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Analysis of beach nourishment and construction in Croatia

Authors:

Tonko Bogovac, mag.phys.geophys
University of Zagreb
Faculty of Civil Engineering
tonko.bogovac@grad.unizg.hr
Corresponding author

Assoc.Prof. Dalibor Carević, PhD. CE
University of Zagreb
Faculty of Civil Engineering
dalibor.carevic@grad.unizg.hr

Assist.Prof. Damjan Bujak, PhD. CE
University of Zagreb
Faculty of Civil Engineering
damjan.bujak@grad.unizg.hr

Vjekoslav Novaković, MCE
University of Zagreb
Faculty of Civil Engineering
vjekoslav.novakovic@grad.unizg.hr

Subject review

Tonko Bogovac, Dalibor Carević, Damjan Bujak, Vjekoslav Novaković

Analysis of beach nourishment and construction in Croatia

Beaches on the eastern Adriatic coast are the basis of Croatia's tourism offering while also being under pressure from climate change. Data is necessary to manage beaches effectively, but data is lacking as well as the long awaited national strategy for coastal management. This paper collected data about beaches from regional documents, nourishment data was obtained by survey from local municipalities while beach construction data was obtained from aerial photogrammetry. Croatia has more than 1904 small gravel beaches and nourishment is performed in small increments beinnaly, while more than 27 % of existing beach area has been constructed all primarily for the needs of beaches, marines and tourism.

Key words:

beach nourishment, beach construction, gravel beaches, beach management, erosion

Pregledni rad

Tonko Bogovac, Dalibor Carević, Damjan Bujak, Vjekoslav Novaković

Analiza dohranjivanja i nasipavanja plaža u Hrvatskoj

Plaže istočne obale Jadrana čine temelj turističke ponude Hrvatske, ali su pod iznimnim pritiskom turizma i klimatskih promjena. Za upravljanje obalom potrebni su podatci, a zasad izostaje i nacionalna strategija. Podatci o plažama prikupljeni su iz regionalnih programa svake županije, potom su prikupljeni podatci o postupku dohranjivanja obale putem ankete jedinica lokalne samouprave, a posebno su i analizirane snimke iz zraka za podatke o nasipavanju (tj. izgradnji) obale. Hrvatska ima 1904 pretežito male šljunčane plaže, provodi dohranu svake druge godine u malim količinama, a ujedno je i nasipala 27 % nove površine, sve pretežito za potrebe plaža, luka i turizma.

Ključne riječi:

dohranjivanje plaža, nasipavanje obale, šljunčane plaže, upravljanje obalom, erozija

1. Introduction

There is limited published data regarding a large number of Croatia's beaches. The total number of beaches is unknown, as well as their sediment composition, length, area, and other relevant data. The lack of data complicates beach management for Croatia's local municipalities, which lack support from a national strategy [1, 2]. Beaches on the Croatian coast are under pressure from both tourism and climate change. The country's tourism industry relies on the "sun and sea" model which accounts for 20 % of GDP owing to prolonged stays which are highly concentrated on the shore and in the summer season [3]. However, winter months are characterised by storm events reshaping beaches and redistributing sediment on the shore. Depending on the intensity of the storms, erosion of the beach and shore may occur. Erosion in this context is the irreversible loss of sediment from the beach caused by the transport of sediment outside of the beach area impacted by waves and therefore cause the beach area to shrink [4]. The impact of storm events on the shore changes owing to climate change and the accompanying change in wind-wave climate [5] and sea level change [6, 7]. According to sources [8-10], climate change is predicted to cause only small changes in the occurrence and intensity of storms and waves, which shape the coast, and no changes are expected in Adriatic storm surges [11]. However, the increase in the mean sea level is expected and considerable for the Adriatic as it will amount to 40 or 80 cm until the end of the century, depending on greenhouse gas emissions and concentrations [12–14]. The occurrence and intensity of extreme sea level events will also change as the mean sea level rises. Extreme sea levels rise, such as 80 on the Southern and 120 cm on the Northern Adriatic, with a current probability of occurring once in a century [15], will become a common occurrence in the future with a probability of occurrence being once every few years, depending on the RCP scenario [16]. This would be a catastrophic change for the coastal environment.

In addition to changes in sea level and the wind-wave climate, material abrasion and sediment transport caused by precipitation runoff can also impact beaches. For instance, the urbanisation of coastal areas or the construction of infrastructure can prevent precipitation runoff and the accompanying sediment accumulation. The construction of a road above the beach Mogren prevented sediment accumulation from precipitation runoff [17] and caused the beach to shrink. If all of these processes are not in balance the beach erodes and disappears, unless humans intervene.

