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COASTAL FOREDUNES AS A RESILIENT FACTOR. THE CASE OF THE BEVANO RIVER MOUTH NATURAL RESERVE, RAVENNA (ITALY).

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General introduction

Coastal dunes are natural accumulations of sand formed by winds. Their occurrence, size and shape mostly depend on: winds strength and direction (Bauer and Davidson-Arnott 2002), grain size, beach width (Davidson-Arnott and Law, 1990, Nordstrom and Jackson, 1992, Bauer and Davidson-Arnott 2002), vegetation cover (Hesp 1981, Arens 1996, Hesp et al, 2005), moisture content (Hotta et al, 1984, Jackson and Nordstrom 1997) and the occurrence of salt crusts (Nickling and Ecclestone, 1981; Nickling, 1984). Another factor that has a very strong (and negative) impact on coastal dunes is human exploitation of the coast. Past policies of coastal bad management, on the North Adriatic coast as on many other coasts of the world, have brought about a very damaged system, where dunes are often stressed or even absent.

In Italy and in many other Countries, coastal dunes have been destroyed by poor land use and coastal management policies adopted in the past (Nordstrom and Jackson 2003). During the 60-70s, tourism development and the increasing demand of sand for construction caused a rapid disappearance of dunes along many stretches of the North Adriatic coast. In the Province of Ravenna alone, coastal dunes that have disappeared during the last 50 years have been calculated to be 75% of the initial coverage (Caruso et al., 2005). Since coastal dunes act as a coastal resilient factor against erosion and saltwater intrusion (Caruso et al, 2006), it is very important to understand their dynamics in order to protect them. During the last decades, along many beaches, coastal dunes disappearance has caused serious damages to coastal environments. Since coastal dunes act as a buffer against storm and erosive events, their presence is fundamental to protect landward areas. Coastal dunes belong to the natural dynamic equilibrium of sandy beaches: they are a non-static element, which is able to migrate in relation to sea level changes and wave attack. Where dunes are absent, the resilient capacity of the coast is lower: because storms can reach more landward areas, because sand that before could be trapped by dunes can now exit from the beach sedimentary budget and because saltwater intrusion can contaminate freshwater resources. The Province of Ravenna (Italy) is particularly affected by subsidence that causes lowering of already depressed areas and worsens the saltwater intrusion phenomenon. Along this coast, dunes are the only element that lay above the ground. Since dunes have a great infiltration capacity

(Tsoar, 2005), they can accumulate fresh groundwater, the water table, which standing above sea level acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head.

The main objectives of this study is to determine which are the most influencing factors on positive and negative development of coastal dunes on the North Adriatic coast and to evaluate their defending potentiality with respect to landward areas. Aiming at accomplishing these objectives, it was individuated a study case where human disturbance is low and on this stretch of coast it was carried out almost the whole study. Moreover two less extended study cases have been carried out on two more developed beaches. The first experiment (Eraclea, Venice) concerns efficiency of beach nourishment in reactivating the beach-dune sediment exchange on a developed coast and the second one (Marina Romea, Ravenna) regards the efficiency of damaged coastal dunes in defending landward areas against saltwater intrusion. It was decided to consider also these study areas, even if the Bevano River Mouth case is a perfectly autonomous study case, because it is very important to evaluate coastal dunes development in the environment they occupy. Since coastal environments have been increasingly changing during the last decades, it was found to be essential to consider also developed coasts. This is very important in a management perspective: because beach nourishment is a very common practice on many stretches of coast all over the world and because coastal dunes can change their efficiency in very stressed environments. The present study does not pretend to explain the complexity of resilience related to coastal foredunes presence only by analyzing these other two study cases, but they are very useful to understand the influence of human alterations on the environment. And this wouldn't have been possible if we had considered only the Bevano study case.

At the Bevano River Mouth Natural Reserve study case it was decided to describe the differences measured in sediment deposition between two different aged foredunes laying on the same beach. The study area is a Natural Reserve where disturbance is quite low during almost the whole year. It was the only possible location for this kind of study case: because of the coexistence of two different aged foredunes on the same beach and because of the low impact of human presence on this area. The scarce human disturbance was fundamental to practically realize the experiment without any external manumissions of the equipments and assured that there weren’t any strong human factors to be considered. Thus differences in sand deposition at two different aged foredunes have been related only to winds, vegetation and dunes morphology. There are no previous publications regarding the way coastal dunes at different stages of their evolution can be affected by differences in sediment accumulations. One of the publications, that are mostly related to this topic, was written by Arens in 1996. Arens treated in detail the patterns of sand transport on two different foredunes in the Netherlands. The two study sites were very far apart and they had different features, but both dunes were in a mature state of their evolution. Arens found that, on the dunes he analyzed, sand transport decreases rapidly landward of the vegetation boundary and this fact found a correspondence with the patterns of sand accumulation on the mature foredune analyzed in the present study. Whereas, differences are evident for the other dune, which is much younger. More comparisons between the present study and Arens and other authors (Hesp et al, 2005) results will be discussed in chapter 2.1.

The way different aged foredunes are affected by different patterns in sand accumulation could help to better understand which are the most vulnerable stages of dunes growth and which factors have most an affect on them. Thus the Bevano River Mouth study case results have been also evaluated as a sort of reference to analyze (not to compare) the other study case (Eraclea, Venice) where differences in sediment deposition at coastal foredunes were measured before and after beach nourishment. The Eraclea field experiment has a different spatial and temporal scale from the Bevano River Mouth one. This is due to the fact that the two study sites have such enormous differences that it was impossible to maintain the same methodology (for both scientific and technical reasons, paragraph 2.2.3.1). Moreover the aims of each study case are quite different: at the Bevano River Mouth the objective is to evaluate the differences in beach-dune sediment exchange at different locations onto different aged coastal foredunes (related to different factors: evolutionary stage, vegetation, morphology, winds) on a undeveloped stretch of coast. At Eraclea the main objective was to evaluate the efficiency of beach nourishment in reactivating the beach-dune sediment exchange on a developed coast. Thus it was important to consider the Bevano River Mouth as a sort of reference for other studies such as the Eraclea one. This means that the results of a study referred to an almost natural situation can be used as a reference but not to compare data with a study case located on a different stretch of coast. And, of course, this is because of the differences existing between the two beaches and between the two methodologies. Anyway the Bevano results can be used to better understand where and which factors have more an affect on the reactivation of the beach-dune exchange after nourishment.

The other topic related to the vulnerability of coastal systems and considered in this research is the saltwater intrusion phenomenon. Many studies (Van Dijk and Grootjans, 1993; Oude Essink, 1996, 2001a, 2001b; Grootjans, et al, 1998; Lammerts, 1999, Lammerts et al, 2001; Choudhury et al, 2001; Kumar, 2001; Ranjan et al, 2005) have been carried out on this very serious environmental problem. But none of them is particularly focused on coastal dunes effectiveness in contrasting saltwater intrusion (see paragraph 1.2.2). At the Bevano study case, on the same dunes analyzed to describe the differences observed in sediment deposition, a study concerning the reconstruction of the shape and the depth of the freshwater lens underneath the dunes was carried out. We described the influence of dunes in minimizing saltwater intrusion by comparing different data obtained from groundwater table height and salinity. The Province of Ravenna is particularly affected by subsidence that causes lowering of already depressed areas and worsens the saltwater intrusion phenomenon. Along this coast, dunes are the only elements that lay above the ground. Moreover, dunes have a great infiltration capacity and they can accumulate fresh groundwater, the water table, standing above sea level, that acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head. This physical principle is described by the Ghyben-Herzberg equation (Oude Essink, 2001a) and it will be treated in paragraph 1.2.1. At the Bevano River Mouth beach, an experiment based on the use of a piezometric network and of resistivity measurements was carried out. Thus, it was possible to reconstruct the thickness and the shape of the freshwater lens laying underneath the dunes. Differences in the piezometric head levels were referred both to dunes and landward areas features. Results highlight that coastal foredunes are really the only elements, which can effectively face and mitigate this problem. This is a very important result, mostly if we consider the strong impacts of this phenomenon on this stretch of coast, which lays below sea level. Nevertheless, there are many important factors, which can reduce dune effectiveness. In fact, dunes efficacy in accumulating fresh groundwater can differ very much, depending on their height, integrity and maturity. Furthermore, there is the evidence that, even in a protected area, the influence of human alterations of the landscape was very strong. And these impacts had brought about a system, which is less effective in contrasting saltwater intrusion. In fact, at the Bevano beach, coastal foredunes seem to be effective only at limited spatial and temporal scales. This is due to the presence of the artificial pine forest, which lays behind the dunes and has a negative impact on saltwater intrusion, In fact, pines may act as a water withdrawal net which causes saltwater upconing, since they have great water extraction capacity due to their transpiration (Lammerts, 1999).

Aiming at determining the impacts of others human activities on the efficiency of coastal dunes and aiming at determining if a more damaged dune system is still effective in contrasting saltwater intrusion, it was carried out another experiment on a more developed stretch of coast (Marina Romea, Ravenna). The methodology applied at the Bevano River Mouth study case is similar to the methodology applied at Marina Romea, since both are based on the use of a piezometric network and of resistivity measurements. In both the study cases, results highlight the great influence of coastal dunes in minimizing the saltwater intrusion phenomenon, provided that they weren't been destroyed, thus that they are big enough, and that landward areas use is compatible with freshwater resources conservation management.

To conclude, this thesis studies in detail two main topics developed at the same study area (the Bevano River Mouth Natural Reserve, Ravenna). The first concerns differences in trapping sediment efficiency at coastal foredunes. This was related to their age, their vegetation coverage, spatial variability on a single dune and wind intensities. The other topic concerns the efficiency of coastal foredunes in contrasting saltwater intrusion toward landward areas. This was related to dune height and maturity and to landward areas features. Moreover, a smaller study case located on a more developed stretch of coast has been related to each one of the previous topics. Results confirmed that coastal foredunes act as a barrier effect in defending landward areas, but they also highlighted which are the most vulnerable stages and factors in this process, highlighting the influence of human impacts even at the Bevano River Mouth Natural Reserve.

Chapter 1: Coastal foredunes: general features and research approaches

1.1 Sediment deposition at coastal foredunes

Much of the world's coastal sand is stored subaerially as dunes and it is this material that forms the front-line of defence against both short- and long-term fluctuations in the sea surface (Carter et al., 1990). This thesis is related to coastal foredunes which have been defined by Hesp (2002) as shore-parallel dune ridges formed on the top of the backshore by aeolian sand deposition within vegetation. Foredunes may range from relatively flat terraces to markedly convex ridges and they have been classified into two main types: incipient and established foredunes. The formation and development of coastal foredunes depend on many factors: wind intensity, frequency and direction, beach amplitude, vegetation coverage, mean grain size, moisture, beach and dune slope and dune height. Coastal foredunes are able to develop and to grow if winds are effective in moving sediment inland (Gares, 1988). They can also change their shape and their position in relation not only to wind but also to beach amplitude, to variation in vegetation coverage and to variations in all the factors (listed below) that affect them. Thus coastal foredunes are a dynamic element of the beach equilibrium, they are a non static feature that increases the resilience of the coast. In fact, they act as a buffer against storms and erosive events. They are able to migrate together with the beach and, since aeolian accumulation at a single location is higher with lower beach variation, coastal dunes reach their budget optimum when the beach has a slightly negative budget (Psuty, 1992). Transport of sand by wind is often an important component in coastal sediment budget. Wind transport can lead to the removal of sand or its redistribution within the littoral zone. Onshore winds carry sand from the beach and deposit it in backshore marshes, in developed backshore areas, or in natural or man-made dunes. Offshore winds, on the other hand, carry sand from the beach into the sea (Hsu and Weggel, 2002). They can also carry sand from the lee side of a dune, from the crest to some seaward part of the dune or toward the beach. In some areas, wind-blown sand is a nuisance and must be controlled. In other areas, the natural growth of protective dunes is limited by the amount of sand transported to them by wind. The transportation of sand by wind is a continual, natural process that is often significant in bringing about beach changes. It is important to be able to quantitatively predict how much sand will be transported by wind at a given coastal site, the direction in which that sand will be transported, and where it will be deposited (Hsu and Weggel, 2002).

Air flow over a flat beach differs from air flow over dunes. Over flat beaches, air flow should follow a logarithmic vertical profile (paragraph 1.1.1), yet it is worth noting that velocity fields vary in both space and time thus their relative vertical profiles may not be log-linear (Bauer et al, 1992; Bauer et al 1996, Nordstrom et al, 1996). Small regions close to the bed do however have a much greater correlation to logarithmic vertical profiles. Contrastingly, there are at least three distinct wind transport zones resulting from the presence of dunes on backbeaches (Hsu 1988). Dunes produce both a stagnation zone on their windward side and a wake zone on their leeward side within which wind patterns are disturbed and no longer exhibit the typical logarithmic distribution in relation to height above the ground. Wind blowing offshore results in a stagnation zone landward of the dune that extends for approximately two to four times the height of the dune. In this zone, wind speeds are lower than the free stream wind speed (region of underspeed); in fact, near the ground they may even blow in the opposite direction to that of the free stream. A wake region (cavity) may extend for a length of up to 10 times the dune height. Within the wake cavity, wind speeds are also reduced and may reverse direction near ground level. Over the dune crest, wind speeds are higher than the free stream speed because the streamlines are compressed and the flow is accelerated (region of overspeed) (Fig 1.1.1).

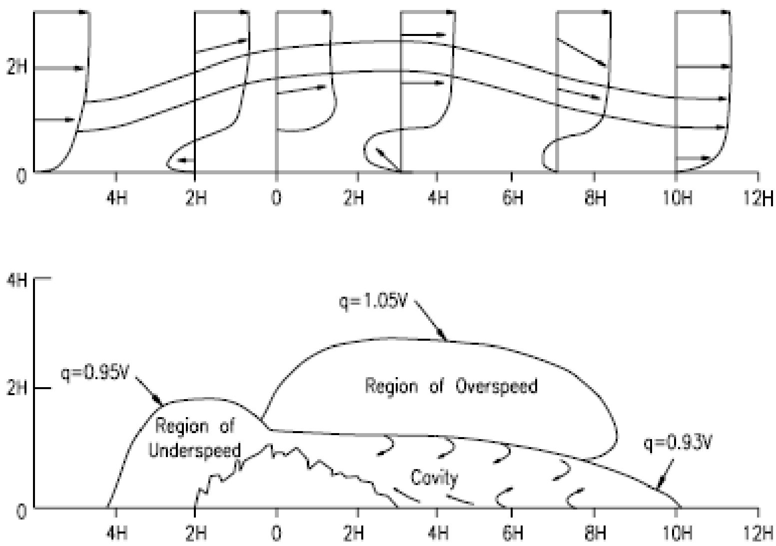


Figure 1.1.1. Wind field in a coastal sand dune system (q is the local resultant mean velocity and v is the reference velocity in the uniform stream above the dune) (Hsu 1988)

Sediment deposition at coastal foredunes is very important since dune growth is an essential factor in coastal preservation. Coastal foredunes act as a buffer against storms and erosive events because they are a natural feature of the coast that can lower the erosive strength of many natural events. Moreover, an incomplete development or the absence of coastal dunes can lead to a landward loss of sediment and, once this sediment is lost landward, it plays no further role in the beach-dune sediment budget. Thus it is very important to understand what the most influencing factors on deposition and erosion on coastal dunes are. A well developed dune is more effective at reducing negative effects of erosion than a lower or damaged one. In other words, a mature dune is more effective at protecting landward areas than a young one, which is more vulnerable. Thus mature dunes are a very important resilient factor of the coast. So one of the most important objectives in this study is to understand how much the evolutional state of a coastal foredune can influence variation in sediment accumulation or erosion.

1.1.1 Equations related to sediment transport

Wind velocity and the vertical gradient of wind speed near the ground are important factors in determining how much sediment will be transported by wind. In addition, sediment characteristics such as size, size distribution, packing, and moisture content play important roles. The vertical gradient of wind speed results in shearing forces within the air and eventually on the ground surface. The movement of sand by wind is the result of momentum transfer from the air to the sediment (Sherman and Hotta, 1990). When vegetation is present, shear stress can be transferred into the uppermost soil layers. The steeper the gradient, the greater the shear stress. The velocity gradient is significantly influenced by local topography, vegetation, and land use. These factors contribute to the “roughness” of the ground surface. In the case of wind transport in coastal areas, local perturbations in the wind field may also be important in determining the eventual erosion and deposition patterns of wind-blown sand. The vertical distribution of wind speed (the velocity profile) generally follows a logarithmic distribution. An important parameter in this representation is the shear velocity defined by:

$$u_* = \sqrt{\frac{\tau}{\rho_a}} \qquad \text{eq 1.1.1.1}$$

in which u_* = the shear or friction velocity, τ = the boundary shear stress (force per unit surface area), and ρ_a = the density of the air. Air flowing across a surface creates shear stress on the surface as a result of a net downward flow of momentum (Sherman and Hotta, 1990). The logarithmic distribution of wind velocity is given by:

$$U_z = \frac{u_*}{k} \ln\left(\frac{Z_0 + Z}{Z_0}\right) \qquad \text{eq 1.1.1.2}$$

in which U_z = the average wind speed as a function of height above ground level, u_* = the shear velocity, Z = the height above ground level, Zo = the roughness length (corresponding to the elevation at which wind speed goes to zero) and k = von Karman's constant (k = 0.4). Wind speed measurements are usually averaged over a period of several minutes to smooth out fluctuations due to gusts. The initiation of sediment movement takes place, in the simplest cases, when, on a cohesionless bed composed of sedimentary particles, shear stress exceeds a threshold value. The forces that oppose motion can be gravitational or cohesive. Cohesive forces (e.g. surface moisture) will be taken into account further on, whereas now only gravitational forces will be considered. Drag force depends on the force of the air acting on exposed areas of a grain and is a function of wind speed and the roughness of the surface (Sherman and Hotta, 1990). Thus a critical shear velocity in relation to an ideal surface, can be written as:

u*t= A (gd (rs-r)/r)0.5 eq 1.1.1.3

where A is the square root of the Shields Function (Miller et al, 1977), g is gravitational acceleration, d is mean grain size diameter and rs is sediment density. So, when the shear velocity exceeds the motion threshold, sand movement takes place. Sand can move as suspension, saltation or traction (creep) load, depending on grain size. The most common phenomenon on beaches and dunes is saltation or creep.

There are many equations that aim at predicting sediment transport. They are based upon estimates of shear velocity and they relate airflow conditions and sediment characteristics. Most of them are based on the seminal work performed by Bagnold

(1941), who based his model on laboratory experiments related to saltation. He assumed that sand movement is the result of momentum transfer directly from wind, thus his equation is:

$$q = C\,(d/D)^{0.5}\,(r/g)u_*^3 \qquad \text{eq 1.1.1.4}$$

where q is the transport rate, C is an empirical coefficient related to sediment size distribution and D is a reference grain size of 0.25 mm. Bagnold (1941) adapted this equation to typical dune sands:

$$q = 1.5 \times 10^{-9}\,(u - u_t)^3 \qquad \text{eq 1.1.1.5}$$

Based on these equations, many other scientists proposed models for sand transport where transport rate is proportional to the cube of shear velocity. Below, the most common are briefly described.

In 1964, Kawamura proposed the following equation:

$$q = K\,r/g\,(u_* + u_t)^2\,(u_* - u_{*t}) \qquad \text{eq 1.1.1.6}$$

Where K is a constant (2.78 according to laboratory findings). In 1977, Lettau and Lettau proposed the following equation:

$$q = C'\,(d/D)^{0.5}\,(u_* - u_{*t})\,u_*^2\,r/g \qquad \text{eq 1.1.1.7}$$

It is worth noting that all these models refer to ideal conditions, that is, surfaces which are horizontal, dry, unobstructed and unvegetated (Sherman and Hotta, 1990). Thus, sand transport prediction is very uncertain: in some cases (Bauer et al, 1990 and Goldsmith et al, 1990) there was a discrepancy higher than two orders of magnitude between measured and calculated transport rates. In fact, the problem of predicting aeolian sediment flux across beaches is indeterminate (with various solutions) because the number of unknown variables necessary to describe the physical system exceeds the number of conventionally-established equations linking the variables by more than one, thus there are too many degrees of freedom (Bauer et al, 1996). Hence all these models perform better over ideal surfaces and during ideal conditions that are difficult to observe on beaches. This also means that prediction is highly overestimated when compared to actual transport rates and, since the velocity field varies in both space and time, the vertical profile may not be log-linear apart from cases related to small regions close to the bed (as proved by Bauer et al, 1992; Bauer et al 1996, Nordstrom et al, 1996).

The previous equations can be improved for moist surface conditions. Hotta et al (1984) carried out laboratory and field experiments to assess the influence of water content on sand movement. Their results highlight that the threshold shear velocity calculated for dry conditions can be modified to perform with moist conditions:

$u_{*tw} = u_{*t} + 7.5\ w$ eq 1.1.1.8

Where w is the percentage of water contained in the upper 5 mm of sand. This equation is valid for $0\% < w < 8\ \%$, and for $0.2\ mm < d < 0.8\ mm$ (Hotta et al, 1984). But even after applying this correction, there are still some causes of uncertainty due to the drying process and due to the difficulty in determining the source of sediment which has been transported across a moist surface (Jackson and Nordstrom, 1997). In fact, the evaporation rate and the drying process are a more important control on entrainment than moisture content (Sherman 1990). Moreover, it is difficult to determine whether trapped sediment originates from a moist surface or from dry sand bedforms deposited on the top of the moist surface. This is due to the fact that sand entrained from a moist surface can possess moisture levels similar to those of dry sand after being transported less than 10 m from its place of origin (Hotta et al., 1984). So, calculated values of u_{*tw} are still characterized by a high level of uncertainty. Until now, there are no models which can be applied to the transport of sediment both on a beach and an adjacent dune area. Probably this is due to geomorphological complexity and its related processes (Meerkerk, 2006).

1.1.2 The role of wind

Wind is the only force that moves sand from the beach to the dunes. Its role is very important since it is the cause of sand transport on the beach surface that leads to dune development. In fact patterns of erosion and deposition can be explained by the patterns of acceleration and deceleration of wind speed (Arens 1995). Wind vertical profile is logarithmic and theoretically it should correspond to the equation 1.1.1.2. But in reality, the velocity field varies in both space and time and the vertical profile may not always be log-linear (Bauer et al., 1992, Nordstrom et al., 1996). In order to use equation 1.1.1.2 to derive estimates of u_*, one must be sure that: (i) the flow is steady and uniform; (ii) the wind speed profile in the bottom boundary layer is log-linear; and (iii) the measurement scheme includes an adequately sampled log-layer, which is usually only the lower 20 % of the boundary layer (Middleton and Southard, 1984). These are ideal conditions that occur only in simplified situations. Whereas, Bauer et al (1996) detected a perturbation in the logarithmic profile in correspondence to the surf and the back beach zone. And it is very important to be aware of the indeterminacy of aeolian sediment transport. Such indeterminacy is mostly due to the high number of unknown variables required to describe the beach-dune physical system. In fact, the wind's effectiveness in moving sand is closely related to many factors including beach amplitude and orientation, grain size, moisture, the presence of vegetation and slope effect. Depending on beach orientation, there are onshore or offshore winds. Effective onshore winds transport sand from the beach toward the dunes whereas effective offshore winds transport sand from dunes and landward areas toward the beach. Generally, onshore winds are more effective in transporting sand since they are less restricted by obstacles and roughness than offshore winds. This happens because of the relative smoothness of the water surface when compared with the rougher land surface (Hsu and Weggel, 2002). Thus, shear stress on the beach due to onshore winds will be greater than shear stress due to offshore winds of the same speed. Regarding airflow alterations due to topographic changes, Hesp et al (2005) highlight that as wind approaches a dune, pressure rises slightly from an increased (positive) build-up, or stagnation (see also fig 1.1.1), resulting in reduced wind speeds and shear stresses and potential deposition at the dune foot. Arens et al (1995) found that flow deceleration and potential deposition at the dune foot was greatest for onshore winds and that this decreased with increasing flow obliquity. Furthermore Hesp et al (2005) proved that differences in wind speeds, provided that the same range of approach is maintained, do not alter the flow structure up the dune. Walker and Nickling (2003) who carried out wind tunnel experiments over and in the lee of unvegetated dunes had the same findings. Also in laboratory experiments the normalized flow structure has been found to remain very similar at a variety of wind speeds. When winds approach a foredune at an oblique angle they tend to be deflected toward crest-normal (Arens et al, 1995) and this effect seems to be higher when incident angles are between 30° and 60°. Hesp et al (2005) concluded that oblique incident onshore flows are stronger than normal incident flows provided that their relative winds are of a similar velocity. Also Arens et al (1995) proved that deceleration near the dune foot is at its greatest with perpendicular onshore winds whereas acceleration increases the more winds turn parallel to the dune. Maximum speed-up on the foredune occurs with perpendicular onshore winds, decreases with oblique winds and is absent with parallel winds. In the case of parallel winds, relative wind speeds reflect the roughness of the foredune surface.

1.1.3 The role of vegetation

Vegetation is a natural obstacle of wind flow and its presence is very important in determining changes relating to the formation and development of coastal foredunes. Over a dry, flat, unvegetated surface, airflow and thus sediment transport can follow the equations explained in paragraph 1.1.1. But the presence and density of vegetation are very influentual factors on sediment accumulation spatial variability. In fact, vegetation can modify the near-surface velocity field reducing the bed shear stress (Hesp, 1981). Bressolier and Thomas (1977) showed that roughness length (Z_0 in equation 1.1.1.2) increases with both vegetation height and density, above all the latter. And Hesp's works (1983 and 1989) confirm that vegetation density is more important than vegetation type. In fact, an increasing density produces an increase in roughness and, consequently, a decrease in wind speed near the surface. Hesp also proved that below a critical level of vegetation density, the roughness elements act independently of each other within the flow and the contribution of the culms to the total drag is less. When vegetation density is high, the foredune traps most of the incoming sand. This causes the dune to grow vertically in place, rather than through slipface deposition and migration (Goldsmith et al., 1990). Hesp (1989) discerns positive feedback between vegetation and deposition: where sand deposition is greatest, plant growth is encouraged, resulting in an increased aerodynamic roughness and higher deposition. From a physical point of view, plant geometry and density can be used to estimate displacement height (Z in equation 1.1.1.2). The displacement height appears in equation 1.1.1.2 as a reference height for the vertical coordinate. Physically, it represents the level at which the mean drag on the surface appears to act. The equations of motion then show that this also coincides with the average displacement thickness for the shear stress (Jackson, 1981). Because vegetation is a roughness element, it will thus increase the average surface elevation as a function of the height and density of the plants. Where vegetation is scarcely distributed or even absent, the sand surface will be the primary control on the displacement height (Sherman and Hotta 1990). Where vegetation is sparse, the relationship is:

$h/H_v = lc_Dc_m$ Equation 1.1.3.1

where h is the displacement height, H_v is the mean plant height, c_D is a drag coefficient, c_m is a moment coefficient and l is vegetation density (Jackson, 1981). For high vegetation density, c_D and l approach unity and c_m equals h/H_v. Nevertheless, even if equation 1.1.3.1 proves to be valid mainly for vegetation densities up to 0.3 (Jackson 1981), it is not sufficient enough to solve the problem of quantitatively determining vegetation effect on sand accumulation or reducing indeterminacy related to sediment transport equations. The estimation of friction velocities and roughness lengths is often difficult to calculate and may be either overestimated or underestimated if obtained from beach measurements. This depends on roughness variability and foredune morphology (Hesp, 2002). It is worth noting that the addition of vegetation into flow and sediment transport models to simulate realistic foredune development is complicated due to the difficulties involved in simulating plant growth and vegetation type and cover (Van Dijk et al, 1999). Thus vegetation effect is very important for sediment transport but relatively little is known about transport rate gradients between beach and vegetated foredunes. Most empirical studies indicate an exponential decrease in transport rates when the sand moves from an unvegetated beach into vegetated foredunes (Arens, 1996). In fact, when the sand passes the partly vegetated dune foot, most of the sand is deposited. Arens (1996) also demonstrated that when the difference in height between the beach and the foredune is too large, the sand is not able to reach the foredune. Thus he suggested that the flow is deflected and the sand is not suspended. This could be the main reason why foredunes with a vegetated slope only reach a certain height. Hesp et al (2005) found a speedup with increasing dune elevation related to higher shear stresses; and while the flow reduction within the vegetation acts to reduce this process, the rate of speedup (u_{crest}/u_{base}) is significantly greater than the drag induced by the vegetation. Thus, even under moderate wind conditions, if there is a sufficiently dense vegetation cover, aeolian sand transport is possible. Hesp et al (2005) observed this over the entire stoss slope. Furthermore, they demonstrated that the increased vegetation density and resulting roughness effect on the flow and flow deceleration, expansion and separation over the dune crest promote significant crest and lee crest slope deposition during moderate to high velocity onshore sand transporting events.

