

Chapter 7

CLASSIFICATION OF WASHOVER

DYNAMICS IN BARRIER ISLAND

SYSTEMS

7.1. INTRODUCTION

Washovers are morphologic features generated by overwash, when there is a super-elevation of the sea level. Sea level super-elevation may be driven by individual factors such as onshore winds, storm surge, spring high tides, storm waves, hurricanes, etc., or a combination of them. Overwash events are usually associated with storms (Morton *et al.*, 2000). The elevation of the water level is a requirement for overwash to occur, but its actual occurrence and location is strongly related with the morphologic conditions. Some authors (e.g. Leatherman, 1976; Dingler and Reiss, 1990; Andrade, 1990; Sallenger *et al.*, 1999; Morton and Sallenger, 2003) have analysed in-depth the role of dune elevation as a major morphologic constraint on overwash occurrence. Moreover, Sallenger *et al.* (1999) and Sallenger (2000) developed a storm impact scale based on the relations between run-up and dune elevations, including an overwash regime (Chapter 2, section 2.2). However, the morphologic conditions that favour overwash (including the lowering of dune elevation) may be generated by other coastal processes. An identification and systematization of the mechanisms that generate morphologically favourable conditions has never been made. Similarly, the mechanisms that may lead to the disappearance of overwash in a barrier without changing the storminess regime has not been investigated in detail.

The main goal of this chapter is the development of a classification of washover dynamics in terms of the mechanisms that promote their formation and disappearance. The general overwash evolutionary trend is also analysed, and incorporated into the classification. The objective is to put forward a compilation of mechanisms and tendencies of washovers in order to produce a preliminary classification, which could be modified with new classes that may be defined by existing or future complementary studies in other coastal settings. The classification of washover dynamics is applied to a case study of the Ria Formosa barrier islands.

7.2. CLASSIFICATION OF WASHOVER DYNAMICS

7.2.1. METHODS

7.2.1.1. Photo-interpretation and geomorphologic criteria

Eleven sets of vertical aerial photographs, dating from 1947 to 2001, covering the Ria Formosa barrier island system (for location see Figure 3.1) were used (Table 7.1). The 11 mosaics of aerial photographs, with scales from 1/8,000 to 1/30,000, were analysed under a mirror stereoscope in order to identify all washover structures present in the barrier system. This technique allows three-dimension vision and good spatial resolution and it is more accurate than digital mosaicing (Santo and Sánchez, 2002).

Three sets of aerial photographs were georeferenced (Table 7.1) to Portuguese Melriça coordinate system (Datum 73), using ArcGIS software. Stable features from a topographic map (scale 1/2,000, year 1977/78) and DGPS points (collected in 2003) such as house corners, road crossings, water deposits, and track crossings (when fixed points were not available) were used as ground control points.

The photo-interpretation was made by establishing the colour, textures, patterns, neighbour affinity and spatial distribution, attributable to the main sedimentary environments of the barrier system. This was made through an overview of the several sets of aerial photos, and complemented with fieldwork and regional literature. The characterisation of the washover types and morphology nomenclature can be found in Chapter 2, section 2.1.

Table 7.1. Coverage and scale of vertical aerial photos used for this study.

		Year											
		1947	1969	1972	1976	1982	1985	1986	1989	1996	1999	2000	2001
		Scale: 1/											
Barrier island	20,000	25,000	6,000	30,000	8,000	15,000	15,000	15,000	10,000	8,000	8,000	8,000	8,000
Ancão Peninsula	✓ _#	✓	✓	✓ _#	✓	✓	✓	✓	✓ _#	✓	±	✓ _#	✓ _#
Barreta Island	✓ _#	✓	✓	✓ _#	✓ _#	✓ _#	✓ _#	✓ _#	±	✓	✓	✓	✓ _#
Culatra Island	✓ _#	✓	✓	✓ _#	✓ _#	✓ _#	✓ _#	✓ _#	✓ _#	✓	✓	✓	✓ _#
Armona Island	✓ _#	✓	✓	✓ _#	✓ _#	✓	✓	✓	✓ _#	✓	✓	✓	✓ _#
Tavira Island	✓ _#	✓	✓	✓ _#	✓ _#	✓	✓	✓	✓ _#	✓	✓	✓	✓ _#
Cabanas Island	±	±	±	✓ _#	✓ _#	✓	✓	✓	✓ _#	✓	✓	✓	✓ _#
Cacela Peninsula	✓ _#	±	✓	✓ _#	✓ _#	✓	✓	✓	± _#	✓	✓	✓	✓ _#

✓ complete aerial cover of barrier island; ± partial aerial cover of barrier island; _# georeferenced aerial photographs

The analysis of washover can present some difficulties either in distinguishing them from neighbouring coastal morphologies or from their relation to recent overwash activity. The present study is focused on washover dynamics; therefore the state of washover evolution had to be distinguished, i.e. active washovers from inactive features. The group of geomorphologic characteristics that required specific criteria were: (1) the washover identification criteria; (2) the active/inactive washover criteria; (3) the washover mouth criteria; (4) the washover intrusion criteria, and (5) shoreline criteria.

Washover identification criteria

The main criteria used to identify washover were based in three aspects: sandy surface, absence of vegetation and adjacent to the oceanic beach. An additional criterion, to have dunes on both sides, was established to differentiate between washover and low-lying areas of the barriers (e.g. next to tidal inlets). The overtopping of coastal structures or other constructions is a case of overwash of an impermeable surface, where the sand is often artificially displaced or totally removed from the area. Therefore, these cases were excluded from the analysis, even if they are known to occur.

Active/inactive washover criteria

The washovers were considered active when at least some parts of the mouth/crest did not exhibit any vegetation, nor any vegetated berm/embryonic dune was formed seaward of the previously active mouth. On the contrary, the inactive washovers corresponded to morphologies generated by past overwash but where there was evidence that overwash was not currently occurring. Only the active washovers were considered for the analysis.

Washover mouth criteria

The washover mouth was defined as the imaginary line that unites the two longshore shoreline positions. In cases of a washover plain the crest is the seaward limit of the washover and it was defined identically to the mouth. The stereoscopic observation of the washovers only allowed the perception of the mouth position in particularly good quality photographs with large scales, because generally the elevation difference between the washover crest and the beach and fan were relatively small.

Washover intrusion criteria

The washover intrusion was defined as the maximum water excursion distance in relation to the mouth, i.e. the length of the central trajectory of the overwash flow. Existence of low alignments (e.g. abandoned tidal creeks) can influence the length and orientation of the washover intrusion.

Shoreline criteria

The reference chosen to define the shoreline position was the seaward edge of the dune vegetation (as used by other authors, e.g., Guy, 1999, Komar *et al.*, 2001). It constitutes the threshold condition to define the occurrence of overwash and it is a relatively well definable feature in aerial photographs. It is a good erosion indicator, however it may not show accretion or will show it with a significant time lag (Boak and Turner, 2005). The shoreline is therefore sharper and easily drawn in retreating dunes and more diffuse in the cases of pioneer vegetation colonisation on a recently accreted berm.

7.2.1.2. Development of the classification

During the observation of the washovers it was noticed that their occurrence, dimensions and morphologies had relationships with other coastal processes and human activities. For example, where human development augmented through time, and consequently the density of tracks augmented, overwash became more frequent and located on the seaward end of the tracks. Also, it was noticed that at the location of washovers in one set of photographs, the next set showed the beach or even the ocean at the same location due to strong erosion and complete disappearance of the foredune. Therefore, each time a new washover appeared in an aerial photograph, the mechanisms that lead to its occurrence were analysed. This was made by analysing its location and morphology, together with the local coastal evolution in-between aerial photos (e.g. shoreline retreat, inlet migration, human development) complemented with regional literature and topographic maps, when available. This analysis was also undertaken for the cases where a washover was observed in a set of aerial photographs and disappeared in the next set. Therefore, an interpretation of the mechanisms of washover formation and disappearance was made, in terms of the main coastal processes determining the coastal evolution and sedimentary balance. After the integrated analysis of the formation and disappearance of all the washovers on all of the barrier islands of the Ria Formosa, for the study period, a systematization was made to produce the classification. The classification was developed by grouping the processes into general broad mechanisms. The classes of mechanisms were defined considering only those that contributed to the washover dynamics of the Ria Formosa barrier system, which in turn was supported by available regional knowledge: tidal inlets (e.g. Weinholtz, 1964; Vila-Concejo, 2003); shoreline retreat (e.g. Ferreira *et al.*, *in press*); dune formation (e.g. Gomes *et al.*, 1994); and coastal engineering structures (e.g. Esaguy, 1987). Nevertheless the categorisation benefits from international scientific knowledge of the relation between overwash and other coastal

morphologies and processes, for example, shoreline positions (Dolan and Hayden, 1981); aeolian processes (McCluskey, 1987); barrier morphology (Pilkey *et al.*, 1989) and foredune elevation (Sallenger, 2000).

The systematic observation of the barriers showed that the amount of washovers and their dimensions varied through time. Therefore, it should be considered that the balance of the formation and disappearance mechanisms may vary over time. For the development of a general classification of washover dynamics, the evolutionary tendency of overwash has to be considered. To define the classes of overwash evolutionary trend, the various types of washover evolution were analysed (enlargement, reduction, coalescence, division) based on the variation of washover dimensions and shape. The variation in washover spatial density on each barrier was also evaluated.

7.2.2. DESCRIPTION OF THE PROPOSED CLASSIFICATION

The two main types of mechanisms to be defined are the formation mechanisms and the disappearance mechanisms. The formation mechanisms are related to the processes that determine the existence of the overwash at a certain location, while the disappearance mechanisms are associated with the post-overwash evolutionary processes that ultimately are responsible for overwash no longer existing in the previously formed washover. It was assumed that the oceanographic conditions were not significantly changed through time, and therefore the changes in overwash were related to the morphologic conditions. The probability of exceedence of a certain sea-level (storm surge + wave regime + tides) was therefore assumed to be constant at the time scale of the analysis. Therefore each barrier island or barrier island system can be classified in terms of the mechanisms responsible for

the formation and for the disappearance of washovers. Five formation mechanisms were identified, and classified as:

1. *Depression in dune elevation*
2. *Structural erosion*
3. *Inlet dynamics*
4. *Washout*
5. *Human intervention*

Each of these formation mechanisms will be further detailed (see section 7.2.2.1). Five mechanisms were identified for washover disappearance, and classified as:

1. *Dune development*
2. *Berm development*
3. *Structural erosion*
4. *Inlet dynamics*
5. *Human intervention*

Each of these disappearance mechanisms will be further detailed (see section 7.2.2.2). In three cases formation and disappearance mechanisms are the same: *Structural erosion*, *Inlet dynamics*, and *Human intervention*, meaning that depending on how the process acts at a barrier it can lead to the existence of overwash or to the disappearance of washovers. There are cases where in the same barrier environment and at the same time it is possible to have mixed processes, such as *human intervention* and *structural erosion* both inducing washover formation. In other cases, the mechanisms of formation and disappearance of washovers are different, for example if a *washout* leads to the occurrence of overwash and *berm development* prevents further overwash.

7.2.2.1. Washover formation mechanisms

The 5 types of washover formation mechanisms that were identified are represented in Figure 7.1.

Depression in dune elevation

In areas with relatively high dunes, the elevation of water levels may induce bluff formation and temporary coastline retreat, but overwash processes are not likely to occur. In areas with relatively low dunes the elevation of the water levels is more likely to reach the overwash threshold. Shorelines can undergo confined overwash in the depressions of the foredune, if the water levels overcome a threshold elevation. This mechanism for washover formation is the most elementary because it could occur in all coastal dunes, provided that the necessary super-elevation of the water levels occurs. It can be divided according to the setting of the depressions in the two types of existing foredunes defined by Hesp (2002): established foredune and incipient foredune (Figure 7.1). The overwash through a depression on an incipient dune is probably related with minor magnitude oceanographic events, and over time the intrusion does not reach the higher elevated foredune. Generally, the overwash of incipient dunes corresponds to transitional situations related with the immaturity of the dunes.

Structural erosion

It is estimated that 70% of the worlds sandy shorelines are eroding (Bird, 1985). Shoreline retreat allows the exposure to the ocean of depressions that would otherwise be located in the backdune area. For overwash to take place through the depressions it is firstly necessary for erosion of the foredune to occur.

