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Measurement and analysis of salinization at the Rječina estuary

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Preliminary note

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Measurement and analysis of salinization at the Rječina estuary

A number of salinity measurements were made in the first half of 2012 at the lower reaches of the Rječina River. The presence of stratified fresh water flow above the salt water wedge was established at the estuary of the Rječina River. Several regression analyses were made in order to describe functional relationship between the Rječina flow rate and the salt wedge length. The comparison of measured salt wedge dimensions and the Keulegan semi-empirical expressions is also presented in the paper.

Key words:
Rječina, salinity, salt wedge, measurement, regression, Keulegan

Prethodno priopćenje

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Mjerenje i analiza zaslanjivanja na ušću Rječine

Tijekom prve polovine 2012. godine proveden je veći broj mjerenja saliniteta u donjem toku Rječine. Pokazalo se kako je u ušću Rječine prisutno uslojeno tečenje slatke riječne vode iznad klina slane morske vode. Izrađeno je nekoliko regresijskih analiza koje opisuju funkcionalnu vezu protoka Rječine s duljinom slanog klina. U radu se također prikazuje usporedba izmjerenih vrijednosti dimenzija slanog klina s Keuleganovim poluempirijskim izrazima.

Ključne riječi:
Rječina, salinitet, slani klin, mjerenje, regresija, Keulegan

Vorherige Mitteilung

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Messung und Analyse der Versalzung an der Mündung des Flusses Rječina

In der ersten Hälfte des Jahres 2012 wurde eine bedeutende Anzahl von Messungen des Salzgehaltes im Unterlauf des Flusses Rječina durchgeführt. In der Mündung des Flusses konnte über dem Salzwasserkeil ein geschichteter Süßwasserstrom festgestellt werden. Eine Reihe von Regressionsanalysen ist durchgeführt worden, die den funktionellen Zusammenhang der Strömung des Flusses Rječina mit der Länge des Salzwasserkeils beschreiben. Außerdem ist in der Arbeit ein Vergleich der durch die Messungen erhaltenen Bemessungswerte des Salzwasserkeils mit den semi-empirischen Ausdrücken nach Keulegan dargestellt.

Schlüsselwörter:
Fluss Rječina, Salzgehalt, Salzwasserkeil, Messung, Regression, Keulegan

1. Introduction

The Rječina River is a typical example of a coastal karst river. It is at the estuary of this river that the town of Rijeka was formed in ancient times and has been developing ever since. The area surrounding the lower reaches of the Rječina has a considerable urban development potential and the tendency of being transformed into the central park of the town of Rijeka [1] whose maintanance would require certain amount of water for irrigation needs. Along with the unavoidable problem of seeking an alternative to drinking water use for street cleaning, it is obvious that there is strong basis in the city of Rijeka for qualitative and quantitative analysis of waters at the lower reaches of Rječina river for various municipal needs.

In general, an estuary is a transition area where fresh river water mixes with sea water. The intrusion of sea water upstream of the river mouth can vary from several hundreds of meters to as many as several hundreds of kilometres, which depends on hydrological conditions, sea tides, and channel bathymetry [2].

The presence of chlorides can affect the quality of water and make it unusable for municipal or agricultural purposes. In that respect, the process of sea water intrusion into the Rječina estuary must be analysed in order to define optimum position of water intake from the area with sufficiently low salinity. The interaction between the sea water and fresh water is a highly complex hydrodynamic problem, which involves a number of processes that have not as yet been sufficiently clarified [2]. Several approaches are currently used: regression methods, empirical expressions, physical models, 1D models of stratified flow and, more recently, 3D numerical models [3, 4, 5]. Although these approaches differ from each other, a requirement common to all of them is the need to conduct field measurements involving a whole array of influence parameters [2].

Depending on the sea water / fresh water mixing intensity, an estuary can be either fully mixed, partly mixed, or a "salt wedge" can be formed. The wedge shaped salinity structure is characterized by a very low turbulence mixing and by a pronounced vertical stratification, with the presence of halocline (discontinuity in salinization), or pycnocline (discontinuity in density). This estuary type is formed in areas with relatively high flow rates, and with very small tidal oscillation amplitudes, i.e. in the so called microtidal seas (amplitudes of less than 2.0 m). [2]

The stationary state in which the salt wedge occurs is called the "arrested salt wedge", and its dimensions have been analysed in full detail from theoretical [6] and experimental [7] standpoints.

2. Investigation zone

The Rječina River is a relatively short allogeneic karst river measuring 18.6 km in length. Its source is at the Rijeka hinterland at 325 m asl, and the river ends at the very centre of the town where it enters the Adriatic Sea. Water resources from the Rječina are mainly used for two purposes: for generation of hydroelectric power (run-of-river hydropower plant with water intake at Valići Dam, and engine room at the centre of the town), and for water supply (main intake points are located at the Rječina spring and at the Zvir Spring).

The water regimen in the middle and lower reaches of the Rječina has changed significantly after construction of the 35-meter high concrete gravity dam Valići In 1969, and following formation of the accumulation of about 0.47 million of cubic metres near the town of Grohovo (Figure 1) [8].