1.1.4 The role of morphology

Foredune morphology has a strong influence on airflow pattern as the presence of the dune itself, as well as its shape, alters the streamlines. The most important geomorphological features are the local slope and the variability of adjacent surfaces. In some cases it can also be useful to measure bedform geometry (Sherman and Hotta, 1990). Hsu (1988, fig 1.1.1) carried out some very important seminal research regarding the role of foredune morphology in relation to sediment transport. He described three distinct airflow zones created by the presence of a foredune. When wind approaches a foredune, its seaward side is characterized by an area of underspeed, the crest and upper landward slope by an area of overspeed, and the lower landward slope by an area of underspeed (paragraph 1.1). This first approximation of foredune flow models relatively steep ridges, but it does not account for dunes with lower, longer stoss and lee slopes (Hesp, 2002). Wind flow is accelerated topographically over foredunes, particularly up stoss slopes, and over crests (Arens, 1994; Arens et al., 1995). It is worth noting that variable vegetation cover and topographic variability lead to local decelerations and variations in roughness length (Arens et al., 1995). Thus, the greater the topographic variability, the greater the variability in surface wind flow and the greater the difficulty in determining shear stress and potential transport or deposition (Rasmussen, 1989; Arens 1997). Although there are no models which are able to quantitatively predict sand deposition accurately, it is possible to predict where areas of higher deposition will lie. In fact, flow reduction and separation are more pronounced as the slope gradient increases toward vertical. Such flow behavior is particularly important for the scarp filling process which follows vertical cliffing caused by storm waves (Hesp et al, 2005) and more generally indicates that accumulation at the dune foot is higher than at other areas of the dune. Arens (1996) linked this assumption to vegetation density. In fact, he suggested that if vegetation density is low, with steeper topography, the amounts of sand transported landward from the dune foot increases. Furthermore, Arens proposed that accumulation at the dune front is also influenced by wind direction: with oblique onshore winds, most sand accumulation occurs at the dune front. Whereas, with perpendicular onshore winds, a large proportion of the sand is deposited landward of the slope. An increase in wind speed was noted towards the crest on the stoss side of the two dunes analyzed by McKenna Neuman et al (1997). They observed speed-up factors (u_{crest}/u_{base}) which ranged from 1.50-3.19, with a corresponding increase in sediment flux of 1-2 orders of magnitude. Furthermore, McKenna Neuman et al observed that the ratio of the flux at the stoss slope crest with respect to that at the base (q_c/q_b) decreased as the incident wind speed (measured at the base of the slope) increased, indicating that sediment transport on the dune became more uniform when $u_{*b}/u_{*t}>>1$. The McKenna Neuman et al experiment demonstrated that the flow acceleration up the dune they analyzed gave rise to an increase in sediment transport toward the crest, by 1-2 orders of magnitude. Hence the crest areas were the most active. Prior studies had demonstrated that deposition occurs mostly at the dune foot, in correspondence to a significant decrease in the wind velocity field. In correspondence to the crest, they showed that there is an increase in the wind velocity field due to the convergence of the streamlines induced by topography itself.

Finally, there is another very important aspect to be considered: the extent to which development and human activity associated with it affect aeolian sediment transport and dune formation still remains to be determined. This is also a very influencing factor on dune morphology. One of the next challenges in coastal foredune research is to understand the impact human activity has on the airflow over dunes and how much it can affect their natural development (chapter 2.2).

1.2 Saltwater intrusion in coastal aquifers and the role of coastal foredunes

Nowadays, many coastal aquifers in the world, especially shallow ones, experience an intensive saltwater intrusion caused by both natural as well as man-induced processes (Oude Essink, 2000, Fetter, 2001). Human interferences, such as mining of natural resources (water, sand, oil and gas) and land reclamation (causing subsidence) threaten coastal lowlands. Consequently, salinities of surface water systems increase and land degradation occurs because soils become more saline. In addition, coastal aquifers within the zone of influence of mean sea level (M.S.L.) are threatened by an accelerated rise in global mean sea level. This could mean a reduction of fresh groundwater resources. In addition, the present capacity of the discharge systems in several coastal lowlands may be insufficient to cope with the excess of seepage water, especially in those coastal areas which are below M.S.L. This seepage will probably have a higher salinity than at present. The present distribution of fresh, brackish and saline water in the subsoil has developed in geologic history and has been and still is affected by several natural processes but also by human intervention. Brackish and saline groundwater can be found in coastal areas, but also further inland (Oude Essink, 2001a). Natural recharge of the groundwater system (infiltrating rain) is the main source of fresh water in formations (Ranjan et al, 2005). Worldwide, excessive overpumping in coastal aquifers is the most important anthropogenic cause of saltwater intrusion. In coastal aquifers, saline groundwater is nearby and upconing of saline groundwater can easily occur. Furthermore, reducing recharge areas to develop touristic centers causes a decrease of outflow of fresh groundwater, inducing an inland shift of the saltwater wedge. In the Province of Ravenna, where this thesis has been carried out, problems related to subsidence are very serious. In fact, past offshore extraction of natural gas led to an extremely damaged system. This activity, carried out in an area where natural subsidence was already occurring, was very damaging and it has now been prohibited. Since this activity ceased, the subsidence rate has started to become lower. Past subsidence rates ranged from 110 to 65 mm/y in 1972-77 (depending on zones), whereas nowadays subsidence is about 2,5 mm/y (Elmi et al, 2006).By lowering the land surface level, the piezometric heads also become lower, and this effect is worsened by the rising sea level. Thus, in this area, problems related to saltwater intrusion are affected not only by fresh groundwater extraction, which is now prohibited, but also subsidence and the rising sea level. Before the great boom in tourism, which occurred in the 1960s, dunes on the North-West Adriatic coast used to be a very common feature of the littoral. Since then, however, they have slowly disappeared due to overdevelopment and nowadays they occupy only limited areas. In the Province of Ravenna alone, coastal dunes that have disappeared during the last 50 years have been calculated to be 75% of the initial coverage (Caruso et al., 2005). Their disappearance, which is due to the construction of many bathing establishments, where once only dunes were situated, has caused many serious environmental problems. One of these problems is related to coastal dune efficacy in contrasting saltwater intrusion. In fact, dunes have a great infiltration capacity, so they can accumulate fresh groundwater. This watertable, laying above sea level, acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head. The fresh-saltwater interface is 30 to 40 times deeper than the freshwater hydraulic head (Ghyben-Herzberg principle, paragraph 1.2.1). Hence, by decreasing the freshwater hydraulic head by 1 m, it causes a 40 m interface upconing. This capacity of coastal dunes is very important to protect landward areas, since dunes can accumulate beneath them a freshwater lens that contrast the saltwater intrusion. So they act as a buffer against saltwater intrusion. In some cases, if the piezometric head is well above sea level, the fresh-saltwater interface can reach the clay basement. When this occurs, landward areas are completely protected against the saltwater intrusion phenomenon. Starting from these considerations, this thesis proved that dunes act as a resilient factor of both developed and undeveloped stretches of the North-West Adriatic coast.

1.2.1 The Ghyben-Herzberg principle

The seminal work separately carried out by Baydon-Ghyben (1888-1889) and A. Herzberg (1901) was very important to develop the study of the fresh-saltwater interface in coastal aquifers. Variability in fresh-saltwater interface depth is dependent on many factors, but mostly on recharge (Ranjan, 2005) and on the presence of coastal dunes. In fact, coastal dunes are the only littoral elements that lay above the ground. Moreover, dunes have a great infiltration capacity and they can accumulate fresh groundwater, the water table that, standing above sea level, acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head.

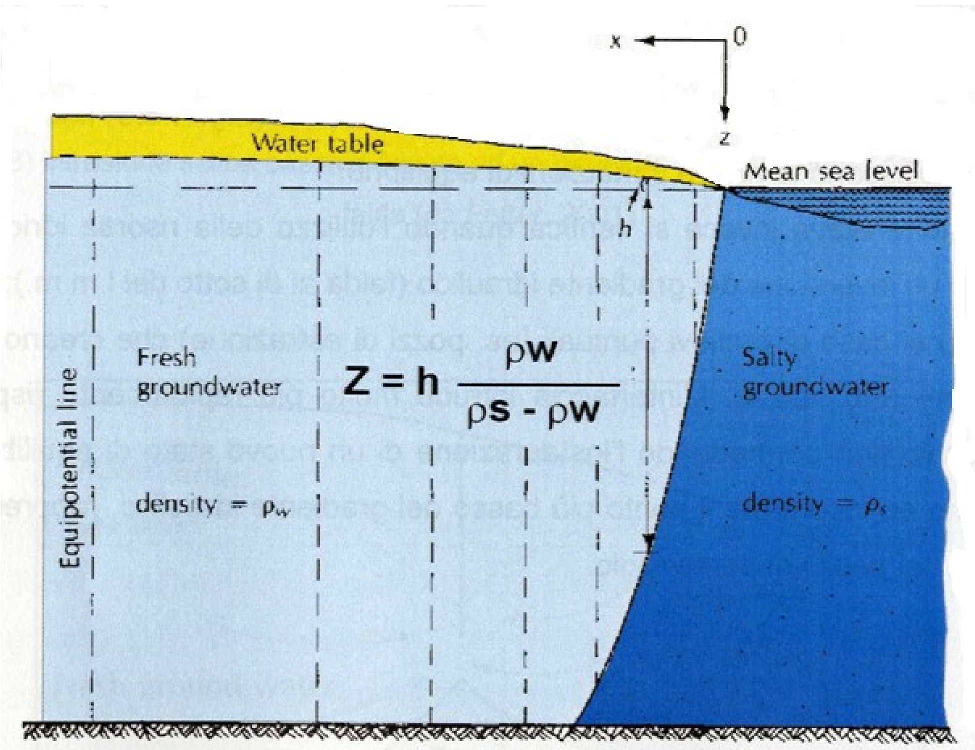


Fig 1.2.1.1: Relationship of freshwater head and depth to saltwater interface (Fetter, 2001)

In a coastal system, it is important to consider the difference between freshwater and saltwater density. Generally this low difference (r_w= 1.000 g/cm^3 and r_s= 1.025 g/cm^3) does not affect the physics of flow. However, if fresh groundwater is adjacent to saline groundwater, the difference in density between dissolved solids becomes very important. Hence, the differences in density have a significant effect on piezometric heads ($h_{(x,y)}$, in eq 1.2.1.1) and thus on the groundwater system (Fetter, 2001). In fact, the fresh-saltwater interface is 30 to 40 times deeper than the freshwater hydraulic head. We can determine that by decreasing the freshwater hydraulic head by 1 m, it causes a 40 m interface upconing. This phenomenon is described by the Ghyben-Herzberg principle (eq. 1.2.1.1, fig 1.2.1.1), which states that:

$$Z_{(x,y)} = \frac{\rho_w}{\rho_s - \rho_w} h_{(x,y)} \qquad \text{eq 1.2.1.1}$$

where:

$Z_{(x,y)}$ is the depth of the salt-freshwater interface below sea level at location (x,y)

$h_{(x,y)}$ is the elevation of the water table above sea level at point (x,y)

r_w is the density of freshwater (g/cm^3)

r_s is the density of saltwater (g/cm^3)

By considering r_w= 1.000 g/cm^3 and r_s= 1.025 g/cm^3, equation 1.2.1.1 becomes:

$Z_{(x,y)} = 40\ h_{(x,y)}$

r_w and r_s values in the area analyzed in this thesis were slightly different and $Z_{(x,y)}$ was considered as 33 $h_{(x,y)}$ Thus, if dunes are effective in accumulating a freshwater lens which stands, for example, 10 cm above sea level, this is enough to lower the fresh-saltwater interface of more than 3 m. The application of this principle is limited to situations in which both the freshwater and the saltwater are static. Thus, the equation is correct if there is only horizontal flow in the fresh water zone and the saline water is stagnant. Though the position of the interface is not correct at the outflow zone, the use of the equation still gives a rather good approximation of the real situation. The Badon Ghyben-Herzberg principle was originally formulated for the situation that the transition zone between fresh and saline groundwater is only a small percentage of the thickness of the saturated freshwater body (thus, mostly in the order of several metres).

Under these circumstances, a fresh-salt interface should be applied. This situation occurs in unspoiled sand-dune areas or (coral) islands, where the freshwater lens evolves by natural groundwater recharge (Oude Essink, 2001a). In addition, the principle can only be applied in case the vertical flow component in the freshwater body is negligible. Actually, however, such systems seldom occur. Most systems are not hydrostatic, and as a result, the formula leads to (small) errors, especially in the vicinity of the outflow zone. Nevertheless, though the position of the interface is not completely correct, the use of the equation still gives a rather good approximation of the real situation. Oude Essink (2001a) indicates that the principle should only be applied under the following conditions: 1) the aquifer is homogeneous; 2) hydrodynamic dispersion is negligible; 3) vertical flow in the aquitard, horizontal flow is negligible; 4) horizontal flow in the aquifer, vertical flow is negligible; 5) saline groundwater is at rest.

1.2.2 Coastal dunes and saltwater intrusion: state of the art in international research

Coastal dunes effectiveness, with respect to saltwater intrusion, has just been discussed in paragraph 1.2.1. Coastal dunes elevation and their infiltration capacity are very important features in determining the formation of a freshwater lens, which, standing above sea level, acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head. Thus, coastal dunes are very important in protecting landward areas against saltwater intrusion. In fact, if the piezometric head is high enough (mostly depending on recharge and on dune height), the fresh-saltwater interface could even reach the clay basement. This would guarantee the complete protection of landward areas against saltwater intrusion. Nevertheless, there are no many publications specifically focused on this argument. Many valuable studies have been focused on dune slack vegetation and its interactions with hydrology (Grootjans, et al, 1998; Lammerts, 1999, Lammerts et al; 2001). Other studies (Choudhury et al, 2001 who used a geophysical methodology, as we did; Ranjan et al, 2005 who focused on climate change effects) regard saline water intrusion in coastal areas, but they are not specifically focused on dunes. Several studies (Van Dijk and Grootjans, 1993;

Lammerts, 1999; Kumar, 2001) concern the impact of human activity on coastal areas. But also those studies do not focused specifically on dune effectiveness in contrasting saltwater intrusion. On the contrary, Oude Essink (1996, 2001a) highlighted the importance of coastal dunes in protecting landward areas. He referred to the case of the drinking water company, Amsterdam Waterworks. This drinking water company has pumped water from a dune area since the middle of the nineteenth century. The freshwater lens under the dune area reaches to a depth of at least 80 m below Mean Sea Level (M.S.L.). This activity caused many serious environmental problems. It is worth noting that, among the most important countermeasures proposed by Oude Essink (1996) there is the widening of the existing sand-dune area. Other general countermeasures, not always applicable, proposed by Oude Essink (2001 a) in similar cases are: a. reclaiming land in front of the coast, thus evolving new freshwater lenses; b. extracting (saline) groundwater, thus decreasing the seepage quantity and chloride load in the polders. This could regrettable result in undesirably low phreatic water levels, especially in shallow coastal groundwater flow regimes. Furthermore, the disposal of the extracted saline or brackish groundwater could meet with problems. c. infiltrating or injecting fresh surface water (called deep-well infiltration), thus replacing the inflow of saline groundwater. d. inundating low-lying polders, thus removing the driving force of the salinisation process; e. creating physical barriers, such as sheet piles, clay trenches and injection of chemicals, thus blocking the free entrance of saline groundwater and halting the salinisation process. f. increase of (artificial) recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal groundwater flow regime, and thus, to reduce the salinisation; g. modifying pumping practice through reduction of withdrawal rates

1.2.3 The main influencing factors on efficiency in freshwater accumulation

Two very important natural processes have affected the distribution of saline and fresh groundwater: natural recharge and transport processes. Natural recharge of the groundwater system (infiltrating rain) is the main source of fresh water in formations. This water travels from the recharge area through permeable formations (aquifers) to the sea or ocean. On its way it may encounter saline aquifers, replacing or mixing with the saline groundwater. The actual distribution of fresh and saline groundwater depends, amongst others, on hydrogeological parameters and the density differences between the liquids (Oude Essink, 2001a). Climatic changes with different rainfall regimes have also influenced salinisation. Seas, oceans, lakes and rivers act mostly as (outflow) boundaries for groundwater systems, so long-term differences in their levels will interfere in the groundwater system. The main transport mechanism is advection: flow of water due to gravity. If density differences occur and the water is stagnant then the least dense water will float on top of the more dense water and a horizontal layering will occur. Flowing fresh and/or saline water will create sloping (density) interfaces. Apart from this, molecular diffusion, a movement of ions, occurs. This process is driven by differences in concentrations, independent of flow and developing proportional to the square root of time. Another important factor, which affected the distribution of fresh and saline water in the subsoil is human activity. In fact, impoldering, extraction of groundwater, artificial recharge of groundwater, lowering of groundwater tables, irrigation and drainage, construction of canals, mining etc. have all led to changes in the hydrogeological regime. The response of the groundwater system is to reach a new state of equilibrium, characterized by a different distribution of fresh and saline groundwater. This may last decennia or even centuries, as groundwater flow is, in general, a very slow process. Worldwide, excessive overpumping of especially coastal aquifers is the most important anthropogenic cause of saltwater intrusion. In coastal aquifers, saline groundwater is nearby and upconing of saline groundwater can easily occur. Exploiting and mining of groundwater regularly take place to mitigate droughts or supply irrigation projects, especially in (semi)arid areas. Fossil and non-renewable groundwater basins are utilized for domestic, industrial and agricultural water supply. Furthermore, reducing recharge areas to develop touristic centers causes a decrease of outflow of fresh groundwater, inducing an inland shift of the saltwater wedge. Lowering of piezometric heads caused by excessive overpumping can also induce a severe land subsidence. Land reclamation can cause a lowering of piezometric heads, and subsequently, seawater can rapidly intrude the coastal aquifer. Nowadays, lowering of the piezometric heads due to overpumping already occurs in many aquifers around the world. It is obvious that, for those systems, the impact of a (relatively small) sea level rise (e.g. 50 cm per century) on the aquifer will be of marginal importance compared to the effect of an increase in extraction rate. As we will demonstrate in this thesis, another very important factors to be considered are the presence of coastal dunes and the state of the environment they occupy. We will see in detail that dunes size (height and extension) has a great affect on saltwater intrusion. Moreover, we will consider several problems related to coastal area use, mostly concerning the artificial plantation of the pine forest (chapter 3).

Chapter 2: Differences in sediment deposition at coastal foredunes

2.1 The influence of morphology, evolutionary stage and vegetation at the Bevano River Mouth Natural Reserve (Ravenna)

2.1.1 Introduction

As already mentioned (General Introduction), during the 60-70s, tourism development caused a rapid disappearance of dunes along many stretches of the North Adriatic coast. In the Province of Ravenna, coastal dunes that have disappeared during the last 50 years have been calculated to be 75% of the initial extension (Caruso et al., 2005). Since coastal dunes act as a coastal resilient factor against erosion and saltwater intrusion (Caruso et al, 2006), it is very important to understand their dynamics in order to protect them. This study aims at describing the differences observed in sediment deposition between two different aged foredunes laying on the same beach. The way dunes at different stages of their evolution can be affected by differences in sediment accumulations has been analyzed in detail in this study. This could help to better understand which are the most vulnerable stages of dunes growth and which factors have most an affect on them.

There are no previous publications regarding the comparison of patterns of sand accumulation at two different aged foredunes. But some publications regarding the dynamics of sand accumulation on vegetated foredunes (Arens 1996; Hesp et al. 2005) were very useful to understand the process that leads to a form in a complex and dynamic environment as a vegetated foredune. The first studies related to aeolian transport connected to dunes were performed in desert environments or in wind tunnels. Nowadays there are still many problems in mathematically describing the physic of transport and mostly of accumulation on vegetated coastal foredunes. This research aims at determining the main influencing factor on sand accumulation over coastal foredunes. The new attempt is to consider, together with vegetation, the evolutional stage of dunes (thus morphology) as a key factor in determining different patterns of sand accumulation.

2.1.2 Study area

The Bevano River Mouth is located on the North Adriatic coast, in the Province of Ravenna (Italy), about 200 km south of Venice (Fig 2.1.2.1)

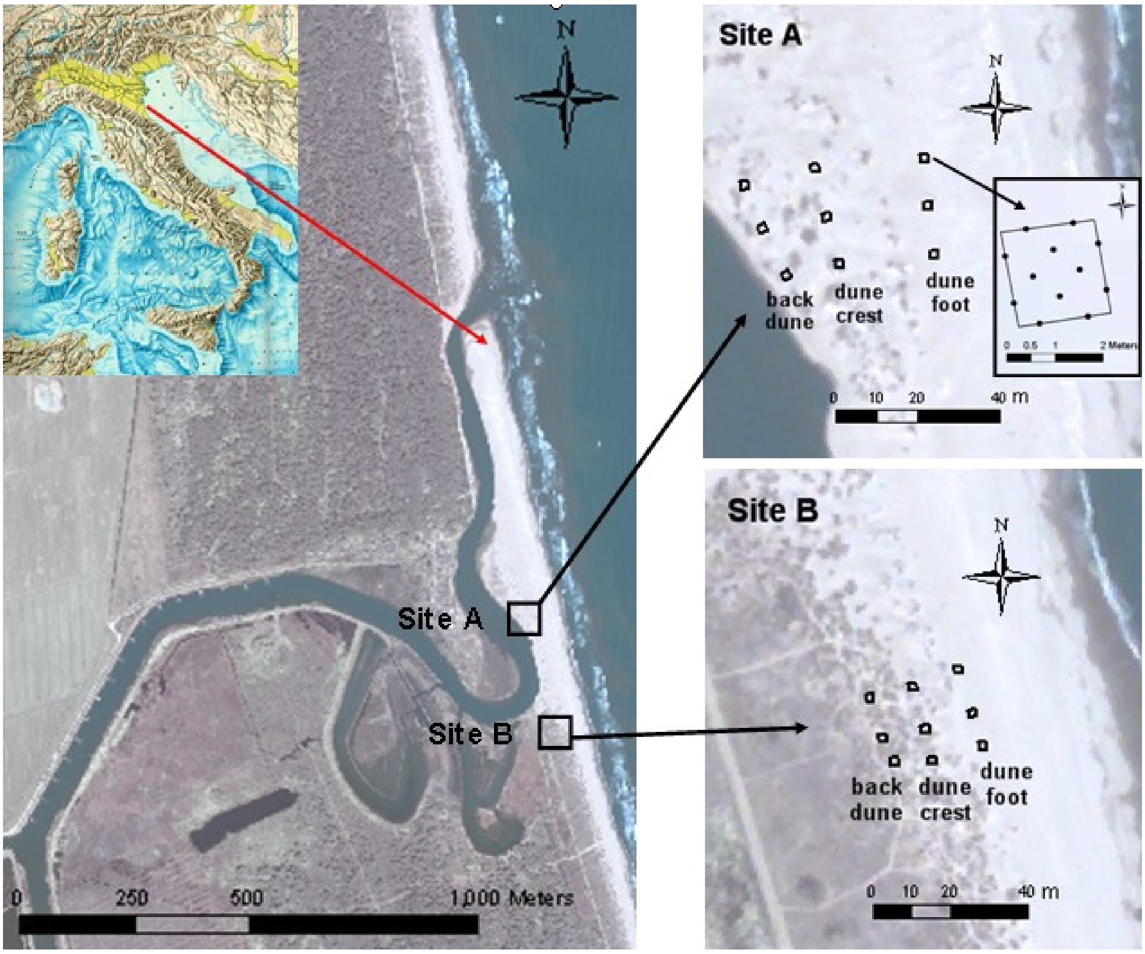


Fig 2.1.2.1: Location of Bevano River Mouth and study sites.

The study area belongs to the Po Delta Regional Park and it is a Natural Reserve. The spit has been formed recently, over the last 30-35 years, while Northern and Southern beaches are more than 50 years old.

Fig 2.1.2.2: Evolution of the Bevano River Mouth coast from 1935 to 2000.

The Bevano River Mouth coast is characterized by the presence of a well developed dune system. In the Province of Ravenna this is the only stretch of coast where dunes are continuous, undamaged and natural looking. The Bevano River Mouth lays between two dune systems and is a natural element of dynamic division of dunes continuity. Going further north, there is a continuous dune system which is more than 3 km long, while further south the dune system is more than 2.2 km long. Both north and south of the River Mouth there are older dunes that are higher (almost 4 m high), more vegetated and more stabilized. While on the dynamic spit created by the river, coastal dunes are younger, lower (about 2 m high), less vegetated and more dynamic. At the Bevano River Mouth, dunes are characterized by a geomorphologic inverse gradient that goes from south to north. In the southern part of the beach, dunes that don’t belong to the spit are higher, then going further north (thus on the spit) dunes get lower and lower. This is due to a rapid progradation rate of the spit (about 14 m/y from 1968 to 1998 and much faster from 1998 to 2003: about 80 m/y) that has led dunes to grow in a very dynamic environment, where sediment accumulation at a single foredune or embryo-dune location is more variable (Psuty, 1992). Two dunes, site A, that lays on the spit with the river landward of it, and site B, having no river landward of it, have been studied. The dune of site A is about 20 years old, while at site B the dune is almost 50 years old (fig 2.1.2.2).

Fig 2.1.2.3: In the upper part, picture refers to site A while in the lower part picture refers to site B.

