EVREST Final Report:

Project Funding: Fundação para a Ciência e a Tecnologia (FCT)

Scientific Domain: Marine Sciences and Earth Sciences - Estuarine Coastal and Littoral Systems

Project reference: PTDC/MAR-EST/1031/2014

Project Title and acronym	Evolution and Resilience of Barrier Island Systems - EVREST
Project reference	PTDC/MAR-EST/1031/2014
Scientific Domain	Marine Sciences and Earth Sciences
Starting date	01/06/2016
End date	30/09/2019
Principal Investigator	Ana Margarida de Almeida Matias
Principal Contractor	Universidade do Algarve
Requested funding	€ 157.188,00

Funded by

Project reference: PTDC/MAR-EST/1031/2014

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1. INTRODUCTION

1.1 Project Goals

The main goal of EVREST project is to develop a resilience conceptual scheme and indexes that identify coastal barrier environments self-organisation capacity and limits of the system to absorb disturbance. This goal can be further detailed in three objectives:

(1) To identify natural mechanisms of barrier island resilience, both in oceanfront and backbarrier environments;

(2) To quantify timescales and evolutionary rates of barrier and lagoon environments recovery in response to coastal change drivers;

(3) To evaluate scenarios of barrier island evolution on a multi-decadal scale based in modelling simulations, considering varying coastal drivers and interactions.

The timeframe for this study is the medium- to long-term, comprehending coastal evolution in periods of years to decades, and the study develops in a multi-inlet barrier island system located in the south of Portugal. Four main geomorphological environments are considered for these purposes: a) sandy barrier islands, b) dunes, c) salt marshes, and d) pristine stable zones unaffected directly by tidal inlets.

1.2 Participating Institutions

Principal Contractor and Research Unit:

Universidade do Algarve (UAlg), Centro de Investigação Marinha e Ambiental (CIMA)
Person*month: 101
Requested funding: € 115.003,00

Participating Institutions:

Associação Oficina Ciência Viva de Tavira (CCV Tavira)
Person*month: 11
Requested funding: € 21.246,00

FCiências.ID – Associação para a Investigação e Desenvolvimento de Ciências (FCiências)
Person*month: 23
Requested funding: € 15.089,70

1.3 Research Team

EVREST research team can be found on Table 1, with reference to affiliation, role in the project, main tasks, % time devoted to the project, and date of start and end of participation as a member of the project.

Table 1: EVREST Research Team.

Name	Role Tasks	% Time	Start	End
Ana Matias (CIMA – UAlg)	PI T1, T2, T3, T4, T5, T6	100	01/06/2016	30/09/2019
Aikaterini Kompiadou (alias Katerina Kombiadou) (CIMA – UAlg)	(a) Grant holder (b) Researcher T1, T2, T3, T4, T5, T6	(a) 100 (b) 15	(a) 05/12/2016 (b) 05/12/2018	(a) 04/09/2018 (b) 30/09/2019
Ana Alexandra Ramos CCV Tavira	Researcher T6	15	21/03/2017	30/09/2019
Ana Rita Carrasco (CIMA – UAlg)	Researcher T2, T3, T4, T5, T6	40	01/06/2016	30/09/2019
Ana Moura CCV Tavira	Researcher T6	15	01/06/2016	21/03/2017
Carlos Antunes FCiências	Researcher T1, T2,	15	01/06/2016	30/09/2019
Carlos Loureiro Ferreira	Researcher T1, T2, T5	20	01/06/2016	30/09/2019
Fábio Madeira FCiências	Grant holder T2, T5	100	12/10/2016	12/10/2017
Óscar Ferreira (CIMA – UAlg)	Researcher T1, T2, T3, T5	15	01/06/2016	30/09/2019
Rui Taborda FCiências	Researcher T2, T3, T4, T5	15	01/06/2016	30/09/2019

Name	Role Tasks	% Time	Start	End
Susana Costas (CIMA – UAlg)	Researcher T5, T6	15	01/06/2016	30/09/2019
Theocharis Plomaritis (CIMA – UAlg)	Researcher T2, T3, T4, T5	20	01/06/2016	30/09/2019
Verónica Belchior CCV Tavira	Contract T6	100	12/12/2017	11/06/2018

1.4 Consultants

EVREST project counts with the scientific support of three consultants (Table 2). Prof. Gerhard Masselink has devoted the last 25 years to research on beach processes. He is a leading international scientist in beach morphodynamic processes therefore his participation is valuable to link barriers response at different timescales. Prof. Roelvink has 25 years of experience in coastal engineering. His field of expertise is in coastal hydrodynamics and morphodynamics modeling. He has managed the development of the Delft3D model system for 2- and 3D simulation of waves, currents, water quality, ecology and morphodynamics. Prof. Moore has devoted the last 20 years to research on barriers evolution. She is specialized in large-scale coastal behavior, coastal change, impacts of climate change on coastal systems, ecomorphodynamic interactions in coastal environments, coupled-natural human dynamics in coastal systems.

Table 2: EVREST project consultants.

Name	Institution	Tasks
Gerhard Masselink	University of Plymouth, UK	T1, T5
Dano Roelvink	UNESCO/IHE, Delft, The Netherlands	T1, T4
Laura Moore	University of North Carolina – Chapel Hill, USA	T1, T5

2. PROJECT IN BRIEF

2.1 SUMMARY OF ACTIVITIES

The main activities developed during EVREST project were: 1) Data collection and database development; 2) Analysis of hydrodynamic and geomorphological datasets; 3) Characterization of barrier evolution; 4) Modelling sea-level rise and storm impact scenarios; 5) Development of a resilience framework; and 6) Dissemination of project results. The project chronogram, comparing task proposal and tasks execution dates, including the project extension, can be found in Figure 1.

	jun.	jul.	agt.	spt.	oct.	nov.	dec.	jan.	feb.	mar.	apr.	may	jun.	jul.	agt.	spt.	oct.	nov.	dec.	jan.	feb.	mar.	apr.	may	jun.	jul.	agt.	spt.	oct.	nov.	dec.	jan.	feb.	mar.	apr.	may	jun	jul	agt	spt
	2016							2017												2018												2019								
Task denomination	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
T1 - Data collection and GIS integration	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x			x					x											
T2 - Quantification of hydrodynamic and morphological variables						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x											
T3 - Identification of evolution and analysis																		x	x	x	x	x	x	x	x	x														
T4 - Modelling barrier island and lagoon system																					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
T5 - Integration of results and quantification of resilience																						x	x	x	x	x	x	x	x	x	x	x								
T6 - Dissemination of results and findings											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

***Figure 1**: EVREST project chronogram in the proposal (blue shadow) and execution (x).*

1**) Data collection and database development** included remote sensing and fieldwork activities.

The data collected for the development of the EVREST GIS platform included aerial photographs, ortho-photographs and high-resolution, LIDAR-based, terrain models, between 1947-2014. Two historical maps were also included (1873 and 1915) on the analysis. Hard-copy aerial photographs were scanned in high-resolution and observed gaps and missing flights were completed, when possible, with digital imagery obtained by the related authorities. Regarding fieldwork, five sets of campaigns were undertaken during the project: i) preparatory and checking fieldwork, ii) Barreta campaign, iii) Culatra campaigns, iv) Tavira campaigns, and v) tide observation campaigns.

This task was scheduled for one year (Figure 1); however, it was considered advantageous for the project to extend its duration to cover mudflat and dune vegetation identification and evolution, complete gaps in data and/or knowledge of the system by performing further fieldwork and testing, and to extend the barrier evolution analysis to the entire barrier system (and not just the four selected field sites, see project objectives in section 1.1).

2**) Analysis of hydrodynamic and geomorphological datasets** included the analysis of wave records, sea-level records, and morphological records.

An analysis was made of existing wave datasets of a two-decade time-series collected just offshore the barrier system, which was complemented with a 60-year wave hindcast dataset. Based on a set of criteria, storm events were identified, separated by incidence on the West and eastern flank of Ria Formosa and an inter-annual to decadal examination was made. The analysis of sea-level records entailed several tasks: the complete century-long time-series of Lagos Tide Gauge was collected, validated and reanalysed, and measurements were made between Lagos Tidal Gauge and Faro region

sea-levels to establish the vertical reference of tides and compare mean sea level of both sites. From the completed data series 1908-2000 it was possible to estimate MSL rise in the last century. The analysis of the morphological records consisted in the measurement of the evolution of distinct geomorphological units in the barriers, after a detailed establishment of boundary criteria and relevant features. This analysis was based on shoreline position variation, barrier unit's width variation and barrier area variation. Particular attention was paid to a backbarrier embayment (including marsh vegetation identification and sedimentary characterization) and to a dune field (identification of dune development and measurement of shore progradation).

The extension of study sites, data gaps detected in task 1, and instrumental issues related to the sea-level series of Lagos brought difficulties to this task, which were solved as much as possible but postponed the end of the task.

3) **Characterization of barrier evolution** included the analysis of areas unaffected by inlet migration, pre-intervention barrier evolution, and separation of cross-shore and alongshore processes.

The geomorphological evolution analysis of Ria Formosa barriers covered the last 70 years and included all the main geomorphologic units of the system (barrier, dune, marsh) and features (cross-shore rates, coverage, widths and inlet characteristics). Among the several relevant processes, the role of extreme storms was detected, migration cycles were measured, backbarrier development/stability was established in relation to inlet and lagoon drivers, and inlet shoals attachment was identified and related to barrier evolution. An assessment was made of the relative importance of artificial and natural drivers in the area (one of the few worldwide for barrier island evolution). Known evolution patterns were validated and new ones were identified, while coastline change rates and barrier and inlet morphological characteristics were updated.

The delays in tasks 1 and 2 conducted to a delay of about seven months on task 3 (Figure 1). However, the extension of the study areas made it possible to identify and quantify, for the first time, the role of human interventions on the system.

4) **Modelling sea-level rise and storm impact scenarios** included the use of Delft3D-FLOW model for the impact of sea-level rise on the lagoon and the use of XBEACH model for the impact of storms.

The impacts of sea-level rise (SLR) over the Ria Formosa lagoon in 2100, from the 2011 baseline year, were accessed for inlets (Faro-Olhão and Armona Inlets) and the main tidal channels running from them (Culatra, Olhão, and Armona channel). Several observation points and cross-sections were distributed in the study area to monitor morphological impacts of sea-level rise. The hydrodynamics module was coupled to morphodynamics for a 2D depth averaged simulation. Sea-level rise estimates used in the modelling scenarios accounted for the latest global IPCC projections. Data collected during overwash were analysed and results were used to setup an XBEACH model for overwash prediction in one of Ria Formosa barrier islands. The baseline model performance was assessed and tested for six verification cases, and considered a relatively reliable tool. Besides overwash prediction, modelling was also used to evaluate the role of several factors that locally influence overwash hydrodynamics.

Modelling sea-level rise impacts within Task 4 was scheduled to end in 30/09/2018; however there were delays in previous tasks and the identified necessity to include additional hydrodynamic data. Nevertheless, the modelling of storm impacts went further than expected and ended on schedule (Figure 1).

5) **Development of a resilience framework** included a cross-disciplinary literature review, the transference of resilience theory to barrier island geomorphology and the application of concepts to the Ria Formosa system. On the literature review, four crucial aspects of resilience were identified:

latitude, resistance, precariousness, and cross-scale interactions. These concepts were transferred to the geomorphological context. Equally important was the identification of the identity, functions, structure and feedbacks of the coastal barrier system. To assess the multi-decadal geomorphological resilience of barrier islands, a proposal was put forward to use the geomorphological units of Beach, Dune and Marsh (BDM), as indicators that express distinct environments (wave-, wind- and tide-dominated, respectively) of the subaerial barrier, corresponding to distinct spatiotemporal scales of change. Barrier states were defined using binary codes (presence/absence) of environments. The approach and concepts on resilience assessment were applied to the Ria Formosa barrier system, using geomorphological data for the period of 1952 to 2014.

This task started earlier than predicted with preparatory work for the quantification of the ecological resilience of the barrier island system, literature review, and definition of key parameters and holistic interpretation of results, and ended according to plan (Figure 1).

6) **Dissemination of project results** included activities of scientific communication/publication between peers and activities with the general public.

The scientific dissemination actions entailed the publication of one book chapter, ten publications in international journals (three undergoing revision), nine communications in international conferences, six communications in national conferences, and 17 reports. EVREST researchers were members of the organization committee of two national conferences. Three open academic seminars and two workshops were organized within the project. Two MSc theses and two internship reports were concluded by MSc students, and two MSc theses are still ongoing. Dissemination of the project topic and results to the general public was made by means of two radio interviews, participation in events such as Science and Technology Week 2016 and 2017, European Researchers Night 2017, Encontro Ciência 2017, Children and Environment Week of Tavira 2018, Ria Formosa Week 2018, Ciência Viva Summer program 2019, invited talks and guided fieldtrips with students. A three session-based Science Club was developed for 4th grade students (215 students, 11 classes). A science & art informal education activity was made six times (112 students). Besides outreach materials (leaflet, rollup, and porters) production, a project website was created and constantly uploaded.

The number of publications, communications and reports exceeded the proposal and dissemination and outreach was surpassed. The task started earlier than expected and ended in due time (Figure 1).

2.2 Main achievements

EVREST project main goals were achieved, and project execution produced a variety of results and findings associated with barrier islands evolution, storm waves, sea-level variations, storm impacts, lagoon evolution and modelling, resilience review, and barrier resilience framework. These results and analyses produced the following main achievements:

Achievement 1. Remote sensing data collected from several institutions along with data available at CIMA – Universidade do Algarve, was digitized and combined in a GIS platform (with associated metadata). This constitutes a solid and comprehensive database for current and future analysis of Ria Formosa barrier island system (described in detail in section 3.1.2).

Achievement 2. Historical documentation of the Lagos tide gauge (1908-1987, 1988-2000) and most recent series (2004-2016) were thoroughly analyzed, compared and combined with fieldwork data collected along the coast of Algarve. A number of corrections and adjustments were necessary to obtain a single and coherent relative mean sea-level curve (described in detail in section 3.2.2.2). One

of the main remarks from this study was that the current SLR rate in Lagos tide gauge is probably underestimated due to instrumental issues. This achievement corresponds to Milestone M2 of the proposal.

Achievement 3. The geomorphological analysis of the Ria Formosa barrier islands, extended beyond the initially defined areas to the entire barrier system (described in detail in section 3.2.2.3). The maps of the entire system of Ria Formosa barriers for the period 1952-2014 were a first level output of the analysis made upon achievement 1 and correspond to Milestone M3 of the proposal. The barrier maps combined wave storm record (described in section 3.2.2.1) and information on the literature, allowed a second level output which was the definition of evolutionary patterns, the role of human interventions, and the identification of major cross-shore and longshore components and drivers of coastal evolution (described in detail in section 3.3.2).

Achievement 4. The conducted research was the first approach to study long-term sediment transport and adjacent morphological evolution in the Ria Formosa lagoon, as response to SLR (described in detail in section 3.4.2). The adopted modelling approach elaborates on a scenario in which human intervention completely limits sediment input into the Ria Formosa lagoon, which can be considered as an extreme scenario. This achievement contributes to Milestone M4 of the proposal.

Achievement 5. Previous achievements and an extensive interdisciplinary literature review of resilience, allowed a transference of concepts into the geomorphological domain. An innovative resilience framework was developed and implemented in the Ria Formosa system that enables an identification and relative analysis of the several environment states and resilience (described in detail in section 3.5.2). This achievement corresponds to Milestone M6 of the proposal.

Achievement 6. Project partners were intensively engaged in communicating science both to peers and to non-specialist audiences. One book chapter, ten publications, fifteen communications and two MSc theses were delivered during the project (details in section 3.6.2). A high number of activities to the general public (including a science club), the website (Milestone M1 of the proposal) and the production of an exhibition module (that is now part of the science centre permanent exhibition, described in detail in section 3.6.3, corresponding to Milestone M5 of the proposal), will probably continue to have repercussions after the project has ended.

2.3 Output indicators

The output indicators of project execution are summarized in Table 3. This table displays output indicators numbers from the initial proposal and the production actually accomplished by EVREST project. More details about the project implementation and outcome indicators can be found in sections 3.1.3, 3.2.3, 3.3.3, 3.4.3, 3.5.3, and 3.6.

The number of publications and communications exceeds the foreseen by the proposal in 67%. Project progress reports were produced once a year, according to FCT rules; however, it was decided to produce extra 14 project reports, two describing EVREST meetings and workshops, four describing fieldwork, and eight reporting task results. In addition to the project workshops and seminars, two national conferences were organized that match the agenda of EVREST project. On advanced training, two master theses were produced (two more are ongoing, but not accounted for on Table 3), and two internships were completed by foreign master students. Therefore, the advance training exceeded the foreseen on the proposal.

Table 3: Account of output indicators, according to FCT application layout, foreseen on the project proposal, delivered during the course of the project, and the balance between delivered and foreseen output indicators.

Indicator	Foreseen	Delivered	Difference
A – Publications	**6**	**10**	**+4**
Books (chapter)	0	1	+1
Papers in international journals	6	10	+4
Papers in national journals	0	0	0
B – Communications	**9**	**15**	**+6**
Communications in international meetings	6	9	+3
Communications in national meetings	3	6	+3
C – Reports	**3**	**17**	**+14**
D – Organization of seminars and conferences	**1**	**2**	**+1**
E – Advanced training	**1**	**4**	**+3**
PhD Theses	0	0	0
Master theses	1	2	+1
Others	0	2*	+2

**Internships reports from foreign Master students.*

3. DETAILED DESCRIPTION OF ACTIVITIES

3.1 Task 1 – Data collection and GIS integration

3.1.1 Task 1 – Objectives and research team

The objective of this task was to collate relevant datasets for barrier island evolution analysis, and to incorporate datasets in a GIS platform through the development of dedicated geodatabases. This task was coordinated by Ana Matias (instead of Carlos Loureiro, on the proposal) and involved C. Antunes, C. Loureiro, K. Kombiadou, and Ó. Ferreira. Fieldwork involved A.R. Carrasco, S. Costas, MSc students (Xabier Otero, Emily Robbins) and the technical support of L. Bom de Sousa and M. Ramires. Field visits also took place with the consultants L. Moore, G. Masselink and D. Roelvink.

3.1.2 Task 1 – Description of activities

3.1.2.1 Remote sensing

The data collected for the development of the EVREST GIS platform include aerial photographs, ortho-photographs and high-resolution, LIDAR-based, terrain models, with the most recent data from 2014 and the oldest from 1947. Hard-copy aerial photographs were scanned in high-resolution (1200-1800dpi). Observed gaps and missing flights were completed, when possible, with digital imagery obtained by the related authorities. This included visits to several institutions (e.g., DGT in November 2016 and IH in February 2017) to consult historical datasets.

Table 4 includes a list of the available aerial or ortho- photographs (raster data) and LIDAR (Light Detection and Ranging) data collected and processed in the framework of the project, along with the main characteristics and the coverage of the flight in each of the four EVREST study cases: Barreta Island, Culatra Island, Tavira Island and Cabanas/Cacela barriers. A map of the study area, showing the location of the seven barriers and six inlets (current configuration) is given in Figure 2.

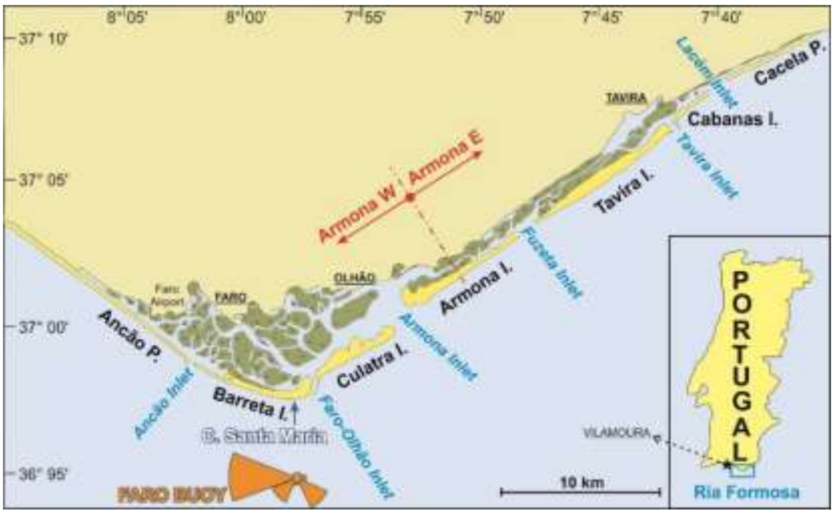

Figure 2: *The Ria Formosa barrier island system; the location of the Faro buoy and the Santa Maria Cape are noted on the map, as well as the names of islands, peninsulas, inlets and the division of Armona to W and E.*

Table 4: List of available raster and LIDAR data, photography type (AP: Aerial Photos; OP: OrthoPhotos), scale, bands (1: BW, 3: RGB, 4: RGB+Infrared) and flight coverage of the four study sites are provided.

Year	Type	Scale	Bands	Study Site Coverage			
				Barreta	Culatra	Tavira	Cabanas /Cacela
1947	AP	unknown	1	full	full	full	full
1952	AP	1:20000	1	full	full	full	full
1958	AP	1:26000	1	full	full	full	full
1969	AP	1:25000	1	none	partial	full	full
1972	AP	1:6000	1	full	full	full	partial
1976	AP	1:30000	1	full	full	full	full
1980	AP	unknown	1	full	full	full	full
1985	AP	1:15000	1	full	full	full	full
1986	AP	1:8000	3	full	full	full	full
1989	AP	1:10000	1	partial	none	full	full
1989	AP	1:8000	3	full	full	full	full
1996	AP	1:8000	3	full	full	full	full
1999	AP	1:8000	3	full	full	full	none
2000	AP	1:8000	3	full	full	full	none
2001	AP	1:8000	3	full	full	full	full
2002	OP	70cm	3	full	full	full	full
2005	OP	70cm	3	full	full	full	full
2008	OP	15cm	4	full	full	full	full
2009	OP	10cm	3	full	full	none	none
2009	LIDAR	10cm	1	full	full	none	none
2011	LIDAR	10cm	1	full	full	full	full
2014	OP	15cm	4	full	full	full	full

Available ortho-photography are ready-to-use with no need for further rectification. On the other hand, aerial photography were unprocessed, raster images, with no geographic information linked to it, which needed to be georeferenced. Regarding processing of aerial photography, non-orthographic imagery (flights 1947-2001) were georeferenced and mosaics of islands and of the entire Ria Formosa were produced. The aerial photos georeferencing process was performed 'backwards' in time, going from the most recent to the oldest photographs. The ortho-photography of 2002 was used as the basis for the georeferencing process.

In general, the georeferencing average error was of the order of 1.0m, which was considered acceptable for the purposes of the project. Most recent flights are high-resolution, which allowed maintaining the RMS error in even lower values (~0.8m). The individual photographs of each flight were included in one mosaicked raster dataset. The available LIDAR data for 2009 and 2011 were collected and processed and the final elevation maps were included in the EVREST geodatabase.

3.1.2.2 Fieldwork

Regarding fieldwork, five sets of campaigns were implemented during the project: 1) preparatory and checking fieldwork, 2) Barreta campaign, 3) Culatra campaigns, 4) Tavira campaigns, and 5) tide observation campaigns.

1) **The preparatory and checking fieldwork campaigns** aimed to assess the suitability of potential sites as study areas of EVREST and also to check elements visible on the aerial photographs or features relevant to the barrier evolution. These fieldwork campaigns took place in July 2016 and October 2018. During the visits, several morphologies were observed. In Barreta Island, dune morphology (several dune ridges), vegetation cover and beach/dune transition were observed (Figure 3). In Culatra Island, the tidal flats and salt marsh areas were observed, including salt marsh maturation level and accessibility.

***Figure 3**: Barreta Island, with path followed and main stops.*

In Tavira Island, the degree of maturation of salt marsh, back-dune morphology and vegetation, and foredune evidences of erosion/accretion were observed. In Cabanas Islands dune morphology was observed, both the naturally built on the inner parts and the dune development inside and on top of the fences. The vegetation was observed in the recent development of salt-marsh on the inner barrier margin. In Cacela, an overview of the Cacela/Cabanas barrier system (Figure 4) was possible, and also the location of the artificially opened Cacela Inlet. In Ancão Peninsula and Barreta Island, the eastern end of the inlet migration path was observed as well as the recent engineering interventions, which deeply altered the area (fieldwork was made on July 2016 and October 2018).

***Figure 4**: Cabanas/Cacela barrier system, with Cacela Inlet to the right of the image.*

2) A **fieldwork campaign** was undertaken **in Barreta Island** on 08/02/2018, in a location were the dune field was wider. Samples were collected from a trench on the dune, at several depths in layers related to several deposition events.

3) During the **campaigns in the embayment of Culatra Island**, in May-June 2017, the greater part of the intertidal flat was surveyed collecting: a) topographic data, b) sediment samples, and c) photographs for the identification of tidal flat, intertidal and upper marsh vegetation in the area. The location of the embayment in Culatra, which is the EVREST study site for saltmarsh evolution, is given in Figure 5. The fieldwork was undertaken to characterise the local eco-geomorphological variety and the ecological development based on the local environmental settings.

***Figure 5**: Location of the EVREST study site in Culatra (orange polygon).*

The field mapping of elevation profiles in the Culatra embayment was carried out using an RTK-DGPS (Real-Time Kinematic Differential Global Positioning System), as well as to obtain the accurate position of sediment collection and vegetation identification stations. Regarding the sediment sampling, a total of 35 surface samples (Figure 6) and three sediment cores (C1, C2, C3 in Figure 6), using a manual metal corer with a 50cm core tube, were collected from the area. Cores C1 and C2 were sectioned on the field every 2-5 cm. The sediment core C3 was frozen and opened by 06/09/2017 (Figure 7) and was split in slices of 1 cm.

