Variation of sedimentation rate in the semi-enclosed bay determined by ^{137}Cs distribution in sediment (Kaštela Bay, Croatia)

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Highlights

- Long-term sedimentation rate increase in the whole bay since the 1950s
- Sedimentaton rate increased due to urbanization and industrialization
- Temporal and spatial sedimentation rate variability observed

Abstract

Purpose of this research was to study the rate at which the semi-enclosed bay such as the Kaštela Bay reacts to the coastal processes of industrialization and urbanization, the extent of the influence of human activities on the bay, and the sediment distribution affected by anthropogenic influence. Temporal and spatial sedimentation rate variations were observed between three studied periods: 1954–2005, 1963–2005/2006, and 1986–2005/2006. Sedimentation rates were in the following ranges: 0.29–0.49 cm/yr for the 1954–2005 period, 0.58–0.95 cm/yr for the 1963–2005/2006 period, and 0.50–1.32 cm/yr for the 1986–2005/2006 period. The average total sedimentation rates for three periods were 0.41cm/yr, 0.81 cm/yr, and 0.61 cm/yr, respectively. Sedimentation rate for the individual 1963–1986 period marked with two ^{137}Cs marker peaks was in the 0.65–1.30 cm/yr range, while the mean value was 1.06 cm/yr. Long-term sedimentation rate increase in the whole Kaštela Bay was observed and clearly connected to the industrialization and urbanization processes in the coastal area. These processes reflect very quickly, in terms of years, in the sedimentation rates. Intensive anthropogenic activities in the coastal area are reflected in the whole bay depending on the amount of the discharged sediment material, topography of the sea bottom, and water currents. Some localized areas of sediment accumulation may form.

***Keywords*: Adriatic Sea, Industrialization, Kaštela Bay, Sedimentation rate, Urbanization, ^{137}Cs distribution

1. Introduction

Coastal areas are particularly important for human activities which makes the marine environment receiving discharges from these areas very sensitive to anthropogenic influence. It has been established that urbanization and industrialization are among the processes with

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the largest direct influence on the sedimentation rate changes in the coastal areas (Lu and Matsumoto, 2005).

^{137}Cs is probably the most frequently used anthropogenic radionuclide for monitoring of the environmental processes (Ayçık et al., 2004; Saxena et al., 2002). It is also one of the most frequently applied tracers for determination of recent sedimentation rates in aquatic environments (Ahn et al., 2006; Kumar et al., 2007; Laissaoui et al., 2008; Lu, 2004; San Miguel et al., 2004; Yao et al., 2008). Determination of the sedimentation rates with the ^{137}Cs method is suitable for sediments of up to 100 years old (Ahn et al., 2006; Mizugaki et al., 2006; Saxena et al., 2002; Schell and Barnes, 1986). ^{137}Cs distribution in undisturbed sediment depth profiles reflects the global deposition pattern of ^{137}Cs due to the atmospheric fallout. It is, therefore, possible to determine the maximum ^{137}Cs activities in sediment columns corresponding to the times of maximum ^{137}Cs input into the environment. This enables its use as a global geochronological marker.

Kaštela Bay coastal area is one of the most industrialized, most urbanized and most densely populated areas in Croatia. It comprises the city of Split, Kaštela, Solin, and Trogir towns, representing the largest urban agglomeration on the east Adriatic coast. Since the 1950s this area was intensively industrialized and urbanized resulting in a sudden and multiple increase of population. The Split urban region had the most dynamic growth in the second half of the 20th century. Population of the city itself increased 3.5 times in app. 50 years (Kranjčević et al., 2014). The past and present industrial activities include chemical factory "Adriavinil", cementworks, ironwork and galvanization facility, shipyard, all located in the east part of the area. Agricultural activities are more significant in the west part of the area. However, intensive industrialization and urbanization were not followed by the intensive infrastructure development and various contaminants were discharged into the Bay. Large amounts of untreated sewage waste waters, runoff, and industrial waters were discharged into the Bay for decades and TENORM was also deposited in the Bay (Margeta, 2002; Ujević et al., 2000) influencing sediment quality in the Bay (Orescanin et al., 2005). These discharges represented a significant anthropogenic source of particulate matter for deposition in the Bay.

The aim of this study was to determine influence of the anthropogenic activities on the sedimentation rates in the Bay considering a significant anthropogenic source of sediment material and spatially concentrated industrial activity and population density. The purpose was to study the rate at which the semi-enclosed bay reacts to the more or less intensive coastal processes of industrialization and urbanization, the extent of the influence of the human activities on the bay, and the sediment distribution affected by anthropogenic influence.

2. Material and methods

2.1. Study area

Kaštela Bay is a semi-enclosed bay with a low-energy environment and one of the largest bays on the east Adriatic coast (Marasović et al., 2005; Margeta, 2002). It is located in the central Adriatic Sea close to the City of Split (Figure 1). In its western part it is connected with the Trogir Bay through the narrow Trogir Channel and in the south-east it is connected with the Split and Brač Channels by wide "gates" between the Split peninsula and the Čiovo

Island. Despite their connection, Kaštela Bay and Split and Brač Channels represent separated marine basins due to different ecological characteristics and terrestrial influences. The Bay is 14.8 km long and 6.6 km wide (Tudor, 1993). Its total area is app. 60 km^2, average depth 23 m, and maximum depth 45–50 m at the entrance of the Bay (Kljaković-Gašpić et al., 2006; Marasović et al., 2005).

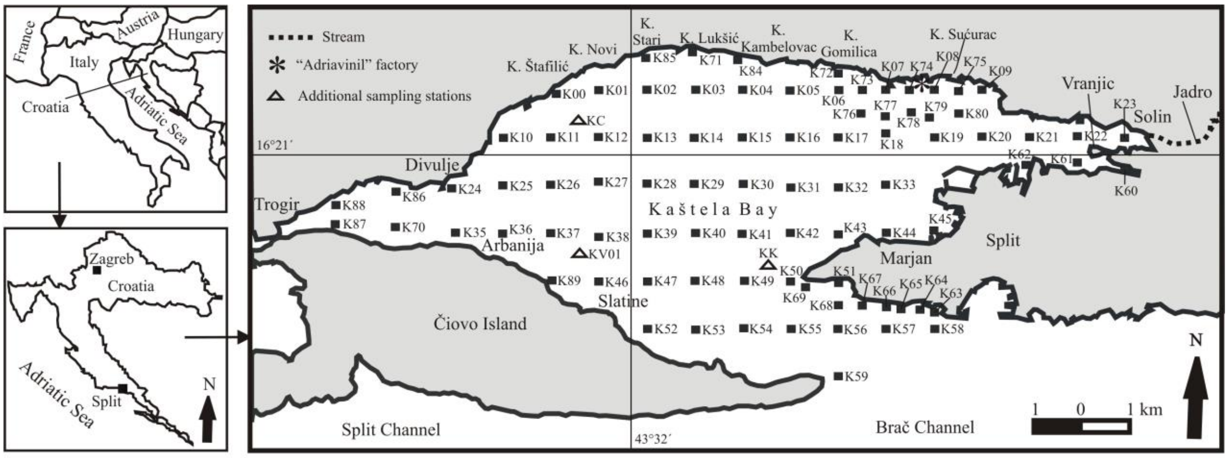

Figure 1. Location of the Kaštela Bay and the sampling stations

According to bathymetric and morphological characteristics two distinctive parts of the Kaštela Bay are differentiated: deeper central and east part and shallower west part of the Bay (Figure 2). Surface sediments of the Kaštela Bay bottom are presented in Figure 3. The largest part of the Bay is covered with muddy sediments while coarse grained sediments are mostly distributed in the shallow west part and along the north coast of the Bay.