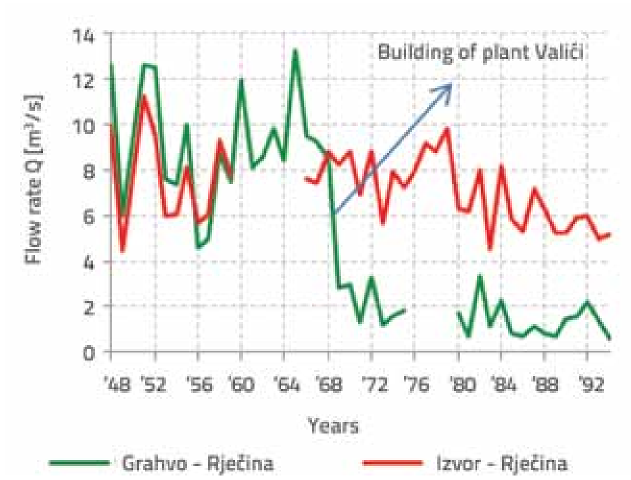

Figure 1. Mean annual flow-rate variations at the stations of Source-Rječina and Grohovo-Rječina (1948-1994) [8]

The Valići Water Storage Reservoir functions as a diurnal balancing reservoir for the Rijeka Hydropower Plant which is located at the very centre of the town. The water transported to the plant via a 3.1 km long tunnel with the capacity of 10.5 m^3/s. Downstream of the dam, the riverbed is dry during most parts of the year, except in periods abounding in water when the dam is overflown. The Zvir Spring is situated at the lower reaches of the Rječina, some 1,700 m away from the sea, at 4.7 m asl. This is the most abundant spring in the wider area of the town of Rijeka. Appropriate construction works were made at the spring site to form a calm lake 24 m in diameter which discharges, at its south side, into the Rječina riverbed. Immediately downstream from the Zvir Spring, the overflowing water from the Rijeka Hydropower Plant also flows into the Rječina riverbed. All these elements of the lower reaches of the Rječina River are shown in Figure 2.

After big flooding occurrences and extensive regulation works conducted in the 19th century at the Rječina estuary, a terrain triangular in shape, and hence named Delta, was formed between the Dead Canal (old Rječina riverbed) and the new Rječina riverbed. The new Rječina riverbed has been extended by long term earth filling activities, and so the present day estuary is bordered with the Delta on the one side, and with the Brajdica Port on the other side (Figure 3).

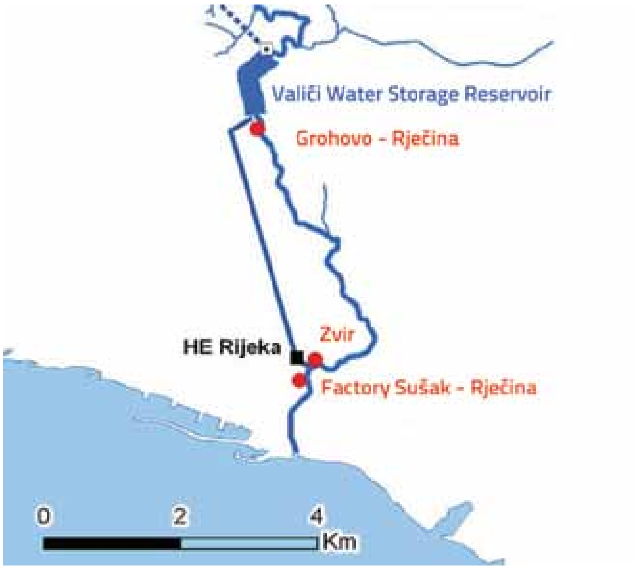

Figure 2. Disposition of water resources and hydrological observing stations at the lower reaches of the Rječina basin

Figure 3. Delta and Rječina estuary zone (photo by: Rino Gropuzzo)

Tidal oscillations at the Adriatic Sea are of mixed type, which means that semi-diurnal components, with two tidal exchanges in a single day, are dominant in one period while diurnal components, with one daily exchange of tides, are dominant in an another period. Daily tidal amplitudes continuously rise from the south part of the Adriatic toward the northern Adriatic, and so the mean daily amplitude of 30 cm was determined based on long-term measurements at the mareograph in Bakar.

The Adriatic Sea has a relatively high mean salinity of 38.3 ‰, when compared to the mean salinity of oceans which amounts to 35 ‰. [9].

3. Hydrological analysis of the lower reaches of the Rječina River

Observations at the downstream-most hydrological station "Sušak Factory – Rječina" have unfortunately not been conducted continuously, mostly due to lack of maintenance and frequent breakdowns at the station. Considering the significance of this final section, the measurements were nevertheless resumed in 1998 (albeit with some shorter interruptions) which enabled a more recent hydrological analysis for the 1999 to 2011 period. The mean annual flow rate at this section (1999 to 2012) amounts to 10.4 m^3/s with a slightly increasing trend, which is somewhat lower when compared to previous mean annual flow rate analyses for the same section, amounting to 12.9 m^3/s. These analyses are based on the balance for the entire drainage basin (1961 – 1990) [10]. This difference can be explained by a relatively short series of years covered by the analysis, which also includes very dry years of 2003 and 2007.

Mean monthly flow rates for the period from 1999 to 2011 are characterized by pronounced seasonal oscillations. Thus, maximum mean monthly flow rates were registered in winter months (51.1 m^3/s in December 2010), while minimum mean monthly flow rates were observed in summer months (0.14 m^3/s in August 2003) when the Rječina spring typically dries up, and so the overflowing waters of the Zvir Spring actually contribute the most to the water balance in the lower reaches. Statistical parameters of mean monthly flow rates at the Sušak Factory – Rječina Station, for the period from 1999 to 2011, are shown in Figure 4. In addition to mean values (*sr*), the minimum (min) and maximum values (max), as well as threshold exceedance probabilities 75 % (Q75 %), 50 % (Q50 %) 25 % (Q25 %), are also presented.

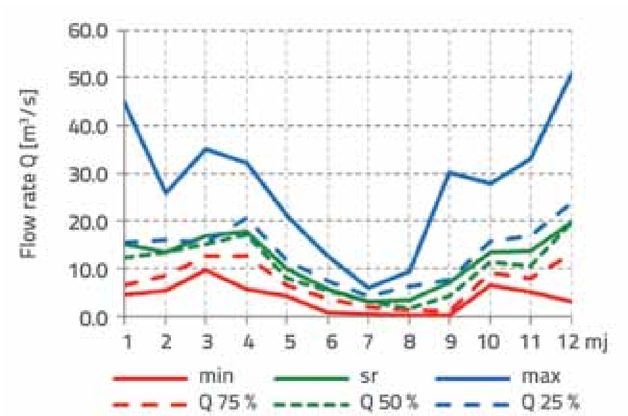

Figure 4. Statistical parameters for mean monthly flow rates at the Sušak Factory – Rječina Station (1999 – 2011)

Over the same period, the maximum daily flow amounted to 124.0 m^3/s (26 January 2001), while the riverbed almost dried up during the months of August and September of the dry year of 2003 (<0.1 m^3/s).

