Study on the presence of sand waves on the Kandestederne coast

Boccia, Maria Camilla; Frigaard, Peter; Margheritini, Lucia

DEPARTMENT OF THE BUILT ENVIRONMENT
AALBORG UNIVERSITY

Study on the presence of sand waves on the Kadestederne coast

Maria Camilla Boccia
Peter Frigaard
Lucia Margheritini

ISSN: 1901-726X
DCE Technical Report No. 313

Aalborg University
Department of the Built Environment
Ocean and Coastal Engineering Research Group

DCE Technical Report No. 313

Study on the presence of sand waves on the Kandestederne coast

by

Maria Camilla Boccia
Peter Frigaard
Lucia Margheritini

June 2023

Published 2023 by
Aalborg University
Department of the Build Environment
Thomas Manns Vej 23
DK-9220 Aalborg E, Denmark

ISSN: 1901-726X
DCE Technical Report No. 313

Preface

In order to investigate whether the buried pressure compensation modules along the Kandestederne coast had made a contribution to the coastal erosion problem, the Ministry of the Environment in June 2022 selected WSP Denmark in collaboration with Aalborg University as a consultant to the assignment. The bathymetric surveys conducted during the three years of observation were kindly made available by Sebastian Westh (WSP Denmark) and used in the following study to analyse the presence of sand waves on the stretch of coast of Kandestederne. The following document represents a final report of the study conducted at the Department of the Built Environment in the Ocean and Coastal Engineering Research Group.

Index

1. Introduction

The Kandestederne’s coast has been affected by strong erosion for years, therefore it has been subjected to numerous studies to counteract and analyze the phenomenon. The stretch of coast analyzed shows significant variations from season to season from a coastal morphological point of view, being exposed to large waves and powerful westerly winds. The transport of sediments is due both to the action of the wind and to the wave motion.

2. Bathymetric survey of the area

The Kandesterne’s coast, from December 2018 to November 2021, was the subject of 10 topographic surveys covering approximately 15 km of coastline. Initially, the purpose of the measurements was to obtain a support to evaluate whether the installation of the pressure equalization modules was able to counteract the coastal erosion by favoring an accumulation of sand. Following their removal, these bathymetric surveys were used in the following study to evaluate the presence of possible sand waves, comparing the morphological variations of the ground level over time. The coast is on average 25 - 100m wide, while the height of the dune reaches peaks of about 20m and is almost totally covered in vegetation.

The analysis was conducted on the stretch of coast between the up-wash zone towards the open sea and from the foot of the dune towards the land. A total of 10 topo-bathymeter surveys were conducted: in particular, 3 times a year from December 2018 to November 2021 using drones. It is important to underline that the coverage of the measurement is variable according to the water level at the moment of the measurement; therefore, consequently some reliefs cover a smaller area than others. As a result, some data are missing in these areas.

The drone used to carry out the measurements is called the DJI Phantom 4 Pro with a 1-inch (25 mm) 20 MP CMOS sensor. The drone surveys were performed through pre-programmed routes through an automatic collection of image data. Taking advantage of the photogrammetric method "Structure from Motion", a cloud of xyz points of the terrain was generated capable of

rendering three-dimensional information of the terrain under examination. By means of superimposed images, their position was obtained.
For the georeferencing of the point cloud in the UTM Zona 32N ETRS89 coordinate system and in the DVR90 elevation system, the ground control points (GCP) and the reference points measured with GPS RTK were used. The dots are observed to have a maximum deviation of 2.0 cm in all directions and a mean vertical deviation of 2.6 cm for all 10 measurements.
Following the georeferencing, the CloudCompare software was used to clean up the point cloud. The terrain height models (DTM) were generated from the point cloud using ArcGis GIS software with 0.4m resolution. The land height models (DTM) have an accuracy of the beach of the order of a few cm; on the contrary, the uncertainty increases in correspondence with the dunes, reaching peaks of 10 cm: this is due to the greater vegetation cover and the lower presence of GCP points.

3. Data analysis and discussion of the results

Since the purpose of the study is to analyze the presence of sand waves on the beach, a boundary is outlined between the foot of the dune and the end of the beach towards the open sea; proceed by evaluating the average punctual height of the stretch of beach excluding the area containing the dunes. Using the Qgis software, a vectorial layer was drawn containing 150 transects perpendicular to the coast.

Image 1. Satellite view obtained from Qgis containing the 150 transepts built on Kandestederne's coast

Each transect was placed at an average distance of 100 m from the next. As reference surveys for the construction of the layer containing the transects, those called Danmark_2007_Hulsig and Danmark_2015_Hulsig were used since they cover the area of interest in a more homogeneous way and represent a more accurate reference than the ten periodic bathymeter surveys. The periodic bathymetric surveys, in fact, have different widths showing a coverage of about 15 km for one survey year and a lower coverage for the following year.

Initially, were analyzed the transects located at a distance of about 1 km from each other. Due to the different extent of the bathymetric surveys a total of 14 profiles were analyzed, so that they included every relief. Was used the tool called "Profile Tool" available on Qgis. It allows to extract, for each profile, the distance along the x direction from the beach to the sea related to the ground level.

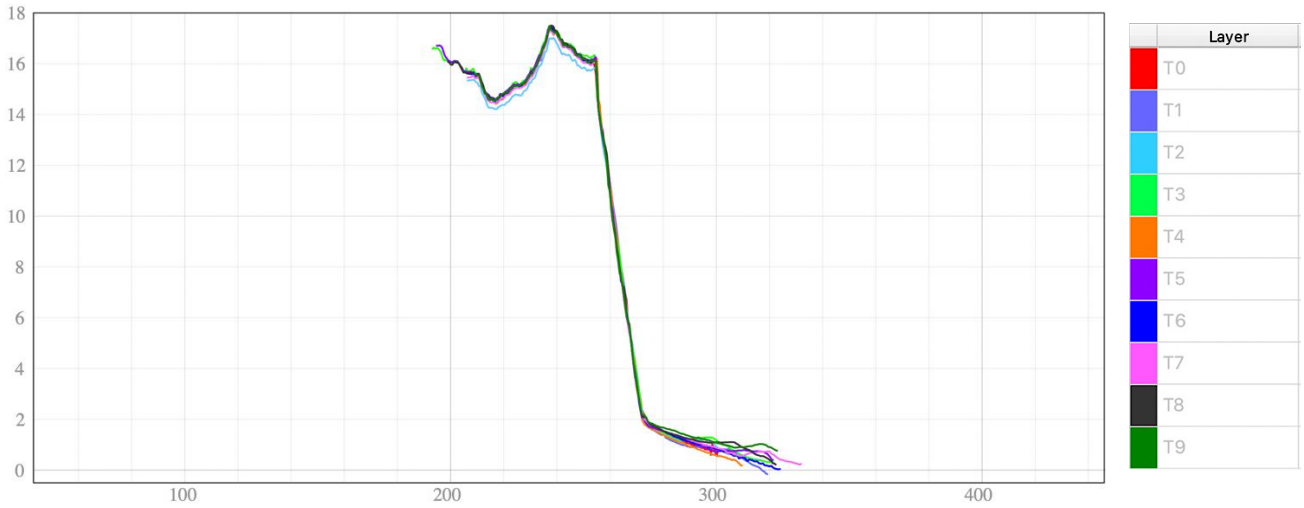


Image 2. From each transect created, 10 profiles are extracted, relating to the period of time in which the survey was performed, using the Qgis software and using the Profile Tool. On the x-axis there is the distance while on the y-axis there is the height. The legend shows the different time periods in which the surveys were conducted, from December 2018 (T0) to November 2021 (T9).

The data relating to each analyzed transect were imported into Excel thus creating a total of 14 spreadsheets, equal to the total number of the analyzed transects. Since 10 topographic surveys relating to different years and periods are available, each spreadsheet describing a transect will contain 10 pairs of columns given by the paired x (distance) and z (level) values.

The topographic surveys were also conducted on the natural dunes, therefore the transepts obtained contain information relating to their elevation. Since the objective of the study is to analyze the presence of sand dunes on to the shoreline, the section that starts close to the foot of the dune and ends at the end of the reliefs towards the sea must be determined for each transect. The stretch of beach is obtained by containing all the available reliefs within it.

The next step is to obtain the mean elevation of each transect for each of the 10 survey periods. For each transect and for each time, the integral calculation is carried out in the stretch associated with the beach. The result of the integral calculation is divided by the respective length of the section relating to the beach, thus obtaining the average elevation of each transect for each of the 10 epochs. The following table shows the average beach level values for each transect and for each period from December 2018 to November 2021.

Profile	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	
3	1.05812319	1.07239225	0.56198045	0.86458072	0.83334999	0.96913089	0.6429985	0.69316384	0.89336011	0.75279539	Average Height
13	1.18036072	0.98867298	1.16046132	1.21893695	1.21308189	1.42315854	1.54478601	1.53693427	1.45869023	1.58929611	Average Height
23	1.61774061	1.64104137	1.63449753	1.65743958	1.5742517	1.60568182	1.69767654	1.78366115	1.73525485	1.76798212	Average Height
33	1.48591604	1.56662162	1.56358427	1.65764141	1.53177929	1.65682056	1.73063188	1.78572091	1.80735731	1.75885616	Average Height
43	1.04289401	1.00742235	1.19572738	1.26116234	1.4026524	1.5607522	1.58324295	1.58577162	1.61086942	1.66440711	Average Height
53	1.33079453	1.37955987	1.40040031	1.54113733	0.96170029	1.26559868	1.36690683	1.27590059	1.32494058	1.41575396	Average Height
63	1.19480479	1.15783385	1.38848885	1.27916444	0.89208456	1.11894006	1.01266807	1.00581818	1.159483	1.09809781	Average Height
73	0.864686	1.19780214	1.17318392	0.88379581	0.85203184	1.11652612	1.20061865	1.07306959	1.12888797	0.9886631	Average Height
83	1.31135082	1.36592885	1.45031103	1.50823616	0.90416721	1.27213323	1.26956717	1.37018925	1.44728756	1.40263333	Average Height
93	1.15780064	1.32231487	1.15828701	1.46069042	1.03883802	1.10999483	1.13395573	1.33276587	1.3765868	1.36229267	Average Height
103	1.29604394	1.1417207	1.2941653	1.20128636	0.84778794	1.01691326	1.20838679	1.19695731	1.25242374	1.26630635	Average Height
113	0.33563281	0.57239871	0.57124479	0.63339658	0.43901547	0.54003724	0.6190038	0.60960706	0.66740911	0.66815435	Average Height
123	1.36301558	1.40413911	1.26468947	1.37929081	0.80892111	0.94621786	1.10374267	1.03884424	0.97858148	0.98328517	Average Height
133	1.23025658	1.31729774	1.21541335	1.35487564	1.30000203	1.11222686	1.24171371	1.08032071	1.18517844	1.17883614	Average Height

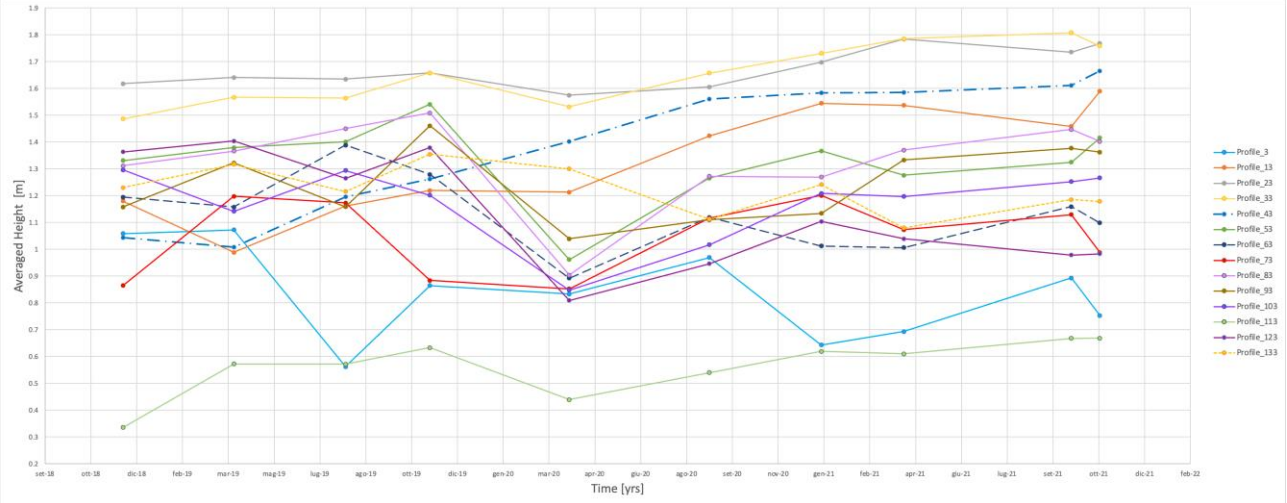
Table 1. Average shoreline level values for each transect and for each period. Profile 3 is the southernmost, Profile 133 is the northernmost.

T0	dic-18
T1	apr-19
T2	ago-19
T3	nov-19
T4	apr-20
T5	set-20
T6	gen-21
T7	apr-21
T8	ott-21
T9	nov-21

Table 2. Periods of time.