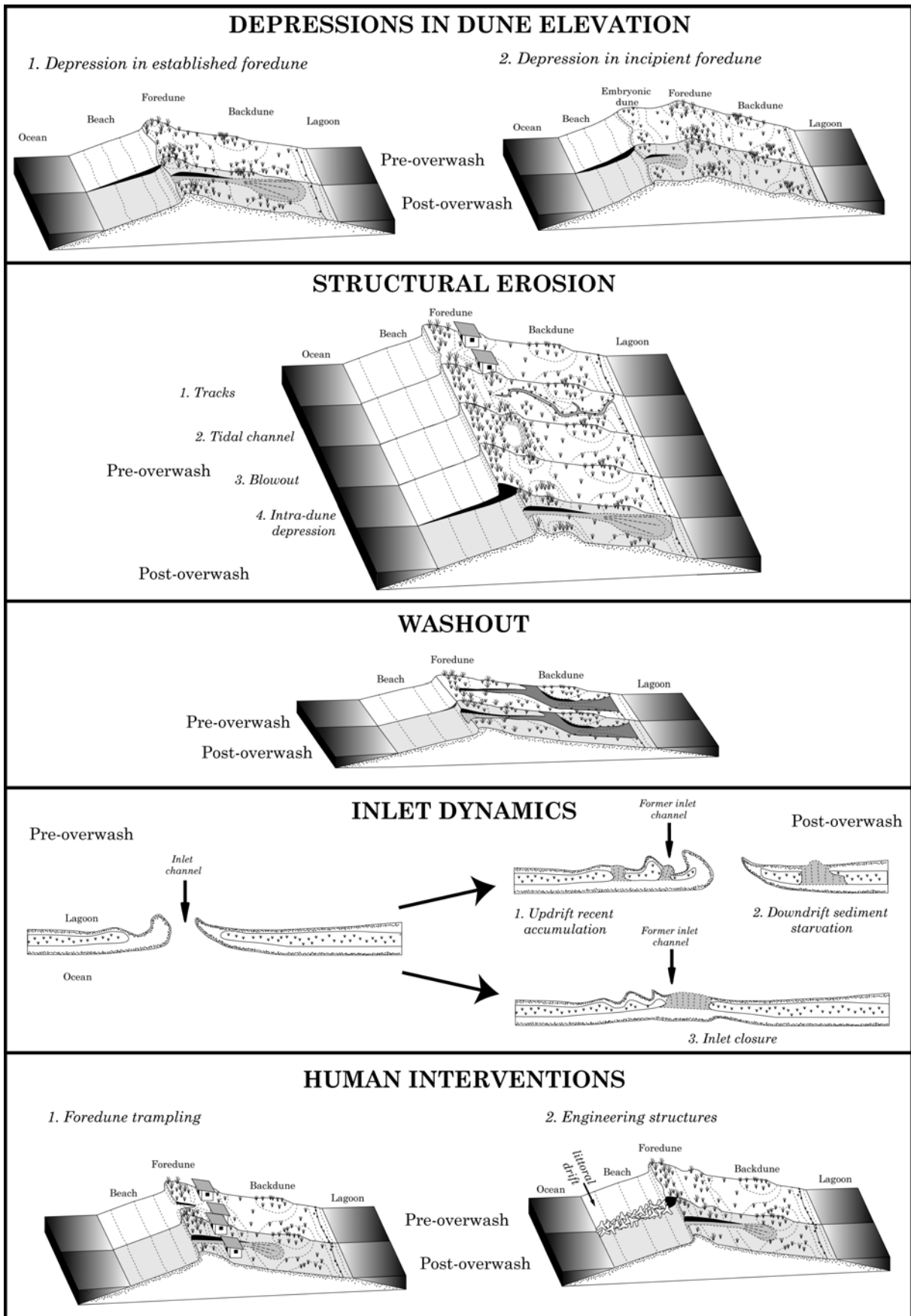


Figure 7.1. Washover formation mechanisms.

The difference between the mechanism of *depressions in dune elevation* and the mechanism of *structural erosion* is that the location of the washover in the first is related to the depressions located in the foredune and in the second is related to depressions formed in the backdune, that are reached at a later time by shoreline retreat. Several types of depressions can exist in the backdune: (1) track, (2) tidal channel, (3) blowout, or (4) undifferentiated intra-dune depression (Figure 7.1).

Washout

Washout is a process opposite to overwash, and involves channel erosion across the beach and foredunes as a result of floodwaters flowing from the lagoon to the ocean (Morton and Sallenger, 2003). The foredune depression generated by washout may be subsequently overwashed when the oceanic water levels are super-elevated (Figure 7.1). Overwash may occur hours to years after the washout took place, with reshaping and overwash sand deposition on the washout channel.

Inlet dynamics

Three main types of *inlet dynamics* mechanisms were identified as contributing to washover formation: (1) recent accumulation on the inlet updrift margin; (2) inlet downdrift starvation, and (3) closure of former inlet channels (Figure 7.1). Many natural inlets of the world undergo a migration process, with formation of sand spits on the updrift margin and erosion of the downdrift areas. As an inlet migrates, it leaves behind a series of curved beach ridges that define the updrift spit (FitzGerald *et al.*, 2001). Dune development is unequal and overwash can occur in lower areas (Figure 7.1). If an inlet suddenly changes its location or closes, then overwash may occur at the location of the closed inlet channel.

The presence of an inlet acts to disrupt any smooth passage of sediment along the shore. A certain amount of the drift may become incorporated in inlet structures (Walton and Dean, 1976). As a consequence, the downdrift barriers often undergo sediment starvation and may experience severe erosion. The sediment starvation induces foredune erosion and permits overwash in depressions of the backdune.

Human intervention

This mechanism does not include overwash in intensively developed areas, where the flow runs over impermeable ground (see criteria in section 7.2.1.1). Two types of human interventions are considered: (1) trampling and (2) coastal engineering structures (Figure 7.1). The trampling of the foredune destroys the dune vegetation and on dune slopes greater shear stress is transmitted to the ground from the foot (Williams *et al.*, 1997). Once the vegetation has gone, sand is eroded by the wind which widens the damaged area and the spreading of blown sand onto the adjoining vegetation reduces its surface density (Ranwell and Boar, 1986). When there is a sufficiently high elevated water level, overwash occurs in the artificially generated dune gap.

Coastal structures such as jetties, groins, seawalls, bulkheads, and revetments are probably the most dramatic cause of man-induced coastal erosion (C.E.R.C., 1984). This *human intervention* is similar to the *structural erosion* and erosion by *inlet dynamics*, except that the main mechanism of sediment starvation was the placement of an updrift artificial structure.

7.2.2.2. Washover disappearance mechanisms

The 5 types of washover disappearance mechanisms that were identified are represented in Figure 7.2.

Dune development

The differences in ecological response to overwash by sand-binding species may influence the development of barrier structures (Godfrey, 1977; Stallins, 2002). For some washovers, the rapid growth of *Ammophila* leads to the development of substantial, stable dune lines (Leatherman, 1976). In others, rapid revegetation of the washover distal fans by *Spartina*, and little deflation of overwash deposits, results in flat topography that leads to an increased likelihood of overwashing (Godfrey *et al.*, 1979). Only in the case of development of frontal dune lines, is washover considered to have disappeared, because the development of incipient foredunes in the washovers mouth (Figure 7.2) is the key indicator of the absence of overwash (criteria in section 7.2.1.1).

Berm development

On strongly accreting coastlines, the sediment excess promotes shoreline advance. Therefore the washover mouths are further away from the shoreline and from the maximum swash, and are not subsequently reworked by overwash (Figure 7.2). This berm development can by itself induce the disappearance of the washover but can also allow evolution towards a situation of dune development. The vertical and horizontal growth of dunes depends on the interaction between sand supply, vegetation growth and the wind field (Carter, 1988).

Structural erosion

The *structural erosion* mechanism for washover disappearance is similar to the washover formation mechanism (section 7.2.2.1). The shoreline is undergoing a retreating structural process and the washover morphology is eroded simultaneously with the surrounding dunes (Figure 7.2). The washover may continue to exist as the shoreline retreats, but if the shoreline retreat is more severe, then the entire washover may be eroded.

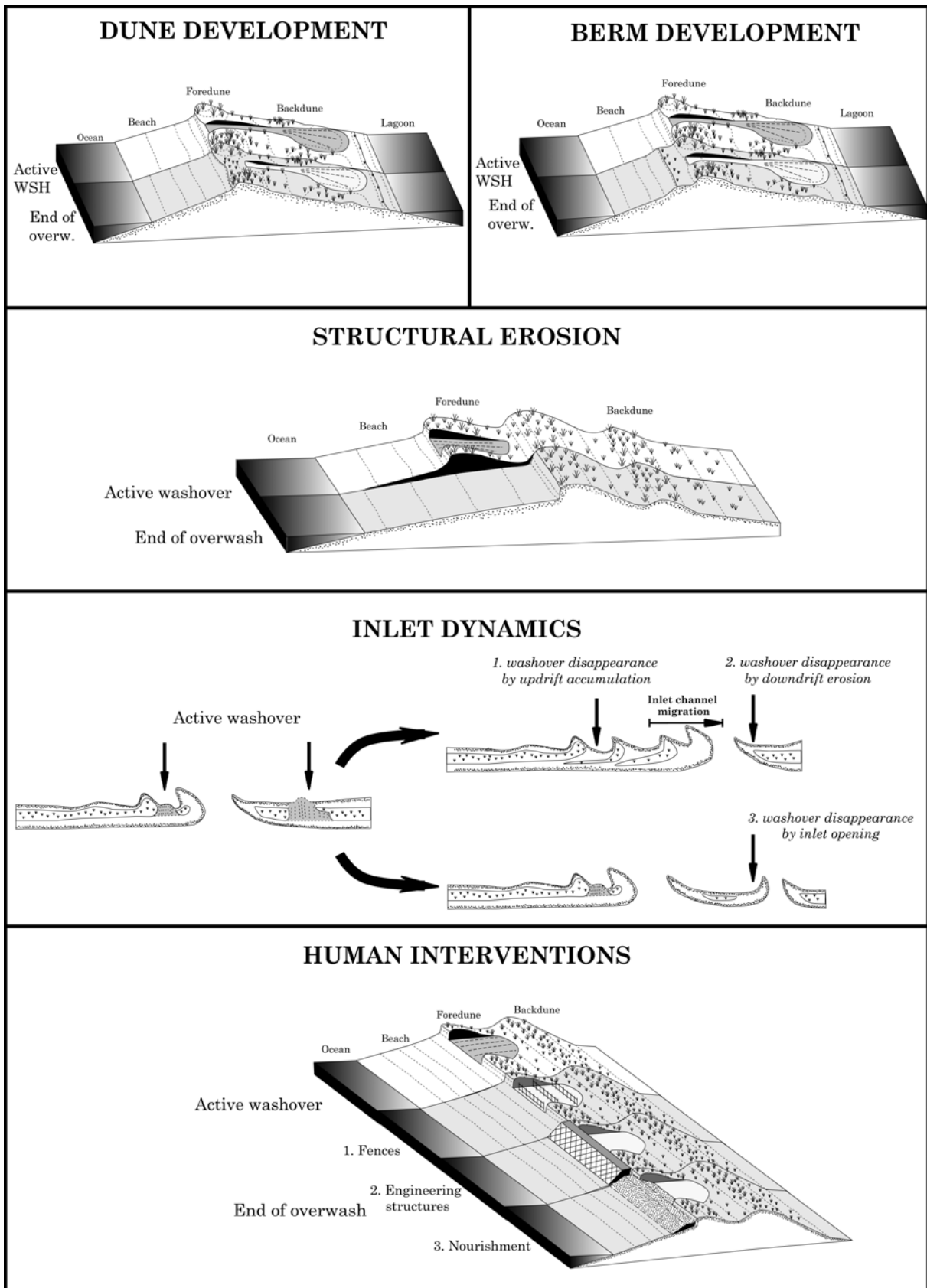


Figure 7.2. Washover disappearance mechanisms.
Note: WSH=Washover; overw.=Overwash.

Inlet dynamics

Three main types of *inlet dynamics* mechanisms were identified: (1) recent accumulation at inlet updrift areas; (2) starvation at inlet downdrift areas, and (3) inlet opening (Figure 7.2).

Washovers present on the immature updrift margin can disappear by the accretion of the spit that accompanies the inlet migration. As the inlet channel migrates, the downdrift margin is eroded. The erosion by *inlet dynamics*, similarly to the washover formation mechanism, is a consequence of the sediment starvation due to the presence of an inlet. The washover completely disappears as well as the dunes around it and eventually all other barrier environments are eroded. Washovers disappear under inlet opening mechanisms when the washover surface is breached and subsequently converted into an inlet channel. Barrier breaching is an ephemeral process caused by overwash. The breaching can either infill and become a washover or if it is hydraulically efficient it will become a new inlet (Kraus *et al.*, 2002). Due to its ephemeral nature, the breaching is not likely to be observed in the aerial photos, but evidence of its occurrence is generally well recognisable.

Human interventions

Human interventions (Figure 7.2) may have a small effect on the coastal sedimentary balance (fences and seawalls), may have dual sedimentary effect (groins and jetties), and may reinforce the sediments on the coast (nourishment). The effect of building fences is a reinforcement of a natural tendency of incipient dunes to develop on the washover mouth. The placement of groins and jetties may lead to washover disappearance by the erosion of the downdrift side and by accretion of the updrift side. In the case of seawalls and revetments constructed immediately seaward of a washover, there is a direct inhibition of further overwash. The nourishment of the beach fronting the washover or of the washover itself is the

only coastal management intervention that actually adds sand back into the littoral system (Pope, 1997). The beach and/or the dune nourishments may temporary inhibit overwash processes, but at the end of the nourishment life-time the washovers may became active again.