The most common countermeasure to beach erosion is beach nourishment [18] or adding gravel or sand material on the beach to replace material previously lost owing to erosion or abrasion. In comparison, beach construction is the measure of constructing new or extending existing beaches. Most European countries regularly nourish their sand beaches, and the practice is also common in Croatia. Croatia is similar to countries such as Italy, Spain, and France which, according to [18], do not have a national beach management strategy and rather react to the occurrence of erosion. Conversely, countries, such as Denmark, the United Kingdom, the Netherlands, and Germany, have national strategies that prescribe nourishment practices, evaluate their effectiveness and, act proactively to prevent future beach losses. Alternatively, Croatia can improve current nourishment practices, primarily by implementing a national strategy and collecting data on beaches and shorelines.

Nourishment is the current dominant practice owing to its versatility to changing shoreline conditions, non-invasiveness into the environment, and ongoing process dynamics on the beach while also having a low environmental impact if performed correctly and occasionally [19]. There is a lack of data on the extent of erosion on the Croatian coast and the efficacy of performed nourishments. Therefore, this study collected data on beaches and nourishments on the Croatian coast from PL/14 forms and a survey addressed to local municipalities. The shoreline change can be observed with different methods in the future with the use of new, cheap, and simple methods for beach monitoring based on photogrammetry [20, 21], while unmanned aerial vehicles [22] allow for the construction of three-dimensional models of the shore in the high resolution and tracking of morphological change. For reconstruction of historical shore data, analysis of historical aerial or satellite images can be performed, such as those used in tracking cliff erosion on the coast of central California, USA [23], or the shoreline change in Campagnia, Italy [24]. Analysis of available aerial images on Geoportal provided data on shoreline change on the Croatian coast for the period from 1968 until 2020.

This study aims to present unpublished data on beaches in Croatia collected from multiple different sources and continuing based on a previously published conference paper [25] and an article on the use of artificial intelligence (AI) to provide estimates of material needed for beach nourishment projects [26]. We collected the number of beaches and basic characteristics from PL/14 forms and surveyed local municipalities for data on nourishment practices. This allows us to compare local practices and position them within an international context. Aerial photos allowed for the determination of constructed shoreline from 1968 until 2020. This presents an overview of Croatian beaches and shores in the context of nourishment and construction.

2. Methods

2.1. Data collection

There is a significant lack of published data on eastern Adriatic beaches. Therefore, we collected data on beaches from local municipalities in charge of beach management and aerial photographs. There are three main sources for this data, the first is counties that collected data to establish regional programmes for managing beaches [27–33] based on filled PL/14 forms (Figure 1) in 2015.

OBRAZAC ZA EVALUACIJU PLAŽA (PL/14)

1. Grad, općina, županija, naziv plaže

Županija:
Grad/općina:
Naziv plaže:

2. Dužina plaže:

	m

Površina plaže:

	m2

3. Klasifikacija plaže:

a) prirodna		b) uređena	
- udaljena		- mjesna	
- ruralna		- urbana	
		- plaža turističkog kompleksa	

4. Ukoliko je prethodni odgovor pod a, odredite stupanj zaštite plaže:

- potpuna zaštita	
- djelomična zaštita	
- bez zaštite	

5. Tip plaže prema značajkama plažnog sedimenta:

Geološki sastav	
Pijesak	
Sitni šljunak	
Šljunak	
Kamen	
Stijene	
Beton	
Ostalo	

6. Dostupnost (prilaz) plaži:

a) asfaltirana cesta	
b) samo morski prilaz	
c) bijela cesta	
d) morski prilaz	
- samo za iskrcaj putnika	
- uređeno pristajalište	
e) pješačka staza	
f) obalni put	

f) nešto drugo, navedite što

7. Da li je plaža pod koncesijom?

a) da		od do
b) ne		

8. Ako postoji koncesija (koncesijsko odobrenje), što obuhvaća koncesija (koncesijsko odobrenje)?

	Koncesija	Koncesijsko odobrenje
a) korištenje plaže		
b) ugostiteljske objekte		
c) sportske sadržaje		
d) parkiralište		
e) sanitarni čvor		
f) ostalo (navedite što!)		

9. Da li plaža ima Plavu zastavu?

a) da		Za koje godine?
b) ne		

10. Da li je plaži dozvoljen pristup kućnim ljubimcima?

a) da	
b) ne	

11. Da li se sustavno prati kakvoća mora po Uredbi o kakvoći mora za kupanje (NN 73/08)?

a) da	
b) ne	

12. Koliki je procijenjeni sadašnji vršni kapacitet plaže u glavnoj turističkoj sezoni?

	kupača

13. Da li je plaža prilagođena osobama s posebnim potrebama?

a) da	
b) ne	

14. Temeljem utvrđenog stanja, što karakterizira plažu?

Prirodni resursi	
zabava	
animacija	
sport i rekreacija	
gastro ponuda	
odmor i relaksacija	
bijeg od svakodnevice	
nudizam	
ponuda za kućne ljubimce	
događanja	
zdravstvene pogodnosti	
škola plivanja	
nešto drugo? (Upišite što!)	