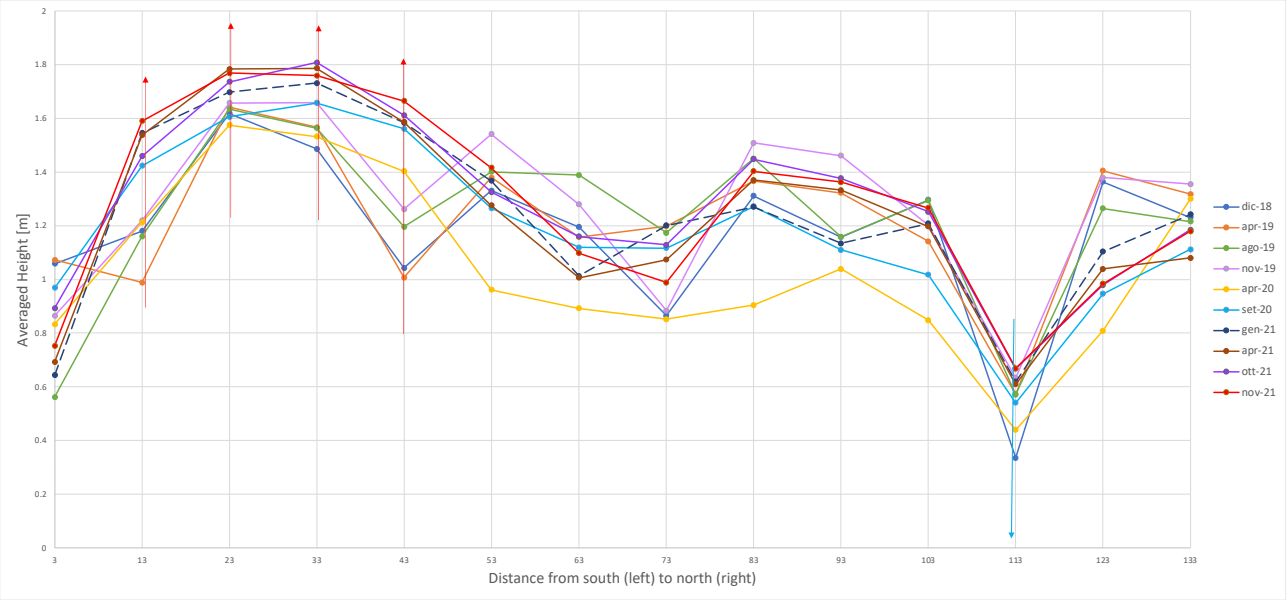
The values are shown in the following two plots. The first one shows the evolution in time of the average height of the shoreline for each profile because each line of the first graph represents a different transect. The time is shown on the x-axis while the average elevation of the beach is shown on the y-axis.

Between March and April 2020 different profiles (93,53,83,63,103,123,113) record a peak of erosion. Profile 113 recorded the lowest average height values ever.



Plot 1. Evolution in time of the average height of the shoreline for each profile.

In the second plot, the profiles are shown on the x-axis while the average elevation of the beach is shown on the y-axis. It describes the trend, from south to north, of the average height of the shoreline analyzed for each epoch. Each line represents different time from December 2018 to November 2021.



Plot 2. Trend, from south to north, of the average height level of the shoreline per each period.

The first graph allows to understand, for a specific reference period, what is the average height of the shoreline for each of the different transects. Also, for a specific reference transect being analyzed, describes its evolution in terms of average height of the shoreline over time since each broken line is a period. The peak of erosion recorded between March and April 2020 in the first graph is reflected in the second one: the yellow line April 2020 records the lower values of the trend. Since in the first graph the profile 113 recorded the lowest average height value, this is reflected in the second graph with a peak of negative values for all the different periods of time.

In the second plot, profile 43 shows the greatest difference in height over time going from about 1 m in April 2019 to about 1.6 m in November 2021. This is reflected in the first graph where it can be seen that profile 43 passes from an average height of 1 m up to approximately 1.6 m from April 2019 to November 2021. In the second plot, profiles 13,23,43 show progressive accumulation over time: the red upward arrows denote progressive accumulation for the same profile over time.

The following table describes the different trends for each profile over time.

Profile	Trend
3	Successive accumulation and erosion in time
13	Initial slight erosion then increasing slight accumulation
23	Unchanged trend: slight accumulation constant over time
33	Unchanged trend: slight accumulation constant over time
43	Initial slight erosion then increasing slight accumulation
53	Initial slight accumulation, then erosion then increasing slight accumulation
63	Initial slight accumulation, then erosion then increasing slight accumulation
73	Initial slight accumulation, then erosion then increasing slight accumulation
83	Initial slight accumulation, then erosion then increasing slight accumulation
93	Initial slight accumulation, then erosion then increasing slight accumulation
103	Initial slight accumulation, then erosion then increasing slight accumulation
113	Initial slight accumulation, then erosion then increasing slight accumulation. Lowest recorded values
123	Initial slight accumulation, then erosion then increasing slight accumulation
133	Initial slight accumulation, then erosion then increasing slight accumulation

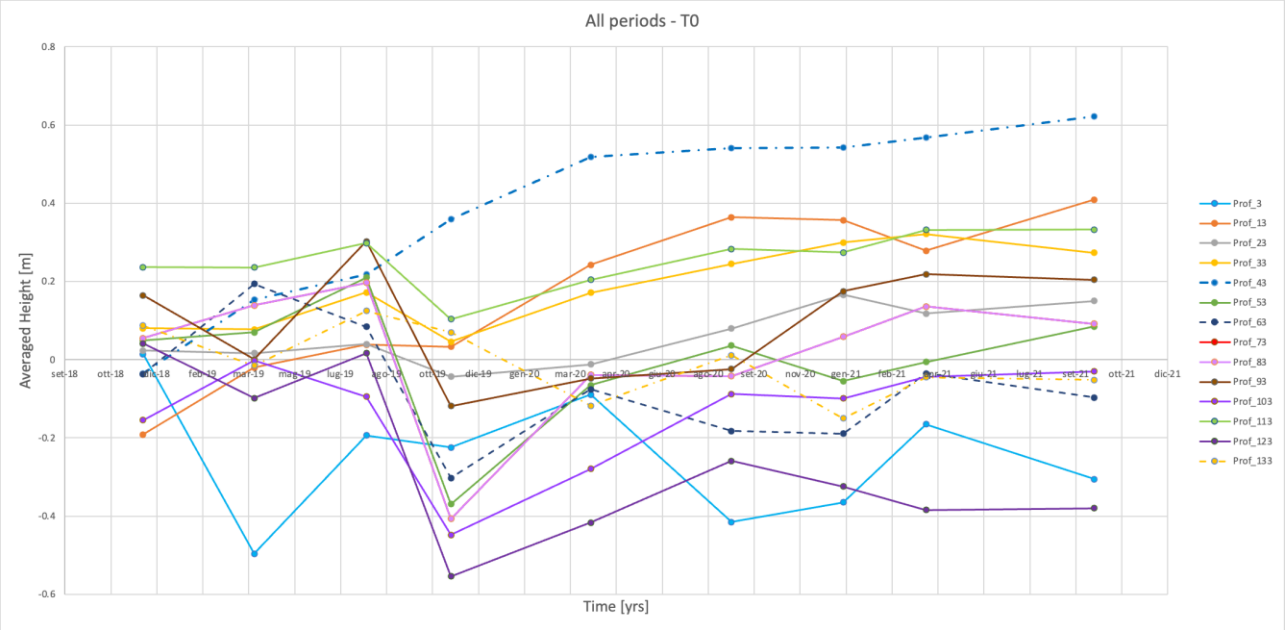
Table 3. Short description of the different profile's trend.

To observe in detail the presence of variations in the average heights of the beach level over time and space, were generated several graphs for each time respectively.

Particularly, a series of graphs that show the difference between the average height of the beach level in one period and the average height of the beach in the following/previous period. Each line represents a different transect. The time is shown on the x-axis while the average elevation of the beach is shown on the y-axis.

Since there are a total of 10 surveys available, each instant was taken into consideration individually and compared with the remaining ones, thus obtaining 10 different graphs.

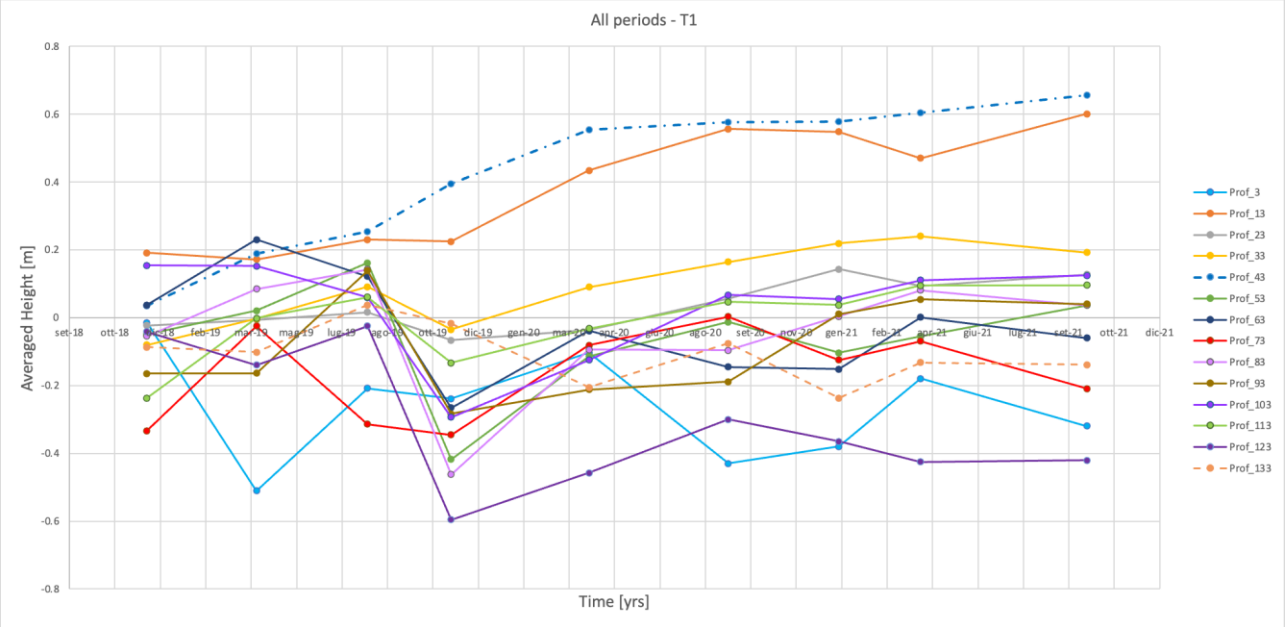
The presence of important differences between the average height of the beach in one time and the next/previous time can be seen if clear peaks are observed in the graph and if the broken lines deviate from zero. A negative value denotes that the mean height of the beach was higher in the next/previous epoch with which it is being compared.



Plot 3. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in December 2018.

	T0								
Profile	T1 - T0	T2 - T0	T3 - T0	T4 - T0	T5 - T0	T6 - T0	T7 - T0	T8 - T0	T9 - T0
3	0.01426907	-0.4961427	-0.1935425	-0.2247732	-0.0889923	-0.4151247	-0.3649593	-0.1647631	-0.3053278
13	-0.1916877	-0.0198994	0.03857623	0.03272117	0.24279782	0.36442529	0.35657355	0.27832951	0.40893539
23	0.02330076	0.01675693	0.03969898	-0.0434889	-0.0120588	0.07993594	0.16592055	0.11751424	0.15024152
33	0.08070558	0.07766823	0.17172538	0.04586325	0.17090452	0.24471585	0.29980487	0.32144127	0.27294012
43	-0.0354717	0.15283337	0.21826833	0.35975839	0.51785819	0.54034893	0.5428776	0.56797541	0.6215131
53	0.04876534	0.06960578	0.21034279	-0.3690942	-0.0651959	0.0361123	-0.0548939	-0.005854	0.08495943
63	-0.036971	0.19368405	0.08435965	-0.3027202	-0.0758647	-0.1821367	-0.1889866	-0.0353218	-0.096707
73	0.33311614	0.30849793	0.01910981	-0.0126542	0.25184012	0.33593265	0.2083836	0.26420197	0.12397711
83	0.05457802	0.13896021	0.19688533	-0.4071836	-0.0392176	-0.0417837	0.05883843	0.13593673	0.09128251
93	0.16451423	0.00048637	0.30288978	-0.1189626	-0.0478058	-0.0238449	0.17496523	0.21878616	0.20449203
103	-0.1543232	-0.0018786	-0.0947576	-0.448256	-0.2791307	-0.0876572	-0.0990866	-0.0436202	-0.0297376
113	0.2367659	0.23561199	0.29776378	0.10338267	0.20440443	0.283371	0.27397425	0.3317763	0.33252155
123	0.04112353	-0.0983261	0.01627523	-0.5540945	-0.4167977	-0.2592729	-0.3241713	-0.3844341	-0.3797304
133	0.08704117	-0.0148432	0.12461906	0.06974545	-0.1180297	0.01145713	-0.1499359	-0.0450781	-0.0514204

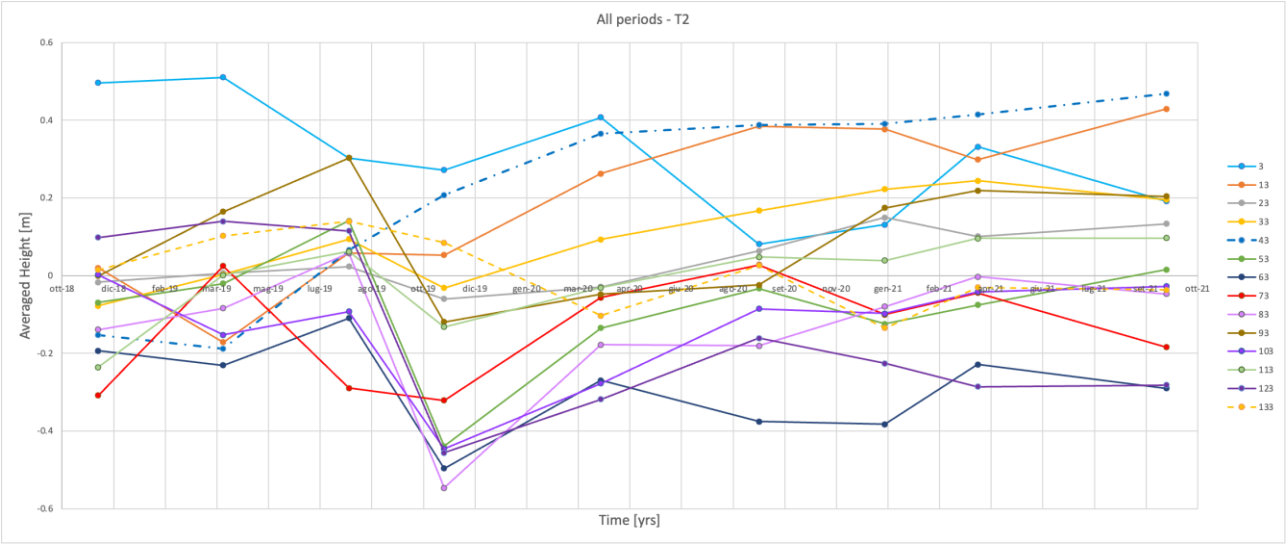
Table 4. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in December 2018.



Plot 4. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in April 2019.

