated by wind (Umgiesser *et al.*, 2014). As observed on the numerical model of the Venice lagoon, the northeast wind creates a surface slope with the surface level being locally higher in the south than in the north. Once the slope is formed, a steady circulation is developed where water comes at the northern inlet and leaves at the southern one, vastly improving water renewal through the whole basin (Cucco and Umgiesser, 2006). Wind stress on the sea surface, that enables momentum transfer from air to seawater, depends on the velocity squared, air density and drag coefficient (Wu, 1969; Large and Pond, 1981). Other research determined that wind is not meaningfully impacting the water renewal in restricted one inlet basins where the wind is primarily mixing the confined seawater in comparison to the Venice lagoon that has multiple inlets (Canu *et al.*, 2012; Umgiesser *et al.*, 2014). The purpose of flushing culverts placed inside breakwaters is to improve the water renewal within an enclosed maritime area, without permitting unwanted wave energy to enter and disturb the harbour basin. Flushing culverts are considered the most cost-effective method of improving water renewal in port engineering.

In this paper, the influence of the various natural flow generators on flushing time is investigated using field measurements conducted in real conditions in marina Opatija. Measured flow of seawater passing through the culvert, in relationship with wind data, were observed and analysed.

2 FIELD MEASURMENTS

In order to provide a deeper insight into the circulation patterns during the presence of various flow generators, field measurements were performed in ACI marina Opatija in northern Croatia, near the city of Rijeka (Figure 1). Since small tidal oscillations at the location were not expected to provide sufficient water renewal through the inlet on their own, marina designer decided that flushing culverts should be built in the marina. Consequentially, the marina primary rouble mound breakwater has a configuration of 8 parallel 1 m diameter culverts placed at the southern part of the marina with the intention to improve water renewal inside the basin. Regarding vertical positioning, culverts were laid so the top of the circular culvert would be placed at mean sea level. The marina is connected to the Adriatic Sea with a 30 m wide inlet (entrance into the marina) and the already mentioned additional 8 flushing culverts. The inlet is constructed at the, opposite to the culverts, northern part of the marina. A vertical seawall was constructed on the shoreline, stretching the whole length of the marina. The mean depth inside the marina is approximately 5 m, with the depth decreasing in the vicinity of the breakwater.

Figure 1. Plan view of the ACI marina Opatija with locations of measuring devices during the winter measuring period and sea surface slopes (S1 and S2) defined near the flushing culverts

The sheltered area extends approximately 350 m alongshore and 150 m cross-shore, forming an area of about 40 000 m^2. The marinas longitudinal axis is oriented approximately 45 degrees from true north. At the Opatija marina regular winds are present although they are not as strong in terms of velocity. The marina location is protected by surrounding islands and therefore previously documented wave events were formed in the vicinity of the marina due to wind. The tidal range is about 0.4 meters at the location of the marina. Freshwater sources at the shoreline have been previously observed by the local residents in the region.

Utilizing field measurements, processes that are hard to produce, capture and measure in a laboratory like wind action, wind and wave interaction and other flow generators could be analysed. In order to take the differences between winter and summer into account, two measuring campaigns were conducted. The first measuring campaign spanned during the last winter months, precisely between February 2nd and March 31st and the second measuring campaign was performed between July 4th and August 31st. Five Acoustic Doppler Current Profilers (ADCPs), one portable flow measurement system for pipes (PCM), one anemometer, one CTD probe and a time lapse camera were placed in ACI marina Opatija during the measuring periods (Figure 1).

Two out of five ADCPs were placed at each side of the flushing culvert (ADCP1 and ADCP2), one was positioned in the centre of the marina (ADCP5), one at the inlet to the marina (ADCP4) and the last one about 100 meters west of the marina location (ADCP3). During the summer period all the measuring devices were positioned at the same location as during the winter except ADCP3, which was moved next to ADCP4 at the marina inlet in an attempt to measure the flow rate through the inlet. Only ADCPs 1 and 2 were measuring wave conditions (wave height, peak wave period and direction of the peak wave period) and sea currents, while the other ADCPs were measuring only sea currents. ADCP1 and ADCP2 provided a burst for 60 s with a sampling rate of 1 Hz every 10 min, while the wave parameters were recorded every 15 min with the same burst characteristics of 2 Hz sampling rate for 60 s. ADCP3 and ADCP4 had the same sampling and output rates regarding the current, but the waves were not recorded. The pipe flow measuring sensor was positioned inside one of the flushing culverts. The device recorded velocities, surface level and subsequently flow inside the culvert. The flow measuring device was powered by external batteries packs in a separate compartment and it outputted data every 2 min with a sampling rate varying depending on the hydraulic and physical conditions of the flow in the culvert (cannot be controlled by the user; programmed by the manufacturer). The flow measuring device will provide valuable data about the flow rate that can be later linked with the properties of different natural generators of flow (e.g. wind, waves and tidal oscillations). A CTD device was fixed next to the flow measuring device in order to recorded the physical characteristics of the sea inside the culvert, 40 cm above the bottom of the culvert. The sampling and output rate for temperature, salinity and density measurements by the CTD device was 1 Hz. The anemometer was deployed at the head of the breakwater, on a lighthouse, where sufficient height would avoid inaccurate wind measurements due to obstruction with vessels. Wind velocity and direction data in the horizontal plane were provided by the anemometer. Because the anemometer was connected into the marinas power grid, power consumption did not pose a problem and therefore the sampling and output rates were constant throughout the measuring period as low as 1 Hz. Vessel count and their positions inside the basin, were taken by a time lapse camera positioned on a high point of view. The sea surface slopes S1 and S2 were defined using the depth measurements of the corresponding ADCPs. In the case of surface slope S1, ADCP1 and ADCP2 depth measurements were utilized. While ADCP2 and ADCP5 depth measurements were used for the slope S2.