15. Da li su određene granice pomorskog dobra?

a) da	
b) ne	
c)djelomično (objašnjenje)	

16. Da li imate interes za uređenje postojećih i novih plažnih prostora?

a) da	
b) ne	

17. Ako je Vaš odgovor na prethodno pitanje DA; da li posjedujete slijedeću dokumentaciju?

	DA	NE
a) izvod iz katastarskog plana s popisom katastarskih čestica na kopnu koje su predmetom uređenja		
b) vlasnički list s popisom čestica (provjeriti da li je upisano pomorsko dobro ili nešto treće)		
c) izdana lokacijska informacija (prema Zakonu o prostornom uređenju NN 153/13, članak 36)		
d) odluka o koncesiji (Zakon o prostornom uređenju NN 153/13, Zakon o koncesijama NN 143/12, Zakon o pomorskom dobru i morskim lukama NN 158/03, 141/06, 38/09 i 123/11)		
e) eventualnu pripadnost plaže sustavu ekološke mreže Natura 2000		
f) izvršenu procjenu okoliša, ako je potrebna, a sukladno Uredbi o procjeni utjecaja na okoliš (NN 64/08, 67/09)		
g) izrađeni idejni projekt uređenja plaže		
h) lokacijsku dozvolu (ako je riječ o zahvatu u prostoru npr. nasipavanju i drugo)		

Figure 1. Empty PL/14 form used to evaluate a beach and to form a regional programme for coastal management

For this study, PL/14 were collected from seven coastal counties with data on beach names, municipality, county, beach length, beach area, and material on the beach. Regarding the material present on the beach, the PL/14 form presented multiple options: sand, fine gravel, gravel, stone, boulder, concrete, and others. However, the PL/14 form and regional programmes using the forms did not detail the methodology used in determining material categories. Based on these data, a database of Croatian beaches was created. From this database, the total number of beaches in the regional programme and the distribution of different materials present on the beaches were determined. Median beach length and area are also derived from these data.

The second data source is the survey (Figure 2) created for project Beachex and the local municipalities to document the data on beach nourishment practices between 2015 and 2019 (inclusive). The survey collected yearly expenses in HRK without VAT, the amount of material used in nourishment per year in m^3, average grain size of the material, name of construction company that performed the nourishment, source of the material used in nourishment, and beach coordinates. The previously created database was updated with these data.

The sediment size of the material used in nourishment was grouped into five categories: sand and fine gravel (0.063–4 mm), fine gravel (4–16 mm), coarse gravel (16–64 mm), mixed material (if the range of sediment size listed in the survey was in between two categories listed previously) and unknown (when no sediment size was listed in the survey). The rate of beach nourishment (the number of times the beach was nourished in the 5 years) and spatial distribution of nourished beaches were visualised using the software package QGIS.

Some of the data on nourishment, sometimes even for entire municipalities, often was exceedingly high or low compared to most of the data collected, implying such data should be treated as an outlier and excluded from further analysis. This was not performed in this study; rather, all data were treated as valid and representative of beach nourishment, but such analysis could be performed in future work. For missing data and where derived variables could not be calculated (e.g., the amount of material used for nourishment per meter of beach length where beach length data were missing), this was noted next to the data.

The last source of data was the website Geoportal from the National Geodetic Administration which hosts aerial photographs of the eastern Adriatic shoreline from 1968. These images were compared to the images from 2020. Comparing the shoreline between the two images allowed for the number and area of constructed shores from 1968 until 2020 to be derived.

2.2. Determining the total yearly and unit financial and material costs of nourishment

Data from the survey were analysed, and the median and average rate of nourishment were determined. The total yearly amount of material used for nourishment and the yearly expense in HRK were also determined for 2015 to 2019. Data were grouped per county. The number of nourished beaches

	Name of the beach	Year	Annual top-up costs without VAT [kn]	Annual amount of feeding [m³]	Name of the top-up contractor	Name of the source of the stone (if known)	Average grain size of the material (if known) [mm]	Geographic coordinates of the beach	
EXAMPLE	1. Plates	2019	20000.00	50	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32	45.340663, 14.370982	EXAMPLE
		2018	23000.00	92	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
		2017	36000.00	145	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
		2016	17000.00	118	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
		2015	50000.00	150	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
	2. Playground to concrete sunbathing area and ramp	2019	5000.00	12	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32	45.339830, 14.375182	
		2018	17000.00	55	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
		2017	12000.00	52	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
		2016	16000.00	108	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		
		2015	25000.00	85	Dohranjivanje d.o.o	Čufar quarry, Brijuni	32		

Figure 2. Example of a filled survey sent out to local municipalities to provide data on nourishment of the beaches they manage

was compared to the total number of beaches listed in the regional programme for each county. Moreover, the percentage of nourished beaches from the number of beaches covered by the survey and from the total number of beaches in that county was determined.

The unit cost of nourishment per meter of the beach (HRK/m) was determined in reference to the meter of coastline for each beach by dividing the total expense of nourishment for the beach with the length of the beach coastline from PL/14 data. Similarly, the unit cost of 1 m³ of the material used for nourishment (HRK/ m³) was determined by dividing the total expense by the amount of material used. In each case, this calculation was performed for each nourishment of the beach, rather than for all nourishments on average. Both the unit cost of nourishment and the materials were averaged not only for all beaches within a county and every year between 2015 and 2019 but also for the entire country. Additionally, a box and whiskers plot was created to display the quartile, median, and average unit cost of the material per category (HRK/m³).