At this point, it should also be noted that the lower reaches of the Rječina River (to the downstream of the overflow from the Rijeka Hydropower Plant) are also characterized by a noticeable daily oscillation of flow due to periodic operation

Figure 5. Layout of gauging sites along the lower reaches of the Rječina River

of the Rijeka Hydropower Plant. In fact, this hydropower plant operates at full capacity (10.5 m^3/s) only for a few hours a day, which means that in dry months the flow rate can suddenly be increased or reduced several times during the same day.

4. Measurement methodology used at the Rječina estuary

Salinity measurements, 16 in total, were conducted along the lower reaches of the Rječina River in the period from February to August 2012. Eight sampling sites were defined (starting from the estuary) in the study zone measuring 613.0 m in total length. All sampling sites were situated at the positions of the existing bridges across the Rječina, which enabled simple and undisturbed measurement under given conditions (Figure 5).

The CTD Diver Schlumberger DI263 was used in these measurements. This device continuously measures and records in digital format the data about conductivity [mS/cm], temperature [°C], and pressure [hPa]. It is programmed to record data at one second intervals, and the speed of instrument immersion into water was set to 10 cm/s or less. During preliminary analyses, measurements were made at several points along the river cross section, and it was established that the vertical section of conductivity and temperature does not greatly differ along the river width, and that only one measurement at each sampling site, i.e. at the greatest depth, is sufficient (Figure 6).

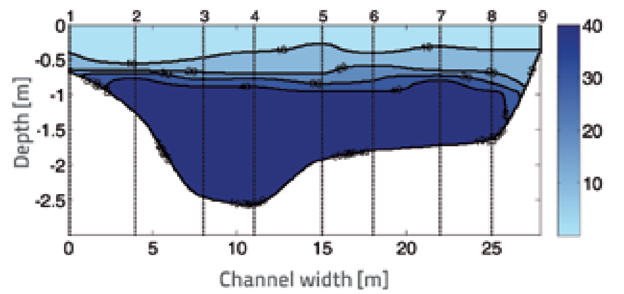

Figure 6. Example of water conductivity values (mS/cm) along the Rječina River cross section (gauging site P4)

Several examples of vertical distribution of the temperature and conductivity data, as measured on 16 April at the flow-rate of Q = 9.2 m^3/s, are presented in Figures 7 and 8. A pronounced stratification between the lower saline water layer, and the upper fresh water layer, can be observed. The transition zone is very short, with the sudden jump, which confirms the presence of the salt wedge.

Immediately before the start of each measurement, the water level at the hydrological station "Sušak Faktory – Rječina"