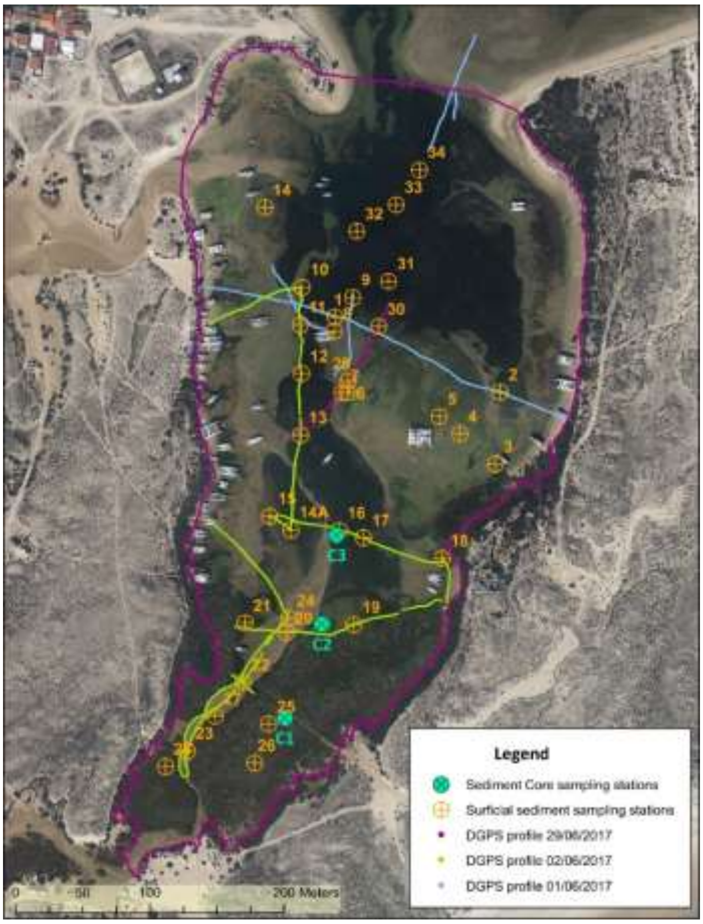

Figure 6*: Surface sediment (orange points) and sediment core sampling stations (green points) and GNSS transects (lines that correspond to measurements on 01/06 [blue], 02/06 [green] and 29/06 [purple]).*

Figure 7*: Photo from sediment core C3 on the laboratory, before sectioning.*

Samples were analysed in the laboratory in terms of granulometry and organic content. The grain size distribution and statistics for all collected samples were defined using the GRADISTAT v.8.0 program (Blott & Pye, 2001). Two field campaigns were implemented in Culatra Island, in the 3rd embayment (from W): a) drone survey (March 2018), including surface elevation measurements and orthophotography, using optical (RGB) and NIR image sensors and b) mapping and sediment sampling survey (May 2018).

4) **The Tavira campaigns** took place in November 2016 and February/March 2017 to measure long-term evolution and morphology and to identify dune and salt-marsh vegetation species, respectively. Fieldwork included GPR (Ground-Penetration Radar) profiling, coring (hand corer and auger, PVC tubes), trenching (Figure 8) and sample collection. Two cores were collected horizontally with a PVC tube. Six samples for sedimentological analysis were taken from Trench 1 and nine from Trench 2.

***Figure 8**: Trench in Tavira Island on the dune field and horizontal core collection.*

5) Regarding the **tide observation campaigns**, the main purpose was to validate the MSL (Mean Sea Level) difference between Lagos, Albufeira and Barreta Island. To that aim, three pressure transducers were deployed in the following locations: Cais da Solaria in Lagos, Porto de Abrigo in Albufeira (Figure 9) and Faro-Olhao inlet in Barreta Island. Data were collected between 26 March and 1 May 2017, and between 19 September and 21 October 2017. Compilation of hydrodynamic datasets (Mean Sea Level and wave record), description can be found in section 3.2.2 of this report.

***Figure 9:** Porto de Abrigo (Albufeira). Left: Preparations for pressure transducer INFINITY placement. Right: PT deployment.*

3.1.3 Task 1 – Implementation and outcome indicators

Implementation and outcome indicators include datasets and reports. Results from Task 1 are also described in methodological sections of publications and communications referenced in sections 3.2.3, 3.3.3, 3.5.3 and 3.6.2 of this report. Task 1 was scheduled for 01/06/2016 until 31/05/2017; however, it was considered advantageous for the project to extend its duration to cover mudflat and dune vegetation identification and evolution, complete gaps in data and/or knowledge of the system by performing further fieldwork and testing, and to extend the barrier evolution analysis to the entire barrier system (and not the four selected field sites, cf. section 3.2.2.3). Task 1 ended in 31/05/2018 (Figure 1).

Datasets:

- Remote Sensing Database: includes aerial photographs, ortho-photographs, high-resolution LIDAR-based terrain models (slideshow sample on EVREST project website). Stored in the EVREST database hard-drive, at CIMA, Universidade do Algarve, available on request.
- Mean-sea level measurements along the Algarve coast. Stored in EVREST database, at Faculdade de Ciências da Universidade de Lisboa, available on request.
- Sediment database: grain-size and organic matter content for all samples collected within EVREST project. Stored in the EVREST database hard-drive, at CIMA, Universidade do Algarve, and included in the IBAM-Sed (Iberian Atlantic Margin Sediments Database), available in https://doi.pangaea.de/10.1594/PANGAEA.883104, created by Costas *et al.* (2017).

Reports:

Antunes, C., Madeira, F. (2017). Tide observation campaign along the Algarve coast. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 4 pp.

Antunes, C., Madeira, F. (2017). Tide observation campaign along the Algarve coast: Lagos and Barreta Island. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 3 pp.

Antunes, C., Madeira, F. (2019). Analysis of Sea Level Rise. CIMA – Universidade do Algarve. 12 pp.

Kombiadou, K., Matias, A. (2017). EVREST GIS Platform Report. CIMA – Universidade do Algarve. 13pp.

Madeira, F. (2017). Análise da variabilidade relativa do nível do mar para a região do Algarve. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 16 pp.

Matias, A., Carrasco, A.R. (2016). Preparatory fieldwork in Ria Formosa. CIMA – Universidade do Algarve. 6 pp.

Matias, A., Kombiadou, K., Carrasco, A.R., Costas, S., Ramires, M., Robbins, E., Sousa, L. B. (2017). Fieldwork in Culatra Island. CIMA – Universidade do Algarve. 30 pp.

3.2 TASK 2 – QUANTIFICATION OF HYDRODYNAMIC AND MORPHOLOGIC VARIABLES

3.2.1 Task 2 – Objectives and research team

The objective of this task was to obtain a dataset of the main hydrodynamic variables and morphologic variables for the study period. This task was coordinated by T. Plomaritis and involved A. Matias, A.R. Carrasco, C. Antunes, C. Loureiro, K. Kombiadou, Ó. Ferreira, F. Madeira, R. Taborda.

3.2.2 Task 2 – Description of activities

3.2.2.1. Analysis of wave records

The main goals of this sub-task (Task 2.1) was the analysis of existing hydrodynamic datasets (both measured and hindcasted) of a two-decade time-series from a wave buoy deployed just offshore the barrier system, which is complemented with a 60-year wave hindcast dataset.

Measured wave data time-series is about 20 years (spanning from 1993 to 2014 with variable time resolution) collected by Faro directional wave-rider buoy located about 10 km offshore of Cabo Santa Maria, in an area with approximately 93 m water depth. This data was obtained and owned by IH - Instituto Hidrográfico de Portugal (http://www.hidrografico.pt/). According to Oliveira *et al.* (2018), along the 28 years of record analysis, unregistered data episodes occurred due to occasional failure of Faro buoy, corresponding to a 19% mean percentage of unregistered data.

Field data was complemented with hindcast results (SIMAR; Spanish State Port Authority; http://www.puertos.es), available for the period 1958-2014. The wave hindcast was produced by the WAM model in its nested form, run in the deep-water mode, therefore the results are appropriate for the locations around the coasts where the bottom effects do not yet start to modify the wave conditions (Rusu *et al.*, 2008).

Simulated significant wave heights were compared to and corrected against the buoy data for the period that the two datasets overlap (1993-2014). After correction, the two datasets were merged and analysed as a whole. The model and measured data were separated in bins of significant wave height, to evaluate model performance within these bins. In addition, due to the cuspate shape of the barrier system (Figure 2), the storms impacting the two flanks needed to be analysed separately. Thus, only waves directly incident to the coast were accounted for in each flank, i.e., for the West flank only waves from the SW sector: W to S; and for the East flank only waves from the SE sector: E to S. It was noted that there was an underestimation of significant wave heights, which was higher for more intense storms. Especially for the case of the East flank, the underestimation was more pronounced.

The results revealed relatively good correlations of the measured and simulated time-series when the full data set is used. The linear correlation parameters for the different bins are similar and correlation coefficients are dropping as the bin cut off is increasing. Given the bimodal nature of the wave direction (storms with East and West components associated with different fetch distances), a correction was performed to improve the underestimation of storm wave heights, noted especially for the waves of the East sector (generated in the Gulf of Cadiz). It consisted in fitting the model wave height to observations, focusing mainly on the case of storm conditions, and evaluating the differences between model and measured wave directions (Figure 10) using a vector correlation approach (Plomaritis *et al.*, 2015). The wave height validation was evaluated by calculating the bias and the brier

skill score (BSS). Both wind waves and swell were analysed together since they coexist during storm events and no spectral information was available. The wave height validation and correction were evaluated through the model bias (corrected: -0.06; initial: -0.1) and the Brier Skill Score (corrected: 0.77; initial: 0.71) values.

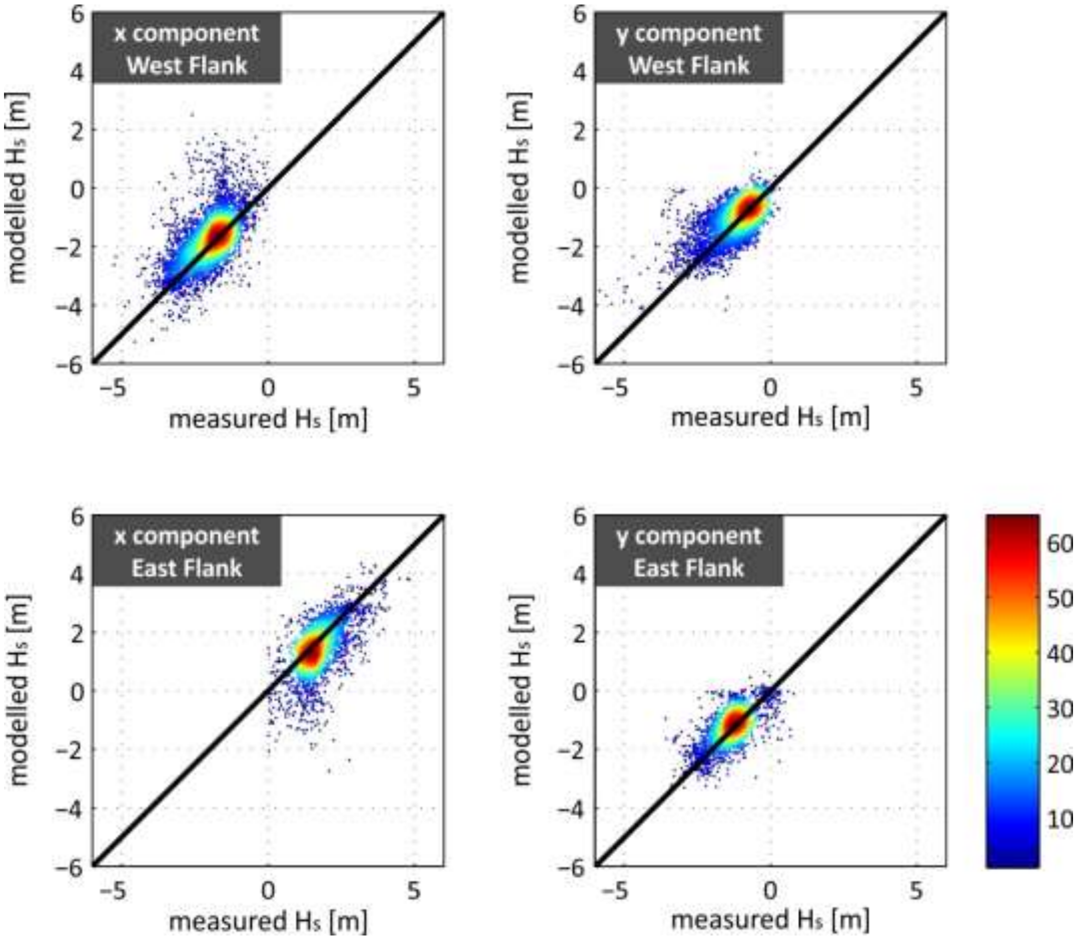

Figure 10: *Comparison of observed (x: buoy data) and post-processed, modelled (y: SIMAR data) significant wave heights [in m], analysed in longitudinal and latitudinal components (left and rights panels, respectively) for the West and East flanks (top and bottom rows, respectively). The colour scale denotes the density of points and the black line the perfect agreement (1:1).*

To identify storm events during the study period, wave records from the Faro buoy (see Figure 2 for location) and modelling results were used. In order to obtain independent events of storm conditions, a peak over threshold analysis (POT) was used (Plomaritis *et al.*, 2018). The threshold value for the POT analysis was set to 2.5 m wave height according to previous thresholds defined in the area (Almeida *et al.*, 2011) and with 0.95 quantile of the time-series as defined by Masselink *et al.* (2014). A storm (or meteorological) independence criteria (time between two consecutive independent storms) was set to 72 h (typical length of a synoptic event (Harley, 2017)). The considered storm duration threshold was 6 hours (Oliveira *et al.*, 2018), corresponding to the 95th percentile of the wave time-series (Plomaritis *et al.*, 2018).

In order to link this data to the geomorphological evolution of the barrier islands in Ria Formosa (Task 3), it was necessary to examine inter-annual to decadal storm incidence in the area and, thus, storm

characteristics needed to be transferred to annual timescales. The yearly time-series of average storm significant wave height and total duration for the two flanks is given in Figure 11.

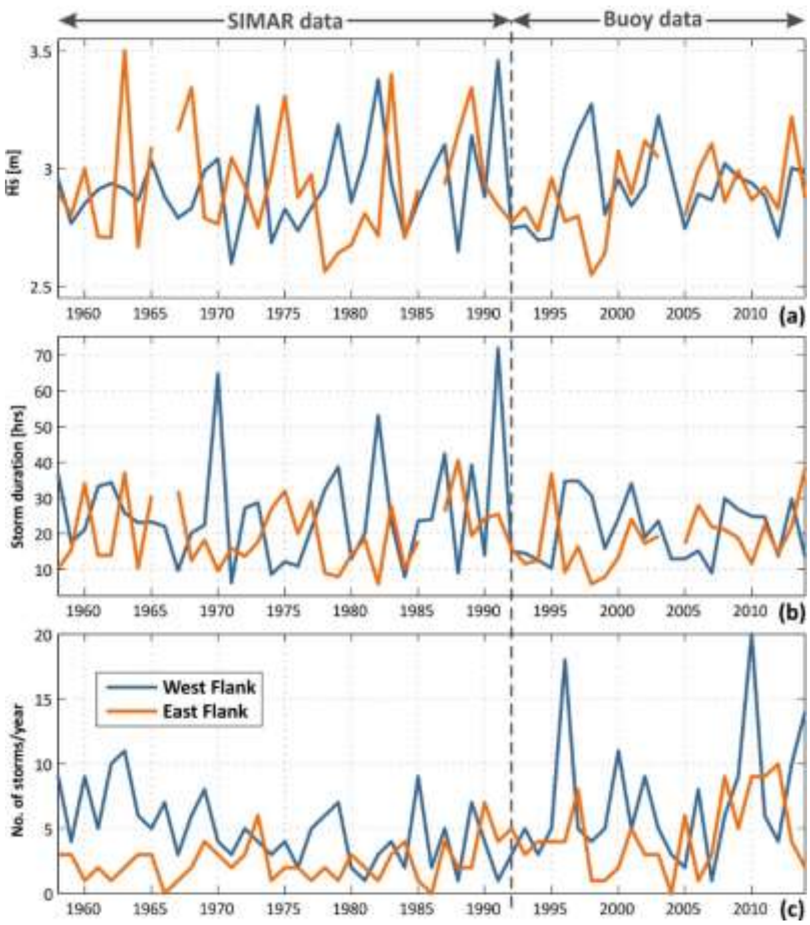

***Figure 11**: Storm waves in the West (blue line) and the East (orange line) flank: average storm significant wave heights (a) and total annual storm duration (b) and number of storms per year (c). The transition between SIMAR (Rusu et al., 2008) and Faro buoy datasets is noted with a dashed line.*

3.2.2.2. Analysis of sea-level records

The main goals of this sub-task (Task 2.2) was to evaluate sea level rise (SLR) rates at Lagos Tide Gauge (LTG) and compare it to Cascais Tide Gauge (CTG) rates, to assess the differences and the behaviour of SLR between the two Atlantic coastal regions, West and south coast. At the same time reference the sea level between LTG and Ria Formosa. To attain the main goals, firstly, the complete century-long time-series of LTG had to be collected, validated and reanalysed, secondly, observation between LTG and Faro region had to be carried out to establish the vertical reference of tides and compare mean sea level of both sites.

The analysis of the monthly data series was made in two steps: the processing of data from the period 1908-1987, from the Permanent Service of Sea Level (PSMSL) dataset and from the 1986-2000 period dataset of the Direção Geral do Território (DGT). The PSMSL official link http://www.psmsl.org/data/obtaining/stations/162.php was accessed to download the LTG dataset for 1908-1987. Revised Local Reference (RLR) used by PSML was removed to turn the vertical reference compatible to local MSL. Some old tide graphs from DGT were digitalized and a few month

daily tides were obtained to validate data and vertical reference. LTG infrastructure interventions for repairing and relocation of LTG, due to an extreme storm in the end of 1950' decade, were verified and levelling data series was checked to access the vertical reference data quality and consistence.

A file provided by the DGT with the hourly mean tide enabled the daily and monthly average computation for the period 1988-2000, to complete the old tide gauge secular series for the XX century. This was the whole observation period for this analogue tide gauge. From free data available at University of Hawaii Sea Level Centre, the reference information of the 1988-2000 LTG series was considered for vertical reference and the series reconstructed. The hourly tidal series was organized and processed in order to calculate the daily average and, consequently, the monthly average, thus, being possible to obtain its mean sea level and the respective moving average (24 months). However, some anomalies were detected at beginning of the 1988-89 period. The detected over-elevations, in the order of decimetres relative to MSL, were compared to the astronomical tide model to assess expected errors possibly related with vertical reference bias. Through the comparison with the astronomical tide model, together with the correlation between storm surge and atmospheric forcing, by access to the meteorological models for the region, it was possible to detect and assess the anomalies. Therefore, the respective errors were found and assessed. A restricted numerical treatment was performed, and a corrected series was obtained with a realistic and compatible behaviour. Once the available data allowed the daily mean sea level assessment, the daily series was processed and considered in the study of SLR. The treatment performed in the series 1988-2000 was very similar to the treatment performed in the monthly series. Harmonic analysis of hourly time-series and atmospheric data were used to correct the error of the first two years of this data series.

One of the main objectives was to join the data MSL series [1908, 1987] and [1988, 2000]. By comparing the common years between the two series (1987-88) and adjusting the overall vertical reference of the series (MSL 1908-1917), it was possible to arrive to the Lagos time-series of MSL between 1908 and 2000 (Figure 12). Therefore, from the completed data series 1908-2000 it is possible to observe that MSL has risen in the last century (90 years) about 20 cm, corresponding to an average rate of 2.2 mm/yr.

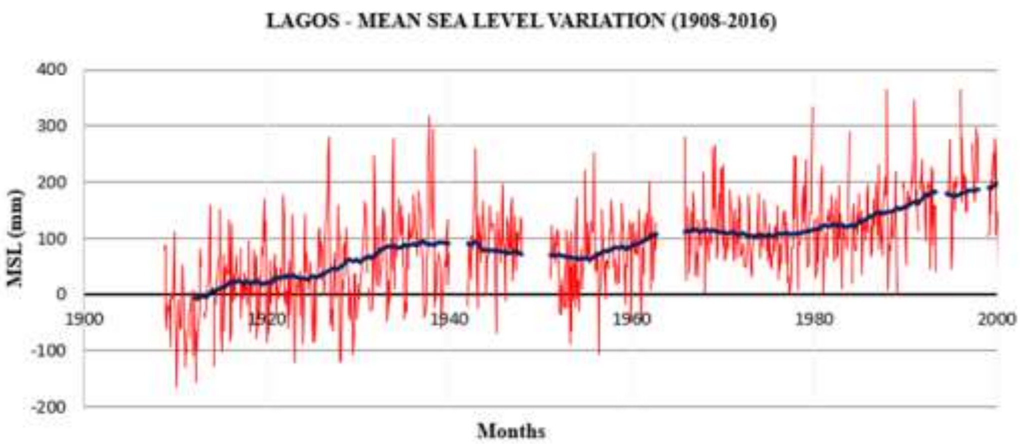

Figure 12: *Lagos time-series of monthly averages (in red) and 24 months moving average (in blue), between 1908-2000.*

In order to obtain greater accuracy of daily data for the most recent years (2004-2016), three corrections were applied: the local vertical velocity correction, the Inverse Barometric Effect correction (IBE) and the seasonal variation. Using geometric leveling observations made by DGT Geodesy services, the relative vertical velocity corrections were recovered, which were applied to the observed daily MSL data series. Correction of the daily MSL values due to settlement was performed by direct adjustment based on the annual vertical velocity values resulting from leveling. The next step was the IBE correction to the daily MSL series. Initially, an instrumental drift was detected in the digital barometer of the tide gauge, which caused an overestimation of 1.46 mm/year. In view of this and before any rectification or replacement through the Air Pressure (AP) values of the series was possible. The AP value, for which the IBE was calculated, was obtained by a 2-year moving average instead of the global mean barometer data for the Lagos tide gauge. The 60-day moving average overlapping the series gave provided the annual MSL change excepted from short-wind period variations. The last step was the correction of seasonal variation. MSL intra-annual variation shows a pattern of variability, with which maximum values can be observed in the last quarter of each year and minimum values from May to July. Seasonal tidal variation, namely the annual harmonic component of the solar influence tide is a parameter to be considered. Removing the seasonal variation average from the AP corrected MSL daily average, results in a reduced series close to what may be called relative eustatic variation. This reduced MSL variation has significantly lower intra-annual variability; however, the SLR rate remains unchanged at 1.83 mm/year. Due to this contradiction in results, the Physical Oceanography Distributed Active Archive Center database was accessed to obtain Sea Surface Height data. Several locations were chosen along the Portuguese coast to get a clearer idea of the behaviour of the ocean surface along the Portuguese coast and southern Spain. From Figure 13 it is visible a common pattern between the various locations used, that is, if there is offshore the Portuguese coast an average sea surface elevation rate of around 2.13 mm, it would be expected to observe in Lagos a very close value for SLR rate.

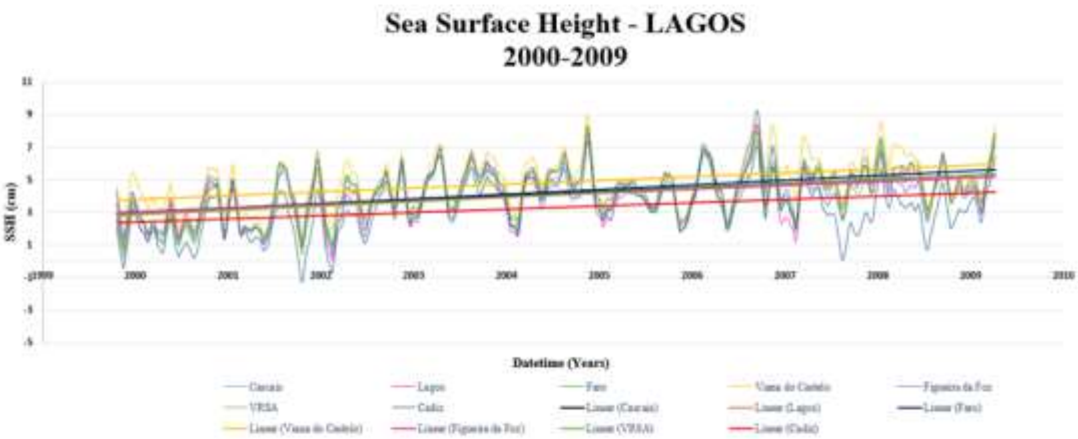

Figure 13: *Time-series of sea surface height anomalies (Viana do Castelo, Figueira da Foz, Cascais, Lagos, Faro, VRSA and Cadiz), from 2000 to 2009.*

3.2.2.3. Analysis of morphologic records

The main goals of this sub-task (Task 2.3) were to obtain the evolution of the distinct geomorphological units in the barriers of the Ria Formosa. This task was set to cover the four selected

study areas mentioned in Task 1 (section 3.1.2.1 of this report), however, it was decided to extend the analysis to the entire barrier system (data on Table 4 extends to data reported in Table 5).

Table 5: Details of the analysed aerial imagery: bands (1: BW, 3: RGB, 4: RGB+NIR), scale, barrier coverage and residual RMSE values related to georeferencing (rectification: error remaining after the applied correction; overall: error due to backwards-in-time georeferencing). Datasets after 2001 are orthoimages.

Flight details				Barrier coverage						Average Residual RMSE [m]	
year	**bands**	**Scale**	**Source***	**Ancão**	**Barreta**	**Culatra**	**Armona**	**Tavira**	**Cabanas -Cacela**	**Rectification**	**Overall**
1952	1	1:20000	CIGeoE	full	full	full	full	full	full	1.1 ± 0.6	1.7 ± 0.1
1958	1	1:26000	CIGeoE	full	full	full	full	full	full	1.1 ± 0.7	2.1 ± 1.3
1969	1	1:25000	FAP	partial	none	partial	full	full	partial	1.1 ± 0.6	1.5 ± 0.7
1972	1	1:6000	IPCC	full	full	full	full	full	partial	0.8 ± 0.5	1.1 ± 0.2
1976	1	1:30000	FAP	full	full	full	full	full	full	1.1 ± 1.6	1.8 ± 1.2
1980	1	variable	DGT	full	full	full	full	full	full	1.0 ± 1.9	1.6 ± 2.2
1985	1	1:15000	FAP	full	full	full	full	full	full	1.2 ± 1.6	1.3 ± 0.5
1986	1	1:8000	FAP	none	partial	partial	none	partial	full	0.7 ± 0.4	1.1 ± 0.5
1989	1	1:10000	FAP	full	full	full	partial	full	full	0.7 ± 0.2	1.2 ± 0.4
1996	3	1:8000	APA	full	full	full	full	full	full	0.8 ± 1.0	1.0 ± 0.3
1999	3	1:8000	CIGeoE	full	full	full	full	full	none	0.6 ± 0.2	0.8 ± 0.1
2000	3	1:8000	CIGeoE	none	full	full	full	full	none	0.7 ± 0.6	0.8 ± 0.1
2001	3	1:8000	CIGeoE	full	full	full	full	full	full	0.6 ± 0.2	0.6 ± 0.2
2002	3	1:7000	DGT	full	full	full	full	full	full	-	-
2005	3	1:7000	DGT	full	full	full	full	full	full	-	-
2008	4	1:1500	DGT	full	full	full	full	full	full	-	-
2009	3	1:1000	CIMA	full	full	full	full	none	none	-	-
2014	4	1:1500	DGT	full	full	full	full	full	full	-	-

**Ownership of aerial photography: CIGeoE (Centro de Informação Geoespacial do Exército), FAP (Força Aérea Portuguesa), IPCC (Instituto Português de Cartografia e Cadastro), DGT (Direção-Geral do Território), CIMA (Centro de Investigação Marinha e Ambiental).*

Distinct geomorphological units were digitised and analysed, using four boundaries: (a) The **ocean-side coastline** (ca. Mean High Water Level: MHWL). The proxies used were the upper debris line or the beach scarp, in cases of debris absence. (b) The **dune line** (ca. Mean Higher High Water Level: MHHWL), using the ocean-side limit of dune vegetation, as proxy for the position of the foredune foot. (c) The **backbarrier coastline** in the lagoon-side (ca. MHWL). In backbarrier stretches with perched marshes, the limit between the upper-marsh vegetation and the barrier/dune was used, identified by the transition to bushy (more rugose, darker) vegetation. In backbarrier beaches, the debris line or beach scarp/dune limit (if no debris was present) were used. (d) The **marsh-edge line** (transition from marsh to tidal flat; ca. MWL). In cases of vegetated tidal flats (e.g. seagrasses), the boundary between emerged and submerged vegetation was identified by differences in colour and texture. Otherwise, the edge of the marsh vegetation was mapped.