The analysis from source [18] was performed for the Croatian dataset by determining the amounts of total material used, length of coastline being subject to nourishment, total length of all nourishment projects, total length of soft coastline (sand or gravel coast), annual volume of materials used in nourishment per meter of coastline, average unit volume for all projects, and average volume of material for nourishment per meter of soft coastline. The following are also determined: the average number of nourishments per beach, average nourishment interval, ratio of nourished coastline and soft coastline, and range of volume of the material used per meter of shoreline. This enabled a comparison of Croatia's data with that of other European countries analysed in [18].

2.3. Deter mining the area of beach construction

Comparing coastlines from two aerial images from 1968 and 2020, the area where the shore was constructed can be determined visually as the difference in coastline area from pictures in 1968 and 2020. Because tides have small amplitudes on the Croatian coast of the Adriatic, the impact of sea level at the moment the pictures were captured was overlooked. This study analysed all locations with a visible increase in shoreline by determining the area of the beach that was constructed and the location. A total of 1026 of these locations were categorised into four different categories: beaches, ports, urban areas, and industry. Because of the difficulties in differentiating between locations being used for industry and ports, those two categories may not be as precise. However, their total sum is accurate. In certain locations, the low quality of the aerial images from 1968 reduced the accuracy of the area determined, but these cases are rare. The accuracy of this method can be further increased using a more rigorous analysis of georeferenced maps.

3. Results and discussion

3.1. Beach nourishment

In regional programs, PL/14 forms reference 1904 distinct beaches on the Croatian coast. In the PL/14 form, multiple different materials could be selected as present on the beach. Based on occurrence, the most common material was gravel (1.108 beaches or 58 % of beaches contained gravel), followed by boulders (792. 42 %), stones (716. 38 %), fine gravel (597. 31 %), and concrete (550. 29 %). Sand was the least common (361.19 %) besides other materials (22. 1 %). The median coastline length for 1740 beaches is 200 m, while the median beach area is 1.456 m^2 on the sample of 1.814 beaches for which the area was listed.

The survey received a response from 89 (68 %) of the 130 municipalities, out of which 56 reported nourishing some of the beaches from the regional programmes, while 33 municipalities reported not performing nourishment projects between 2015 and 2019. The 89 municipalities that did respond to the survey manage 1400 different beaches out of which 256 were nourished approximately 828 times between 2015 and 2019. On average and in the median, the rate of beach nourishment is three times in 5 years or approximately every 2 years. Table 1 presents the data on nourishment per county.

The largest number of beaches are in Primorje–Gorski Kotar County (406), while the beaches in Zadar County are the most nourished in absolute (67 beaches) and relative (22.3 % of beaches within that county) numbers. Lika–Senj County nourishes the least in absolute numbers (15 beaches), while Split–Dalmatia County relatively nourishes the least number of beaches (7.6 %). Most values are probably higher than those listed in the table, as a third of the municipalities did not reply to the survey. Most of the beach nourishment, approximately 75 %, costs less than 30.000 HRK and uses less than 120 m^3 of the material per nourishment. Consequently, only a few nourishments (15 %) comprise the most or 75 % of the total financial and material costs.

The total financial cost of nourishment from 2015 to 2019 is approximately 33.58 million HRK, while the total cost per year is shown in Figure 3. From 2015 to 2019, the yearly financial cost of nourishment increased. The costs reached their peak in 2018, with a total of 10.75 million HRK spent.

Figure 4 shows the total material cost of nourishment based on data collected from the survey. The total material cost for nourishment between 2015 and 2019 was 194.000 m^3 of different materials. A significant increase in material cost was observed in 2018 and 2019, with 4 and 2.5 times more material being used compared to the previous 3 years (2015 to 2017).

Accounting for the third of municipalities that did not respond to the survey, it can be presumed that the total financial and material cost for 2015–2019 was most likely larger. Analysis performed in [25] uses a correction factor to determine the probable total amounts, suggesting that the total cost may be

Table 1. Data on the number of beaches and nourished beaches per county and the financial and material costs of nourishment

County	No. of municipalities	No. of beaches	No. of nourished beaches	No. of surveyed beaches	% of beaches nourished relative to the No. of beaches surveyed	% nourished beaches relative to the total No. of beaches	Total financial cost of nourishment [kn]	Total material cost of nourishment [m^3]
Dubrovnik-Neretva	18	278	28	205	13.7	10.1	1.596.461.20	4.182.00
Lika-Senj	3	181	15	60	25	8.3	637.000.00	4.900.00
Split-Dalmatia	32	347	26	206	12.6	7.5	8.090.718.41	54.889.41
Šibenik-Knin	10	142	27	81	33.3	19	4.310.369.24	30.026.21
Istria	21	250	35	239	14.6	14	2.427.748.36	8.944.53
Primorje-Gorski Kotar	20	406	58	345	16.8	14.3	4.068.070.50	17.849.11
Zadar	26	300	67	264	25.4	22.3	12.448.394.51	74.088.99
Total	130	1904	256	1400	18.3	13.4	33.578.762.22	194.880.25

approximately 47 million HRK and 280.000 m^3 of the material for 2015–2019.