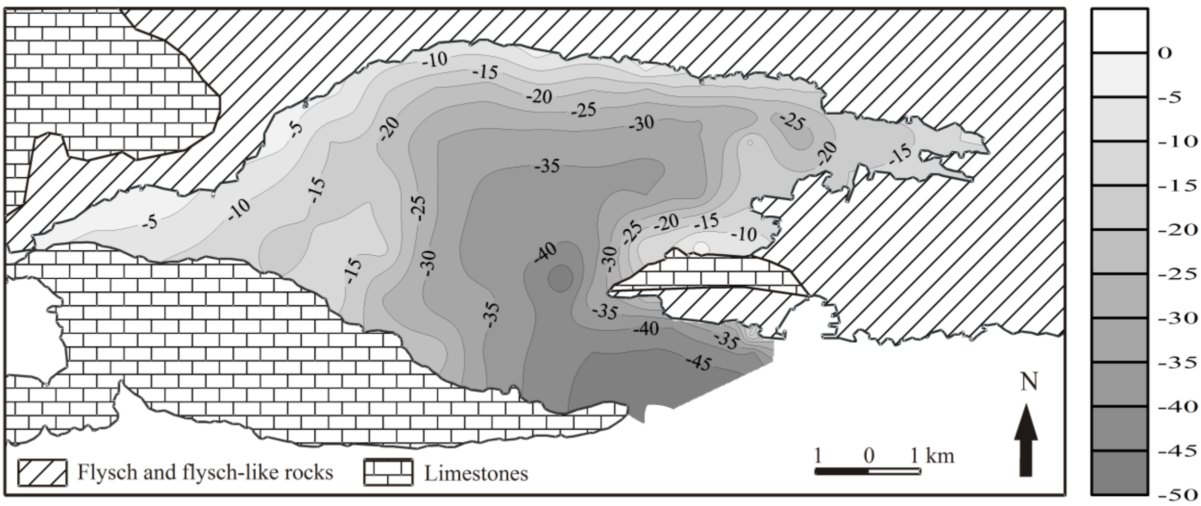

Figure 2. Contour bathymetric map of the Kaštela Bay and simplified lithological units of the surrounding area

Based on changes in oxygen concentrations in surface and bottom water, primary production, water transparency, phytoplankton composition, and other physical, chemical, and biological parameters it was concluded that the eutrophication in the Kaštela Bay has started at the beginning of the 1970s pointing to the contamination with high concentrations of nutrients of anthropogenic origin (Barić et al., 1992). The Bay was characterized as a eutrophic to highly eutrophic area, especially its east part. The main sources of contamination, including excess organic matter, in the Bay were considered to be untreated industrial and municipal waste waters and urban area runoff (Bogner et al., 1998; Milun et al., 2004; Milun et al., 2006; Ujević et al., 1998a) containing high concentrations of organic matter. These effluents were discharged mostly into the east part of the Bay.

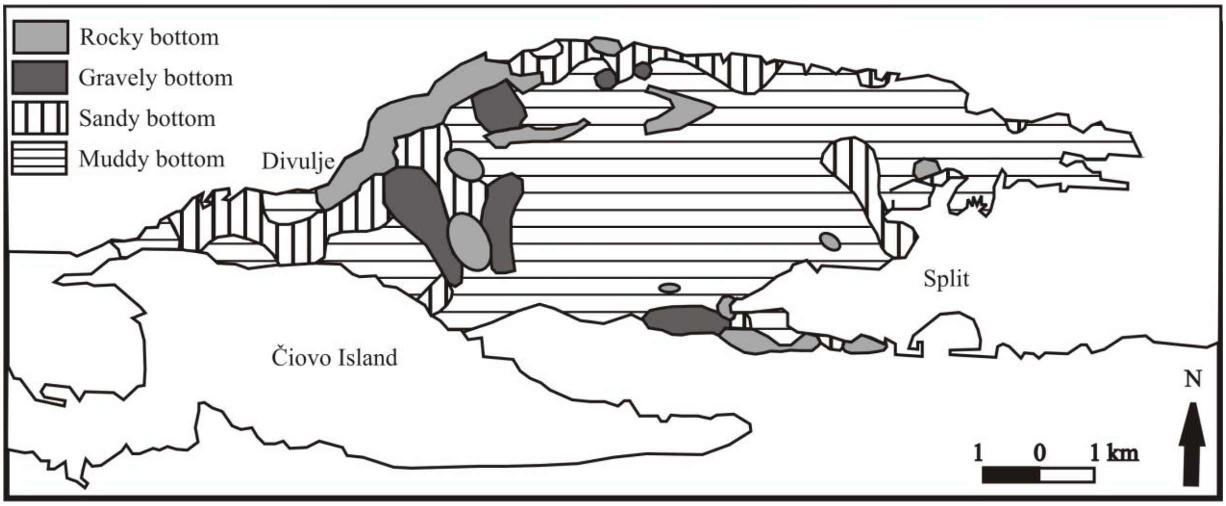

Figure 3. Surface sediments of the Kaštela Bay bottom (after Alfirević, 1980)

Vertical stratification of the water column occurs in the warm period of the year (from April to October), with the thermocline present at 10–25 m depth, while during the winter (from November to March) the water column is well mixed (Kljaković-Gašpić et al., 2006; Margeta, 2002). Circulation in the surface water layer of the Bay is predominantly of the cyclonic direction (Kljaković-Gašpić et al., 2006; Zore-Armanda, 1980). This type of circulation is established under the influence of the bora (NE wind) and mistral (NW wind) winds. Anticyclonic circulation is established under the influence of the scirocco wind (SE wind) (Zore-Armanda, 1980). A combination of these two circulation types is also possible. Although the Kaštela Bay is a separate water body separated from the Brač and Split Channels, the exchange of water between the Kaštela Bay and the Brač Channel exists as a consequence of the wind influence mostly (Marasović et al., 2005). The average water replacement time in the whole Bay is app. one month and in the east part of the Bay app. 15 days which can be reduced to five days in cases of strong winds (Marasović et al., 2005; Margeta, 2002). Wind influence is relatively weak and the fresh water inflow is low during the warmest part of the year (from July to September) causing long water replacement time in the Bay. Closed circular current is formed in the east part of the Bay during the summer months. Hence, almost no water exchange occurs between the east part of the Bay and its other parts (Barić, 1995).

The coastal area around the Bay and its hinterland are generally built of two types of rocks (Figure 2). The predominant rocks on the north coast of the Bay and the Split peninsula are flysch and flysch-like rocks while the Čiovo Island and the hinterland are mostly built of different varieties of limestones with some dolomites (Marinčić et al., 1971). The carbonate rocks are intensively karstified and fractured which has a significant influence on the hydrographic net around the Bay. The only permanent surface stream is the Jadro River in the easternmost part of the Bay (Figure 1) representing the most important source of the fresh water for the Bay. Its average annual inflow is app. 8–10 m^3/s (Barić, 1995; Marasović et al., 2005; Margeta, 2002) while the average maximum inflow is 66 m^3/s (Margeta, 2002). Other surface streams in a form of small brooks are numerous on the north coast of the Bay but are less important as a source of fresh water for the Bay. Their inflow depends on the amount of received precipitation and therefore it is not uncommon for them to dry up even several years in a row.

2.2. Sampling

Sediment samples were collected in a regular 1×1 km grid across the whole Kaštela Bay and in a 500×500 m grid around the "Adriavinil" factory (Figure 1). Additional samples were taken at three stations outside the regular grid: KV01 due to vicinity of the Slatina submarine spring; KK in the deepest, muddy part of the Bay; and KC in the shallower, sandy part of the Bay (Figure 1). KK and KC stations were sampled for grain size composition determination on locations where sufficiently long sediment core could be collected.

Table 1. Sea bottom depths and geographical coordinates of the sampling stations in the Kaštela Bay selected for sedimentation rate calculation (all except the KK and KC stations) and grain size composition determination by instrumental methods (KK and KC stations)

Sampling station	Sea bottom depth (m)	Coordinates		Sampling station	Sea bottom depth (m)	Coordinates	
		N	E			N	E
K02	20	43° 32.492'	16° 20.931'	K50	31	43° 30.372'	16° 23.194'
K03	22	43° 32.525'	16° 21.713'	K53	37	43° 29.830'	16° 21.703'
K04	16	43° 32.535'	16° 22.442'	K54	41	43° 29.814'	16° 22.433'
K05	20	43° 32.554'	16° 23.204'	K55	45	43° 29.820'	16° 23.165'
K06	21	43° 32.533'	16° 23.824'	K56	45	43° 29.804'	16° 23.881'
K07	16	43° 32.548'	16° 24.445'	K58	41	43° 29.824'	16° 25.315'
K08	15	43° 32.528'	16° 25.031'	K59	50	43° 29.291'	16° 23.884'
K09	13	43° 32.529'	16° 25.617'	K61	14	43° 31.762'	16° 27.556'
K12	22	43° 32.009'	16° 20.177'	K62	15	43° 31.747'	16° 26.633'
K13	30	43° 31.993'	16° 20.917'	K64	32	43° 30.045'	16° 25.040'
K16	32	43° 32.002'	16° 23.203'	K65	34	43° 30.060'	16° 24.748'
K18	30	43° 32.040'	16° 24.431'	K67	40	43° 30.044'	16° 24.200'
K22	16	43° 32.006'	16° 27.539'	K68	41	43° 30.041'	16° 23.877'
K28	30	43° 31.466'	16° 20.923'	K70	8.5	43° 31.004'	16° 16.703'
K29	36	43° 31.476'	16° 21.694'	K73	15	43° 32.526'	16° 24.171'
K30	36	43° 31.463'	16° 22.444'	K74	16	43° 32.529'	16° 24.725'
K31	36	43° 31.439'	16° 23.168'	K75	15	43° 32.523'	16° 25.295'
K33	33	43° 31.483'	16° 24.651'	K76	29	43° 32.287'	16° 24.127'
K36	17	43° 30.908'	16° 18.540'	K77	30	43° 32.260'	16° 24.448'
K40	38	43° 30.915'	16° 21.704'	K79	29	43° 32.259'	16° 24.993'
K42	37	43° 30.900'	16° 23.185'	K80	26	43° 32.270'	16° 25.337'
K43	11	43° 30.873'	16° 23.847'	K87	6	43° 31.023'	16° 15.976'
K46	26	43° 30.386'	16° 20.206'	KK	50	43º 30.588'	16º 22.712'
K47	33	43° 30.392'	16° 20.892'	KC	12	43º 32.236'	16º 19.957'
K49	41	43° 30.373'	16° 22.401'				

These two stations were selected due to different expected sediment types representing different sedimentary environments. In total, 577 samples were collected at 89 sampling stations during the 2005 and 2006. Only ^{137}Cs depth profiles with recognizable 1963 and/or 1986 ^{137}Cs peaks and profiles in which the maximum ^{137}Cs penetration depth could be determined were later used for sedimentation rate calculation and interpretation of results and therefore only a part of the sampling stations included into the initial sampling campaign was comprised by this research. Geographical coordinates and sea bottom depths of the sampling stations with selected ^{137}Cs depth profiles and the stations selected for grain size composition determination are presented in Table 1.