The raw data presented by the measuring devices had different frequencies of measurement, ranging from 1 Hz to 0.001 Hz depending on the power availability to the device. With the intention of easily comparable data between different devices, the data has been hourly averaged. This data averaging is considered reasonable because flushing times of most harbours and marinas are in the order of days.

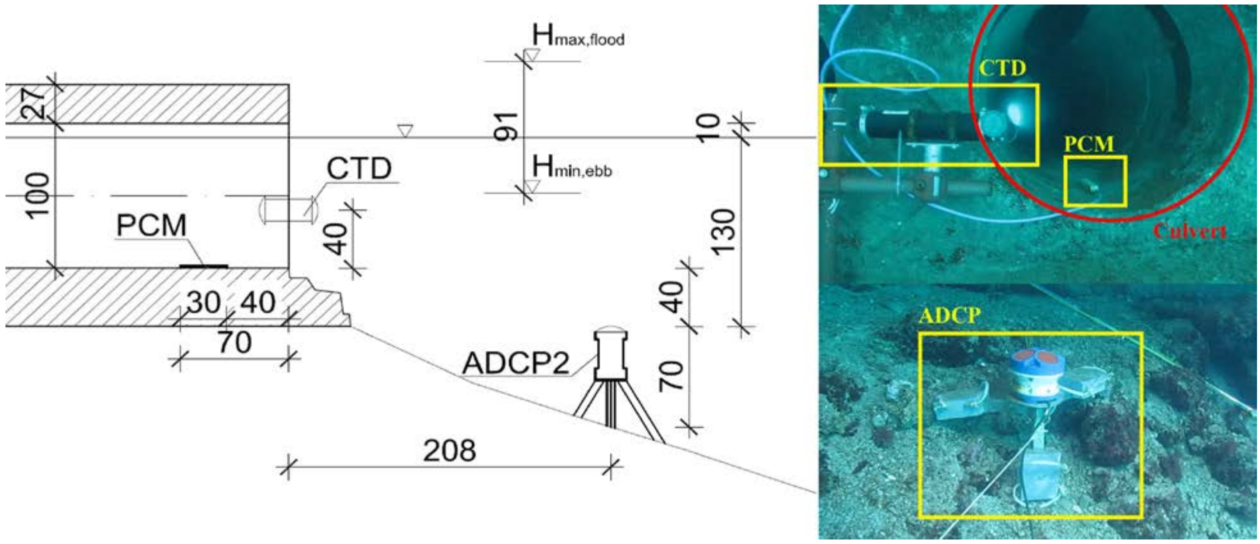

Figure 2. Cross section through the flushing culvert and mmeasurement devices (ADCP2, PCM, CTD) mounted at their respective positions at marina Opatija

3 RESULTS AND DISCUSSION

3.1 Influence of submarine freshwater sources

Measurements utilizing the CTD probe present a vertical salinity distribution near the surface, which point to a stratified state regarding salinity inside the marina during the winter measuring period (Figure 3). The salinity at a depth of 0.2 m falls off to nearly 15 psu, which would indicate a layer of freshwater of a few centimetres at the surface. A probable cause of the surface salinity reduction are the freshwater sources previously acknowledged by the local residents in the region near the location of the marina. Freshwater is entering through the seashore made of karstic rock into the costal basin. Since freshwater has lower density then salty seawater, it was expected that the freshwater fluxes would drift above the salty seawater, which results in a thin layer of freshwater on the surface. The salinity naturally diffuses over time to the upper thin freshwater layer and therefore produces a transition layer between the freshwater and salty seawater. At a depth of 1 m the salinity had already increased to 37.5 psu and continues linearly to the bottom where its value rises to 38.0 psu. The salinity distribution below 1 m was established with the use of vertical CTD measurements at measuring device locations in the marina on the day of deployment and retrieval of measuring devices. It could be estimated that the salinity transition layer ends at a depth of roughly 1 m.