The two sites are quite close to each other (250 m) thus they lay on a beach that has the same width (about 40 m) and is generally formed by fine-medium sand (the mean grain size values of the samples ranged between 0.23 to 0.55 mm) that is a little bit coarser and better sorted at site B than at site A.

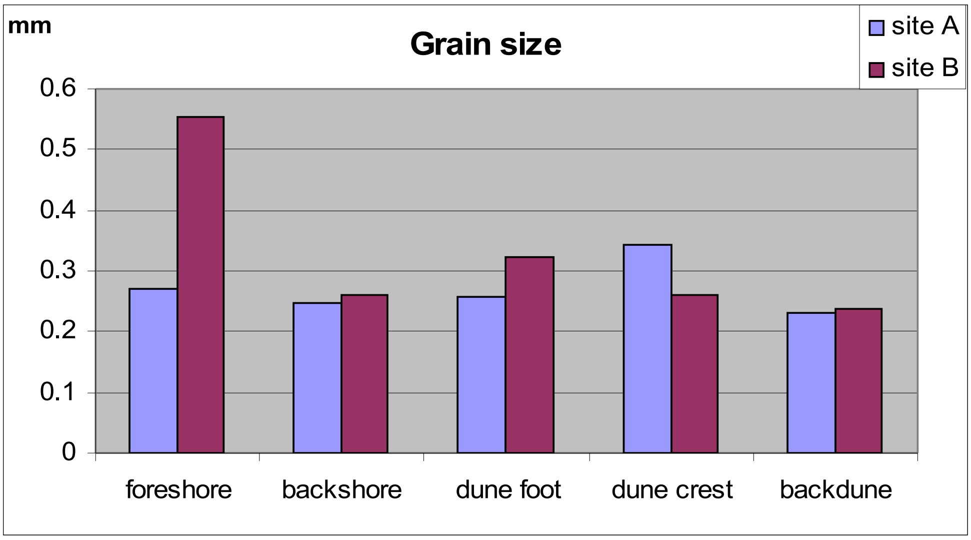


Fig 2.1.2.3: Site A and B mean grain size.

The beach is oriented NNW-SSE. Prevailing winds come from WNW and dominant ones come from NE-ENE. Figure 2.1.2.4 was obtained by considering only effective winds, thus winds which can transport sand from the surface and move it toward another place on the beach. Such winds are those which exceed the critical value (equations 2.1.3.1 and 2.1.3.2) which could change depending on moisture conditions. The wind rose of fig. 2.1.2.4 was obtained by considering only the effective winds among that recorded during each period. The area is subjected to a microtidal regime (maximum values are lower than 1 m). The strongest storm events (offshore wave height more than 4 m) happen during Autumn and Winter, mainly due to winds coming from the first quadrant.

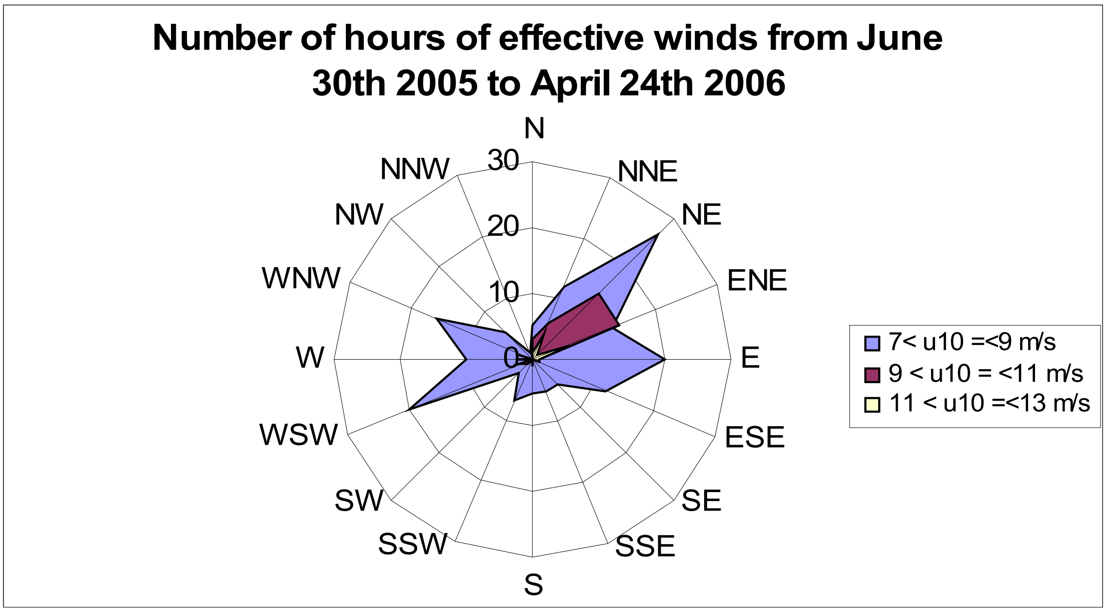


Fig 2.1.2.4:Wind rose referred to the study period (from June 2005 to April 2006)

2.1.3 Methodology

Aiming at determining differences in sand accumulation between two dunes at different stages of their evolution, it was decided to follow the Davidson-Arnott and Law methodology (1990). This choice was made due to the necessity of measuring and determining patterns of sand accumulation rather than transport on foredunes. This methodology is very effective, affordable and guarantees a high precision (the margin of error of readings is a maximum of 4 mm). The study has been in progress since June 2005. At each site (A and B, Fig 2.1.2.1) twelve sediment deposition readings were taken within nine 2x2 metre areas every 20 days (due to some problems in reaching the place during winter, the time between some readings was longer). Measurements of sediment deposition were taken using a bedframe device consisting of a 2x2 square angle aluminium frame (Fig 2.1.3.1). Twelve sections of pipe, 20 cm long and with an internal diameter of 1.6 cm, are mounted on the frame in a regular pattern so as to provide a uniform coverage of the area within it. Each pipe forms a vertical sleeve for 1.5 m long PVC rods. At each measurements station, four PVC rods, marking the corners of the station, are driven into the sand for approximately half their length and their tops levelled. In order to make measurements, the frame is placed over the measurement station so that the four corner posts engage in the corners of the frame. The PVC rods are allowed to drop to the bed and the distance from the ground to the frame measured for each of the twelve rods. Changes in the bed elevation through time are determined by subtracting the distance to the bed at each rod from the distance measured previously. The frame is moved from one station to the next to obtain the measurements, and is stored away from the site, so that the stations themselves are marked only by the four corner posts.

Fig 2.1.3.1: The aluminium bedframe device mounted on the fixed PVC rods that mark the corners of each station. The station represented in this picture is square number 3 at the backdune of site B.

Since topography affects wind field and thus sand accumulation, squares were positioned in relation to the main topographic changes in dune morphology: at the dune foot, at the dune crest and at the backdune. Three squares were positioned (Fig 2.1.2.1) at each geomorphological feature (hence at the dune foot, at the dune crest and at the backdune) of both site A and B. Davidson-Arnott and Law established 36 bedframe stations at each study site but this would have been a too big effort since there were only two people disposable for the monitoring. With our means the maximum effort could be to establish 9 station in each site. The final position of the squares is due to the fact that great changes in morphology causes great changes in transport, so it has been decided to establish the stations in correspondence to great changes rather than in homogenous situations. Besides, by establishing the squares in relation to the same topographic changes on the two dunes, it is possible to compare them.

Elevation changes of each period were calculated by using Surfer 8 ® software (Golden Software Inc. Co). To interpolate the 12 points belonging to each square a Multiquadratic method among the Radial Basis Function interpolation options was chosen. This choice was due to the number of points measured in each square: it is high enough in relation to the investigated area (each square is 4 m^2) and the process analyzed, but such data (only 12 points) could only be interpolated by using the Kriging or the Radial Basis Function methods. A study by Chen et al (2000) demonstrates that the Radial Basis Function performs better than the Kriging one both in average accuracy and robustness. Moreover the procedure to use the Radial Basis Function is much easier and faster than the Kriging one. And since every 20 days there were 18 stations to interpolate, it was found even more reasonable to chose the Radial Basis Function. Then Surfer 8 ® allowed us to calculate the cut & fill of each square for each period easily. Thus for each square it was calculated a single value of elevation change for each period. The cut & fill is a calculation of the difference between two surfaces: the first is formed by elevation changes at the points of measure (from time t_0 to time t_1, 20 days later) and the second one is a surface at level 0. Thus the dataset contains cut & fill data from each period and from each square collected from June 10th 2005 to April 24th 2006. The software calculates the volumetric difference by using three different methods (Trapezoidal Rule, Simpson's Rule and Simpson's 3/8 Rule). The three methods gave reasonably similar results for all squares and for all periods.

The similarity between elevation changes of every square for each period was calculated by the use of the Community Analysis Package (CAP, Pisces Conservation LTD) software. This analysis produced a dendrogram that shows similarities between squares calculated by comparing what happened in every square during the same periods.

One altimetric survey of each dune, including quote and position of each PVC rod, was realized with the DGPS Real Time Kinematic Technics (RTK), using a couple of receivers Topcon GB500 (Base and Rover), which guarantees a centimetric precision of measurements. Moreover the dataset contains the number of hours of winds stronger than 8 m/s for each period and data regarding vegetation cover in each square. Wind data were obtained by a standard meteorological station located in Cervia, about 10 km further south of the study area. Hourly mean wind speed and direction at a height of 10 m were downloaded at www.eurometeo.com. Wind data have been ordered by excluding values below the threshold velocity of aeolian transport. All the equations refer to the shear velocity u_* (see also paragraph 1.1.1) whose threshold value is:

$$u_{*_t} = A_t \sqrt{\frac{(\rho_s - \rho_a) g D}{\rho_a}}$$ Equation 2.1.3.1

In which r_s is the mass density of the sediment, r_a is the mass density of the air and A_t is a dimensionless constant (A_t=0.118). The effect of soil moisture that increases the critical shear stress is not considered in this equation, but it can be considered by adding a term proportional to humidity:

$$u_{*_{tw}} = u_{*_t} + 7{,}5W$$ Equation 2.1.3.2

in which W is the fraction water content in the upper 5 mm of the sand (Hotta et al. 1985). W has been considered to be 3.3 %, since is the mean value of our field data, referred to samples gathered during two rainy days.

Thus, after some rainy hours, the value of the critical shear velocity was corrected by adding the term 0.2475. So the data collected by the standard meteorological station located in Cervia were sifted: if it didn't rain during the previous hours only the values higher than 8 m/s were considered, whereas, if it rained before, only the values higher than 11 m/s were considered.

Vegetation cover values were obtained by doing several phytosociologic surveys (Braun Blanquet, 1964) for every 2x2 metre squares. Data refer to percentage vegetation coverage and they are subdivided into 5 classes:

1 corresponds to 0-20%
2 corresponds to 20-40%
3 corresponds to 40-60 %
4 corresponds to 60-80 %
5 corresponds to 80-100 %

Total coverage values were used to calculate regression values between vegetation coverage and a measure of wind intensity or between vegetation coverage and elevation changes.

2.1.4 Results

Looking at the topographic profiles of dunes A and B (fig 2.1.4.1), the difference between their stages of evolution is evident. In fact dune B is much higher and well formed while dune A doesn’t have a continuous crest and is much lower.

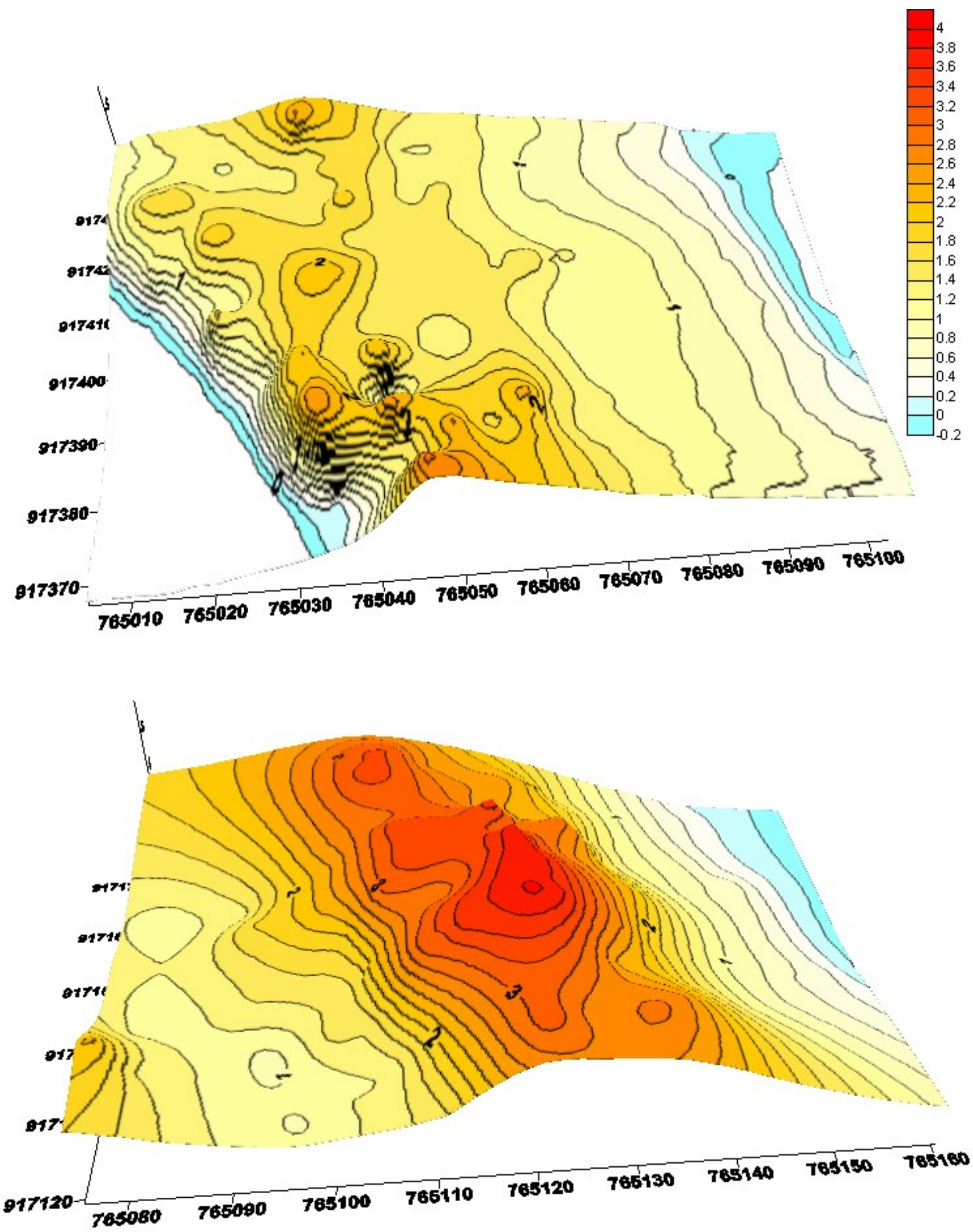
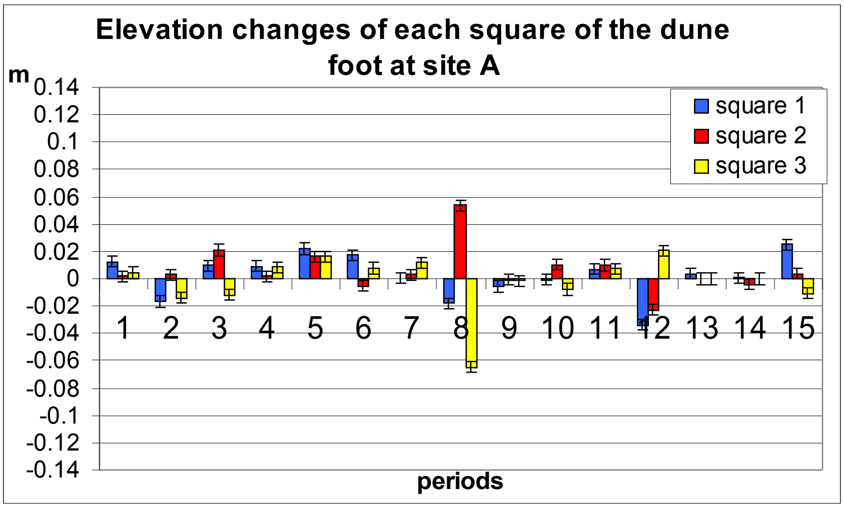
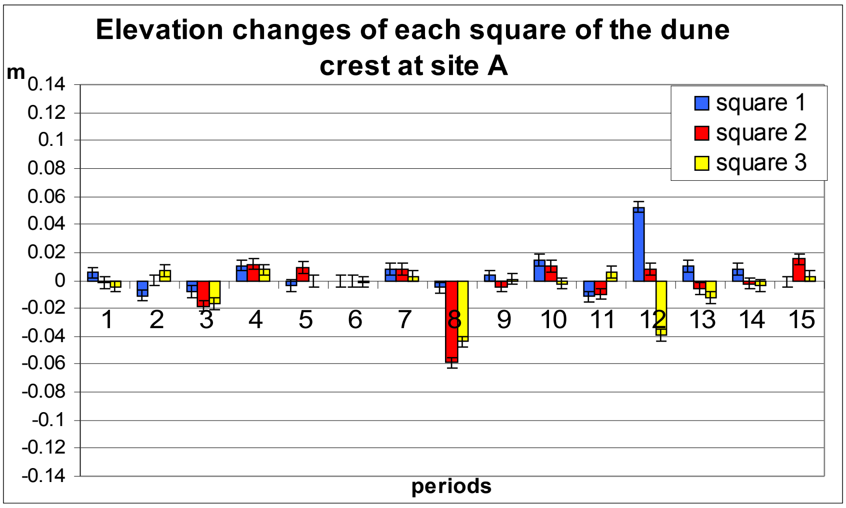


Fig 2.1.4.1: DGPS profiles of both dune A (in the upper part) and dune B (in the lower part).

Elevation changes at each square during each period are summarized in fig 2.1.4.2 for site A and in fig 2.1.4.3 for site B.





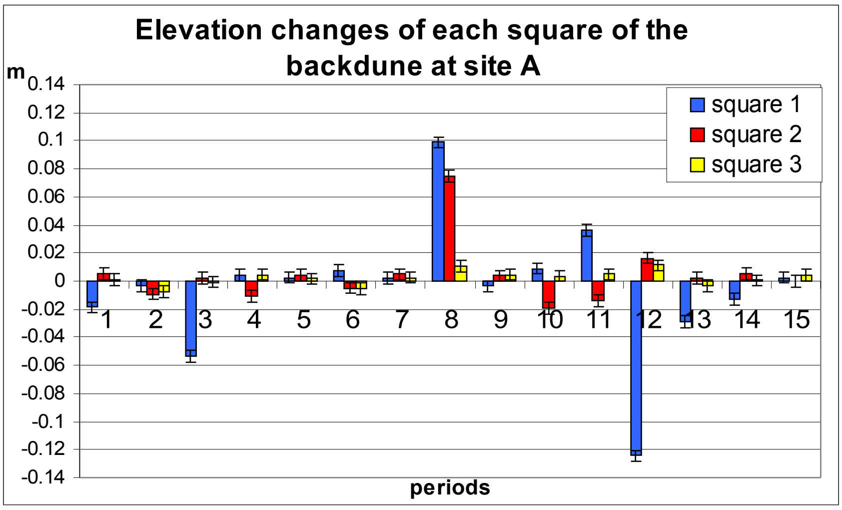
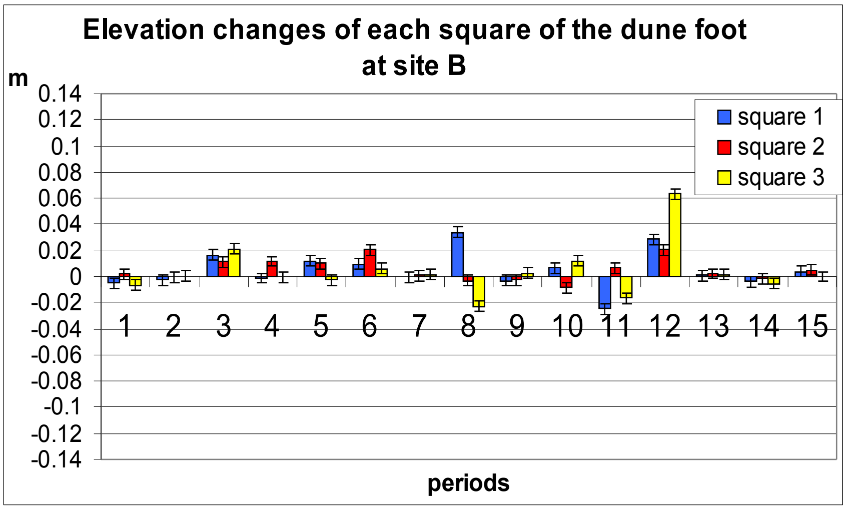
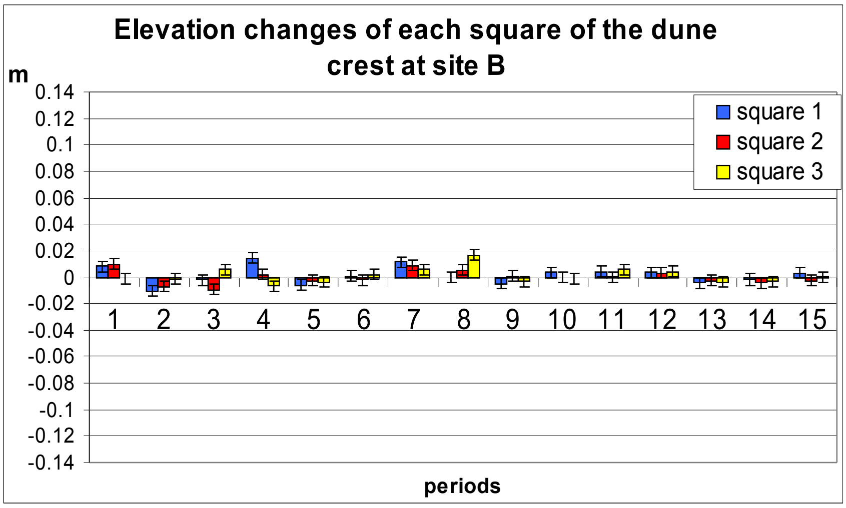


Fig 2.1.4.2: Elevation changes at the dune foot, at the dune crest and at the backdune of site A.


Elevation changes of each square of the dune foot at site B
m
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
square 1
square 2
square 3
periods


Elevation changes of each square of the dune crest at site B
m
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
square 1
square 2
square 3
periods

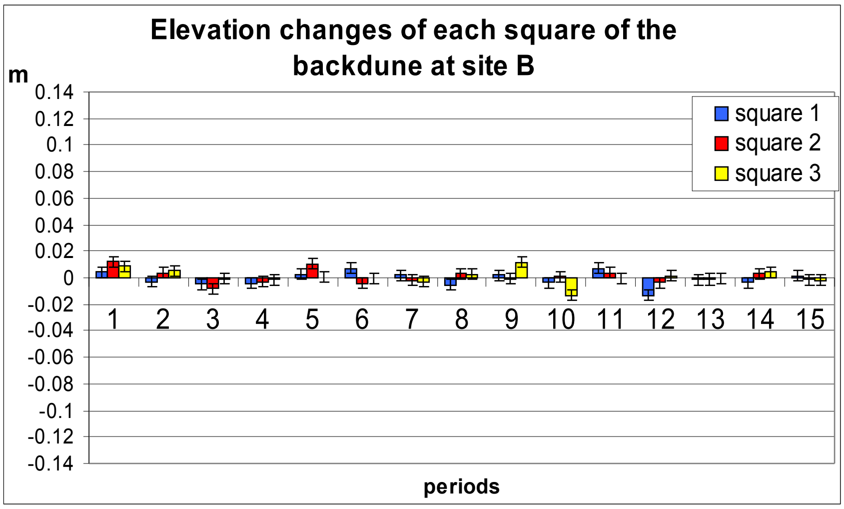
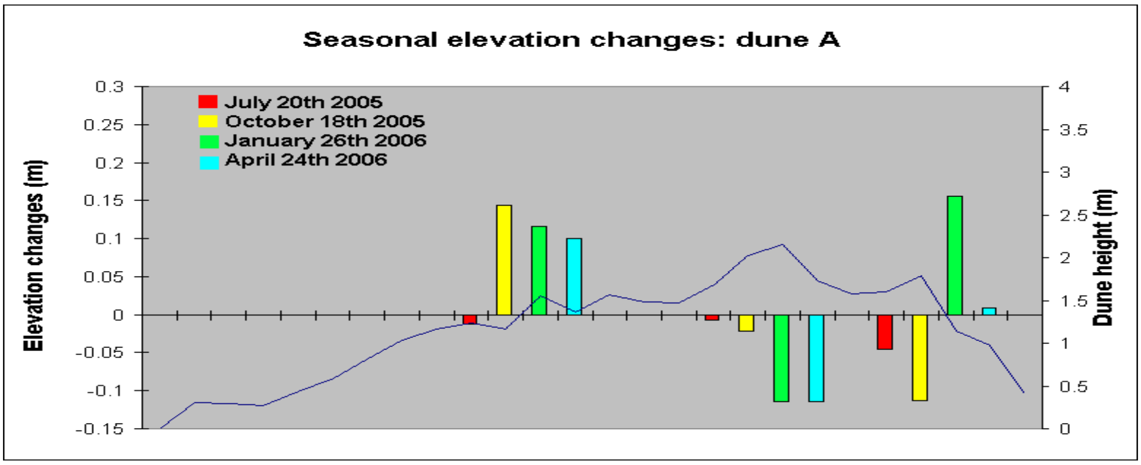


Fig 2.1.4.3: Elevation changes at the dune foot, at the dune crest and at the backdune of site B

It is worth noting that variability between squares is higher at site A than at site B. At both dune feet, there was a high variability between squares and between different periods. While differences between sites were remarkable both comparing the crests and the backdunes. It is also evident that the windiest periods (8 and 12) had more an affect on site A than on site B. Moreover, erosion is more frequent at site A and in particular in unvegetated or scarcely vegetated squares (see also tab 2.1.4.1). Figure 2.1.4.4 shows the cumulative elevation change (referred to three month periods) at each profile over time along dune A and dune B. The 3 squares of each line were averaged, so the information is much more resumed than in fig 2.1.4.2 and 2.1.4.3. But differences between dune A and B are even more evident: at both dune feet there was a general growth, but at site B it was higher and more continuous. At the dune crest of site A, mostly during winter, there was a significant erosion, whereas during the same period at the dune crest of site B there was a general (see also fig 2.1.4.2 and 2.1.4.3) growth in height (about 5 cm). The backdune of site B was quite constant, while at the backdune of site A at first there was erosion and then (mostly during winter) a great deposition. Sand accumulation at this location means that some sediment was being transported beyond this point and so a bit of the total accumulation was missed landward (into the river).