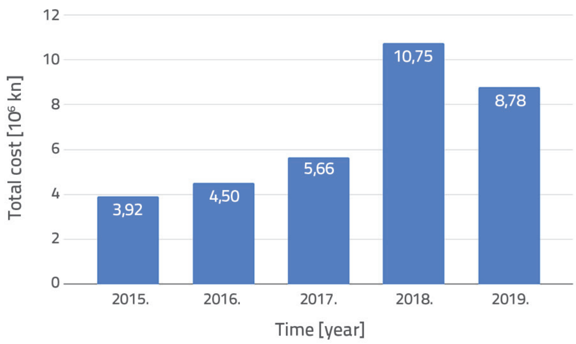

Figure 3. Total financial cost of nourishment in Croatia based on data from the survey in millions of HRK without VAT

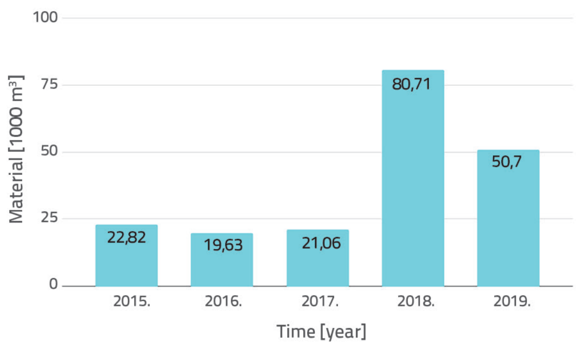

Figure 4. Total material used for nourishment in Croatia based on the survey, in thousands of m^3

A positive trend in financial costs is observed annually, while in material costs, a longer series of data would be required to assess the long-term change. The sharp jump in financial and material costs that occurred in 2018 prevents a definitive conclusion. Part of the increase in 2018 is owing to the reconstruction of beach Ždrijac near the city of Nin which accounted for 2.6 million HRK in financial and 33,235 m^3 in material expenses. Similarly, Kraljičina plaža next to Nin used more than 1.2 million HRK and 15,110 m^3 in the material. Nourishments next to Nin are specific owing to dredging of the material from the seabed, which is excessively expensive compared to other cases where fluvial sediment is used. However, the trend observed in Figure 3 remains even after removing these costs.

Figure 5 shows the average unit cost of nourishment per meter of coastline for each county and for Croatia in total, for each year. A positive trend in the unit cost of nourishment per meter of coastline is also visible, with an increase from 75 HRK/m in 2015 to 139 HRK/m in 2019 on a national scale. A possible explanation for the increase in costs (total and unit) is in the grants provided by the Ministry of Tourism as part of the call for subsidising tourism infrastructure, including beaches. In [25], Figure 4 depicts an identical analysis, out of which nourishments with high total or unit costs are excluded. In the data and results presented here, without excluding any of the data, the unit costs of nourishment are higher than in [25], and the trend in financial costs is present in both cases.

Under-average nourishment costs in comparison to the national average are observed in Lika–Senj, Istria, and Šibenik–Knin County, while Zadar County's cost increased above the national average in the 2015–2019 period. Dubrovnik–Neretva County has the highest unit cost of nourishment, Primorje–Gorski Kotar County reduces unit costs below the national average, and Split–Dalmatia County increases its unit costs of nourishment and exceeds the national average.

In [18], the European practices of beach nourishment were analysed and a comparison was made. To compare Croatia to the countries in [18], an analysis in Table 2 was performed. The number of years of fills or nourishment (Y) for the dataset used here is short, and only five years compared to the 10–48 years used in [18] because of the lack of a longer dataset. The total nourishment volume in Croatia is 100 times smaller than in other European countries, where it is measured in tens of millions of cubic meters. However, other European countries have datasets for longer periods and slightly longer shorelines. The total length of coastline subject to nourishment (LN, where each meter of coast counts only once if nourished) and the total length of all nourished projects (LP, where each meter of the coast is counted per nourishment) were 107 and 285 km, respectively, which is comparable to other countries that on average have a larger coastline,