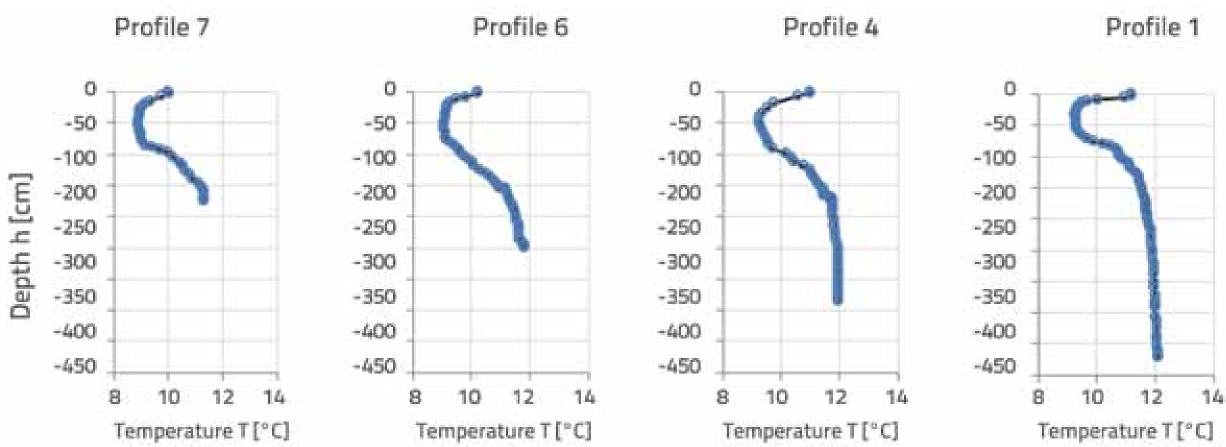

Figure 7. Vertical water temperature profiles measured on 16 April

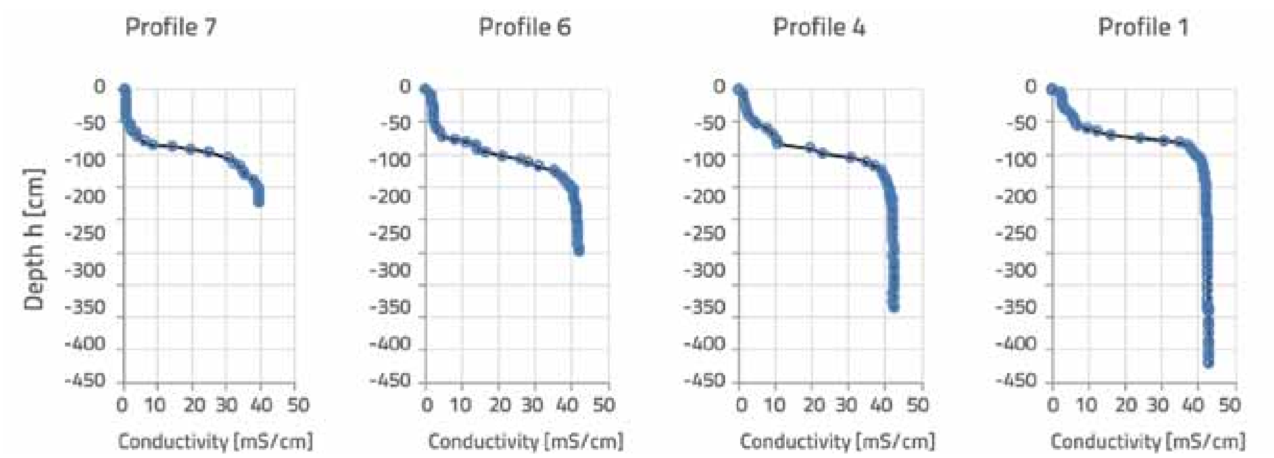

Figure 8. Vertical water conductivity profiles measured on 16 April

(outside of the maximum salt wedge intrusion) was measured and converted into flow rate using the existing flow rating. With the known geometry of the upstream-most cross section (Profile P8), the velocity of water averaged along the cross section was also calculated. In cases when the presence of saline water was registered at the upstream-most profile, the velocity of water was calculated based on the cross-sectional area of the top fresh-water layer. Measurements were usually conducted two times a day, namely at high tide and low tide.

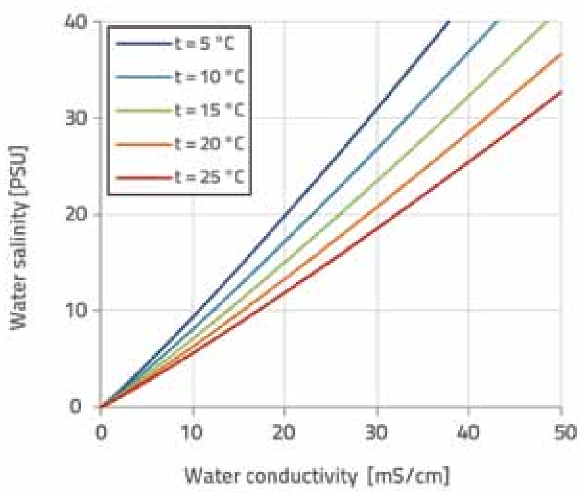

Figure 9. Correlation of water conductivity and salinity at various temperatures

The practical salinity value (hereinafter: salinity) was calculated in accordance with known empirical expressions [11] based on conductivity, temperature and pressure data. Although practical salinity is a dimensionless value, it is very often expressed in practice by means of the PSU unit (Practical Salinity Unit). Even though the conductivity measurement is often defined as an indirect method for measuring salinity, we should bear in mind the fact that their relationship is nonlinear, and that it depends both on pressure and temperature. When conductivity is measured in shallow rivers the influence of pressure is practically negligible, but temperature is of high significance for the calculation of salinity (and also density). The diagram showing the relationship between conductivity and salinity for different water temperatures, at the depth of 1.0 m, is presented in Figure 9.

As longitudinal distances between individual profiles are relatively short, the values between two neighbouring profiles have been interpolated (bicubic spline interpolation) so as to enable a more accurate presentation of isohalines (contours of equal salinity) along the Rječina estuary (Figures 16 a, b, c, and d).

5. Measured salt-wedge dimensions

Flow rates registered at the analysed part of the Rječina, sea levels, total water depths, physical properties of river and sea water, and measured, predicted (regression analysis), and calculated (Keulegan equation) salt-wedge length parameters, and the depth of the density inteface at the mouth, are all presented in Table 1.

The density interface is defined as the isoline of the 50% value in between the maximum and minimum density of fluid (corresponding most often to the maximum density gradient) [12]. Taking this into account, and according to recent literature [13], the salt wedge length L_{30} is defined as the horizontal distance of the 30 PSU isohaline from the mouth, while the density interface depth h_{15} is defined as the vertical distance of the 15 PSU isohaline from the water surface.

In all 16 measurements, the full stratification was registered in each vertical profile, which proves that the salt wedge is present in the entire range of measured flow rates (2.9 m^3/s – 30.4 m^3/s) and sea levels (from -0.05 to +0.47 m asl). According to Hansen – Rattray classification [14], the Rječina River estuary can be classified into the Type 4 – Salt Wedge. The presence of salt wedges has already been registered in most Mediterranean rivers: Rhone in France and Ebro in Spain [15], Po in Italy [16], Strymon in Greece [13], and Mirna, Raša [17] and Neretva rivers [18] in Croatia.