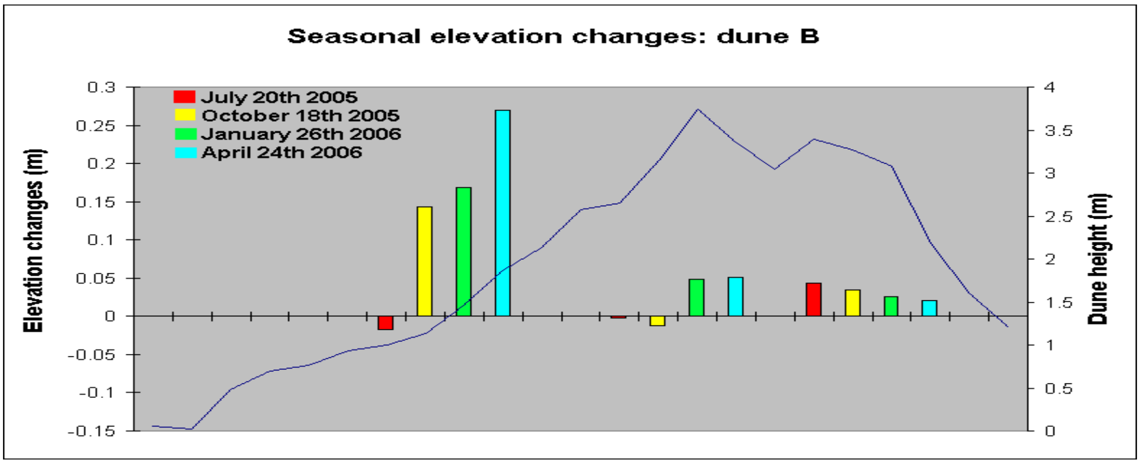


Fig 2.1.4.4: Cumulative elevation changes (referred 3 month periods) for both dune A and B. Distance is referred to shoreline: at 40 m there is the dune foot, at 50 m the dune crest and at 60 m the backdune.

During the periods of strongest winds, periods 8 and 12 (fig 2.1.2.8), there were high variations in elevation and erosion mainly at site A. During those periods there were also high variations at site B but only at the dune foot. It is worth noting that there was a general increase in growth at this site. Winds that had mostly affected sand accumulation or erosion belong to period 8 (from November 12th to December 16th 2005). During this period, 48 % of the total effective winds stronger than 10 m/s and 39 % of the total effective winds stronger than 8 m/s were recorded (fig 2.1.4.6).

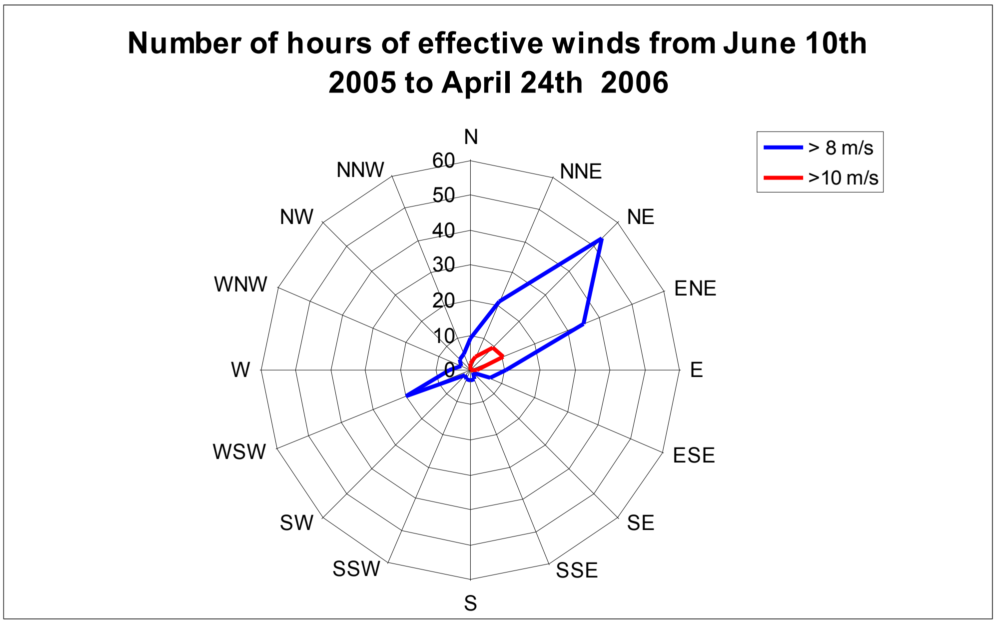


Fig 2.1.4.5: Wind rose. Winds are divided in classes of different intensities.

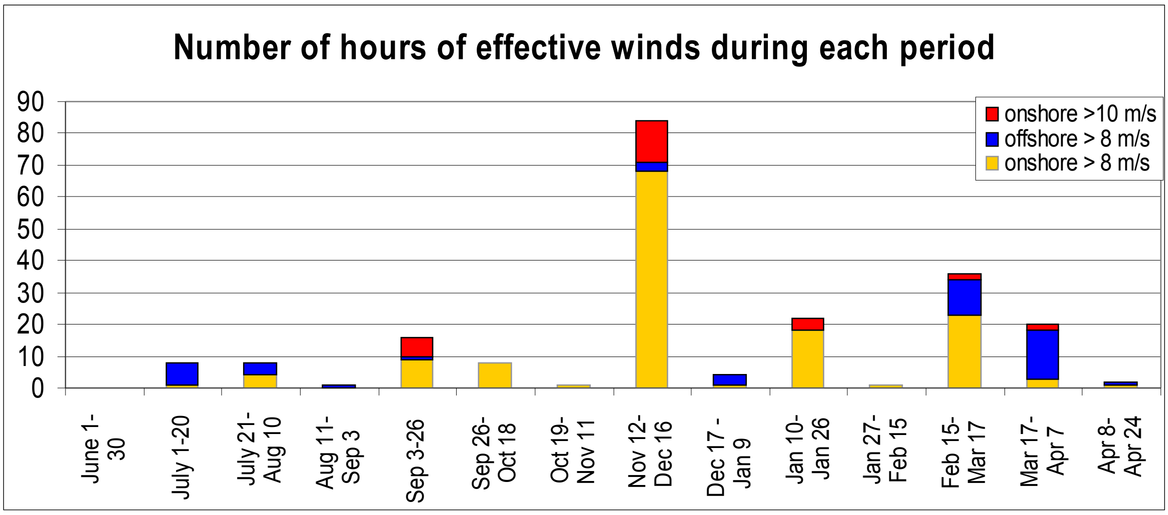
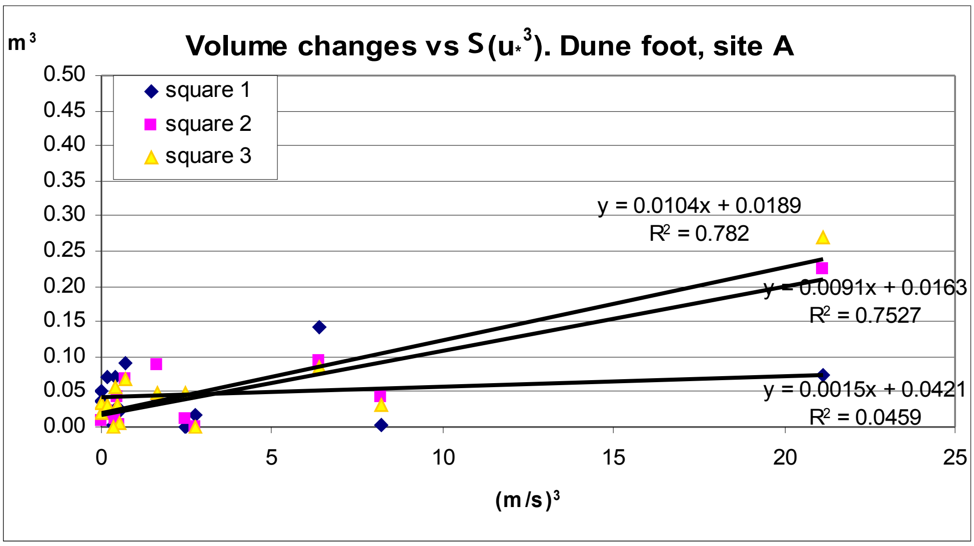
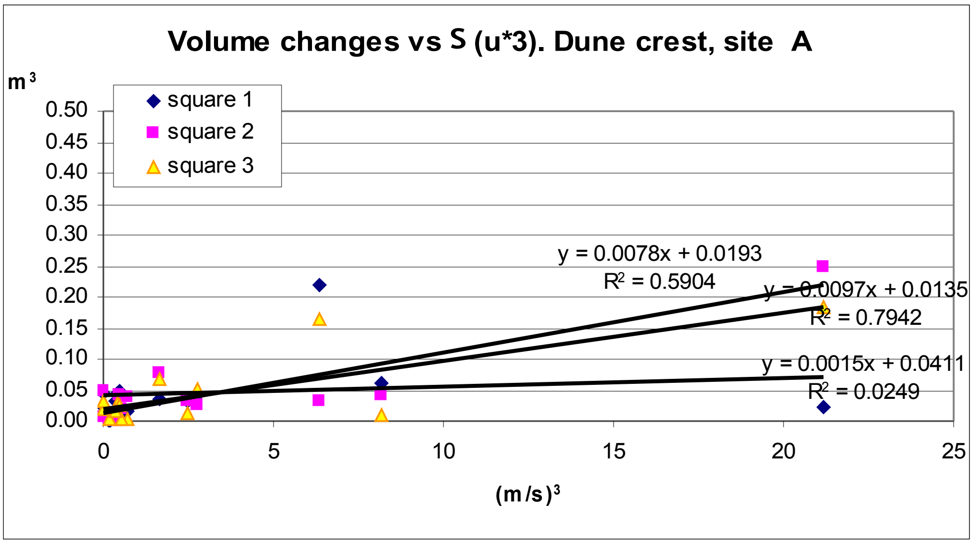


Fig 2.1.4.6: Number of hours of effective winds (divided into classes) during each period analyzed.

The absolute values of volume changes versus the sum of the u_* cube referred to each hour of each period were plotted in fig 2.1.4.7 for site A and in fig 2.1.4.8 for site B. Only winds much stronger than the calculated effective winds were considered. In fact, although 8 m/s at a height of 10 m corresponds to a shear velocity that is higher than the threshold value, it was found to be more suitable to use this value because weaker winds blew frequently but they weren't very effective in determining elevation changes.

At site A, the best regression results corresponded to some scarcely vegetated or unvegetated squares (tab 2.1.4.1) while at site B regression values were lower than site A and they weren't related to their vegetation coverage. The number of measures (N) corresponds to the number of periods analyzed, thus 14. So, to every period analyzed corresponds a value of volume change calculated by interpolating the differences in elevation measured (at time t_0 and at time t_1) in each of the 12 points belonging to every 2x2 m square. Regression values are much higher at site A than at site B, moreover at site A the most significant correlation values correspond to unvegetated or scarcely vegetated squares. Thus it is evident that erosion or accretion at the young dune depend more on strong wind duration than at the old one. It is worth noting that only some unvegetated areas of site A tend to change much with increasing winds duration and this fact is very often related to erosion. More specifically, onshore winds seem to have more affect on changes in elevation than offshore winds, even if there is some uncertainty due to the interaction of winds coming from different directions during the same periods analyzed.





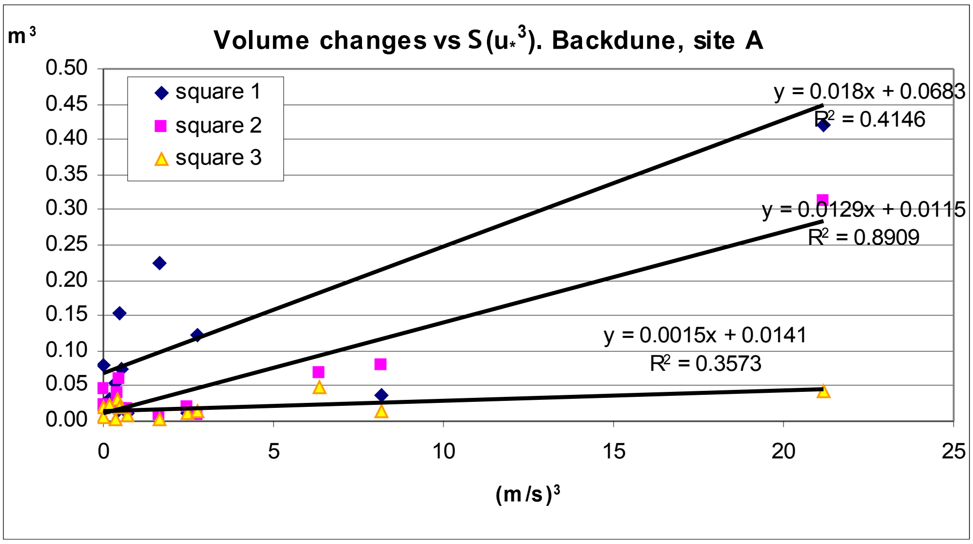
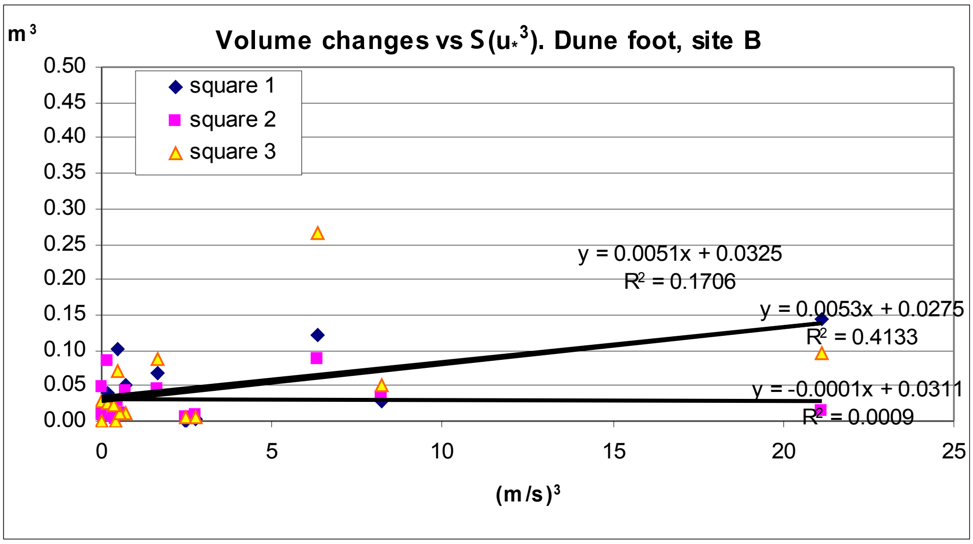
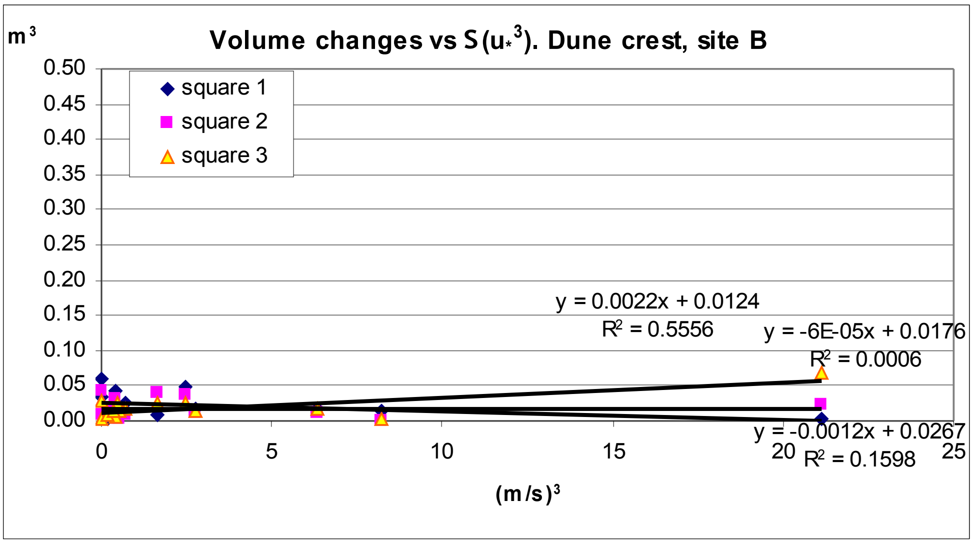


Fig 2.1.4.7: Absolute values of volume changes versus the sum of the u* cube referred to each hour of each period at site A.


m³
Volume changes vs S(u*³). Dune foot, site B
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
square 1
square 2
square 3
y = 0.0051x + 0.0325
R² = 0.1706
y = 0.0053x + 0.0275
R² = 0.4133
y = -0.0001x + 0.0311
R² = 0.0009
0
5
10
15
20
25
(m/s)³


m³
Volume changes vs S(u*³). Dune crest, site B
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
square 1
square 2
square 3
y = 0.0022x + 0.0124
R² = 0.5556
y = -6E-05x + 0.0176
R² = 0.0006
y = -0.0012x + 0.0267
R² = 0.1598
0
5
10
15
20
25
(m/s)³

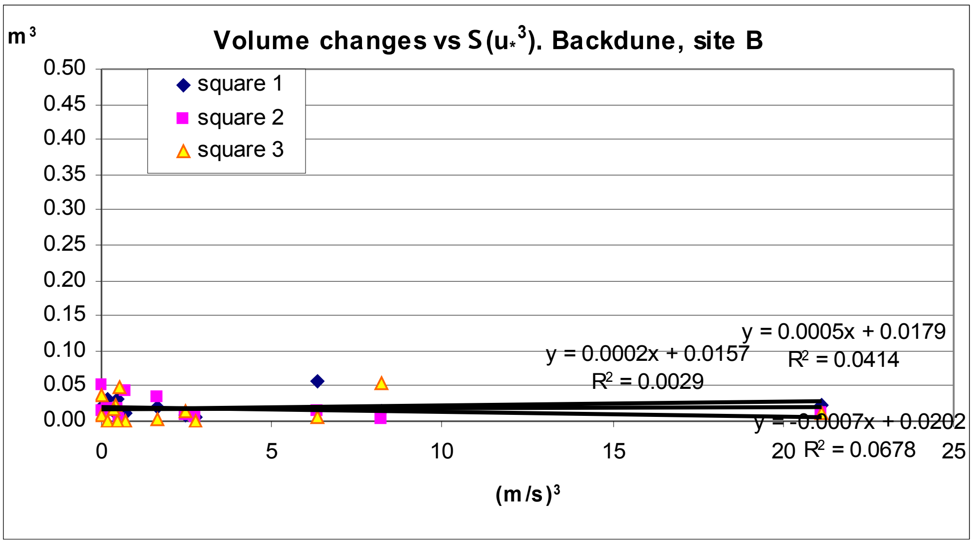

m³
Volume changes vs S(u*³). Backdune, site B
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
square 1
square 2
square 3
y = 0.0005x + 0.0179
R² = 0.0414
y = 0.0002x + 0.0157
R² = 0.0029
y = -0.0007x + 0.0202
R² = 0.0678
0
5
10
15
20
25
(m/s)³

Fig 2.1.4.8: Absolute values of volume changes versus the sum of the u* cube referred to each hour of each period at site B.

The standard deviation of each square was calculated over time (table 2.1.4.1). The highest values are those corresponding to the scarcely vegetated squares (square 1 and 2) at the backdune of site A, on the inlet. While the lowest are those at the backdune of site B, where the backdune is more vegetated and unaffected by the spit dynamism.

site	geomorphologic feature	square	sum (m)	mean (m)	standard deviation (m)	total vegetation coverage (%)
A	foot	1	0.002	0.000	0.016	2
		2	0.091	0.007	0.018	30
		3	-0.023	-0.002	0.021	0
	crest	1	0.054	0.004	0.017	70
		2	-0.047	-0.004	0.019	50
		3	-0.083	-0.006	0.017	5
	back	1	-0.043	-0.003	0.050	3
		2	0.053	0.004	0.023	1
		3	0.032	0.002	0.005	100
B	foot	1	0.071	0.005	0.015	100
		2	0.069	0.005	0.009	25
		3	0.059	0.005	0.021	4
	crest	1	0.023	0.002	0.007	60
		2	0.009	0.001	0.005	50
		3	0.024	0.002	0.006	40
	back	1	-0.009	-0.001	0.006	70
		2	0.012	0.001	0.006	60
		3	0.011	0.001	0.006	100

Table 2.1.4.1: Sum of all elevation changes of each square, mean of elevation changes and standard deviation. Highlighted values correspond to completely or almost completely unvegetated squares.

Moreover, during the entire study, the older dune (site B) grew more. There was an average increase in height at the dune foot of almost 7 cm, an increase of about 2 cm at the dune crest and quite a constant situation at the backdune. Site A grew much less and without any uniform pattern: at the dune foot there was a little growth (about 2 cm), it was eroded at the dune crest (-2.5 cm) and there was a little increase at the backdune (+ 1.4 cm). At the dune foot of site A square 2 grew a lot, even if it wasn't densely vegetated. Anyway it is remarkable that it is the only vegetated square of dune foot of site A. Whereas at the dune foot of site B, all the 3 squares (vegetated and unvegetated) grew a lot. At the dune crest of site A the most vegetated square (square 1) grew, while a non densely vegetated square (square 2) was eroded and an almost unvegetated square (square 3) was eroded even more. Whereas, at the dune crest of site B, there was a general increase in height, but the highest value referred to the least vegetated square (square 3) which is also the less elevated, since it is located on a lower part of the dune crest (fig 2.1.5.1)

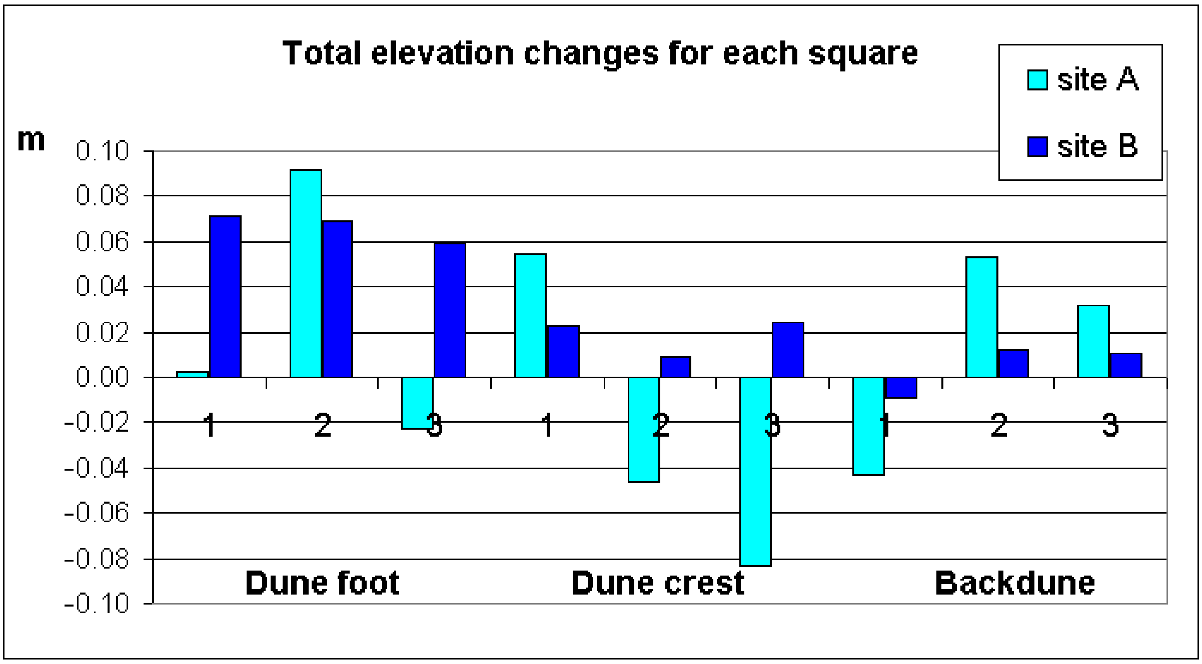


Fig 2.1.4.9: Sum of the elevation changes at each square (from the first to the last period analyzed). In correspondence of each geomorphological feature (dune foot, dune crest, backdune) are represented the three squares belonging to each site.

At the backdune of site A, two unvegetated squares (squares 1 and 2) had the highest standard deviation values and they behaved very differently to each other. One (square 2) was mainly affected by onshore winds and the other one (square 1) much less. The last square (square 3) was the most vegetated of site A and it was very similar to squares of dune B as the dendrogram shows (Fig 2.1.4.10). The dendrogram was obtained by ordering the complete cut and fill data matrix that contained values referred to each period and to each square. It was performed an agglomerative clustering by using the average linkage and the Euclidean distance.

This kind of ordination is useful because it takes into consideration the similarities between different squares during each period. Thus the dendrogram shows the great similarity between squares belonging to the crest and the backdune of site B. It is worth noting that the most similar square to this group is square number 3 of the backdune of site A that is densely vegetated.

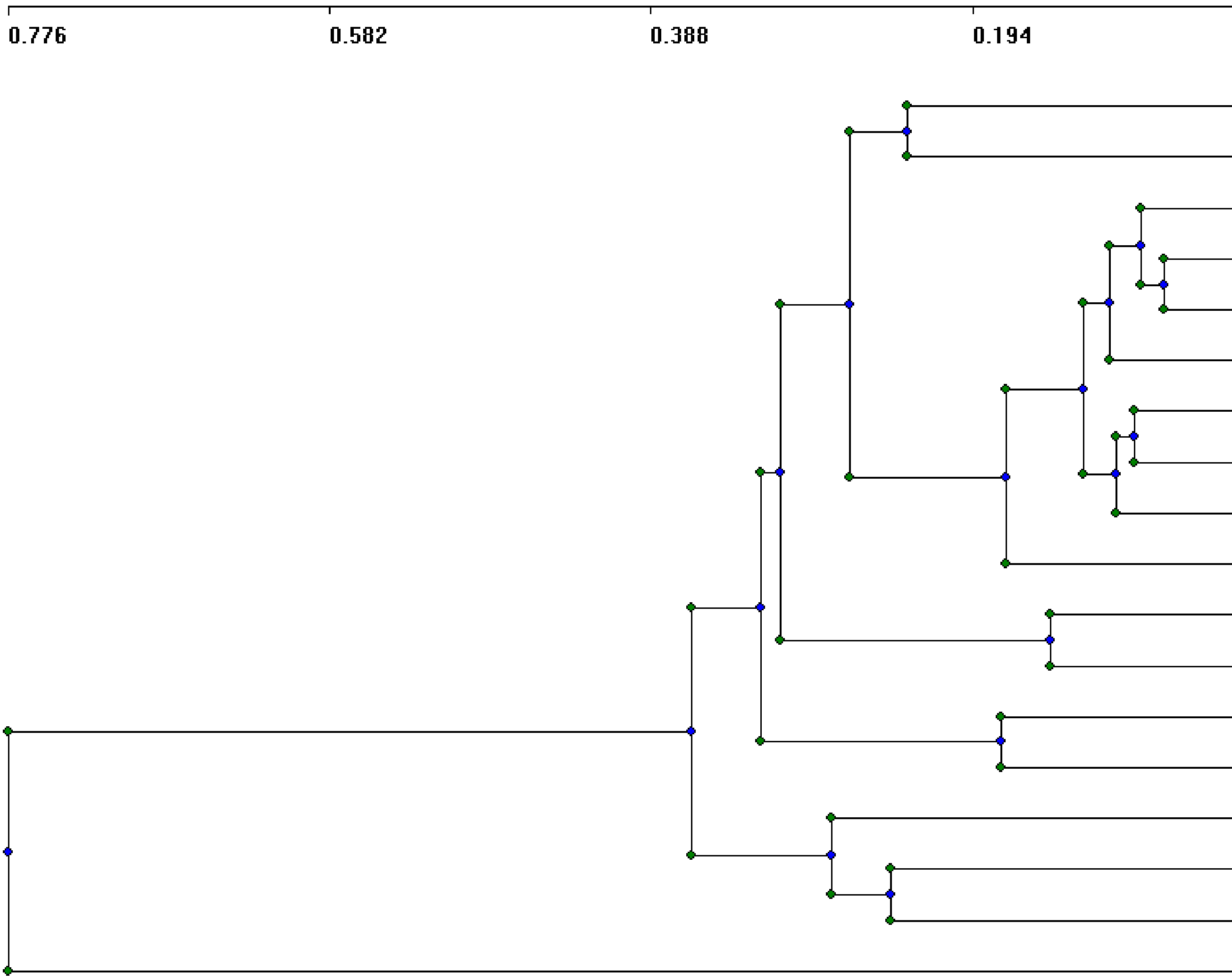


Fig 2.1.4.10: Dendrogram referred to the complete cut & fill data matrix.