	T1								
Profile	T0 - T1	T2 - T1	T3 - T1	T4 - T1	T5 - T1	T6 - T1	T7 - T1	T8 - T1	T9 - T1
3	-0.0142691	-0.5104118	-0.2078115	-0.2390423	-0.1032614	-0.4293938	-0.3792284	-0.1790321	-0.3195969
13	0.19168774	0.17178834	0.23026397	0.22440891	0.43448556	0.55611304	0.54826129	0.47001725	0.60062313
23	-0.0233008	-0.0065438	0.01639821	-0.0667897	-0.0353595	0.05663517	0.14261978	0.09421348	0.12694075
33	-0.0807056	-0.0030373	0.0910198	-0.0348423	0.09019894	0.16401027	0.21909929	0.24073569	0.19223454
43	0.03547166	0.18830503	0.25373999	0.39523005	0.55332985	0.5758206	0.57834926	0.60344707	0.65698476
53	-0.0487653	0.02084045	0.16157746	-0.4178596	-0.1139612	-0.012653	-0.1036593	-0.0546193	0.03619409
63	0.03697095	0.230655	0.1213306	-0.2657493	-0.0388938	-0.1451658	-0.1520157	0.00164915	-0.059736
73	-0.3331161	-0.0246182	-0.3140063	-0.3457703	-0.081276	0.00281651	-0.1247325	-0.0689142	-0.209139
83	-0.054578	0.08438218	0.14230731	-0.4617616	-0.0937956	-0.0963617	0.00426041	0.08135871	0.03670448
93	-0.1645142	-0.1640279	0.13837555	-0.2834769	-0.21232	-0.1883591	0.010451	0.05427193	0.0399778
103	0.15432324	0.1524446	0.05956566	-0.2939328	-0.1248074	0.06666609	0.0552366	0.11070304	0.12458565
113	-0.2367659	-0.0011539	0.06099787	-0.1333832	-0.0323615	0.04660509	0.03720835	0.0950104	0.09575564
123	-0.0411235	-0.1394496	-0.0248483	-0.595218	-0.4579212	-0.3003964	-0.3652949	-0.4255576	-0.4208539
133	-0.0870412	-0.1018844	0.03757789	-0.0172957	-0.2050709	-0.075584	-0.236977	-0.1321193	-0.1384616

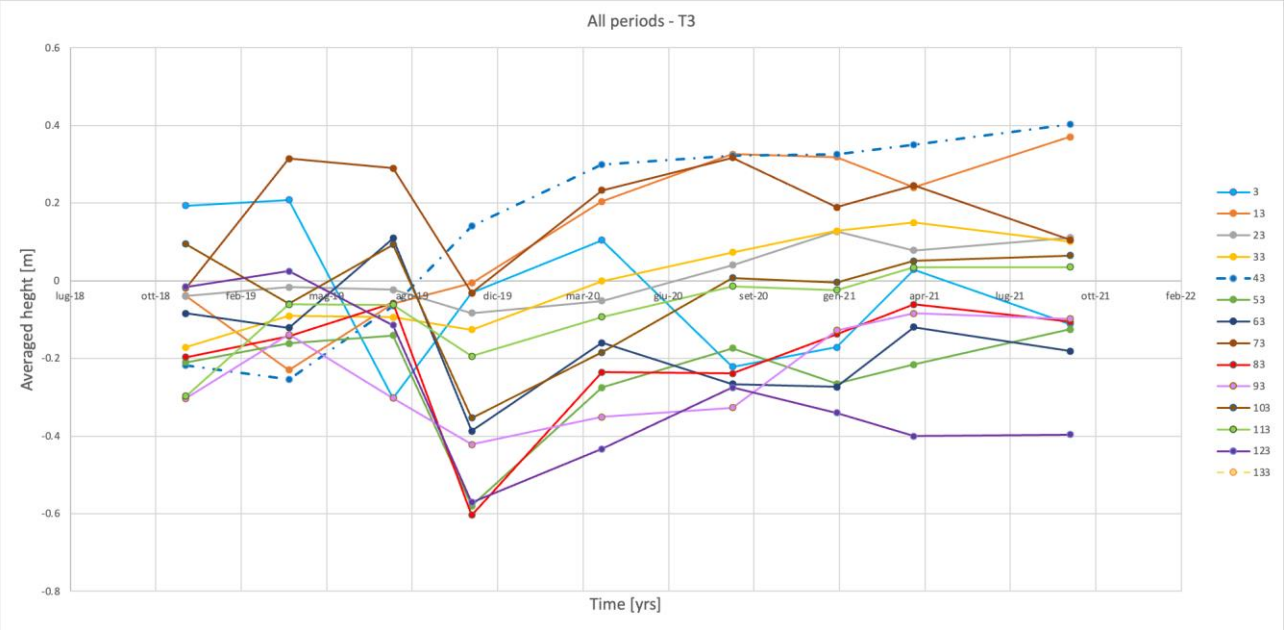
Table 5. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in April 2019.



Plot 5. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in August 2019.

T2									
Profile	T0 - T2	T1 - T2	T3 - T2	T4 - T2	T5 - T2	T6 - T2	T7 - T2	T8 - T2	T9 - T2
3	0.49614274	0.5104118	0.30260027	0.27136954	0.40715044	0.08101805	0.13118339	0.33137967	0.19081494
13	0.0198994	-0.1717883	0.05847563	0.05262057	0.26269722	0.38432469	0.37647295	0.29822891	0.42883479
23	-0.0167569	0.00654384	0.02294205	-0.0602458	-0.0288157	0.06317901	0.14916362	0.10075732	0.13348459
33	-0.0776682	0.00303735	0.09405714	-0.031805	0.09323629	0.16704761	0.22213664	0.24377304	0.19527189
43	-0.1528334	-0.188305	0.06543496	0.20692502	0.36502481	0.38751556	0.39004423	0.41514204	0.46867973
53	-0.0696058	-0.0208404	0.14073701	-0.4387	-0.1348016	-0.0334935	-0.1244997	-0.0754597	0.01535364
63	-0.1936841	-0.230655	-0.1093244	-0.4964043	-0.2695488	-0.3758208	-0.3826707	-0.2290058	-0.290391
73	-0.3084979	0.02461821	-0.2893881	-0.3211521	-0.0566578	0.02743473	-0.1001143	-0.044296	-0.1845208
83	-0.1389602	-0.0843822	0.05792513	-0.5461438	-0.1781778	-0.1807439	-0.0801218	-0.0030235	-0.0476777
93	-0.0004864	0.16402786	0.30240341	-0.119449	-0.0482922	-0.0243313	0.17447887	0.21829979	0.20400566
103	0.00187864	-0.1524446	-0.0928789	-0.4463774	-0.277252	-0.0857785	-0.097208	-0.0417416	-0.027859
113	-0.235612	0.00115391	0.06215179	-0.1322293	-0.0312076	0.04775901	0.03836227	0.09616431	0.09690956
123	0.0983261	0.13944963	0.11460134	-0.4557684	-0.3184716	-0.1609468	-0.2258452	-0.286108	-0.2814043
133	0.01484323	0.1018844	0.13946229	0.08458868	-0.1031865	0.02630036	-0.1350926	-0.0302349	-0.0365772

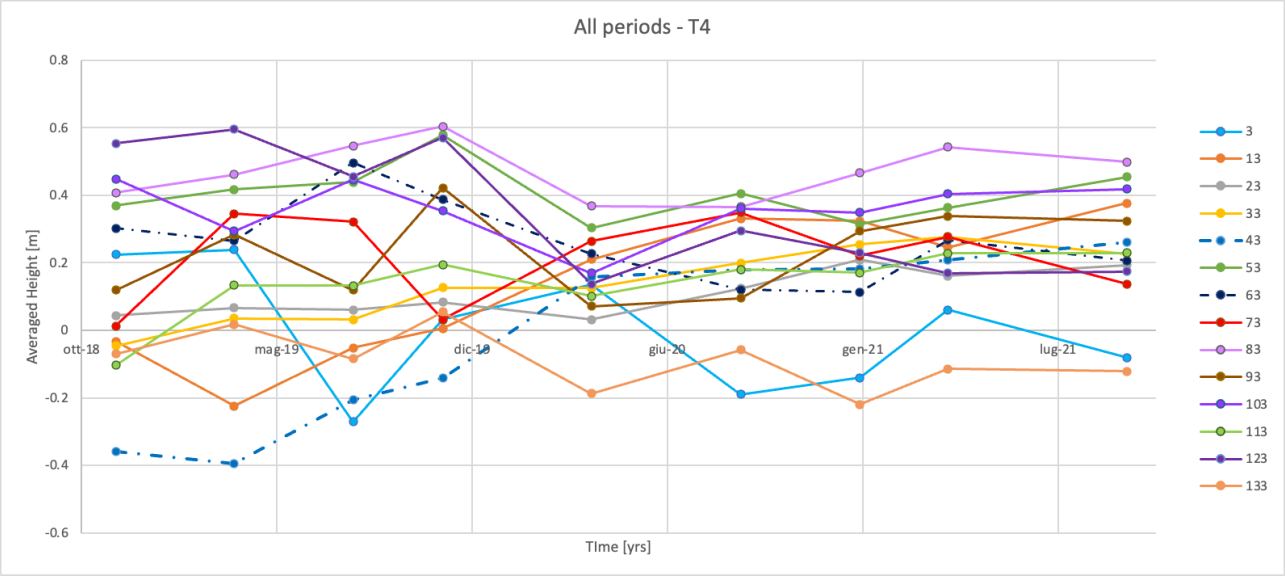
Table 6. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in August 2019.



Plot 6. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in November 2019.

T3									
Profile	T0 - T3	T1 - T3	T2 - T3	T4 - T3	T5 - T3	T6 - T3	T7 - T3	T8 - T3	T9 - T3
3	0.19354246	0.20781153	-0.3026003	-0.0312307	0.10455017	-0.2215822	-0.1714169	0.02877939	-0.1117853
13	-0.0385762	-0.230264	-0.0584756	-0.0058551	0.20422159	0.32584906	0.31799732	0.23975328	0.37035915
23	-0.039699	-0.0163982	-0.0229421	-0.0831879	-0.0517578	0.04023696	0.12622157	0.07781527	0.11054254
33	-0.1717254	-0.0910198	-0.0940571	-0.1258621	-0.0008209	0.07299047	0.1280795	0.14971589	0.10121474
43	-0.2182683	-0.25374	-0.065435	0.14149006	0.29958986	0.3220806	0.32460927	0.34970708	0.40324477
53	-0.2103428	-0.1615775	-0.140737	-0.579437	-0.2755386	-0.1742305	-0.2652367	-0.2161967	-0.1253834
63	-0.0843596	-0.1213306	0.1093244	-0.3870799	-0.1602244	-0.2664964	-0.2733463	-0.1196814	-0.1810666
73	-0.0191098	0.31400633	0.28938812	-0.031764	0.23273031	0.31682284	0.18927379	0.24509216	0.1048673
83	-0.1968853	-0.1423073	-0.0579251	-0.6040689	-0.2361029	-0.238669	-0.1380469	-0.0609486	-0.1056028
93	-0.3028898	-0.1383755	-0.3024034	-0.4218524	-0.3506956	-0.3267347	-0.1279245	-0.0841036	-0.0983978
103	0.09475758	-0.0595657	0.09287894	-0.3534984	-0.1843731	0.00710043	-0.0043291	0.05113738	0.06501999
113	-0.2977638	-0.0609979	-0.0621518	-0.1943811	-0.0933593	-0.0143928	-0.0237895	0.03401252	0.03475777
123	-0.0162752	0.0248483	-0.1146013	-0.5703697	-0.433073	-0.2755481	-0.3404466	-0.4007093	-0.3960056
133	-0.1246191	-0.0375779	-0.1394623	-0.0548736	-0.2426488	-0.1131619	-0.2745549	-0.1696972	-0.1760395

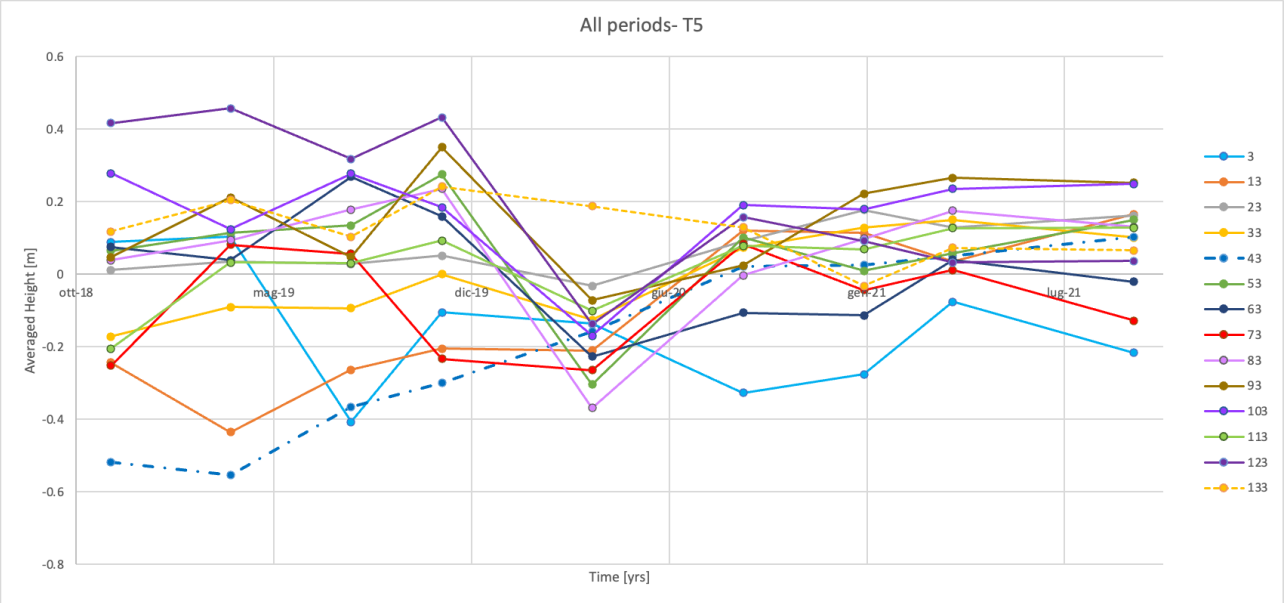
Table 7. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in November 2019.



Plot 7. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in April 2020.