Table 1. Measured and calculated salt wedge parameters

DATE AND TIME OF MEASUREMENT	22.2.'12.	16.3.'12.	16.3.'12.	21.3.'12.	21.3.'12.	5.4.'12.	5.4.'12.	16.4.'12.	17.4.'12.	17.4.'12.	20.4.'12.	20.4.'12.	26.4.'12.	8.5.'12.	9.5.'12.	12.8.'12.
	14:00	10:30	19:00	13:00	20:00	14:00	20:00	17:00	13:00	20:00	14:30	20:00	17:00	21:00	11:00	17:00
Sea level as related to chart datum [cm]	-5	11	39	11	50	12	57	42	15	51	21	54	37	54	25	47
Hydrological station – Sušak Factory																
River water flow Q [m³/s]	4.3	5.1	4.4	6.1	14.8	6.3	15.6	9.2	17.3	13.5	17.9	16.2	29.0	30.4	24.8	2.9
Profile P1 – Estuary																
Total water depth at the estuary h' [m]	2.86	3.51	3.85	3.42	3.83	3.67	4.11	4.20	3.82	4.22	4.06	3.93	3.95	4.08	3.82	3.95
Sea water salinity S_s [PSU]	37.8	38.0	37.7	37.6	37.9	38.2	38.3	37.8	38.4	37.8	37.6	37.7	37.0	37.4	37.5	37.8
Sea water temperature t_s [°C]	9.1	9.7	9.8	10.1	10.1	12.0	11.8	12.1	12.0	12.1	12.6	12.6	12.9	17.6	15.8	22.6
Sea water density ρ_s [kg/m³]	1029.3	1029.3	1029.1	1029.0	1029.2	1029.1	1029.2	1028.8	1029.2	1028.8	1028.5	1028.6	1028.0	1027.3	1027.8	1026.3
Profile P8 – Upstream-most Profile																
River water depth h [m]	1.12	1.08	1.43	1.00	1.43	1.38	1.67	1.75	1.47	1.77	1.62	2.00	1.68	1.68	1.30	1.57
River water flow rate v [m/s]	0.14	0.17	0.12	0.21	0.40	0.17	0.37	0.21	0.46	0.31	0.44	0.33	0.69	0.72	0.72	0.07
River water salinity S_r [PSU]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
River water temperature t_r [°C]	8.7	9.3	9.5	9.7	8.6	10.1	10.9	9.8	8.3	8.7	8.7	8.7	11.7	8.9	11.1	15.9
River water density ρ_r [kg/m³]	999.6	999.6	999.6	999.5	999.6	999.5	999.5	999.5	999.7	999.6	999.6	999.6	999.3	999.6	999.4	999.6
River water viscosity ν [cm²/s x 10^{-6}]	1.36	1.33	1.32	1.32	1.36	1.30	1.32	1.32	1.37	1.36	1.36	1.36	1.25	1.35	1.27	1.32
Reynolds density number Re [x 10^6]	0.47	0.45	0.69	0.40	0.67	0.66	0.88	0.93	0.69	0.80	0.92	1.10	0.92	0.84	0.61	0.76
Froude number Fr	0.042	0.052	0.032	0.068	0.107	0.047	0.092	0.051	0.121	0.110	0.074	0.075	0.170	0.177	0.203	0.019
Froude density number Fr_ρ	0.241	0.300	0.187	0.399	0.623	0.276	0.534	0.298	0.706	0.648	0.432	0.438	1.007	1.065	1.203	0.113
MEASURED																
Layer dividing line depth at the estuary h_{15}' [m]	0.3	0.42	0.33	0.4	1.08	0.44	1.1	0.72	1.37	1.15	1.34	1.25	1.96	1.84	1.74	0.29
Salt wedge length L_{30}' [m]	490	500	590	490	340	540	350	560	300	425	300	420	120	110	100	710
PREDICTED																
Layer dividing line depth at the estuary h_{15} [m]	0.36	0.42	0.37	0.50	1.13	0.52	1.18	0.74	1.28	1.04	1.32	1.21	1.89	1.95	1.70	0.25
Salt wedge length L_{30} [m]	511.9	506.2	640.5	497.7	392.2	496.2	375.4	521.7	313.3	421.0	299.5	632.6	125.9	105.3	195.9	680.5
CALCULATED																
Salt wedge height at the estuary H_s [m]	2.42	3.03	3.38	2.88	2.79	3.09	3.01	3.42	2.66	3.21	2.85	2.78	2.26	2.32	2.35	3.58
Layer dividing line depth at the estuary h_c [m]	0.44	0.48	0.47	0.54	1.04	0.58	1.10	0.78	1.16	1.01	1.21	1.15	1.68	1.76	1.47	0.37
Salt wedge length L_s [m]	2056.1	1143.9	5453.1	500.0	268.0	1967.1	491.2	2247.1	201.8	895.6	285.4	1017.9	102.1	87.1	45.8	21434.4
Modified salt wedge length L_s' [m]	600	540	600	490	300	580	340	600	270	420	300	420	120	105	80	>620

The obtained values of parameters selected in the measurement have greatly contributed to proper understanding of the salt wedge occurrences in the lower reaches of the Rječina River. The maximum salt wedge length of about L_{30} = 710 m (outside of the measurement range) was registered on 12 August at the flow rate of Q = 2.9 m^3/s, during the high tide (+0.47 m). The minimum slat wedge length of about L_{30} = 100 m (outside of the measurement zone) was registered on 9 May at the flow rate of Q = 24.8 m^3/s, when the sea level amounted to (+0.25 m). At even higher flow rates, e.g. on 26 April (Q = 29 m^3/s) or on 8 May (Q = 30.4 m^3/s), the salt wedges were somewhat longer, which can be explained by greater sea level at the time the measurements were made. No case flashing out of salt wedge from the estuary was registered during the measurements.
As could have been expected, the maximum depth of the density interface (h_{13}=1.96 m) was registered during a very high flow rate on 26 April (Q = 29 m^3/s). During the maximum flow rate of Q = 30.4 m^3/s, as registered on 8 May, the depth of the density interface was somewhat lower, i.e. h_{13} = 1.84 m. The minimum depth of h_{13} = 0.29 m was registered on 12 August (Q = 2.9 m^3/s) during the minimum flow rate.
Although the Rijeka Hydropower Plant was in operation during several measurements (21 March, 5 April, 26 April, 8 May), it should be noted that these measurements were conducted within the period with no oscillation of the incoming flow (which is why this flow can be characterized as stationary). However, due to insufficient knowledge about inertness of the salt wedge (time after change in flow in which the salt wedge assumes its equilibrium position), it is still unclear whether the measured position of the salt wedge could be considered stationary.
It can be concluded from the above discussion that the flow rate of the Rječina River greatly influences the length and depth of the salt wedge. The sea tides are also significant, especially during very low flow rates (<4 m^3/s) when, due to inclination of the riverbed, the length of salt wedge propagation is mostly dependent on the sea level.

6. Regression Analysis of Salt Wedge Dimensions

Several regression equations describing the functional relationship between the flow rate and the salt wedge length (Figure 10), i.e. between the flow rate and the density interface at the mouth (Figure 11), were derived on the basis of measured salinity values. The best results were obtained fitting the data with the linear function in case of the salt wedge length, and the 2nd degree polynomial in case of the density interface, by means of which this relationship is described through the following expressions:

$$L_{30} = 657,85 - 19,208 \times Q \quad (1)$$

$$h_{15} = 0,08724 \times Q - 0,00076 \times Q^2 \quad (2)$$

where L_{30} is the horizontal distance between the isohaline of 30 PSU and the estuary in [m], h_{15} is the vertical distance between the isohaline of 15 PSU and the surface in [m], and Q is the Rječina flow rate upstream of the estuary in [m^3/s].