7.2.2.3. Overwash evolutionary trend

The evolutionary trend of overwash processes on barrier islands can be evaluated by the analysis of the variation of washover occurrence and washover dimensions. The washover occurrence may be expressed either in the number of washovers/barrier or in density (number of washovers/longshore km/barrier); thus the washover occurrence is expressed for each of the observed aerial photos as a # or #/km. The occurrence of washovers can be classified in four ways: increase, decrease, oscillatory, and be constant. The washover dimensions evolution is mostly related to the variation of overwash magnitude. An increase in overwash magnitude produces the enlargement of the washover dimensions, and vice-versa. The dimensions of the washovers are the horizontal area enclosed by the washover margins and may be expressed in m². The three types of washover dimensions variation are: enlargement, maintenance, and reduction.

The classes of overwash evolutionary trend result from the combination of these two types of behaviour: variation in washover occurrence and variation in washover dimensions (Table 7.2). The evolutionary trend towards an increase of overwash processes results from an increase in the occurrence and/or in the dimensions of the washovers. The decrease in overwash processes occurs when there is a decrease in washover numbers and/or dimensions. The more complex cases are when a reduction in occurrence is associated with an increase in washover dimensions or an increase in washover number is associated with a reduction in washover dimensions.

Table 7.2. Classification of overwash evolutionary trend.

		Washovers dimensions variation		
		enlargement	maintenance	reduction
Variation in occurrence	Increase	Increase of overwash processes		Change in coastal morphology or prevailing mechanism
	Constant	Similar overwash processes <i>*over longer time scales</i>		<i>If WSH division</i>
	Oscillatory*			
	Decrease	<i>If WSH coalescence</i>	Decrease of overwash processes	
Change in coastal morphology or prevailing mechanisms				

Note: WSH = washover

In several cases these complex situations are associated to regional changes in coastal morphology (e.g. due to human interventions or to sediment starvation) or to changes in prevailing mechanisms (e.g. changes in storminess, accelerated sea level rise). In such cases, where the previous conditions are not maintained, the previously observed evolution is not expected in the future and an evolutionary trend cannot be established. However, the above mentioned complex situations can also occur under maintenance of both regional morphology and prevailing mechanisms. In such cases a reduction of washover dimensions associated to an increase in washover occurrences can be explained by a local change in washover morphology, with the division of a previously single washover into several washovers. An enlargement of washover dimensions associated with a decrease in washover occurrences can be explained by the coalescence of several small washovers. If lateral coalescence occurs then average dimensions increase, the number of washovers decrease, and globally there is an increase in overwash processes. On the contrary, when dune development in parts of the washover induces its division, then the average dimensions decrease, the number of washovers increase and globally there is a decrease in overwash processes. However, it should be mentioned that in a barrier, the coalescence of washovers may also be coincident

with an increase in washover numbers if they form at other locations. Also, the washover division may occur in barriers where the number of washovers is increasing, but more often is associated with a decrease in washover occurrences, within the context of dune development.

7.2.3. DISCUSSION OF THE CLASSIFICATION

7.2.3.1. Limitations of the aerial photograph interpretation

The aerial photos appear to be the most adequate data source for the washover classification. Historical aerial photographs are used in a number of coastal studies based on digital mosaic or traditional photo-interpretation, involving storm impact (e.g., Morton and Sallenger, 2003), blowout dynamics (e.g., Dech *et al.*, 2005), sediment budget (e.g. Inman and Dolan, 1989), land-cover shifts (e.g. Gonzalez *et al.*, 2005), coastal hazards (e.g. Moore *et al.*, 1999), future predictions (e.g. McBride and Byrnes, 1997), and others. The use of aerial photographs for washover related studies has been frequently done, especially for post-storm evaluation (e.g. Nordstrom and Jackson, 1995; Stumpf *et al.*, 1996; Morton *et al.*, 2003). However, washover observation, interpretation and measurements based on aerial photographs have several limitations. Aerial photography techniques require interpretation based on an understanding of local coastal processes, geomorphology, and human impacts operating past and present (McBride and Byrnes, 1997). The identification and interpretation of the washovers according to the geomorphologic criteria defined in section 7.2.1.1 and mechanisms classification described in sections 7.2.2.1 and 7.2.2.2 is somewhat dependent on the knowledge and fieldwork experience of the researcher as well as on the quality of the aerial photos and other background information of the study area. This may be responsible for a certain degree of subjectivity in the classification of the washover dynamics.

One of the methodological difficulties in the application of this classification is the definition of active and inactive washover (see section 7.2.1.1). When the overwash is no longer occurring, the washover becomes a “relic structure”, but its characteristics are evident for 5 to 15 years after the overwash, and in complete vegetation recovery, the outline of the fan is often clearly evident (Cleary and Hosier, 1979). In aerial photographs with scales smaller than 1/20,000, taken shortly after the overwash event (less than 1-2 years), the pioneer colonization may be indistinguishable, and therefore the washover may be considered active although overwash is no longer occurring. On the other hand, the overwash debris near the washover mouth may be misinterpreted as vegetation if the photos scale and quality are poor, which is more likely to occur for older flights.

The boundaries of a washover may also be difficult to define, especially if the overwash occurs in sparsely vegetated dunes, or if abandoned tidal creeks are intercepted. Also, it is relatively frequent that the overwash occurs over a previously generated washover. In these situations, if the modern overwash event has smaller magnitude than the older one, and if no other coastal process significantly changed the washover, it may be impossible to distinguish the two sand deposits.

7.2.3.2. Classification guidelines and limitations

Washover classification based on the mechanisms that are responsible for their formation and disappearance relies on identifying the relative importance of the major processes that effect coastal sediments on barrier islands. A major storm striking the coast would generate overwash on many coastlines, with the dimensions of the washover varying according to the coastal morphology. In this case, if the storm did not occur, overwash would likewise not have occurred. But in the case of formation mechanisms such as *structural erosion* or *washout*, the washovers would not occur or have that location unless these

mechanisms operated first. Only the *depression in dune elevation* results from a basic process of overwash in barrier dynamics (Figure 7.1). The other mechanisms result from secondary overwash in the sense that other processes created the threshold conditions for overwash.

The distinction of the dominant mechanism responsible for the formation of the washovers is a key topic of the classification (section 7.2.2.1 and Figure 7.1). Often more than one mechanism is present, or in other cases different mechanisms result in similar coastal morphologic changes. The *structural erosion*, the *inlet downdrift sediment starvation* and the *engineering structure downdrift erosion*, may be deducted from the same coastal change (such as the shoreline retreat and appearance of a washover on a former back-dune depression). To distinguish these mechanisms it is necessary to determine the influence area of a natural or artificial structure that traps sediments. Another difference between erosion by *inlet dynamics* mechanism and *structural erosion* mechanism is that the first may be ephemeral, and eventually disappear as the inlet migrates to a downdrift position. In cases where the distinction of the dominant mechanism is not feasible or the formation of a washover results from an even combination of processes, then the washover dynamics can be classified as dominated by several mechanisms. The formation mechanism of a washover may be, for example, as 0.5 *inlet dynamics* and 0.5 *human intervention*. This means that for the determination of the general classification of a certain barrier, the number of washovers formed by a certain mechanism may not be an integer but a decimal number.

In washover dynamics dominated by structural erosion there is a consistent shoreline retreat resulting from a structural deficit in sediments on the foreshore. The identification of the type of backdune depression that acts as overwash preferential structure (section 7.2.2.1 and Figure 7.1) is not essential for the classification. The intra-dune depressions are important in determining the site for future overwash and may be natural or man made (tracks). The existence of tracks resulted from human actions in the dunes but, in terms of washover

dynamics, they were not the cause of the erosion that allowed overwash to occur. Thus, tracks are features that play a passive role in the overwash occurrence, and the formation mechanism was the *structural erosion*. Similarly, the tidal channels in the backdune are most likely abandoned structures, or at least there are no evidences that the lagoon waters were promoting seaward displacement of the channel head.

The inlet dynamics is the most heterogeneous washover formation mechanism (Figure 7.1). It includes washovers related with sediment starvation and with accretion areas. The common factor is the existence of a large enough inlet (updrift, downdrift, or closed) that determines the sediment transport patterns and magnitudes in the adjacent coastal areas. The washovers generated on the updrift margin of an inlet or at the location of the inlet closure were related to a transitional state between inlet morphologies and dune morphologies.

The overwash may occur through a dune depression generated by washout. The *washout* was considered separately because it requires that the lagoon water level is higher than the foredunes (El Ashry and Wanless, 1968). The washout is an active lagoon process, but for a washover to be dominated by *washout*, subsequent overwash has to occur through the generated foredune depression.

The distinction of the mechanisms responsible for the disappearance of the washover is another key topic of the classification. Again more than one mechanism may be present, and therefore a decimal number of washovers may be related to a particular disappearance mechanism.

Aeolian processes, which operate on a more continual basis than overwash, can deposit or erode sand from the washover fan surface (Kochel and Wamfler, 1989). The disappearance of washovers is possible if the aeolian transported sand is deposited in the washover mouth, and not deflated into the distal fan. The distinction between dune development and berm development is that the first results from aeolian deposition in the washover mouth and the

second from aeolian deposition over a marine deposit (a berm) seaward of the washover. The classification as *berm development* disappearance mechanism can be difficult to distinguish from *inlet updrift accumulation*. The existence of an inlet may provide the necessary sediment retention to allow the development of a beach berm in the areas updrift. However, this positive sediment balance extends over a certain distance updrift from the inlet, and therefore the determination of the inlet influence area is needed to determine which of the processes is the prevailing one for washover dynamics.

As explained for the formation mechanisms, it may be difficult to classify the dominant disappearance mechanism as *inlet downdrift erosion*, *structural erosion* and *engineering structure downdrift erosion*. Additionally, structural erosion may induce washover disappearance in several ways. The necessary shoreline retreat to make the washover disappear can occur suddenly during a major storm, especially if the washover intrusion is relatively small. Another possibility is that the shoreline progressively retreats during regular winter conditions coupled with spring tides, and the washover does not translate landward (for example due to a distal “obstacle” such as a second backdune ridge). In this second case, if a coastal structure is built during the retreating process, the washover disappearance is probably accelerated and a mixed prevailing mechanism has to be considered.

The *human interventions* may be the formation and/or disappearance mechanism, but only engineering structures may have the dual effect. In the case of the formation mechanism, the trampling generates the foredune depressions where overwash processes take place. If dunes were sufficiently high and without these manmade depressions, then dune bluff erosion would probably occur, during storms. Hard engineering structures are more dramatic for overwash persistence since they induce a sedimentary deficit that promotes foredune erosion and overwash processes. This same process, in the case that large bypass of the structure does not occur may lead to the total erosion of previously formed washovers, similar to *structural*

erosion. On the contrary, fencing and nourishment are human actions that, if efficient, result in the termination of overwash processes, producing an inactive washover. Nourishments however have a limited life-time, depending on their volumes, grain size, and coastal characteristics (e.g. Matias *et al.*, 2004). If the time interval between aerial photos is large or if the nourishment has a short life-time, then the disappearance of the active washover may not be observed.

Overwash processes may increase over time if the formation mechanisms become more effective and the disappearance mechanisms become less effective. This balance results in an increase in washover occurrence and/or an increase in washover dimensions over time (Table 7.2). The change in number of washovers over time is the most objective parameter of the classification. This parameter can be used to understand the washover evolution through time for an entire barrier system. However, for comparison of several barriers from the same system, the density of washovers has to be determined, in order to normalise the occurrences with relation to the length of barrier.

The variation of the washover dimensions constitutes a proxy for the evolution of the magnitude of the overwash processes. Two types of evidence are associated with overwash increase: mouth increase and intrusion increase. However, the overwash flow may be influenced by the backdune topography either to disperse or contain the overwash flow (e.g. Schwartz, 1975; Leatherman, 1976; Fisher and Simpson, 1979). The increase of the washover mouth results from the erosion of the lateral margins of the mouth by concentration of the overwash flow (see section 4.4.1), by run-up impingement over the soft dune bluff or by run-up capacity to overwash the relatively low elevation margins of the mouth. If the margins are resilient (such as high dunes or houses), then the increase in overwash magnitude leads to an increase in washover intrusion. The washover area is the best parameter for evaluating the

variation in washover dimensions since the intrusion and the mouth may have different, and in some cases opposite, variations over time.

If the washovers maintain their dimensions through time, it is assumed that there is a continuity of the oceanographic and geomorphologic conditions. This process is common in non-storm overwashes on relatively high washover plains (e.g. the washover plain of GO.3 fieldwork, see section 4.4.1). Several mechanisms contribute to a reduction in washover dimensions, denoting a decrease in overwash magnitude, some of which have already been discussed as disappearance mechanisms of washovers (dune development, structural erosion, and human interventions). *Human interventions* can allow washover to remain active, and can enlarge or reduce its dimensions. Mechanisms of washover maintenance and enlargement due to human intervention and overwash processes are reciprocal. Overwash creates dune gaps that are functional for human purposes (beach access to people and small boats), and these human activities lower the surface elevation allowing the maintenance or increase of overwash. Housing on the washover may reduce its apparent dimensions, but if the overwash magnitude is not reduced during subsequent episodes then an enlargement of other parts of the washover will probably occur, and possible property damage may result.