These boundaries delimit the selected morphologies as follows: i) Barrier: wave dominated part, delimited by the ocean-side (a) and the backbarrier (c) coastlines, both corresponding to the same water level (ca. MHWL); and ii) Dune: wind dominated part, delimited by the dune line (b) in the ocean-side (ca. MHHWL) and the backbarrier line (d) in the lagoon-side (ca. MHWL).

Only flights with full barrier coverage were used to calculate geomorphological unit areas and widths and, since elevation data were not available, the analysis was restricted to a planimetric basis. Inlet width and position were mapped for non-stabilised inlets. The former was identified as the minimal distance between the debris line boundaries (ca. MHWL) of the barriers on either side of the inlet (inlet throat). The latter was mapped as the midpoint of the intersection of the inlet throat and the inlet channel(s).

The coastlines and environments were analysed in terms of medium-term (multi-decadal) and short-term (years to decades) evolution and behaviour. To that end, three parameters were quantified and analysed: a) boundary line cross-shore change rates (in m/yr), b) geomorphological unit widths (in m) along the barrier and c) barrier areas (in m^2).

Weighted Least Squares Regression was performed on the entire dataset using the Digital Shoreline Analysis Tool (Thieler *et al.*, 2009) that defines the shoreline changes along transects, cast perpendicular to a reference baseline. Weighted Linear Regression (WLR) rate were preferred over simple linear rate, as it is weighted toward more accurate coastline positions (Terrano *et al.*, 2016). The uncertainty of coastline position (total error) was assessed as the sum of squares of all measurement errors (Morton *et al.*, 2004). For coastlines derived from aerial photographs, these errors were related to rectification and digitization. The former is the error remaining after georeferencing, taken equal to the overall residual RMSE for each barrier (average values in Table 5). The latter depends on the raster resolution and was taken equal to four times the image cell size (Jabaloy-Sánchez *et al.*, 2014).

The results of the long-term morphological analysis for each of the Ria Formosa barrier islands can be found in Figures 14 to 19.

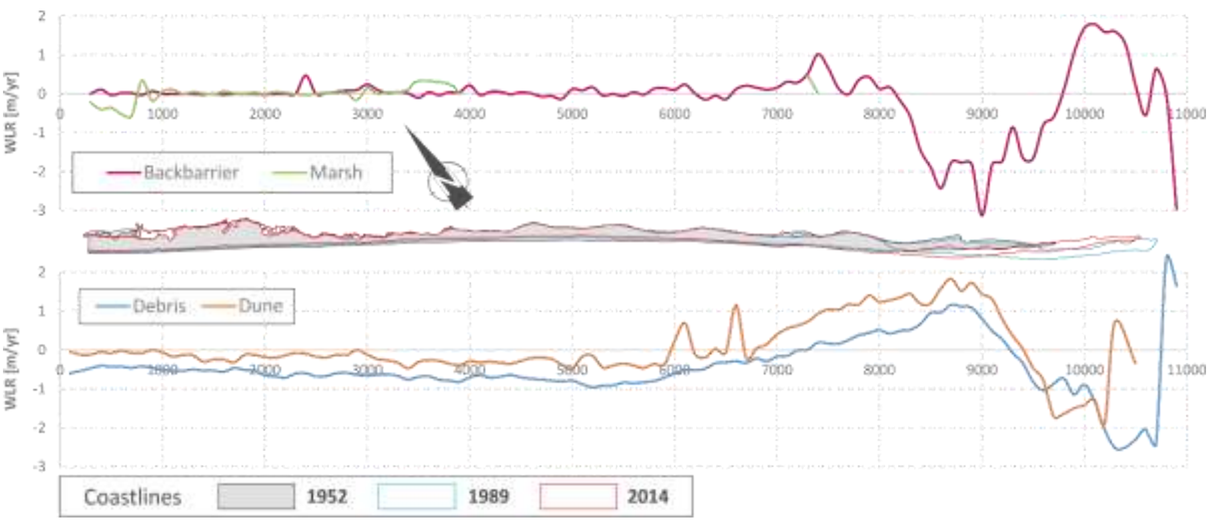

Figure 14: *WLR rates for Ancão Peninsula; the top graph corresponds to lagoon-side boundary lines and the bottom graph to ocean-side ones. Tree different barrier morphologies (1952, 1989 and 2014) are shown.*

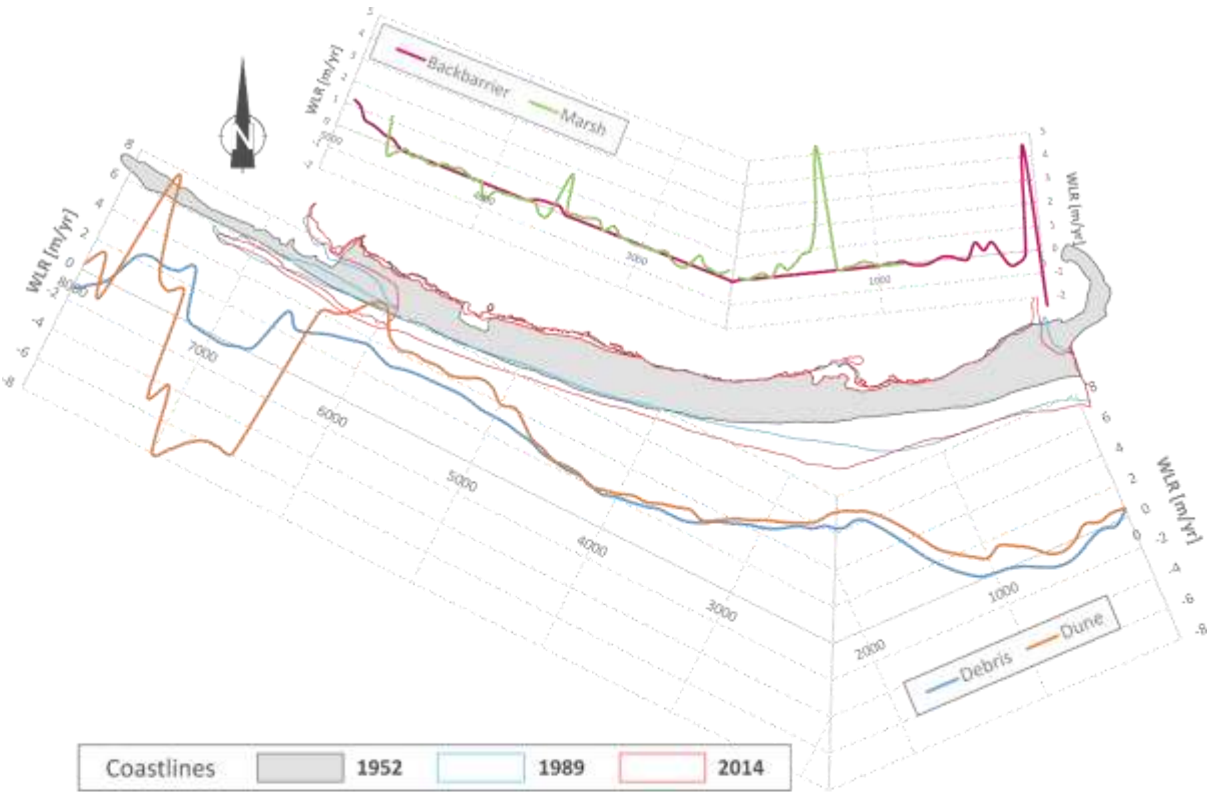

***Figure** 15: WLR rates for Barreta Island; the top graph corresponds to lagoon-side boundary lines and the bottom graph to ocean-side ones. Three different barrier morphologies (1952, 1989 and 2014) are shown.*

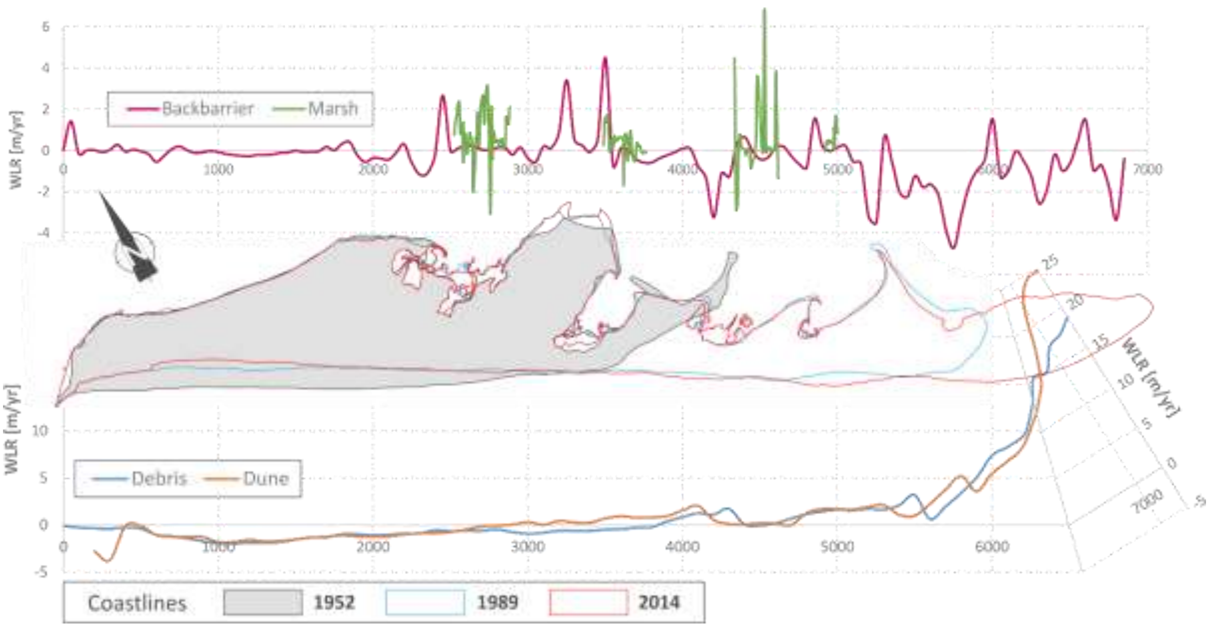

***Figure 16:** WLR rates for Culatra Island; the top graph corresponds to lagoon-side boundary lines and the bottom graph to ocean-side ones. Three different barrier morphologies (1952, 1989 and 2014) are shown.*

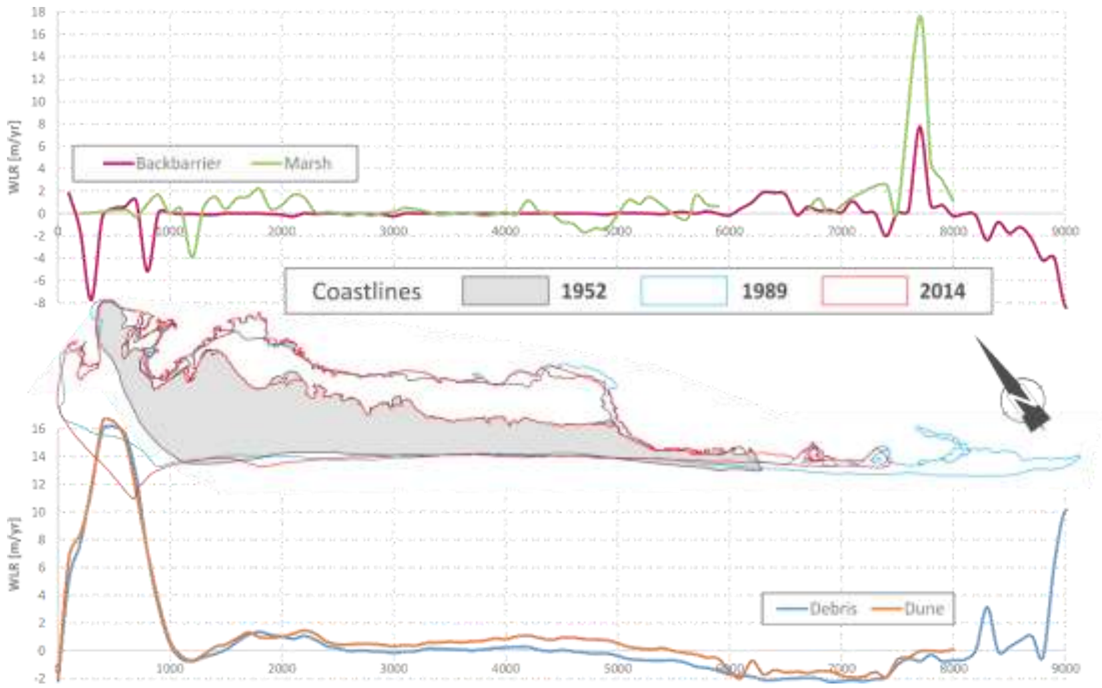

***Figure 17**: WLR rates for Armona Island; the top graph corresponds to lagoon-side boundary lines and the bottom graph to ocean-side ones. Three different barrier morphologies (1952, 1989 and 2014) are shown.*

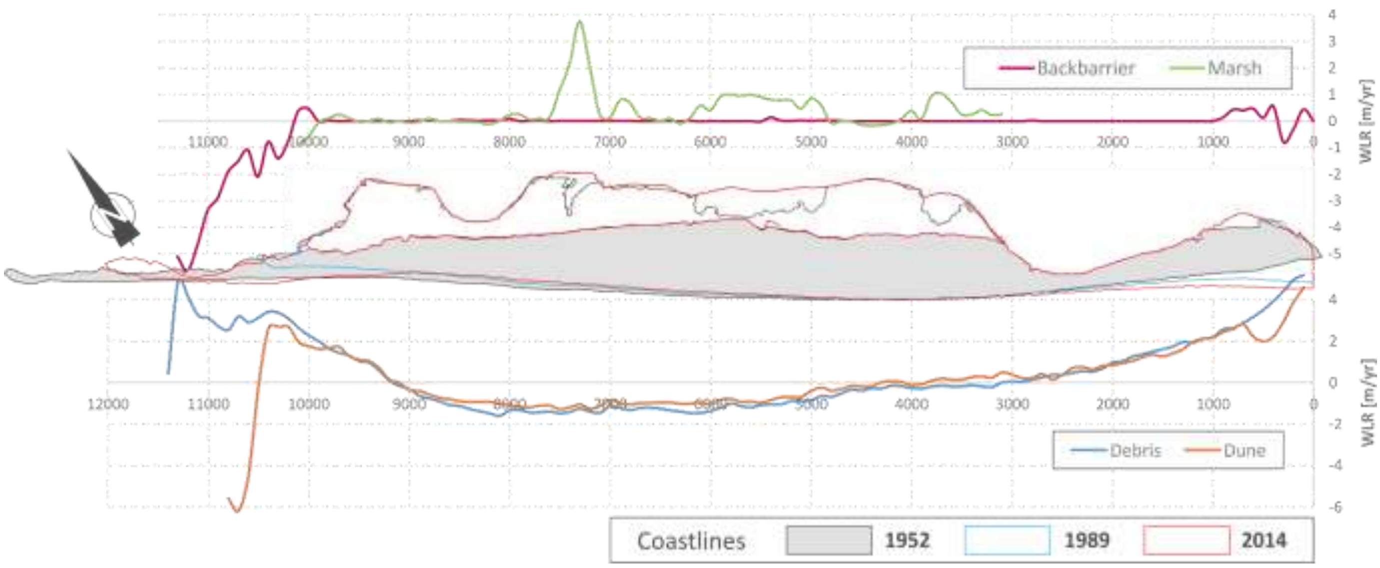

***Figure 18:** WLR rates for Tavira Island; the top graph corresponds to lagoon-side boundary lines and the bottom graph to ocean-side ones. Three different barrier morphologies (1952, 1989 and 2014) are shown.*

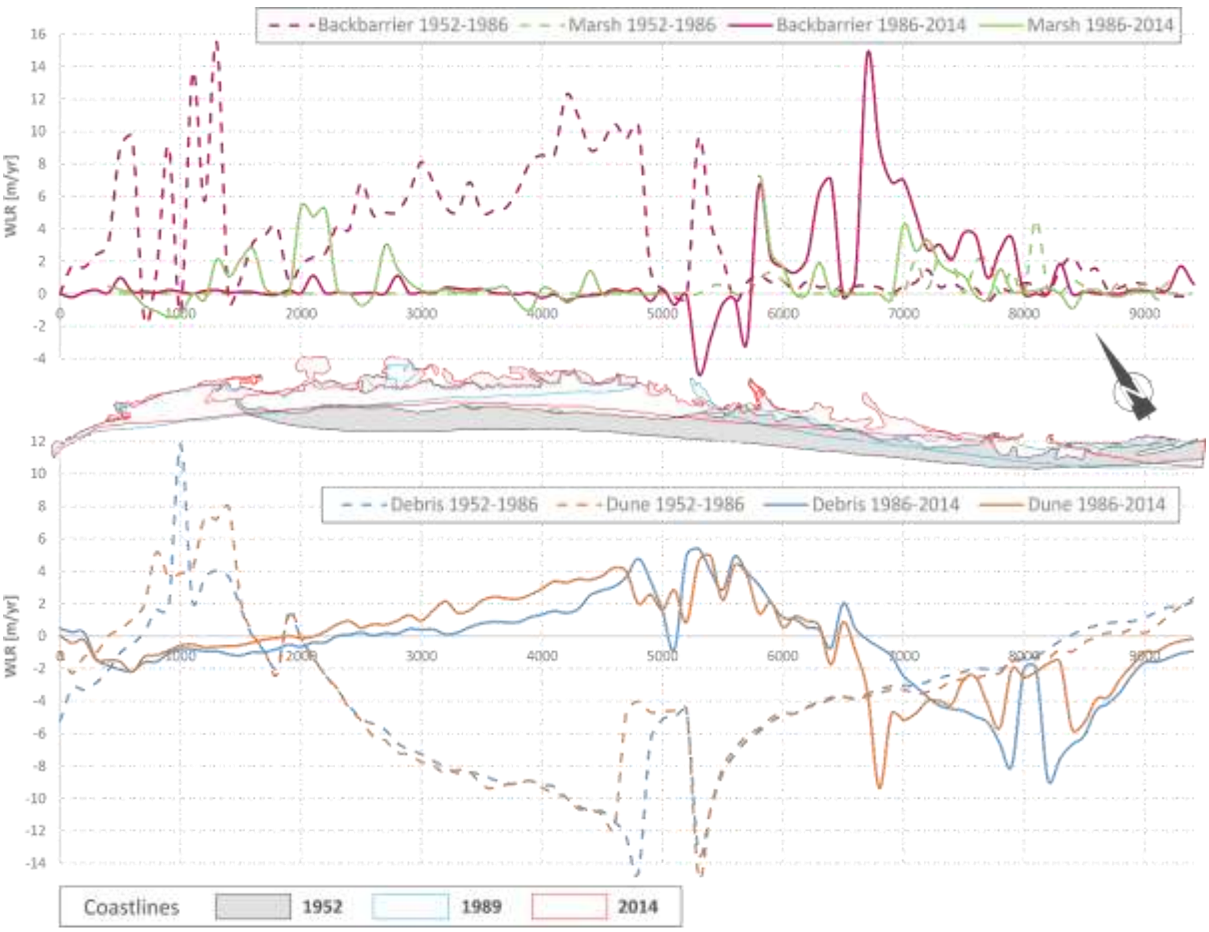

Figure 19: *WLR rates for Cabanas Island and Cacela Peninsula; the top graph corresponds to lagoon-side boundary lines and the bottom graph to ocean-side ones, with dashed lines showing the rates from 1952 to 1986 and solid lines the rates from 1986 to 2014. Three different barrier morphologies (1952, 1989 and 2014) are shown.*

In Ancão Peninsula (Figure 14a), the West-central coast showed mild erosion. Eastwards, accretive tendencies and dune construction prevailed, with highly variable rates in the inlet-affected zone. Negligible rates were recorded along almost the entire backbarrier, with a seaward shift near the inlet. Marshes were stable, with low average growth rates, except for a human-induced erosion (aquaculture unit construction) event at the western edge of the peninsula. Ancão showed the lowest barrier and dune widths of the system. Along the western-central part, barrier widths decrease by 0.53 m/yr and dunes were stable, while eastwards both units showed a tendency for narrowing.

The width of Ancão Inlet (Figure 20) ranged between 80 and 580 m (average = 287±114 m); and a double-inlet configuration existed in 1958 and 2014. Three migration cycles were identified during the study period: 1952-1972, 1976-1996 and 1999-2014. The closer the inlet gets to its limiting, eastward position, the faster the migration rates (in accordance with Vila-Concejo *et al.* (2002)). Towards the end of the study period (2009-2014), which corresponds to the last stage of the third migration cycle, the inlet exhibited peak migration rates.

In Barreta Island (Figure 15), along 6 km westwards from the jetty, the sub-aerial beach was dominated by strong accretion and foredune progradation, with peak values at Santa Maria Cape. The limited erosive tendencies near Faro-Olhão Inlet were probably due to local flow conditions near the updrift jetty. In the zone affected by the Ancão Inlet migration, the coastline was prograding seawards and

dune variability was high. The backbarrier coast was a broad and mature marsh that was either stable or growing. Localised erosion in the East and west edges of the backbarrier was due to channel dredging and Ancão Inlet migration.

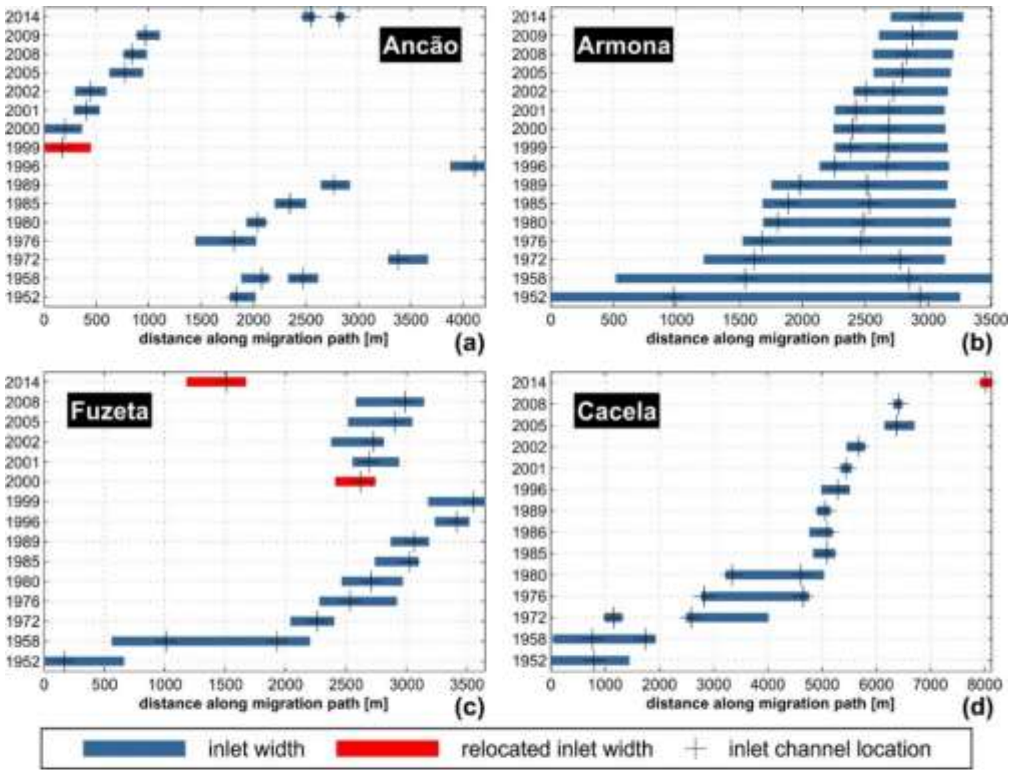

***Figure 20**. Evolution of inlet width and channel location for the non-stabilised inlets of Ria Formosa (a: Ancão, b: Armona, c: Fuzeta and d: Cacela); bar widths express inlet width, red bars denote inlet characteristics following a relocation and crosses denote inlet channel(s) locations.*

In relation to the eastern, wider area of Barreta Island, complementary work was made. Dune units were identified with shorelines when possible (Figure 21) in order to give them a temporal scale. To identify former coastline position, the seaward vegetation limit was chosen as a relatively stable, and thus more reliable proxy. Once the time-series of shorelines was extracted, progradation rates were calculated using the Digital Shoreline Analysis Tool (Thieler *et al.*, 2009) over uniformly spaced (100 m intervals) shore-perpendicular transects. The establishment of a timescale, along with the ridge unit volumes (data from the 2011 LiDAR), enabled the subsequent calculation of average accumulation rates (i.e. m^3 of sediment accumulated per year). Assuming that only the foredune is active and all the older relict ridges have stopped growing, it follows that the amount of deposited sand (above berm height) within the ridge can be divided with the total duration of the ridge formation, to determine the accumulation rates (m^3/a). These rates were, in turn, rescaled, dividing with the total ridge area (m^3/m^2 a), giving rise to aggradation rates (m/a). The impact of meteorological and oceanographic conditions on ridge aggradation were assessed through available data series, partially covering the study period.