T4									
Profile	T0 - T4	T1 - T4	T2 - T4	T3 - T4	T5 - T4	T6- T4	T7 - T4	T8 - T4	T9 - T4
3	0.2247732	0.23904226	-0.2713695	0.03123073	0.1357809	-0.1903515	-0.1401861	0.06001012	-0.0805546
13	-0.0327212	-0.2244089	-0.0526206	0.00585507	0.21007665	0.33170413	0.32385238	0.24560834	0.37621422
23	0.04348891	0.06678967	0.06024584	0.08318789	0.03143013	0.12342485	0.20940946	0.16100315	0.19373043
33	-0.0458632	0.03484233	0.03180498	0.12586213	0.12504127	0.1988526	0.25394162	0.27557802	0.22707687
43	-0.3597584	-0.39523	-0.206925	-0.1414901	0.1580998	0.18059055	0.18311922	0.20821702	0.26175471
53	0.36909424	0.41785957	0.43870002	0.57943703	0.30389838	0.40520654	0.3142003	0.36324028	0.45405366
63	0.30272024	0.26574929	0.49640429	0.38707989	0.2268555	0.12058352	0.11373362	0.26739844	0.20601326
73	0.01265416	0.3457703	0.32115208	0.03176397	0.26449428	0.34858681	0.22103775	0.27685613	0.13663126
83	0.40718361	0.46176163	0.54614382	0.60406895	0.36796602	0.36539995	0.46602204	0.54312035	0.49846612
93	0.11896262	0.28347685	0.11944899	0.4218524	0.07115681	0.09511771	0.29392785	0.33774878	0.32345465
103	0.448256	0.29393276	0.44637736	0.35349842	0.16912532	0.36059885	0.34916937	0.4046358	0.41851841
113	-0.1033827	0.13338324	0.13222932	0.19438111	0.10102177	0.17998833	0.17059159	0.22839364	0.22913888
123	0.55409447	0.595218	0.45576837	0.5703697	0.13729675	0.29482156	0.22992314	0.16966037	0.17436406
133	-0.0697455	0.01729571	-0.0845887	0.05487361	-0.1877752	-0.0582883	-0.2196813	-0.1148236	-0.1211659

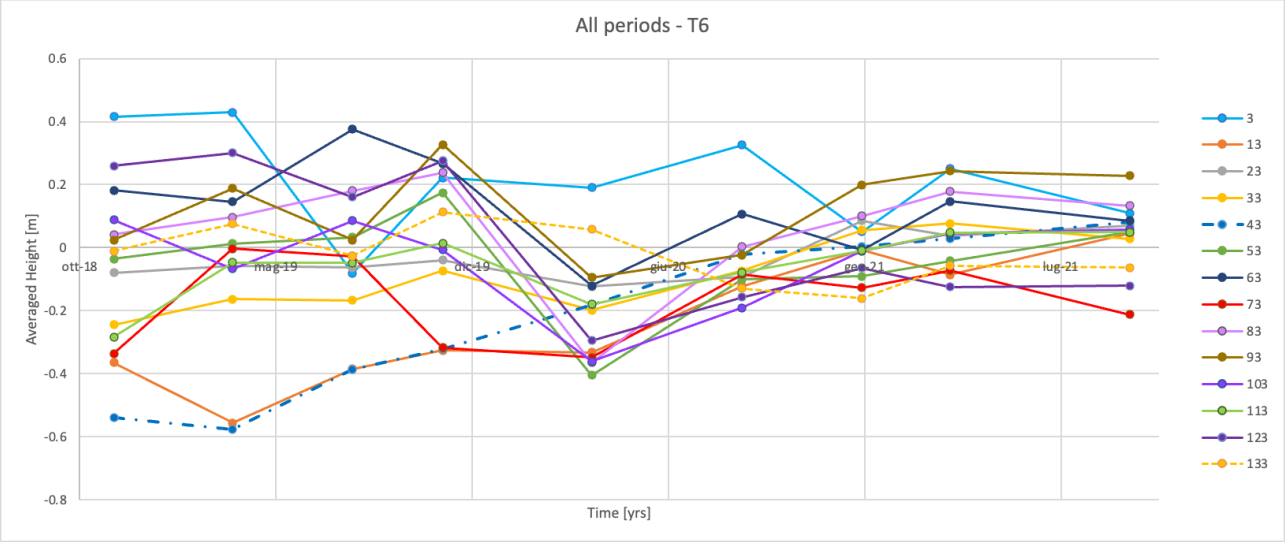
Table 8. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in April 2020.



Plot 8. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in September 2020.

T5									
Profile	T0 - T5	T1 - T5	T2 - T5	T3 - T5	T4 - T5	T6- T5	T7 - T5	T8 - T5	T9 - T5
3	0.08899229	0.10326136	-0.4071504	-0.1045502	-0.1357809	-0.3261324	-0.2759671	-0.0757708	-0.2163355
13	-0.2427978	-0.4344856	-0.2626972	-0.2042216	-0.2100767	0.12162747	0.11377573	0.03553169	0.16613757
23	0.01205878	0.03535955	0.02881571	0.05175776	-0.0314301	0.09199472	0.17797933	0.12957303	0.1623003
33	-0.1709045	-0.0901989	-0.0932363	0.00082086	-0.1250413	0.07381133	0.12890035	0.15053675	0.1020356
43	-0.5178582	-0.5533298	-0.3650248	-0.2995899	-0.1580998	0.02249075	0.02501942	0.05011722	0.10365491
53	0.06519585	0.11396119	0.13480164	0.27553865	-0.3038984	0.10130816	0.01030191	0.0593419	0.15015528
63	0.07586473	0.03889378	0.26954878	0.16022438	-0.2268555	-0.106272	-0.1131219	0.04054294	-0.0208422
73	-0.2518401	0.08127602	0.05665781	-0.2327303	-0.2644943	0.08409253	-0.0434565	0.01236185	-0.127863
83	0.03921759	0.09379562	0.1781778	0.23610293	-0.367966	-0.0025661	0.09805602	0.17515433	0.1305001
93	0.04780581	0.21232004	0.04829218	0.35069559	-0.0711568	0.0239609	0.22277104	0.26659197	0.25229784
103	0.27913068	0.12480744	0.27725204	0.1843731	-0.1691253	0.19147353	0.18004405	0.23551048	0.24939309
113	-0.2044044	0.03236147	0.03120755	0.09335934	-0.1010218	0.07896656	0.06956982	0.12737187	0.12811711
123	0.41679772	0.45792125	0.31847162	0.43307295	-0.1372967	0.15752481	0.09262639	0.03236362	0.03706731
133	0.11802971	0.20507088	0.10318648	0.24264877	0.18777516	0.12948685	-0.0319062	0.07295158	0.06660928

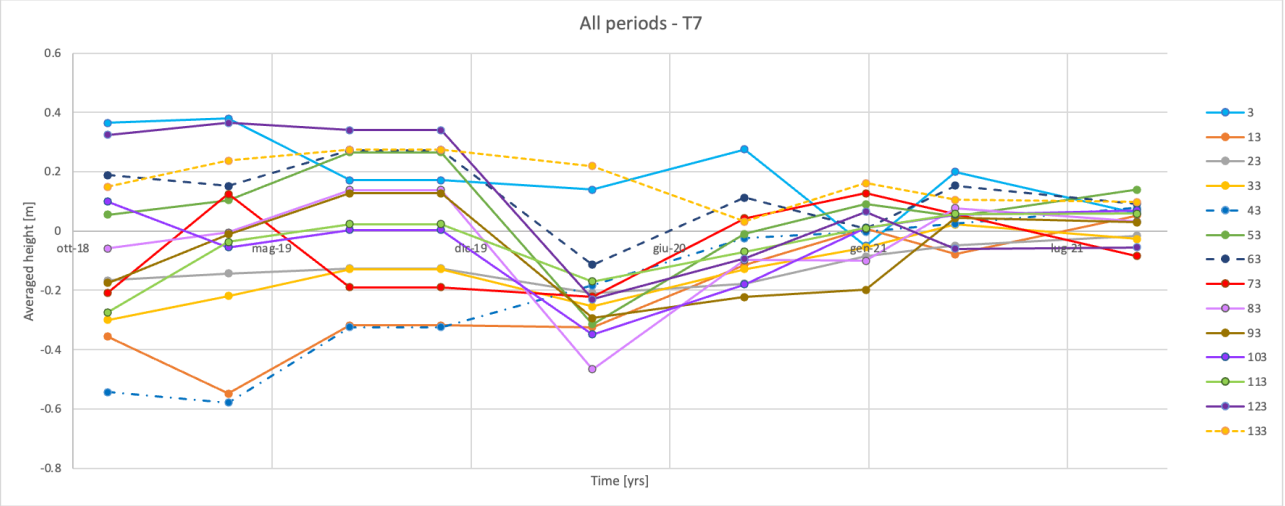
Table 9. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in September 2020.



Plot 9. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in January 2021.

T6									
Profile	T0 - T6	T1 - T6	T2 - T6	T3 - T6	T4 - T6	T5 - T6	T7 - T6	T8 - T6	T9 - T6
3	0.41512468	0.42939375	-0.0810181	0.22158222	0.19035149	0.32613239	0.05016534	0.25036161	0.10979688
13	-0.3644253	-0.556113	-0.3843247	-0.3258491	-0.3317041	-0.1216275	-0.0078517	-0.0860958	0.04451009
23	-0.0799359	-0.0566352	-0.063179	-0.040237	-0.1234248	-0.0919947	0.08598461	0.03757831	0.07030558
33	-0.2447158	-0.1640103	-0.1670476	-0.0729905	-0.1988526	-0.0738113	0.05508902	0.07672542	0.02822427
43	-0.5403489	-0.5758206	-0.3875156	-0.3220806	-0.1805905	-0.0224907	0.00252867	0.02762647	0.08116416
53	-0.0361123	0.01265303	0.03349348	0.17423049	-0.4052065	-0.1013082	-0.0910062	-0.0419663	0.04884712
63	0.18213672	0.14516577	0.37582077	0.26649637	-0.1205835	0.10627199	-0.0068499	0.14681493	0.08542974
73	-0.3359327	-0.0028165	-0.0274347	-0.3168228	-0.3485868	-0.0840925	-0.1275491	-0.0717307	-0.2119555
83	0.04178366	0.09636168	0.18074386	0.23866899	-0.3654	0.00256606	0.10062209	0.17772039	0.13306616
93	0.02384491	0.18835914	0.02433128	0.32673469	-0.0951177	-0.0239609	0.19881015	0.24263107	0.22833694
103	0.08765715	-0.0666661	0.08577851	-0.0071004	-0.3605989	-0.1914735	-0.0114295	0.04403695	0.05791956
113	-0.283371	-0.0466051	-0.047759	0.01439278	-0.1799883	-0.0789666	-0.0093967	0.0484053	0.04915055
123	0.2592729	0.30039643	0.1609468	0.27554814	-0.2948216	-0.1575248	-0.0648984	-0.1251612	-0.1204575
133	-0.0114571	0.07558403	-0.0263004	0.11316193	0.05828832	-0.1294868	-0.161393	-0.0565353	-0.0628776

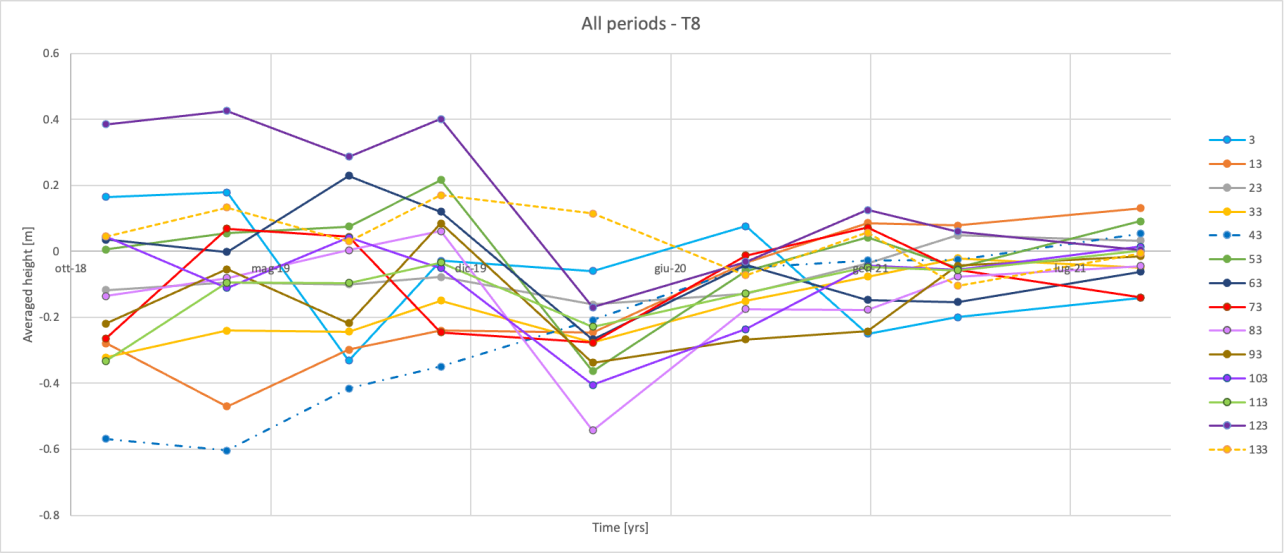
Table 10. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in January 2021.



Plot 10. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in April 2021.