The situations were there was opposite tendencies of washovers dimensions and occurrences; it was considered that it is not possible to establish an overwash evolutionary trend. A decrease in washover occurrences coincident with a trend towards washover enlargement that does not occur by washover coalescence may be related to differences in the coastal morphology. For example, if structural erosion led to the shoreline retreat and the backdune area is relatively low, then it is possible that overwash leads to the formation of washover plains rather than washover lobes. In such a case, because the washover plains are generally extensive features, then the washover number is reduced but the area is enlarged. But in this case, the coastal morphology was altered and therefore the type of overwash

processes changed, and the observation time has to be extended to understand the more recent evolutionary trend of the barrier. The other situation where it is not possible to determine the overwash evolutionary trend is when the washover occurrences increase but their dimensions decrease. For example, if at the beginning of the study period major storms (50 to 100 year return period) strike the barriers and large scale overwash lead to the formation of extensive washovers. Afterwards, the storms magnitude diminishes and therefore induces the formation of smaller washovers, probably only in the more vulnerable parts of the former features. In this case, the number of washover occurrences may remain similar or even increase, depending on the coastal morphology. Therefore, the changes in storminess through the study period induced changes in the type and dimensions of washovers, and, until full recovery from the major storm is accomplished, a tendency cannot be deduced.

The proposed classifications were developed for barrier islands and were based on direct observations and analysis made by the author. Other washover-related mechanisms described in the literature that were not observed in this study were not included since there is an incomplete knowledge of their occurrence and site-specificities. This includes, for example, flooding by hurricane passage (Fletcher *et al.*, 1995) or El Niño associated processes (Morton *et al.*, 2000), washovers in lacustrine barriers (Bray and Carter, 1992), or gravel-barrier response to sea-level rise (Orford *et al.*, 1995). The classification would benefit from the analysis of other barrier island washovers, in order to refine the established classes and probably to add other formation and disappearance mechanisms. A broader analysis, considering other barrier systems, in other oceanographic settings, may provide data for a quantification of the boundaries between classes, especially for the definition of the tendency of overwash processes.

7.3. CASE STUDY: RIA FORMOSA BARRIER ISLANDS

7.3.1. METHODS OF APPLICATION OF THE CLASSIFICATION

The set of aerial photographs described in Table 7.1 was analysed for the classification of the washovers dynamics of the Ria Formosa barrier island system. The configuration of the barrier islands changed over the study period (see section 3.3.1) fundamentally due to inlet migration. As a consequence, a given coastal area may be included in one island or the next depending on the migration of the nearest tidal inlet. Therefore, the islands were not analysed as independent entities, but in barrier sectors with constant length. Eighteen barrier sectors were defined in the study area (Figure 7.3).

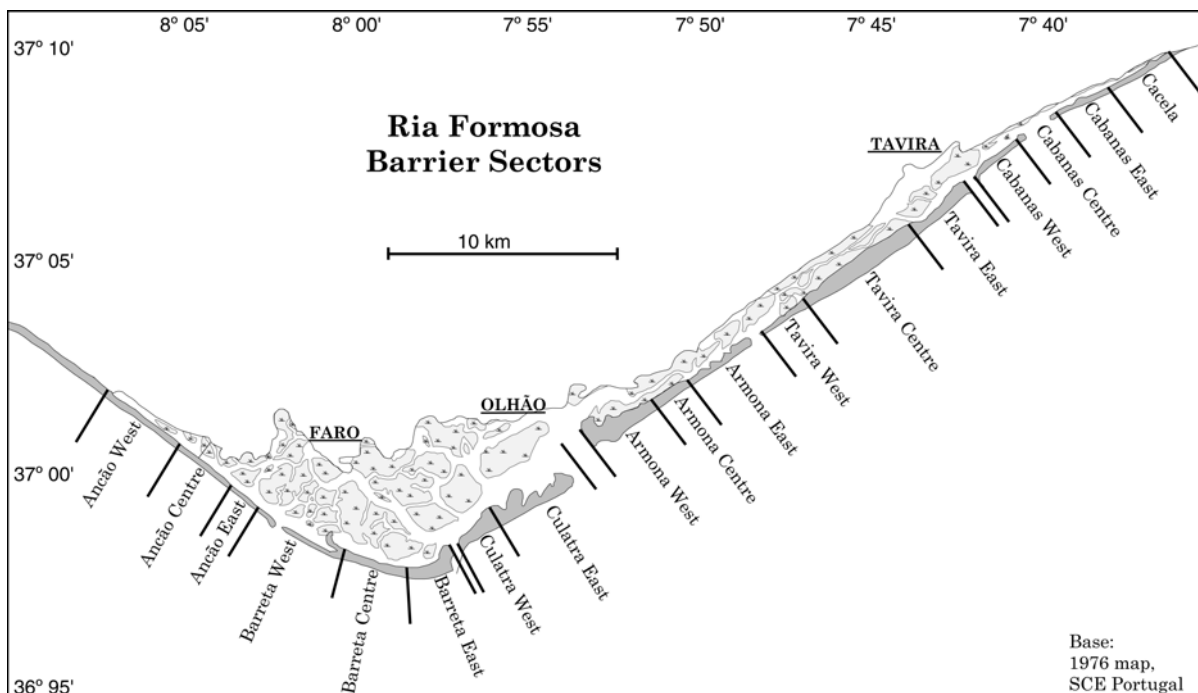


Figure 7.3. Location of the defined sectors for the Ria Formosa barrier islands.

Distinctive characteristics were used to define the sectors (Table 7.3) including geomorphologic characteristics (e.g. part of Armona Island), human interventions (e.g. Ancão

Peninsula), recent coastline evolution (e.g. part of Tavira Island) and inlet migration paths (e.g. Cabanas Island).

Table 7.3. Barrier islands sectors name, length and distinctive characteristics.

Barrier Island	Barrier sector	Length (m)	Distinctive characteristic
Ancão	Ancão West	4,000	Reduced to moderate human pressure
	Ancão Centre	2,900	Urbanised area
	Ancão East	1,700	Moderate human pressure
Barreta	Barreta West	4,300	Ancão Inlet migration path
	Barreta Centre	2,700	Relatively stable barrier
	Barreta East	2,300	Accretion by downdrift jetty construction
Culatra	Culatra West	1,900	Erosion by updrift jetty construction
	Culatra East	4,400	Accretion of recurved spits
Armona	Armona West	3,200	Broad backbarrier areas
	Armona Centre	2,200	Relatively stable area
	Armona East	3,500	Fuzeta Inlet migration path
Tavira	Tavira West	2,300	Shoreline retreat
	Tavira Centre	5,700	Relative stability
	Tavira East	3,000	Accretion by downdrift jetty construction
Cabanas	Cabanas West	2,300	Updrift accretion related to Lacém Inlet
	Cabanas Centre	2,400	Accretion/erosion related to Lacém Inlet
	Cabanas East	2,100	Downdrift erosion related to Lacém Inlet
Cacela	Cacela	2,900	Without inlet channel in the last 50 years

The comparison of the different sets of photos allowed the study of the washover dynamics mechanisms. Each washover was numbered and labelled according to its position in

relation to the western extreme of each island. Complementary observations of the general evolution of the barrier islands and tidal inlets, including shoreline changes, dune development, inlet migration, and human interventions were made. This study was focused on the long-term evolution, but the signals of short- to medium-term evolution were also observed, for example, the formation of beach berm, dune bluffs, beach cusps, high-water marks.

The determination of the formation mechanisms in the study area was made following the interpretation procedures described in Figure 7.4, and the disappearance mechanisms following the ones described in Figure 7.5. Any newly formed washover had to meet the geomorphologic criteria described in section 7.2.1.1. The determination of the formation mechanism was performed by answering the yes/no questions, from the top to the bottom of the scheme (Figure 7.4), complemented with the explanations for each of the mechanisms given in section 7.2.2.1. The determination of the disappearance mechanism was performed by answering the yes/no questions, from the top left to the bottom of the scheme (Figure 7.5), complemented with the explanations for each of the mechanisms given in section 7.2.2.2.

For the georeferenced photos, the washovers and the shoreline were digitised using ArcGIS software, from which washover mouth, intrusion and total area were calculated. The measurements of dimensions were analysed considering each of the barrier islands sectors previously defined (Figure 7.3 and Table 7.3). For each sector, for each selected year (1947, 1976, 1985/89, and 2001) the average, standard deviation (st. dev.), minimum and maximum of the washover mouth, intrusion and total area were calculated. For all aerial photo sets, the number of washover, as well as the density of washovers was calculated. The density was obtained by considering the number of active washovers per km of barrier sector.

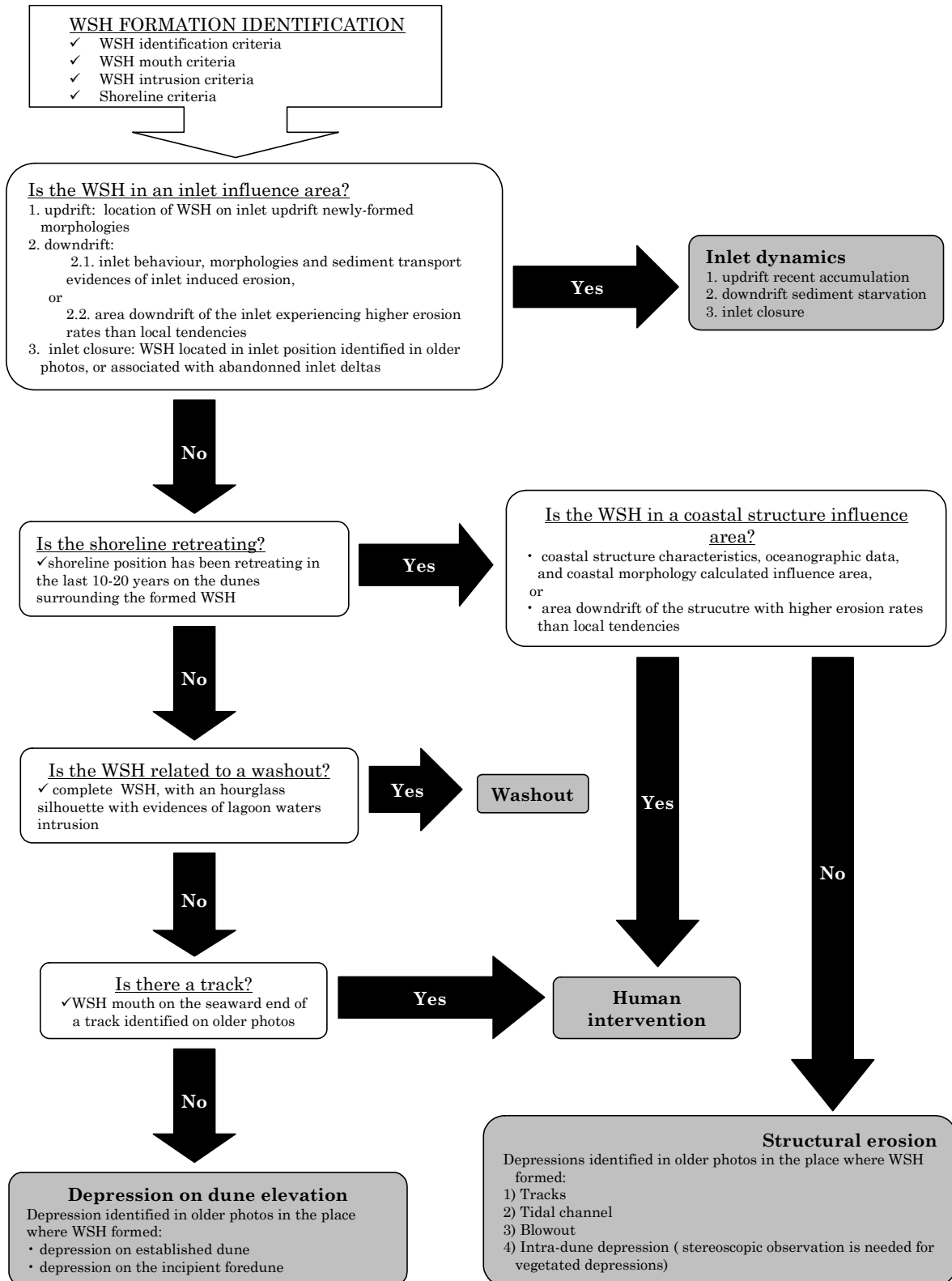


Figure 7.4. Criteria for the determination of washover (WSH) formation mechanism.