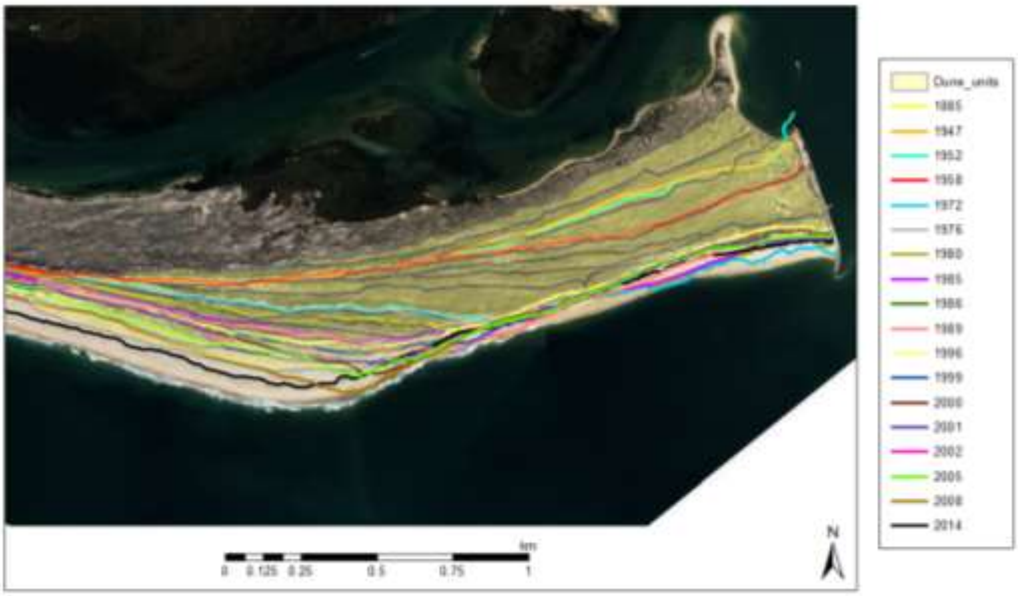

Figure 21. *Dune units on Barreta Island Eastern sector. Former shoreline positions were identified with different colours.*

West Culatra Island showed erosive trends over the ocean shore (Figure 16) that extend up to 3-3.5 km eastwards (downdrift) from Faro-Olhão Inlet. The near-zero coastline rates over the first 600 m downdrift were due to the stabilisation by a rubble mound revetment. For 3.5 km eastwards and onwards from the jetty, accretion and dune building prevailed, with increasing rates towards the Armona Inlet. The elongation of the island between 1952 and 2014 was around 3.2 km (~50 m/yr). In the western, oldest part, the backbarrier was relatively stable. In the recently-formed eastern part, backbarrier rates were more variable, with erosional average values (-0.5m/yr). These cross-shore trends translate to overall narrowing tendencies for both barrier and dune in the western, older part (barrier loss of 100 m from 1952 to 2014) and constant growth in the eastern one. Marshes in Culatra developed within its four enclosed bays and localised marsh-loss was probably related to human activities (i.e. navigation, shellfish gathering, etc.).

The results of the sedimentological analysis of Culatra embayment are given in Figure 22 for sand, mud and gravel and mean sediment diameter. The areas of high mud content (and, therefore, lower mean diameter) correspond to the vegetated areas of the bay. There is high correlation between mud content and organic content in the sediment, while, at the same time, sediment sorting in these areas tends to be poor. Results from the granulometric analysis of Core C1 (as an example) are given in Figure 23, regarding the depth distribution of gravel, sand and mud, the mean diameter (Folk & Ward, 1957) and the organic content of the sediment. The upper 5cm of the core contain sediment with a significant fine fraction (50%) and mean sediment diameter around 20μm, characterised as coarse silt. The sand content increases with depth up to the layer of 9.5cm, with mean sediment diameter values of 65μm to 0.35mm. Below 9.5cm, the sediment becomes more homogenous (sorting varies from moderately to moderately well), comprising medium sand (D50=0.31-0.37mm). The organic content in the core is relatively low and varies little with depth, ranging between 1.5 and 2.5%.

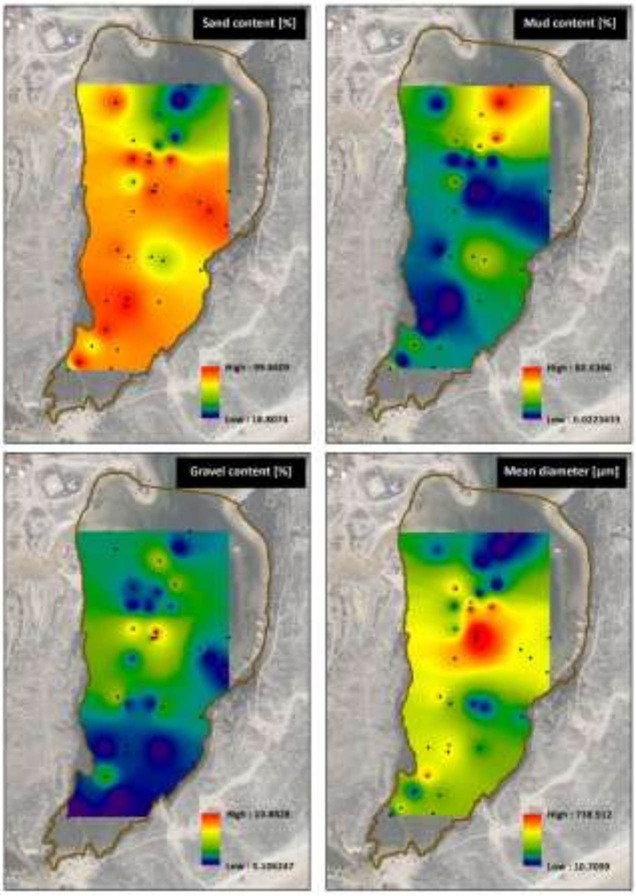

Figure 22: *Distributions of sand, mud and gravel content and mean sediment diameter. The sampling stations' locations (Figure 6) are noted with black dots.*

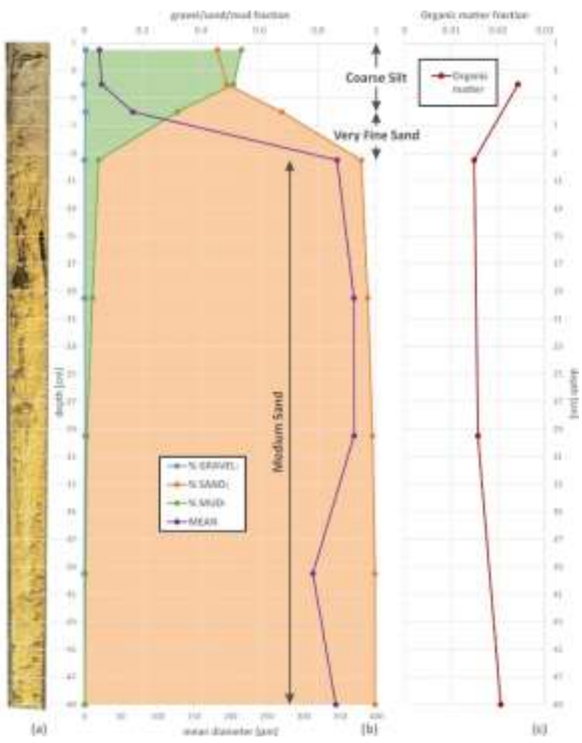

Figure 23: *Distribution with depth of % gravel, sand and mud (with reference to the top x-axis) and mean sediment diameter (with reference to the bottom x-axis) and of organic content from the granulometric analysis of Core C1. A photo of the entire core, in scale with the plots, is also represented.*

In relation to the identification of intertidal and marsh vegetation in this embayment, the dominant species in the muddy areas of the tidal flat and low marsh was *Zostera noltei* with dense meadows in stations 1, 2, 9, 16 and lower population densities in stations 14 and 15 (location of stations can be found in Figure 6). The deeper channels and low-depth plateau in the central part of the bay consisted of sandy matter with no rooted vegetation (stations 4, 5, 6, 7, 8, 20 & 22), while floating vegetation (Ulva) was also present in areas of the plateau (station 6). The upper part of the marsh in the southern part of the bay was muddy (stations 3, 19 & 21) and vegetated with a succession *of Spartina maritima*, *Salicornia ramosissima* and *Limoniastrum monopetalum*. The succession can be seen in Figure 24. The edge of the *Limoniastrum monopetalum* presence in the upper marsh defines a distinct 'barrier' in the domain, which was mapped during the field campaign and is presented as purple line in Figure 6 (section 3.1.2.2). Other species, such as *Sarcocornia perennis*, *Arthrocnemum macrostachyum* and *Limonium ovalifolium*, were also present in the upper marsh, even though at lower densities compared to the three main species, mentioned previously. Dense meadows of *Zostera maritima* were found in stations 22 to 24 and cover the deeper parts of the bay, near the entrance; the specie was also found at the edges of zostera noltei meadows, developing along the sandy channels of the bay).

The width of Armona Inlet (Figure 20) has been reducing exponentially throughout the study period, possibly tending to morphodynamic stability. Up to 2002 two channels existed and after 2005, Culatra Island started growing on top of the West channel, leaving the East one as the sole inlet channel. The evolution of Armona Inlet was essentially a readjustment, with narrowing of the mouth (primarily from its west edge) and eastward migration of the inlet throat by 1.5 km (25 m/yr) during the study period.

Armona Island (Figure 17) evolution was characterised by strong coastline and dune progradation (470 m towards SW) in the western part. Accretive tendencies extended along the ocean side up to the middle of the island, with decreasing rates towards the East, that turn erosive near Fuzeta Inlet. The island had an extensive backbarrier platform that was stable, apart from the vicinity of inlets. The western part showed fast barrier and dune width enlargement (~4.5 m/yr) and became the widest section in the barrier system. The central and eastern parts showed no discernible trend for barrier widths, while dune widths show consistent growth (0.4-0.5 m/yr). The marsh, perched on the backbarrier platform of Armona, grown in the western part and was stable at the centre. Marsh erosion near the eastern edge was artificially induced due to dredging and reformulation of the backbarrier channel between 1999 and 2000 (Dias *et al.*, 2003). Near Fuzeta Inlet, artificial embayments, formed after disposal of dredged material, created favourable conditions for marsh development.

Fuzeta Inlet (Figure 20) showed variable widths and was migrating eastwards with generally low average rates (40±16 m/yr) after 1958. Between 1952 and 1958, the inlet migrated by 180 m/yr, due to inlet breaching, which caused widening and double-channel formation. Overall, two migration cycles were identified: from 1952 to 1999 and from 2000 to 2008. The relocation of 2010 has initiated another migration cycle, not entirely covered by the analysed dataset.

The oceanfront of Tavira Island (Figure 18) was accreting near Tavira Inlet due to sediment accumulation against the jetty and retreating in the central part. In the western part, not directly affected by the Fuzeta Inlet migration, both dune and barrier advanced seawards. The lagoon-side coastline showed remarkable stability throughout the study period.

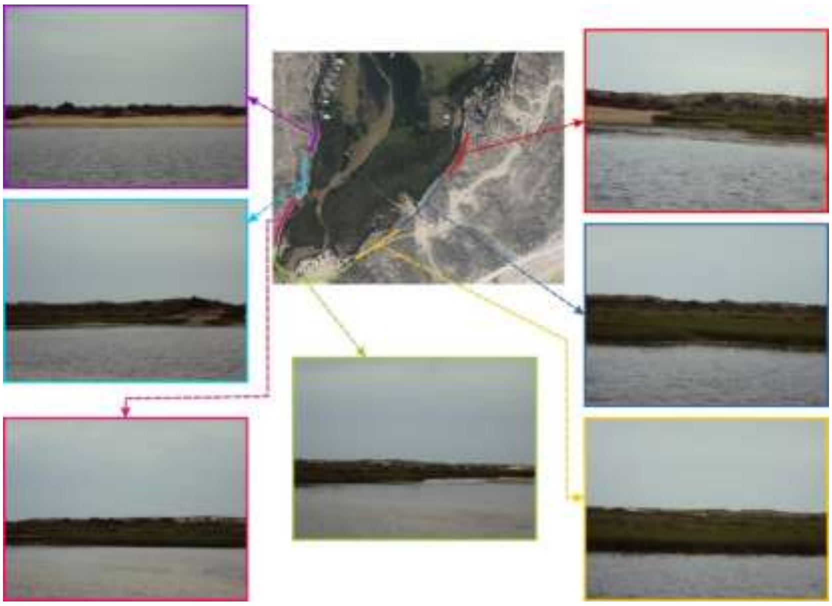

Figure 24: *Series of 'panoramic' photos for the southern part of the bay, where the vegetation species succession in the upper marsh can be noted.*

The results for Cabanas Island and Cacela Peninsula (C-C), are given in Figure 19. Due to a shift in the evolution of the island around 1986 (1952-1986: landward migration; 1986-2014: seaward progradation), the study period was split in two parts (before and after 1986). Between 1952 and 1986 (dashed lines in Figure 19), the C-C subsystem rolled over, with peak erosion trends over the central part and decreasing coastal retreat rates towards the NE. In the SW part, both coastline and backbarrier showed high accumulation rates, attributed to frequent small-scale nourishments with dredged material from the channel. The backbarrier was also migrating landwards in the West-central part. In the rest of the subsystem (Cacela Peninsula), the backbarrier was more stable and it was the only part with growing perched marsh. The retrograding of C-C was fed by frequent overwash (Matias *et al.*, 2008) that moved sediment inland and, combined with the low depths of the backbarrier bay (flood deltas and inlet-related shoals), allowed the barriers to shift landwards. From 1986 to 2014, the oceanfront of C-C (solid lines in Figure 19) accreted in the central part, with limited erosion in the West and stronger coastal retreat and dune erosion in the East. The shoreline advance was combined with backbarrier stability in the western half of C-C (Cabanas Island). The rest of the backbarrier was more variable, with an overall tendency for landward shift, under the influence of the eastward migration of Cacela Inlet. Overall, marshes were growing or were stable. Evolution over this stretch was highly influenced by artificial interventions, though replenishments and Tavira jetties impacts.

Cacela Inlet (Figure 20) had high variability in width (165 to 2000 m) and migration rates (3 to 215 m/yr). Peak migration was noted between 1972 and 1976 (425 m/yr), due to the transition from a double to a single-inlet configuration, as the West inlet got infilled.

3.2.3 Task 2 – Implementation and outcome indicators

Implementation and outcome indicators include datasets, reports and communications. Results from Task 2 are also presented in the methods and results sections of publications referenced in sections 3.3.3, 3.5.3 and 3.6.2 of this report. Task 2 was scheduled for 01/11/2016 until 31/10/2017, however Task 2 was dependent on Task 1, and therefore previously mentioned delays in Task 1 were reflected

in delays in Task 2 (related mostly with the decision to extend the analysis beyond the four study sites). Additionally, the analysis of sea-level encounter more issues than expected (instrumental problems) which was reflected in additional tests and corrections. Task 2 ended in 30/06/2018 (Figure 1).

Datasets:

- Milestone M2, Mean-sea level record for the Algarve coast (Lagos tide gauge). Includes monthly data 1908-1987, 1988-2000, daily data 1988-2000, 2004-2016, and field data (rate 5-10 minutes) 2017. Stored in EVREST database, at Faculdade de Ciências da Universidade de Lisboa, available on request.
- Wave record for Faro buoy & storm analysis for Faro coast. Includes daily datasets of wave characteristics of buoy data and hindcast data and a double list of storms according to incidence on West and East flank of Ria Formosa. Buoy data belongs to IH, all other data are stored in the EVREST database hard-drive, at CIMA, Universidade do Algarve, available on request.
- Milestone M3, Maps of Ria Formosa evolution. Includes the Mean Water Level, Mean High Water Level, and dune lines, the coastline variation rates and the area variations of barrier, dune and marsh, between 1947 and 2014. Stored in the EVREST database hard-drive, at CIMA, Universidade do Algarve, available on request.

Reports and thesis:

Antunes, C., Madeira, F. (2017). Tide observation campaign along the Algarve coast. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 4 pp.

Antunes, C., Madeira, F. (2017). Tide observation campaign along the Algarve coast: Lagos and Barreta Island. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 3 pp.

Antunes, C., Madeira, F. (2019). Analysis of Sea Level Rise. CIMA – Universidade do Algarve. 12 pp.

Madeira, F. (2017). Análise da variabilidade relativa do nível do mar para a região do Algarve. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 16 pp.

Matias, A., Kombiadou, K., Carrasco, A.R., Costas, S., Ramires, M., Robbins, E., Sousa, L. B. (2017). Fieldwork in Culatra Island. CIMA – Universidade do Algarve. 30 pp.

Plomaritis, T., Kombiadou, K., Matias, A. (2019). Analysis of wave climate. CIMA – Universidade do Algarve. 10 pp.

Xabier Herrero Otero (2018). Evaluation of coastal barrier constructive processes on Barreta Island, Southern Portugal. MSc, University of Algarve & Vrije Universiteit Amsterdam.

Communications:

Madeira, F., Antunes C. (2018). Análise da variabilidade relativa do Nível do Mar para a região do Algarve. 5as Jornadas de Engenharia Hidrográfica, June 19, 2018, Lisbon, Portugal.

3.3 Task 3 – Analysis of geomorphological evolution

3.3.1 Task 3 – Objectives and research team

The objectives of this task were to quantify evolution rates, to identify resilient environments, to identify differences on environments resilience, and to compare datasets covering different timeframes. This task was coordinated by Ó. Ferreira and involved A. Matias, A.R. Carrasco, K. Kombiadou, R. Taborda and T. Plomaritis.

3.3.2 Task 3 – Description of activities

3.3.2.1. Impacts of human interventions on barrier evolution

Human interventions in the barriers of Ria Formosa were inventoried and characterised as much as possible based on reports and literature. Local human pressures such as urban development (e.g. Ancão and Culatra) and dredging of backbarrier channels for navigability (e.g. Ancão and Tavira channels) were not considered in the analysis, since the changes are normally small and episodic. Various hard and soft engineering interventions, undertaken since the 1950s, have affected the hydro-sedimentary dynamics of the system. Timing and types of interventions are represented in Figure 25.

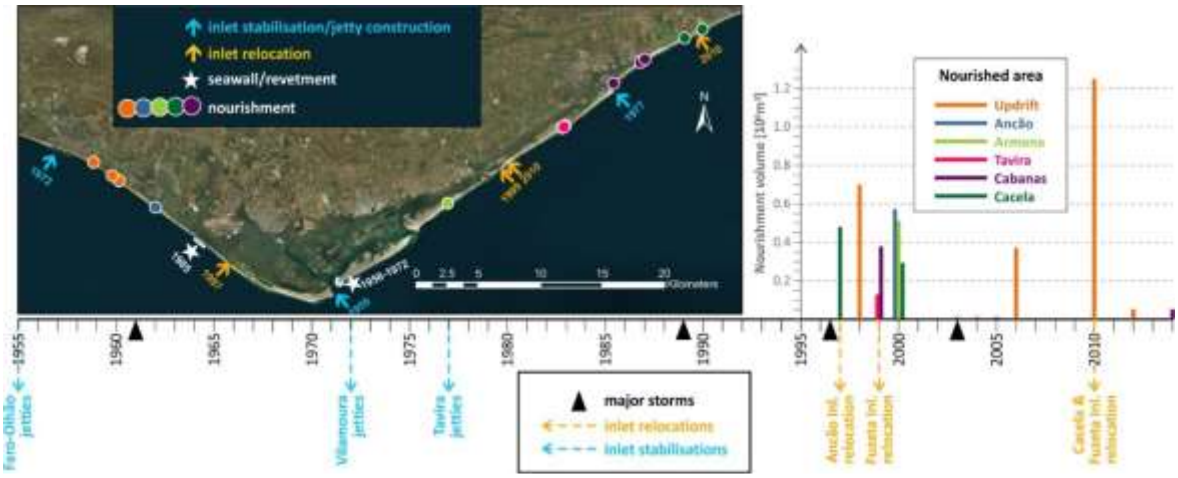

Figure 25*: Timeline of human interventions in the barriers of Ria Formosa and in the updrift coastal zone from the 1950s up to 2014. The lower panel (timeline) shows the inlet-related interventions (stabilisations: cyan; relocations: yellow) and major storm events (black triangles). The upper right panel refers to the nourishments undertaken in the area (after 1997; volumes after Pinto et al. (2018)), while the top-left map shows the location of all interventions.*

To determine the barrier evolution rate prior to inlet stabilisation, the barrier areas mapped using the historical maps of 1873 and 1915 (depending on coverage) were compared either with each other, or with the ones obtained from the oldest flight (i.e. 1873 or 1915 versus 1952). To assess the impacts of the stabilisations of Faro-Olhão Inlet to the downdrift zone and of Tavira Inlet to the updrift zone, Armona Island was split in two parts (W and E), which were added to Culatra and Tavira, respectively. Two historical maps from 1873 and 1915 show conditions prior to the opening and stabilisation of Faro-Olhão and Tavira Inlets (see Table 5). The 1873 map (published in 1885) covers the West part of

Ria Formosa (Ancão, Barreta and Culatra) and the 1915 map covers the entire study area except for Ancão Peninsula.

To assess the impacts of human interventions, barrier area (Figure 26) was calculated over zones unaffected by inlet migration. This was done, either including only the barrier area outside the inlet migration path (Ancão and Barreta) or incorporating inlet-related changes into the adjacent barriers (East flank). Thus, the morphological changes of Armona and Fuzeta Inlets (Figure 20) were assimilated, splitting Armona Island in two parts, W and E (see Figure 2 for location), which were added to each neighbouring barrier (Culatra+ArmonaW and ArmonaE+Tavira in Figure 26d and 26e, respectively). The same was made for Cacela Inlet, since the C-C barriers were analysed as a whole. Pre-intervention barrier evolution was assessed using the two available historical maps (barrier morphologies shown in Figures 27 and 28) and, when necessary the oldest available flight (1952) because barrier was covered only in one map.

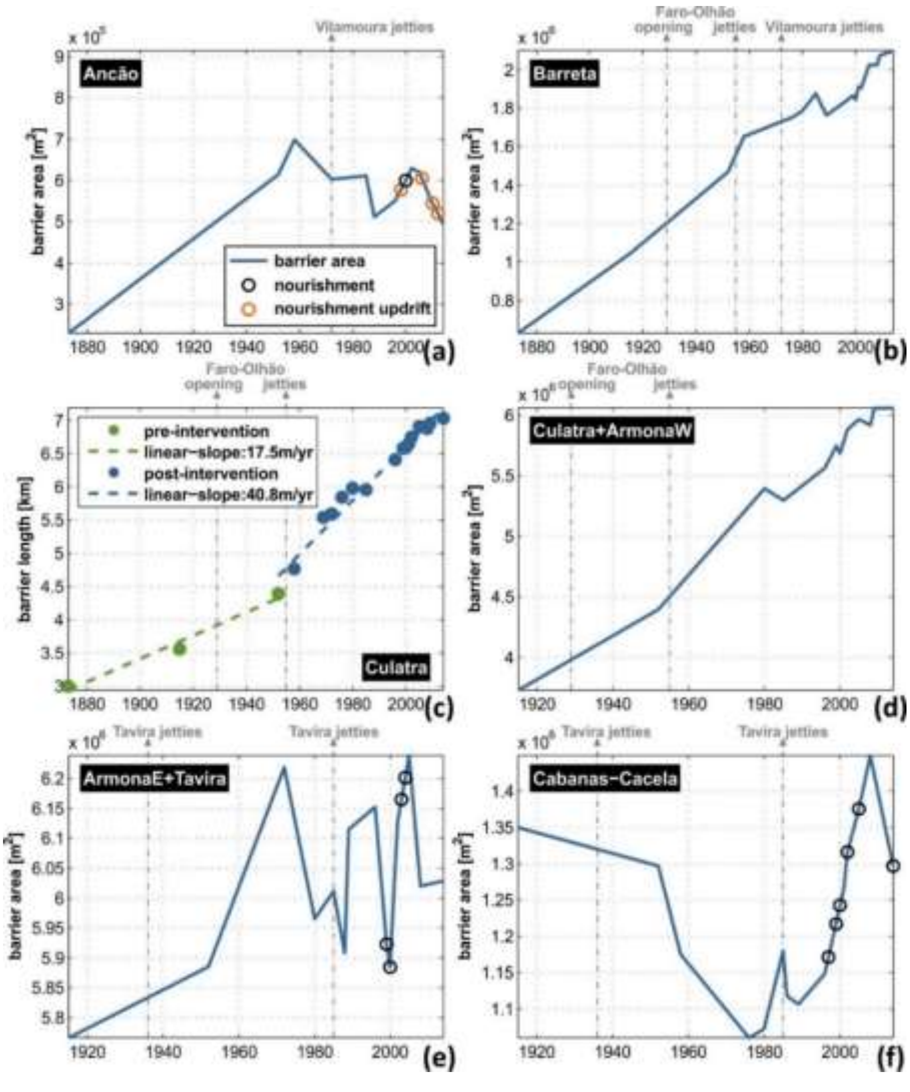

Figure 26: *Barrier area evolution (blue lines) for: Ancão (a), Barreta (b), Culatra+ArmonaW (d), ArmonaE+Tavira (e) and C-C (f) and natural (green dots; prior to Faro-Olhão jetties) versus post-intervention (blue dots) elongation and related linear trends (dashed lines) for Culatra Island (c). Note that the vertical axis scale is different in each plot. Major interventions are noted with grey dash-doe arrows and black and orange (in a) circles denote nourishments in barriers and the updrift zone, respectively.*

For Ancão, growth of $4.6 \cdot 10^3$ m^2/yr was calculated using barrier coverage of 1873 and 1952, while a similar rate of $4.4 \cdot 10^3$ m^2/yr was obtained using the period up to 1972 (Vilamoura jetties' construction). The growth of Barreta Island prior to the Faro-Olhão stabilisation was around 10^4 m^2/yr (1873-1915: $9.8 \cdot 10^3$ m^2/yr; 1915-1952: $1.15 \cdot 10^4$ m^2/yr; 1873-1952: $1.06 \cdot 10^4$ m^2/yr). Regarding the entire West flank, pre-intervention growth was estimated at $8.6 \cdot 10^3$ m^2/yr, from the barrier areas of 1873 and 1952 (Ancão missing in the 1915 map). Culatra Island (present in both maps) grew $1.6 \cdot 10^4$ m^2/yr between 1873 and 1952. For the rest of the East flank, only one historical map was available (1915), hence it was necessary to use the 1915-1952 period to assess pre-intervention evolution.