The same freshwater influence was not observed during the summer measuring period, with the seawater salinity throughout the whole measuring depth, from 0.2 m to 1 m, staying constant at about 38.0 psu. This could indicate that freshwater fluxes are not present or at least not as strong during the summer as they were during the winter. The vertical salinity measurements of the entire depth during the measuring instrument deployment and retrieval confirm a constant salinity to the bottom.

It can be further observed that daily rainfall, measured at the nearest rain gauge in Rijeka during the summer period, is not a significantly smaller amount than in the winter (Figure 3). The city of Rijeka is located approximately 10 km in the western direction from the site of ACI marina Opatija. Although rain in Rijeka does not necessarily implicate rainfall at the location of the marina, the recordings on the time lapse camera were observed and there was indeed rainfall at the marina when rainfall in the city of Rijeka was measured. In summary, during the entire winter period there were 120 mm of rain measured in Rijeka and during the summer 95 mm of rain. In the course of the winter, the amount of 38 mm was the highest recorded value of daily rainfall and during the summer the highest value was 28 mm. If the length of the measuring period is considered, the winter measuring period was shorter in comparison to the summer measuring period, with the winter measuring period taking 33 days and the summer period lasting 58 days. The average rainfall during winter and summer periods are 3.64 mm/day and 1.64 mm/day respectively. The discrepancy, between the rainfall and salinity response inside the marina, would suggest that the measured rainfall does not necessary translate into freshwater outflows in the region where ACI marina Opatija is located.

If freshwater sources at the coast are nevertheless caused by rainfall, the vegetation on the steep slopes located just above the marina probably play a role. During the summer temperatures are higher and the vegetation flourishes, therefore the combination of higher evapotranspiration by the vegetation and dryer ground results in less runoff through the small natural channels to the coast. In addition, during February and March snow previously accumulated at the peak of the Učka mountain should start to melt which provides extra freshwater runoff down the mountain slope.

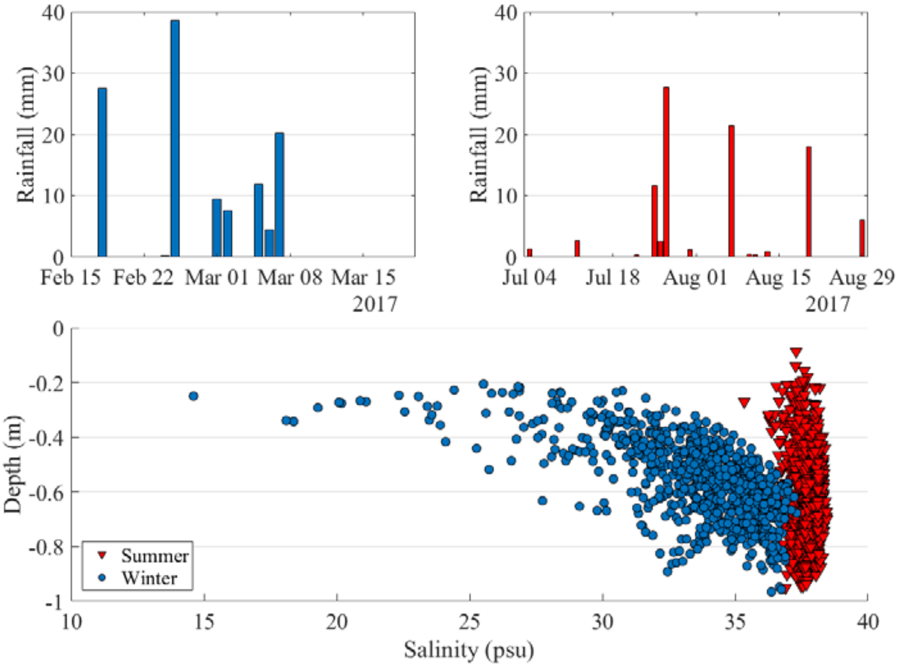

Figure 3. Daily rainfall measurements conducted at a rain gauge in the city of Rijeka and vertical salinity distribution near the sea surface measured by the CTD probe during the winter and summer measuring periods