It was plotted the total volume changes versus the vegetation cover of each square. So in each graph there are 3 values referred to the 3 squares of each line for both sites.

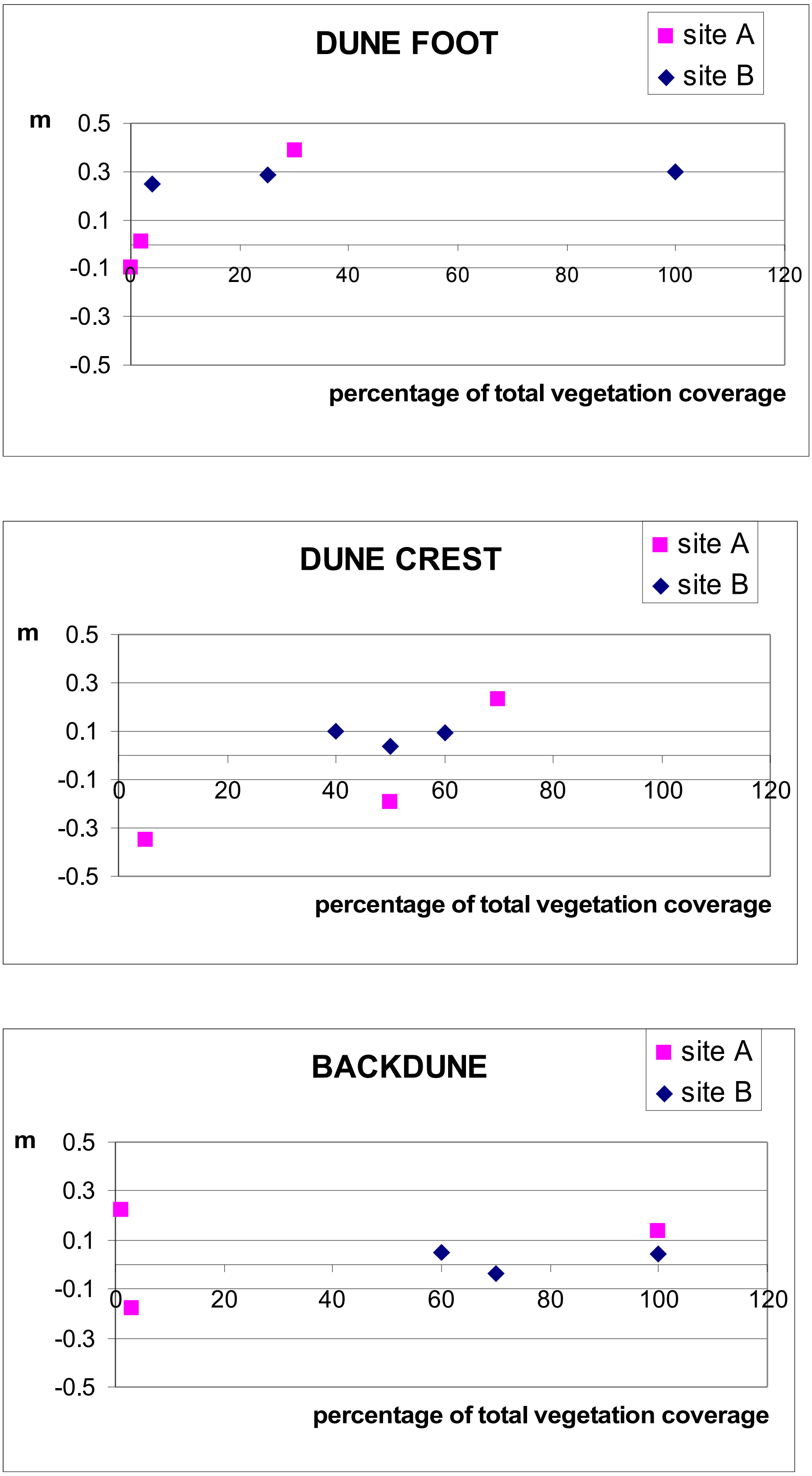


Fig 2.1.4.11: Elevation changes versus percentages of total vegetation coverage.

At the dune foot of both sites, higher values of vegetation cover corresponded to higher values of growth in height. But relationships between vegetation coverage and sediment accumulation were very different: at the young dune a small increase in vegetation coverage corresponded to very high increase in height, whereas the dune foot of the old dune grew quite uniformly and didn't seem to be affected very much by vegetation coverage. At the dune crests, sediment accumulation was lower at both sites. However, the younger one, dune A, continued to be affected by vegetation cover, while dune B varied very little and seemed to be unaffected by differences in vegetation coverage. At the backdune there were very few variations at site B, and great variations at site A, where there were 2 bare sand squares that behaved very differently from the others

2.1.5. Discussion

Sand accumulation depends on many factors (Sherman and Hotta, 1990): wind intensity and direction, grain size, beach amplitude, vegetation cover or/and the presence of other obstacles, i.e. beach deposits such as the high-water drift lines (Lemoine and Faucon, 2005), beach humidity and climate (Tsoar, 2005). By observing these study results, it is evident that another factor to be considered is the evolutional phase, thus the morphology, of dunes.

The two dunes here analyzed were equally exposed to the same winds and were affected by the same fetch amplitude in front of them. But the old dune, during the whole period analyzed (from June 10th 2005 to April 24th 2006), had an average increase in elevation more than 10 times higher than the young one (tab 2.1.4.1). Moreover, at site B (figg 2.1.4.3 and 2.1.4.4), there was a general and continuous growth in height both at the dune foot and at the dune crest, while at the backdune, erosion and accumulation were so little that this could be due to errors associated to the readings (4 mm), thus the backdune was unchanged. Whereas, at site A (figg 2.1.4.2 and 2.1.4.4), there was a discontinuous growth both at the dune foot and at the backdune while at the dune crest, mostly during winter, there was a significant erosion.

By looking at figg 2.1.4.3 and 2.1.4.4, the most evident result is the difference between sites: the dune crest and the backdune of site B were affected by a low variation in elevation changes even during periods of strong winds, while at site A there was a great variability between all squares and periods (the standard deviation column of table 2.1.4.1 confirms the higher variability existing at site A). Also the dendrogram confirms the great similarity existing between squares belonging to the crest and the backdune of site B. These squares were all densely vegetated (table 2.1.4.1) and it is worth noting that square number 3 of the backdune of site A was very similar to this group. This is evidence of the way vegetation can affect variability in sediment accumulation at site A. In fact this square was completely vegetated with typical backdune plants and was the only one of site A similar to the dune crest and the backdune of site B. This fact means that if the backdune of site A had been densely vegetated there wouldn't have been any erosion or lost of sediment landward, like at the older dune.

Thus, it is evident that at the backdune of site A the main influencing factor on deposition is vegetation coverage, while at the backdune of site B differences in accumulation are very low and they aren't related to vegetation coverage (fig 2.1.4.11). Even if square 3 of site A is similar to the squares of the backdune of site B, deposition at the backdune of site A is much higher (3,4 cm versus 1,2 cm), for the same vegetation coverage (100%, tab 2.1.4.1). This is due to morphology: in fact the backdune of site B is well stabilized and more sheltered by the crest, so its changes were lower.

Where there is dense vegetation coverage or when dune is mature, erosion at the backdune and loss of sediment landward were blocked. In fact, correlation between strong winds and elevation changes was highly significant only in the unvegetated or scarcely vegetated squares of the young dune (fig 2.1.4.7), with the exception of square number 3 of the dune crest of site B, whose case will be discussed further on. Square 1 of the backdune of site A has quite low regression values even if it is almost completely unvegetated. This is due to the shelter offered by surrounding vegetation located landward. Square 1 is more sheltered than square 2 and this could explain differences in sediment accumulation. At the backdune of site A at first there was erosion and then (mostly during winter) a great deposition (fig 2.1.4.2). Accumulation at this location means that some sediment was being transported beyond this point and so a bit of the total accumulation was missed landward (into the river).

On the contrary, vegetated areas tend to change less and they mostly accrete not erode (Hesp 1989, Arens et al., 1995, Hesp at al., 2005). Regarding morphology, no scarcely vegetated square of dune B had high regression values. This is evidence of the fact that the young dune is more vulnerable on its unvegetated areas than the mature dune. At site B only two squares has significant correlation values. The unvegetated square of the dune foot of site B has a significant correlation value. This square is more affected by strong winds than the other squares of the dune foot, even if its dependence from winds intensities is much lower than at the unvegetated squares of site A.

It is worth noting the case of square number 3 at the dune crest of the old site. In fact, this is the only square of site B whose correlation value between elevation changes and $S(u_*)^3$ is significant (fig 2.1.4.8). And this isn't due to the scarce vegetation coverage; in fact, 40 % is a quite high value and besides square 3 total elevation changes value is more similar to square 1 (vegetation coverage 60%) than to square 2 (vegetation coverage 50%) (fig 2.1.4.11). So at the dune crest of site B, the only significant correlation between the absolute value of elevation changes and $S(u_*)^3$ has been determined in a vegetated square. This fact proves that vegetation isn't a key factor in determining elevation changes at the dune crest and at the backdune of site B. In fact at site B, morphology is a more important influencing factor on elevation changes than at site A. In figure 2.1.5.1, it is represented squares location on the dune B crest and it is remarkable that square 3 is located on a less high area of the dune crest.

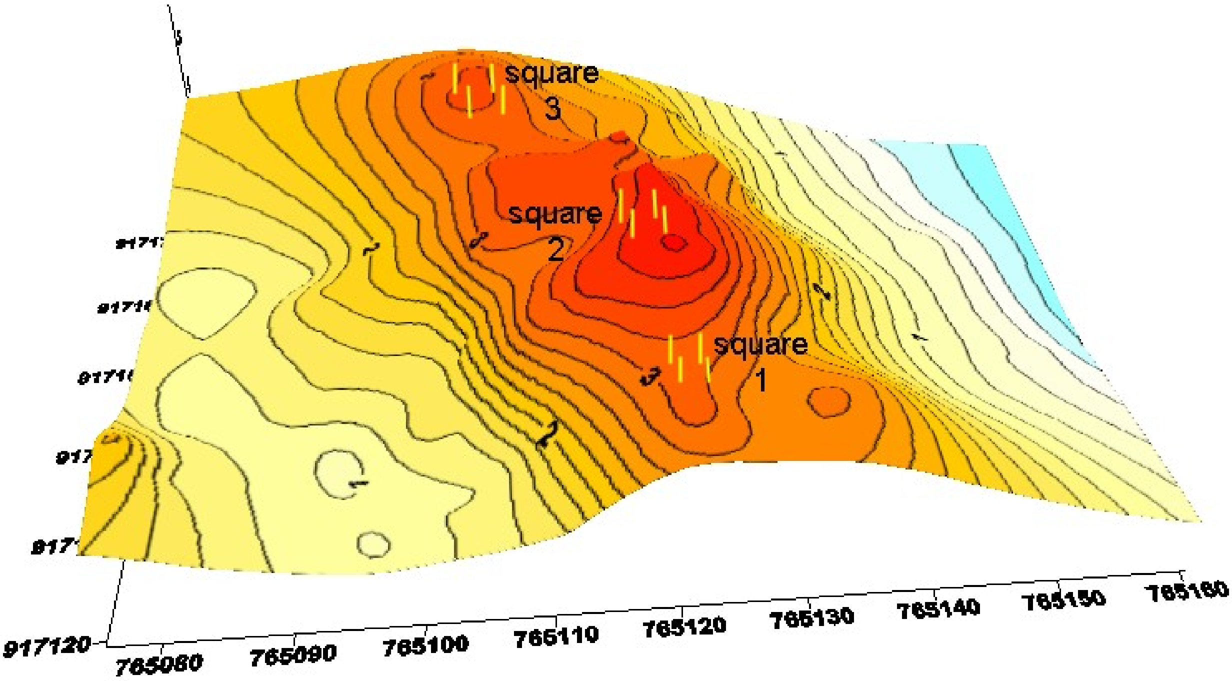


Fig 2.1.5.1: Location of the squares belonging to the dune crest of site B. Square number 3 is lower than squares 1 and 2.

This is in agreement with Arens (1996), Hesp and Thom (1990), Gares (1990), Davidson-Arnott and Law (1996) who demonstrated that the crest of a mature coastal dune is quite stable and doesn't grow much further. But a less vegetated and stabilized part of the dune crest can grow as much as a more densely vegetated and mature part of it, provided that the first is less elevated than the second. Thus, a less mature and stabilized part of the dune crest is much more dependent on strong winds events than a more mature and stabilized area. But this fact doesn't seem to be related to erosion as at the unvegetated or scarcely vegetated squares of site A. It rather seems to be related to accretion (fig 2.1.4.3). The comparison between the two crests (tab 2.1.4.1) highlights that at site A elevation changes (in absolute values) are about ten times higher than at site B. And this is evidence of the way morphology can have an important role in determining changes in deposition between the dune crests of site A and B. In fact, for the same vegetation coverage (50%), dune crest of site A was affected by a strong erosion (-5 cm) while dune crest of site B was affected by a slight deposition (1 cm, tab 2.1.4.1).

The dune foot of site A is highly affected by vegetation coverage while at the dune foot of site B growth in height is slightly dependent on vegetation and it is high even in the unvegetated square. This is due to the fact that dune B is a great obstacle against wind and so sediment is deposed at its foot both in vegetated and unvegetated squares. But morphology had an affect also on the young dune: in fact by comparing the dune foot and the dune crest, it is evident that, for the same vegetation coverage, deposition was higher (or erosion was lower) at the dune foot (fig 2.1.4.11).

Another important factor on sediment accumulation is the irregular morphology of dune A. During the earliest stages of its formation, a foredune is characterized by a higher irregularity in its morphology. This fact, together with vegetation coverage, had a strong affect on wind deposition and erosion patterns. Thus an irregularity in morphology is reflected by an irregularity in sediment deposition patterns. On the contrary, dune B, which is characterized by a much more regular morphology is less dependent on vegetation coverage, since deposition occurs even in unvegetated areas and erosion is quite rare. In fact, in the entire study site (at the dune foot, at the dune crest and at the backdune), variations in sediment accumulation along the young dune profile seemed to be mostly related to the percentage of vegetation coverage. This is evident by observing fig 2.1.4.11. Moreover, the dendrogram shows the similarity between unvegetated or scarcely vegetated squares of site A (square 1 of dune foot is similar to square 3 of dune crest and square 3 of dune foot is similar to square 2 of dune crest): they were quite similar even if they belonged to different morphologies (dune foot and dune crest) of the same site. Whereas the most vegetated square of the crest of site A was similar to the unvegetated square of the dune foot of site B. Moreover, during the entire study period, at the dune foot of site B and at the most vegetated square of the dune crest of site A there was the highest growth in height (tab 2.1.4.1). Thus the crest of the young dune can accumulate as much sediment as the foot of the mature dune; provided that the crest of the young dune is densely vegetated. Two differently vegetated squares belonging to different morphological features (foot and crest) of two different sites can have a high similarity. At the dune foot of site B, there is the highest accumulation capacity that is due to morphology rather than to vegetation (fig 2.1.4.11), since dune B is a great obstacle against wind and so sediment is deposed at its foot. Whereas at the dune crest of site A, sediment accumulation is highly dependent on vegetation cover (fig 2.1.4.11): growth in height can be similar to the dune foot of site B only if there is a dense vegetation cover.

2.1.6. Conclusions

Many previous studies focused on the scarce elevation variability on a mature and vegetated dune crest and backdune (Arens 1996, Hesp and Thom 1990, Gares 1990, Davidson-Arnott and Law 1996) and our results: 1) confirm that the evolutional stage of dunes is a very important factor in determining patterns of sand accumulation; 2) quantify differences between two different aged foredunes; 3) focus on the main influencing factors on accumulation at the two foredunes. The old dune here analyzed grew much more, particularly at the dune foot, than the young one. At the old dune, morphology was a key factor in dune growth while, at the young one, changes in elevation were mostly due to vegetation coverage. A great role was played by irregularity in dune morphology, which is strictly related to dune maturity. Where dune morphology is regular and continuous, sediment deposition is higher and follows a regular depositional pattern, which is not strictly dependent on deposition. The young dune was extremely affected by the presence of vegetation and by strong onshore winds activity while the old dune was unaffected by the absence of vegetation at the dune foot and by differences in the vegetation coverage at the dune crest and at the backdune. The young dune was extremely affected by erosion in unvegetated areas and generally has high deposition rates in vegetated areas. There were evidences of sediment transportation beyond the backdune so a bit of the total accumulation was missed landward. Thus, since an older dune is characterized by a lower variability in sand accumulation and a higher resilience against erosive events, it should be a priority to protect coastal dunes during their most vulnerable stages.

2.2 The influence of human activity on coastal areas

2.2.1 Introduction: goals achieved and future steps in international research

Dunes are one component of coastal systems, which can be severely altered by development. The first scientific work concerning aeolian sediment transport were performed in natural areas and quantified the relationship between wind velocity, grain size and sediment transport (Bagnold, 1941). Scientists demonstrated the effect of vegetation on sediment accumulation (Arens, 1996; Hesp, 1983; Hesp et al, 2005), and they observed changes in wind flow patterns, which were due to dune topography (Hsu, 1988, McKenna Neuman et al, 1997). There is also a branch of aeolian research, which is focoused on discovering the impact of human activity on wind flow. Such activities include presence of buildings or sand fences (Castro, 1971; Phillips and Willets, 1979, Nordstrom and McCluskey, 1985, Nordstrom, 2000). In 1990, Gares affirmed that, despite the information provided by previous studies, the extent to which development and human activity associated with it affected aeolian sediment transport and dune formation still remained to be determined. Gares found that different dune morphologies and dune dynamics exist at developed and undeveloped sites. At developed sites, the amount of sand transported by wind and trapped within the dunes is lower than at undeveloped sites. Several features of developed sites such as the presence of buildings and roads negatively affect wind transport. These structures create a stagnation zone where sand deposition occurs. So beach buildings trap sediment that should instead form and nourish coastal dunes. It is worth noting that the location of dunes on the cross-shore profile in developed areas often differs from the location where they would occur under natural conditions. This is due to the fact that dune position is dictated by direct human actions and by the passive effects of existing human structures rather than the free interplay between vegetation growth, sediment supply and wave erosion (Nordstrom, 2000). After Gares' work, during the last 15 years, a lot of effort has been made to study the influence of human activity on coastal dune systems. There are still, however, many features of human-altered landforms that are yet to be studied or quantified. Future steps in aeolian research carried out in human-altered areas should examine to a greater depth the problem of (spatial and temporal) scale investigation, given the scale of human alteration is increasing. This phenomenon is becoming so common that scientists should probably start considering developed coasts and their peculiar dynamics as the norm. Having this as an aim, it is necessary for scientists and planners to work together in harmony on the coast. Overexploited coastal areas are very fragile, damaged ecosystems, which are probably quite different to what they would be if man didn't exist. Nordstrom (2000) stated that developed coasts are characterized by altered landforms which differ from natural landforms internally and externally and are generally: 1) less dynamic, 2) less diverse in vegetation cover, 3) smaller in area, 4) subject to cycles of evolution that correspond more closely to human processes than to natural processes (at least in the depositional phase). Nordstrom and Jackson (2003) identified six different gradients (fig 2.2.11) related to human influence on coastal systems.

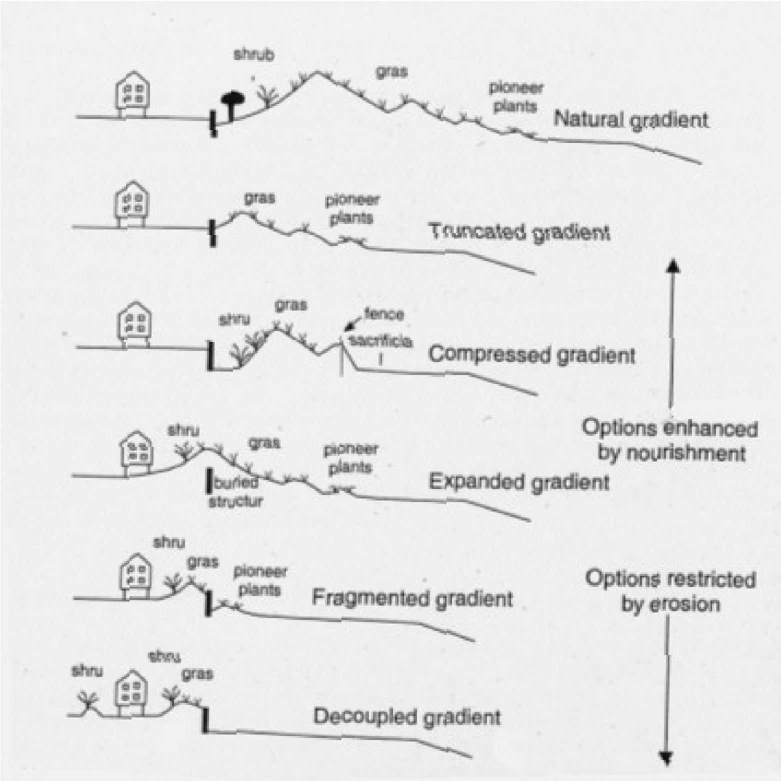


Fig 2.2.1.1: Six beach-dune gradients on developed coasts identified by Nordstrom and Jackson (2003)

Nordstrom and Jackson (2003) affirmed that the similarity between developed and undeveloped dunes depends on the amount of space available and the degree to which natural processes and landforms are allowed to function within that space. Generally, dunes on developed coasts are smaller and they have fewer distinctive sub environments, with less connectivity between them.

Gòmez-Pina et al (2002) listed the main causes of dune degradation in Spain and almost all of them are valid explanations of dune degradation in Italy: massive tourism development, road and boulevard constructions, dune mining, littoral drift interruption, dune recreational pressure, human trampling, off-road vehicles and parking lots, water extraction, civil engineering works and military use. Another important cause of dune degradation, which should be added to the Gòmez-Pina et al list, is related to the problem of beach raking. Lemoine and Faucon (2005) reported the results obtained by limiting mechanical raking along a 1,5 km long stretch of coast, in Northern France. They observed the appearance of habitats that didn't exist before on that beach. The new vegetation association was very effective in producing new accumulation phenomena which lead to the formation of new embryo dunes. Thus it is evident that some very simple, cheap and low impact interventions, like limiting beach raking, can give good results. It is also true, however, that some artificial interventions, although carried out in order to protect coastal areas, can cause very serious damage. Castro (1988) presented the case of the artificial construction of foredunes on the Chilean coast. This intervention seriously altered the beach-dune interaction, because the artificial features had much different characteristics than the natural dunes. This caused the artificial dune to be scarped throughout the year with a low profile in front of the high ridge. Many similar interventions have been carried out all over the world during the last decades, but the majority of them were not studied by scientists. The most common approach is to plan an intervention from a mere management point of view, without a great feedback with the scientific community. So the next great challenge is to create a better connection and interaction between Local Administrations and scientists. This is very important because, as explained further on, interventions are usually planned without any awareness of the real dynamics of the problem (involved variables, relationships between forms and processes, variability of the system, indeterminacy in sediment transport). Anyway it is worth noting that research on developed coasts landforms is still too preliminary to provide the basis for a definitive classification based on a single set of criteria or even a single methodology (Nordstrom, 2000). This is mainly due to the fact that geomorphological characteristics can account for a large percentage of the variance in shoreline characteristics, well after a shoreline is developed or protected (Jackson et al, 1999).

2.2.2 The North Adriatic coast: features and impacts of human activity

The Adriatic Sea is the biggest semi closed basin in the Mediterranean Sea. It is orientated SSE-NNW, its maximum extension is 800 Km whereas the minimum is 200 km. Thus it is a narrow basin with a north-south depth gradient: the southern part is deeper, while, going further north, the basin becomes shallower. The most important winds, related to foredunes formation on this coast, are Scirocco and Bora. Scirocco (SE-NW) blows over the longest fetch, while Bora (NE-SW) has a shorter fetch but it is the dominant wind on the Northern part of the basin. The Northern part of the Adriatic coast is mainly characterized by dissipative sandy beaches. During the last decades, development has brought about a very damaged system, whereas only fifty years ago beaches were generally wider and dunes were more extended. Only in the Province of Ravenna, coastal dunes that have disappeared during the last 50 years have been calculated to be 75% of the initial extension (Caruso et al., 2005). Coastal foredunes disappearance has been mainly caused by tourism development: in fact, along the Northern Adriatic coast, a decade after the end of the Second World War, many buildings and the railway were constructed without any awareness of their environmental impact. Problems related to past bad policies of coastal management are still evident on this coast. Primarily, there is a lack of sustainable planning of coastal activities. In fact, many activities related to tourism are just carried out in a slapdash way: it is very common to observe many different pathways breaching dunes in the neighborhood of beach establishments. Some simple fencing could be very effective in discouraging people from crossing dunes outside the main pathway, but on the North Adriatic coast this kind of protections are almost absent. Caruso et al (2005) demonstrated that, on eight different dunes of the Province of Ravenna, the highest values of species richness was found on the only fenced dune of the area analyzed. Another important problem is related to beach raking on the majority of the North Adriatic beaches. This activity, linked to tourism, is very damaging to coastal environment. In fact, by raking the beach, natural features of the beach and its slope are flattened and this causes the disappearance of beach landforms that are a natural defense against storms and erosive events. Moreover, beach roughness (related to the presence of vegetation, of geomorphological elements such as embryo dunes, of any kind of obstacles) is very important in reducing airflow strength and in inducing sand deposition (paragraph 1.1.1). In conclusion, it is necessary to take into consideration that the North Adriatic coast is one of the most developed and touristy area of Europe. Unfortunately the process which leads to such development is not controlled by a sustainable reasoning but, on the contrary, it follows only the business interests. Nowadays, problems related to coastal erosion are getting bigger and bigger. Local Administrations are now a little bit more aware that it is better to face this problem by protecting natural systems (mainly coastal foredunes) than by constructing artificial hard defenses (groins, barriers, jetties). One of the most common soft interventions on coastal areas threatened by increasing erosion is beach nourishment. And in this chapter it will be analyzed a study case, located in the Province of Venice, where nourishment was carried out.