Samples were taken using a gravity corer or by autonomous diving using plastic hand corer where sampling by gravity corer was not applicable due to the sediment characteristics (low plasticity of coarse grained sediment mostly in shallower parts of the Bay). Three sediment cores were taken by gravity corer at each sampling station (except at the KK and KC stations where only one core was taken) in order to obtain enough sample for the analyses. Gravity corer characteristics were as follows: model – Hydrowerk; length – 1 m; diameter – 41 mm. At stations where hand corer was used only one sediment core was taken per station due to difficult penetration of the corer into the sediment, limited number of dives per day for a diver as well as due to the corer diameter which was large enough to collect sufficient amount of sample. Hand corer had the following characteristics: length – 0.5 m, outer diameter – 90 mm, inner diameter – 82 mm.

Whenever possible, samples were collected up to a 50 cm sediment depth. Sediment cores were sliced according to depth into 5 cm segments from the sediment surface to 30 cm depth and into 10 cm segments from 30 cm to 50 cm depth. Sediment segments (or samples) obtained from three cores at one sampling station were combined into one sample. All samples were stored into the labelled plastic bags and transported into the laboratory.

2.3. Gamma-spectrometric analysis

Prior to gamma-spectrometric analysis samples were dried at 105 ºC overnight to achieve the constant mass, than ground in a mill with agate spherules or in an agate mortar, homogenized, stored into plastic containers of the 125 cm^3 volume, and weighted. Plastic containers were sealed with a self-adhesive tape.

Gamma-spectrometry was performed using HPGe detectors with relative efficiencies of 25.3 % (coaxial detector) and 25.4 % (InSpector 2000) coupled with multichannel analysers with 8192 channels (Canberra Industries). Resolution at 1332.5 keV (^{60}Co) was 1.75 keV and 1.80 keV for the coaxial detector and InSpector 2000, respectively. Spectra were collected 80 000 s and analysed with Genie 2000 software package (Canberra Industries). ^{137}Cs activities were determined using the characteristic 661.7 keV peak. All activities were recalculated to the chosen reference date (6th June 2005).

Energy calibration was performed using point sources of ^{109}Cd, ^{137}Cs (Canberra Industries), and ^{60}Co (Amersham Buchler GmbH & CoKG). Multi-gamma type CBSS 2 certified reference material (Czech metrological institute) was used for efficiency calibration. Quality control was assured by using reference materials with density and matrix composition comparable to the average sediment composition (stream sediments IAEA-313 and IAEA-

314), interlaboratory comparison reference material of soil (Environmental Resource Associates, MRAD-8), and certified reference material NIST 4357 (ocean sediment).

2.4. Granulometry

Granulometric composition of the sediment was determined for all sediment segments of the cores taken at the KC and KK sampling stations using instrumental techniques. Granulometric analysis was performed by a combination of sieving and Casagrande's areometric method. Sediment was wet sieved on a sieve with a 0.063 mm mesh. Finer fraction which passed through the sieve was analysed by the areometric method and fraction which remained on the sieve was dried and sieved through sieves with 0.125, 0.5, 1, 2, and 4 mm meshes. Sediment type was determined according to Shepard's (1954) and Folk's (1954) classifications.

At sampling stations selected for sedimentation rate calculation grain size composition was determined visually on site for the whole core as one sample due to mostly uniform grain size composition observed through the whole cores.

2.5. Determination of organic matter content

Organic matter content was determined in all samples of the sediment cores selected for sedimentation rate calculation and in samples collected at the KK and KC sampling stations. Samples were first oven-dried at 105 ºC overnight to achieve the constant mass, ground in a mill with agate spherules or in an agate mortar, and homogenized. The organic matter content was determined by loss on ignition at 375 ºC.

2.6. Vertical ^{137}Cs depth profile classification, selection, and sedimentation rate calculation

Shape of the vertical depth profiles of ^{137}Cs massic activities is important for the applicability of profiles for sedimentation rate calculation if the characteristic marker peaks are applied. Therefore, the profiles were compared with the ideal profile representing ^{137}Cs atmospheric deposition pattern expected in the Adriatic Sea and classified into groups according to their shape. Deviation of the profile from the ideal shape and presence or absence of ^{137}Cs peaks attributed to sedimentation in the profile in 1963 and 1986 were taken into account. Only profiles with minimum four measurement results of ^{137}Cs massic activities at different consecutive depths or sediment core segments starting from the sediment surface were classified. According to these criteria profiles were classified into six groups (Table 2).

Profiles at three sampling stations sampled outside the regular grid (KV01, KK, and KC) were not found useful for sedimentation rate calculation. Only three core segments (subsamples), up to the 15 cm depth, were collected at the KV01 station which was insufficient for further use. ^{137}Cs profiles at the KK and KC stations were disturbed and no ^{137}Cs peaks could be determined.

At the time of sampling ^{137}Cs in the Adriatic Sea originated from the nuclear weapons tests and the Chernobyl accident (Laissaoui et al., 2008; Papucci and Delfanti, 1999). Therefore, it was possible to register the characteristic ^{137}Cs peaks from the 1963 and 1986 in the Kaštela Bay sediments which were used to estimate the sedimentation rates. In cases when ^{137}Cs was registered in the sediment profile, but no distinctive maxima were observed, sedimentation rate was estimated from the maximum penetration depth of ^{137}Cs in sediment representing the sediment surface in 1954. According to Andersen et al. (2000) and Singh et al. (2008) the first globally detectable ^{137}Cs activities in the environment occurred in the 1952 while according to others (Ligero et al., 2005; Mizugaki et al., 2006; Plater and Appleby, 2004; Sommerfield and Nittrouer, 1999) they occurred in the 1954. In this study, more conservative approach was selected and the 1954 was chosen as the year of the first globally significant ^{137}Cs occurrence because in both cases ^{137}Cs would be present in the 1954 but not in the 1952. Sediment profiles selected for sedimentation rate calculation by any of the two approaches are listed in Table 2.

Table 2. Classification of ^{137}Cs vertical depth profiles of massic activities and profiles selected for sedimentation rate calculation by any method

<table>
<tr><th colspan="2">Group/ Subgroup type</th><th colspan="2">Classification criterion</th><th>Selected profiles (sampling stations)</th></tr>
<tr><td colspan="2">1</td><td colspan="2">Undisturbed or relatively undisturbed profiles with two distinguishable peaks marking the sedimentation surfaces in 1963 and 1986</td><td>K13, K16, K29, K40, K42, K61, K67</td></tr>
<tr><td colspan="2">2</td><td colspan="2">Undisturbed or relatively undisturbed profiles with only one peak marking the sedimentation surface in 1986; profiles marked with asterisk were also used for ^{137}Cs maximum penetration depth determination</td><td>K06, K07, K09*, K30, K31*, K33, K47, K62, K64*, K65*, K68*, K70*, K74*, K75*, K76, K77, K79, K80, K87</td></tr>
<tr><td colspan="2">3</td><td colspan="2">Undisturbed or relatively undisturbed profiles with only one peak marking the sedimentation surface in 1963</td><td>K02, K04, K12, K43, K56, K73</td></tr>
<tr><td colspan="2">4</td><td colspan="2">Undisturbed or relatively undisturbed profiles not showing clearly reconizable peaks but usefull for ^{137}Cs maximum penetration depth determination</td><td>K05, K08, K28, K36, K46, K49, K50, K53, K54, K55, K59</td></tr>
<tr><td colspan="2">5</td><td colspan="2">Profiles disturbed in upper layers showing relatively uniform ^{137}Cs massic activities and usefull for ^{137}Cs maximum penetration depth determination</td><td>K03, K58</td></tr>
<tr><td rowspan="4">6</td><td>a</td><td rowspan="4">Disturbed profiles of different types</td><td>Profiles showing clearly recognizable peak representing the sedimentation surface in 1986 and untypical ^{137}Cs massic activity increase in upper layers</td><td>K18, K22</td></tr>
<tr><td>b</td><td>Profiles showing abrupt increase or decrease of ^{137}Cs massic activity at any depth</td><td>–</td></tr>
<tr><td>c</td><td>Profiles of different shapes as a possible consequence of anthropogenic influence</td><td>–</td></tr>
<tr><td>d</td><td>Other profiles not attributed to any of the previous subgroups</td><td>–</td></tr>
</table>

Sedimentation rate was calculated by the following equation:

$v = d/(t_0 – t_{ref})$,

where: v – average sedimentation rate (cm/yr); d – depth of the marker peak or the maximum ^{137}Cs penetration in sediment profile (cm); t_0 – year corresponding to the surface sediment at any specific time or the sampling year (yr); t_{ref} – year corresponding to the characteristic ^{137}Cs peaks in profile (in the 1963 and 1986) or to the first ^{137}Cs occurrence in sediment (in the 1954) (yr).