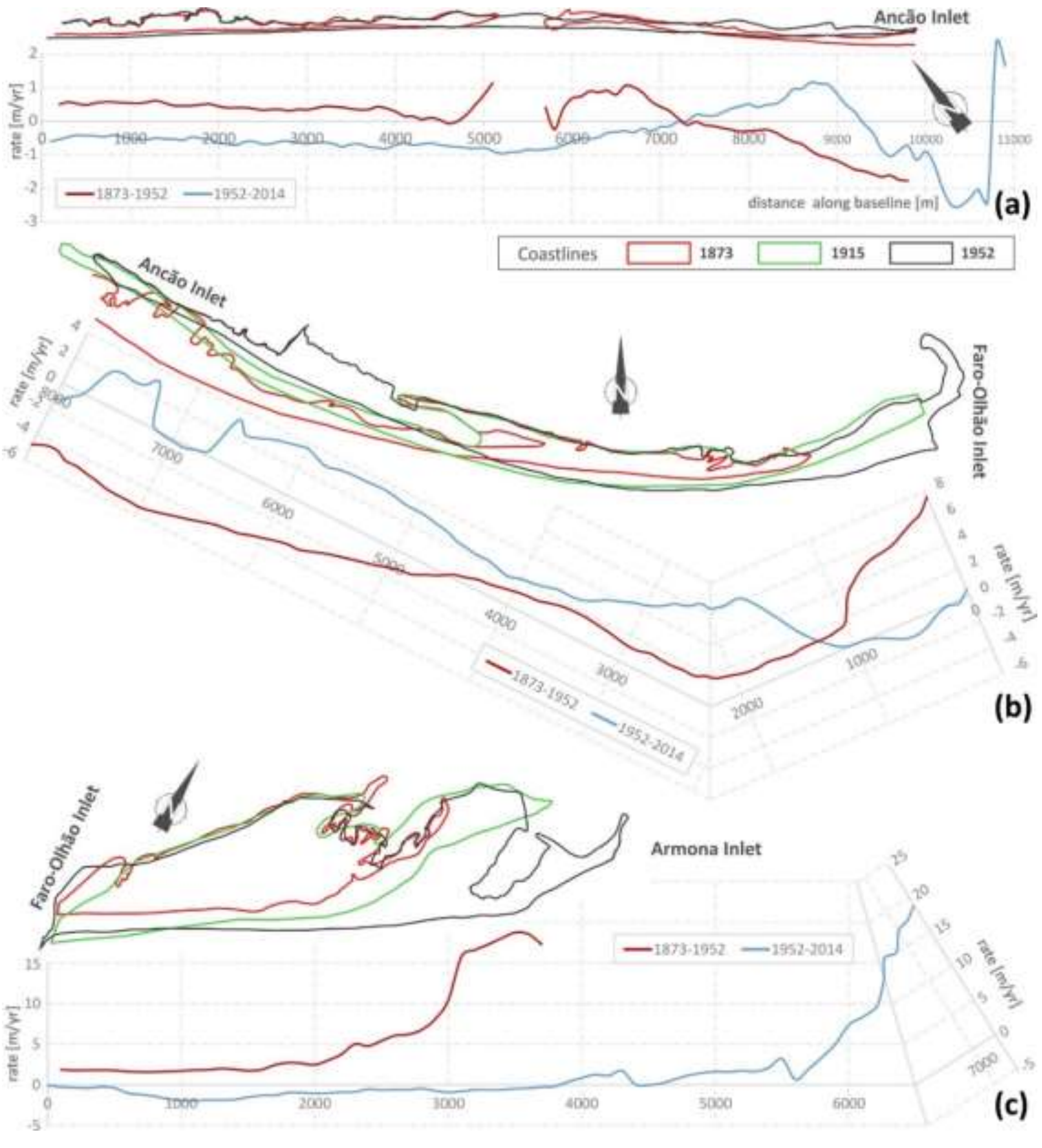

Figure 27: *Barrier morphologies, obtained from the maps of 1873 and 1915 (depending on coverage), and cross-shore rates before (red line) and after 1952 (blue line), for Ancão (a), Barreta (b) and Culatra (c).*

For Culatra and West Armona, the main human intervention was the Faro-Olhão stabilisation, completed in 1955 and, therefore, the estimated growth of $1.8 \cdot 10^4$ m^2/yr can be considered a valid

approximation for the pre-intervention period. For Tavira Inlet, stabilised in 1936, the oldest available raster (1952) is posterior to the jetty construction. However, in lack of other data sources, the 1915-1952 period was used to assess pre-intervention rates. Thus, the near-natural evolution rate of East Armona and Tavira was estimated at $3.2{\cdot}10^3$ m^2/yr and of C-C at $1.4{\cdot}10^3$ m^2/yr (the only part of the system with net erosion rate).

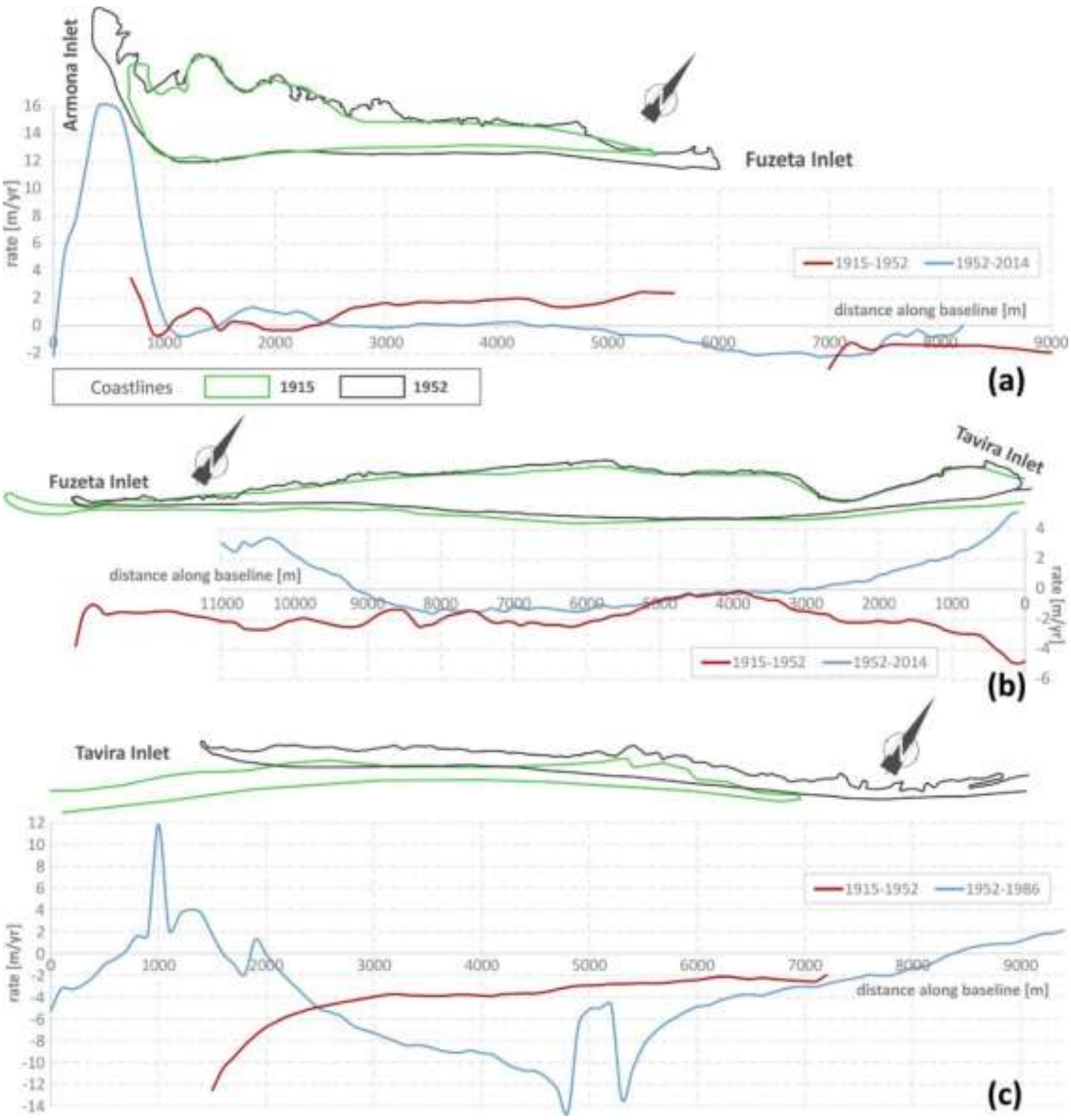

Figure 28: *Barrier morphologies, obtained from the map of 1915, and cross-shore rates before (red line) and after 1952 (blue line), for Armona (a), Tavira (b) and Cabanas-Cacela (c)*

The effect of the Vilamoura jetties' construction in 1972 on Ancão Peninsula evolution is evident (Figure 26a), with the artificially induced coastal retreat throughout the remaining study period and over a span of 7 km from the base of the peninsula (Figure 14). Minimum barrier widths, identified in 1989-1996 and 2014, are, most likely, related to storms (late 1990's to early 2000's; Figure 11a). Other works (e.g., Ceia *et al.*, 2010; Ferreira *et al.*, 2006) have documented the initiation of an erosion cycle for the peninsula after the marina construction.

The stabilisation of Faro-Olhão promoted barrier growth of Barreta (Figure 27b), at rates that generally exceed the pre-intervention period (Figure 26b). Barrier growth slows down only in the 1990s (1985-2000; Figure 26b), probably due to storm impacts (Figure 11a). This is in accordance with the reported severe storm incidence in the West flank around 1989 (Ceia *et al.*, 2010), with similar impacts noted in Ancão. Given that the entire length of the Faro-Olhão Inlet western jetty had already been infilled with sand since the early 1970s, it follows that sediment accumulation in the supratidal barrier reached a form of 'saturation'. Examining the area directly updrift from the jetty, two distinct phases were identified, one of fast growth ($1.2 \cdot 10^4$ m^2/yr) up to 1985 and another of significantly slower progradation ($3.5 \cdot 10^3$ m2/yr) thereafter. The changes in the morphology of Barreta Island since 1985 have been largely limited to a westward shift of the Santa Maria Cape (Figure 15); this agrees with Pacheco *et al.* (2008), who stated that recent sediment accumulation in the area occurs as submerged sand banks in front of the island.

Regarding the entire West flank (Ancão and Barreta), barrier growth seems to slow down, especially after 2005 ($-1.3 \cdot 10^4$ m^2/yr for 2005-2014), with the 2014 values dropping to the levels of 1972. This indicates that sediment starvation in Ancão (Figure 26a) and reduced sediment accumulation in Barreta (Figure 26b), have lowered barrier growth in the flank to the levels prior to the Faro-Olhão jetty construction. Thus, the negative impacts of the Vilamoura jetty appear to have counterbalanced the artificially boosted growth by the inlet stabilisation. Considering that the nourishments (performed mainly in the updrift area; Figure 25) coincide with barrier growth, it follows that erosion would likely have been even higher, without the artificial supply of sediment.

The impacts of Faro-Olhão to the East flank, in particular to Culatra and Armona W (Figure 26c), involve an overall increase in barrier area, in relation to the projected evolution prior to the stabilization. The total barrier area of Culatra and Armona W increased by 38% between 1952 and 2014, with a linear trend of $2.6 \cdot 10^4$ m2/yr (R^2=0.97, p<0.001). This artificially enhanced growth was extending around 11 km downdrift from the Faro-Olhão Inlet. Small-scale losses, such as the ones between 1980-85, 1999-2000 and 2005-2008, were attributed to storm impacts (storms of 1983, 2000 and 2007; Figure 11). At the same time, the evolution of Culatra Island's length (Figure 26d) had two distinct phases in growth, before and after 1952, with elongation rates of 17.5 m/yr (R^2=0.98) and 40.8 m/yr (R^2=0.97, p<0.001), respectively. Hence, the stabilisation of Faro-Olhão caused an artificial acceleration of barrier longshore growth of 2.3 times, which corresponds to 30% of the total island length in 2014. The artificial increase in elongation (Pilkey *et al.*, 1989; Garcia *et al.*, 2002;) was due to the loss of tidal prism in the downdrift Armona Inlet after the stabilisation of Faro-Olhão (Pacheco *et al.*, 2008, 2010). This caused the remobilisation of ebb shoals, deposited under previous hydraulic conditions, and their attachment to East Culatra and West Armona (Pacheco *et al.*, 2011). The deceleration of Armona Inlet narrowing (Figure 20b) supports the theory that the inlet is reaching morphodynamic stability, concurrently to the attained hydrodynamic stability of the interconnected Faro-Olhão Inlet (Pacheco *et al.*, 2008, 2010). It also explains the lower elongation rate of Culatra, compared to earlier studies with shorter temporal coverage (e.g. 47 m/yr for 1952-2001; Garcia *et al.* (2002)).

Regarding the stabilisation of Tavira, the barrier area evolution in the updrift zone (Figure 26e) showed high variability and no significant trend. The small increase in sediment accumulation between 1985 and 1997 could be linked to the extension of the Tavira jetties, while the changes after 1997 were likely related to storm impacts (Figure 11b). The contribution of beach nourishments (1999, 2003 and 2004) was probably low, given the low volumes and localised nature of the interventions. The high variability and small difference between pre- and post-intervention evolution showed that there was no clear response to the inlet stabilisation. Furthermore, average cross-shore rates at the ocean-side over the non-inlet affected barrier (Figure 18) are small (0.07 m/yr), showing that accretion and

erosion balance out. Therefore, the overall medium-term impact of the intervention to barrier growth was minor, limited to a reshaping of the barrier (erosion at West-centre and accretion at East).

A clearer impact was identified for the barriers downdrift from Tavira jetties (Figure 26f), extending over the entire stretch of C-C. Erosive trends ($-1.4 \cdot 10^3$ m^2/yr), initiated after the opening of Tavira Inlet, were intensified by the presence of the jetties, reaching -10^4 m^2/yr between 1952 and 1976. Afterwards, the barriers recovered slowly, until the jetty extension of 1985. Between 1989 and 2008 a remarkable recovery period was noted, with southward progradation and linear growth of $1.9 \cdot 10^4$ m^2/yr (R^2=0.94, $p<0.01$), that translated into a barrier increase of 31% (1989-2008). Between 2008 and 2014, barrier area reduced by 10%, to the levels of 1952, most likely due to the combined impacts of storms (i.e. 2013 storms, Figure 11) and the artificial opening of a new inlet in 2010 (Figure 25). Even though the first recorded nourishment in C-C (1997) was done several years after the early signs of barrier recovery, meaning that the process was initiated naturally, the artificial supply of sediment must have enhanced barrier growth. The lag between implementation and barrier response is due to the nourishment type (dune and beach) and the high post-storm volume retention of nourished profiles (Matias *et al.*, 2005; Sá-Pires *et al.*, 2002).

The evolution of total barrier area in the East flank had a linear growth of $3.2 \cdot 10^4$ m^2/yr (R^2=0.94, $p<0.01$) during the study period.

3.3.2.2. Evolution regimes at Ria Formosa

Barrier area in the Ria Formosa system grew by $2.5 \cdot 10^6$ m^2 (17%) during the study period, with a linear trend of $4.3 \cdot 10^5$ m^2/yr (R^2=0.95, $p<0.01$) up to 2005 and negligible rates thereafter, which could indicate that the system is reaching morphodynamic stability. Therefore, the barrier system was effective in trapping and incorporating sediment, with the principal mechanisms of barrier growth related to attachment of shoals and Longshore Sediment Transport (LST). Shoal attachment has been shown to be the main mechanism responsible for morphological change in Culatra and West Armona islands, through the remobilization and landward transport of ebb delta sediments by waves and flood tidal currents, after the ebb tidal current loss in Armona Inlet (Pacheco *et al.*, 2011). The dominance of LST in the remaining barriers is substantiated by the prevailing eastward inlet migration. Potential secondary contributions, such as interannual variability in cross-shore sediment exchange, cannot be separated from the primary ones in the analysis performed. It is noted that the landward migration of C-C (up to 1986) was also assisted by the presence of flood delta and/or inlet related deposits that allowed the growth of Cabanas Island. Assuming that the growth of Culatra and Armona W was exclusively due to shoal attachment and that the rest of the barriers grew only due to LST (lines in Figure 29), it follows that shoal incorporation was the main mechanism promoting growth in Ria Formosa (70% ±5.8%). Shoal attachment took place almost equally between Culatra and Armona W (60% and 40% ±2.3%, respectively). The incorporation of these shoals promoted a wide morphology in Armona W, very different to the elongated spit formations in East Culatra. Barreta dominates the growth due to LST in system, while the relative contribution of Ancão decreases with time. LST incorporation in Ancão relative to 1952 is steadily negative after 2001, which, combined with the erosion in West Ancão (Figure 14), indicated that the Vilamoura jetties have significantly limited barrier growth. Growth in C-C regained pre-intervention values after 2002, with full barrier recovery circa 40 years after the first signs of coastal retreat.

The major shoreline evolution trends of Ria Formosa between 1952 and 2014 are summarised in Figure 29. Table 6 includes a synopsis of the main evolution regimes and the related controlling factors promoting or inhibiting growth or stability (artificial or natural). Soft interventions, such as beach and dune nourishments generally promote growth, while inlet relocations inhibit natural inlet breaching/closure and start a new migration cycle.

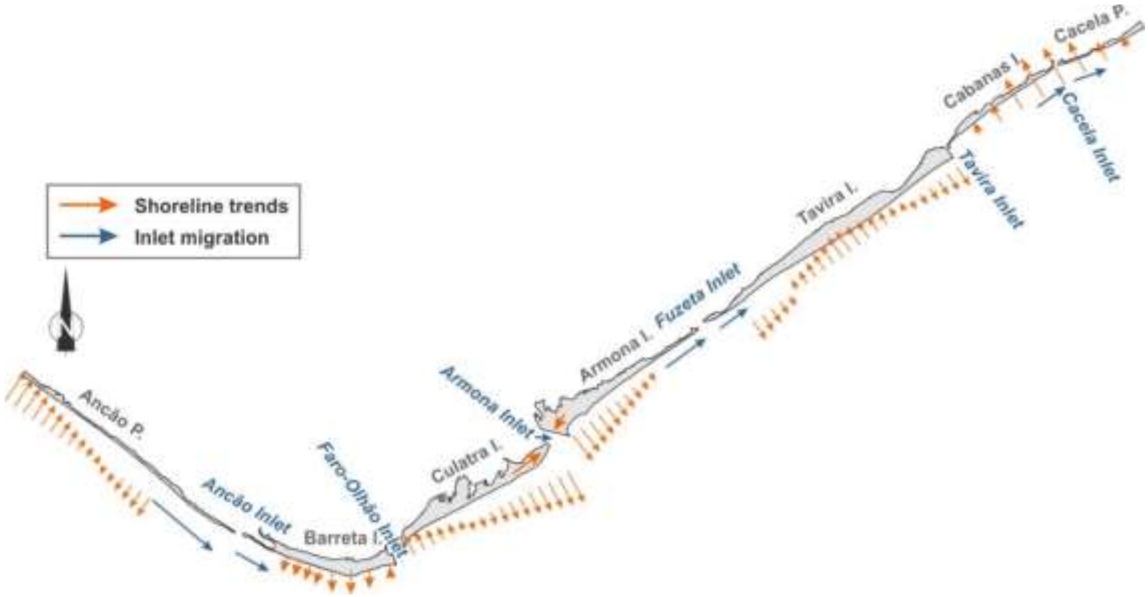

Figure 29*: Schematic representation of the multi-decadal morphological response of the Ria Formosa barriers for 1952-2014. The major trends are noted as arrows (orange for shoreline and blue for Inlets) on the 2014 map. The shoreline trend of C-C reflects the 'net' barrier movement for the entire study period.*

Based on this analysis, the following evolution regimes are identified: a) artificially enhanced growth (Barreta, Culatra and Armona W), b) stability, promoted by natural (Armona E) and natural +artificial factors (Tavira), c) artificially triggered decay (Ancão) that can lead to inland migration (C-C for 1952-1986) and d) natural growth (C-C for 1986-2014).

Table 6. Morphological barrier evolution regimes regarding overall trends (LSG: Long-Shore Growth; CSG: Cross-Shore Growth; CSN: Cross-Shore Narrowing), backbarrier and marsh and related main artificial (V.: Vilamoura; F-O: Faro-Olhão; NR: Nourishment; IR: Inlet Relocations) and natural drivers of change (LST: Longshore Sediment Transport; SBL: Shallow Backbarrier Lagoon). Factors inhibiting and promoting barrier growth and/or stability are denoted with [-] and [+], respectively.

Barrier	**Evolution Regime**			**Factors Inhibiting [-] & Promoting [+] Barrier Growth/Stability**	
	Trend	**Backbarrier**	**Marsh**	**Artificial**	**Natural**
Ancão	LSG, CSN	stable	stable, mature	V. jetties [-], NR [+], IR [-]	LST [+]
Barreta	CSG	stable	stable, mature	F-O jetties [+], IR [+]	LST [+]
Culatra	LSG	stable	stable, immature	F-O jetties [+]	LST [+], shoals [+]
Armona W	LSG	stable	stable, mature	F-O jetties [+]	LST [+], shoals [+]

	E	stability	stable	growing, mature	IR [-]	LST [+], broad backbarrier [+]
	Tavira	stability	stable	stable, mature	Tavira jetties [+], IR [+]	broad backbarrier [+]
C-C	**1952-1986**	CSN	retrograding	stable, mature	Tavira jetties [-]	SBL [+], overwash [+], inlet breaching [-]
	1986-2014	CSG	stable	growing, immature	Tavira jetties [-], NR [+], IR [-] [+]*	LST [+]

**IR for C-C are mentioned as both inhibiting and promoting factor, given that the two barriers are examined jointly. The inhibiting impacts refer to Cacela and the promoting ones to Cabanas.*

3.3.3 Task 3 – Implementation and outcome indicators

Implementation and outcome indicators include reports, theses, communications and publications. Results from Task 3 are also presented in the results and discussion sections of communications and publications referenced below and in section 3.5.3. URL of publications and communications can be found in section 3.6.2 of this report. Task 3 was scheduled for 01/05/2017 until 31/12/2017, however Task 3 is dependent on task 2.2, and therefore delays in previous tasks were reflected in delays in Task 3 (related mostly with the decision to extend the analysis beyond the four study sites). Task 3 ended in 31/07/2018 (Figure 1).

Reports and thesis:

Kombiadou, K., Matias, A. (2018). Synthetic report on geomorphological evolution of the study sites. CIMA – Universidade do Algarve. 38 pp.

Emily Robbins (2017). *Evolution and resilience of barrier islands systems*. Internship for the MSc in Expertise and management of the coastal environment. University of Algarve & European Institute for Marine Studies (IUEM) in Brest, France.

Dimitra Alkisti Pliatsika (2018). *Exploring aeolian sediment transport potentials and aeolian activity at Ria Formosa*. MSc Marine and Coastal Systems, University of Algarve.

Marine Fouin (2018). *Long term evolution of the salt marsh area within the Ria Formosa lagoon*. Internship for the MSc in Environmental management and rural development. University of Algarve & Université de Lorraine Ecole Nationale Superieure d'Agronomie et des Industries Alimentaires in Nancy, France.

Xabier Herrero Otero (2018). Evaluation of coastal barrier constructive processes on Barreta Island, Southern Portugal. MSc, University of Algarve & Vrije Universiteit Amsterdam.

Gustavo Carvalho Braga Vieira (ongoing). Storm impact and recovery of sand barriers after extreme events. MSc Marine and Coastal Systems, University of Algarve.

Pedro Miguel de Sousa Vinagre Amado (ongoing). Salt marsh response to changing hydrodynamics: the case of Ancão Inlet migration (Ria Formosa coastal lagoon). MSc Marine and Coastal Systems, University of Algarve.

Communications:

Carrasco, A.R., Kombiadou, K., Matias, A. (2018). The influence of sediment availability to coastal ecosystem services provision. ESP2018, 15-19 October 2018, S. Sebastian, Spain. Format: Poster presentation.

Carrasco, A.R., Kombiadou, K., Matias, A., Costas, S., Ferreira, Ó. (2018). Ecosystem processes and services provision in salt marshes facing varying sediment availability. IX Symposium on the Iberian Atlantic Margin, 4-7 September 2018, Coimbra, Portugal. Format: Poster presentation.

Carrasco, A.R. & Matias, A. (2019). "Backbarrier shores along the Ria Formosa lagoon". In: Aníbal, J., Gomes, A., Mendes, I., Moura, D. (eds.), *Ria Formosa: challenges of a coastal lagoon in a changing environment*. 1st edition. University of Algarve, Faro, ISBN 978-989-8859-72-3, pp. 17-28.

Kombiadou, K., Matias, A., Costas, S., Carrasco, A.R., Ferreira, Ó., Plomaritis, T. (2019). Assessment of Natural and Anthropic Drivers to the Evolution of Ria Formosa Barrier Island System. 9th International Conference on Coastal Sediments 2019, 27 – 31 May 2019, Tampa/St. Petersburg, Florida, USA, pp. 57-70. Format: Oral presentation.

Matias, A., Carrasco, A.R., Loureiro, C., Andriolo, U., Masselink, G., Guerreiro, M., Pacheco, A., McCall, R., Ferreira, Ó., Plomaritis, T. (2017). Parameters influencing overwash hydrodynamics. 4ª Conferência sobre Morfodinâmica Estuarina e Costeira, 18-19 May 2017, Oporto, Portugal. Format: Oral presentation.

Publications:

Carrasco, A.R. (2019). Simple assessment of spatio-temporal of salt marshes ecological services. Frontiers in Ecology and Evolution: 7, 77.

Ferreira, Ó., Plomaritis, T.A., Costas, S. (2019). "Effectiveness assessment of risk reduction measures at coastal areas using a decision support system: Findings from Emma storm". Science of the Total Environment: 657, 124-135.

Herrero, X., Costas, S., Kombiadou, K. (2019, in press). Coastal ridge constructive processes at a multi-decadal scale in Barreta Island (Southern Portugal). Earth Surface Processes and Landforms.

Kombiadou, K., Matias, A., Ferreira, Ó., Carrasco, A.R., Costas, S., Plomaritis, T. (2019). Impact of human interventions on the evolution of the Ria Formosa barrier island system (S. Portugal). Geomorphology: 343, 129-144.

Lazarus, E.D., Davenport, K.L., Matias, A. (2019). Dynamic allometry in coastal overwash morphology. Earth Surface Dynamics.

3.4 TASK 4 – MODELLING BARRIER ISLAND AND LAGOON SYSTEM

3.4.1 Task 4 – Objectives and research team

The objective of this task was to assess the morphological evolution of the barrier islands and lagoon system according to different SLR and storm impact scenarios. This task was coordinated by A.R. Carrasco, and involved A. Matias, K. Kombiadou, R. Taborda, T. Plomaritis and consultant D. Roelvink.

3.4.2 Task 4 – Description of activities

3.4.2.1. Modelling morphological impact of sea-level rise in the Ria Formosa lagoon

The impacts of sea-level rise (SLR) over the Ria Formosa lagoon in 2100, from the 2011 baseline year, were accessed for the tidal channels and inlets identified in Figure 30. The study area includes the Faro-Olhão and Armona inlets and the main tidal channels running from them, Culatra, Olhão, and Armona channel (Figure 30). Olhão channel starts at the Faro-Olhão inlet and runs up to the port of Olhão. Culatra channel flows north of Culatra island, in between the bifurcation from Olhão channel and Armona inlet. Armona channel runs between Armona inlet and Olhão port.

Figure 30: *Study area in the Ria Formosa lagoon including Olhão (red), Culatra (orange), Armona (yellow) channels and Faro-Olhão and Armona inlets. Photographs taken from Google Earth (images obtained on 19/11/2017) (Hoven, 2019).*

A modelling approach previously used by Gonzalez-Gorbeña *et al.* (2018) and Carrasco *et al.* (2018), using Delft3D-FLOW was applied. The hydrodynamics module was coupled to morphodynamics for a

2D depth averaged simulation (Lesser *et al.*, 2004). Building on a calibrated and validated baseline model from Gonzalez-Gorbeña *et al.* (2018), a few adjustments were made to optimize settings for the present research focus. Several observation points and cross-sections were distributed in the study area to monitor morphological impacts of sea-level rise (Figure 31).