T7									
Profile	T0 - T7	T1 - T7	T2 - T7	T3 - T7	T4 - T7	T5 - T7	T6 - T7	T8 - T7	T9 - T7
3	0.36495934	0.37922841	0.17141688	0.17141688	0.14018615	0.27596705	-0.0501653	0.20019627	0.05963154
13	-0.3565735	-0.5482613	-0.3179973	-0.3179973	-0.3238524	-0.1137757	0.00785174	-0.078244	0.05236184
23	-0.1659205	-0.1426198	-0.1262216	-0.1262216	-0.2094095	-0.1779793	-0.0859846	-0.0484063	-0.015679
33	-0.2998049	-0.2190993	-0.1280795	-0.1280795	-0.2539416	-0.1289004	-0.055089	0.0216364	-0.0268648
43	-0.5428776	-0.5783493	-0.3246093	-0.3246093	-0.1831192	-0.0250194	-0.0025287	0.0250978	0.07863549
53	0.05489394	0.10365927	0.26523673	0.26523673	-0.3142003	-0.0103019	0.09100624	0.04903998	0.13985337
63	0.18898662	0.15201567	0.27334627	0.27334627	-0.1137336	0.11312188	0.00684989	0.15366482	0.09227964
73	-0.2083836	0.12473255	-0.1892738	-0.1892738	-0.2210378	0.04345652	0.12754906	0.05581838	-0.0844065
83	-0.0588384	-0.0042604	0.1380469	0.1380469	-0.466022	-0.098056	-0.1006221	0.0770983	0.03244408
93	-0.1749652	-0.010451	0.12792454	0.12792454	-0.2939279	-0.222771	-0.1988101	0.04382093	0.02952679
103	0.09908663	-0.0552366	0.00432905	0.00432905	-0.3491694	-0.180044	0.01142948	0.05546643	0.06934904
113	-0.2739743	-0.0372084	0.02378952	0.02378952	-0.1705916	-0.0695698	0.00939674	0.05780205	0.05854729
123	0.32417133	0.36529486	0.34044657	0.34044657	-0.2299231	-0.0926264	0.06489843	-0.0602628	-0.0555591
133	0.14993587	0.23697704	0.27455493	0.27455493	0.21968132	0.03190616	0.161393	0.10485773	0.09851544

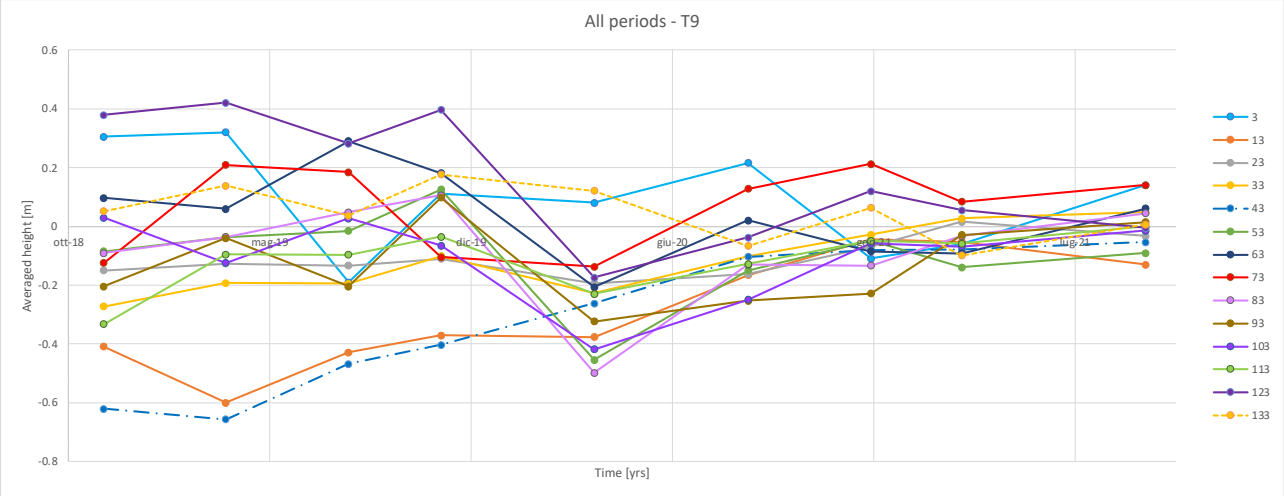
Table 11. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in April 2021.



Plot 11. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline beach in October 2021.

T8									
Profile	T0 - T8	T1 - T8	T2 - T8	T3 - T8	T4 - T8	T5 - T8	T6 - T8	T7 - T8	T9 - T8
3	0.16476307	0.17903214	-0.3313797	-0.0287794	-0.0600101	0.07577078	-0.2503616	-0.2001963	-0.1405647
13	-0.2783295	-0.4700173	-0.2982289	-0.2397533	-0.2456083	-0.0355317	0.08609578	0.07824404	0.13060587
23	-0.1175142	-0.0942135	-0.1007573	-0.0778153	-0.1610032	-0.129573	-0.0375783	0.0484063	0.03272727
33	-0.3214413	-0.2407357	-0.243773	-0.1497159	-0.275578	-0.1505367	-0.0767254	-0.0216364	-0.0485011
43	-0.5679754	-0.6034471	-0.415142	-0.3497071	-0.208217	-0.0501172	-0.0276265	-0.0250978	0.05353769
53	0.00585396	0.05461929	0.07545974	0.21619675	-0.3632403	-0.0593419	0.04196626	-0.04904	0.09081338
63	0.0353218	-0.0016492	0.22900585	0.11968144	-0.2673984	-0.0405429	-0.1468149	-0.1536648	-0.0613852
73	-0.264202	0.06891417	0.04429595	-0.2450922	-0.2768561	-0.0123619	0.07173068	-0.0558184	-0.1402249
83	-0.1359367	-0.0813587	0.00302347	0.0609486	-0.5431203	-0.1751543	-0.1777204	-0.0770983	-0.0446542
93	-0.2187862	-0.0542719	-0.2182998	0.08410362	-0.3377488	-0.266592	-0.2426311	-0.0438209	-0.0142941
103	0.0436202	-0.110703	0.04174156	-0.0511374	-0.4046358	-0.2355105	-0.044037	-0.0554664	0.01388261
113	-0.3317763	-0.0950104	-0.0961643	-0.0340125	-0.2283936	-0.1273719	-0.0484053	-0.057802	0.00074525
123	0.3844341	0.42555763	0.286108	0.40070933	-0.1696604	-0.0323636	0.12516119	0.06026277	0.00470369
133	0.04507813	0.1321193	0.03023491	0.16969719	0.11482359	-0.0729516	0.05653527	-0.1048577	-0.0063423

Table 12. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in October 2021.



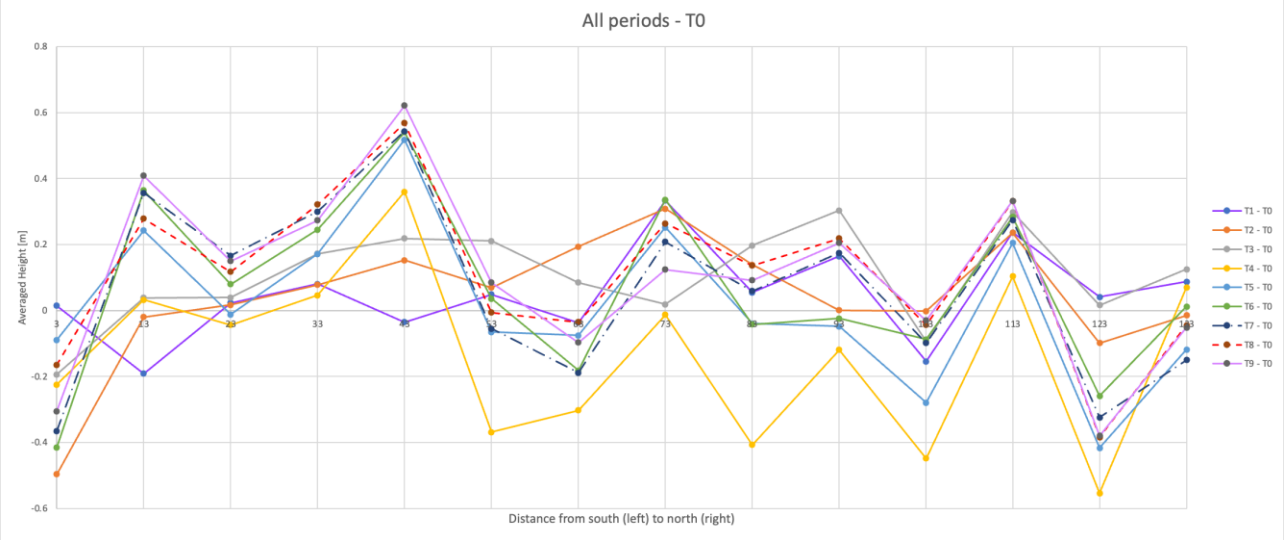
Plot 12. Evolution of the difference between the average height of the shoreline in one period of time and the average height of the shoreline in November 2021.

T9									
Profile	T0 - T9	T1 - T9	T2 - T9	T3 - T9	T4 - T9	T5 - T9	T6 - T9	T7 - T9	T8 - T9
3	0.3053278	0.31959687	-0.1908149	0.11178534	0.0805546	0.21633551	-0.1097969	-0.0596315	0.14056473
13	-0.4089354	-0.6006231	-0.4288348	-0.3703592	-0.3762142	-0.1661376	-0.0445101	-0.0523618	-0.1306059
23	-0.1502415	-0.1269408	-0.1334846	-0.1105425	-0.1937304	-0.1623003	-0.0703056	0.01567903	-0.0327273
33	-0.2729401	-0.1922345	-0.1952719	-0.1012147	-0.2270769	-0.1020356	-0.0282243	0.02686475	0.04850115
43	-0.6215131	-0.6569848	-0.4686797	-0.4032448	-0.2617547	-0.1036549	-0.0811642	-0.0786355	-0.0535377
53	-0.0849594	-0.0361941	-0.0153536	0.12538337	-0.4540537	-0.1501553	-0.0488471	-0.1398534	-0.0908134
63	0.09670698	0.05973603	0.29039103	0.18106663	-0.2060133	0.02084225	-0.0854297	-0.0922796	0.06138519
73	-0.1239771	0.20913904	0.18452082	-0.1048673	-0.1366313	0.12786301	0.21195555	0.08440649	0.14022487
83	-0.0912825	-0.0367045	0.0476777	0.10560283	-0.4984661	-0.1305001	-0.1330662	-0.0324441	0.04465423
93	-0.204492	-0.0399778	-0.2040057	0.09839775	-0.3234546	-0.2522978	-0.2283369	-0.0295268	0.01429413
103	0.02973759	-0.1245856	0.02785895	-0.06502	-0.4185184	-0.2493931	-0.0579196	-0.069349	-0.0138826
113	-0.3325215	-0.0957556	-0.0969096	-0.0347578	-0.2291389	-0.1281171	-0.0491505	-0.0585473	-0.0007452
123	0.37973041	0.42085394	0.28140431	0.39600564	-0.1743641	-0.0370673	0.12045751	0.05555908	-0.0047037
133	0.05142043	0.1384616	0.0365772	0.17603949	0.12116589	-0.0666093	0.06287757	-0.0985154	0.0063423

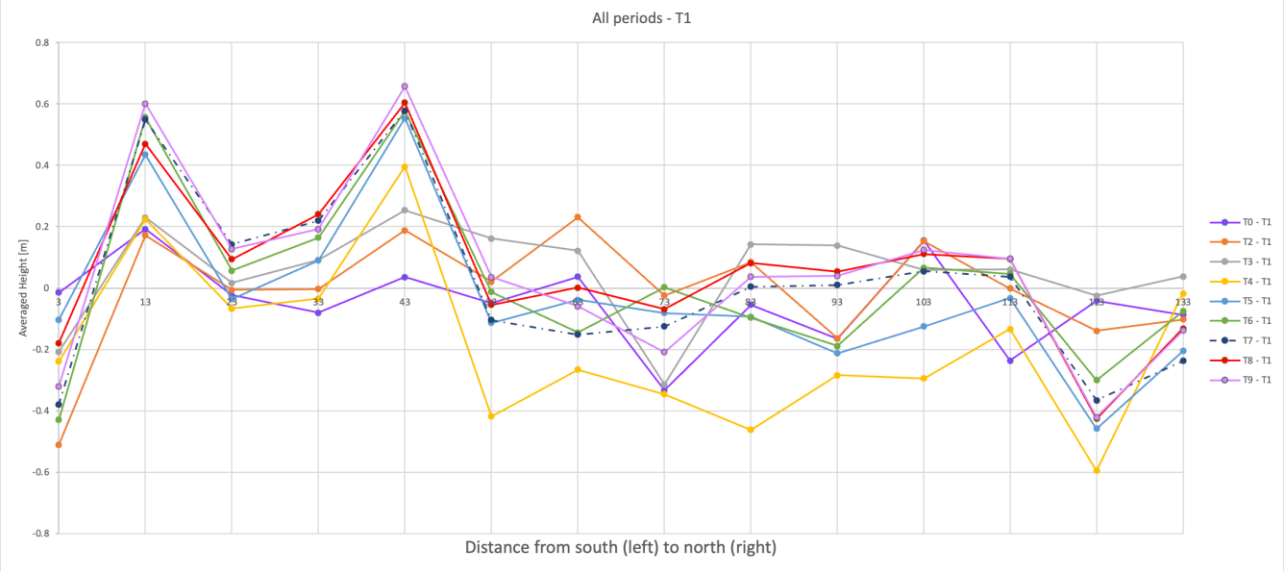
Table 13. Difference between the average heights of the shoreline in all the periods of time and the average height of the beach in November 2021.

As for the previous case, have been generated graphs that have the different transects arranged on the x-axis while the differences between the average height of the beach in one time and the average height of the beach in the next/previous time are arranged on the y-axis. This type of graph allows to compare the average heights over time for a specific transect analyzed: if in some points the graph shows negative peaks, it means that the average height of the beach in the comparison period was higher, while if the peaks are positive means that the average height of the beach in the comparison period was lower. If the points settle close to zero, it implies that the difference

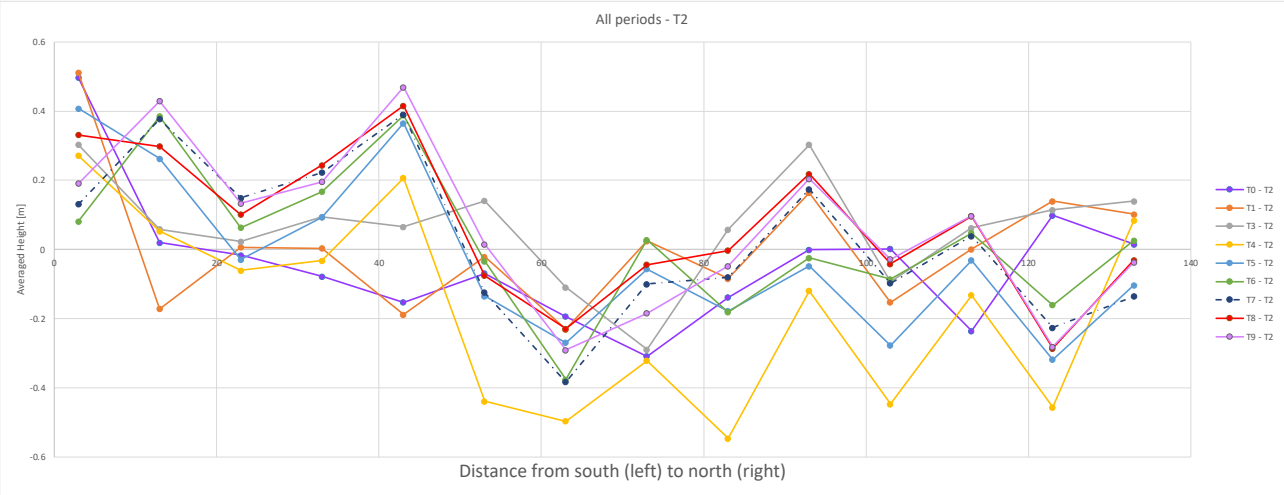
between the average height of the beach in one period and the next/previous period is zero.