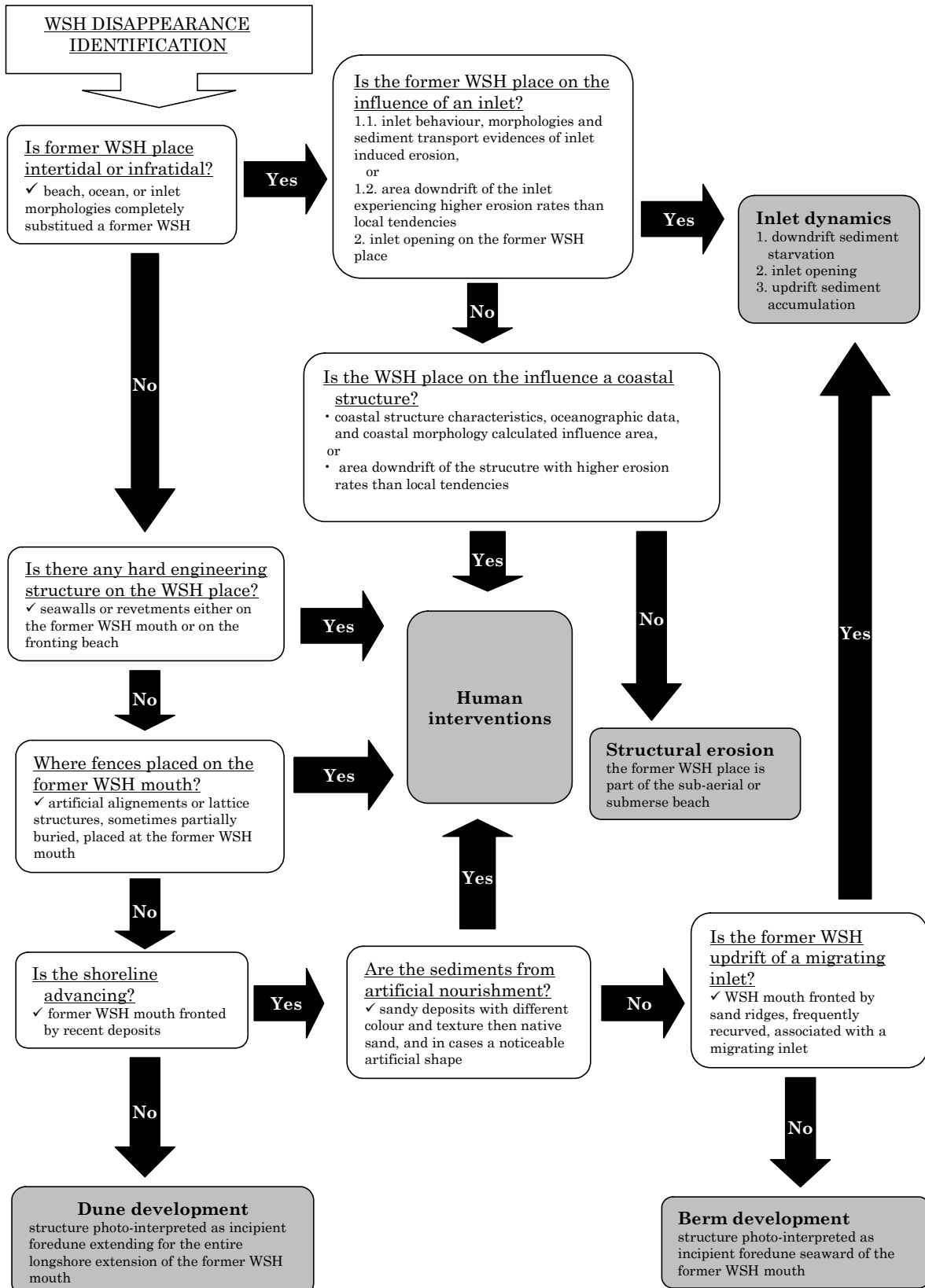


Figure 7.5. Criteria for the determination of washover (WSH) disappearance mechanisms.

7.3.2. RESULTS OF THE CASE STUDY

The classification of the washover dynamics mechanisms described in section 7.2.2 was applied to the Ria Formosa barrier sectors according to the methods described in section 7.3.1. In some cases, it was noted that two or more mechanisms contributed to the formation or disappearance of the washovers. Generally, the integrated coastal analysis of the coastal sectors allowed the identification of which of the identified processes was dominant in the barrier dynamics. The main formation mechanism was defined for each of the 209 newly formed washovers, identified for the study period, based on the procedures described in Figure 7.4. The main disappearance mechanism was defined for each of the 303 washovers that disappeared during the study period, based on the procedures described in Figure 7.5.

The application of the classification showed that there was a large variability of mechanisms of washover dynamics. Both temporal and spatial variability was identified, including differences in intra-barrier-sectors and inter-barrier-sectors. The most important mechanisms of the barrier system, for the 54 years analysed, were the following.

7.3.2.1. Formation mechanisms

The most frequent formation mechanism was *inlet dynamics* (Figure 7.6) that induced the formation of about 57% of the washovers. The accumulation and erosion by *inlet dynamics* had similar contributions, 57% and 40% respectively (Figure 7.7, as examples). Inlet closure induced only a few washovers, probably because this process has longer recurrence intervals. In two barrier sectors (Barreta West and Cabanas West, see Figure 7.3 for location of sectors) *inlet dynamics* induced 100% of washovers that formed during the study period. In three other sectors (Culatra East, Armona East and Cabanas Centre) the *inlet dynamics* induced the formation of more than 80% of washovers.

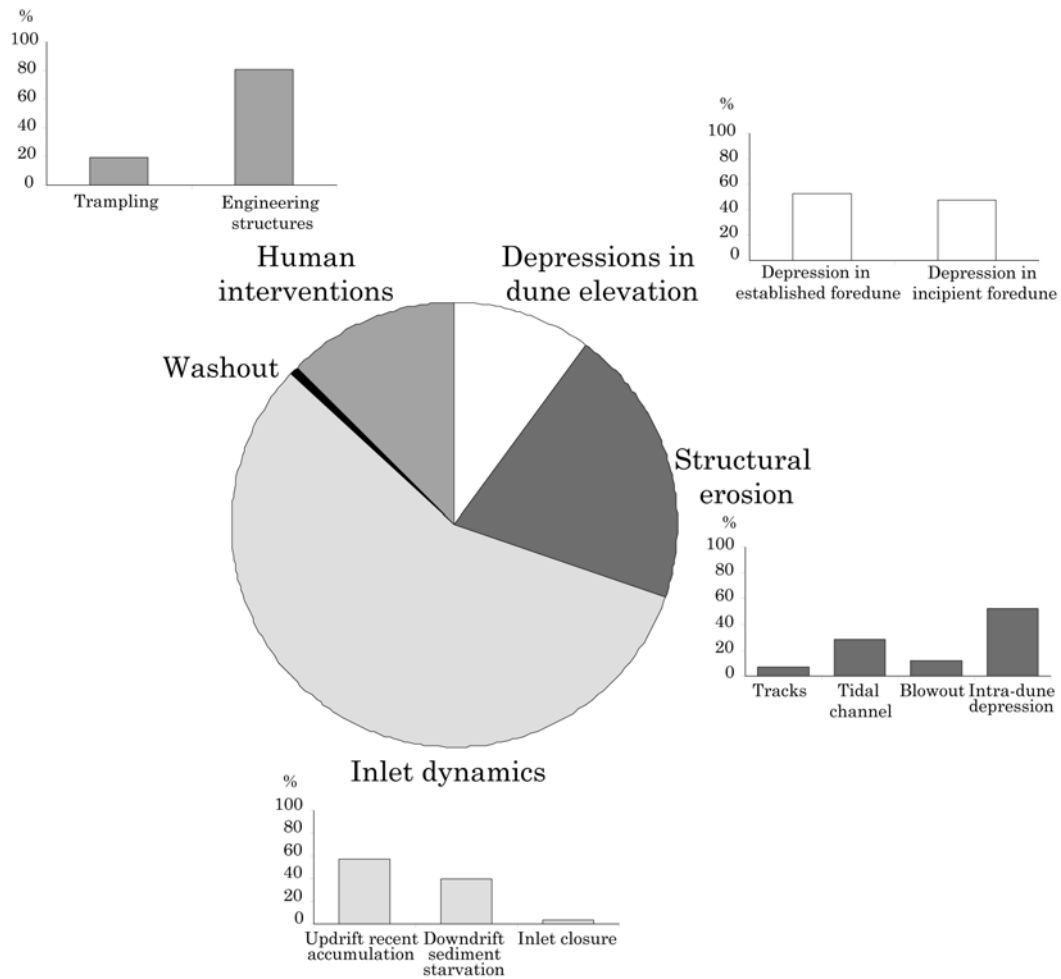


Figure 7.6. Formation mechanisms of the washovers of the Ria Formosa barrier islands.

Depressions in dune elevation were the cause for the generation of only about 10% of the washovers, as an isolated formation mechanism. The formation of washovers through *depressions in dune elevation* occurred equally on established foredunes (52%) and in incipient foredunes (48%, Figure 7.6). The *depressions in dune elevation* mechanism was not the dominant mechanism for any of the 18 barrier sectors, but accounted for about 45% of the washovers formed on Tavira Centre sector.

Structural erosion, was the most important formation mechanism in sectors without tidal inlets (e.g. Ancão West and Cacela, at the two mainland attachment locations of the barrier system, Figure 7.3). Generally structural erosion induced the formation of a washover

in undifferentiated intra-dune depressions (Figure 7.8) however, the interception of tidal channels by shoreline retreat was also important (about 30% of *structural erosion*).

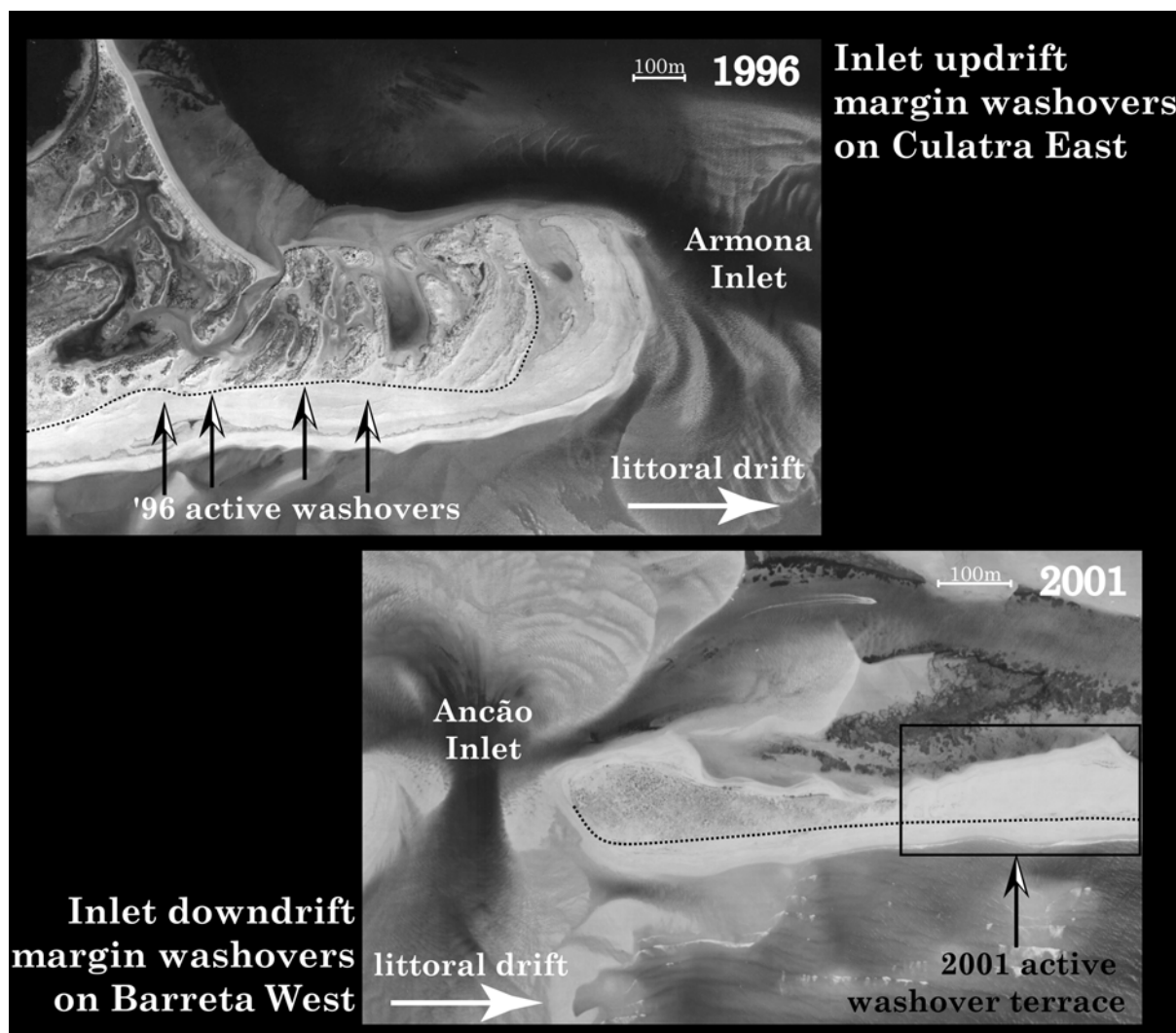


Figure 7.7. Examples of washovers formed by inlet dynamics mechanisms. The washovers located on Culatra East sector, updrift of Armona Inlet, were formed by updrift accumulation. The washovers located on Barreta West sector, downdrift of Ancão Inlet, were formed by downdrift erosion. For location of barrier sectors see Figure 7.3, for location of tidal inlets see Figure 3.1.