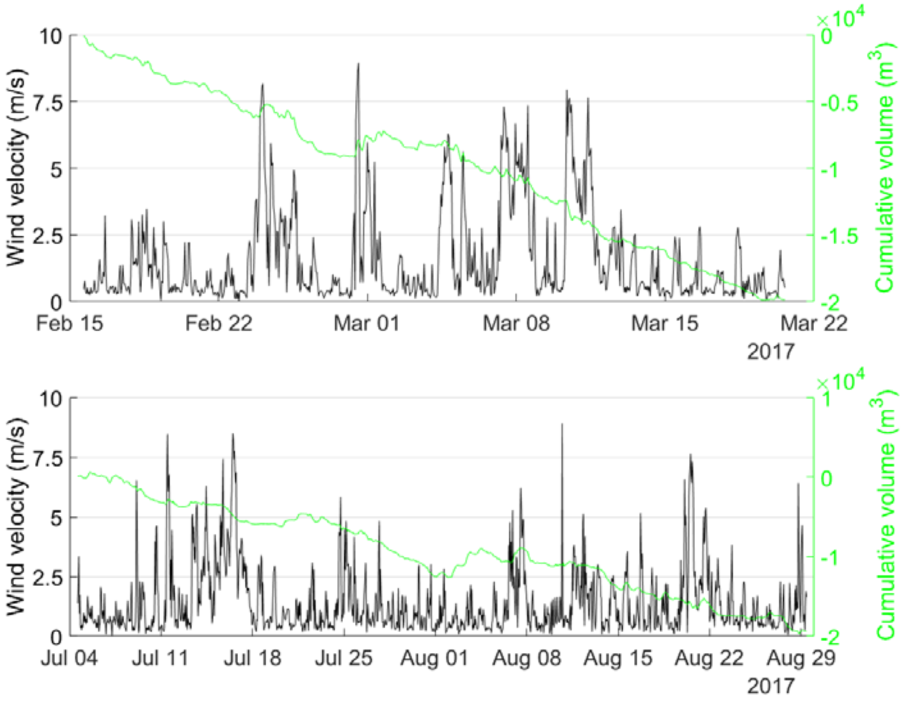

Figure 4. Time series of wind velocity measured by the anemometer at the head of the breakwater and cumulative volume that passed through one flushing culvert measured by the flow measuring device (PCM) during summer and winter; a negative value is assign to outflow from the marina and a positive to inflow into the marina

During both winter and summer periods an overall average outflow through the flushing culvert has been observed. Thorough the course of both measuring intervals about the same amount of seawater has cumulatively left the marina through one flushing culvert, roughly 20000 m^3 (Figure 4). Because the summer measuring period was somewhat longer, taking as long as 58 days in comparison to 33 days measuring period during the winter, the average cumulative flow through the flushing culvert for the two measuring periods are rather different (Table 1). During the winter the mean cumulative flow is estimated at 25 m^3/h and in the course of the summer it dropped 40% to a value of 15 m^3/h. Although a general outflow trend is observed during both measuring periods, short periods of inflow can be also detected. In the course of the winter most inflow periods, of short duration albeit of noticeable inflow volume, occurred during southern wind events. Long inflow volumes have been also recorded during the summer with no wind and wave action present at the marina.

If the absolute volume sum amount of water that has passed through the flushing culvert in both directions is considered, the summer time has seen more water exchange between the two measuring periods. This again can be contributed to the longer measuring period, because the average value of flow in both directions during the summer (55 m^3/h) is actually 15% less than the average value during the course of the winter (64 m^3/h). The discrepancy between the percentage drop of the measured flow between the cumulative hourly average flow through the culvert and the absolute hourly average flow is due to the different amounts of inflow that occurred in each period. During the summer measuring interval, a noticeably larger amount of water entered through the flushing culvert into the marina. In regard to the absolute sum volume that passed through the culvert, in the course of the summer 37% of the volume has been inflow and during the winter 30%. If only tidal forcing would act on the water inside the marina, we would naturally expect for this percentage to be around 50%. A higher value of mean inflow and a smaller sum of inflow during the entire winter measuring period would suggest, in general, strong and short bursts of flow entering the marina mostly during wind and wave situations. Whereas for the duration of the summer, the inflow lasted a longer time and was less intensive in comparison to the winter period. The values of the mean outflow through both measuring intervals are nearly same, with the summer mean outflow being only 6% less than the winter outflow. Comparable values of the mean outflow for both periods would suggest that freshwater sources, detected in the winter with the CTD probe, did not have a substantial impact on the amount of water flow passing through the flushing culvert.

Table 1. Statistical values regarding the flow measured inside the flushing culvert; a negative value is assign to outflow from the marina and a positive to inflow into the marina through the flushing culvert

	Measurement duration (day)	Sum inflow (m^3)	Sum outflow (m^3)	Sum (m^3)	Absolute sum (m^3)	Mean (inflow) (m^3/h)	Mean (outflow) (m^3/h)	Mean (sum) (m^3/h)	Mean (abs. sum) (m^3/h)
Winter	33	15551	-35391	-19840	50942	73	-60	-25	64
Summer	58	28791	-48175	-19384	76966	54	-56	-15	55

3.2 Influence of tidal oscillations

In order to investigate the slope variation throughout the measuring periods, the slope time series were subdued to a high pass filter in order to exclude the low frequency variations due to atmospheric and oceanographic effects from the total slope variation. Firstly, a low pass filter was constructed using the Butterworth IRR signal processing filter design (Roberts and Roberts, 1978). The sample rate of the signal was 1 Hz, the passband frequency for the filter design was defined at 1/120 Hz and the stopband frequency at 1/96 Hz. This low pass filter design would filter out phenomenon whose periods were lower than 4 days, which in effect would remove the effects of tidal oscillations, winds, waves and so forth. Next, if the high frequency signal would have needed to be observed, the low pass filtered signal time series is subtracted from the total signal time series. As a result, the high frequency time series signal includes only effects that have a period lower than 4 days, like tidal oscillations, etc.