2.2.3 Beach-dune sediment budget on nourished beaches: can nourishment reactivate a developed stretch of coast?

Beach nourishment is often used as a method to compensate for marine erosion in sandy coastal areas (Davison et al., 1992). The method implies a direct supply of sand to a beach, so that the sand acts as a buffer against wave energy during extreme events. In addition, it affects the sediment exchange rate between the beach and dunes by aeolian processes (Van der Wal, 1998). Compared with other methods of protecting the coastline, beach replenishment is not only more flexible but also offers potential benefits in terms of safeguarding the environment and the provision of improved recreational facilities (Adriaanse and Coosen, 1991). During the last decades, beach nourishment has become very popular as a solution to beach erosion problems and is now used nearly routinely around the shorelines of the world. Beaches which are in an eroded state for whatever reason can be reinstated by the placement of a borrow material, preferably with the same textural properties as the native material. Borrow material finer than the native material is assumed less stable and losses would be greater, thus necessitating the original placement of larger volumes of beach fill in order to achieve the same result (Swart, 1991). Van der Waal (1998, 2004) carried out several studies on the impact of beach nourishment on coastal foredunes. She affirmed (1998) that changes in the rate of aeolian sand transport depend on location, size and shape of the nourishment and fill material. In particular, sediment flux may be affected by fetch of wind over beach sand and characteristics of the sand at the surface. Since beach width (and fetch) is enhanced by beach nourishment, this suggests that larger sediment fluxes (and more erosion), as compared to before nourishment, can be expected. The effect will be largest just after nourishment and will gradually decrease as the size and width of the nourishment diminishes as a result of marine and aeolian processes. However, the relation between aeolian sand transport and fetch can be seriously affected by several factors, such as the variability in surface characteristics. Fill of some studied nourished beaches contained considerable amounts of shells. The aeolian sand transport on the beach can be reduced, but the transport does not cease.

In this thesis, a short case study is described (2.2.3.1). On this beach, a big nourishment was carried out covering a seawall which before caused several problems. As confirmed in many previous studies, beach nourishment seemed to be useful in protecting beaches and in reactivating coastal foredunes.

2.2.3.1 The case of Eraclea beach (Venice).

Eraclea beach is located on the North Adriatic coast, only 10 km further North of the Venice Lagoon. The study case analyzed in this thesis is a 350 m long stretch of coast, where there are 2 bathing establishments.

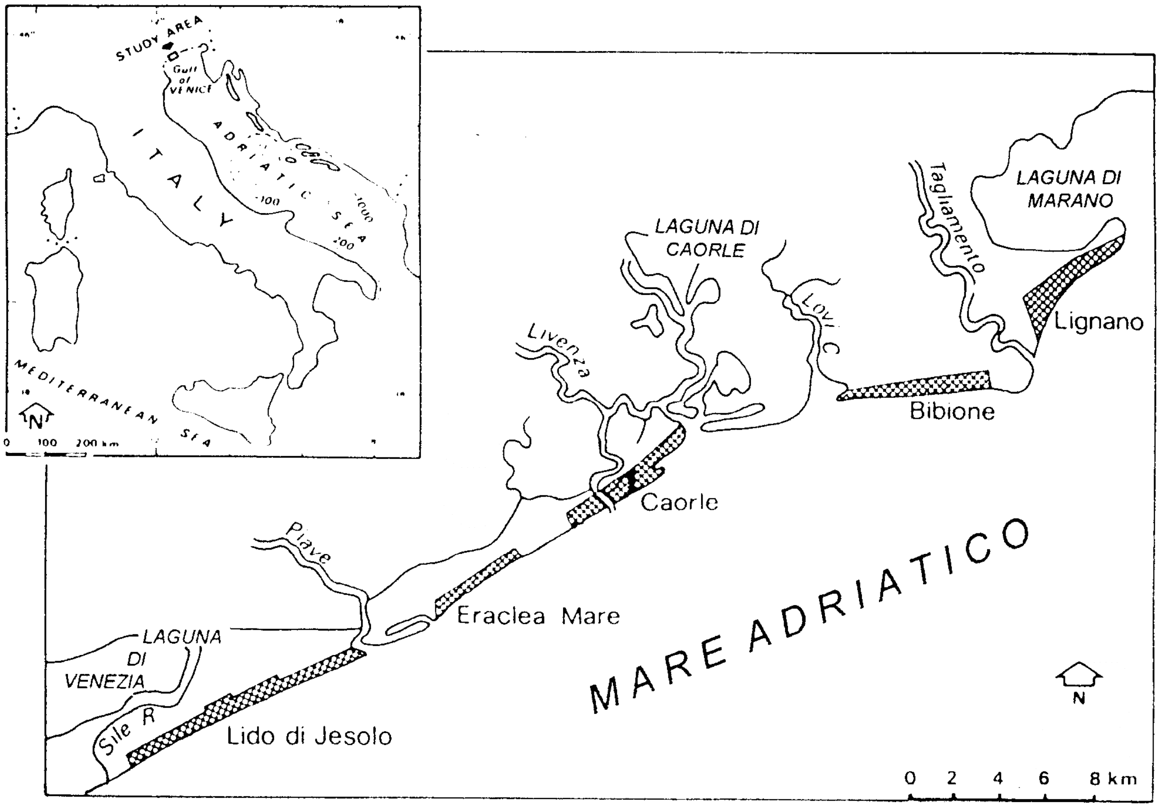


Fig 2.2.3.1.1: Location of the study site.

Beach is oriented ENE-WSW. Both prevailing and dominant winds come from NE. Winter winds can blow at speeds higher than 80 Km/h. In fact, on the North Adriatic coast, Bora wind (coming from NE) is very common during winter and is also very

DATI VENTO 1951-1988 (VENEZIA)

Dir (°)	Classi di velocita' (km/h)							
	1,85	7,41	14,82	24,08	35,19	48,15	64,82	TOT
0°	4,18	2,26	0,57	0,20	0,05	0,01	0,01	7,28
45°	5,82	6,71	3,54	2,21	0,88	0,19	0,03	19,37
90°	2,15	2,90	1,97	1,36	0,51	0,12	0,01	9,02
135°	1,77	2,93	0,93	0,29	0,11	0,02	0,00	6,04
180°	3,00	5,12	1,32	0,32	0,07	0,01	0,00	9,84
225°	1,15	1,00	0,44	0,14	0,02	0,00	0,00	2,75
270°	1,50	0,90	0,28	0,10	0,02	0,00	0,00	2,81
315°	1,80	0,60	0,11	0,04	0,01	0,00	0,00	2,55
TOT	21,37	22,42	9,16	4,65	1,67	0,34	0,05	59,67

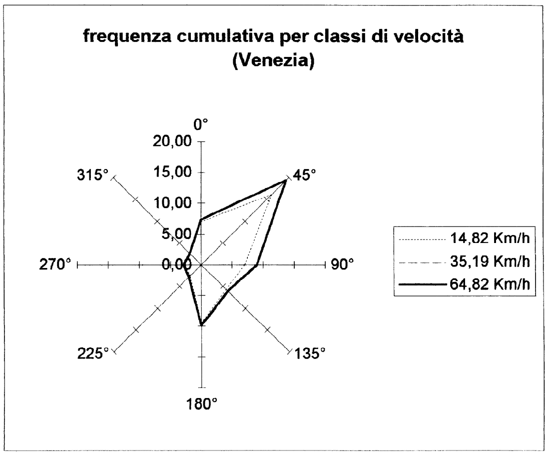


Fig 3.1

strong (fig 2.2.3.1.2)

Fig: 2.2.3.1.2: Cumulative frequency of wind divided into velocity classes at Venice from 1951 to 1988.

On this beach there is prevalently fine and well sorted sand (mean grain size values are very close to 180 micron). In fig 2.2.3.1.3 it is showed the cumulative frequency of grain size of one representative sample, P502.

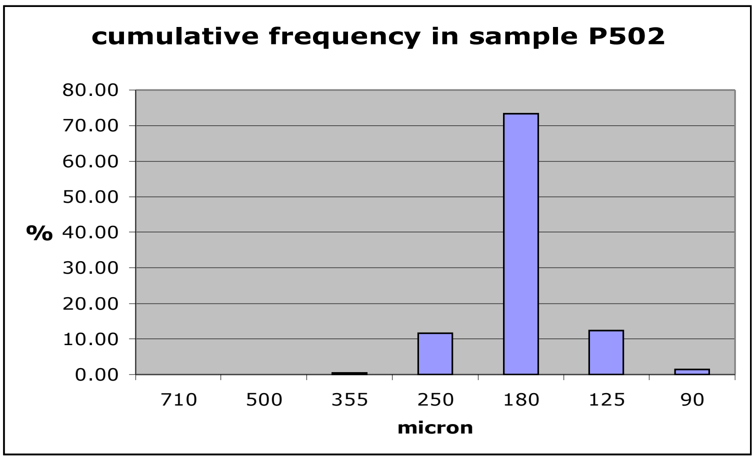


Fig 2.2.3.1.3: cumulative frequency in sample P502

Eraclea beach is located on a very tourist stretch of coast where human pressure is very high, particularly from May to September. Every year, before the tourism season, the beach is raked, many umbrellas are planted and human trampling becomes very intense. Also human protective interventions had brought about a very unnatural landscape. Since the beach was threatened by erosion, in 2000, a big intervention was carried out by demolishing many old groins that were too close to each other and by elongating some of them. Hence, 135 m long groins were positioned every 240 m, forming 8 cells. This kind of hard intervention could affect wind dynamics, since groins are very long and high Then during May and June 2004, a soft intervention, nourishment, was carried out on Eraclea beach. The total volume of sand brought on the beach was 300.000 m^3. This sand was obtained by offshore dredging in the sea in front of Eraclea beach. Its mean grain size was about 220-230 micron and it was compatible with the original sand (Ing. Ardone, CVN, personal communications). Just after the nourishment the beach was 70-80 m wide, whereas now it is about 60 m wide. The fill was grey, whereas the color of the autochthon sand was yellow, thus it was quite easy to distinguish between them before chemical analysis. The fill covered an old seawall that used to cause many problems related to overexcavation, wave reflection and seawater stagnation on the backbeach (fig 2.2.3.1.4). The latter problem was strictly related to sand supply to coastal foredunes. In fact, after a sea storm, the water was trapped behind the seawall thus exposing the dunes to unnatural and abnormal conditions.

Fig 2.2.3.1.4: the seawall before nourishment.

The fetch in front of coastal foredunes was small (about 25 m or less) and often wet for long periods, due to the seawall presence that lead to seawater stagnation. This part of the beach was completely excluded by aeolian dynamics: in fact, even when it became dry it was characterized by a hard mud surface. Thus dunes were constrained to a sort of inactivity caused by the lack of sediment supply. After nourishment, the growth of the beach (about 60) and the burial of the seawall had brought about a new favorable situation for coastal foredunes reactivation. Pre-nourishment topographic data were compared to post-nourishment topographic data to assess the efficacy of this soft engineering solution in reactivating the beach-dune sand interchange.

2.2.3.2 Methodology

This work was made possible due to the availability of topographic data obtained in 1998 (Pillon). Pillon took topographic measurements along 12 profiles. Four of his profiles were used as a basis for the present thesis. Then topographic data taken on the same 4 profiles were compared to that of 1998. These 4 profiles were chosen because there were different foredunes laying in those areas (two mature and high foredunes and two young and low foredunes). Another reason is that they were next to each other, thus it was possible to analyze a cell, formed by two groins (fig 2.2.3.2.1). In fact, there was a profile located updrift, two profiles laid within the cell and the last one is located downdrift. The first measurement campaign was carried out in January 2005, the second in September 2005 and the third in July 2006. Methodology adopted for the first and the second campaign was the same used by Pillon in 1998. Thus topographic surveys were obtained by the use of a total station (Zeiss elta 3 total station). Whereas, during the last campaign (July 2006), a Thales Navigation DGPS system with two ProMark™3 receivers was adopted. The first receiver was used as reference station and the second as rover. The reference station was located in correspondence to the 56_270-G260 benchmark whose specific features were kindly provided by Consorzio Venezia Nuova. Both total station and DGPS profiles cover the beach zone that goes from the shoreline to the backdune. The location of the five profiles is showed in fig 2.2.3.2.1. Survey names are those used by Pillon in his thesis.

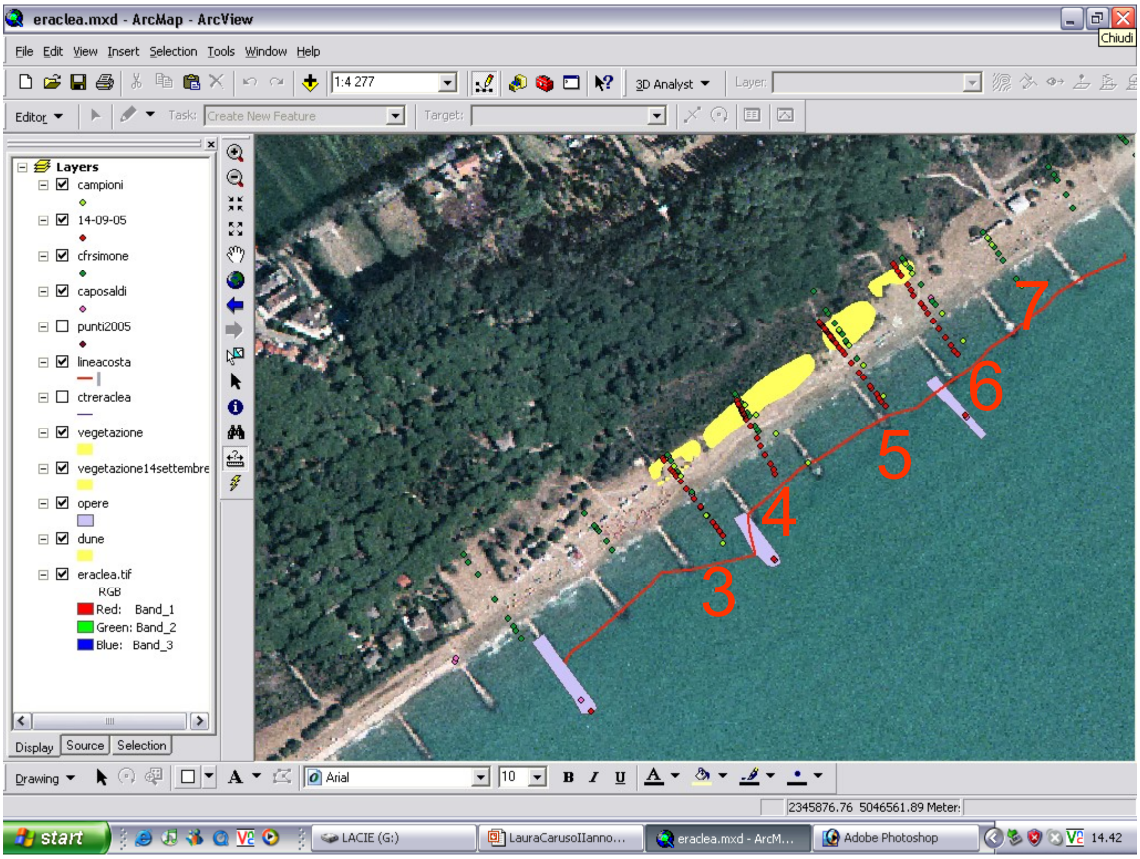


Fig 2.2.3.2.1: topographic surveys location.

Along each survey, during January 2005 campaign, were gathered 4 sediment samples. The first was gathered on the shoreline, the second on the backbeach, the third at the dune foot, the fourth at the dune crest. The total number of samples is therefore 16. Grain size characteristics were obtained by using a sedimentation tube (macrogranometer, fig 2.2.3.2.2).

Fig 2.2.3.2.2: the sedimentation tube used for the grain size analysis.

The same samples were analyzed also from a chemical point of view, by using the X-ray fluorescence spectrometry technique. This methodology was indispensable to identify which elements were present in each sample and in which percentage. And this made possible to chemically characterize the autochthon sand and the fill, since the color of the two sand was so different that in some areas (mainly on the backbeach) there was surely only the fill, while in other areas, such as the crest, sand was not yet contaminated by nourishment sand.

2.2.3.3 Results

The four topographic surveys have been compared to those carried out by Pillon in 1998. Survey number 3 (fig 2.2.3.2.1, 2.2.3.3.1 and 2.2.3.3.2) is the most western of the profiles analyzed. This area is characterized by two parallel ridges: the seaward one is much lower than the landward one. This profile is also lower and geomorphologically younger than profile 4 and 5 (whereas dune height at profile 6 is quite similar) and it is very stressed by human trampling.

Fig 2.2.3.3.1: profile number 3. September 2005.

On this dune, vegetation is sparse between the two ridges and typical species of the backdune are now on the front, as *Tamarix*. This is evidence of an artificial plantation of this specie. During summer 2005, a hard pathway was constructed around the dune as a sort of perimeter. This kind of completely heedless action, carried out by local stakeholders and accepted by local administrations, is very damaging for coastal foredune dynamics. In fact, dune front is a very dynamic element, where most of the sand that reaches a dune is trapped. The comparison between recent surveys and 1998 is illustrated in fig 2.2.3.3.2.

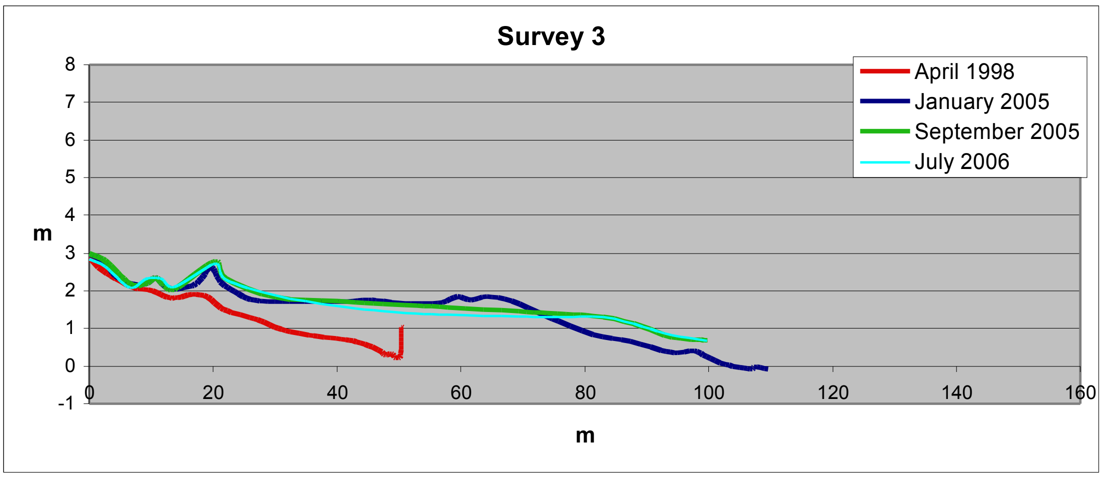


Fig 2.2.3.3.2: comparison between different topographic surveys of profile number 3

Survey number 4 is located (fig 2.2.3.2.1) in correspondence to a 5 m high coastal dune, which has two vegetated ridges. The active ridge is lower (about 4m). Vegetation does not follow its typical succession, but appears very stressed and spatial distributed in an unnatural way. In front of this dune, during the holidays season there is a little bathing establishment.

Fig 2.2.3.3.3: profile number 4. September 2005.

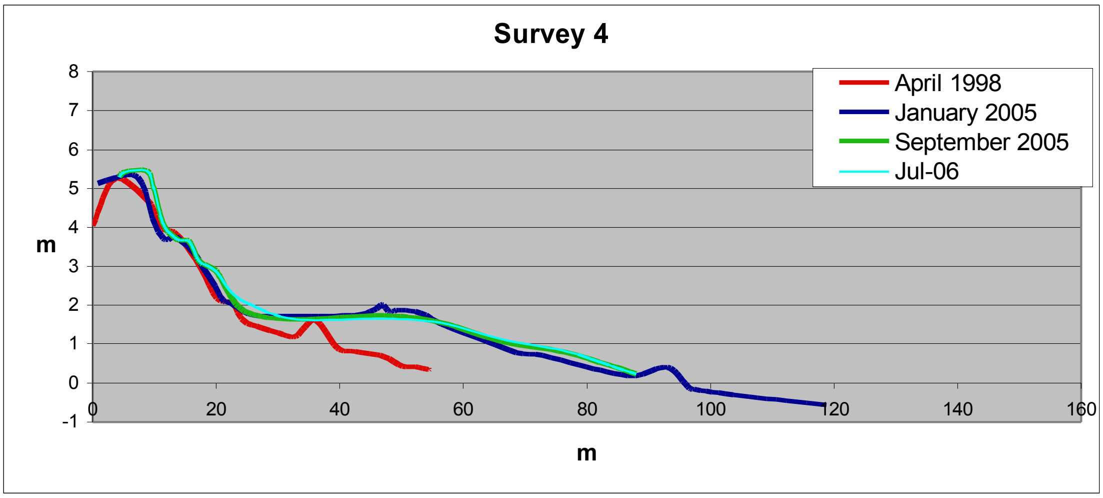


Fig 2.2.3.3.4: comparison between different topographic surveys of profile number 4

Survey number 5 was located (fig 2.2.3.2.1) further east, in correspondence to a 7 m high coastal dune, which has two vegetated ridges. The seaward ridge was lower (3 m) and active. Between the two ridges there was a vegetation gap due to intense human trampling. As in the other profiles it was not possible to recognize a well developed association in this dune, mainly because of human trampling but it was also due to artificial *Tamarix* plantation.

Fig 2.2.3.3.5: survey number 5. September 2005.

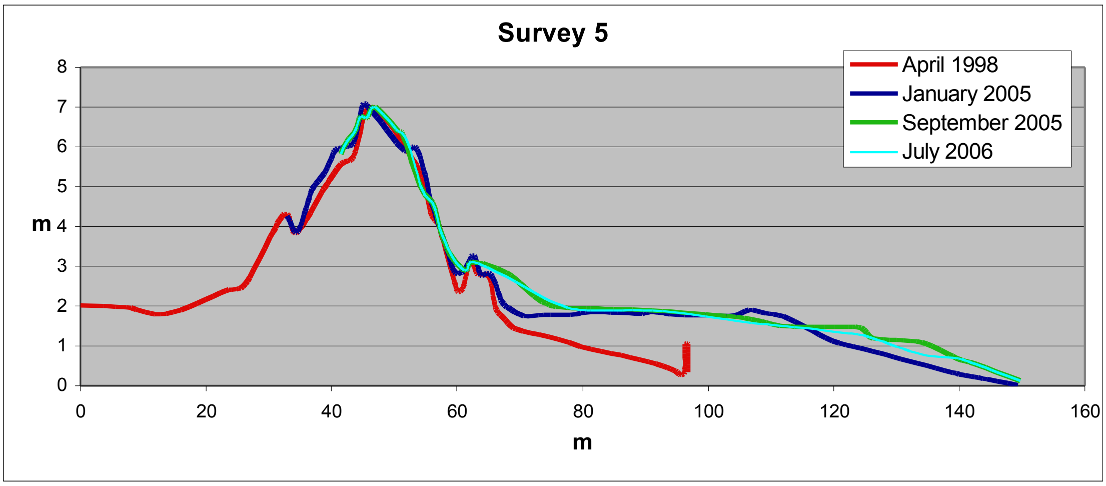


Fig 2.2.3.3.6: comparison between different topographic surveys of profile number 5

Survey number 6 was the easternmost profile (fig 2.2.3.2.1). It was located in correspondence to a quite low dune (3 m), which had two vegetated ridges. The seaward ridge was a little bit lower. Between the two ridges there is a vegetation gap due to intense human trampling. As in the other profiles it is not possible to recognize a well developed association in this dune, mainly because of human disturbance.

Fig 2.2.3.3.7: survey number 6. September 2005

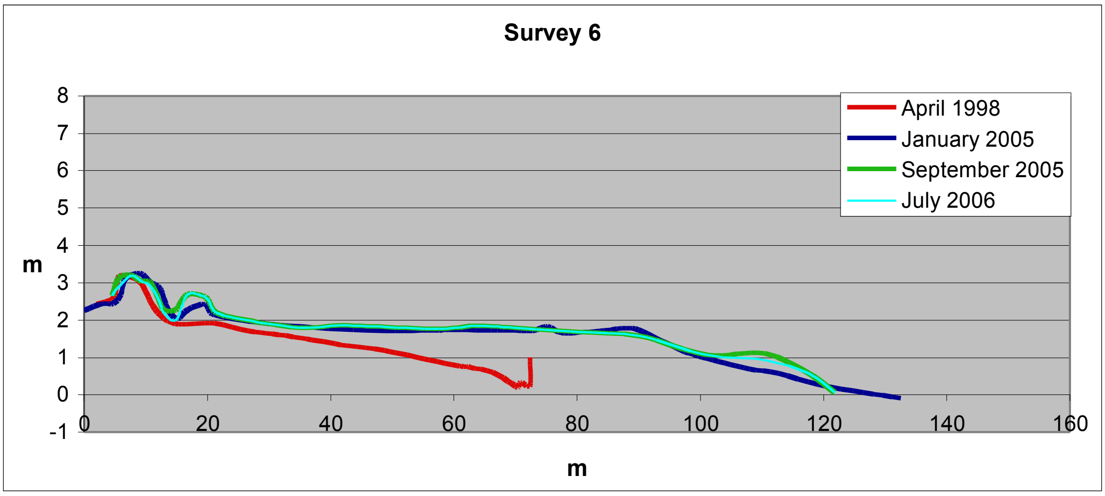


Fig 2.2.3.3.8: comparison between different topographic surveys of profile number 6

Samples location is showed in fig 2.2.3.2.1. Grain size analysis of each sample highlights the presence of fine and well sorted sand on Eraclea beach (fig 2.2.3.3.9).