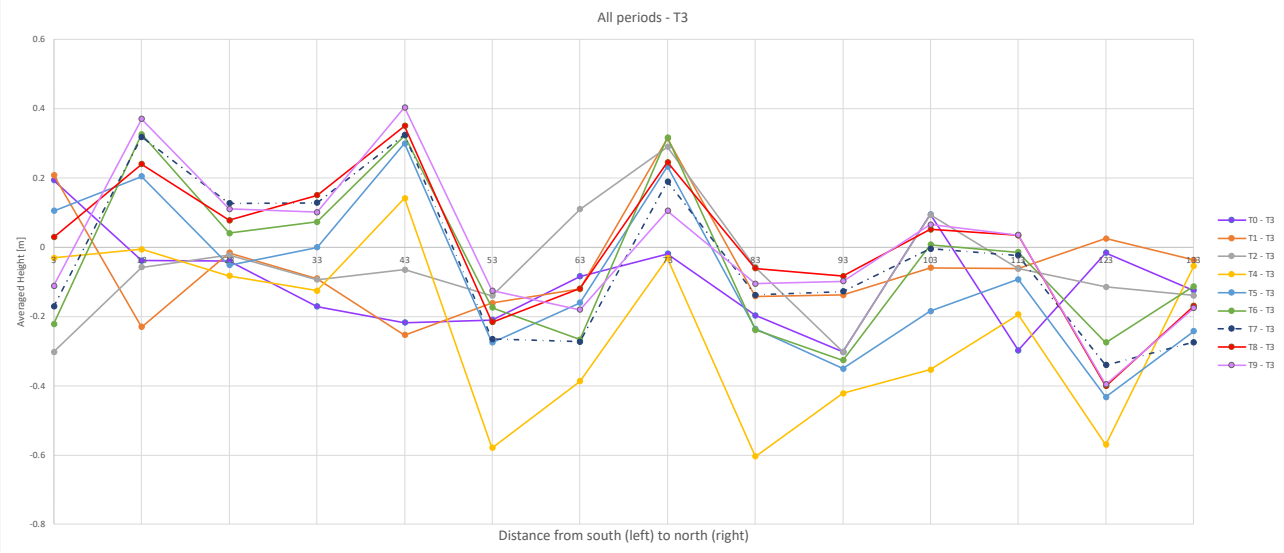
Plot 13. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in December 2018.



Plot 14. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in April 2019.

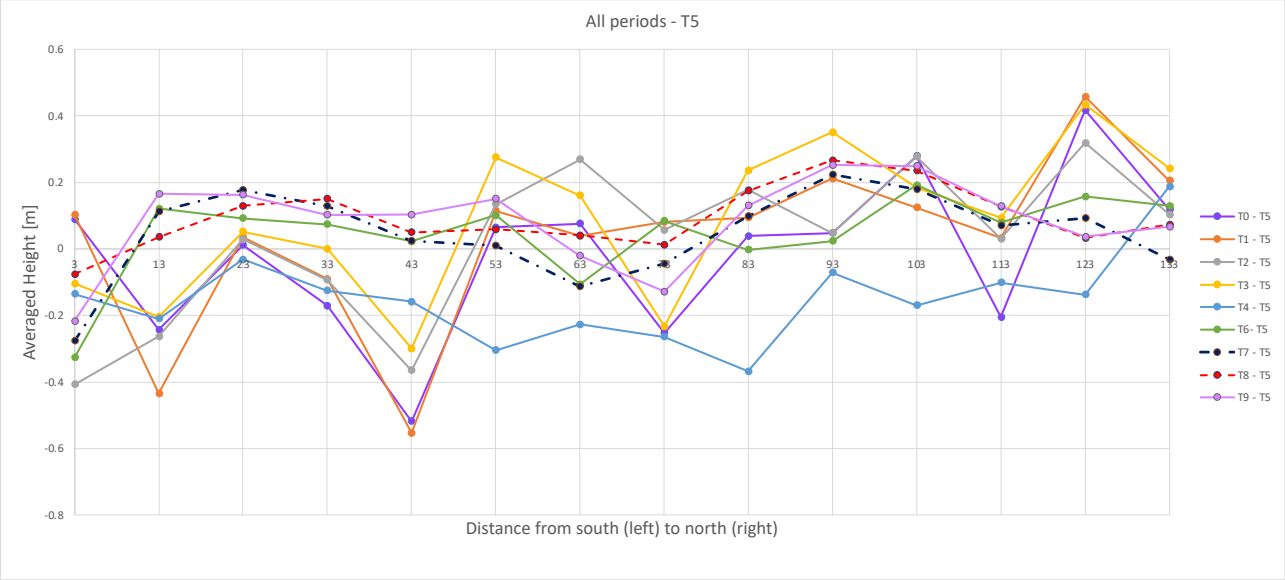


Plot 15. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in August 2019.

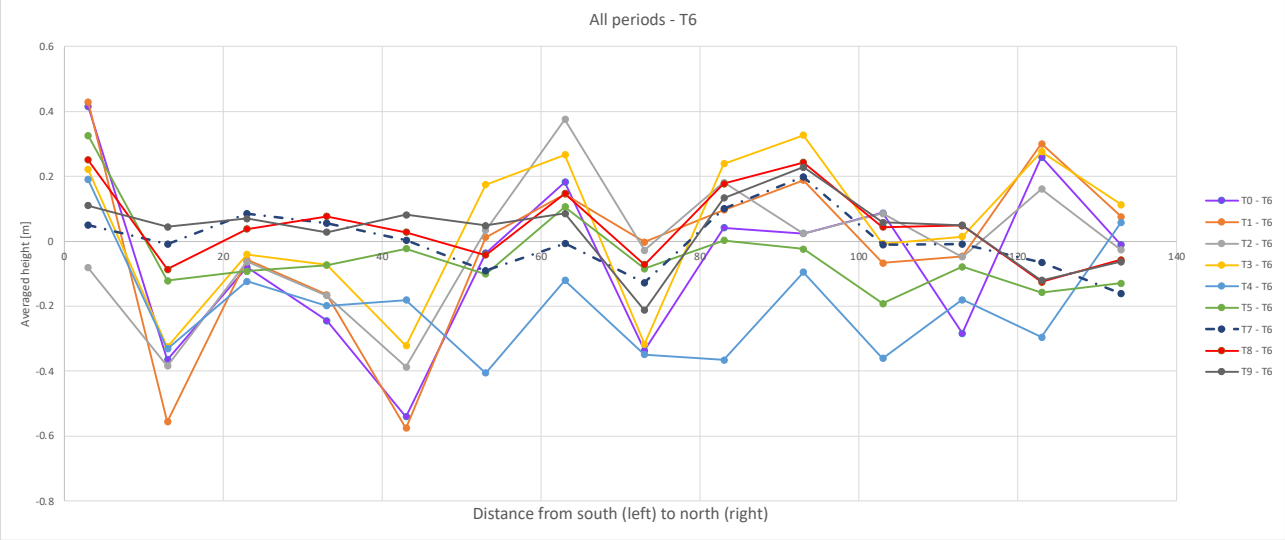


Plot 16. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in November 2019.

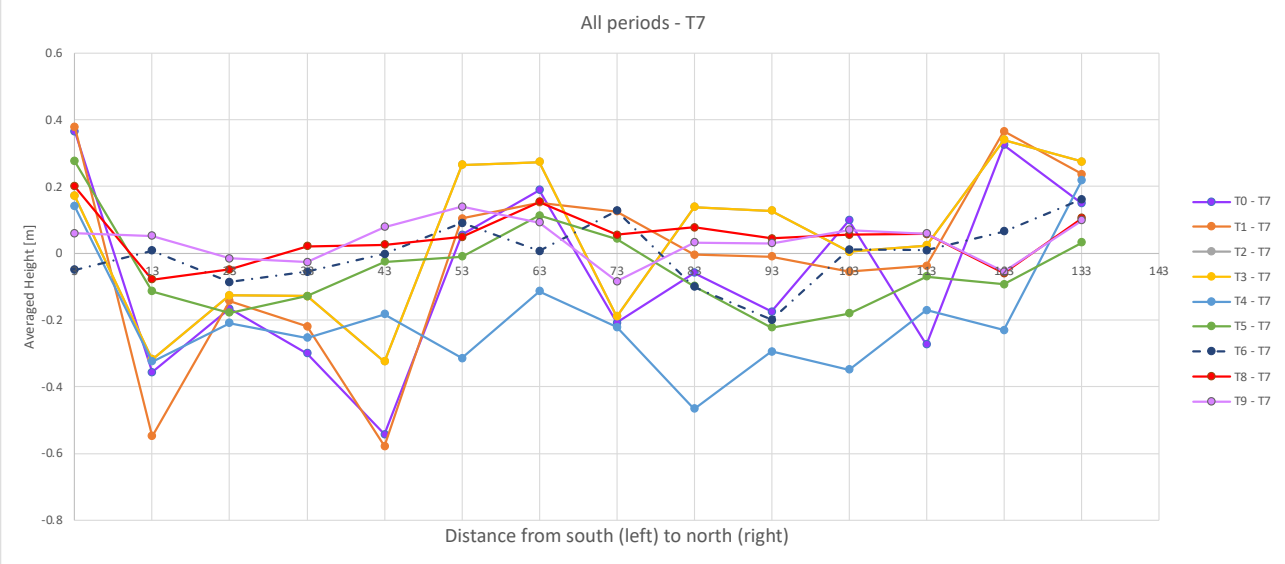
Plot 17. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in April 2020.



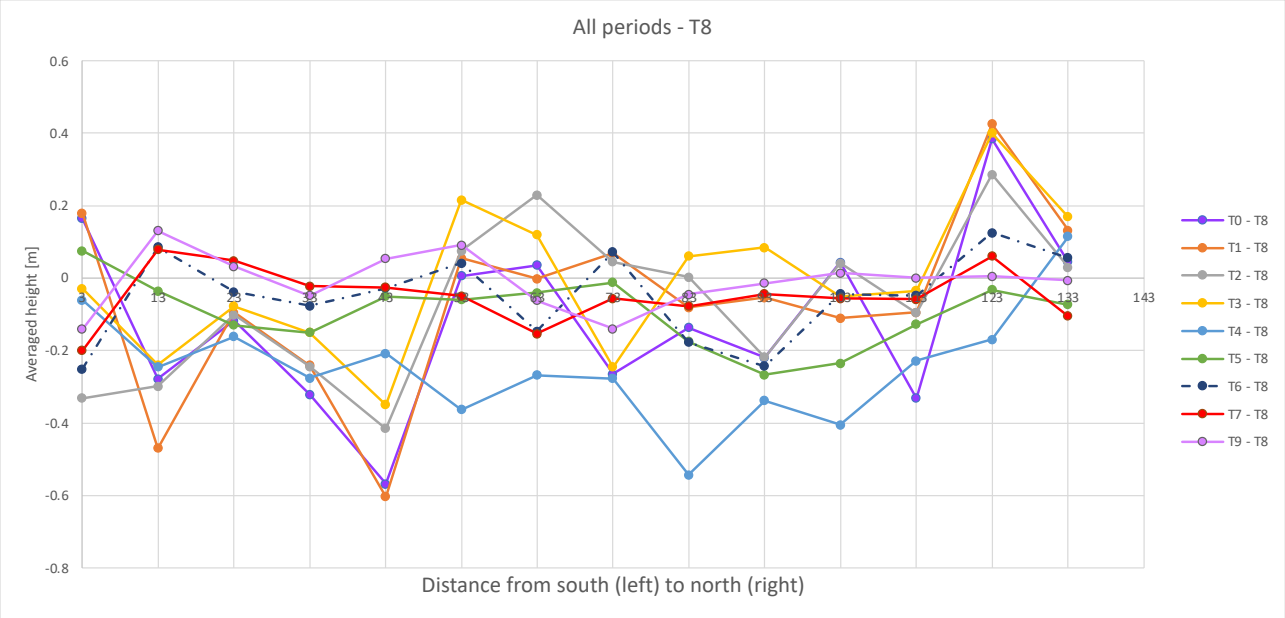
Plot 18. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in September 2020.



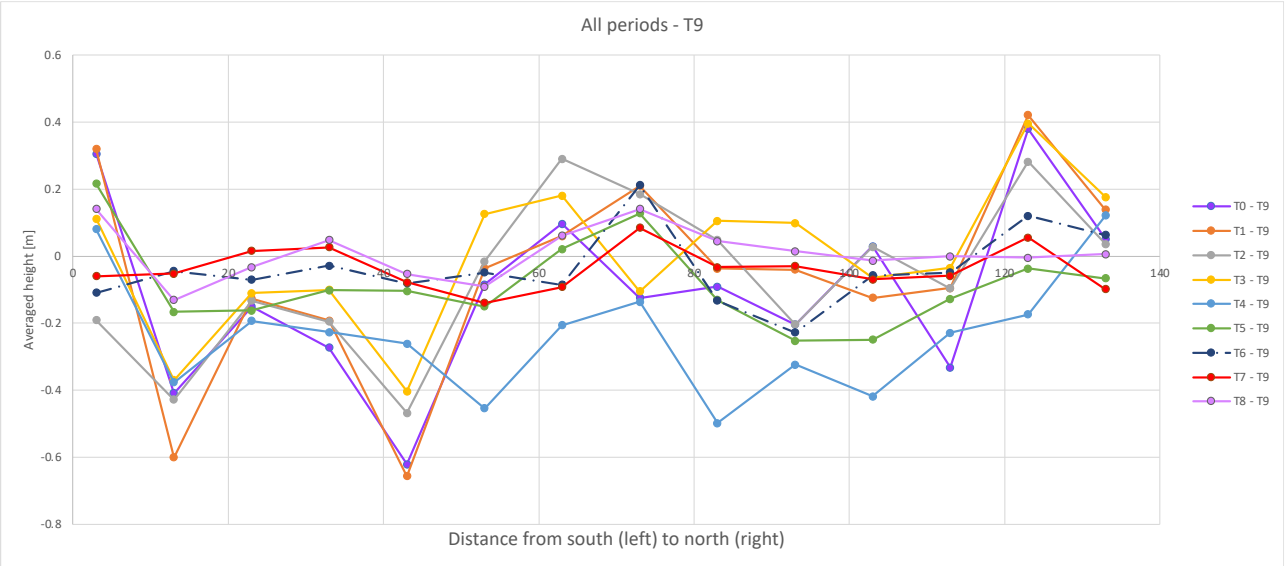
Plot 19. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in January 2021.