Lower sediment segment boundaries were taken as the sediment depth in the sediment core used for sedimentation rate calculation. Sedimentation rate was calculated for four periods: 1954–2005, 1963–2005/2006, 1986–2005/2006, and 1963–1986. It was not calculated for the 1954–1963 period because no profiles in which both the ^{137}Cs marker peak from the 1963 and the maximum ^{137}Cs penetration depth could be determined reliably were found.

Measurement uncertainties for sedimentation rate were estimated taking into account the uncertainties due to depth determination of the characteristic peaks (in the 1963 and 1986) and maximum ^{137}Cs penetration in sediment (for the 1954). In cases when sedimentation rate was calculated only by maximum ^{137}Cs penetration depth the uncertainties due to possible occurrence of ^{137}Cs in sediment earlier than in the 1954, i.e. in 1952, and due to possible ^{137}Cs diffusion in sediment were taken into account as well. Some authors found that ^{137}Cs was strongly bound to sediment particles and that its diffusion mobility was negligible (Gascó et al., 2002; Pfitzner et al., 2004; Sommerfield and Nittrouer, 1999), while others concluded that by diffusion it can potentially move upwards and downwards (up to 2–4 cm) in marine sediment column (Pfitzner et al., 2004; Sommerfield and Nittrouer, 1999; Zuo et al., 1997).

3. Results

3.1. Grain size composition

Grain size composition determined by instrumental methods for two representative sediment cores at the KC and KK sampling stations is presented in Table 3.

Table 3. Grain size composition of sediment at the KC and KK sampling stations in the Kaštela Bay

Sediment segment	Sediment depth (cm)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
KC01	0–5	16.0	57.5	23.5	3.0
KC02	5–10	7.5	66.5	21.0	5.0
KC03	10–15	11.5	61.5	20.0	7.0
KC04	15–20	10.5	61.0	23.5	5.0
KC05	20–25	10.0	60.0	21.0	9.0
KC06	25–30	9.0	59.5	24.0	7.5
KK01	0–5	0.0	6.5	57.5	36.0
KK02	5–10	0.0	6.5	57.5	36.0
KK03	10–15	0.0	6.5	57.5	36.0
KK04	15–20	0.0	4.5	60.0	35.5
KK05	20–25	0.0	5.0	57.5	37.5
KK06	25–30	0.0	6.0	56.5	37.5
KK07	30–40	0.5	3.5	57.5	38.5
KK08	40–50	0.5	3.5	56.5	39.5

Sediment at the KC station was coarse grained, consisting predominantly of the sand fraction, and was classified as the silty sand according to Shepard (1954) or gravelly muddy sand according to Folk (1954). Sediment at the KK station was a fine grained one, consisting predominantly of silt and clay, and was classified as the clayey silt according to Shepard (1954) or mud according to Folk (1954). Sediment at both stations was classified as the same sediment type in all segments of the respective sediment cores. Variability of the grain size distribution with depth was tested with one-way ANOVA ($p < 0.05$). F-values were in the range 0.115 (silt) to 0.174 (clay), while the p-values were in the range 0.982 (clay) to 0.994 (silt). The test showed no statistically significant difference between samples from different depths in both sediment cores.

Table 4. Visually on site determined grain size composition of the marine sediments at sampling stations selected for sedimentation rate calculation; + – presence of the specific grain size; G – gravel, S – sand, CS – clay and silt, * – possible bioturbation

Sampling station	Grain size			Comment
	G	S	CS	
K02	+	+		–
K03	+	+	+	In K0307 and K0308 gravels found; Sediment predominantly sand and clay
K04		+		–
K05		+	+	–
K06		+	+	–
K07	+	+	+	–
K08*		+	+	Worm colony found
K09		+	+	–
K12			+	–
K13			+	–
K16			+	–
K18			+	–
K22*			+	Worm colony found
K28			+	–
K29			+	–
K30			+	–
K31			+	–
K33			+	–
K36		+	+	–
K40			+	–
K42			+	–
K43			+	–
K46		+	+	Sediment rich in organic matter
K47	+	+	+	–
K49			+	–
K50		+		–
K53			+	–
K54			+	–
K55			+	–
K56			+	–
K58			+	–
K59			+	–
K61			+	Liquid mud with lots of or organic matter; Deeper core samples richer in clay
K62			+	Liquid mud
K64			+	In K6405 coal fragment found
K65			+	–
K67		+	+	In the K6705–K6706 transition sand or gravel found

Sampling station	Grain size			Comment
	G	S	CS	
K68			+	–
K70			+	–
K73		+	+	In K7301 and K7308 fly ash found
K74	+	+	+	Gravel in deeper core samples; In K7402 coal fragments and in K7405 fly ash found
K75		+	+	–
K76			+	–
K77			+	–
K79			+	In K7905 fly ash found
K80			+	–
K87*			+	Gravel and shells found in deeper core samples

Visually on site determined grain size composition of the sediments at the sampling stations selected for sedimentation rate calculation is presented in Table 4. Sediments were generally fine grained, consisting of clay and silt, and mostly uniform with depth. At some stations coarser sediment fractions were observed, mostly as sand, while gravel was found at only few stations (K02, K03, K07, K47, K74, K87) in some sediment segments. Fly ash or coal fragments were also observed in a few sediment segments of four sediment cores (K64, K73, K74, K79). Traces of possible bioturbation were found at only three sampling stations (K08, K22, K87) where worm colonies or shells were found in some sediment segments. No other evidence of bioturbation was observed.

3.2. ^{137}Cs vertical depth profiles

Vertical depth profiles of ^{137}Cs massic activities representative for each classification group from the Table 2. are presented in Figure 4. Only seven undisturbed or relatively undisturbed profiles exhibited both ^{137}Cs marker peaks (group 1) enabling calculation of sedimentation rates for the 1963–1986 period (Figures 4.a) and 4.b)). In most of the profiles only the 1986 ^{137}Cs marker peak was visible (groups 2 and 6a) (Figures 4.c)–4.g)) and in a few profiles only the 1963 peak was observed (group 3) (Figure 4.h)). This was not unexpected due to exposure of the Kaštela Bay to the ^{137}Cs atmospheric fallout typical for north hemisphere. ^{137}Cs massic activities for the 1963 peak were around 1 Bq/kg maximum while the activities for the 1986 peak were 10 times higher making the 1986 peak more pronounced. Profiles showing no characteristic ^{137}Cs peaks are in the groups 4 and 5 (Figures 4.i) and 4.j)) and were used only to determine the maximum penetration depth of ^{137}Cs in sediment. Some profiles from the group 2 were used for this purpose as well.