If the high frequency slope time series is observed, sea surface slopes mainly correspond to the tidal oscillations. When ebbs are present, a downward sea surface slope is observed on slope S1 through the flushing culvert from ADCP2 to ADCP1 also designated with a negative slope value (Figure 5). A negative S1 slope corresponds to seawater outflow through the flushing culvert, which is expected during ebbs. During ebbs a downward sea surface slope, designated with a negative slope value, is also observed on slope S2 from ADCP2 to ADCP5, which corresponds to seawater flow from ADCP2 to ADCP5. During floods the sea surface slopes are naturally reversed and therefore correspond to inflow into the marina which is also anticipated. Therefore, the surface slopes correspond to the expected flow direction during tidal oscillations. In the course of both floods and ebbs, the depth at ADCP5 responds faster to the tidal oscillations of sea surface outside of the marina than the depth at ADCP2. This would suggest that the inlet (main entrance into the marina) is still a stronger influence on the on the depth at position where ADCP5 is located, although ADCP5 is actually located significantly closer to the flushing culverts. A significantly bigger flow rate through the inlet than the flow rate through the flushing culverts is expected to be the cause of this particular flow pattern. The sea surface slope data will be further assessed in relation to flushing culvert flow rate and utilized as boundary conditions in future planned numerical modelling studies.

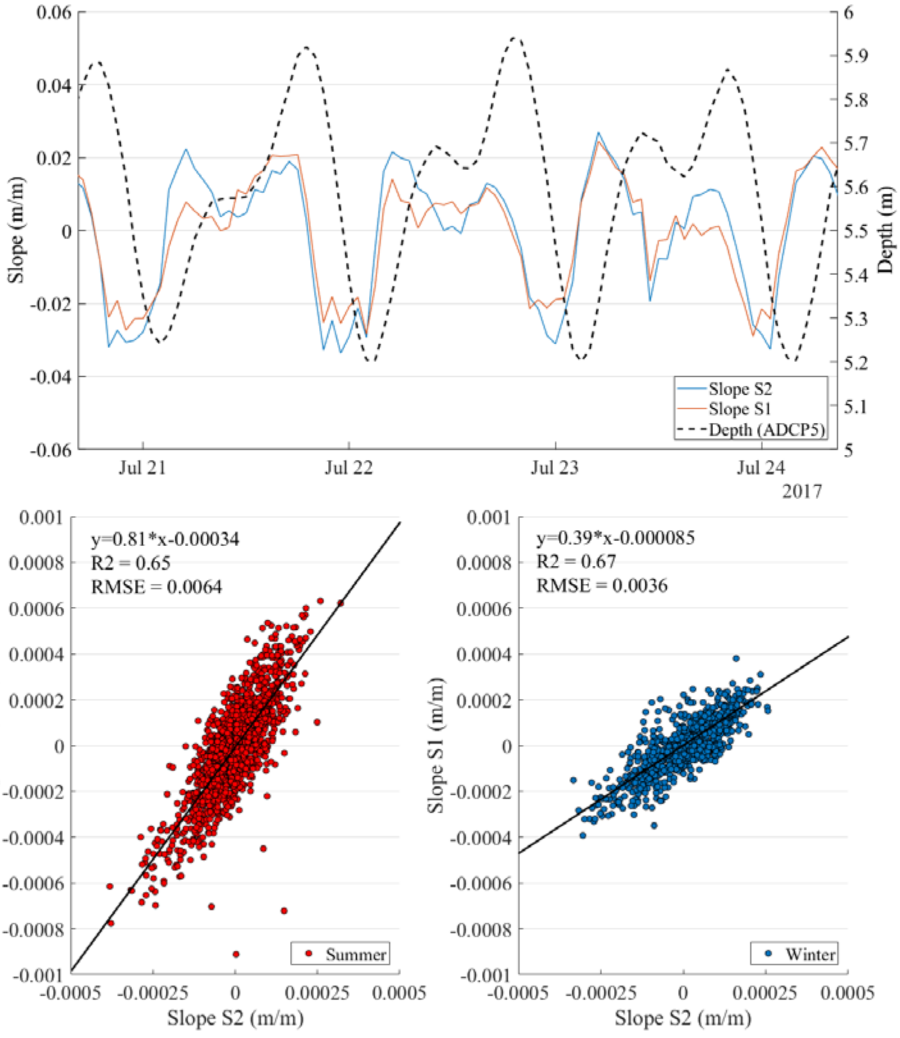

Figure 5. a) Time series segment of depth and slopes measurement inside the marina and b) Correlation between the slope from the centre of the marina to the leeward side of the flushing culvert (S2) and slope through the flushing culvert (S1); A positive slope S1 responds to a downward slope from ADCP1 to ADCP2 and a positive S2 slope responds to a downward slope from ADCP5 to ADCP2