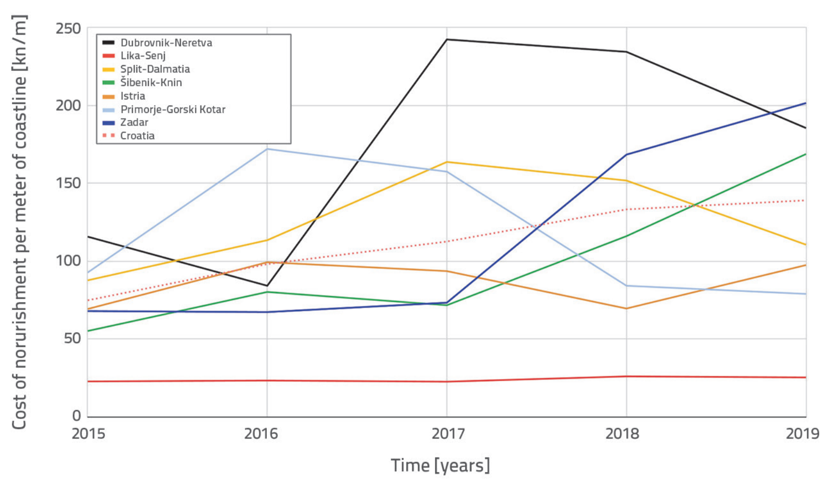

Figure 5. Average unit cost of nourishment per meter of shoreline averaged by county and the national average on the sample of 794 nourishments (95.9 % of 828 nourishments; 34 nourishments did not have data on beach length)

Table 2. Parameters describing nourishment practices per country allow for comparison between data for Croatia and data for other European countries from [18]

Country	HR	FR	IT	DE	NL	ES	UK	DK	USA
Y = number of years of nourishment [years]	5	33	37	48	10	13	44	24	46
V = total volume of material used [10^6 m^3]	0.196	12	15	50	60.2	110	20	31	144
LN = length of coastline subject to nourishment (counting only once for all nourishments) [km]	107	35	73	128	152	200	/	80	350
LP = total length of all nourishment projects (counting each nourishment) [km]	285	190	85	313	297	525	/	515	/
LS = total length of soft (sand and/or gravel) coastline [km]	618	1960	6320	602	292	1760	3670	500	61400
AVN = annual fill volume per m of coastline subject to nourishment = V/LN/Y [m^3/m/years]	0.36	10.4	5.6	10	39.6	42.3	/	16	9
AVP = average unit volume tor all projects = V/LP [m^3/m]	0.68	63	176	210	207	210	/	60	/
AVS = annual nourishment volume per m of total length of soft coastline = V/LS/Y [m^3/m/years]	0.06	0.19	0.11	1.7	20.6	4.8	/	2.6	0.05
ANF = average number of nourishments on a particular project site = LP/LN (/)	2.66	5.4	1.2	2.4	1.9	2.6	/	6.4	/
ARI = average renourishment interval = Y/ANF [years]	1.88	6.1	31.8	19.6	5.2	4.9	/	3.7	/
Percent of nourished shoreline LN/LS [%]	17	1.8	2	21.6	52.1	11.4	/	16	0.6
RUV = range of unit volume used for individual projects [m^3/m]	0.004-10.8	3.3-400	19-511	30-500	31-596	70-450	/	10-100	/

both total and soft coastline (LS). The total volume of the material used for nourishment (V) is low compared to other European countries by a factor of 100. Consequently, all variables derived from V are also lower (e.g., AVN, AVP, and AVS) by a few orders of magnitude. The average number of fills per location (ANF) is comparable to other countries but also high if we consider that the data for Croatia is only for 5 years. Meanwhile, other countries have data for anywhere between 10 and 48 years. Similarly, the average renourishment rate (ARI) is 2 years, which is significantly higher than in the rest of Europe.

The percentage of nourished shoreline is high, at 17 %, particularly considering that an average Croatian beach is only 200 m long, despite that we can compare the percentage of nourished shoreline to countries such as Germany and Denmark. The range of unit volume used for individual projects (RUV) is quite lower than in other countries; that is, Croatian beaches are nourished with small amounts of the materials.

Figure 1 displays a box-and-whiskers plot for a unit price of 1 m^3 in HRK of three different materials used in nourishment (i.e. sand and fine gravel, fine gravel, and coarse gravel). The median unit price is the lowest for fine gravel (4 to 16 mm) at 152 HRK/m^3, then comes sand and fine gravel (0,06 to 4 mm) at 200 HRK/m^3, and finally coarse gravel (16 to 64 mm) at 286 HRK/m^3. The average unit costs are only approximately 10 % higher than the median. The unit cost of coarse gravel exhibits the highest variability from 193 to 366 HRK/m^3.

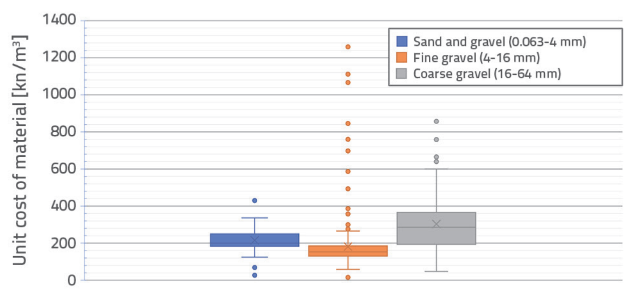

Figure 6. Box and whiskers plot of the unit cost of 1 m^3 of three different materials used in nourishment projects – sand and fine gravel (0.063–4 mm), fine gravel (4–16 mm) and coarse gravel (16–64 mm)