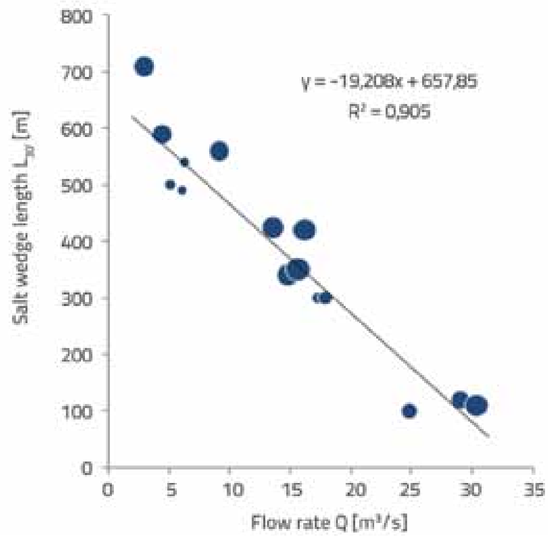

Figure 10. Regression function of measured flow rates and salt wedge length (the dot size corresponds to the sea level above the chart datum)

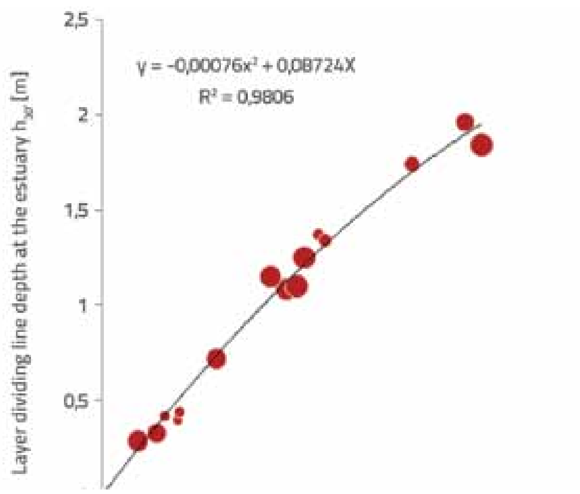

Figure 11. Regression function of measured flow rates and the layer dividing line depth (the dot size corresponds to the sea level above the chart datum)

The regression equation (2) for the depth of the density interface at the mouth is very closely related to the Rječina flow rate (R^2 = 0.988), which could have been expected as the fresh water layer thickness at the estuary is exclusively dependent on hydraulic properties (velocity and depth). Although the regression equation (1) for the salt wedge length also points to the strong connection with the flow rate (R^2 = 0.9), some dissipation has still been noted (Figure 11). This is very probably due to uneven riverbed on the one side, and

to the influence of sea level (RM) on the change of hydraulic properties of the flow (influence of backwater), on the other.
In an attempt to establish a more accurate correlation between the flow rate and the wedge length, an additional regression analysis was made for the measured wedge length values at high tide (RM > 25 cm) and at low tide (RM < 25 cm), (Figure 12). In this case, an even closer connection was obtained (R^2 = 0.965 at high tide, and R^2 = 0.983 at low tide):

$$L_{30,plima} = 759{,}68 - 27{,}897 \times Q + 0{,}2091 \times Q,\ za\ RM > 25\ cm \quad (3)$$

$$L_{30,oseka} = 527{,}79 - 0{,}9009 \times Q - 0{,}6653 \times Q^2,\ za\ RM < 25\ cm \quad (4)$$

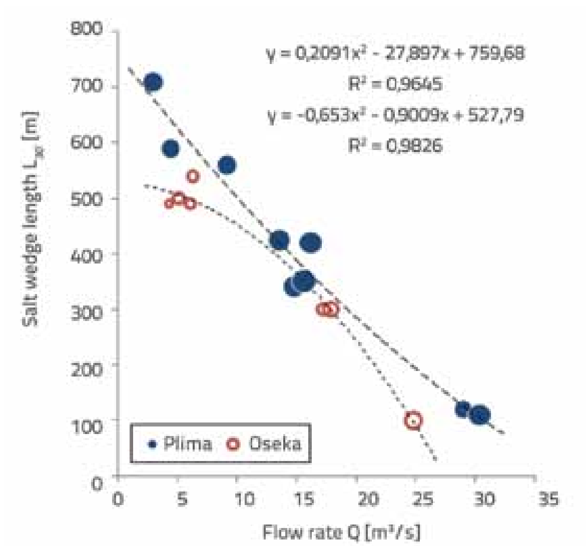

Figure 12. Regression functions of measured flow rates and the salt wedge length at high and low tides (the size of the dot is proportional to the sea level above the chart datum)

It can be seen from Figure 12 that regression curves for the high tide (3) and the low tide (4) are practically identical for mean flow rates, while differences are the greatest at very low and very high flow rates. In both extremes these differences are quite possible and very indicative. In fact, in case of very low flow rates, the intensity of inertial forces is insufficient and it can not prevent advancement of saline water to the upstream of the estuary, and so the slope of the riverbed bottom is actually the main factor that limits such intrusion. In a hypothetical situation of dry riverbed and extremely high tide, the maximum length of intrusion has not been measured nor can it be anticipated without a detailed analysis of the riverbed bathymetry in the zone to the upstream of the last profile. According to regression equations (3) and (4), the maximum salt wedge length at Q = 0 m³/s amounts to 528 m at low tide, and to 760 m at high tide (here we are obviously taking into account average values of the tides, as this length can be somewhat greater in case of an extremely high tide corresponding to a multiannual return period).