The least significant mechanism was *washout* (0.5%). This process occurred only in Cabanas Centre sector, where the backdune morphology was particularly low and the foredune was immature.

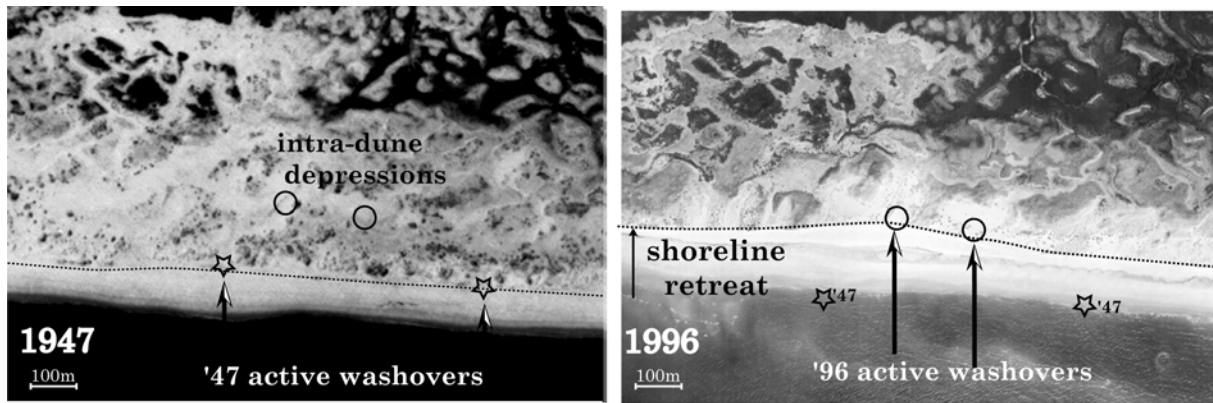


Figure 7.8. Example of the formation and the disappearance of washovers, on Tavira West sector. The formation mechanism was the structural erosion with interception of intra-dune depressions (circles in the photos). The washovers that disappeared by structural erosion are shown by the stars on the photos.

The *human interventions* mechanisms that contributed most to washover formation were the coastal engineering structures (Figure 7.6). The most important *human intervention* was the construction of the Faro-Olhão jetties that artificially stabilised the inlet channel, and induced significant downdrift sediment starvation on Culatra West sector (section 3.3.1). On Ancão Centre sector, 75% of the washovers formed by *human intervention*, but in this case due to foredune trampling. The Ancão Centre sector aside from the washovers formed by trampling also had urban development that completely destroyed the dunes. However, a significant part of this sector was not analysed because the buildings and roads conditioned and in some cases inhibited the sedimentary transport and deposition. Therefore, areas where urban development was more intense and it was not possible for the sedimentary criteria to be applied were excluded from this analysis: parts of Ancão Centre, Culatra West, and Armona East.

7.3.2.2. Disappearance mechanisms

Several mechanisms were responsible for washover disappearance and all were relatively equal in importance in the Ria Formosa (Figure 7.9). The most frequent disappearance mechanism was *dune development* (33%). *Structural erosion* and *inlet dynamics* were almost equally important (19% and 24%, respectively). The natural

mechanisms associated with accretion (*dune development*, *berm development*, and accumulation by *inlet dynamics*) were dominant (about 60%) in relation with the ones associated with erosion (*structural erosion* and erosion by *inlet dynamics*).

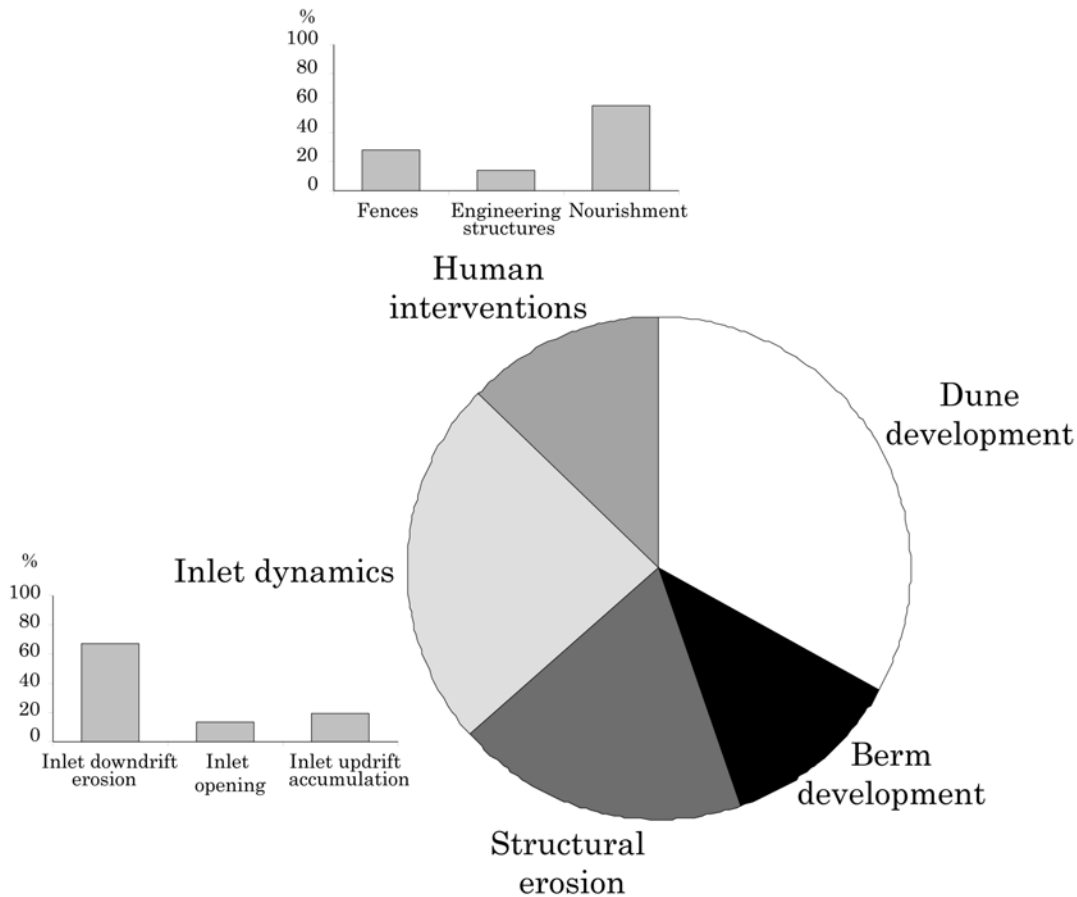


Figure 7.9. Disappearance mechanisms of the washovers of the Ria Formosa barrier islands.

The *dune development* mechanism was the most ubiquitous mechanism of washover disappearance, occurring in almost every barrier sector, with the exception of Culatra West sector. The relative importance of *dune development* for washover disappearance was variable, between 100% (Barreta Centre) and 2% (Cabanas East). *Berm development* was a relatively less frequent mechanism (12%), even if in certain sectors it was the dominant mechanism (e.g. Cabanas Centre, Figure 7.10). The *structural erosion* was infrequently the

dominant disappearance mechanism of washover dynamics, but its occurrence was noticed in 50% of all barrier sectors.

The *inlet dynamics* downdrift erosion mechanism was clearly dominating (67%) the inlet processes responsible for the disappearance of the washover (Figure 7.9). *Inlet dynamics* was the prevailing mechanism only for Cabanas East sector, but it led to the disappearance of washovers in 10 of the 18 barrier sectors. Inlet opening over a formed washover occurred only once during the study period in the whole system (in Cacela sector).

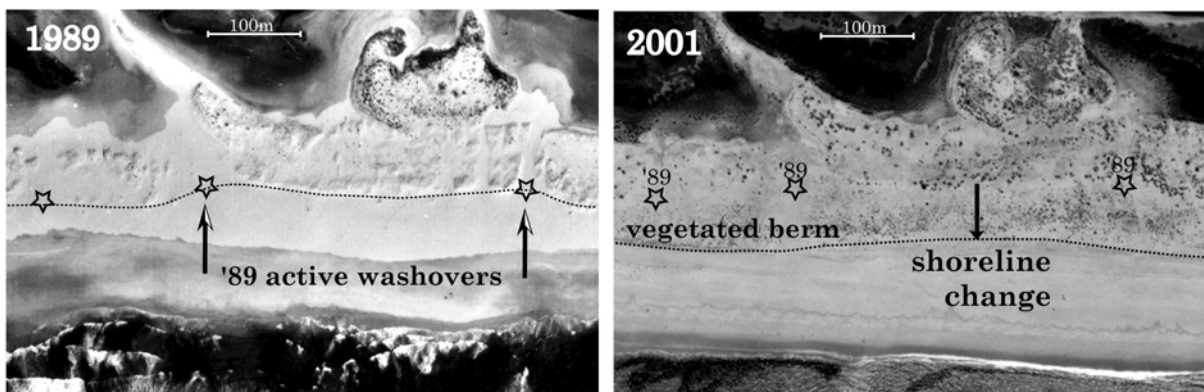


Figure 7.10. Example of the disappearance of washovers by berm development, on Cabanas Centre sector. The washovers that disappeared are shown by the stars on the photos. Note that the three marked washovers were complete in 1989.

Human intervention was not found to be the dominant mechanism of washover disappearance for any of the barrier sectors, with a maximum contribution of 32% in Culatra East. The human intervention that contributed most to washover disappearance was nourishment (58%, see Figure 7.11 as examples of human interventions). The two coastal structures that led to washover disappearance were the Faro-Olhão Inlet jetties and Tavira Inlet jetties that induced downdrift shoreline retreat. These two coastal engineering structures accounted for only 14% of the *human intervention* mechanisms.

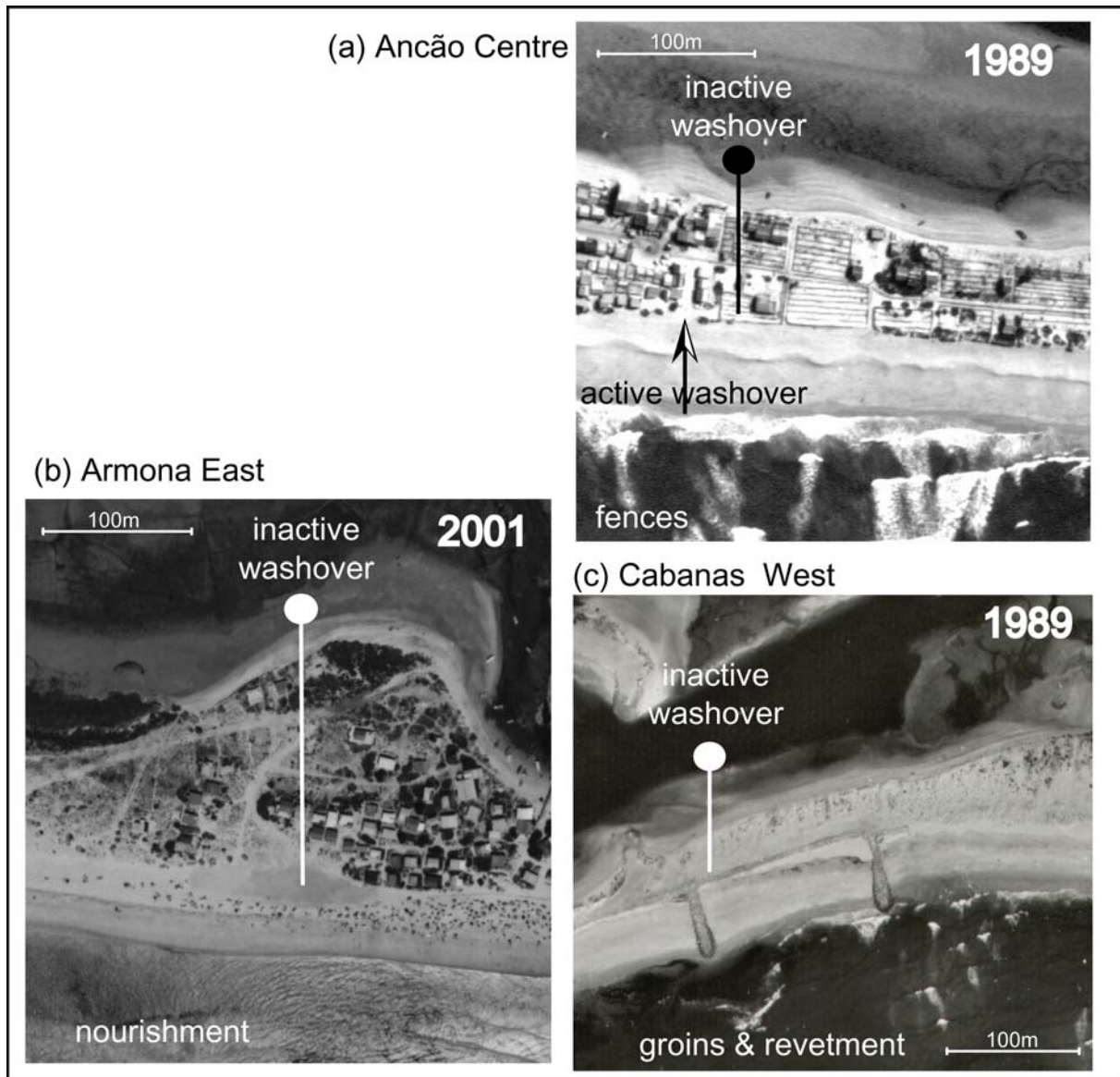


Figure 7.11. Example of the disappearance of washovers by human interventions: (a) placement of fences on Ancão Centre sector, (b) nourishment on Armona East sector, and (c) groins and revetment on Cabanas West sector.