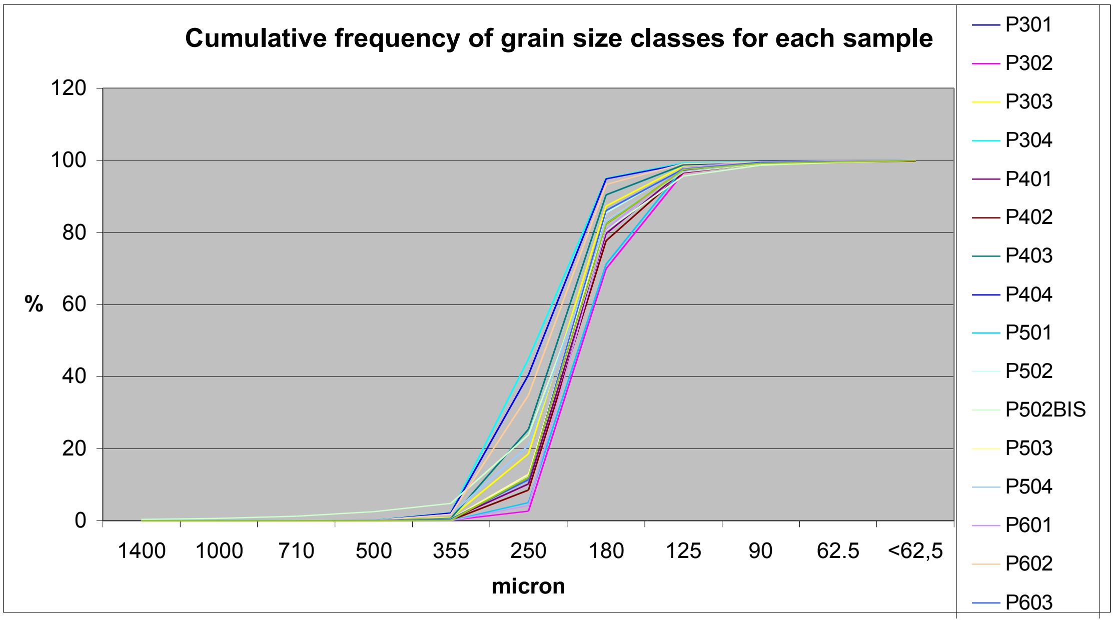


Fig 2.2.3.3.9: cumulative frequency of grain size classes for each sample.

Chemical analysis, carried out by the use of the x ray fluorescence spectrometry, made possible to identify which kind of sand was present on the beach. Samples location is showed in fig 2.2.3.2.1. On the shoreline and on the backbeach there is a grey sand (the fill) whereas at the dune foot and at the dune crest the color of the sand was yellow. In fig 2.2.3.3.10 is showed the chemical composition of each sample.

Fig 2.2.3.3.10: dolomite, calcite and other components of each sample in each profile.

2.2.3.4 Discussion

Aiming at determining if the beach nourishment carried out on Eraclea beach in 2004 was effective in reactivating the beach-dune sediment interchange, several topographic surveys and chemical analysis were carried out. Chemical analysis made possible to identify which kind of sand was present on the beach. Samples location is showed in fig 2.2.3.2.1. Results highlight that autochthon sand was principally composed by dolomite (between 72 and 52 %, depending on sample location), then by calcite (between 25 and 36 %) and then by silicate (from 21 to 42 %). Fill sand is also composed by the same minerals but with different percentages. Dolomite is from 53 to 39 %, calcite is from 30 to 36 % and silicate from 21 to 42 %. In the fill there is a higher concentration of silicate. Silicate percentage along each profile is higher at the shoreline zone and then, going landward, it decreases. While on the crest there is an increase with respect to the dune foot. Variability increases following an east-west gradient (due to Bora wind). Thus, this is evidence of the way sediment can reach the crest of the dune, even if accumulations at this location were almost irrelevant as topographic surveys showed. By observing the comparison between the 1998 survey and the recent ones, a great beach growth (50-60 m) is evident. In the oldest surveys it was still evident the presence of the seawall. Then, comparison between 1998 survey and the more recent ones highlights the appearance of new bedforms on the beach, which are generally more developed during winter also because of the intense beach raking. The greatest difference between surveys is obviously the one between April 1988 and January 2005. It is worth noting that, between January 2005, September 2005 and July 2006, differences were almost irrelevant. Only the difference between winter profile and summer profile is remarkable, due to raking activity. The four dunes analyzed are quite different to each other (paragraph 2.2.3.3). Dunes of profiles 3 and 6 are the lowest and they are characterized by two parallel ridges (the formation of the most seaward of them was induced by artificial *Tamarix* plantation). Whereas, dunes belonging to profiles 4 and 5 are much higher. At the dune foot of profile 5 it is evident a quite relevant growth, whereas at the dune foot of profile 4 there was a little growth but it seems like irrelevant. It is worth noting that accumulation at these dunes is localized at the dune foot in correspondence to artificially planted species. The scarce accumulation at dune foot of site 4 seems to be due to a vegetation gap (fig 2.2.3.4.1). In fact at the dune foot of profile 4, plants patches were isolated. Moreover the profile passed through a not densely vegetated zone. This is the main reason that can explain differences between accumulations at dune foot on that beach.

Fig 2.2.3.4.1: Profile 4. September 2005.

Thus, sand accumulation at foredunes, after beach nourishment, can be enhanced, because of the bigger fetch. In the Eraclea case, the fill characteristics were favorable to beach-dunes dynamics. Moreover, on a fetch that is 60 m wider, transport is greater (Davidson-Arnott and Law, 1990). Bezzi and Fontolan (1999; 2003) carried out several studies on the North Adriatic coast aiming at determining the foredunes development potential. They put in relation two parameters: beach amplitude and effective azimut. Thus they found the foredunes development potential index (IPS):

$$IPS = \frac{(As \cdot Az)}{100}$$

Where As is beach amplitude and Az is the effective azimut. This is a very simple and approximate parameter, whose uncertainty is very high. But it can be used as an indicative parameter to determine whether foredunes have chance to develop or not. Before the nourishment the IPS at Eraclea was 5, which is a very low value, typical of beaches in a very erosive state or whose exposure to wind is not effective. After nourishment, the IPS triplicated. This value is higher and it is evidence of the way a wider beach can influence sediment transport. It is worth noting, anyway, that the presence and density of vegetation is fundamental in inducing sediment accumulation. In fact the profile where sediment accumulation at the dune foot was smaller is the only one where the dune foot was sparsely vegetated. It is remarkable the influence of vegetation, even if it is artificially planted and located in an unnatural zone of the dune, like *Tamarix* at the dune foot.

2.2.3.5 Conclusions

Nowadays nourishment is becoming one of the most common protection interventions carried out on developed coasts. On the North Adriatic coast this is a very common practice and the Eraclea study case was chosen with the aim of determining the effectiveness of such an intervention in reactivating the beach-dune dynamics. Topographic surveys and chemical analysis of sediment confirm that nourishment could be effective in reactivating a developed stretch of coast, providing that some precaution were taken. The main accumulations were observed at the dune foot for both mature dunes (profiles 4 and 5) and lower and younger ones (profiles 3 and 6). Nevertheless there is an evidence of sand transport even on the dune crest. At every profile (for both mature and young dunes) a very important role in inducing sediment accumulation is played by vegetation presence and density. In fact, the most irrelevant growth was observed at the dune foot survey number 4. This correspond to a very sparse vegetation dune front, where there were many unvegetated areas covered by bare sand and some little patches of vegetation. Thus, it is worth noting that at Eraclea beach, vegetation (even if artificial planted) is very effective in inducing sediment accumulation, whereas dunes morphology is a factor that has less an affect on sand accumulation. In fact, at such a location, it would be normal to expect a higher accumulation at both the mature dunes. This is evidence of the way vegetation can influence variability in sand accumulation, mostly on developed coasts. Our results confirm that a beach enlargement carried out without an adequate coastal protection plan is not effective in reactivating dune systems. This is a very important issue that should be taken in to consideration as fundamental part of every good ICZM. Beach nourishment effects on every dune system can be improved by the creation of a buffer zone. This could be a respect zone comprehending the dune, its foot and a little part of the back beach, where transit, dune trampling and beach raking are not allowed. In this buffer zone, vegetation would be undisturbed and it could grow quicker. This would lead to new accumulation of sand at the dune foot, as demonstrated in our study. It is remarkable, that this kind of approach does not clash with tourism needs, since the buffer zone is usually unutilized for tourism purposes.

2.3 General Conclusions

The main objective of this section of the thesis was to determine which are the most influencing factors on sand accumulation at coastal foredunes on the North-West Adriatic coast. Aiming at accomplishing these objectives, a case study of a coastal area where human disturbance is low (Bevano river mouth Natural Reserve) was chosen and almost the entirety of this thesis is related to such study. Moreover a less extended case study has been carried out on a more developed beach, which had been nourished in 2004 (Eraclea, Venice). It was decided to consider also the Eraclea case study as well as the Bevano River Mouth beach, which was a perfect site for an independent study to be made at. This was due to the necessity of taking into consideration also a case study, which were more representative of the North-West Adriatic coast. In fact, on this coast, beaches are often overdeveloped and nourishment is a very common practice. The Eraclea field experiment has a different spatial and temporal scale from the Bevano River Mouth one. This is due to the fact that the two study sites have such enormous differences that it was impossible to maintain the same methodology (for both scientific and technical reasons). Moreover the aims of each study case are quite different: at the Bevano River Mouth our goal was to evaluate the differences in beach-dune sediment exchange at different locations onto two different aged coastal foredunes on a undeveloped stretch of coast. At Eraclea, the main objective was to identify factors affecting effectiveness of beach nourishment in reactivating the beach-dune sediment exchange on a developed coast. The Bevano results can be used to better understand where and which factors have more an affect on the reactivation of the beach-dune exchange after nourishment. But it must be made clear that the two beaches are completely different and comparing them to each other was not our goal. Results obtained at the Bevano case study demonstrated that morphological maturity of dunes is a very important factor in determining differences in sand accumulation. In fact, at the old dune, morphology was a key factor in dune growth while, at the young one, changes in elevation were mostly due to vegetation coverage. The young dune was extremely affected by the presence of vegetation and by strong onshore winds activity while the old dune was unaffected by the absence of vegetation at the dune foot and by differences in the vegetation coverage at the dune crest and at the backdune. The young dune was extremely affected by erosion in unvegetated areas and generally has high deposition rates in vegetated areas. There were evidences of sediment transportation beyond the young dune, so a bit of the total accumulation was missed landward. Results obtained at the Bevano river mouth study site highlight that the older dune is characterized by a lower variability in sand accumulation and a higher resilience against erosive events. This is a result that coastal managers should take into consideration. In fact, it should be a priority to protect coastal dunes during their most vulnerable stages. Dunes laying on undeveloped coasts can reach bigger height and they are generally characterized by more continuous profiles (Nordstrom, 2000). Our results highlight that, on undeveloped coasts, mature dunes are less dependent on vegetation than during their earlier stages. This is because their morphology itself acts as a trap for sediment transport. On the contrary, at Eraclea beach, dunes are damaged and their morphology is not natural. Once again, it must be made clear that the two beaches are completely different and this is not a comparison between sites but a site internal comparison referred to different dunes laying on the same beach. Results obtained at Eraclea beach, confirm that the development rate of the beach can affect very much dune effectiveness in sediment accumulation. Thus at Eraclea beach, after nourishment, which demonstrated to reactivate beach-dune sand interchange, the most influencing factor on sand accumulation was not morphology but vegetation. The main accumulations were observed at the dune foot for both mature dunes and lower and younger ones. Nevertheless there is an evidence of sand transport even on the dune crest. At every profile (for both mature and young dunes) a very important role in inducing sediment accumulation is played by vegetation presence and density. In fact, the most irrelevant growth was observed at the foot of a dune where there was a very sparse vegetation, many unvegetated areas covered by bare sand and some little patches of vegetation. Thus, it is worth noting that at Eraclea beach, vegetation (even if artificial planted) is very effective in inducing sediment accumulation, whereas dunes morphology is a factor that has less an affect on sand accumulation. In fact, at such a location, it would be normal to expect a higher accumulation at both the mature dunes. This is evidence of the way vegetation can influence variability in sand accumulation, mostly on developed coasts. Thus, beach nourishment should be carried out on beaches where vegetation is not disturbed or where there is a plan to protect it. In conclusion, sediment accumulation at different foredunes can be highly variable, depending on morphology, vegetation and beach development. Our study highlight that vegetation is the most important factor on sand accumulation at vulnerable dunes. When dunes are young or overdeveloped, their dependence on vegetation is higher. Whereas, mature dunes grow more and even in unvegetated areas.

Chapter 3:
Efficiency of coastal foredunes in contrasting saltwater intrusion

3. The case of the Bevano River Mouth Natural Reserve (Ravenna)

3.1.1 Introduction

The Province of Ravenna is affected by subsidence that causes lowering of already depressed areas and worsens the saltwater intrusion phenomenon. Along this coast, dunes are the only elements that lay above the ground. Moreover, dunes have a great infiltration capacity and they can accumulate fresh groundwater. Their water table, standing above sea level, acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head. This physical principle is described by the Ghyben-Herzberg equation (Essink, 2001) and it has been treated in 1.2.1. The study area is part of the Po Delta Regional Park and it is a Natural Reserve. This is the only stretch of coast in the Province of Ravenna (and one of the few on the North-West Adriatic coast), which has not been over-exploited for tourism purposes and is still natural looking. Two different methodologies were adopted with the aim of determining the fresh-saltwater interface depth. This enabled us to understand which the most influencing factors on dune efficacy were in contrasting saltwater intrusion. The physical principle, which explains this phenomenon, is called the Ghyben-Herzberg principle (paragraph 1.2.1). This approach was chosen because in this area it is possible to determine the most favorable conditions for the development of coastal foredunes and thus ideal conditions for contrasting saltwater intrusion effectively. The choice of the Bevano River Mouth as a study site was also based on the fact that in this particular area, it was possible to compare two differently aged foredunes. From a sedimentological point of view, the two dunes are exposed to the same conditions (beach amplitude and orientation, wind regime, grain size). Yet, from a hydrogeological point of view, as will be explained further on, there are many different factors that characterize these two systems. Thus, the study area was enlarged for hydrogeological purposes and it included a 3 km long dune system. It was possible to reconstruct the depth and the shape of the freshwater lens present beneath the dune system. These coastal foredunes seemed to be effective in creating freshwater accumulation, but their positive effect on the environment is very localized because of its close proximity to an artificially created pine forest. Hence, although the area is well protected, results obtained highlight a negative influence of human activity, mostly related to the artificial plantation of the pine forest.

3.1.2 Study area

The Bevano River Mouth is located on the North Adriatic coast, near the city of Ravenna (Italy), about 200 km south of Venice (fig 3.1.2.1).

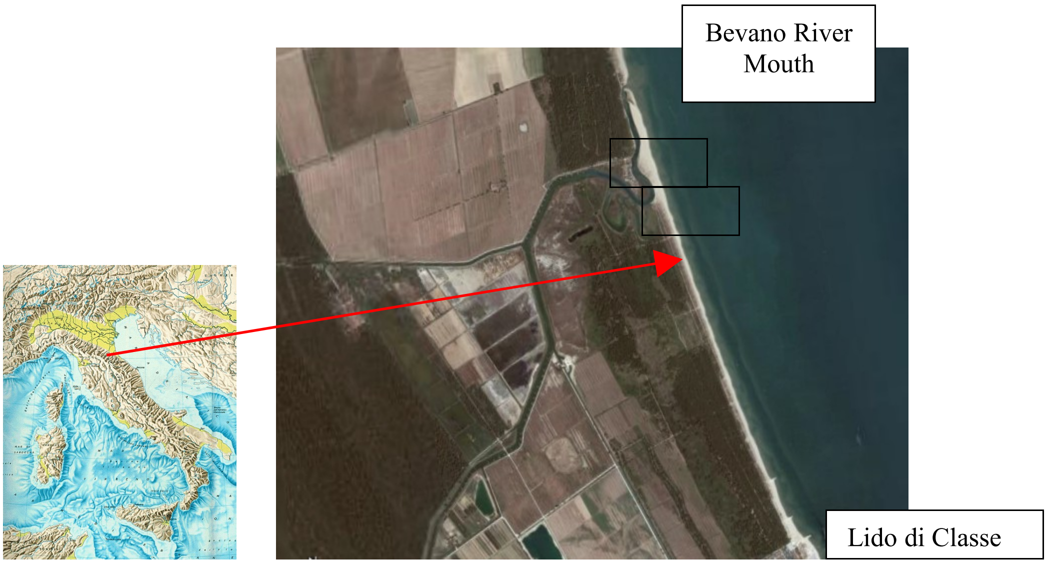


Fig 3.1.2.1: Location of the study area.

The study area is part of the Po Delta Regional Park and it is a natural reserve. The spit is of recent formation (over the last 30-35 years), whereas the beaches located to North and South of the area are more than 50 years old (fig 2.1.2.2). The study was carried out on the dunes belonging to the spit (site A, paragraph 2.1.2) and on 3 profiles located on the dune ridge, which runs from *Lido di Classe* to the Bevano River meander. The Northernmost dune is the same site, which was analyzed in chapter 2.1 (site B, Fig 3.1.2.1). Dunes belonging to this 3 km ridge are about 4 m high and well developed. It is worth noting that at the Southernmost part of the ridge, there are more human disturbances, as the beach is closer to *Lido di Classe* village and the shoreline access is very close to a parking area. The meander area, however, can only be reached on foot or by bicycle following a 3 km long path, which crosses the pine forest. No cars are permitted along this path, except for those belonging to the local forest rangers. The pine forest is about 1.8 km^2. It has been artificially planted and preserved from centuries. Nowadays, new pines are still planted to replace dead ones, mostly after fires.

In 2002 there was a large fire, which caused the death of many pines and its effects are still evident in recently taken aerial images. In picture 3.1.2.1, in fact, there is an area, in the middle of the pine forest, where there are no trees. The whole study area has been the object of several studies. One of the most important, with reference to this particular research, is that carried out by the Emila-Romagna Region (http://geo.regione.emilia-romagna.it/carg/viewer.htm)

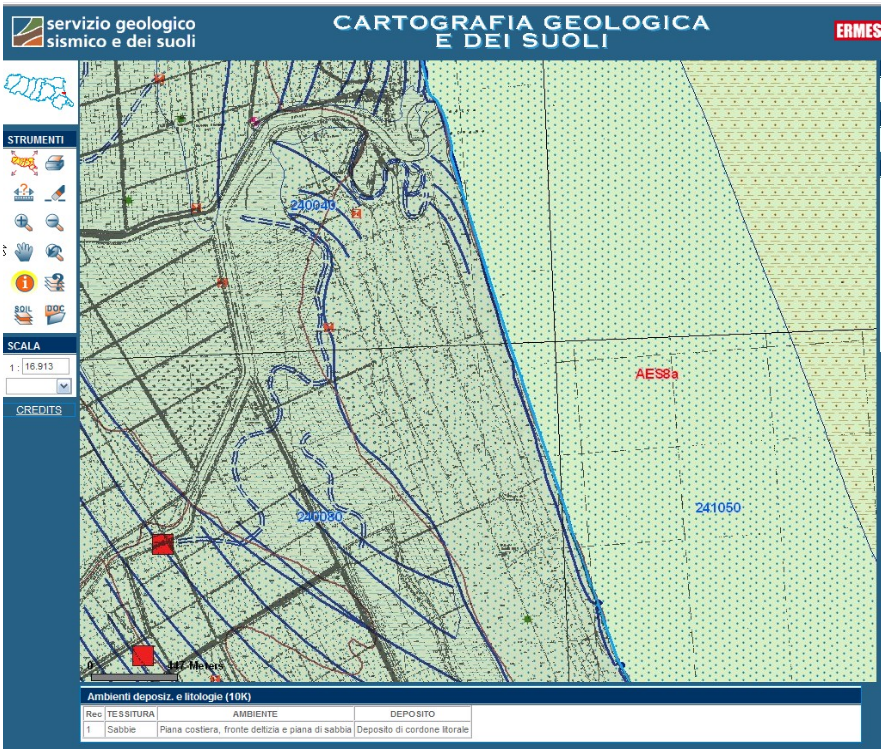


Fig 3.1.2.2: geological cartography of the area (http://geo.regione.emilia-romagna.it/carg/viewer.htm)

This study looks at the superficial stratigraphy of the area and it shows that the uppermost layers (at a depth of less than 10 m) are homogenously composed of sand.

3.1.3 Methodology

With the aim of describing the historical evolution of the study site, organizing data and quantifying several parameters on a geographic base, a GIS was created to support the aerial imagery analysis. Furthermore, an altimetric survey was carried out (with Real Time Kinematic Techniques, RTK), to characterize the morphology of the coastal foredunes analyzed. A couple of Topcon GB500 (Base and Rover) receivers, which guarantee centimetric precision of measurements, were used. In order to monitor the state of the groundwater table, 4 piezometers were constructed and positioned along site A and B (fig 3.1.3.1), at both the dune foot (PA1 and PB1) and the dune crest (PA2 and PB2).

Fig 3.1.3.1: Location of the 4 piezometers.

Several measurements were also taken using electrical resistivity methods along the coastal foredune ridge which runs from site B to Lido di Classe,. Measurements were taken along several profiles, shown in fig 3.1.3.2.

Fig 3.1.3.1: Location and names the resistivity profiles

At each profile, 3 or 4 measurements were taken. The most seaward measurement was taken at the dune foot. Others were taken at the dune crest, the backdune and in the pinewood. In some profiles (1, 3 and 4) it was not possible to take all the measurements, due to the lack of geographical features. The name and the location of each single reading point is shown in fig 3.1.3.2.

Fig 3.1.3.2: Names and locations of resistivity measuring points. In the upper picture, profiles 2, 3 and 4 (close to the meander) are shown; whereas the lower picture refers to profile 1 (Lido di Classe)

The PVC piezometers used were about 5 m long, had a 5 cm diameter and 9 holes at one end covered by a finely meshed fabric. Readings were taken using a phreatimeter and a conducimeter, which provide data concerning groundwater depth and salinity. Electrical resistivity methods directly gage the bulk electrical resistivity of the ground by measuring voltage created by sending electrical current between electrodes in the ground at different distances. The resistivity of the ground depends on several parameters including lithology, presence of clay minerals, porosity, temperature, water content and groundwater salinity. Resistivity measurements were obtained by sending current into the ground through two current electrodes (A and B, Fig 3.1.3.3), and measuring the resulting voltage difference at two potential electrodes (M and N).

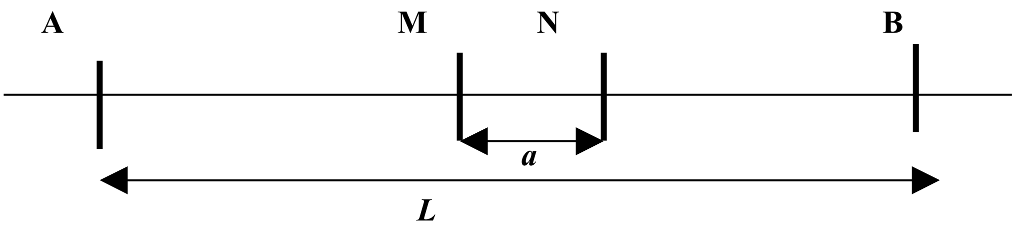


Fig 3.1.3.3: A diagram of the electrical resistivity method.

A constant 1.5 m inter-potential-electrode spacing was maintained, whereas various inter-current-electrode spacings were used (15m, 20m, 25m, 30m, 40m). Independent measurements were taken at each quadripole position according to the Schlumberger configuration. This enabled different resistivity values related to different investigation depths to be taken (respectively: 3m, 4m, 5m, 6m, 8m from the ground-surface) (Edwards, 1977). Data were collected, using the methodology described above, along 4 transects (see Fig 3.1.3.1).

Fig 3.1.3.4: Electrical resistivity instrument.

Measurement heights were taken using a DGPS. Since lithologic composition of the study area is homogeneous (sand) at the depths analyzed, variations in resistivity indicate the presence of water with different salinity characteristics. A very rapid variation in resistivity could be explained by the presence of a saltwater-freshwater interface. The use of both methodologies, piezometric and resistivity techniques, is very important. In fact, piezometers provide direct measurements of freshwater lens thickness and position above sea level; but due to limited resources we were able to place a small number of them. On the other hand, resistivity measurements are fast and easy to take, but they are indirect and their interpretation can lead to some uncertainties. It was for this reason that both methodologies were chosen. By directly measuring (with a piezometer) the height of the freshwater lens above sea level, in fact, it was possible to obtain an accurate value from which resistivity measurements could be calibrated. The resistivity methodology, calibrated by taking readings close to the four piezometers, was used to measure the freshwater lens thickness and depth at many different points. Then, resistivity data were processed using VES software (Vertical Electrical Sounding, RockWare, Inc. Earth Science & GIS Software). This model provides a reconstruction of the ground, where there are three layers (fig 3.1.3.5): the first corresponds to dry sand, the second corresponds to sand saturated with freshwater and the third to sand saturated with saltwater.

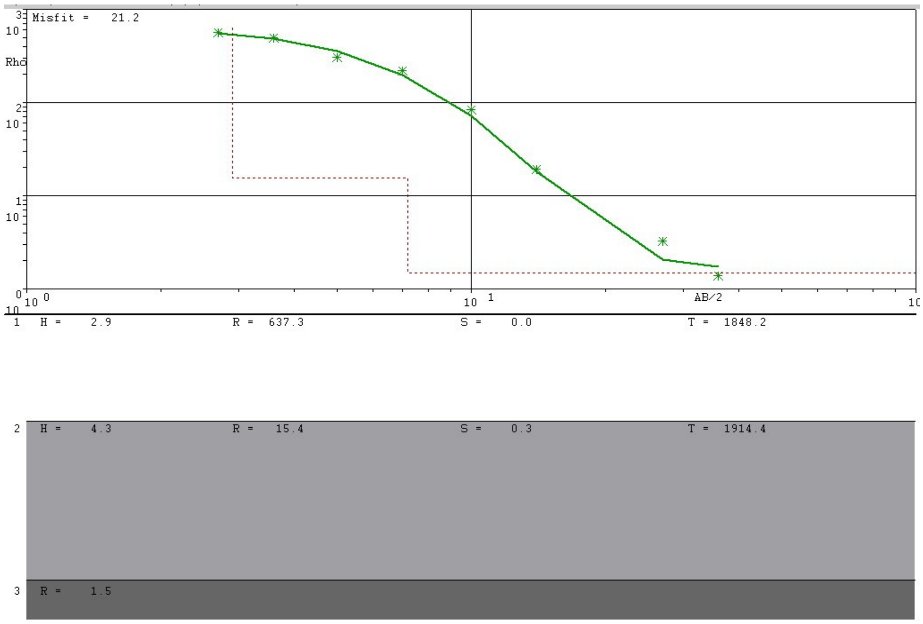


Fig 3.1.3.5: VES software results referring to point 2.

Piezometric data were used to calibrate the VES model. There are two parameters that can be slightly modified by the operator: the layer depth and resistivity values. Direct readings taken from the piezometer enabled us to determine the depth of the first layer. From here it is possible to understand which resistivity values are typical for that layer. At piezometers PA1, PA2 and PB1 it was possible to directly measure the fresh-saltwater interface, since at these locations the freshwater lens was very thin. Hence, these values were very useful to calibrate the third layer of the model. This methodology allows us to determine the freshwater height above sea level and fresh-saltwater interface depth. These data are crucial in order to apply the Ghyben-Herzberg equation (eq 1.2.1.1) and monitor the environmental state of this coastal system. Resistivity data were also used to reconstruct the depth and the shape of the freshwater lens, which lies beneath the dune ridge that goes from Lido di Classe to the Bevano River Mouth. A nearest neighbour interpolation was obtained by using the software Surfer 8. Due to the low number of reading points, interpolation was not very accurate. However, with the few resources at hand, we were able to determine whether there was a trend and, if so, the kind of trend it was, in relation to the shape and thickness of the freshwater lens accumulated by the dunes analyzed. A comparison of the 4 different profiles confirmed that there was a north-south gradient, which was also highlighted by the interpolation (fig 3.1.4.8), related to both the presence of the river and the presence of the pine forest.