Figure 6. Tide and ebb flow pattern inside the marina according to sea surface slopes measured with ADCPs

3.3 Influence of wind

The wind climate between summer and winter periods has presented some differences (Figure 4). For the duration of the winter the winds have been longer, sometimes taking up to 1.5 days, while during the summer the duration of the wind events tends to last only for a few hours. The peak wind velocities in the course of the winter also tend to be a little higher, with hourly averaged velocities maxing out at roughly 8 m/s. The first three wind events during the winter measuring period are incoming from the south-southeast, with a tendency to generate waves. These wave situations tend to have hourly averaged significant wave heights measured with ADCP1 in front of the culvert from 0.8 m to 1.1 m depending on the wind event. The last two wind events are incoming from the north-northeast and do not produce waves due to their direction, although they do produce higher water exchange through the culvert. During the summer winds are most of the time incoming from the north-northwest and east directions, with the winds from the east direction producing wave situations with hourly averaged significant wave heights in front of the culvert ranging from 0.5 m to 0.6 m depending on the wind.

The wind influence can be observed on the sea temperature measurements. To begin with, the sea temperature measurements conducted with ADCP and CTD devices point to a strong relationship between the air temperature and the sea temperature during summer (Figure 7). Reasonably, if the air temperature is higher than the sea temperature, it warms the sea and gives rise to sea temperature at all observed locations and depths. On the other hand, if the air temperature is lower than the sea temperature, it cools the sea. The sea temperatures were not as sensitive to air temperature fluctuation in the winter like they were during the summer. Nevertheless, a rising air temperature trend is observed with a corresponding steady sea temperature rise throughout the measuring period.

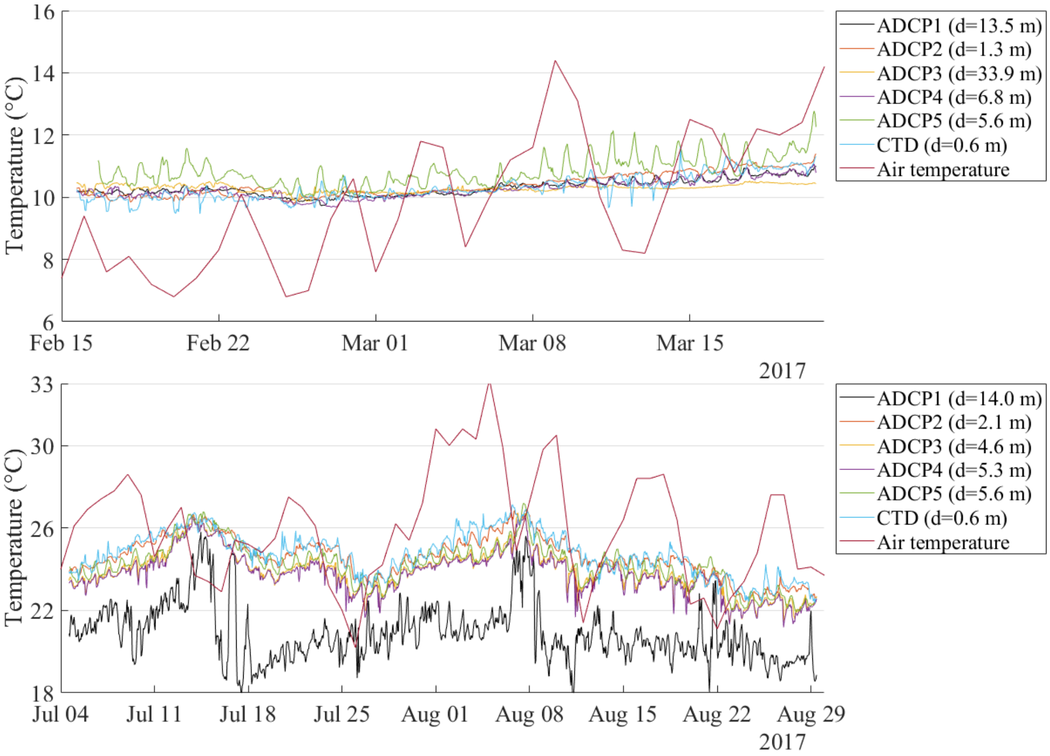

Figure 7. Time series of measured temperatures at various sea depths by ADCP and CTD probes with air temperature recorded in Rijeka during the winter and summer measuring periods