The salt wedge length L_{30}' is also influenced by sea water level at greater flow rates (Q > 20 m³/s). According to the regression analysis (3) and (4), the full removal of the salt wedge from the estuary L_{30} = 0 occurs much earlier in case of low tide ($Q_{crit,\ low\ tide}$ = 27.5 m³/s) that in case of high tide ($Q_{crit,\ high\ tide}$ = 38.1 m³/s)

7. Semi-empirical models

During his research on physical models, Keulegan developed a semi-empirical expression for determining the salt wedge length in regularly-shaped canals with horizontal bottom [7]. Rattray and Mitsuda (according to Ibanez [15]) have shown that results obtained on the field correspond very well to Keulegan's expression when the relationship between the salt wedge length and water depth ranges from 10^2 to 10^4, which is also the case for the Rječina River, except at very high flow rates when the salt wedge is almost flushed out of the estuary.
The comparison of measured and calculated salt wedge lengths, according to Keulegan L_s, is presented in Table 1. The Keulegan coefficient is defined through calibration with measurements, and was adopted as K=2 in case of the basic Keulegan expression, and as K=1.2 in case of the modified Keulegan expression.
Measured and calculated values agree quite well at the flow rate of Q > 14 m³/s, while at lower flow rates calculated salt wedge lengths greatly exceed the measured ones, which points to the fact that the salt wedge would move even further upstream if there were no real slope of the riverbed. Similar conclusions were made by Ibanez during his salt wedge studies for the Rhone and Ebro estuaries [15].
As the Rječina riverbed is irregular in shape, and as its slope is relatively high (I = 0.5%), the Keulegan expression was partly modified and used as explained in more detail in the following text.

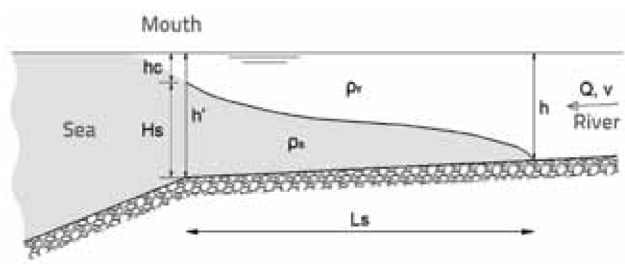

Figure 13. Schematic view of the salt wedge

The basic Keulegan expression for the salt wedge length is [7]

$$\frac{L_s}{h} = K \cdot \mathrm{Re}_\rho^{1/4} \cdot Fr_\rho^{-5/2} \quad (5)$$

where L_s is the salt wedge length, h is the constant water depth, K is the Keulegan coefficient, Re_ρ is the densimetric Reynlods number, and Fr_ρ is the densimetric Froud number.
The densimetric Froud number is defined as

$$Fr_\rho = \frac{v}{\sqrt{gh}} \cdot \sqrt{\frac{\bar{\rho}}{\Delta\rho}} \tag{6}$$

where v is the water flow rate, g is gravitational acceleration, h is water depth, $\bar{\rho} = \frac{\rho_s + \rho_r}{2}$ is the mean density, $\Delta\rho = \rho_s - \rho_r$ is the difference between densities (ρ_s is the sea water density, and ρ_r is the fresh water density). The densimetric Reynolds number is defined by the following expression:

$$Re_\rho = \frac{1}{\upsilon} \cdot \sqrt{\frac{gh^3\Delta\rho}{\bar{\rho}}} \tag{7}$$

where u is the kinematic viscosity of fresh water, while other parameters have already been described above.
In case the water depth at the estuary h' differs from the water depth h to the upstream of the salt wedge (Figure 13), the Keulegan expression (5) is modified in such a way that the wedge length L_s' becomes a function of the water depth at the estuary h', and is limited by the point of intersection with the riverbed line.

$$\frac{L_s'}{h'} = K \cdot \mathrm{Re}_\rho^{1/4} \cdot Fr_\rho^{-5/2} \tag{8}$$

The fresh water layer thickness at the estuary h_c was derived analytically by Keulegan [7] as a function of the densimetric Froud number, which is independent of the riverbed slope and freshwater depth at the mouth.

$$\frac{h_c}{h} = Fr_\rho^{2/3} \tag{9}$$

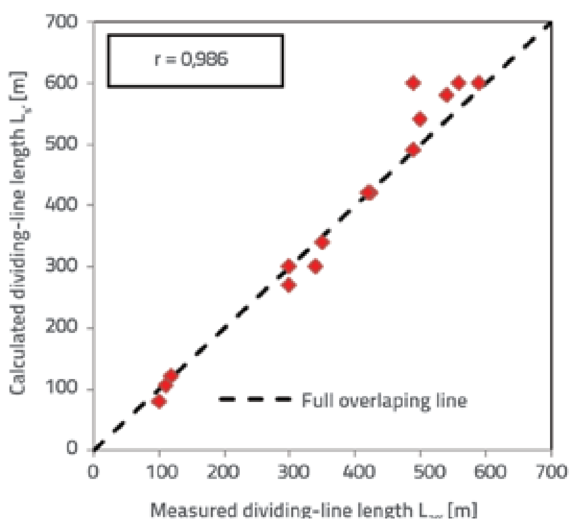

Figure 14. Correlation between the measured L_{30}' and calcuated L_s' (8) salt wedge lengths

The comparison between the measured salt wedge lengths L_{30}' and the values calculated according to the modified Keulegan expression L_s' is also presented in Table 1. The expression modified according to Keulegan shows an excellent correlation with measured salt wedge length and depth values at the Rječina River. The Pearson coefficient of correlation between measured and calculated salt wedge length values amounts to r = 0.986 (Figure 14), while it amounts to r = 0.991 for the density interface depths (Figure 15).