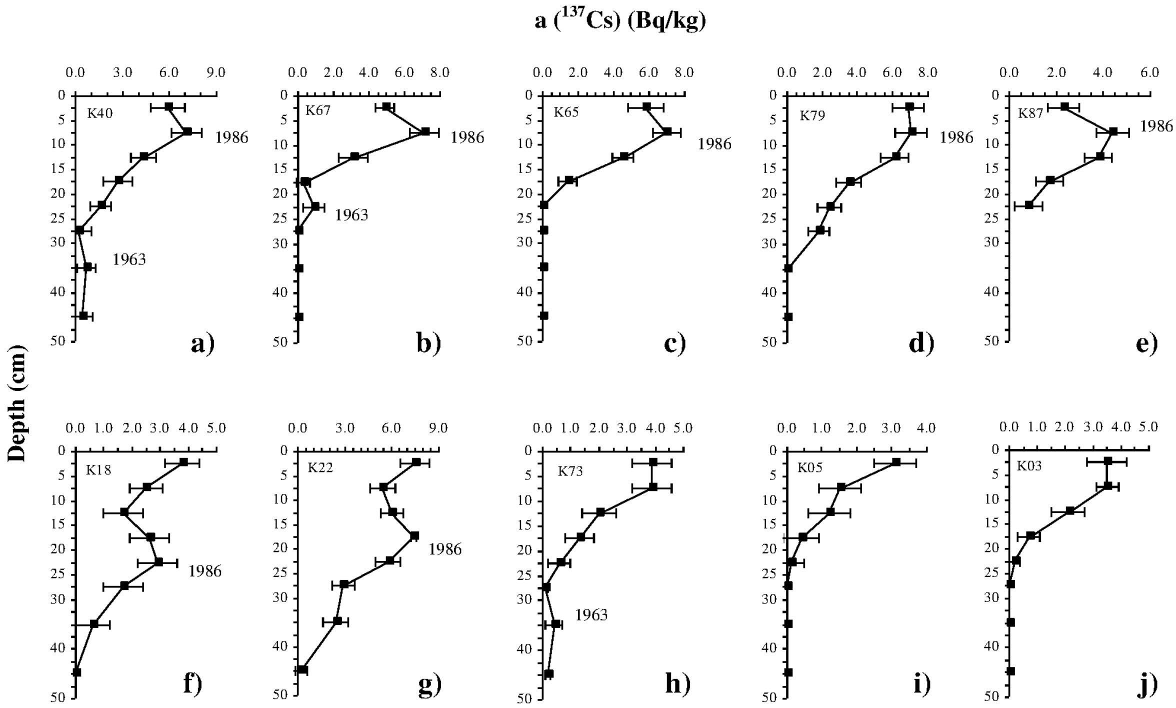

Figure 4. Representative profiles of different group types of ^{137}Cs massic activities vertical depth profiles in sediments of the Kaštela Bay according to the classification criteria; **a)** and **b)** Group type 1; **c)**, **d)**, and **e)** Group type 2; **f)** and **g)** Group type 6a; **h)** Group type 3; **i)** Group type 4; **j)** Group type 5; Horizontal bars represent measurement uncertainties expressed for coverage probability p = 95 % and coverage factor k = 2.

3.3. Organic matter content

Organic matter mass fractions were determined in 381 samples in total. Results were in the 1.07–7.88 % range with a mean value 3.08 %, median 3.05 %, and standard deviation 1.02 %. Two outliers were found using box and whisker plot for all the data: samples K6101 with 7,88 % of organic matter and K4301 with 7.23 %. Without these outliers the upper range limit would be 6.79 %.

3.4. Correlations between grain size fractions, ^{137}Cs massic activities, and organic matter content

Results of the correlations between grain size fractions, ^{137}Cs massic activities, and organic matter mass fractions in samples collected at the KC and KK sampling stations are presented in Table 5. Very high statistically significant correlations were observed among all grain size fractions and between all grain size fractions and organic matter. ^{137}Cs massic activities showed statistically significant high positive correlation only with organic matter mass fractions. Two groups of paramenters were clearly distinguished: fine grained sediment fractions (include silt, clay, and organic matter) and coarse grained fractions (include gravel and sand). Correlations inside one group were positive, while between groups were negative.

Table 5. Correlation between grain size fractions, ^{137}Cs massic activities, and organic matter mass fractions in samples collected at the KC and KK sampling stations; Bold numbers denote correlations significant at $p < 0.05$; N = 14; OM – organic matter

	Gravel	**Sand**	**Silt**	**Clay**	**^{137}Cs**	**OM**
Gravel	1.00					
Sand	**0.93**	1.00				
Silt	**-0.94**	**-1.00**	1.00			
Clay	**-0.96**	**-0.99**	**0.99**	1.00		
^{137}Cs	-0.50	-0.49	0.53	0.45	1.00	
OM	**-0.81**	**-0.84**	**0.86**	**0.82**	**0.71**	1.00

Correlation of only ^{137}Cs massic activities with organic matter mass fractions was also performed for all collected samples, 381 in total, and the result is shown in the Figure 5. Real significant positive correlation (r = 0.59) was found. This is in agreement with the result presented in Table 5 where high positive correlation was shown. Almost identical result was obtained (r = 0.57) when two outliers were excluded. The data in Figure 5 also reveal that the major part of the organic matter mass fraction was below 4.5 % and ^{137}Cs massic activities below 8 Bq/kg.

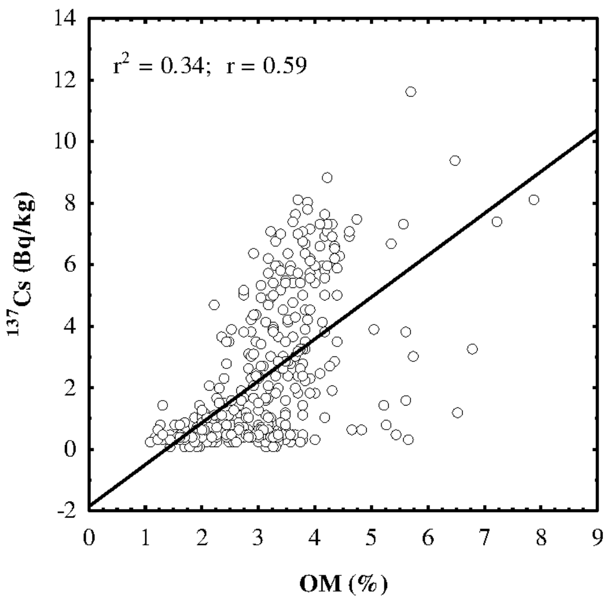

Figure 5. Scatter plot of ^{137}Cs massic activities in relation to the organic matter mass fractions in all samples from the sampling stations selected for sedimentation rate calculation and instrumental grain size determination

3.5. Sedimentation rates

Sedimentation rates for four periods (1963–1986, 1986–2005/2006, 1963–2005/2006, and 1954–2005) are presented in Table 6. Temporal and spatial sedimentation rate variations are presented in maps in Figure 6 showing sedimentation rates in the Kaštela Bay for periods from the 1954, 1963, and 1986 to the year of sampling (2005 or 2006).

Table 6. Sedimentation rates for three periods (1963 – 1986, 1986 – 2005/2006, 1963 – 2005/2006) determined through ^{137}Cs marker peaks and for one period (1954 – 2005) determined through the maximum depth of ^{137}Cs penetration in sediment; Measurement uncertainties expressed for coverage probability p = 95 % and coverage factor k = 2; "–" – sedimentation rate not calculated, N – number of results, $\bar{x}$ – average sedimentation rate, SD – standard deviation

Sampling station	Sedimentation rate for period (cm/yr)				Period 2/Period 1 ratio
	1963–1986 (Period 1)	1986–2005/2006* (Period 2)	1963–2005/2006* (Period 3)	1954–2005 (Period 4)	
K02	–	–	0.58±0.03*	–	–
K03	–	–	–	0.49±0.10	–
K05	–	–	–	0.49±0.10	–
K04	–	–	0.60±0.03	–	–
K06	–	0.53±0.06	–	–	–
K07	–	0.53±0.06	–	–	–
K08	–	–	–	0.39±0.09	–
K09	–	0.53±0.06	–	0.49±0.10	–
K12	–	–	0.71±0.03	–	–
K13	1.30±0.05	0.53±0.06	0.95±0.03	–	0.40±0.05
K16	0.87±0.05	1.05±0.06	0.95±0.03	–	1.21±0.10
K18	–	1.32±0.06	–	–	–
K22	–	1.05±0.06	–	–	–
K28	–	–	–	0.39±0.09	–
K29	1.30±0.05	0.53±0.06	0.95±0.03	–	0.40±0.05
K30	–	0.53±0.06	–	–	–
K31	–	0.79±0.06	–	0.49±0.10	–
K33	–	0.53±0.06	–	–	–
K36	–	–	–	0.39±0.09	–
K40	1.30±0.05	0.53±0.06	0.95±0.03	–	0.40±0.05
K42	0.87±0.05	0.53±0.06	0.71±0.03	–	0.61±0.08
K43	–	–	0.95±0.03	–	–
K46	–	–	–	0.39±0.09	–
K47	–	0.53±0.06	–	–	–
K49	–	–	–	0.49±0.10	–
K50	–	–	–	0.29±0.09	–
K53	–	–	–	0.39±0.09	–
K54	–	–	–	0.39±0.09	–
K55	–	–	–	0.29±0.09	–
K56	–	–	0.71±0.03	–	–
K58	–	–	–	0.39±0.09	–
K59	–	–	–	0.29±0.09	–
K61	1.09±0.05	0.79±0.06	0.95±0.03	–	0.73±0.07
K62	–	0.53±0.06	–	–	–
K64	–	0.53±0.06	–	0.39±0.09	–
K65	–	0.53±0.06	–	0.39±0.09	–
K67	0.65±0.05	0.53±0.06	0.60±0.03	–	0.81±0.11
K68	–	0.53±0.06	–	0.49±0.10	–
K70	–	0.53±0.06	–	0.39±0.09	–
K73	–	–	0.95±0.03	–	–

Sampling station	Sedimentation rate for period (cm/yr)				Period 2/Period 1 ratio
	1963–1986 (Period 1)	1986–2005/2006* (Period 2)	1963–2005/2006* (Period 3)	1954–2005 (Period 4)	
K74	–	0.53±0.06	–	0.39±0.09	–
K75	–	0.53±0.06	–	0.49±0.10	–
K76	–	0.53±0.06	–	–	–
K77	–	0.53±0.06	–	–	–
K79	–	0.53±0.06	–	–	–
K80	–	0.53±0.06	–	–	–
K87	–	0.50±0.06*	–	–	–
N	7	28	13	21	7
Minimum	0.65±0.05	0.50±0.06	0.58±0.03	0.29±0.09	0.40±0.05
Maximum	1.30±0.05	1.32±0.06	0.95±0.03	0.49±0.10	1.21±0.10
$\bar{x}$	1.06	0.61	0.81	0.41	0.65
SD	0.26	0.20	0.16	0.07	0.30

* Samples collected in 2006. All other samples collected in 2005.