For the duration of the summer measuring period, only measurements done with ADCP1 do not follow the temperature trends measured with other devices as precisely because the mentioned ADCP is positioned at a greater depth of 14 m outside the marina in front of the culvert. This suggests a strong stratification in temperature trough the water column during summer which was also verified with vertical CTD measurements on the day of measuring instrument deployment and retrieval. While most of the time there was a constant temperature difference between the sea temperature measured with devices positioned closer to the sea surface and the sea temperature measurements by deeper positioned measuring devices (the difference in temperature corresponds to the depth difference magnitude between devices), there were three distinct situations where the sea temperature at the bottom of the marina was the same as the sea temperature at the surface. Even the temperature at the sea bottom just outside the marina at the position of ADCP1 witnessed a significant temperature jump during said events. These situations lasted approximately for 1 day and their respective dates were as follows: July 16, August 7 and August 21. These events are in conjunction with strong wind events with an hourly averaged wind velocity of at least 6 m/s with a general northeast direction. The vertical temperature equalization through the water column is probably due to seawater mixing induced by wind inside the marina. While the same wind events produced downwelling as a consequence of north-eastern winds which manifested in a significant sea temperature drop at the sea bottom outside of the marina at ADCP1. As a result, the less dense and warmer surface seawater submerged to the bottom at the coast equalizing the measured values of temperatures at several depths.

The probable Ekman transport induced downwelling could not be deduced in the winter because the sea temperatures where more vertically uniform during the measuring period and therefore, no differences in sea temperature could be observed during strong northeast winds. Temperature readings in the centre of the marina (provided by ADCP5) reveal significant temperature jumps of about 1 °C on a daily basis, primarily during ebbs, during both winter and summer periods. As the sea temperature is more vertically uniform during the winter in comparison to the summer, these jumps in sea temperature are more pronounced during the winter period, even though they also occur in the summer.

Wind has already been identified as a major contributor to seawater exchange through the flushing culverts. Specific wind power could be identified as a reference value for the influence of wind action on the water exchange. According to previous research (Wu, 1969), wind stress on sea surface was defined as

$$\tau = C_d \cdot \rho \cdot v^2, \tag{1}$$

where C_d is the drag coefficient, ρ is the air density (1.22 kg/m^3) and v is the wind velocity. To present the wind stress as wind power per area, Equation (1) should be multiplied with velocity and resulting in

$$\tau \cdot v = C_d \cdot \rho \cdot v^3 = P/A. \tag{2}$$

If the velocity range is between 4 m/s and 11 m/s, a commonly assigned value to the drag coefficient is 0.0012 (Large and Pond, 1981). To estimate the amount of wind energy transferred to the sea surface during one wind event, the specific wind power defined with Equation (2) has been integrated through time for each wind event with a distinct direction. Consequently, resulting in one wind energy value that specifies the amount of energy that has been transferred to the sea, for each wind event.

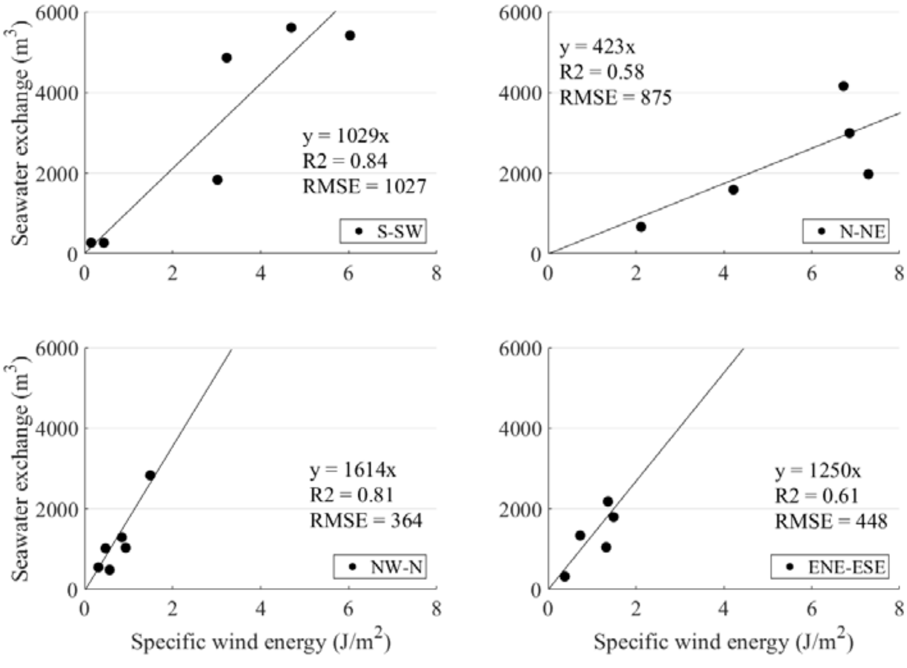

Figure 8. Seawater exchange through the flushing culvert imbedded in the breakwater due to wind action from 4 directions: a) From south to southwest b) From north to northeast c) From northwest to north d) From east-northeast to east-southeast