7.3.2.3. Overwash evolutionary trend

A total of 369 washovers were observed for all 18 sectors (defined and located in Figure 7.3 and Table 7.3) in the Ria Formosa between 1947 and 2001. A maximum of 152 simultaneous washovers were observed in 1976 and a minimum of 45 washovers were observed in 2001 (Figure 7.12). The number of washovers was relatively stable for the first 25 years of the study period, and increased dramatically between 1972 and 1976 (about 38%).

During the last 25 years there was a fairly constant but rapid declining of washovers number, at a rate of -4 washovers/year.

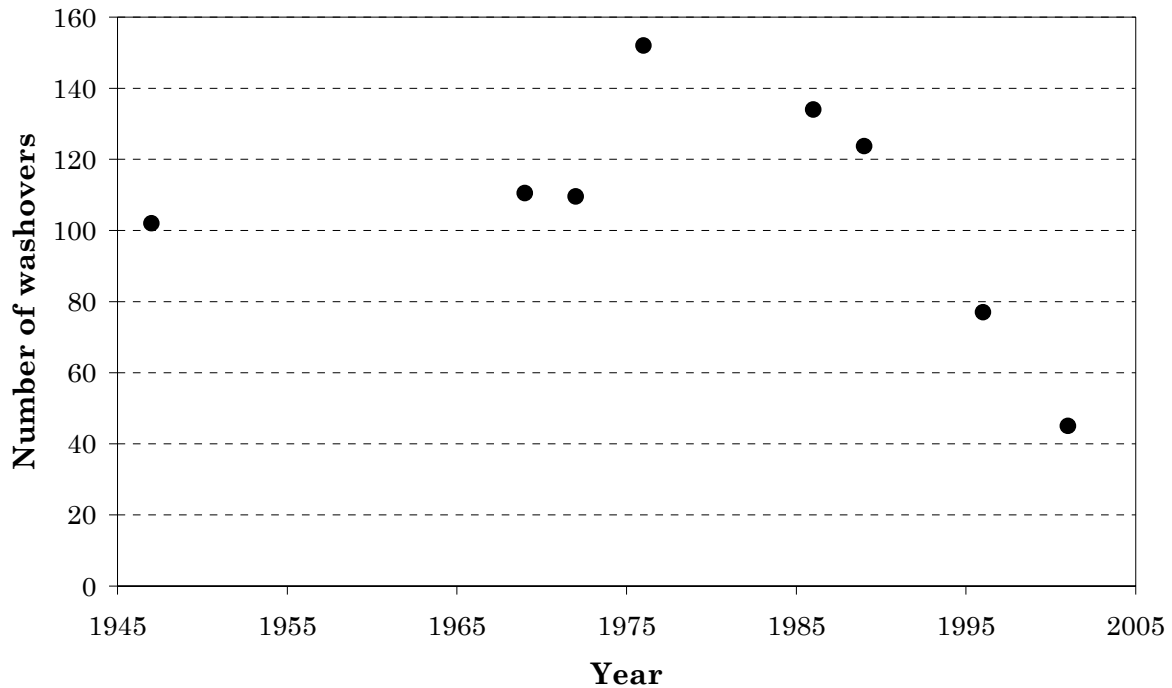


Figure 7.12. Evolution of the number of washovers for the Ria Formosa barrier islands, through the study period.

Over the total shoreline length that was analysed (almost 54 km), the maximum washover density for the entire study period (Figure 7.13) was observed in Cabanas East (about 24 washovers/km), and the minimum was in Barreta Centre (less than 2 washovers/km). The average density was about 7 washovers/km, and only 22% of the sectors had densities higher than 10 washovers/km.

The washover dimensions were only calculated for the georeferenced sets of aerial photographs (1947, 1976, 1985-89, 2001, Table 7.1). The average width of washover mouths was 86 m (st. dev.= 195 m), the average length of washover intrusion was 53 m (st. dev.= 40 m), and the average washover area was 4,300 m² (st. dev.= 13,500 m²). The maximum width of washover mouth was 2,071 m and the maximum length of washover intrusion was 254 m. The minimum washover mouth and intrusion was about 5 m.

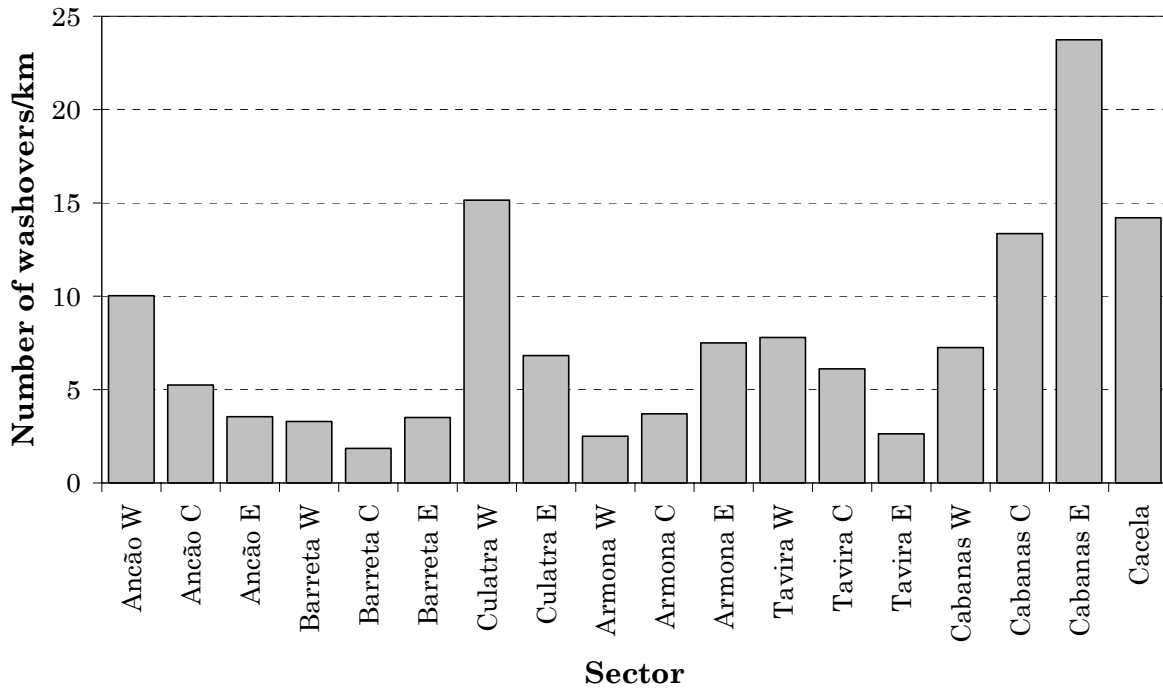


Figure 7.13. Density of washovers for all barrier sectors, considering the entire study period.

The distribution of the washover dimensions (mouth *versus* intrusion, Figure 7.14) did not show significant changes through time. However, the smallest washovers were measured either in 1989 or 2001. The average washover mouth and intrusion were both greater in 1947, but the smallest mouth was recorded in 1989 while the smallest intrusion was recorded in 2001. The data from the Ria Formosa showed that there is a slight tendency to an increase in washover mouth with the increase in washover intrusion. However, the relationship between the mouth and the intrusion (Figure 7.14) is not significant for any of the selected dates, but significant when all data is considered ($R=0.31$, for linear regression). There seems to be a limit of about 250 m for washover intrusion, even considering very wide washover mouths. This limit may be related with the overwash flow capacity for sand transport and/or with the barrier island width at those locations. The overwash flow is retarded as it progresses through the dunes, and once the overwash reaches the lagoon waters there is an abrupt loss of the flow capacity (Chapter 4).

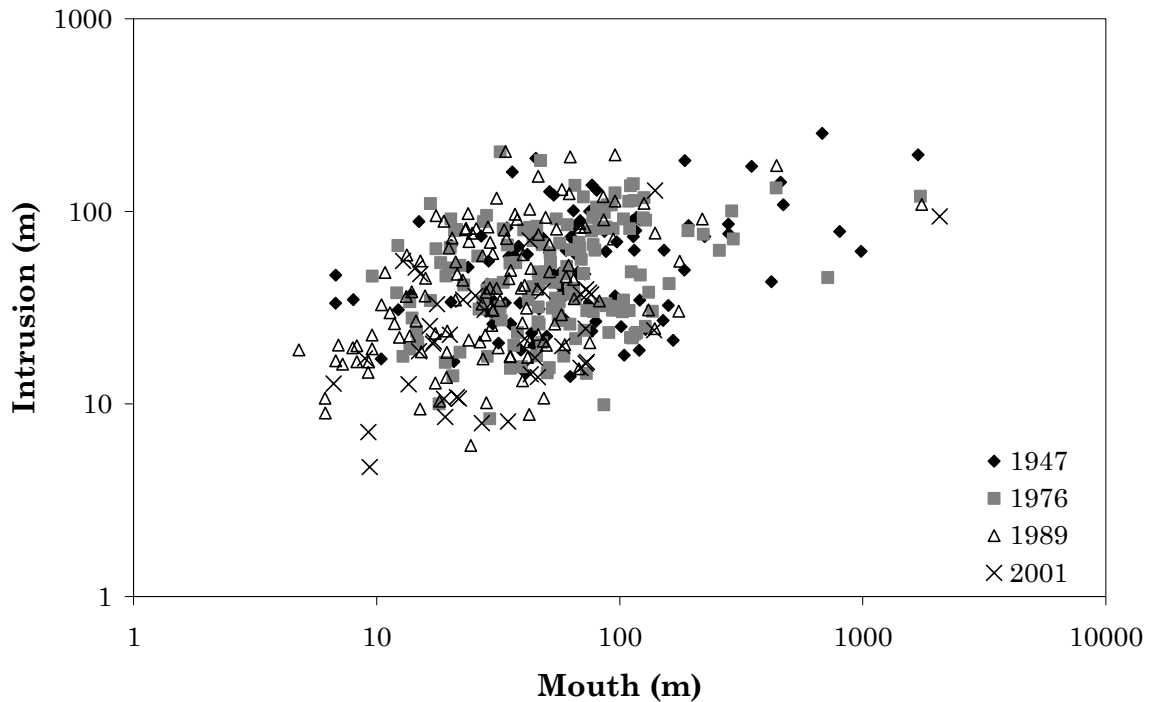


Figure 7.14. Distribution of the washover mouth *versus* intrusion, considering all barrier sectors, for the selected georeferenced aerial photos.

The largest average washover mouth and intrusion were found in the sectors of Barreta Island (reaching 760 m and 140 m, respectively). The smallest average mouth was recorded in Ancão Peninsula (1976 and 1989) and in Cabanas Island (1947 and 2001), while the smallest average intrusions varied between Ancão (1989), Armona (2001), Tavira (1976) and Cabanas (1947) Islands.

In general terms, the washovers of the Ria Formosa had a reduction of their average dimensions over the last 50 years. The average washover area was about 7,420 m² in 1947 and about 2,900 m² in 2001. This reduction was related to a reduction in washover average intrusion (a reduction of about 47% between 1947 and 2001), whereas washover average mouth width had an oscillatory evolution. A part of the average washover reduction was due to dune development on intermediate and distal parts of the washovers, which in some cases caused washover division (see Figure 7.15 as an example). The human intervention in

washover maintenance, enlargement and reduction was relatively unimportant compared with the natural processes.

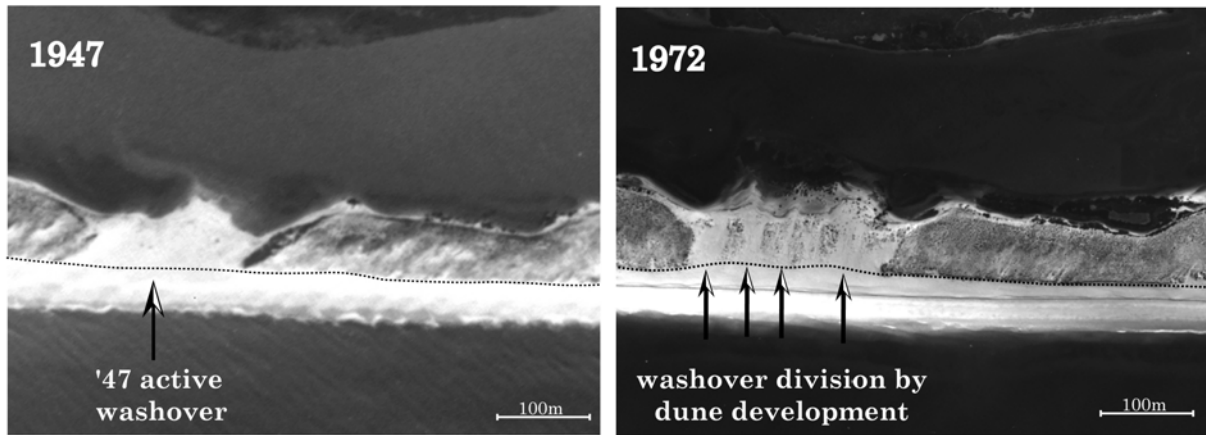


Figure 7.15. Example of the evolution of a washover, with division due to intermediate and distal dune development, on Ancão West sector. Note that in this case the washover occurrences increased but washover dimensions decreased.