Sedimentation rate was the lowest for the 1954–2005 period. The lowest rate in this period was 0.29 cm/yr, the highest was 0.49 cm/yr, and the average rate was 0.41 cm/yr (Table 6). The lowest sedimentation rate variability was also observed in this period. It was shown that most of the sediment material has been deposited in the central part of the Bay and partly along the section of the Čiovo Island coast, along part of the south coast of the Split peninsula, and along the part of the north-east coast of the Bay (Figure 6.a)). Maximum sedimentation rate was in the central part of the Bay around the K30 sampling station and was approximately 0.5 cm/yr. The lowest sedimentation rates were observed along the large part of the north coast of the Bay and in the west part of the Bay. Area next to the north coast of the Split peninsula can also be designated as the area with lower sedimentation rate.

Period 3 (1963–2005/2006), comprising periods 1 and 2, can be considered as the longer summary period represented by the average total sedimentation rate. The average sedimentation rate for this period was 0.81 cm/yr and the most frequent rate was 0.95 cm/yr which is also the maximum sedimentation rate observed in this period (Table 6). Minimum rate was 0.58 cm/yr (Table 6). Significant sedimentation rate increase in almost whole Bay was observed in this period (Figure 6.b)). Only some west parts of the Bay were excluded from this trend. Also, for part of the west part of the Bay it was not possible to estimate the sedimentation rates because the data for ^{137}Cs massic activities could not be obtained from mostly sandy and gravelly sediments found in this area. ^{137}Cs was determined in fine grained sediments found in the rest of the Bay (Table 4). The map in Figure 6.b) shows that the area with the maximum sedimentation rate, which was higher than 0.9 cm/yr, was significantly larger than in the period from the 1954. This area comprised not only a relatively small area around the K30 station like in the previous period, but extended to the K13, K16, K29, and K40 stations as well. Also, other isolated areas of maximum sedimentation rates around the K73 and K43 stations and in the easternmost part of the Bay around Vranjic (stations K22 and K61) were formed. The lowest sedimentation rates were still found along the large part of the north coast of the Bay and in the west part of the Bay. Area adjacent to the north coast of the Split peninsula was still the area with lower sedimentation rate although this rate significantly increased compared to the period from the 1954. Important change in this period was a significant rate increase in the easternmost part of the Bay around Vranjic.

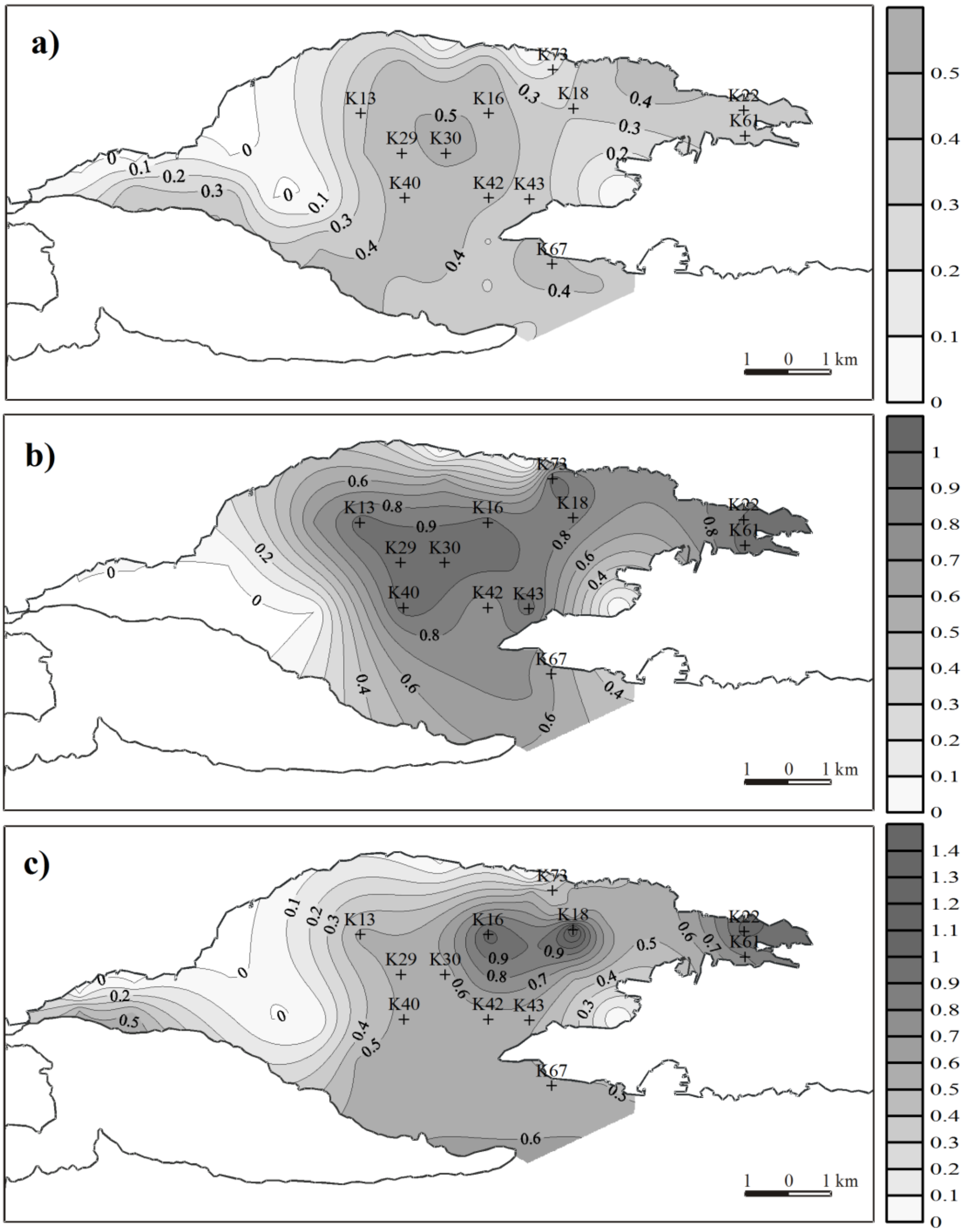

Figure 6. Maps of sedimentation rates in the Kaštela Bay for three periods: **a)** 1954–2005; **b)** 1963–2005/2006; **c)** 1986–2005/2006; Sedimentation rates are expressed in cm/yr; Reference stations are marked for comparison of rates from different periods.

It is particularly interesting to compare the period 1 (1963–1986) to period 2 (1986–2005/2006). Minimum and maximum sedimentation rates in these two periods were not significantly different. Minimum rate was 0.65 cm/yr in the period 1, while in the period 2 it was 0.50 cm/yr (Table 6). Maximum values were 1.30 cm/yr for period 1 and 1.32 cm/yr for period 2 (Table 6). However, comparing the average sedimentation rates and the values with the highest frequencies for these two periods, significant difference between the sedimentation rate before the 1986 (period 1) and after the 1986 (period 2) was observed. The average sedimentation rate at all sampling stations was 1.06 cm/yr before the 1986 and 0.61 cm/yr after the 1986 (Table 6). Before the 1986 the most frequent value was 1.30 cm/yr while after it was 0.53 cm/yr (Table 6). Almost identical results were obtained by comparing the sedimentation rates before and after the 1986 at only seven sampling stations (K13, K16, K29, K40, K42, K61, and K67) at which both ^{137}Cs marker peaks were observed in sediment profiles. Sedimentation rate decrease was registered at six stations (K13, K29, K40, K42, K61, and K67) and increase was registered at only one station (K16) (Table 6).