Wind events from distinct directions will be observed separately, in order to assess the most effective wind direction at sea water exchange at the location of the marina. Water exchange will be defined as an absolute value, taking into account the sum of flow through the flushing culvert in both directions. The time series of seawater exchange measured in the flushing culvert using a PCM is subjected to high pass filtering, again utilizing the Butterworth method (Roberts and Roberts, 1978) previously used to for filtering sea surface slopes between ADCP locations, in order to remove the influence of high period effects (periods higher than 4 days) on flow production through the flushing culvert imbedded inside the breakwater. It should be also noted that the flow through the flushing culverts due to tidal oscillations are not excluded by said filtering process.

Specific wind energy delivered to the sea surface at the location of the marina and water exchange through the culvert seem to have a linear relationship (Figure 8). Wind events from the northwestern and eastern direction have generally produced smaller amounts of wind energy, because these summer winds are a lot shorter in duration (mostly about 6 hour) in comparison to the southwestern and northeastern winds in winter (up to 36 hours). Wind events with a north-northwestern general direction appear to have the most effective wind energy transfer to the sea surface (Figure 8 c)). On the other hand, the winds from the north-northeast seem to yield the least effective energy transfer to water exchange through the flushing culvert (Figure 8 b)). The less effective north-northeastern winds are almost 3.8 times less efficient than the north-northwestern winds. The reason for the significant difference in the efficiency of energy transfer is probably due to the angle between the direction of the wind and the direction of the culvert. The angle between the wind direction and culvert direction in the case of the most effective energy transfer wind events is only 20°, while in the least effective case the angle is bigger at 65°. It could be concluded that in order to maximise water exchange through the flushing culvert, it is favorable to direct the flushing culvert in the direction of the dominant winds in the area.

Although winds approaching from the south-southwest also have a rather large angle to the flushing culvert at 65°, the wind energy transfer to water exchange efficiency appears to be 2.5 times more effective than during north-northeastern winds. This is probably due to wind waves, generated by the wind far off the marina location, arriving to the flushing culvert and producing additional flow. Therefore, waves present an impact on water exchange through the flushing culvert comparable with wind effects themselves.

The transfer of wind energy to the sea surface can manifest itself through wind setup, wave induced currents, wind waves and so forth. From the sea surface slope measurement between the entrance of the marina (ADCP4) and the centre of the marina (ADCP5), no visible wind setup response to winds in the longitudinal direction was observed as suggested by previous research in the Venice lagoon (Cucco and Umgiesser, 2006). This discrepancy is probably due to the significantly smaller length of the basin in the longitudinal direction at marina Opatija, with a length of only 350 m in comparison to the longitudinal length of tens of kilometers in the Venice lagoon. The very small length of the basin omits significant wind setup responses inside the marina. The vessels present inside the marina probably also have an adverse influence on wind setup. The response of the temperature vertical distribution at the marina during north-northeastern wind events suggest wind induced currents which may also be the generator of flow through the flushing culverts.

4 CONCLUSION

In this work, the influence of various generators of flow was observed using field measurements conducted in ACI marina Opatija. Field measurements were conducted during both winter and summer season in order to encompass season atmospheric and oceanographic variability.

In the course of the winter significant freshwater inflow through the karst into the basin was detected, whereas during the summer the freshwater sources seemed to be inactive in the marina. The rainfall during winter and summer periods was comparable in magnitude, which therefore point to a non-causational relationship between the rainfall and freshwater sources or a significantly different impact of vegetation in the region to the rain runoff between the two measuring periods. The summer mean outflow through the culvert witnessed a 6% reduction in comparison to the winter mean outflow, with freshwater sources probably being the main cause of the minor difference.

Sea surface slopes during both summer and winter coincide with the expected flow directions during ebbs and floods. In regard to the sea surface slopes, the flow pattern inside the marina suggests a stronger influence on the tidal oscillations in the centre of the marina through the inlet than through the flushing culverts. This was observed even though the distance from the centre of the marina to the flushing culverts was two times smaller than the distance to the inlet.

Wind energy as a reference value of wind action influence on the water exchange rate, point to a substantial impact of the angle between wind direction and flushing culvert direction. It is preferred that the angle between the wind direction and the culvert direction should be as small as possible in order to provide significantly larger amounts of water exchange. Wind induced currents and waves seem to be the main mechanism that provide water exchange through the culvert by wind action, with wind setup not manifesting itself in the marina during wind events, probably due to the extremely short longitudinal length of the marina.

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