The Ria Formosa overwash evolutionary trend can be deduced from two main aspects: a decrease in washover occurrence in the past 25 years, and a global trend toward a reduction of the average washover dimensions. The application of the domains defined in Table 7.2, allow the definition of the evolutionary trend of the Ria Formosa as a barrier system in a trend towards a *decrease of overwash processes*.

7.3.3. DISCUSSION OF THE CASE STUDY

In the case of the Ria Formosa, the main formation mechanism of washovers was *inlet dynamics* (Figure 7.6), therefore, the washovers that were identified and studied were mainly secondary structures that were generated by inlet processes. Because of this, the Ria Formosa barrier island washover dynamics was classified as “*inlet dynamics dominated*”. The *updrift recent accumulation* was mainly due to the formation of the updrift spits of the Armona Inlet (Culatra East sector), Fuseta Inlet (Armona East sector) and Lacém Inlet (Cabanas Centre and East sectors). In the first case, the reduction of the Armona Inlet was accompanied by a remarkable growth of the updrift Culatra Island, at a rate of about 52 m/year (Dias, 1988). In the second case, the Fuseta Inlet width reduction was dramatic (inlet width about 2,050 m in 1964 and 130 m in 1996, Vila-Concejo, 2003) leading to the formation of a low-lying barrier stretch of about 3,500 m. In the third case, the whole Cabanas Island grew during the study period forming the updrift margin of Lacém Inlet (as described in Chapter 3, section 3.3.1). The Armona and Lacém Inlets, and the second part of the Fuseta Inlet evolution followed the typical low-energy migration patterns (Vila-Concejo *et al.*, 2002) where the eastward migration is accompanied by strong constructional processes on the updrift barrier leading to inlet width reduction (Pilkey *et al.*, 1989). Therefore, the *updrift recent accumulation* at the inlets following the low-energy migration patterns is one of the main mechanisms of washover formation in the Ria Formosa. The other mechanism of inlet dynamics contributing to the washover dynamics of the Ria Formosa was the *downdrift sediment starvation* at the margins of Fuseta Inlet (Tavira West sector) and Lacém Inlet (Cabanas East/Cacela sectors). The complex combination and timings of the washovers formed by inlet updrift and downdrift dynamics was responsible for the peak in washover occurrences between 1972 and 1976 (Figure 7.12). During this period, the updrift margins developed enough to induce the growth

of immature and frequently overwashed low-lying barriers, but this development trapped the sediments and caused erosion and overwash on the downdrift margins.

Because the Ria Formosa is a multi-inlet barrier island system, where inlets migrate, most of the system is directly or indirectly influenced by tidal inlets. In the few sectors where there is small influence of inlets, other mechanisms became dominant, and the washover formation was due to the mechanisms of *structural erosion* or *human intervention*. The Ancão West sector, Tavira Centre sector and the eastern part of Cacela sector were dominated by structural erosion, with shoreline retreat rates of: 0.8 m/year for Ancão West (Ferreira *et al.*, *in press*); 1.3 m/year for Tavira Centre (Garcia *et al.*, 2005) and 1.5 m/year, for eastern Cacela (Matias, 2000). The retreat rates were relatively small but were sufficient to allow the overwash intrusion over the dune depressions located landward of the eroded former foredune. In the Tavira Centre sector, where the shoreline retreat was very small, the washovers formed directly on the foredune, and the second mechanism of washover formation in this sector was therefore *depression in dune elevation*.

The case of Culatra West sector was complex because the strong shoreline retreat could be attributable to the updrift Faro-Olhão Inlet (*inlet dynamics* mechanisms) or to the engineering structures that were built to stabilize that inlet (*human interventions* mechanisms). The artificial stabilization of the inlet with long jetties caused important effects on the littoral physiography, as well as in the hydrodynamic behaviour of the lagoon, as a consequence of the capture of a large tidal prism, the disruption of the natural longshore transport pattern, and the erosion induced by the large ebb jet flow (Andrade, 1990). Because the major global effect attributable to these engineering structures was the drastic reduction of the downdrift sediment budget (Salles, 2001), the formation of the washovers at Culatra West sector was attributed to *human interventions* mechanisms.

The main disappearance mechanism was *dune development* (Figure 7.9); therefore, the washovers that were identified and studied mostly developed dunes on the top of the overwashed surface. However, conversely to what was obtained for the formation mechanisms, the disappearance mechanisms were relatively equal in importance. This was probably due to the nature of disappearance mechanisms, i.e., the mechanisms that operated on a continual basis after the end of overwash. In the case where no other mechanism operates, then dune development is expected to occur. This is why dune development occurs in almost every barrier sector, but on average only accounts for 33% of the total washover disappearances. It was observed that *inlet dynamics* dominates the formation but not the disappearance of the washovers of the Ria Formosa. The downdrift erosion associated with inlet migration induces similar percentages of formation (Figure 7.6) and disappearance (Figure 7.9) of washovers, but the updrift accumulation induced about 33% of washover formation but only about 5% of washover disappearance. On the updrift immature margins of migrating inlets, washovers were formed but the new spits that encompass the inlet migration develop mostly downdrift of the incipient foredunes, with a very limited seaward component.

Human intervention was the least important mechanism of washover disappearance, and resulted mostly from nourishment operations and from the erosion on the downdrift of engineering structures (Tavira Inlet jetties and Faro-Olhão Inlet jetties). Most of the nourishments were part of a major program performed in 1999/2000 where about 2,650,000 m³ were dredged from the lagoon channels (Ramos and Dias, 2000). The dredged sediments were placed on the beach and dunes or in the nearshore when they were too fine (Dias *et al.*, 2003), and in Cacela sector the dunes, washovers and a recently formed tidal inlet were completely covered with dredge spoils (Matias *et al.*, 2005). The sediments nourished almost all barriers of the system (except Barreta and Culatra Islands), and were responsible for the disappearance of washovers in Tavira Centre, all Cabanas sectors and Cacela sector.

During the study period, a general decrease in washover occurrence was noticed, especially since 1976 (Figure 7.12). The variation of washover dimensions showed a general tendency towards a reduction, evidenced mostly by a reduction of washover intrusion. These two variations implied a tendency for a decrease in importance of overwash processes in the Ria Formosa. This can be related to an overall tendency for vertical barrier accretion, an increase in inlet maturity, and/or a decrease in the storm frequency. The vertical accretion of barriers due to dune development can be a consequence of smaller overwash and inlet landward sedimentary contributions. Moreover, it was observed that there was a relation between the occurrence of major storms and the inlet cycles for the low-energy flank of the Ria Formosa (Pilkey *et al.*, 1989; Vila-Concejo *et al.*, 2002). Considering that a decrease in storm frequency occurred, then less overwash occurred, large inlets did not open, and dune development was enhanced. However, it must be hypothesized that the study period corresponded to a situation in-between major storms, i.e. those with long return periods (greater than 50 years). Kochel and Wampfler (1989) and Leatherman (1976) observed different relative roles of overwash and aeolian processes for the same barrier island because of differences in the timing and duration of the study period. Therefore, in this alternative scenario, a dramatic change in the washover occurrences and dimensions may be expected in the future in the case that a major storm, or set of storms, occurs.

7.4. CONCLUSIONS

The classification of the washover dynamics provides a systematization of the observed processes, incorporating the more important formation and disappearance mechanisms. This classification addresses the mechanisms of washover dynamics (i.e. the causes), instead of analysing the washover occurrence characteristics (i.e. the effects). For the development of the classification a set of aerial photographs covering the Ria Formosa barrier islands, dating from 1947 to 2001, were analysed. The determination of the coastal processes governing coastal evolution and the washover dynamics was based on the photo-interpretation and regional literature. The classification was developed by grouping the processes into general broad mechanisms of washover formation and disappearance. The identified mechanisms of washover formation were: (1) *depressions in dune elevation*; (2) *structural erosion*; (3) *inlet dynamics*; (4) *washout*; and (5) *human interventions*. The *depressions in dune elevation* may be in the foredune or in incipient dune, and the *structural erosion* may induce the formation of washovers in tracks, tidal channels, blowouts or in undifferentiated intra-dune depressions. *Inlet dynamics* may induce washover formation on the updrift margin where there is recent accumulation, on the downdrift margin due to erosion, or at the location of a former inlet channel. The *human interventions* that promote washover formation are the foredune trampling and the engineering coastal structures that induce downdrift sediment starvation. The identified disappearance mechanisms were: (1) *dune development*; (2) *berm development*; (3) *structural erosion*; (4) *inlet dynamics*; and (5) *human interventions*. Similarly to the formation mechanisms, the *inlet dynamics* may induce washover disappearance by updrift accumulation, downdrift erosion or by opening of inlets in former washovers. The *human interventions* that induce the cessation of overwash are the placement of fences, the building

of engineering structures (transversal structures or longitudinal structures) or nourishment (the frontal beach or the washover).

The classification of the overwash evolutionary trend was defined by considering two types of washover variations: the variation in washover occurrences, and the variation of washover dimensions. The variations in washover occurrence may be towards an increase, decrease, be constant or oscillatory through time. The washover dimensions may be enlarged, reduced or maintained through the study period. The combination of the variation of occurrences and dimensions of the washovers, define a trend of an increase or decrease, or similarity of overwash processes. In cases of change in coastal morphology or prevailing mechanisms, a tendency can not be derived from the study period.

The Ria Formosa barrier islands were the case study for the application of the developed classification of washover dynamics. The global classification of the barrier system was that the washover formation is dominated by *inlet dynamics* and their disappearance was mainly due to *dune development*. The overwash evolutionary trend of the barrier system was towards a decrease in overwash processes. The classification showed the importance of the tidal inlets in the islands morphology and sedimentary balance. In some cases, the overwash was almost chronic (as in the case of the Barreta East), because it is on the migration pattern of the Ancão Inlet. In other cases, the overwash was related to transient immature states of dune development, subsequently to spit formation on the updrift inlet margin (as in case of Culatra Island and almost the whole of Cabanas Island). The washover dynamics was mostly related with natural processes, however *human interventions* accounted for 12% and 13% of the formation and disappearance mechanisms, respectively.

The classification of washover dynamics is useful to understand the integrated coastal processes and also to define the areas vulnerable to future overwash processes. The most vulnerable areas may not be the ones exhibiting more washovers, but the ones with no recent

history of overwash but prone to the mechanisms that were observed to dominate the washover dynamics in the barrier system. In the case that *depressions in dune elevation* was the dominant formation mechanism, the most vulnerable dunes are the ones with lower foredunes, at the time of the classification. However, if a barrier system is dominated by *inlet dynamics*, then the areas more vulnerable to overwash are related to the ones that have higher inlet hazard (as determined for the study case by Vila-Concejo *et al.*, *in press b*). In other areas, where *structural erosion* is the dominant mechanism, a shoreline prediction analysis is the most useful tool to determine overwash potential areas (e.g. for Ancão Peninsula, Ferreira *et al.*, *in press*). In such a case, the analysis has to be complemented with digital terrain models (for intra-dune depressions identification), blowout dynamics studies, tidal channel patterns analysis, etc. When *human-interventions* are the dominant mechanisms for washovers dynamics, the urban planning and management options may be the more determinant factor in washover dynamics.

The disappearance mechanism provides information that may be useful if intervention actions are being considered to artificially close the washovers. If *dune development*, *berm development* or *inlet updrift dynamics* are the dominant disappearance mechanism, there may be no need for human intervention because the coastal dynamics will probably naturally infill the washovers, at a rate related with the sedimentary balance, the wind regime and the availability of dry sand. If the rate of dune recovery is relatively slow, then fencing is an option. However, if *structural erosion* is the main mechanism for washover disappearance, the fences would probably be destroyed in a short-period after their placement. In this case, beach or dune nourishment would probably constitute a better option for delaying dune/washover erosion.

The overwash evolutionary trend is of most importance for coastal management because it determines the strategy for coastal planning. The tendency for an increase in overwash

processes in a given coastal area may abbreviate the timing of coastal protection, determine the need for relocation plans, and alter the geometry of future urban expansion. The tendency for a decrease in overwash processes does not necessarily imply less need for coastal planning. For example, a decrease in washovers dominated by *inlet dynamics* may reflect ultimate stages of inlet maturity, and in such a case, special attention has to be given to barrier breaching in updrift locations. In cases of massive urban development, washover formation is no longer possible but an increase of overtopping and coastal flooding may substitute the overwash processes.