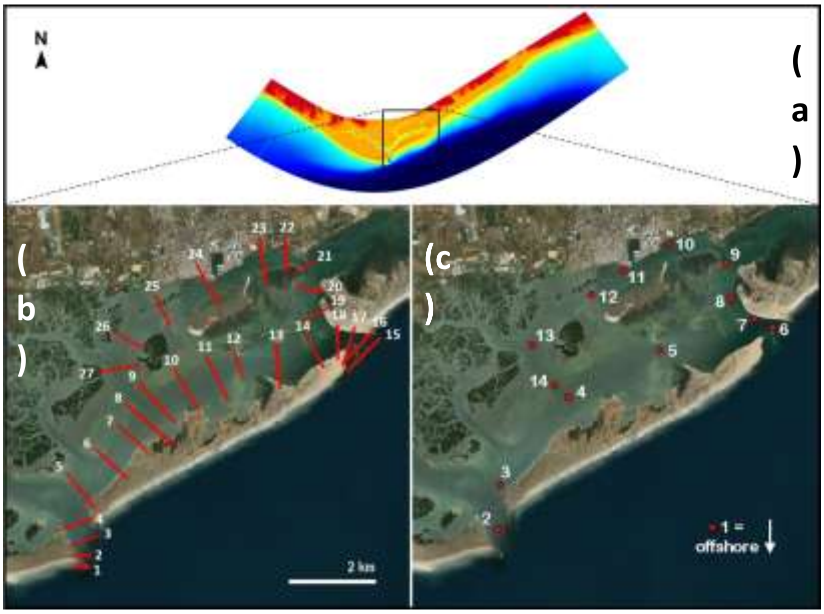

Figure 31*: (a) Model domain, (b) zoom to study area showing the cross sections used to monitor the bathymetric changes, and (c) zoom to the study area showing the observation points used to monitor the hydrodynamic changes induced by sea-level rise (adapted from Hoven, 2019).*

The model bathymetry was based on LIDAR data obtained in 2011 and bathymetric surveys from 2016 (González-Gorbeña *et al.*, 2018). A curvilinear orthogonal grid followed the cuspate shape of the Ria Formosa lagoon. The 492 N x 1100 M grid had a varying resolution to capture the complex morphology. Resolution differed from 750 x 175 m offshore to 20 x 15 m in the inlets and was continuously refined. Waves were neglected in the model set-up. The model was forced with an offshore water level boundary and with water level gradients at the cross-shore Neumann boundaries. Astronomical forcing consisted of a combination of the M2 component, an M2 amplitude correction factor, and a morphological tide correction (details in Gonzalez-Gorbeña *et al.*, 2018). The main local tidal constituents were derived from the TPXO global tidal model (Egbert & Erofeeva, 2002). The amplitude of the main tidal constituent, the M2, was corrected to the Ria Formosa area. The morphological tide was applied to represent a full year astronomical tide in combination with the use of a morphological acceleration factor (morfac, see Lesser *et al.*, 2004), by producing similar residual transport and morphological evolution (Lesser, 2009). A spin-up time of 1 day and a time-step of 30 seconds were adopted. Manning coefficient values were assigned for bottom friction. Besides the original morfac value of 48, an additional morfac value of 100 was tested to evaluate the effect of a stronger morphological acceleration on the morphological evolution of the tidal channels. The conducted simulations enclosed a simulation time frame of 92.25 days (details in Hoven, 2019).

Sea-level rise estimates used in the modelling scenarios accounted for the latest global IPCC projections (in agreement with Carrasco *et al.*, 2018). The worst-case scenario RCP8.5, predicting an increase of 0.98 m SLR by 2100 (highest value of the likely range), was tested in this study (IPCC, 2014;

2019). Sea-level rise was incorporated in the model as a linear increase of water level over time (e.g., Best *et al.*, 2018)

The morphological evolution of the lagoon was predicted for 2011 to 2100 period. Two modelling conditions were simulated: (1) without SLR; and (2) with SLR. The following time steps were used for analysis: year 2011 (model baseline), 2036, 2061, 2086, and 2100 (end of simulation after 89 years).

Small accretion and erosion patterns were observed in the study area between 2011 and 2100, for both modelling conditions, without and with SLR. Being most apparent in the tidal inlet regions, in the channels near the inlets, and in the region West of Faro-Olhão inlet (in between Faro-Olhão inlet and Ancão inlet, Figure 31); within these regions, bathymetric differences of about 1 m between the two modelling conditions were observed (Figure 32). Saltmarsh areas and the secondary tidal channels revealed low magnitude bathymetric changes (Figure 32).

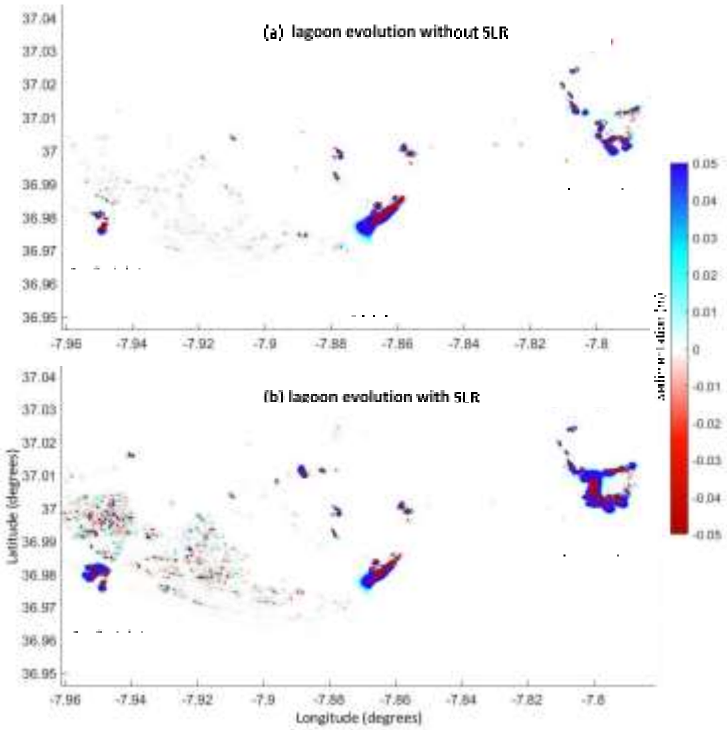

Figure 32: *Bathymetric differences between the baseline bathymetry from 2011 and the bathymetry at the end of the simulations, year 2100, for the two modelling conditions: (a) without sea-level rise (SLR), and (b) with SLR (FO inlet refers to Faro-Olhão inlet; red colour refers to bottom erosion, blue colour refers to bottom accretion) (adapted from Hoven, 2019).*

The bathymetry of Culatra channel and the upstream part of Olhão channel seemed unchangeable during the 89 years of simulation, regardless of the application of SLR. The Olhão and Armona channels showed channel axis displacement towards the mainland in 2100. However, moving further away from the inlets, bathymetry of secondary tidal channels remained almost unchanged between 2011 and 2100 (Figure 33).

The low magnitude changes observed between 2011 and 2100 might be related to the low sediment transport concentrations verified during simulations, which could in turn be caused by the absence of additional sediment input sources in the model setup. Also, cohesive sediment was not modelled, and

no mud transfer or transport within the system was considered. With limited sedimentary input, the only sediment exchange occurred by local erosion and accretion of the initial bathymetry. This can explain why bathymetric changes were focussed in the tidal inlet's vicinity, where velocity currents are usually high enough to enable sediment mobilization. Nevertheless, additional tests, are needed to be run.

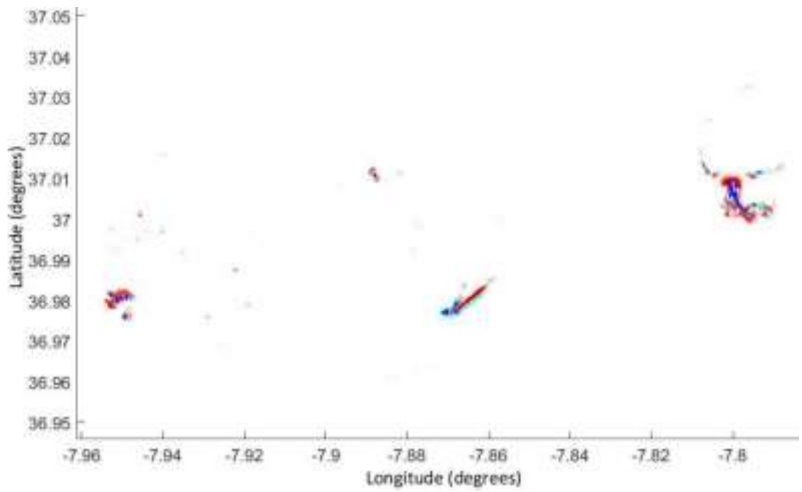

Figure 33: *Bathymetric differences between the two modelling conditions, without sea-level rise (SLR) and with SLR, in 2100 (FO inlet refers to Faro-Olhão inlet; red colour refers to bottom erosion, blue colour refers to bottom accretion) (adapted from Hoven, 2019).*

3.4.2.2. Modelling storm impact in barrier islands

Data collected during fieldwork were analysed and results were used to develop a reliable model for overwash prediction in a barrier island and to evaluate the role of several factors that locally influence overwash hydrodynamics on a low-lying barrier island.

Fieldwork was performed on the western part of Barreta Island (Portugal) in December 2013, during neap tides and under energetic conditions, with significant wave height reaching 2.6 m. During approximately 4 hours, more than 120 shallow overwash events were measured with a video - camera, a pressure transducer and a current-meter. This high-frequency fieldwork dataset includes runup, overwash number, depth and velocity. Details of this fieldwork can be found in Matias *et al.* (2017, 2019), referenced in section 3.5.2. of this report.

Fieldwork data along with information from literature were used as input parameters (Table 7) to implement XBeach model in non-hydrostatic mode (wave-resolving).

The baseline model performance was assessed, and results indicated that the model overestimates the number of overwash events by approximately 25 %. Overwash depth and velocity are also overestimated by about 20%; however, these values are very small (0.02 m and 0.4 ms^{-1}) and within the error margin of the measurements under the demanding fieldwork conditions. The baseline model was tested for six verification cases (Figure 34); the model was able to predict overwash in five.

Table 7 – Input parameters for XBeach model.

Parameter	
Minimum grid size (m)	0.1
Maximum grid size (m)	3
Minimum points per wavelength	50
Offshore boundary	Z = -15 m
Duration (s)	2340; including 600 s spin-up
Output timestep (s)	0.25
D_{50} (m)	0.00061
K (ms^{-1})	0.0015

Based in performance metrics and the verification cases, it was considered that the Barreta baseline overwash model is a reliable tool for the prediction of overwash hydrodynamics. The baseline model was then forced to simulate overwash under different hydrodynamic conditions (different waves, Figure 35, and lagoon water level) and morpho-sedimentary settings (nearshore topography and beach grain-size, Figure 36), within the range of values characteristic for the study area.

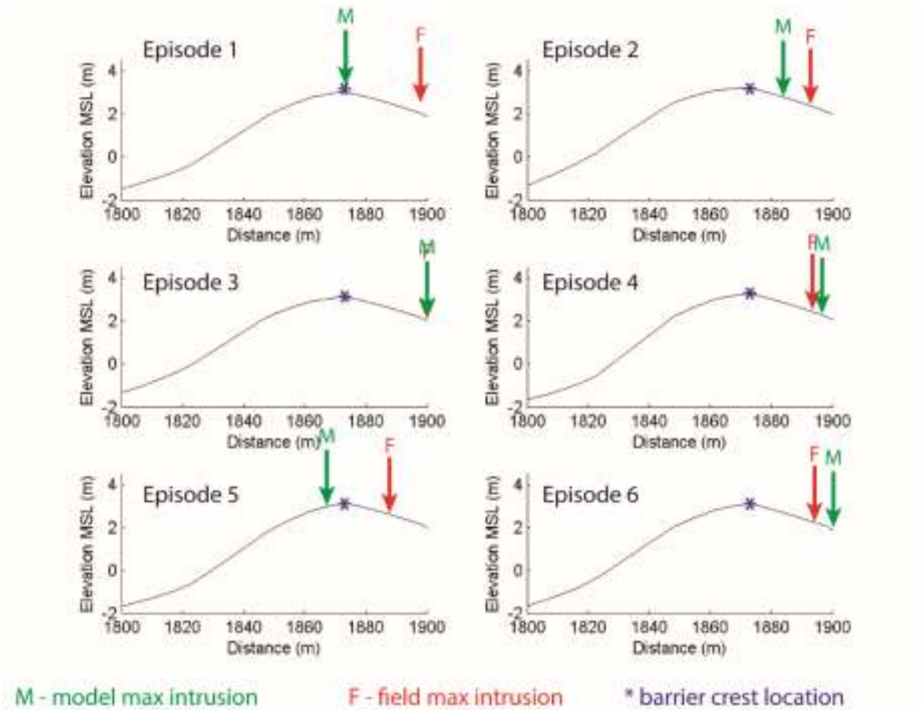

Figure 34: *Maximum overwash water intrusion over the barrier crest obtained during fieldwork measurements and after modelling results.*

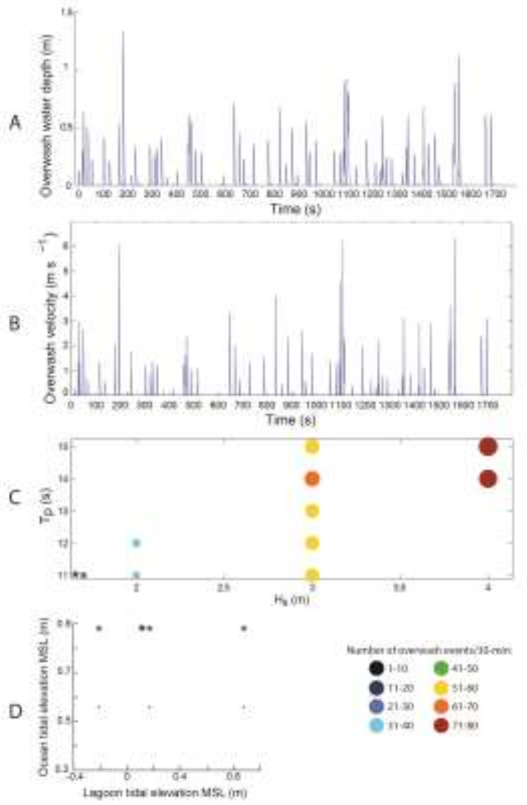

Figure 35*: Time-series of overwash depth (A) and overwash velocity (B) for one of the replicates of series waveplus, run 9 (Hs = 4 m; Tp = 15 s). C. Comparison between different waveplus models with varying Hs and Tp. D. Comparison between different lagoon water level tests. The circle size is proportional to the number of overwash events. The stars identify the baseline model.*

Based on this study, the order of importance of factors controlling overwash predictability in the study area are: 1st) wave height (more than wave period) can promote overwash 3-4 times more intense than the one recorded during fieldwork; 2nd) nearshore bathymetry, particularly shallower submerge bars, can promote an average decrease of about 30% in overwash; 3rd) grain-size, finer sediment produced an 11% increase in overwash due to reduced infiltration; and 4th) lagoon water level, only negligible differences were evidenced by changes in the lagoon level. This implies that for model predictions to be reliable, accurate wave forecast are necessary and topo-bathymetric configuration needs to be monitored frequently.

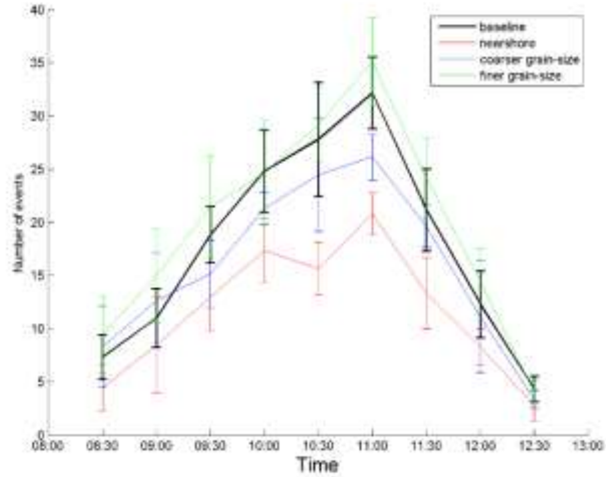

Figure 36*: Average and standard deviation of overwash number of events for each time-step of the baseline model, nearshore model, coarser and finer grain-size models.*

3.4.3 Task 4 – Implementation and outcome indicators

Implementation and outcome indicators include reports, communications and publications. URL of publications and communications can be found in section 3.6.2. Task 4 was scheduled for 01/08/2017 until 30/09/2018, however delays in previous tasks and the identified necessity to include additional hydrodynamic data, were reflected in delays in task 4. Nevertheless, the modelling of storm impacts went further than expected and ended on schedule. Task 4 ended in 30/09/2019 (Figure 1).

Reports:

Carrasco, R., van den Hoven, K., Ferreira, Ó. (2019). Modelling morphological impact of sea-level rise in the Ria Formosa lagoon. CIMA – Universidade do Algarve. 8 pp.

Communications:

Matias, A., Carrasco, A.R., Loureiro, C., Andriolo, U., Masselink, G., Guerreiro, M., Pacheco, A., McCall, R., Ferreira, Ó., Plomaritis, T., (2017). Measuring and modelling overwash hydrodynamics on a barrier Island, Coastal Dynamics 2017 Conference, 12-16 June 2017, Helsingør, Denmark.

Matias, A., Carrasco, A.R., Loureiro, C., Andriolo, U., Masselink, G., Guerreiro, M., Pacheco, A., McCall, R., Ferreira, Ó., Plomaritis, T. (2017). Parameters influencing overwash hydrodynamics. 4ª Conferência sobre Morfodinâmica Estuarina e Costeira, 18-19 May 2017, Oporto, Portugal.

Taborda, R., Ribeiro, M. (2019). Modeling shoreline evolution and headland sediment bypassing at platform beaches. 9th International Conference on Coastal Sediments 2019, 27 – 31 May 2019, Tampa/St. Petersburg, Florida, USA, pp. 2746-2760.

Publications:

Carrasco, A.R., Plomaritis, T., Reyns, J., Ferreira, Ó., Roelvink, D. (2018). Tide circulation patterns in a coastal lagoon under sea-level rise. Ocean Dynamics: 68(9), 1121-1139.

Matias, A., Carrasco, A.R., Loureiro, C., Masselink, G., Andriolo, U., McCall, R., Ferreira, Ó., Plomaritis, T.A., Pacheco, A., Guerreiro, M. (2019). Field measurements and hydrodynamic modelling to evaluate the importance of factors controlling overwash. Coastal Engineering: 152, 103523.

3.5 Task 5 – Integration of results and quantification of resilience

3.5.1 Task 5 – Objectives and research team

The objective of this task was to integrate results obtained in previous tasks, and to propose innovative resilient parameters. This task was coordinated by A. Matias, and involved A.R. Carrasco, C. Loureiro, F. Madeira, K. Kombiadou, Ó. Ferreira, R. Taborda, S. Costas, T. Plomaritis and consultants L. Moore and G. Masselink.

3.5.2 Task 5 – Description of activities

3.5.2.1. Literature review

The extensive literature review is not fully described here; only a resumed report is provided. Details can be found in Kombiadou and Matias (2019) and in Kombiadou *et al.* (2019), both references in section 4.5.3.

Resilience, highly important in the context of achieving sustainability (Brand & Jax, 2007), is a multi-faceted concept that has been adapted differently to various uses and contexts (Alexander, 2013). The term was historically grounded in law and politics (Flood & Schechtman, 2014), passed from mechanics to ecology and psychology, and then was adopted by social science and sustainability science (Alexander, 2013). The multiple levels of meaning of resilience include a sustainability-related metaphor, a property of dynamic models and a measurable attribute of socioecological systems (Carpenter *et al.*, 2001). These multiple uses of the term, with different objectives, over a broad contextual frame and with a mixture of descriptive and normative aspects has led to divergent conceptions of resilience, ambiguous uses of terminology and to an increasingly diluted and unclear specific meaning of resilience (Brand & Jax, 2007). Distinct views, perceptions and definitions seem to coexist even within disciplines (e.g., physics, ecology, geography, psychology, economy), while, between disciplines, the differences are even more significant (Piégay *et al.*, 2018).

Both scientific interest and confusion regarding the application of resilience theories to natural systems is high, whereas little focus has been given to complex coastal systems like barrier islands. Thoms *et al.* (2018) specify three main emerging issues in a resilience-based approach to geomorphology: (1) confusion over resilience terminology across social and physical sciences; (2) the role of humans as external drivers or internal components of geomorphic systems and what this means for system resilience; and (3) questions of scale in general, involving how to address cross-scale interactions in social-ecological systems. Furthermore, humans and geomorphic systems are inextricably linked, given that human activity influences bio-geophysical processes and events, which, in turn influence human reactions and decision making (Berkes & Ross, 2016; Chaffin & Scown, 2018).

There are two main schools of thought regarding resilience, representing distinct views and focal points, one concentrating on recovery and return time following a disturbance, and the other on how much a system can be disturbed and still persist without changing function (Miller et al., 2010). The former corresponds to the engineering principle, which is the resilience to non-permanent disturbances (after some time the system relaxes to its previous state), whereas the latter refers to the ecological resilience and is associated with a changing set of internal or external drivers (Piégay *et al.*, 2018). These different views on resilience are fundamental, with the engineering view concerned with maintaining efficiency of function and the ecosystem one on maintaining existence of function

(Gunderson & Holling, 2002). They are often depicted using the ball-and-cup analogy (Figure 37), where the cup represents the 'basin of attraction', defined by all possible values of system variables of interest, and the ball represents the state of the system at a given temporal point (Flood & Schechtman, 2014). Engineering resilience considers a single basin of attraction and is interested in whether the system can remain at its bottom, whereas ecological resilience accepts multiple basins of attraction and focuses on whether the system can remain within the current basin (Holling, 1996). Ecological resilience is currently defined as 'the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same functions, structure, identity and feedbacks' (Flood & Schechtman, 2014; Folke, 2006; Scheffer & Carpenter, 2003; Walker *et al.*, 2004).

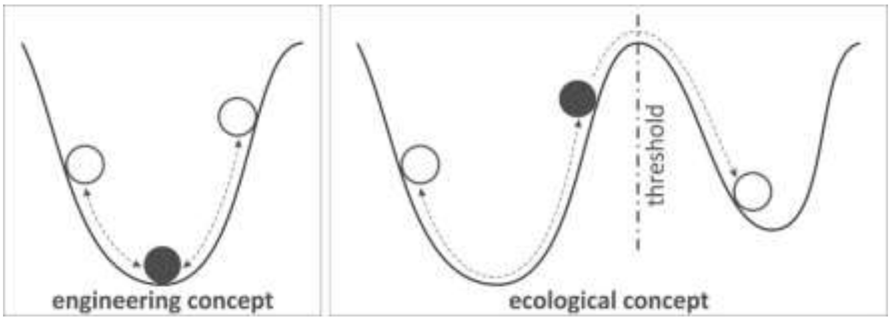

Figure 37*: Graphical representation of the different views on resilience under the engineering and ecological concepts, using the ball-and-cup analogy; after Holling (1996).*

The notion of the adaptive cycle has a key role in the resilience interpretation of natural systems (Gunderson & Holling, 2002). According to the theory of the adaptive cycle (**Figure** 38), dynamical systems, such as ecosystems, societies, corporations, economies, nations, and socioecological systems, do not tend toward some stable or equilibrium condition (Carpenter *et al.*, 2001). Instead, they pass through four characteristic phases: rapid growth and exploitation (r), conservation (K), collapse or release (or "creative destruction", Ω), and renewal or reorganization (α). Two opposing loops form the adaptive cycle: (a) the development (or 'fore') loop, characterized by the accumulation of capital and by stability and conservation and b) the release and reorganization (or "back") loop, characterized by uncertainty, novelty, and experimentation (Walker & Salt, 2006).

To express cross-scale influences and interactions in complex adaptive systems, Gunderson & Holling (2002) proposed the notion of panarchy (instead of hierarchy), as a way to view and understand the manner in which elements of complex adaptive systems nest in one another. Since the word hierarchy is so burdened by the rigid, top-down nature of its common meaning, Gunderson and Holling (2002) invented the term 'panarchy' that captures the adaptive and evolutionary nature of adaptive cycles that are nested one within the other across space and time scales. The levels of a panarchy can be drawn as a nested set of adaptive cycles (Figure 39), potentially with multiple connections between phases at one level and phases at another level. Two are most significant in assessing sustainability, the connections labelled "Revolt" and "Remember" in Figure 39. The Revolt and Remember connections become important at times of change in the adaptive cycles.