Plot 20. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in April 2021.

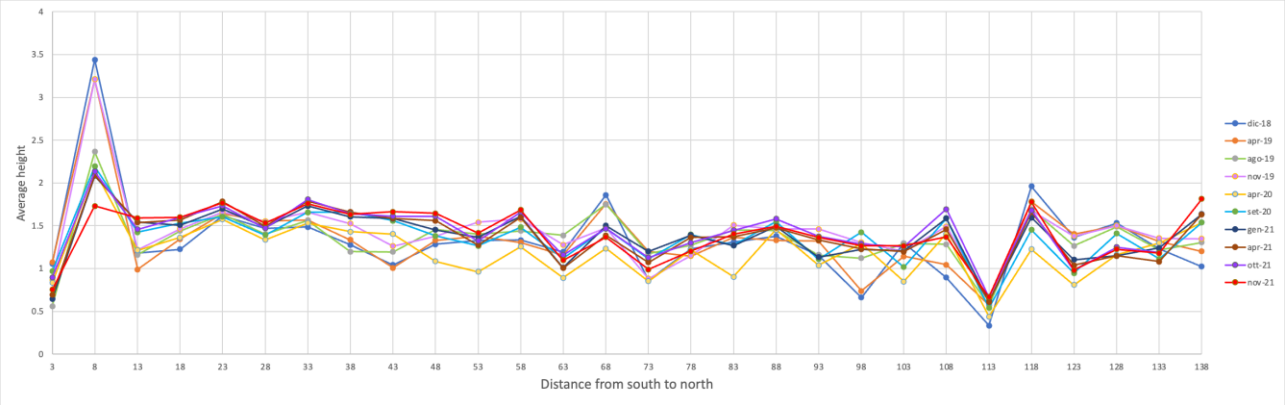


Plot 21. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in October 2021.



Plot 22. Difference between the average height of the shoreline in one period of time and the average height of the shoreline in November 2021.

Up to now the transects positioned at about 1 km from each other have been analysed. To increase the degree of detail of the study, it was decided to examine the transects positioned halfway between those analyzed so far, thus to obtain information every 500 m from each other. Sand waves, probably, could have a smaller extension of the order of km and therefore it is advisable to refine the analysis.



Plot 23. Trend, from south to north, of the average height level of the shoreline per each period analyzed every 500 m.Profile 3 is the southernmost, Profile 138 is the northernmost.

For profiles 13, 18, 38, 43, 48, 58 and 98 accumulations of sediment can be observed with an associated increase in the average level of the beach: for profile 43, for example, it goes from about 1 m in December 2018 to about 1.5 m in November 2021. Also, profile 98 shows an accumulation from about 0.6 m in December 2018 to about 1.25 m in November 2021. Profile 113 recorded the lowest values ever.

To test the presence of sand waves close to the coast, we should have profiles showing an accumulation of sediment over time, followed by profiles showing a reduction in the average height of the beach or the opposite. It's possible to observe a sharp reduction in the average height of the shoreline for profile 8 over time, followed by an increasing accumulation of sediment for profile 13. There is also an up and down trend for some profiles 1 km of distance from each other: profiles 58 and 68 and also profiles 113 and 123 shows an succession of accumulation and more evident erosion.

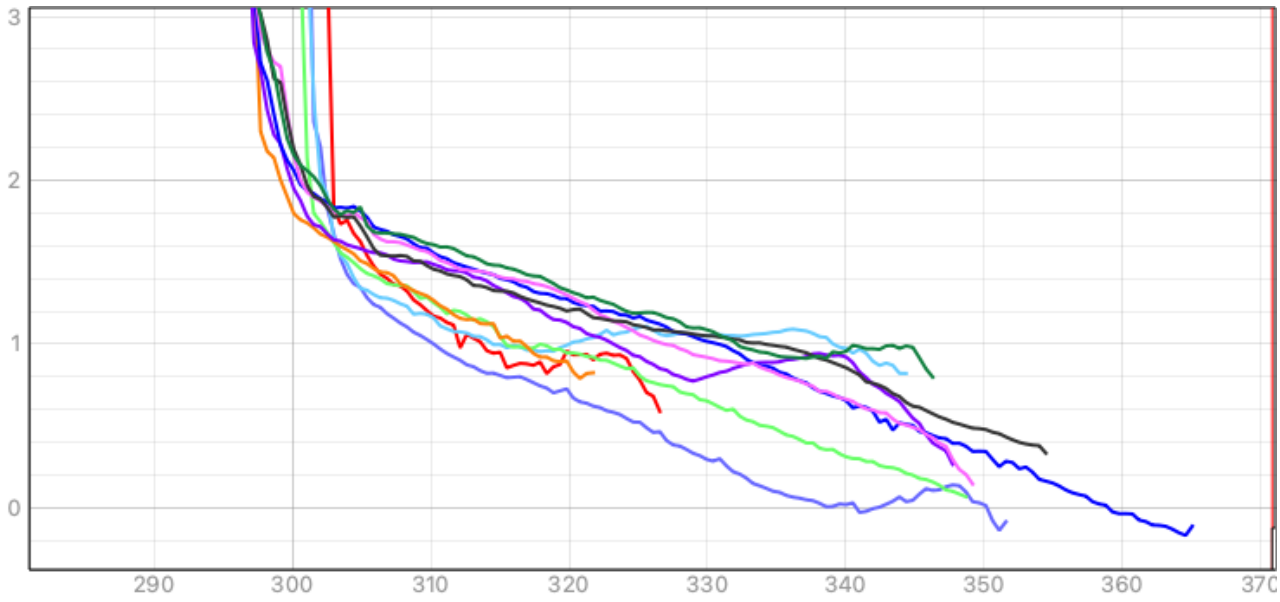
So far, the average heights of the beach have been analyzed, but to increase the degree of detail of the following study, the transects have been analyzed individually in order to verify the presence of trends that may be attributable to sand waves. It has been possible using again the software Qgis and the tool Profile Terrain.

Each graph is zoomed in the area of interest contained between the foot of the dune and the end of the profiles. Some profiles, which therefore recorded evident accumulations of sediment or reduction in the height of the beach over time, will be shown below.

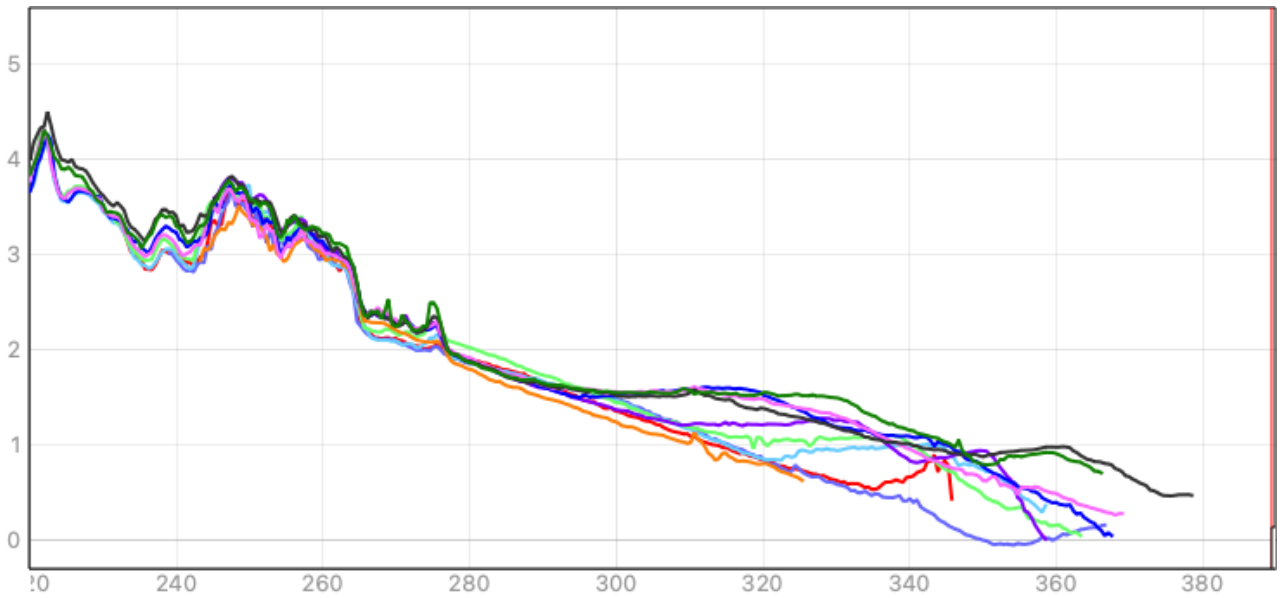
The following legend describes the color associated with the time of survey. Each bathymetric survey is associated with the time in which it was conducted and is correlated to a code: they are described in table 2 at page 5.

Image 2. Legend.

For transect number 13, a sediment accumulation of about 1 m was observed from April 2019 to November 2021. Similarly, for transect number 20, a sediment accumulation of about 1 m was recorded in the same time interval.

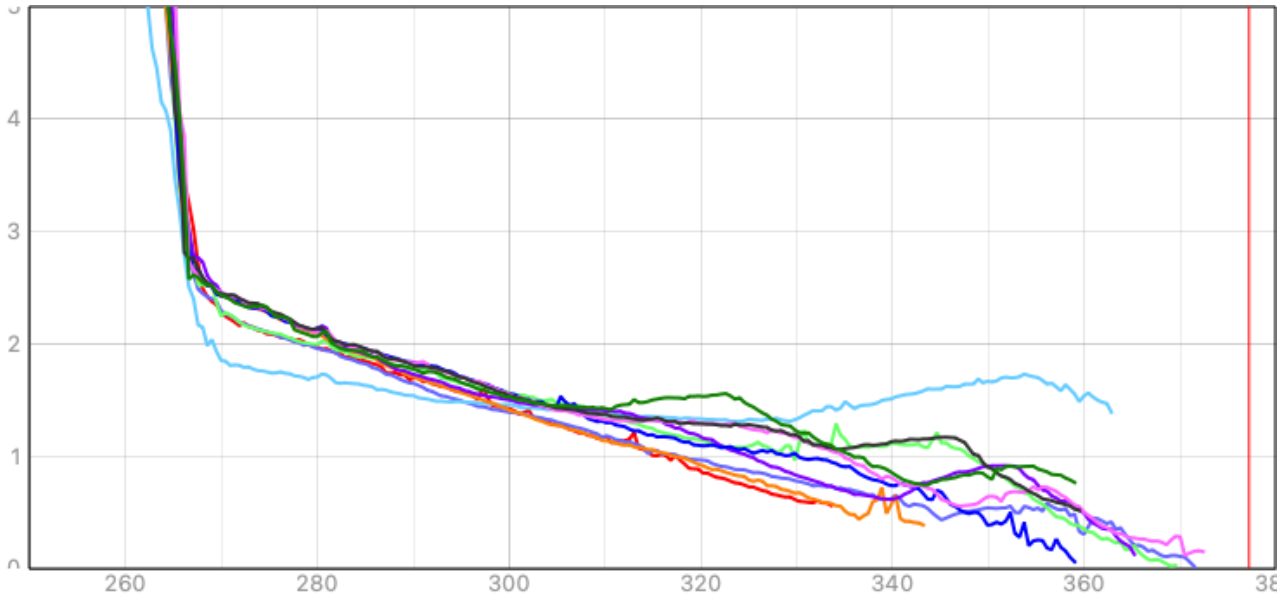


Plot 24. Transect 13.



Plot 25. Transect 20.

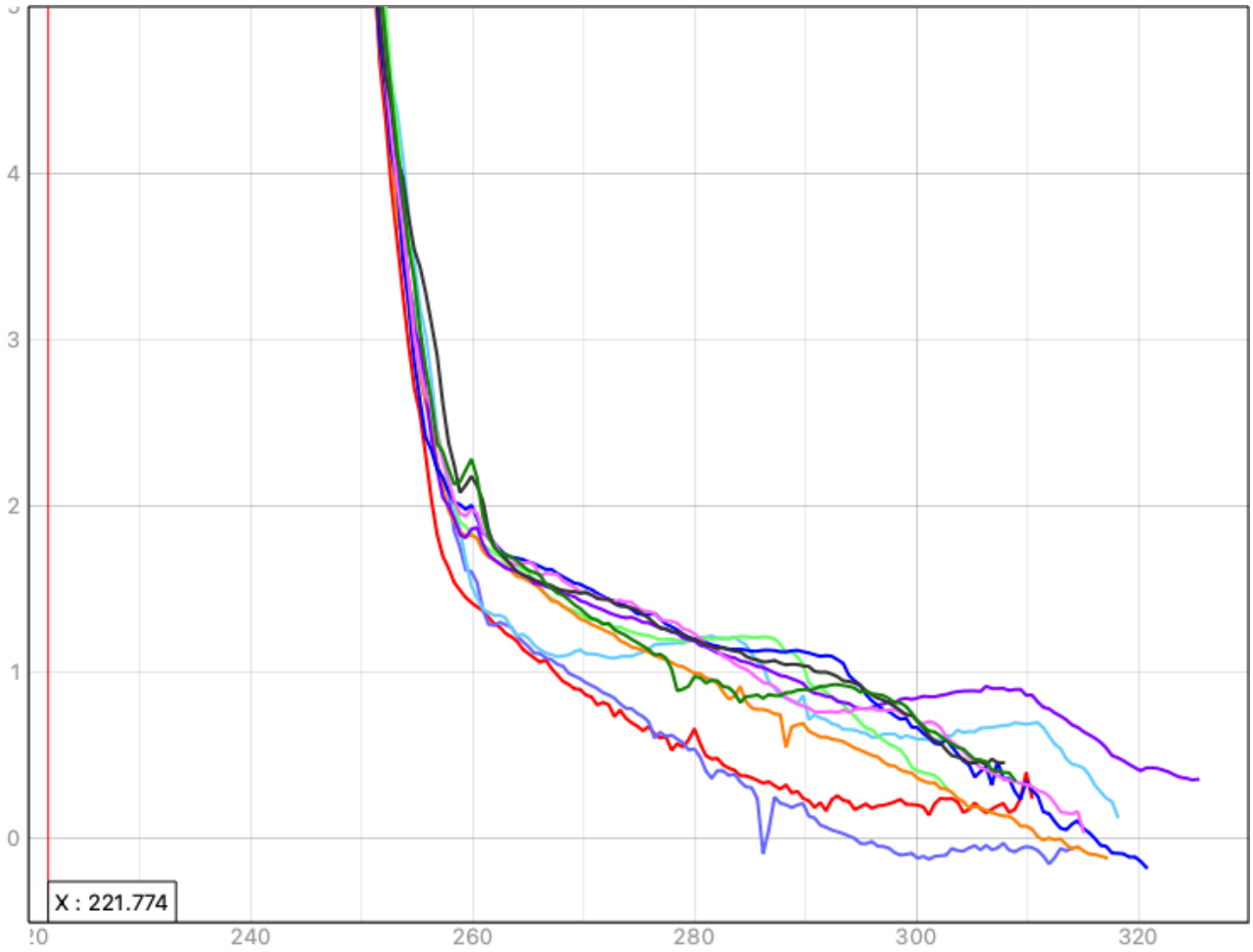
For profile 35 in August 2019 erosion was observed at the foot of the dune and accumulation of sediment up to about 1.8 m near the shoreline. In the following times, the height of the beach at the shoreline decreases over time but in general from December 2018 to November 2021 the height of the beach increased by about
1m.