Relationship between sedimentation rates before and after the 1986 is shown by the Period 2/Period 1 ratio in Table 6. At stations with decreased sedimentation rates the ratio varied from 0.40 (stations K13, K29, and K40) to 0.81 (station K67). This shows that the largest sedimentation rate decrease occured at the K13, K29, and K40 stations. Increased sedimentation rate was observed only at the K16 sampling station where the Period 2/Period 1 ratio was 1.21. The areas of maximum sedimentation rates were markedly localized, smaller, and shifted from the central part of the Bay in the north-east direction during the 1986–2005/2006 period (Figure 4.c)). These areas were localized around the K16 and K18 stations where the sedimentation rates were 1.05 cm/yr and 1.32 cm/yr, respectively. At the K13, K29, K30, and K40 stations which were the area of the maximum sedimentation rate in the previous period, sedimentation rate decreased in comparison with the previous period. Equally as in the previous period, the easternmost part of the Bay around Vranjic (K22 and K61 stations) was the area of the increased sedimentation rate, especially around the K22 station where the rate was 1.05 cm/yr. Pattern of the sedimentation rate distribution was not more significantly changed in other parts of the Bay. The lowest rates were still found along the large part of the north coast of the Bay, in the west part of the Bay, and adjacent to the north coast of the Split peninsula. Such sedimentation rates distribution for these parts of the Bay was very similar to the distribution for the 1954–2005 period. Only small increase of the sedimentation rate in the westmost part of the Bay along the Čiovo Island coast was observed. It was also shown that the sedimentation rates in the largest part of the Bay, except in the small localized areas with increased rates, were uniform which is similar to the situation observed for the 1954–2005 period.

4. Discussion

4.1. ^{137}Cs massic activities and relations with sediment physical properties

Granulometry results for the KC and KK sampling stations (Table 3) are in accordance with the surface sediment types of the Kaštela Bay bottom (Figure 3) (Alfirević, 1980). The KC sampling station is located in the area where rocky, gravely, and sandy bottoms are exchanging, while the KK station is in the muddy bottom area. Sediment types at these two stations are closely connected with the sea bottom depth. The KC station is located in the shallow part of the Bay at 12 m depth, while the KK station is in the deep area at 50 m depth. Different sediment types at these stations reflect different sedimentation/depositional conditions at the stations. Depositional environment at the KC station is the high-energy environment limiting the fine grained sediment deposition, while the KK station is in the low-energy environment which supports the fine grained sediment deposition. This was confirmed with the organic matter content and ^{137}Cs massic activities found at these two stations. Both, organic matter mass fractions and ^{137}Cs massic activities were lower at the KC sampling station (2.29–2.72 % and 1.0–1.9 Bq/kg, respectively) than at the KK station (2.84–4.45 % and < 0.4–7.8 Bq/kg, respectively). Albertazzi et al. (1987) also attributed low ^{137}Cs activities in the Adriatic Sea sediments to high-energy environment with minimal deposition of fine particles. ANOVA results suggested uniform grain size composition of the sediment cores. This, together with the results showing the same sediment type in the whole KC and KK sediment cores (Table 3), points to the constant sedimentation conditions. Petrinec et al. (2012) also connected homogeneous grain size composition of the whole sediment core to the uniform sedimentation. Generally fine grained visually observed sediments (Table 4) were also in accordance with the situation presented in the Figure 3. Although statistically significant correlations of ^{137}Cs massic activities with the grain size fractions were not found (Table 5), observed correlations definitely imply a trend by having positive correlations with silt and clay (fine grained fraction) and negative with gravel and sand (coarse grained fraction). It poins to the preferential ^{137}Cs binding to the fine grained sediment fraction. Since these results were obtained from only 14 measurement data, they can be considered as only approximate and showing general trends.

Organic matter mass fractions determined in this study were in accordance with the results obtained by other authors. Bogner (1996) determined organic matter mass fractions in the Kaštela Bay sediments in the 1.95–9.98 % range at the 0–27 cm sediment depth. The highest mass fractions were determined in surficial sediment (0–1 cm depth) close to the former “Adriavinil” factory. Lower limit of this range and the one found in the current research were comparable to the middle Adriatic sediment influenced by the open sea (Dolenec et al., 1998) or uncontaminated sediment. Upper limits found in both studies were considered high and were comparable to the organic matter content in polluted east Adriatic coastal sediments or sediments exposed to the influence of surface waters (Ujević et al., 1998) which in the Kaštala Bay would be the Jadro River, urban runoff, and industrial discharges. Ujević et al. (1998a) found that the organic matter was homogeneously vertically distributed in the Kaštela Bay sediments. Statistically significant positive correlations of ^{137}Cs massic activities and organic matter mass fractions (Table 5, Figure 5) suggest that ^{137}Cs was preferably bound to organic matter. It agrees with the correlations established between ^{137}Cs and grain size fractions.

The data about bioturbation were very limited in this study (Table 4). Since no significant bioturbation traces were observed during the field work, it can be assumed that the bioturbation processes did not significantly influence vertical sediment distribution. Furthermore, in order to study bioturbation, data about the biological communities would be necessary and these data were not collected in the sampling campaign.

4.2. Comparison with the previously established sedimentation rates

Bogner (1996) earlier determined sedimentation rates in different parts of the Bay: at the Bay’s entrance (close to the K55 sampling station), in front of the “Adriavinil” factory (close to the K74 station), and in the easternmost part of the Bay (close to the K23 station).

Sedimentation rate of 0.0022–0.0025 cm/yr was assumed for the Bay's entrance which is two orders of magnitude lower than the rates estimated in the current research for any of the studied periods. It is possible that such large difference in the results is a consequence of different methodologies applied. Bogner (1996) estimated the sedimentation rate using the Pleistocene foraminifer species found in sediment. It is possible that these biogenic particles were not autochthonous and that they gave the erroneous information about the sedimentation rate. In front of the "Adriavinil" factory sedimentation rate was estimated to be 0.2 cm/yr (Bogner, 1996) while in this research rates in different periods were in the app. range 0.3–0.8 cm/yr which is comparable to the previously determined value. In the easternmost part of the Bay Bogner (1996) estimated sedimentation rate to be higher than 0.36 cm/yr and in the current study the rates in different periods in this part of the Bay were in the app. range 0.3–1.0 cm/yr which is in good agreement with the earlier estimated value.

Crmarić et al. (1999) assumed the average sedimentation rate for the east part of the Bay to be lower than 0.04 cm/yr which is an order of magnitude lower than the values obtained in the current study. The discrepancy could again be the consequence of different methodologies applied. Crmarić et al. (1999) determined the average sedimentation rate for the period of 10 000 years, while this research covered a period of around only the last 50 years. Sedimentation conditions could have been significantly changing in the last 10 000 years and differing from the conditions in the last few decades or even centuries. Also, sediment compaction should be taken into account. In a 4 m sediment column, measured by Crmarić et al. (1999), compaction is not negligible. Taking it into account, larger real thickness of the deposited sediment in the same time interval would be obtained which would give the higher estimated sedimentation rate closer to the rate estimated in the current study.

Sedimentation rates similar to the ones determined in the Kaštela Bay by this research were established in the Rijeka harbour (Adriatic Sea) using ^{137}Cs vertical depth profiles. The rates were in the range 0.5–0.7 cm/yr and at 2 km distance from the harbour the rates were estimated in a range 0.3–0.4 cm/yr (Cukrov et al., 2011).

4.3. Temporal sedimentation rate variations

Temporal variations of the average sedimentation rates before and after the 1986 were observed by comparing the periods 1 and 2 (Table 6). Average sedimentation rates and the most frequent values point to the decrease of sedimentation rate after the 1986. This situation was confirmed when comparing periods 2, 3, and 4 (from the 1986, 1963, and 1954 to the 2005/2006) (Table 6). The lowest average total sedimentation rate was estimated for period 4 starting from the 1954. In the next period 3 from the 1963 this rate was the highest and in the most recent period 2 from the 1986 the rate decreased compared to the previous period, but was still higher than the rate from the period 4 at the begining of the 1950s.

The results show that the final long-term effect in the Kaštela Bay was sedimentation rate increase. Very similar situation was observed in the Ise Bay in Japan (Lu and Matsumoto, 2005). Such temporal sedimentation rate variability can be closely related to industrialization and urbanization of the Kaštela Bay which started in the middle of the 20th century (Kranjčević et al., 2014) and to the landuse in the coastal area (Ahn et al., 2006; Ionita et al., 2000; Lu and Matsumoto, 2005; Mizugaki et al., 2006; Yeager et al., 2006). These factors can significantly influence on the amount of sediment available for deposition in the Bay. Until the middle of the 20th century Croatia was agricultural, poorly urbanized country (Kranjčević et al., 2014) and, therefore, the main source of sediment material to the Kaštela Bay were agricultural surfaces. In the 1953 only 30.4 % of the Croatian population lived in cities compared to the 1991 when it was 54.7 % (Filipić et al., 1998). This was reflected in a relatively low sedimentation rates determined for the 1954–2005 period (Table 6, Figure 6). Since the 1950s intensive industrialization and urbanization of the country took place.