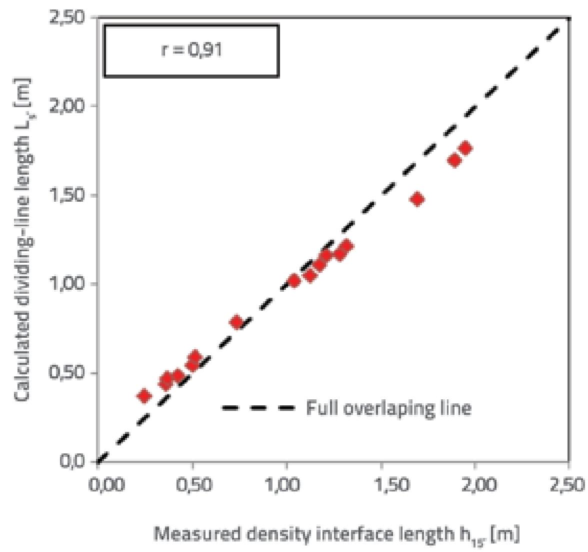

Figure 15. Correlation between the measured h_{15}' and calcuated h_c' (9) dividing-line depths at the estuary

A graphical presentation of measured salt wedge values and calculated density interface salinity 15 PS, according to the modified Keulegan expression, is given in Figures 16 a, b, c, and d. The shape of the Idensity interface is approximated using the quadratic function.

8. Conclusion

The salt wedge dynamics at river estuaries is a very complex process that is influenced almost equally by sea and river parameters. Although hydrodynamic numerical models have been intensively developed in recent years, and are becoming increasingly accessible, it is still impossible to make sufficiently reliable descriptions of salt wedge upstream intrusions without field measurements.
The Rječina estuary is a highly specific area because of a very short stretch where the interaction of the saline and fresh water takes place (maximum salt wedge length is less than 1 km), significant seasonal and daily flow-rate oscillations, and uneven and relatively steep slope of the riverbed in the studied zone.
The sea water intrusion into the Rječina riverbed in the zone to the upstream of the estuary was registered through salinity measurements conducted in the lower reaches of the Rječina in the period from February to August 2012. It was also established that the salt wedge is present under all hydrological conditions. It is evident that the Rječina flow rate is of dominant significance for the salt wedge formation, while the influence of the sea tides is smaller but is not negligible. The greatest salt wedge length of 710 m was recorded at the high tide

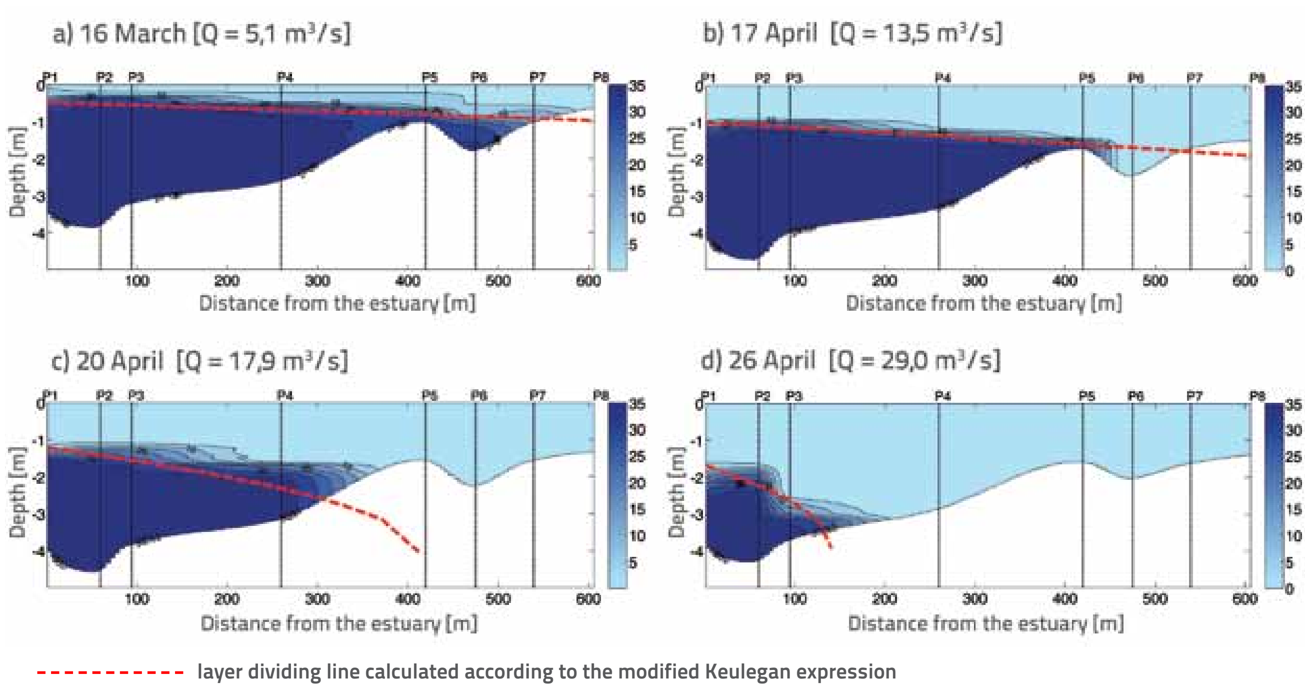

Figure 16. Longitudinal section of the Rječina River with presentation of measured salinity values (PSU) and with the calculated layer dividing line amounting to 15 PSU

and at the flow rate of 2.9 m^3/s. The case of salt wedge flushed out from the estuary was not recorded in the period under study, although the measurements suggest that this should occur at the flow rate of 27.5 m^3/s at low tide, or at 38.1 m^3/s at high tide.

Highly realistic prognostic expressions, which link the Rječina flow rate with the salt wedge length (separately for high and low tides), and with the density interface depth at the estuary, were derived by means of the regression analysis. It was also demonstrated that the Keulegan expression can be used, with smaller modifications, for calculating the salt wedge length with a sufficient level of accuracy, provided that hydraulic parameters are known (densimetric Froud and Reynolds number).

Further investigations in this area will focus on the development of a numerical model that could prove useful, together with detailed and multiple daily measurements, in the analysis of salt wedge dynamics under non-stationary conditions as well.

Although the salt wedge behaviour at the Rječina estuary could be described in greater detail by means of one of the existing numerical models, the regression expressions presented in this paper are accurate enough for preliminary and planning considerations about possible use of Rječina water for municipal needs. Before making any kind of decision, other physical and biochemical parameters influencing the quality of water, must also be studied.

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