Plot 26. Transect 35.

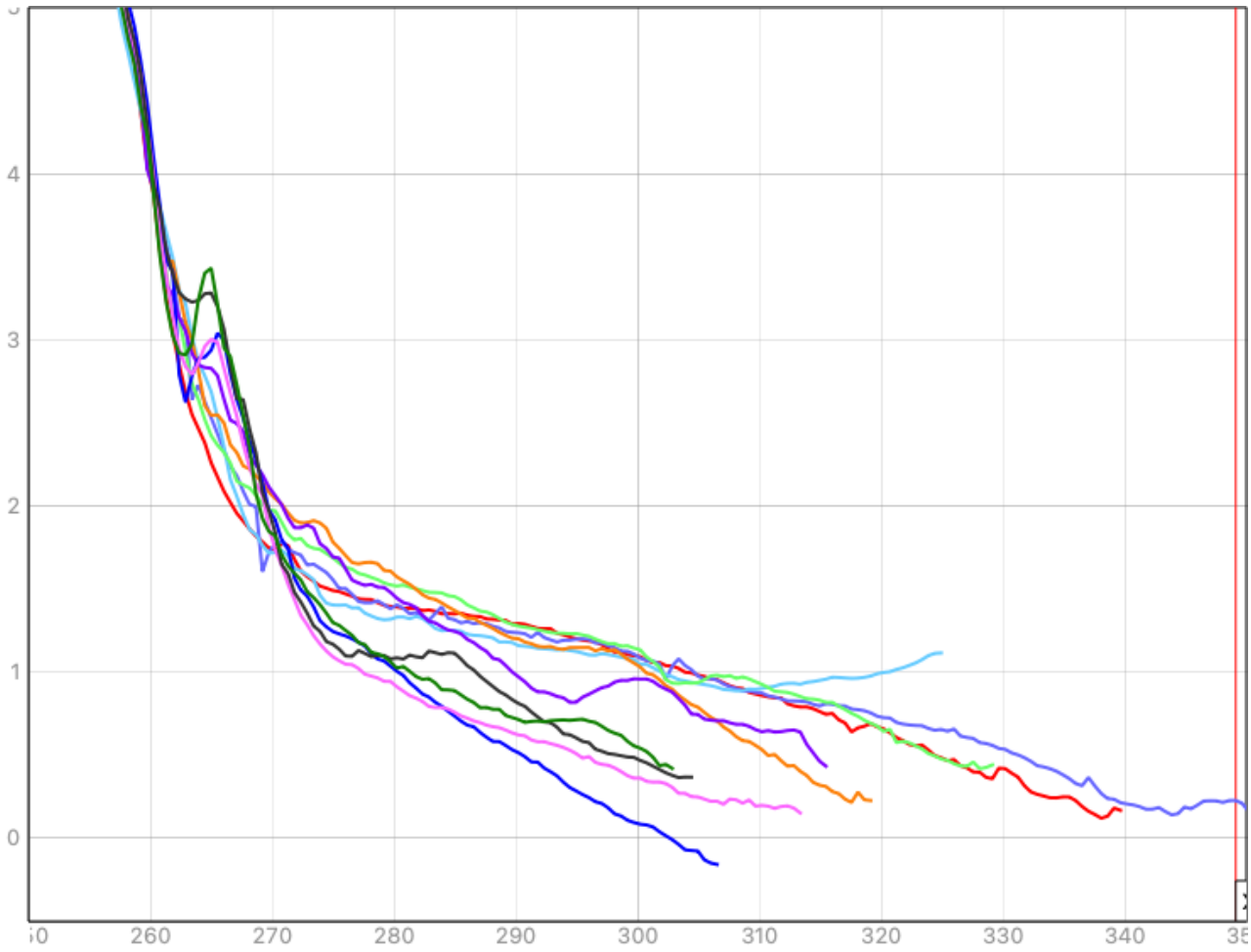
Another condition of accumulation over time is observed for transect 99: an accumulation of sediment of about 1 m was recorded from December 2018 to

November 2021, although the accumulation and erosion trend over time is not linear.



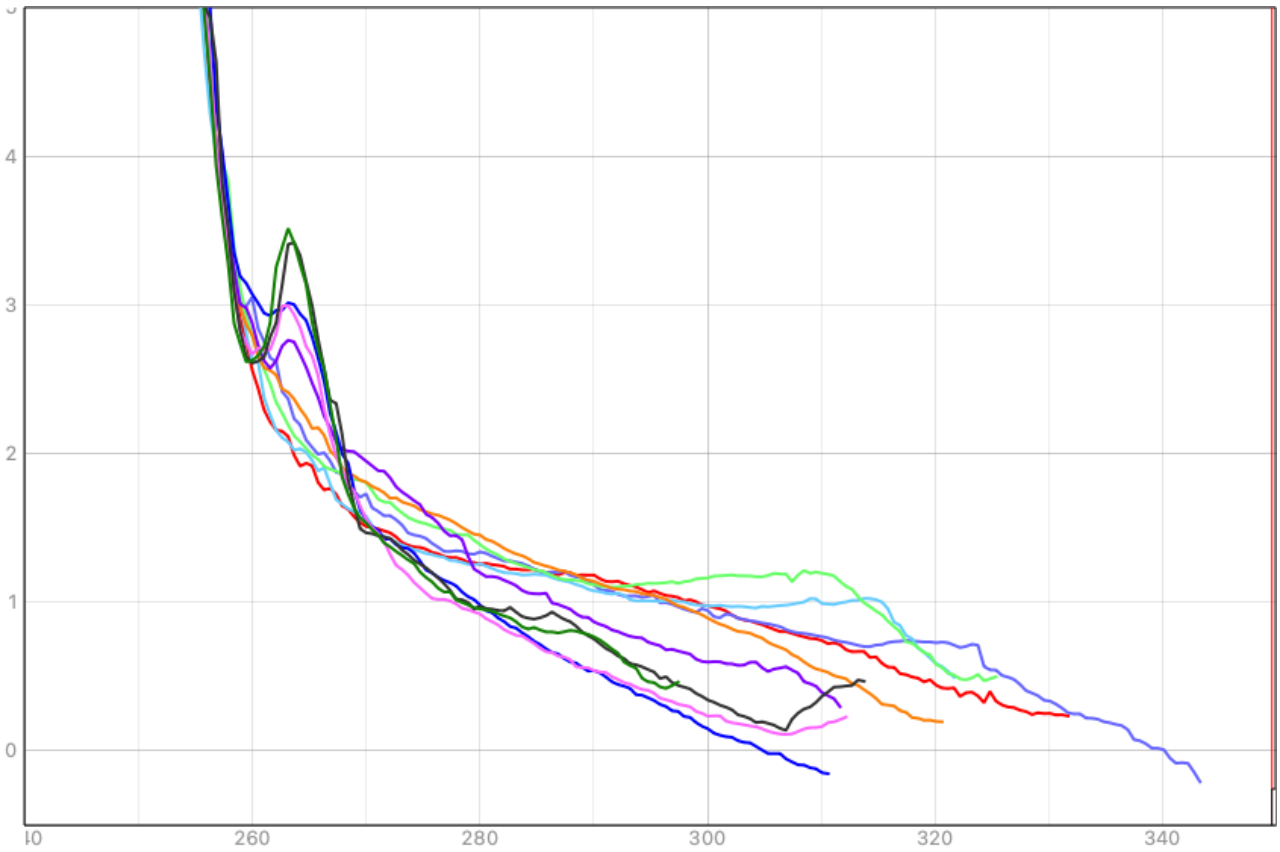
Plot 27. Transect 99.

The opposite is observed for transept number 131: there is a progressive reduction in the height of the beach which reaches about – 1 m from April 2019 to January 2021, reducing to – 0.5 m if is consider the time interval from April 2019 in November 2021.



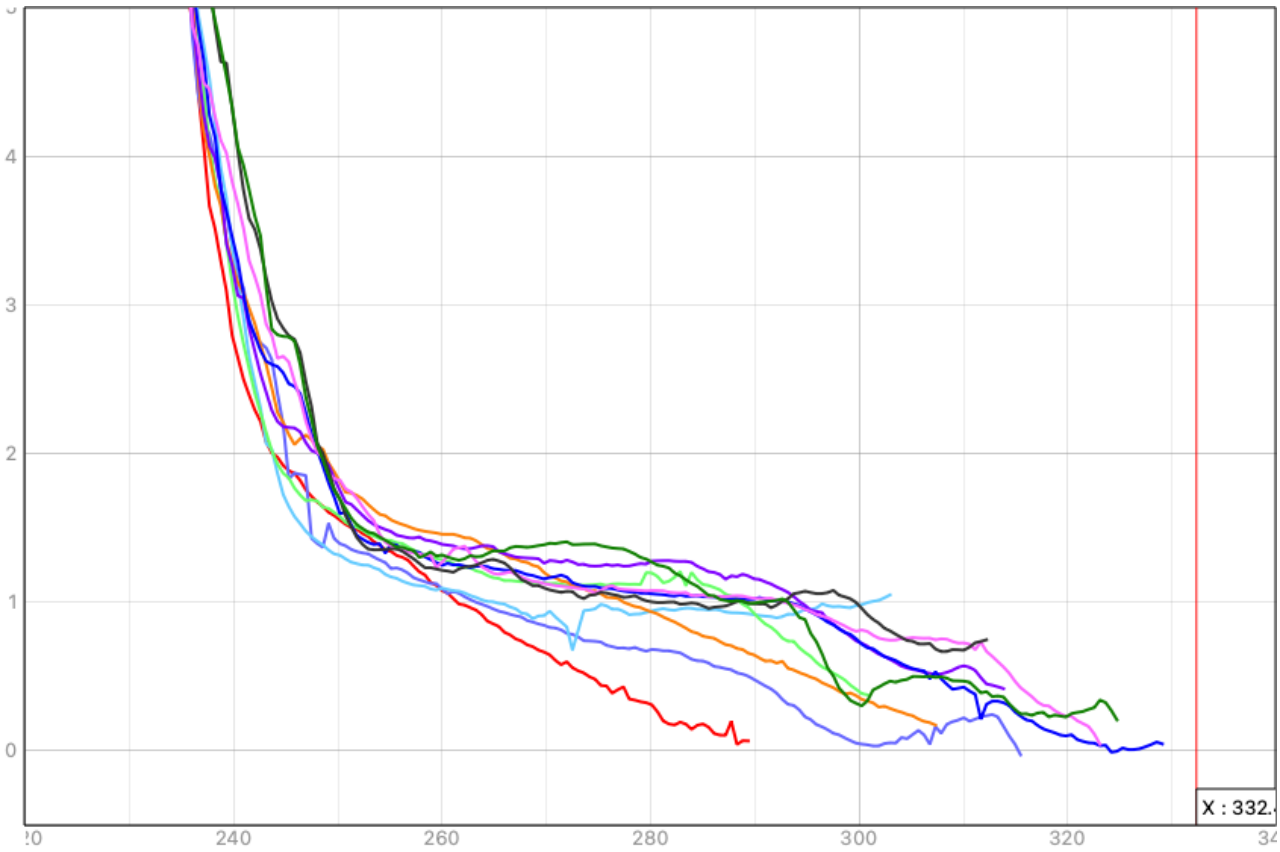
Plot 28. Transect 131.

The plot of profile 133 shows how, from November 2019 to January 2021, the height of the beach decreases by about - 1.4 m in a shorter period of time than the entire observation interval.
Close to the foot of the dune, for Transepts 131 and 1331, there is also an accumulation of sediment with a peak of about 1.5 m; it originates in the time interval from December 2018 to November 2021 and could be both due to the presence of sand that has fallen over time from the dune and from sand accumulated due to sand waves.



Plot 29. Transect 133.

Lastly, Transect number 137 shows a condition of evident accumulation between December 2018 and November 2021 which reaches about 1 m in height of sediment.



Plot 30. Transect 137.

4. Conclusions

In conclusion, given the results obtained, it can be confirmed that a constant trend over time of accumulation and erosion of sediments that could be associated with the presence of sand waves has not been found. Some profiles undoubtedly show accumulation of sediment on the surface which leads to an increase in the height of the beach or, conversely, erosion of sediment which induces a decrease in height but in general these trends do not follow a linear trend to confirm the presence of waves of sand.

It should be underlined that some reliefs in many areas do not completely cover the present beach, therefore, some important information regarding the height of the beach is not accessible.

In addition, transepts were built every 500 m on an available stretch of 15 km. It is possible that the waves of sand, if present, have an extension of less than 500m: it would be desirable to refine the analysis of the transects, plotting the profiles every 100m or possibly further reducing the distance between one transect and the next.

5. Acknowledge

We all sincerely thank Sebastian Westh for having made available the bathymetric surveys, without which this work would not have been possible.

6. Reference

"Forsøg med trykudligningsmoduler som kystbeskyttelsesmetode", WSP Denmark, June 2022