3.2. Beach construction

The results obtained from the comparisons of aerial images from 1968 to 2020 are analysed here. In the aforementioned period, a total area of 7.513 km^2 of the coast was constructed. For comparison, the total maritime area is 38.235 km^2, meaning from 1968 to 2020 maritime area increased by 19.6 % owing to construction. The maritime area was determined as the multiple of Croatia's total coastline length of 6.372.57

Table 3. Number of locations with the construction of the shore from 1968 until 2020 and the constructed areas

County	Beach construction	Port construction	Urban area construction	Industry area construction	Total number of locations	Total area constructed [km²]
Istria	96	46	25	4	171	0.974
Primorje-Gorski Kotar	44	35	30	5	114	1.073
Lika-Senj	41	24	15	2	82	0.202
Zadar	136	107	60	6	309	2.092
Šibenik-Knin	20	17	8	2	47	0.593
Split-Dalmatia	68	30	28	4	130	2.000
Dubrovnik-Neretva	80	44	46	3	173	0.579
Total number of locations	485	303	212	26	1026	7.513
Total area constructed [km²]	1.859	3.107	1.677	0.869		

km and the width of the maritime area (prescribed by law [34]) of 6 m.

The total number of locations where the shore was constructed is grouped by counties and categories shown in Table 3. Most of the shore construction was categorised as beach construction with 485 locations, followed by ports with 303 locations, and then urban areas with 212 and industry with 26. If analysed by area, the most of shore construction was performed for ports with 3.07 km^2 followed by beaches with 1.859 km^2. This high area of construction for ports implies a significant investment into tourism (construction of marinas) and in the transport connections between the island and land (public ports) and communal ports from 1968 to 2020.

The largest number of construction locations is in Zadar County in all categories with 309 different locations, followed by Dubrovnik–Neretva County with 173 locations. The national average of the constructed area is 1,073 km^2. Compared to this average, Zadar and Split–Dalmatia counties exceeded the average shore construction, with average construction being performed in Primorje–Gorski Kotar County, while other counties performed construction below the national average. The largest construction in Zadar County was for port Gaženica with an area of 0.452 km^2, while Split-Dalmatia County has the largest construction for a beach with an area of 0.277 km^2 for beach Žnjan.

Beach construction was performed on 485 different locations which, when compared to the 1.904 beaches from PL/14 form, accounts for a quarter of all beaches.

Figure 7 shows the ratio of constructed shore area and the total county shoreline (including islands). In this manner, the size of the county and its shoreline are represented in the extent of shore construction. Shoreline lengths with island shoreline included are, per county: Istria County 576.9 km, Primorje–Gorski Kotar 1.118.7 km, Lika–Senj 282.73 km, Zadar 1.344.65 km, Šibenik–Knin 814.28 km, Split–Dalmatia 1.097.5 km, and Dubrovnik–Neretva County 1.138 km. Publicly available data were used to reference those values. In Figure 7, the counties with the largest ratio of construction to the shoreline are Zadar County in the category ports, Istria county in the category urban shore, and Split–Dalmatia county in the category beaches and industry. For Istria county, this ratio is increased owing to Istria having the smallest islands compared to the total shoreline.

Counties with the largest construction of the shore for ports (tourist, local, and public) are Zadar and Split-Dalmatia counties. For the category of industry, those are Split–Dalmatia, Primorje–Gorski Kotar, and Istria counties. Seaward expansion for constructing additional beach areas was dominant in Split–Dalmatia and Istria counties. Urban areas expanded seaward the most in Istria and Zadar counties. Counties exceeding the national average for coastal

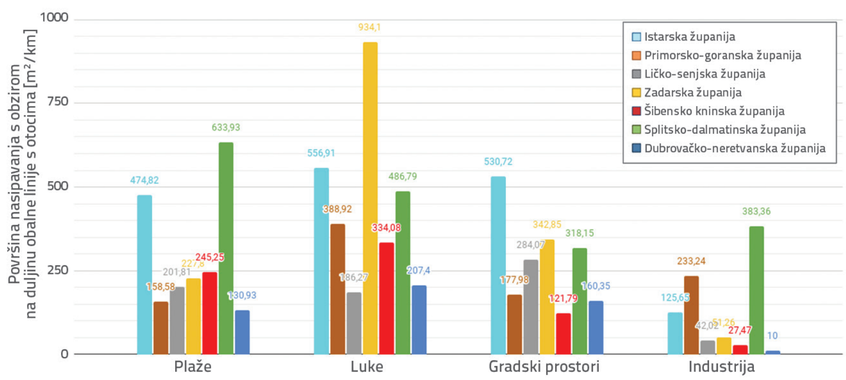

Figure 7. Area constructed in ratio with the shoreline length per county and category