At the begining of urbanization and industrialization large construction works, such as building of the roads, factories, and residential blocks, are initiated which promotes increased release of the sediment material available for deposition in the Bay and thus increasing the sedimentation rate (Ahn et al., 2006; Lu and Matsumoto, 2005; Saxena et al., 2002) as observed after the 1963 in the Kaštela Bay (Table 6, Figure 6). At the same time, decrease of the agricultural land area, which might have been one of the most important sources of sediment material in the Kaštela Bay prior industrialization and urbanization, and increase of the urban and industrial areas which are less important sources of sediment material occur (Mizugaki et al., 2006). This was supported by the information about the development of Croatian urban areas, including the Split City and its urban region comprising the Kaštela Bay coastal area. The period between the 1961 and 1981 was the most dynamic period in urban development of Croatian cities. Since the 1960s to the 1980s economy was intensively developing, especially industry, tourism, catering industry, commerce, and traffic (Kranjčević et al., 2014). During the 1960s and 1970s one third of the Split City was built which produced large amounts of sediment material to be sedimented in the marine environment. In the 1960s large number of faculties were established in the Split City and in the 1975 the university was established (Split, 2016). In the 1966 the Split aeroport was opened (Gamulin, 1999). The important event in the City's history were the Mediterranean games held in the 1979. For this reason, large and numerous construction works were undertaken (Cukrov, 2016; Gamulin, 1999). The Poljud stadium and swimming pool complex, the Gripe sport halls, tennis-courts complex, small halls complex for martial arts, residential area (Split 3), and two hotels were built. Also, the City club's stadium, Gripe basketball hall, and a playing field in Kaštel Gomilica were renovated. The accompanying infrastructure was built as well: big passenger terminal on the Resnik aeroport, nautical-passenger terminal in the City port, new TV centre, and the tunnel through Marjan hill. Traffic infrastructure (roads and railway), electrodistribution network, sewage system, telecommunication network, and two hotels were also reconstructed. Industrialization was one of the key processes influencing the development of the urban areas. Other key process was the lithoralization, i.e. movement of the population to the coastal areas which was particularly characteristic for Split and Kaštela areas where large population was concentrated on a relatively small coastal area. Large increase of the population in urban areas continued until the 1980s with its maximum between the 1961 and 1971 (Kranjčević et al., 2014). In the 1960s Split City experienced a great demographic boom, stimulated by the sudden industrialization, when the population doubled (Gamulin, 1999; Klempić, 2004). In the 1978 the population doubled again.

By reaching the high level of urbanization and industrialization, when the largest part of the Bay's coast was transformed from agricultural into urban and industrial land and when there were significantly less large construction works present, significant change of the source of sediment material and the amount of material reaching the Bay may have occured.

Considering that the urban and industrial lands are less pronounced source of sediment material than the agricultural land and that they also represent a tight barriers for sediment material (Lu and Matsumoto, 2005; Yeager et al., 2006), the amount of material reaching the Bay might have been decreased thus decreasing the sedimentation rate as observed after the 1986 in the Kaštela Bay (Table 6, Figure 6). This is in accordance with the information about the urban development of the Croatian cities. Since the 1980s urban population and industrialization were in stagnation or decreasing (Kranjčević et al., 2014). After the 1981 population increase was slower in the Split City and construction works were not so numerous due to the economic crisis (Gamulin, 1999; Klempić, 2004). However, compared to the situation from the middle of the 20th century, it can still be concluded that the long-term sedimentation rate increase was present. It was attributed to the discharge of large amounts of industrial and municipal waste waters into the Bay (Knezić and Margeta, 2001; Margeta, 2002; Ujević et al., 2000) as a consequence of existing level of urbanization and industrialization (Lu and Matsumoto, 2005; Singh et al., 2008).

4.4. Spatial sedimentation rate variations

Sedimentation in the Kaštela Bay was generally uniform in the 1954–2005 period (Figure 6.a)). No areas with significantly higher or lower sedimentation rates than in the rest of the Bay were observed. Sedimentation rate distribution pattern (Figure 6.a)) in this period was closely comparable with the bathymetric characteristics of the Kaštela Bay (Figure 2). It suggests that the depth of the sea bottom was the most important factor influencing the sedimentation rate distribution pattern in this period because anthropogenic influence was not yet significantly expressed.

Significantly increased sedimentation rates in almost whole Bay after the 1963 (Figure 6.b)) suggest the increase of anthropogenic influence in the Bay, especially in its central and easternmost part. Such increase of the sedimentation rate points to the significantly increased amount of sediment discharged into the Bay which corresponds to the intensive urbanization and industrialization processes taking place at that time. Water currents play an important role in distributing the sediment across the whole Bay thus spreading the anthropogenic influence on the whole Bay. Different circulation types existing in the Kaštela Bay, well mixed water column in part of the year, and the relatively short average water replacement time enable the distribution of sediment through the whole Bay regardless of the sediment source position. Higher sedimentation rate in the easternmost part around Vranjic may to a lesser extent be a result of the larger discharge of the sediment material by the Jadro River and to a greater extent of the long-term discharge of large amounts of untreated industrial and municipal waste waters with high suspended matter content. High suspended matter content is in accordance with the observed fine grain size sediment at the K22 and K61 sampling stations (Table 4). The highest sedimentation rates observed in deeper part of the Bay, and in the Vranjic area, show that the bathymetric characteristics of the Bay were still important for the sedimentation but not as much as in the preindustrialization/preurbanization period because the anthropogenic influence spreads through the whole Bay masking the natural factors responsible for undisturbed sedimentation in the Bay.

Increased sedimentation rate in the easternmost area around Vranjic in the most recent period after the 1986 (Figure 6. c)) was again a result of the combined discharge of the sediment material by the Jadro River and waste waters. Increased input of the particulate matter was mostly a consequence of the anthropogenic influence considering that the Jadro River drains the same geological basement in all three studied periods and does not transport large amounts of natural particulate matter into the Bay. This was observed around the Jadro River mouth in the period from the 1954 (Figure 6.a)) where sedimentation rate was not increased because there wasn't significant accumulation of the sediment material transported by the River. However, in the later periods (Figure 6.b) and c)) sedimentation rates around the Jadro River mouth were significantly increased. Considering that the Jadro River always drains the same area, differences in the amount of the deposited material in the easternmost part of the Bay during long periods should be a result of the anthropogenic activity. Closed circular circulation which forms in the summer months in the east part of the Kaštela Bay and long water replacement time cause the non existence of hardly any water exchange between this part of the Bay and the rest of the Bay (Barić, 1995). Together with the Jadro River and waste water discharge this facilitates fine particles sedimentation in the east part of the Bay.

Generally, the sedimentation rates in the Kaštela Bay increased since the 1954 and localized areas of significantly increased rates were formed in the east part of the Bay. Depending on the material input, sedimentation conditions, bottom topography, and wave and current influence these localized areas can be subjected to change of position.

5. Conclusions

Temporal and spatial sedimentation rate variabilities were observed in the Kaštela Bay and were closely related to industrialization and urbanization of the coastal area. The average total sedimentation rates for the 1954–2005, 1963–2005/2006, and 1986–2005/2006 periods were 0.41cm/yr, 0.81 cm/yr, and 0.61 cm/yr, respectively. Although the sedimentation rates decreased after the 1986, the long-term sedimentation rate increase in the Bay was established in relation to the 1950s due to the anthropogenic influence. The easternmost part of the Bay was exposed to the greatest sediment material input and to the largest sedimentation rates changes. High sedimentation rates in this part of the Bay were a result of the combined sediment material discharge from the Jadro River and waste waters.

Urban and industrial development of the coastal area is very quickly, in terms of few years, reflected in the sedimentation rates of the semi-enclosed bay. Changes in the intensity of anthropogenic activities are also clearly reflected in the sedimentation rates. With the increase of intensity of the human activities the affected area of the bay increases due to larger amounts of sediment material available for deposition and some localized areas of sediment accumulation may form. Sedimentation rates increase in the areas directly exposed to increased sediment input and in deeper parts of the bay. Semi-enclosed bay retains most of the sediment inside the bay and the exchange of sediment between the bay and other marine water bodies is present but slower than the sedimentation rate changes in the bay. It largely depends on the topographic characteristics of the sea bottom, prevailing currents, and the amount of the sediment material discharged into the bay.

The results of this study can be considered to be approximate, until confirmed with another method, due to ^{137}Cs method limitations. However, the trends in sedimentation rates and spatial deposition patterns were distinguishable showing that by using only ^{137}Cs as a marker it is still possible to determine the environmental condition of the area in relation to the anthropogenic influence and sedimentation. Sufficient number of representative sediment cores covering the entire studied area is important to obtain reliable data about the sedimentation trends. These data provide useful basis for estimation of the future environmental condition of the area influenced by the changes in sediment material input. This is especially important in polluted areas and improves marine management planning in such areas. By determining the areas of increased sedimentation rates it is potentially possible to predict the areas most vulnerable to accumulation of particle binding pollutants.

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