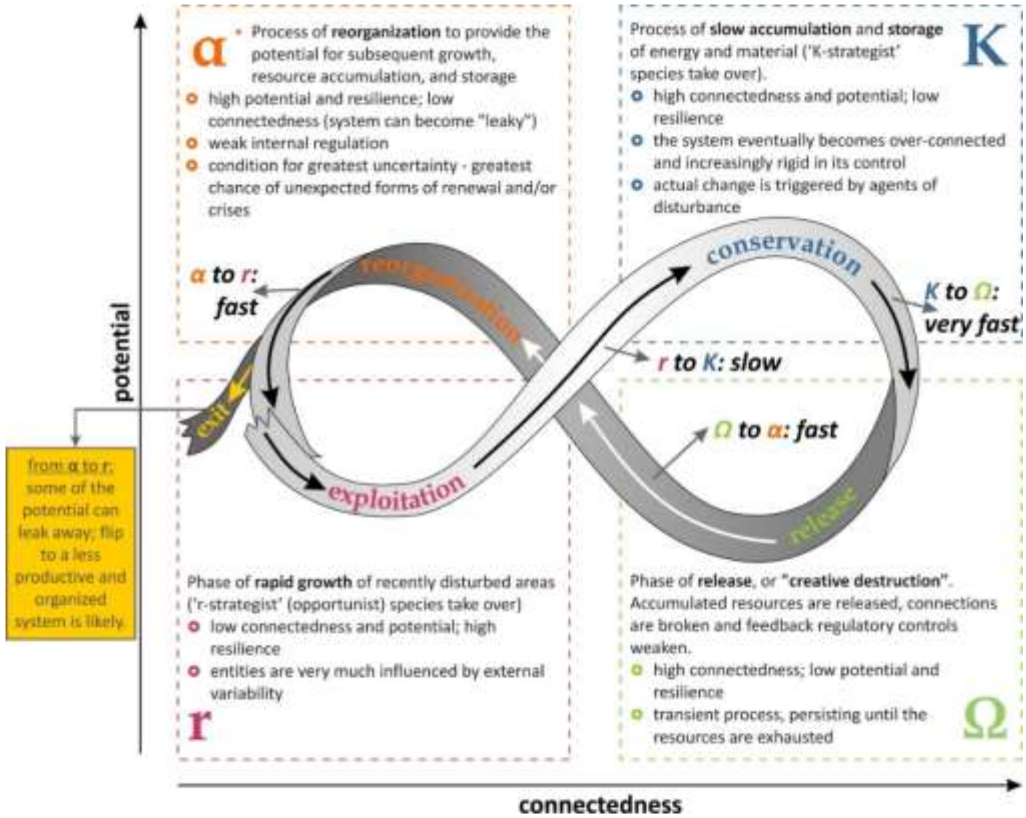

Figure 38: *Graphic representation of the adaptive cycle (modified after Gunderson et al., 2009; Gunderson & Holling, 2002). The four phases of the cycle, their characteristics and the transition from phase to phase are presented, along with the dimensions of potential and connectedness. Resilience, the third dimension of the cycle, is vertical to the plot, expanding near α and r and contracting towards K and Ω.*

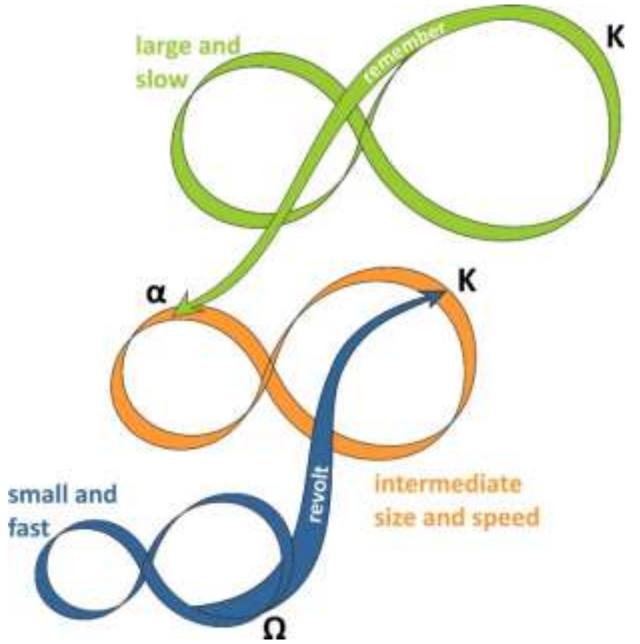

Figure 39*: Panarchical connections, modified after Gunderson & Holling (2002). Three selected levels of a panarchy are illustrated, to emphasize the two connections that are critical in creating and sustaining adaptive capability*

There are four crucial aspects of resilience (Gunderson *et al.*, 2009; Walker *et al.*, 2004):

1. **Latitude**: the maximum amount a system can be changed before losing its ability to recover within the same state (before crossing a threshold), equal to the width of the basin of attraction.
2. **Resistance**: the ease or difficulty of changing the system; deep basins of attraction indicate that greater disturbances are required to change the current state of the system away from the attractor.
3. **Precariousness**: how close the current state of the system is to a limit or "threshold" that, if breached, makes reorganization difficult or impossible.
4. **Cross-scale interactions** (i.e. Panarchy): the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below. They express how the other three attributes are influenced by the states and dynamics of the (sub)systems at scales above and below the scale of interest.

The first three 'dimensions' of resilience are related to the shape of the basin of attraction and the system state (ball), as graphically depicted in Figure 6. The shape of the stability domain (basin) and of the entire stability landscape are continuously changing in response to the combined effects of natural processes and interactions and external disturbances (i.e. Figure 5), as well as the system state itself.

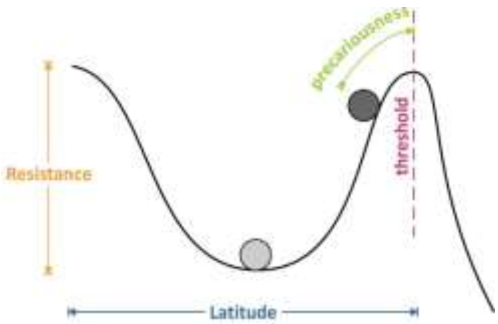

***Figure 40**: The four crucial aspects of resilience: (a) Latitude, Resistance and Precariousness, with respect to the dimensions of a basin of attraction.*

3.5.2.2. Transferring resilience theory to barrier island geomorphology

In order to pass on from a geomorphological analysis to a resilience assessment of complex systems, a series of fundamental aspects of resilience theory need to be interpreted to geomorphological principles and/or features. Going back to the definition of resilience, it becomes evident that one needs to start from identifying the identity, functions, structure and feedbacks of the coastal barrier system:

- In terms of identity, a coastal barrier can be defined as a strip of sand and/or gravel, backed by a shallow coastal bay, separated wholly or partly from the mainland shore (Stutz & Pilkey, 2002).
- Its main functions are to support its habitats, species and anthropogenic activities and to provide storm protection and sheltering to the lagoon and its supported habitats and to the mainland (Moore & Murray, 2018).
- From a geomorphological point of view, the structure of a coastal barrier can be analysed using six main components or sub-environments (Davidson-Arnott, 2009): (1) mainland coast; (2) the lagoon, bay or marsh that separates barrier and mainland; (3) subaerial barrier (beach, dunes and backbarrier deposits); (4) subaqueous sediments platform (on which the subaerial barrier is built); (5) shoreface extending offshore from the exposed beach; and (6) inlets and associated tidal deltas.

- The diverse range of evolutionary pathways of barriers is a result of the complex feedbacks between 4 spheres: atmosphere, hydrosphere, lithosphere and biosphere (Barrineau *et al.*, 2015).

From the listed sub-environments, some (mainland, lagoon bay, and inlets) do not form part of the barrier body itself and others (subaqueous platform, tidal deltas and shoreface) pertain to the (permanently or temporarily) submerged part of the system. Focussing on the subaerial barrier (part above the Mean Sea Level), the considered components can be divided with respect to the principal forces acting upon them, into wave- wind- and tide-dominated parts. This division is also meaningful in terms of distinct habitats, as these parts can be simply referred to as beach, dune and marsh (BDM). Considering the three units beach, dune and marsh, geomorphological dimensions and/or processes can be used to determine the four crucial aspects of resilience, as shown in Figure 41. The **latitude** (width of the basin), or else the maximum amount a system can be changed before losing its ability to recover within the same state, should be expressed by the total width of all units (barrier and perched marsh), given that, if this width decreases below a critical value (Lat_{crit} in Figure 42), all units would have disappeared. The reason for including marsh width in the latitude dimension is to account for the presence of the marsh platform that can assist barrier rollover. The **resistance** (basin height) can be related to the dune height, as an indicator of the difficulty of the barrier to be inundated. The **precariousness**, or the proximity of the system to a critical "threshold", over which reorganization is difficult or impossible, can be straightforwardly linked to the proximity of the (back)barrier to the mainland, given that it is a direct measure of the space available to the barrier for inland migration before it welds to the mainland. Crossing such a threshold (Pr_{crit} in Figure 42) would mean an irreversible loss of resilience (identity, functions, structure and feedbacks).

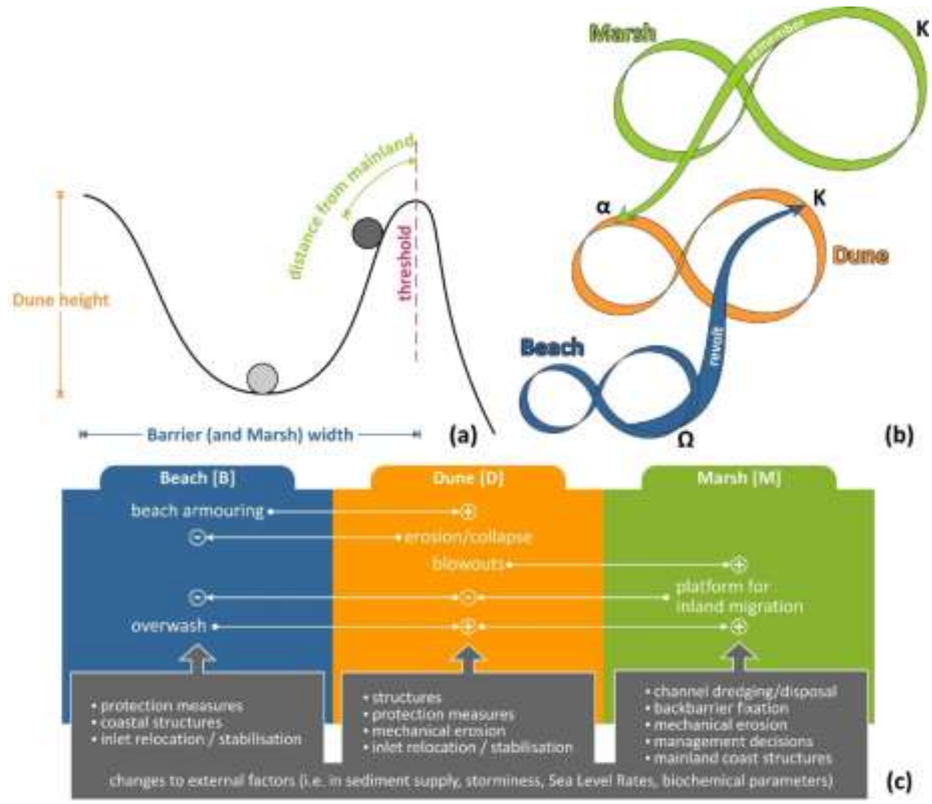

Figure 41: *Barrier resilience 'dimensions' using three panarchical levels (B, D, M): (a) dimensions of a basin of attraction, (b) cross-scale interactions and (c) potential feedbacks (+: positive; -: negative) between the three levels, including human-induced ones and broader feedbacks, external to the system (grey areas).*

These dimensions can be used to visualise changes to the stability landscape and to assess the implications to the resilience of the system (as in the example of Figure 42d), where the different zones correspond to different combinations of the three parameters and, therefore, to different scales of resilience. For instance, a wide barrier with high dune that is far from the mainland (high resistance and resilience and low precariousness) would belong in the top-right quadrant of the upper panel of the plot in Figure 42d and the bottom-right quadrant of the lower panel of the plot.

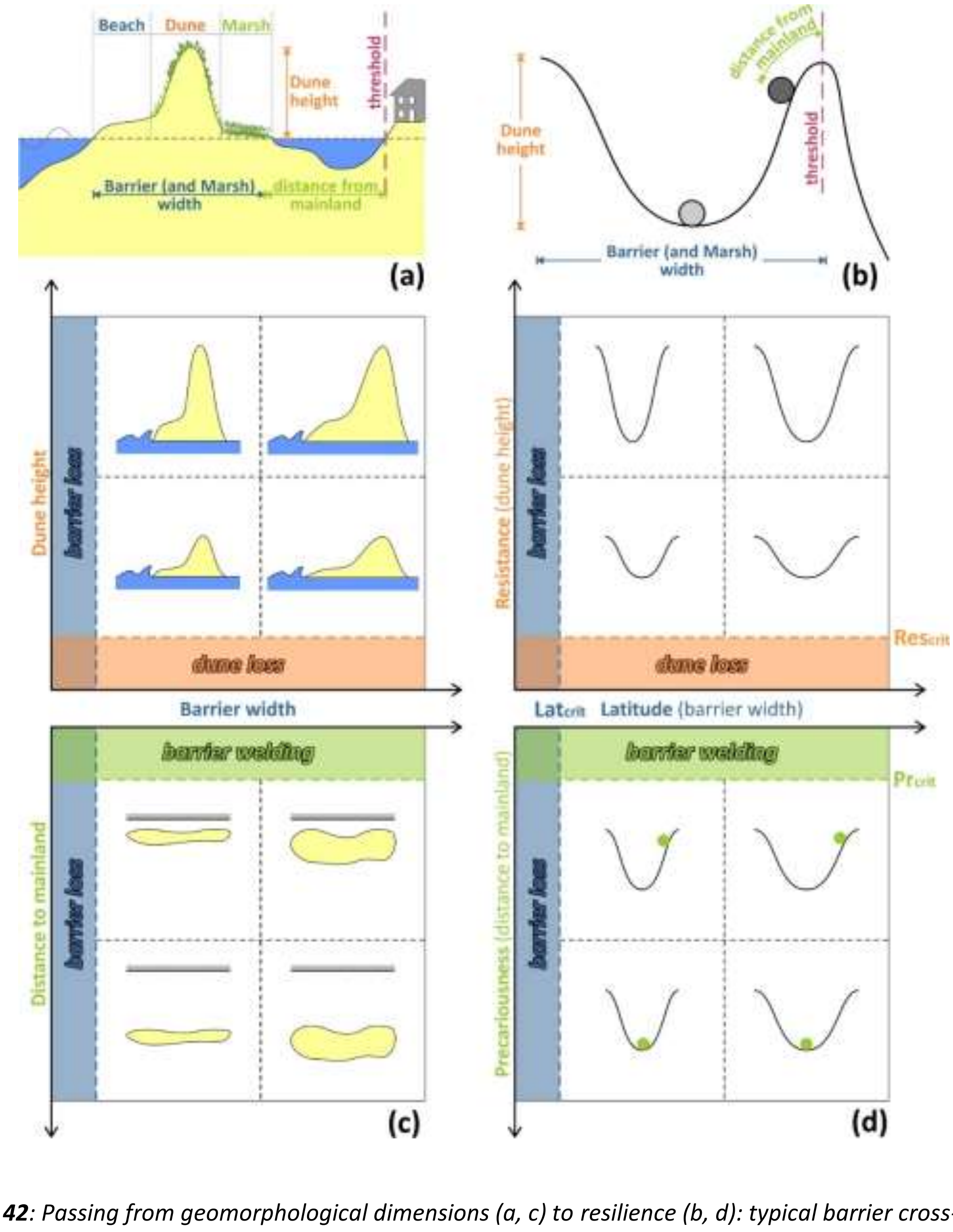

***Figure 42**: Passing from geomorphological dimensions (a, c) to resilience (b, d): typical barrier cross-section, where three main geomorphological dimensions (barrier width, dune height and distance from mainland) are noted (a), transference to dimensions of the basin of attraction (b) and variability of the three dimensions, in relation to coastal geomorphology (c) and in relation to resilience (d). The shape of basin (cup) is defined by the dune height and the barrier width (top part of graph in d), while the system state (ball position) is related to the available accommodation space (bottom part of graph in d). The thresholds in (c) and (d) denote loss of resilience (Lat_{crit}, Res_{crit} and Pr_{crit} are critical values for latitude, resistance and precariousness, respectively); not all thresholds can be included in the plot.*

To assess the multi-decadal geomorphological resilience of barrier islands, we propose using the geomorphological units of Beach, Dune and Marsh (BDM), as indicators that express distinct environments (wave-, wind- and tide-dominated, respectively) of the subaerial barrier, corresponding to distinct spatiotemporal scales of change. The data were used to determine the widths of the three morphological units (B-D-M), using a common baseline and the digitised coastlines, delimiting the selected morphologies as follows:

i) **Barrier**: wave dominated part, delimited by the ocean-side and the backbarrier coastlines, both corresponding to the same water level (ca. MHWL);

ii) **Dune**: wind dominated part, delimited by the dune line in the ocean-side (ca. MHHWL) and the backbarrier line in the lagoon-side (ca. MHWL); and

iii) **Marsh**: tide dominated part of the backbarrier, delimited by the backbarrier coastline and the marsh edge line (both in the lagoon-side). These limits correspond to the levels between MWL and MHWL.

Splitting barrier evolution to these three units expresses the inherent scales within the barrier, since the same forcing conditions are expected to affect these units at different scales (faster to slower: B-D-M). Expressing the presence and the absence of a unit within the BDM sequence and using the values 1 and 0, respectively, can be used to simplify the distinction between potential barrier states or changes between them and, therefore, to simplify the resilience analysis. Using this 'coding', the potential barrier states range between 111 (all BDM units present) and 000 (no units present) and the transition between then under destructive or constructive regimes can be viewed as the scheme below (Figure 43).

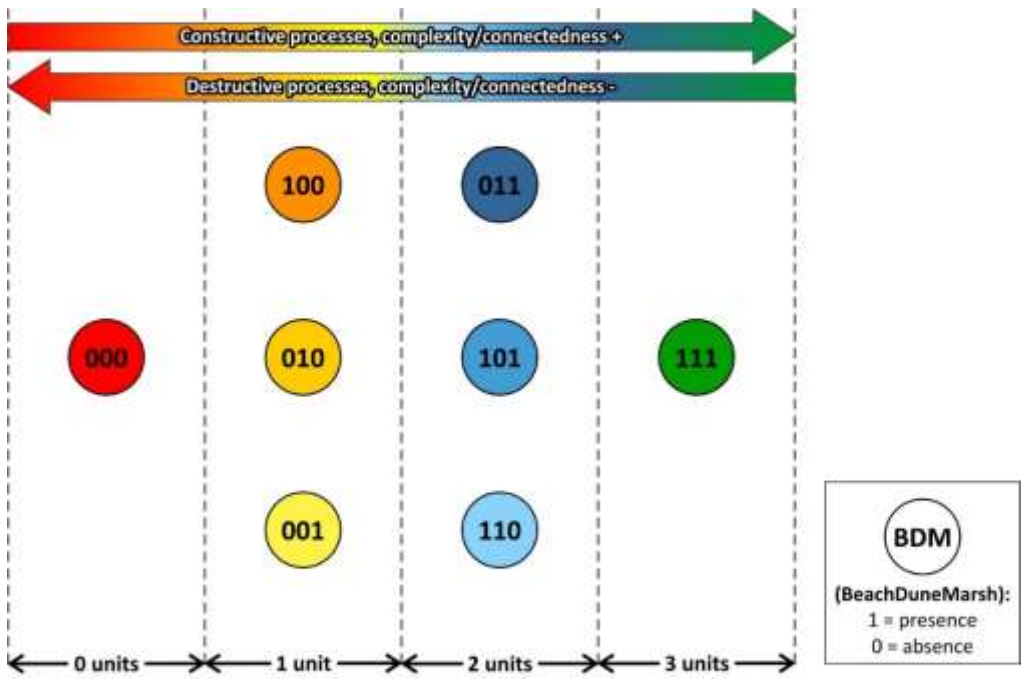

Figure 43: Conceptual scheme of alternative states, considering the BDM panarchical levels. Dashed lines present thresholds under destructive natural processes. Some states (e.g., 001 and 101) are short-term.

3.5.2.3. Application of concepts to the Ria Formosa barrier system

The previously analysed approach and concepts on resilience assessment were applied to the Ria Formosa barrier system, using geomorphological data for the period of 1952 to 2014. More information on the available data and the methodology applied can be found in Kombiadou *et al.* (2019) and in the EVREST report on Task 3 (References in section 3.6.2 of this report). Only flights with full coverage of the barrier were used to calculate geomorphological unit areas and that, given that elevation data were not available, the analysis was restricted to a planimetric basis.

The steps of the BDM barrier state and resilience analysis are presented using the example of Cabanas Island and Cacela Peninsula (C-C), the barrier subsystem with the most significant morphological changes in Ria Formosa. Initially, the calculated unit widths (per 100 m cross-shore sector) were used to identify the spatiotemporal variability of BDM states in the barrier. The summarized results for C-C (averaged per 500 m) are shown in **Figure**44. The results can effectively visualise the constructive and destructive processes in the barriers, as for example the barrier breaching between 1958 and 1972 over the transects 4 to 8 and its subsequent recovery (1972 to 1986), or the natural maturation of the barrier over transects 1 to 10, with gradual marsh establishment (1985-2005).

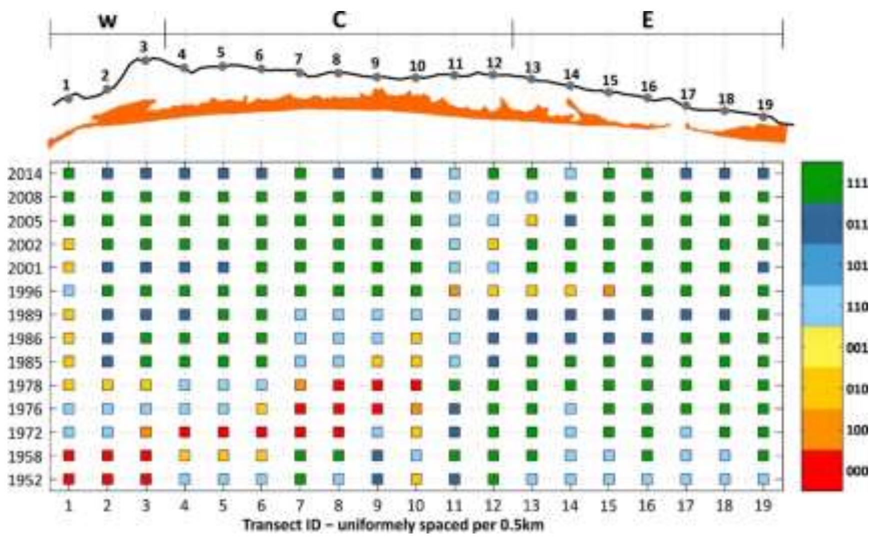

Figure 44: *Changes to the barrier state (BDM, defined as before) along the stretch of C-C (x-axis; map of 2014 given above) for all the available flights (y-axis).*

Three sectors (West, Central and East) were identified by analysing the similarity of neighbouring transects in terms of morphological evolution and grouping transects with high correlation of unit widths. The widths of the units and the distance to mainland (distance between backbarrier and mainland coastlines), averaged among the three sectors of the barriers are given in Figure 45, with the colour coding of the points to denote the system state of the sector. The dominant barrier state of each sector was determined using the most abundant state (in cases of equal presence of two states, the most mature one was selected as characteristic). Comparing Figure 44 and Figure 45, it can be seen that the main shifts of each sector are represented appropriately (i.e. the destruction of the C sector between 1958 and 1972). In terms of resilience dimensions, the values effectively express the recuperation through the increase of latitude (i.e., increase in barrier width) in the W and C sectors, with concurrent reduction of the E one. All sectors show an increase in precariousness (reduced accommodation space), which, however seems stabilised after 1986.

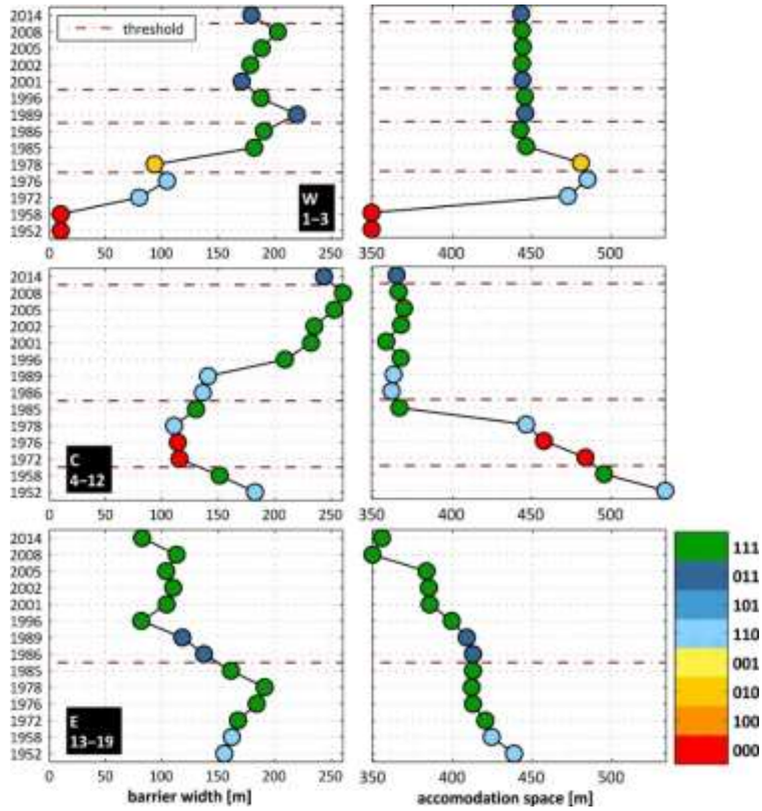

Figure 45: *Changes to BDM barrier state (circle colour with reference to the colour bar) and the evolution of average barrier width (left) and distance to the mainland (right) for the three sectors of C-C (top to bottom: 1-3, 4-12 and 13-18). Dashed lines denote threshold crossing.*

The results of the spatiotemporal evolution of barrier state and resilience dimensions along barrier sectors for the barriers of Ancão, Barreta, Culatra, Armona and Tavira were also made, however they are not presented in this report for shortness.

3.5.3 Task 5 – Implementation and outcome indicators

Implementation and outcome indicators include reports, communications and publications. URL of publications and communications can be found in section 3.6.2 of this report. Task 5 was scheduled for 01/06/2018 until 31/01/2019. This task started earlier than predicted with preparatory work for the quantification of the ecological resilience of the barrier island system, literature review, and definition of key parameters and holistic interpretation of results. Task 5 ended according to plan.

Reports:

Kombiadou, K., Matias, A. (2019). Report on the resilience of barrier systems. CIMA – Universidade do Algarve. 42 pp.

Communications:

Matias, A., Kombiadou, K., Carrasco, A.R., Ferreira, Ó., Costas, S., Plomaritis, T. (2017). The EVREST project: evolution and resilience of barrier Island systems. 4ª Conferência sobre Morfodinâmica Estuarina e Costeira, 18-19 May 2017, Oporto, Portugal.

Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., Plomaritis, T., (2018). "Towards Assessing the Resilience of Complex Coastal Systems: Examples from Ria Formosa (South Portugal)". Proceedings from the International Coastal Symposium (ICS) 2018, 13-18 May 2018, Busan, Republic of Korea. Format: Oral presentation.

Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., Plomaritis, T., (2018) 'Assessing the Resilience of the Ria Formosa Barrier Island System: Preliminary Findings', Protection and Restoration of the Environment, 3-6 July 2018, Thessaloniki, Greece.

Kombiadou, K., Costas, S., Carrasco, A.R., Plomaritis, T., Ferreira, Ó., Matias, A., (2019). From geomorphology to resilience of barrier islands: transferring concepts from theory to application. X Jornadas de Geomorfología Litoral, 4-6 September 2019, Castelldefels, Spain.

Publications:

Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., Vieira, G. (2018). "Towards Assessing the Resilience of Complex Coastal Systems: Examples from Ria Formosa (South Portugal)". Journal of Coastal Research: SI 85, 646–650.

Kombiadou, K., Costas, S., Carrasco, A.R., Plomaritis, T.A., Ferreira, Ó., Matias, A. (2019). Bridging the gap between resilience and geomorphology of complex coastal systems. Earth-Science Reviews: 198, 102934.