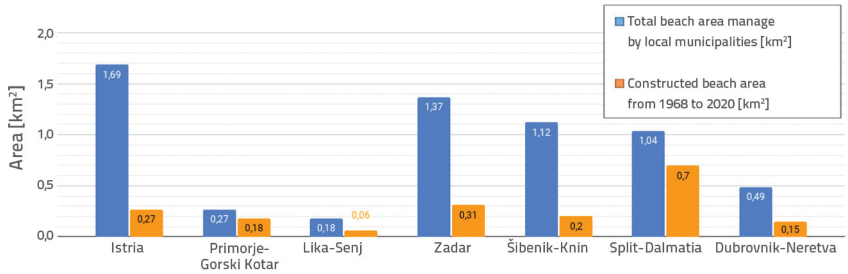

Figure 8. Ratio of the total and constructed area

construction in urban and beach categories should adopt better zoning and urban planning to reverse this trend in the long term. Limiting shore construction for port and industrial needs is contrary to the principles of economic development and population needs. Therefore, other technical solutions should be found to develop such infrastructure on existing land and hinterland or in existing brownfield areas.

Figure 8 shows the comparison of beach area from PL/14 per county (blue columns) and the beach area constructed (brown column) from 1968 until 2020 for each county. The ratio of the constructed versus current total beach area is between 17.8 % for Šibenik–Knin county and 67 % for Split–Dalmatia county. On a national scale, this ratio is 27 % of the total beach area. Some counties exceeded the national average in beach construction (Split–Dalmatia, Lika–Senj, and Dubrovnik–Neretva counties) and should reorient on the hinterlands and their economic development as an attractive tourist destinations.

This analysis is limited owing to the total number of beaches and beach area being higher than listed by PL/14 forms. In [2], it is presumed that Croatia has approximately 2,000 beaches. Methodological limitations exist as some small constructions, including piers, quays, moorings, groins, and similar structures, were not included in the analysis. Therefore, the total constructed area of the shoreline could be higher.

4. Conclusion

The lack of fundamental data on Croatia's beaches and shore present a challenge in science and coastal management. Data collected from regional programmes to form a (never made) national strategy of coastal management were analysed in this study. That analysis presents an overview of Croatia's beaches primarily for tourism. Additional data on beach nourishment from 2015 to 2019 were collected through a separate survey. Finally, an analysis of aerial images from 1968 and 2020 provided data on shore construction.

Croatia is rich with beaches, at least 1,904 primarily gravel beaches, while only a small percentage of beaches contain sand. An average beach is 200 m long with an aerial of 1.456 m^2. Nonetheless, the total shoreline length of Croatia is comparable to Germany, Netherlands, or Denmark, except for nourishments being performed biennially on average, rather than every 21, 52, or 16 years on average [18]. The volume of the material used in nourishment every year and per meter of shoreline differ significantly also: Croatia uses only 0.36 m^3 of material per meter of shoreline annually, while the aforementioned countries use approximately 10 m^3 per meter annually or even 2 or 3 times more. Over the observed 5-year period for the total financial cost of nourishment accumulated to 33 million HRK, while over 194,000 m^3 of the sand and gravel material was deposited on 256 different beaches, with some finding its way to the sea. The financial costs of nourishment show an increasing tendency. Approximately 17 % of the soft (gravel and sand) coastline in Croatia is nourished by these practices.

All those results favour the conclusion that nourishment in Croatia is a tool for managing beaches for tourism, rather than to combat the loss of shoreline caused by erosion. The lack of a national coastline management strategy [1], combined with the growing tourism industry, has contributed to the prevalence of these different management practices in Croatia. This is potentially detrimental to the environment since repeat nourishment can cause damage to the environment [19]. Future research should focus on specific locations, considering the wind-wave climate of the area and the redistribution of sediment caused by storms to eliminate the need for and the effects of nourishment performed in a Croatian manner. A detailed analysis of a few nourishment projects consuming the vast majority of material and/or funds should also be performed. Some of those nourishments can be compared to European projects, such as the case of nourishments in the city of Nin, while, in some cases, the need for nourishment should be questioned as some of those projects could be shore construction in disguise.

In the larger period, shore construction was common and primarily used to serve the needs of tourism and beach construction, as indicated by the number of locations. Simultaneously, the largest constructed areas were intended for ports – this can also be considered a subcategory of tourism since tourists need marinas and ports for public transport to islands. The sea area was reduced with shore construction for 7.5 km^2, which represents an increase inshore of 20 % of the current maritime area or approximately 27 % of the existing beach area.

The data presented here did not represent conclusive results on the number of beaches, number of nourishments or construction projects, and other relevant data; rather, additional research and a national coastal management plan are required. However, the high percentage of constructed coast and the high volume of the material used contradict the protocol of the integrated coastal zone management [35]. By signing the protocol, Croatia was obliged to form a coastal break of 100 m from the coastline, with an explicit ban on construction in that area to preserve the environment and manage space more rationally.

Both the legislative and tourism pressure should force Croatia to completely and strategically adopt a national coastal management strategy. Furthermore, with this strategy, the main objective should be to minimise the impact of current and future climate change.

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