3.6 Task 6 – Dissemination of results and findings

3.6.1 Task 6 – Objectives and research team

The objective of this task was to increase awareness and to provide wide dissemination of the results obtained within the project, from international scientific research level to the general public. This task was coordinated by A. Moura or A.A. Ramos, and involved A. Matias, V. Belchior, A.R. Carrasco, K. Kombiadou and S. Costas for the dissemination to the general public and A. Matias, A.R. Carrasco, C. Antunes, K. Kombiadou, F. Madeira, Ó. Ferreira, R. Taborda, S. Costas, and T. Plomaritis for the dissemination of results within the scientific community.

3.6.2 Task 6 – Description of activities of scientific dissemination

Scientific dissemination covers results and findings from several project tasks, and it includes publications, communications, reports, organization of seminars and conferences, and advanced training. The project website was created in 09/11/2016 and regularly updated by uploading project deliverables (papers, reports, datasets), adding media materials as they were produced (leaflet, posters, radio broadcasts), and news about the project progress, participation in conferences, and students that were involved.

3.6.2.1 Publications

Book chapters

Carrasco, A.R. & Matias, A. (2019). "Backbarrier shores along the Ria Formosa lagoon". In: Aníbal, J., Gomes, A., Mendes, I., Moura, D. (eds.), *Ria Formosa: challenges of a coastal lagoon in a changing environment*. 1st edition. University of Algarve, Faro, ISBN 978-989-8859-72-3, pp. 17-28. URL: https://sapientia.ualg.pt/handle/10400.1/12475

Papers in international journals

1. Carrasco, A.R., Plomaritis, T., Reyns, J., Ferreira, Ó., Roelvink, D. (2018). "Tide circulation patterns in a coastal lagoon under sea-level rise". Ocean Dynamics: 68(9), 1121-1139. URL: https://doi.org/10.1007/s10236-018-1178-0
2. Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., Vieira, G. (2018). "Towards Assessing the Resilience of Complex Coastal Systems: Examples from Ria Formosa (South Portugal)". Journal of Coastal Research: SI 85, 646–650. URL: https://doi.org/10.2112/SI85-130.1
3. Ferreira, Ó., Plomaritis, T.A., Costas, S. (2019). "Effectiveness assessment of risk reduction measures at coastal areas using a decision support system: Findings from Emma storm". Science of the Total Environment: 657, 124-135. URL: https://doi.org/10.1016/j.scitotenv.2018.11.478
4. Kombiadou, K., Matias, A., Ferreira, Ó., Carrasco, A.R., Costas, S., Plomaritis, T. (2019). Impact of human interventions on the evolution of the Ria Formosa barrier island system (S. Portugal). Geomorphology: 343, 129-144. URL: https://doi.org/10.1016/j.geomorph.2019.07.006

5. Matias, A., Carrasco, A.R., Loureiro, C., Masselink, G., Andriolo, U., McCall, R., Ferreira, Ó., Plomaritis, T.A., Pacheco, A., Guerreiro, M. (2019). Field measurements and hydrodynamic modelling to evaluate the importance of factors controlling overwash. Coastal Engineering: 152, 103523. URL: https://doi.org/10.1016/j.coastaleng.2019.103523
6. Carrasco, A.R. (2019). Simple assessment of spatio-temporal of salt marshes ecological services. Frontiers in Ecology and Evolution: 7, 77.
   URL: https://doi.org/10.3389/fevo.2019.00077
7. Kombiadou, K., Costas, S., Carrasco, A.R., Plomaritis, T.A., Ferreira, Ó., Matias, A. (2019). Bridging the gap between resilience and geomorphology of complex coastal systems. Earth-Science Reviews: 198, 102934. URL: https://doi.org/10.1016/j.earscirev.2019.102934
8. Lazarus, E.D., Davenport, K.L., Matias, A. (2019). Dynamic allometry in coastal overwash morphology. Earth Surface Dynamics. URL : https://doi.org/10.5194/esurf-2019-39
9. Herrero, X., Costas, S., Kombiadou, K. (2019, accepted). Coastal ridge constructive processes at a multi-decadal scale in Barreta Island (Southern Portugal). Earth Surface Processes and Landforms.
10. Matias, A., Carrasco, A.R., Ramos, A., Borges, R. (2019, in revision). Engaging children in geosciences through storytelling and creative dance. Geosciences Communication. URL : https://www.geosci-commun-discuss.net/gc-2019-21/gc-2019-21.pdf

3.6.2.2 Communications

Communications in international meetings

1. Matias, A., Carrasco, A.R., Loureiro, C., Andriolo, U., Masselink, G., Guerreiro, M., Pacheco, A., McCall, R., Ferreira, Ó., Plomaritis, T., (2017). "Measuring and modelling overwash hydrodynamics on a barrier Island", Coastal Dynamics 2017 Conference, 12-16 June 2017, Helsingør, Denmark. Format: Oral communication.
   URL: http://coastaldynamics2017.dk/onewebmedia/105_ana_matias.pdf
2. Matias, A., Carrasco, A.R., Ramos, A., Borges, R. (2018). "Coastal geology to children through performative arts". EGU General Assembly 2018, 8–13 April 2018, Vienna, Austria, Geophysical Research Abstracts, Vol. 20, EGU2018-2729. Format: Interactive Content presentation.
   URL: https://meetingorganizer.copernicus.org/EGU2018/EGU2018-2729.pdf
3. Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., Plomaritis, T., (2018). "Towards Assessing the Resilience of Complex Coastal Systems: Examples from Ria Formosa (South Portugal)". Proceedings from the International Coastal Symposium (ICS) 2018, 13-18 May 2018, Busan, Republic of Korea. Format: Oral presentation.
   URL: http://ics2018.org/html/?pmode=notice&smode=view&seq=372
4. Kombiadou, K., Matias, A., Carrasco, R., Ferreira, Ó., Costas, S., Plomaritis, T., (2018) 'Assessing the Resilience of the Ria Formosa Barrier Island System: Preliminary Findings', Protection and Restoration of the Environment, 3-6 July 2018, Thessaloniki, Greece. Format: Oral presentation.
   URL: http://pre14.civil.auth.gr/
5. Carrasco, A.R., Kombiadou, K., Matias, A. (2018). The influence of sediment availability to coastal ecosystem services provision. ESP2018, 15-19 October 2018, S. Sebastian, Spain. Format: Poster presentation.
   URL: https://www.espconference.org/eu2018/wiki/384868/book-of-abstracts#T.%20Thematic%20Sessions

6. Carrasco, A.R., Kombiadou, K., Matias, A., Costas, S., Ferreira, Ó. (2018). Ecosystem processes and services provision in salt marshes facing varying sediment availability. IX Symposium on the Iberian Atlantic Margin, 4-7 September 2018, Coimbra, Portugal. Format: Poster presentation.
   URL: http://evrest.cvtavira.pt/wp-content/uploads/2018/09/051_CarrascoEtAl-MIA2018.pdf
7. Kombiadou, K., Matias, A., Costas, S., Carrasco, A.R., Ferreira, Ó., Plomaritis, T. (2019). Assessment of Natural and Anthropic Drivers to the Evolution of Ria Formosa Barrier Island System. 9th International Conference on Coastal Sediments 2019, 27 – 31 May 2019, Tampa/St. Petersburg, Florida, USA, pp. 57-70. Format: Oral presentation. URL: https://www.worldscientific.com/doi/abs/10.1142/9789811204487_0006
8. Taborda, R., Ribeiro, M. (2019). Modeling shoreline evolution and headland sediment bypassing at platform beaches. 9th International Conference on Coastal Sediments 2019, 27 – 31 May 2019, Tampa/St. Petersburg, Florida, USA, pp. 2746-2760. Format: Oral presentation. URL: https://www.worldscientific.com/doi/10.1142/9789811204487_0235
9. Kombiadou, K., Costas, S., Carrasco, A.R., Plomaritis, T., Ferreira, Ó., Matias, A., (2019). From geomorphology to resilience of barrier islands: transferring concepts from theory to application. X Jornadas de Geomorfología Litoral, 4-6 September 2019, Castelldefels, Spain. Format: Oral presentation.
   URL: https://xjornadasgeomorfologialitoral.icm.csic.es/.

Communications in national meetings

1. Matias, A., Kombiadou, K., Carrasco, A.R., Ferreira, Ó., Costas, S., Plomaritis, T. (2017). The EVREST project: evolution and resilience of barrier Island systems. 4ª Conferência sobre Morfodinâmica Estuarina e Costeira, 18-19 May 2017, Oporto, Portugal. Format: Oral presentation. URL: http://mec2017.lnec.pt/pdf/resumos_final_v2.pdf
2. Matias, A., Carrasco, A.R., Loureiro, C., Andriolo, U., Masselink, G., Guerreiro, M., Pacheco, A., McCall, R., Ferreira, Ó., Plomaritis, T. (2017). Parameters influencing overwash hydrodynamics. 4ª Conferência sobre Morfodinâmica Estuarina e Costeira, 18-19 May 2017, Oporto, Portugal. Format: Oral presentation. URL: http://mec2017.lnec.pt/pdf/resumos_final_v2.pdf
3. Madeira, F., Antunes C. (2018). Análise da variabilidade relativa do Nível do Mar para a região do Algarve. 5as Jornadas de Engenharia Hidrográfica, June 19, 2018, Lisbon, Portugal. Format: Oral presentation. URL: http://www.hidrografico.pt/jornadas2018.php
4. Matias, A., Carrasco, A.R., Borges, R. (2018). Recurso à dança criativa e "storytelling" para a comunicação de ciência. 6º SciComPT 2018, 10-12 October 2018, Figueira de Castelo Rodrigo, Portugal. Format: Poster presentation. Format: Oral presentation. URL: http://scicom.pt/wp-content/uploads/2018/10/SciComPT-2018_Programa-Detalhado.pdf
5. Matias, A., Vicente, P.N., Mena, A. (2019). Projeto 'Dar corpo às memórias': Uma experiência de Ciência & Arte para a inclusão social. 7º Congresso da Rede de Comunicação de Ciência e Tecnologia de Portugal – SciComPT 2019, 29-31 May 2019, Aveiro, Portugal. Format: Oral presentation. URL: http://www.scicom2019.pt/wp-content/uploads/2019/02/livro-resumos.pdf
6. Matias, A., Carrasco, A.R. (2019). Assets of coastal geoscience communication. 5ª Conferência sobre Morfodinâmica Estuarina e Costeira, 24-26 June 2019, Lisbon, Portugal. Format: Oral presentation. URL: http://mec2019.lnec.pt/pdf/MEC2019_LivrosResumos.pdf

4.6.2.3 Reports

1. Matias, A., Carrasco, A.R. (2016). Preparatory fieldwork in Ria Formosa. CIMA – Universidade do Algarve. 6 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2017/03/Progress_Report_First_Meeting_EVREST.pdf
2. Matias, A., Kombiadou, K. (2016). Progress report on the first meeting/workshop of EVREST project. CIMA – Universidade do Algarve. 7 pp. URL : http://evrest.cvtavira.pt/wp-content/uploads/2017/03/Progress_Report_First_Meeting_EVREST.pdf
3. Antunes, C., Madeira, F. (2017). Tide observation campaign along the Algarve coast. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 4 pp. URL : http://evrest.cvtavira.pt/wp-content/uploads/2017/06/EVREST_Report_tide_observation.pdf
4. Antunes, C., Madeira, F. (2017). Tide observation campaign along the Algarve coast: Lagos and Barreta Island. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 3 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2017/11/EVREST_Report_tide_observation2.pdf
5. Kombiadou, K., Matias, A. (2017). EVREST GIS Platform Report. CIMA – Universidade do Algarve. 13pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2017/07/EVREST_Remote_sensing_database_Report.pdf
6. Madeira, F. (2017). Análise da variabilidade relativa do nível do mar para a região do Algarve. Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa. 16 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2017/11/Report_Regional_SLR_rates.pdf
7. Matias, A., Kombiadou, K., Carrasco, A.R., Costas, S., Ramires, M., Robbins, E., Sousa, L. B. (2017). Fieldwork in Culatra Island. CIMA – Universidade do Algarve. 30 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2017/06/EVREST_Report_CulatraFieldworkJune2017.pdf
8. Matias, A., Kombiadou, K. (2017). First Annual Report. CIMA – Universidade do Algarve. 4 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2017/06/EVREST_Progress_Report_1st_Year_Final.pdf
9. Kombiadou, K., Matias, A. (2018). Synthetic report on geomorphological evolution of the study sites. CIMA – Universidade do Algarve. 38 pp. URL : http://evrest.cvtavira.pt/wp-content/uploads/2018/05/EVREST_Task3_evolution_analysis.pdf
10. Kombiadou, K., Matias, A. (2018). Progress report on the third meeting/workshop of EVREST project. 5 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2018/10/Progress_Report_Third_Meeting_EVREST.pdf
11. Matias, A., Kombiadou, K. (2018). Second Annual Report. CIMA – Universidade do Algarve. 5 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2018/06/EVREST_Progress_Report_2nd_Year.pdf
12. Antunes, C., Madeira, F. (2019). Analysis of Sea Level Rise. CIMA – Universidade do Algarve. 12 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2019/10/EVREST_SeaLevelRise_Report.pdf
13. Carrasco, R., van den Hoven, K., Ferreira, Ó. (2019). Modelling morphological impact of sea-level rise in the Ria Formosa lagoon. CIMA – Universidade do Algarve. 8 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2019/10/EVREST_Modelling_Report09_2019.pdf

14.Kombiadou, K., Matias, A. (2019). Report on the resilience of barrier systems. CIMA – Universidade do Algarve. 42 pp. URL : http://evrest.cvtavira.pt/wp-content/uploads/2019/09/EVREST_Report_Task5_barrier_resilience.pdf
15.Matias, A., Ramos, A. (2019). Dissemination and Outreach Report. Centro de Ciência Viva de Tavira. 21 pp. URL: http://evrest.cvtavira.pt/wp-content/uploads/2019/10/EVREST_Dissemination_Report.pdf
16.Plomaritis, T., Kombiadou, K., Matias, A. (2019). Analysis of wave climate. CIMA – Universidade do Algarve. 10 pp. URL : http://evrest.cvtavira.pt/wp-content/uploads/2019/09/EVREST_WaveClimate_Report.pdf
17. Matias, A. (2019). EVREST Final Report. CIMA – Universidade do Algarve. 55 pp.

4.6.2.4 Organization of seminars and conferences

Three members of the EVREST project team (A. Matias, Ó. Ferreira, R. Taborda) participated on the organizing committee of two national conferences (Figure 46), promoting opportunities to disseminate project results:

4ª Conferência sobre Morfodinâmica Estuarina e Costeira, 18-19 May 2017, Oporto, Portugal.

5ª Conferência sobre Morfodinâmica Estuarina e Costeira, 24-26 June 2019, Lisbon, Portugal

Figure 46: *Webpages of national conferences MEC2017 and MEC2019, co-organized by EVREST project team members A. Matias, Ó. Ferreira, and R. Taborda. MEC2017 conference invited speaker was EVREST consultant* Prof. Gerhard Masselink, that contributed within the tasks of results discussion of EVREST project.

Within the EVREST project, three open seminars to the academic audiences were organized. The lectures given by L. Moore and G. Masselink were also organized in the framework of the MSc programme 'Marine and Coastal Systems' of the University of Algarve (Figure 47). Seminar details:

22nd September 2016: CIMA Advanced Open Seminar and MSc. Opening Lecture by Laura J. Moore, from the University of North Carolina – Chapel Hill, USA, entitled "Barrier island ecomorphodynamics and response to changing climate", at Pedagogical Complex, Amphitheater A.

17th February 2017: CIMA Advanced Open Seminar by Mónica Martins, from Instituto de Geografia e Ordenamento do Território da Universidade de Lisboa, entitled “How dune plants translate sea erosion: A case study along the Portuguese coast”, at Building 8, Room 3.24.

27th September 2018: CIMA Advanced Open Seminar and MSc. Opening Lecture by Gerd Masselink, from the University of Plymouth, entitled “Variability in the north-east Atlantic wave climate and its influence on annual-to-decadal beach dynamics”, at Pedagogical Complex, Amphitheatre A.

Figure 47: *L. Moore and G. Masselink seminars advertisement.*

Within the EVREST project, two workshops were organized for the project researchers, students involved in the project, and science communication staff. Workshop details:

1st EVREST workshop took in 21-12 September 2016, at Building 7, room 2.57. The workshop included a geomorphological field trip to Culatra Island and Barreta Island, an ecological field trip to Tavira Island, a visit to Centro Ciência Viva de Tavira exhibitions (Figure 48), and the following presentations:

- Matias, A.: “EVREST project in brief”
- Ferreira, Ó.: “The Ria Formosa barrier islands”
- Costas, S.: “Dunes and barrier of the past”
- Roelvink, D.: “Modelling on the West Frisian barrier islands”
- Antunes, C. & Taborda, R.: “The sea-level records of Portugal”
- Plomaritis, T. & Carrasco, A.R.: “Modelling storm and sea-level rise impacts on barriers”
- L. Moore: “Barrier island ecomorphodynamics and response to changing climate”

2nd EVREST workshop took place in 27-28 September 2018, at Building 2, room 2.11. The workshop included presentations of scientific results and of the dissemination activities. The second part was composed of a brain-storm open discussion the project results. Presentations were the following:

- Matias, A.: “Introduction/Welcome”
- Kombiadou, K.: “Recent barrier evolution in Ria Formosa”
- Carrasco, A.R.: “Marsh evolution in the Ria Formosa lagoon”

- Otero, X.: "Evaluation of coastal barrier constructive processes on Barreta Island"
- Roelvink, D.: "Modelling on the West Frisian barrier islands"
- Madeira, F.: "Assessment of relative sea level rise for Algarve region"
- Ramos, A. & Afonso, J.: "CCVT dissemination activities – EVREST Science Club"
- Kombiadou, K.: "Passing from evolution to resilience"
- Masselink, G.: "Variability in the north-east Atlantic wave climate and its influence on annual-to-decadal beach dynamics".

Figure 48: *Sample images from the 1st workshop, September 2016.*

4.6.2.5 Advanced training

Emily Robbins (2017). *Evolution and resilience of barrier islands systems*. Internship for the MSc in Expertise and management of the coastal environment. University of Algarve & European Institute for Marine Studies (IUEM) in Brest, France. http://evrest.cvtavira.pt/wp-content/uploads/2017/09/Report_Emily_Robbins_MasterStudentInternship.pdf

Xabier Herrero Otero (2018). *Evaluation of coastal barrier constructive processes on Barreta Island, Southern Portugal*. MSc, University of Algarve & Vrije Universiteit Amsterdam.

Dimitra Alkisti Pliatsika (2018). *Exploring aeolian sediment transport potentials and aeolian activity at Ria Formosa*. MSc Marine and Coastal Systems, University of Algarve.

Marine Fouin (2018). *Long term evolution of the salt marsh area within the Ria Formosa lagoon*. Internship for the MSc in Environmental management and rural development. University of Algarve & Université de Lorraine Ecole Nationale Superieure d'Agronomie et des Industries Alimentaires in Nancy, France.

Gustavo Carvalho Braga Vieira (ongoing). Storm impact and recovery of sand barriers after extreme events. MSc Marine and Coastal Systems, University of Algarve.

Pedro Miguel de Sousa Vinagre Amado (ongoing). Salt marsh response to changing hydrodynamics: the case of Ancão Inlet migration (Ria Formosa coastal lagoon). MSc Marine and Coastal Systems, University of Algarve.

3.6.3 Task 6 – Description of activities of dissemination to the general public

3.6.3.1 Participation in media

National radio (Antena 1) interview to A. Matias for the series '90 segundos de ciência', where EVREST project was approached. The interview was broadcast on 30/03/2017 and 31/03/2017. It can be found in https://www.90segundosdeciencia.pt/episodes/ep-94-ana-matias/.

Regional radio (RUA FM) interview to A. Matias for the series 'Projetoscópio', where EVREST project was briefly described. The interview was broadcast on in 28/03/2018. It can be found in https://www.mixcloud.com/RUAFM/projetosc%C3%B3pio-28mar-evrest-cima-ana-matias-000406/.

3.6.3.2 Participation in events

The EVREST team participated in Science and Technology Week 2016, with the lecture by A. Matias & A.R. Carrasco "Construction and destruction of the islands in Ria Formosa", to high-school students, at Escola Secundária de Tavira, on 24 November 2016. The presentation is available at http://evrest.cvtavira.pt/wp-content/uploads/2017/03/SemanaCT_2016_MATIASCARRASCO.pdf

Team member Óscar Ferreira presented an invited talk at the high-school of Vila Real de Santo Antonio (VRSA), entitled "A Geologia Ambiental das praias de VRSA", given to 150 students within the scope of the ECOESCOLAS Day. 8 March 2019

Team member Óscar Ferreira presented invited talk at Escola de Hotelaria e Turismo (Faro), under the scope of the event Faro e a Ria Formosa, organised by the União das Freguesias de Faro, entitled "O Sistema de Ilhas Barreira da Ria Formosa: Caracterização e Evolução", given to a broad audience of about 80 persons. 29 March 2019.

The EVREST team participated in the "Ria Formosa Week 2018", by invitation of Centro Ciência Viva do Algarve and Câmara Municipal de Faro, by means of a field trip to Culatra Island with three classes of 4th grade students from Faro. The students visited the several barrier environments (marsh, dune and beach) and participated in hands-on activities (Figure 49).

Figure 49: *Field trip to Culatra Island in the framework of "Semana da Ria Formosa", April 2018.*

Team member Óscar Ferreira guided a field trip to the Ria Formosa (Culatra Island) covering an overall explanation of the Ria Formosa evolution and environments within the event "Saberes da Ria II" organised by Faro municipality, attended by 40 persons, 8 May 2019. He also guided a field trip with students (40) from IHE UNESCO (Delft, Netherlands) to Ria Formosa (Culatra Island) to show the environments and evolution of the barrier island, 20 May 2019.

The EVREST project participated in the annual meeting of the Portuguese science and technology community "Encontro Ciência 2017", held at the Centro de Congressos de Lisboa. On 3 July 2017, an EVREST stand was set at the exhibition hall, including the EVREST roll-ups, posters, flyers, and a permanent presentation on display (Figure 50). Three EVREST team members were present to provide additional information.

Figure 50: *Stand of EVREST project in "Ciência 2017".*

The EVREST team participated in European Researchers Night 2017, at the Centro Ciência Viva de Tavira on Friday, September 29th, with the following activities:

10:00 - 13:00: Presentation of the EVREST project (posters, presentation, discussions).
10:00 - 12:00: Activities with primary school students "O mar enrola na areia": The activities are designed to familiarise students with the sediment transport processes in beaches. The activity was conceived and interpreted by EVREST team members A. Matias and A.R. Carrasco from CIMA - University of Algarve.

21:00 - 22:00: Science café event about “Climate Changes: Impact in Marine Life and Coastal Zones”. Participating researchers from EVREST: Ferreira, Ó., Costas, S. and Borges, R. (Figure 51).

Figure 51: *Science Café event in Centro Ciência Viva de Tavira, in the framework of European Researchers Night 2017.*

EVREST project tasks and results were presented during the Science and Technology Week 2017 – Science Fair organized at CCV Tavira, on 24 November 2017. 148 students mainly from high schools participated in the different activities.

CCV Tavira team developed activities related to dune formation and shoreline protection (dunes and saltmarsh) for more than 200 children (kindergarten and primary school) during the Children and Environment Week of Tavira (4-8 June 2018).

Figure 52: Activities developed during the Children and Environment Week of Tavira.

A field trip to the Barril beach (Tavira island) was conducted for the general public during the Ciência Viva Summer program 2019 (21 August, 10 participants).

3.6.3.3 EVREST science club

A three session-based Science Club (2 sessions at the class-room and 1 field-trip, Figure 53) was developed for the 4th grade students of Tavira Municipality during 2018 (215 students, 11 classes). The class-room activities consisted of hands-on activities focusing on sediment composition of the saltmarsh (1st session, March to April) and dunes formation and their role on shoreline protection (2nd session, April to May). In addition to the classroom sessions, 10 classes participated in a field trip to the Barril beach (Tavira island) to observe and identify the different habitats (salt marsh and dune system, forest), sediment (mud and sand) and fauna and flora.

Figure 53: *Science Club activities.*

The Science Club visited the UALG 2018 Easter Camp and a total of 24 students (1^{st} to the 6^{th} grades) participated in the dune formation and shoreline protection (dunes and saltmarsh) hands-on activities.

3.6.3.4 Science & Art activities

An informal education activity called "The Sea Rolls the Sand" focusing on ocean dynamics was designed for 10-year-old students (sample video here: http://evrest.cvtavira.pt/wp-content/uploads/2017/12/MOV01638.mp4). The activity was developed by merging techniques and tools from arts, science, science communication and storytelling. It combines coastal science concepts (wind, waves, currents, and sand), storytelling techniques (narrative arc), and creative dance techniques (movement, imaginative play, and sensory engagement). A sequence of six exercises was proposed starting in the generation of offshore ocean waves and ending with sediment transport on the beach, during storm/fair-weather conditions (Figure 53). Scientific concepts were then translated into structured creative movements, within imaginary scenarios, and accompanied by sounds or music. The programme was performed six times, within national and international initiatives. During the first two times, the sessions were included in the programme of the "European Researcher Night", in September, 29th, 2017. These sessions took place in the educational laboratory of the science centre, which was emptied as much as possible to create space for physical activities. The other four times, the sessions were included in a

national initiative "Science and Technology Week", in November 23th and 24th, 2017. These sessions took place in three schools, including private and public schools, on classrooms and in the gym. Overall 112 students participated in the programme, divided in school classes, varying between 15 and 22 students per session. summing 112 students. It was an inclusive programme since all students in the class participated, including children with several mild types of cognitive and neurological impairment.

Figure 53: *Sample pictures of the activity "The Sea Rolls the Sand" covering different sessions.*

3.6.3.5 Outreach materials

An informative leaflet on the project, directed to the public, has been designed and distributed in related events since June 2017. The leaflet is available at http://evrest.cvtavira.pt/wp-content/uploads/2017/06/EVREST_flyer.pdf

A rollup for the project was designed and printed in June 2017 and has been, since, used in related activities. The rollup is shown in Figure 50.

Six A0 format posters were prepared and printed on rigid cardboard with information about: 1) location and main characteristics of Ria Formosa barrier islands (visible in Figure 8), 2) barrier islands sedimentary environments; 3) threats and sustainable conservation of barrier islands, 4) evolution and morphodynamics of Ancão Peninsula, 5) evolution and morpho-dynamics of Culatra Island (visible in Figure 8), and 6) evolution and morphodynamics of Cabanas and Cacela barriers, 4). These posters have been used in field visits (e.g. in field visits in Figures 48 and 49) and other dissemination activities (e.g. Ciência 2017, Figure 50), as visual aids on the evolution of the system and the supported habitats.

3.6.3 Task 6 – Implementation and outcome indicators

Outcome indicators were described in previous sections of this chapter (3.6.2 and 3.6.3). Task 6 was scheduled for 01/06/2017 until 30/09/2019. This task started earlier than predicted with dissemination of the project objectives and preliminary results to scientific conferences. Task 6 ended according to plan.

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