3.1.4 Results

Measurements taken from the 4 piezometers enabled us to directly determine the height of the freshwater lens above sea level. Data obtained are shown in fig 3.1.4.1.

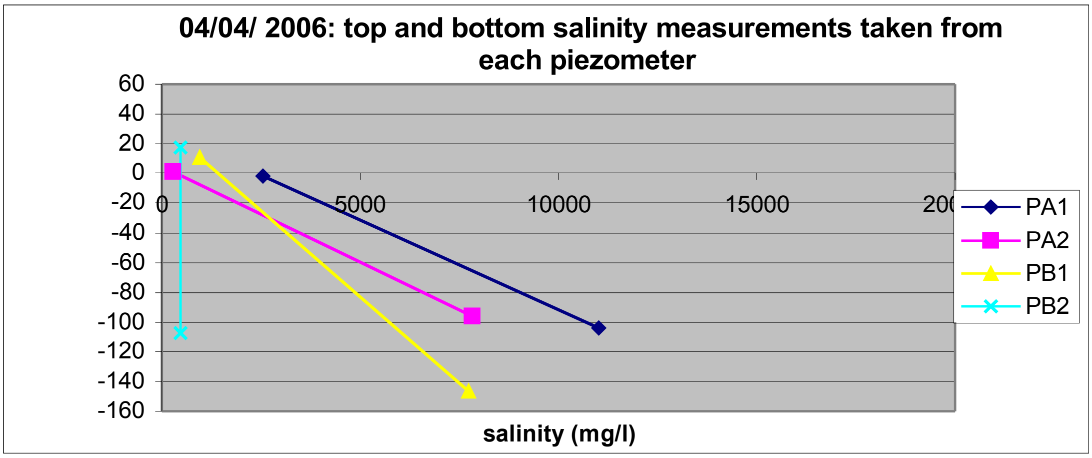
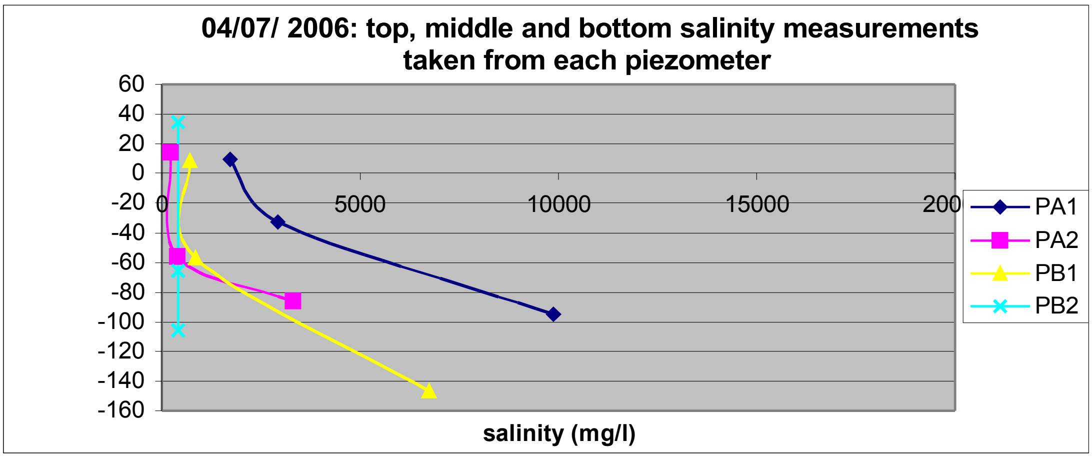
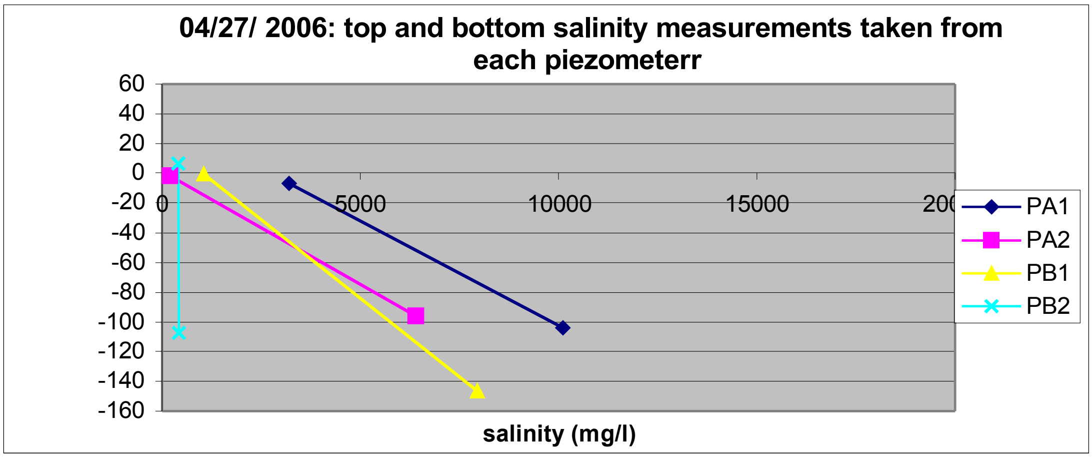
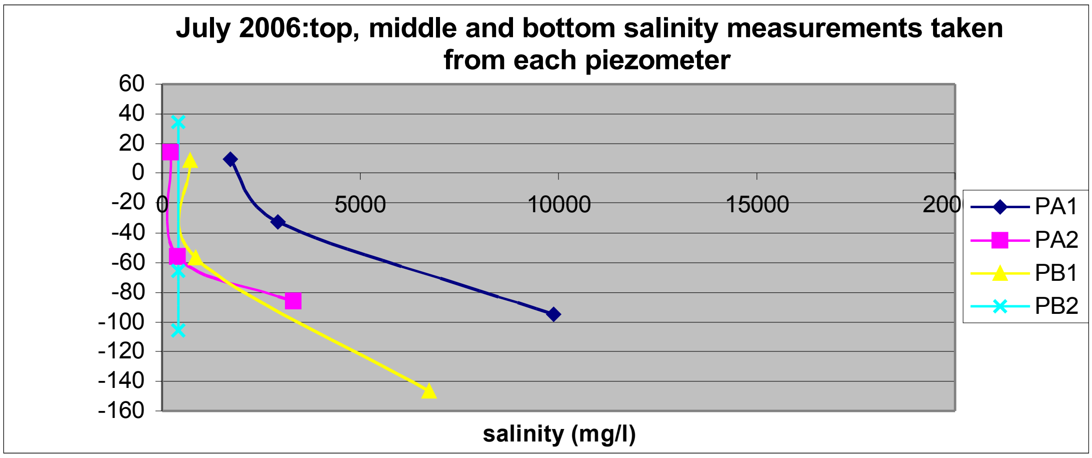


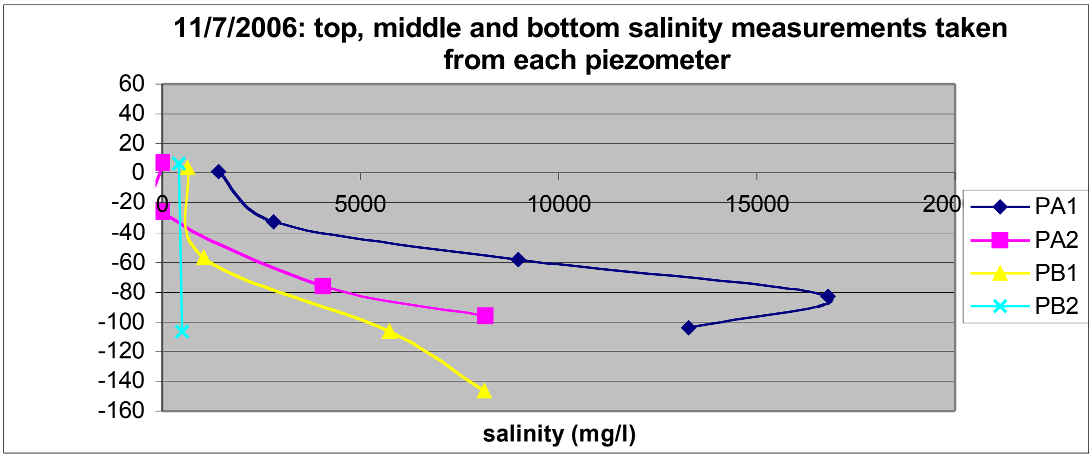
Fig 3.1.4.1: piezometric data (water height in relation to sea level vs salinity). The y axes refers to height above and below sea level.

Where it is evident that in each piezometer freshwater stands above sea level. These data were compared to several subsequent measurements (Fig 3.1.4.2). It is evident that there is a great variability in the height of the piezometric head above (and sometimes below) sea level. This variability does not seem to be related to seasonal effects but to local rainfall.




04/27/ 2006: top and bottom salinity measurements taken from each piezometerr
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0
5000
10000
15000
200
PA1
PA2
PB1
PB2
salinity (mg/l)


July 2006:top, middle and bottom salinity measurements taken from each piezometer
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
0
5000
10000
15000
200
PA1
PA2
PB1
PB2
salinity (mg/l)



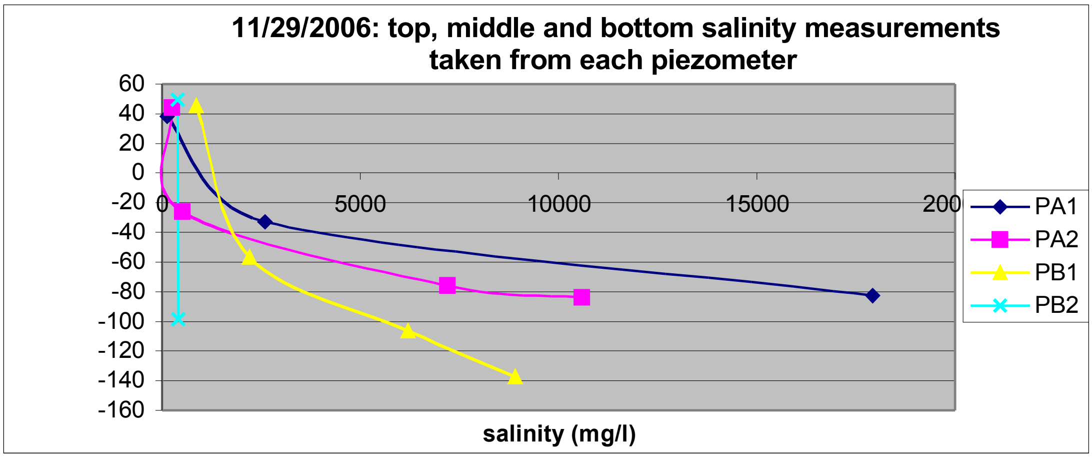


Fig 3.1.4.2: Subsequent piezometric measurements.

Resistivity data were processed using VES software (paragraph 3.1.3). Results highlight the presence of a freshwater lens localized beneath the dunes at profile number 1 (fig 3.1.4.3), which is the closest to Lido *di Classe* (fig 3.1.3.1).

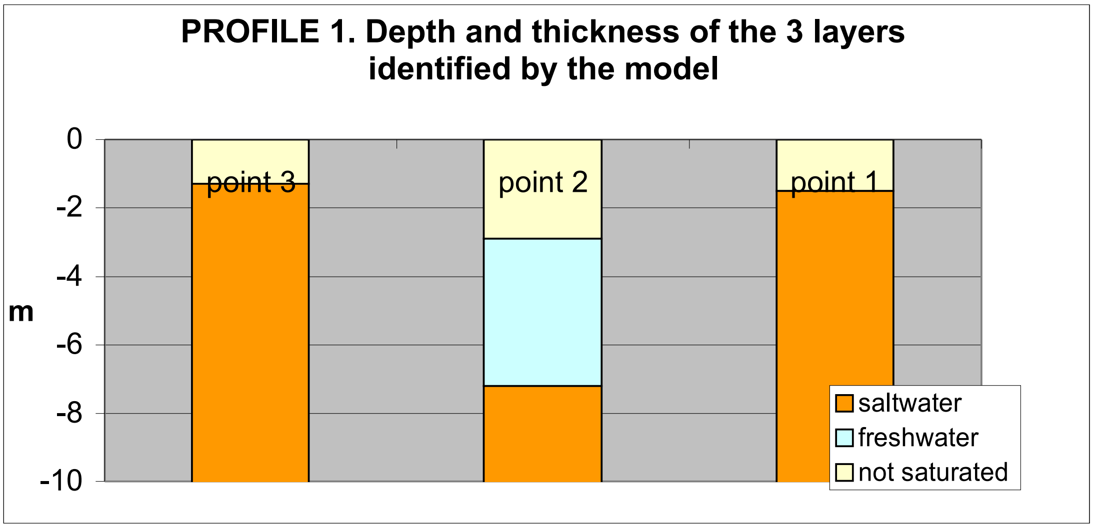
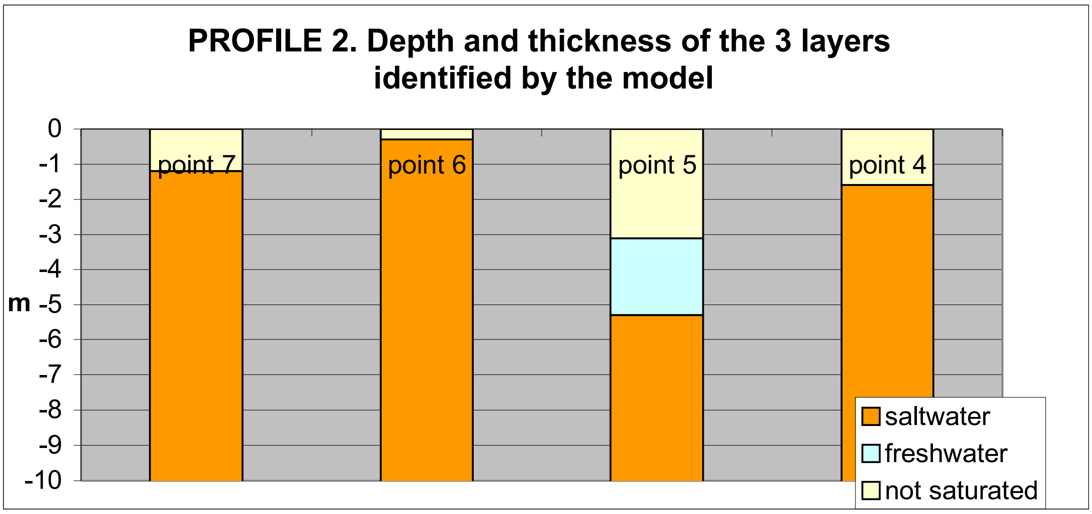


Fig 3.1.4.3: PROFILE 1. The first picture shows depth and thickness of the 3 layers identified by the VES model. The second shows the localization of the profile.

At profile 2 the presence of the freshwater lens is also localized beneath the dune, whereas it is absent at the backdune and in the pine forest.



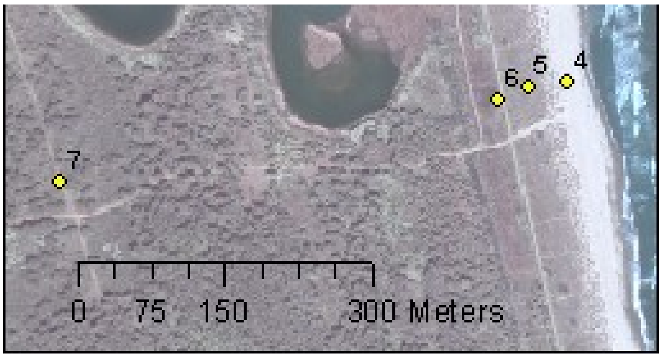


Fig 3.1.4.4: PROFILE 2. The first picture shows depth and thickness of the 3 layers identified by the VES model. The second shows the localization of the profile.

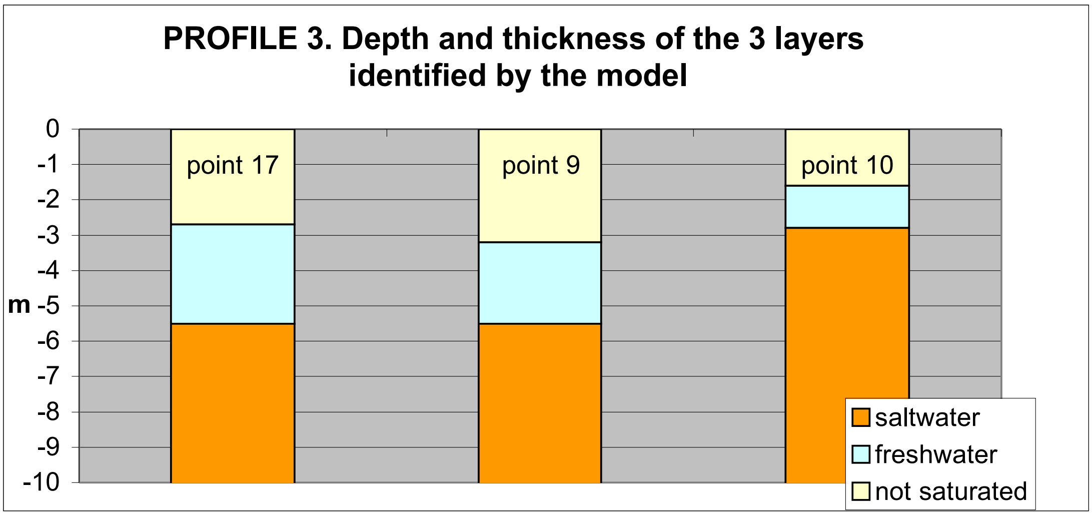


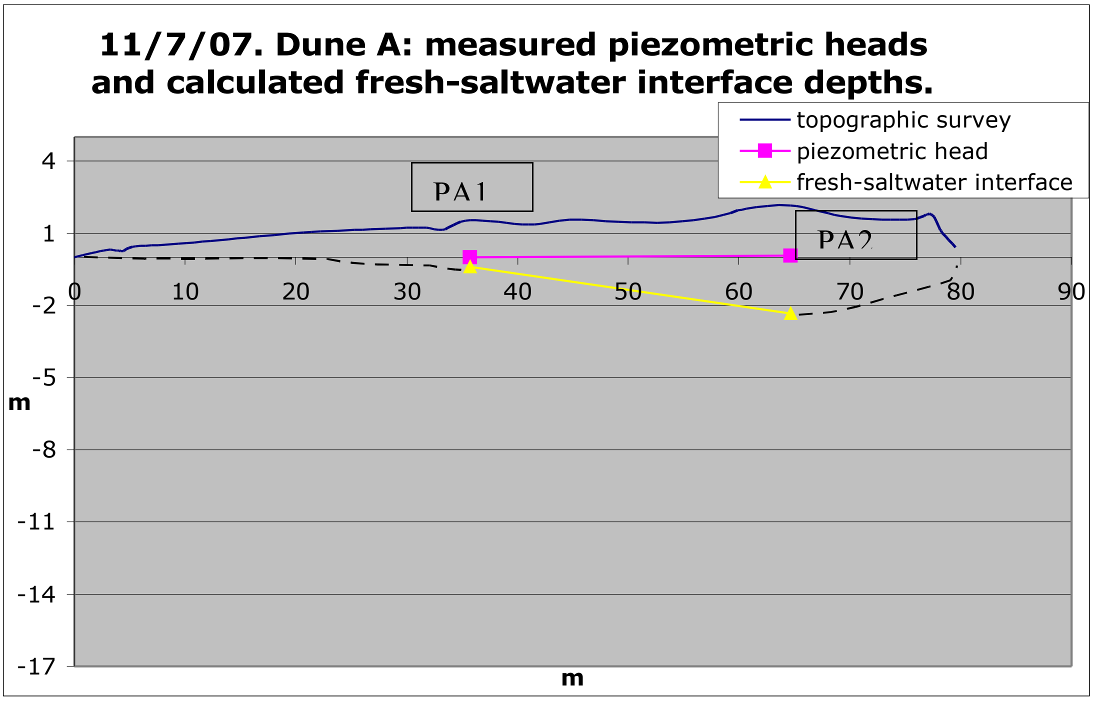
Fig 3.1.4.5: PROFILE 3.. The first picture shows depth and thickness of the 3 layers identified by the VES model. The second shows the localization of the profile.

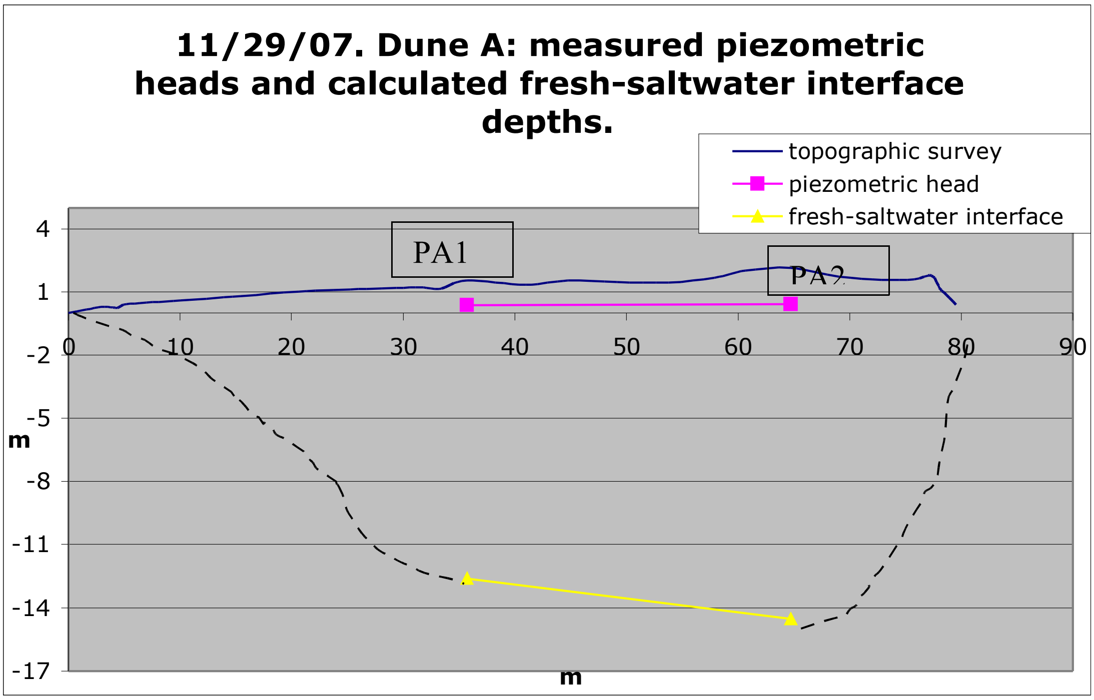
At profile 4, resistivity measurements were very difficult to take. Piezometric data highlighted the presence of a thin freshwater lens, undetectable when using resistivity methods only. This was due to interference caused by the close proximity of saltwater. The freshwater lens shape and thickness can be reconstructed by taking into account the piezometric level above the sea (figg 3.1.4.6 and 3.1.4.7). This was made possible by applying the Ghyben-Herzberg principle, with which we calculated the freshwater-saltwater interface depth (paragraph 1.2.1). The following table (tab 3.1.4.1) shows the height above (and in same cases below) sea level reached by the freshwater lens at each piezometer. The next column shows the depth of the fresh-saltwater interface calculated by using equation 1.2.1.1.

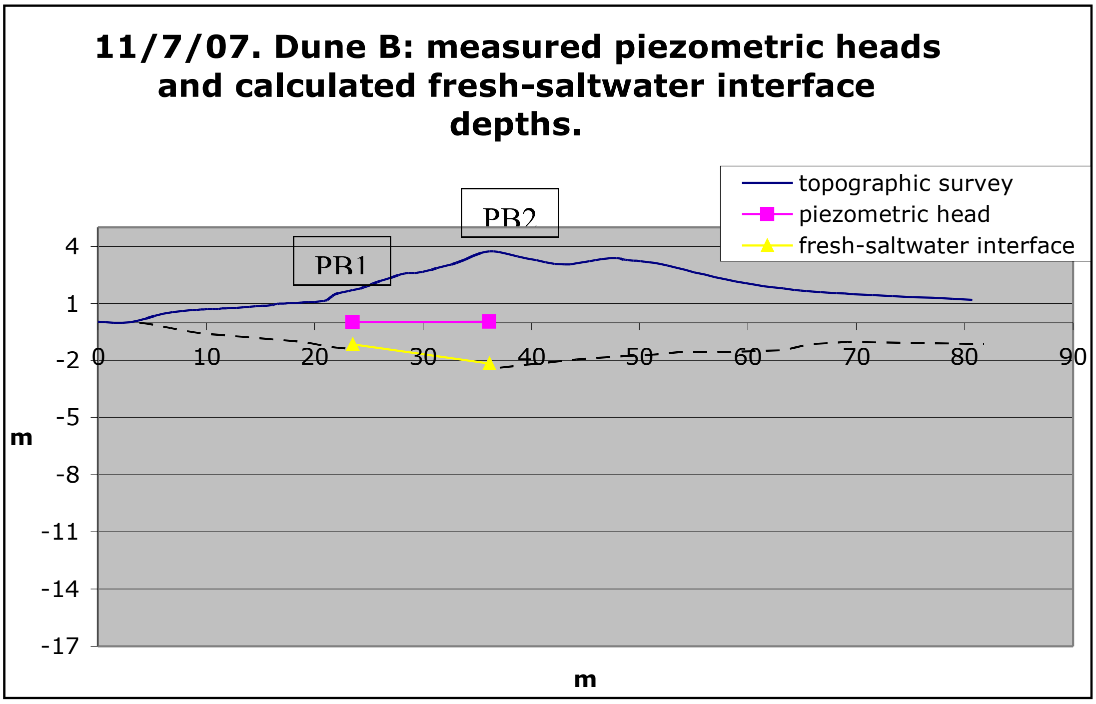
	Date	Height of piezometric head above sea level (cm)	fresh-saltwater interface depth below sea level (m)
piezometer PA1	4/4/06	-1.8	0.0
	4/7/06	9.2	-3.0
	4/27/06	-6.8	0.0
	7/2/06	9.2	-3.0
	11/7/06	1.2	-0.4
	29/11/06	38.2	-12.6
piezometer PA2	4/4/06	1.0	-0.3
	4/7/06	14.0	-4.6
	4/27/06	-2.0	0.0
	7/2/06	14.0	-4.6
	11/7/06	7.0	-2.3
	29/11/06	44.0	-14.5
piezometer PB1	4/4/06	10.5	-3.5
	4/7/06	8.5	-2.8
	4/27/06	-0.5	0.0
	7/2/06	8.5	-2.8
	11/7/06	3.5	-1.1
	29/11/06	45.5	-15.0
piezometer PB2	4/4/06	17.5	-5.8
	4/7/06	34.5	-11.4
	4/27/06	6.5	-2.2
	7/2/06	34.5	-11.4
	11/7/06	6.5	-2.2
	29/11/06	49.5	-16.3

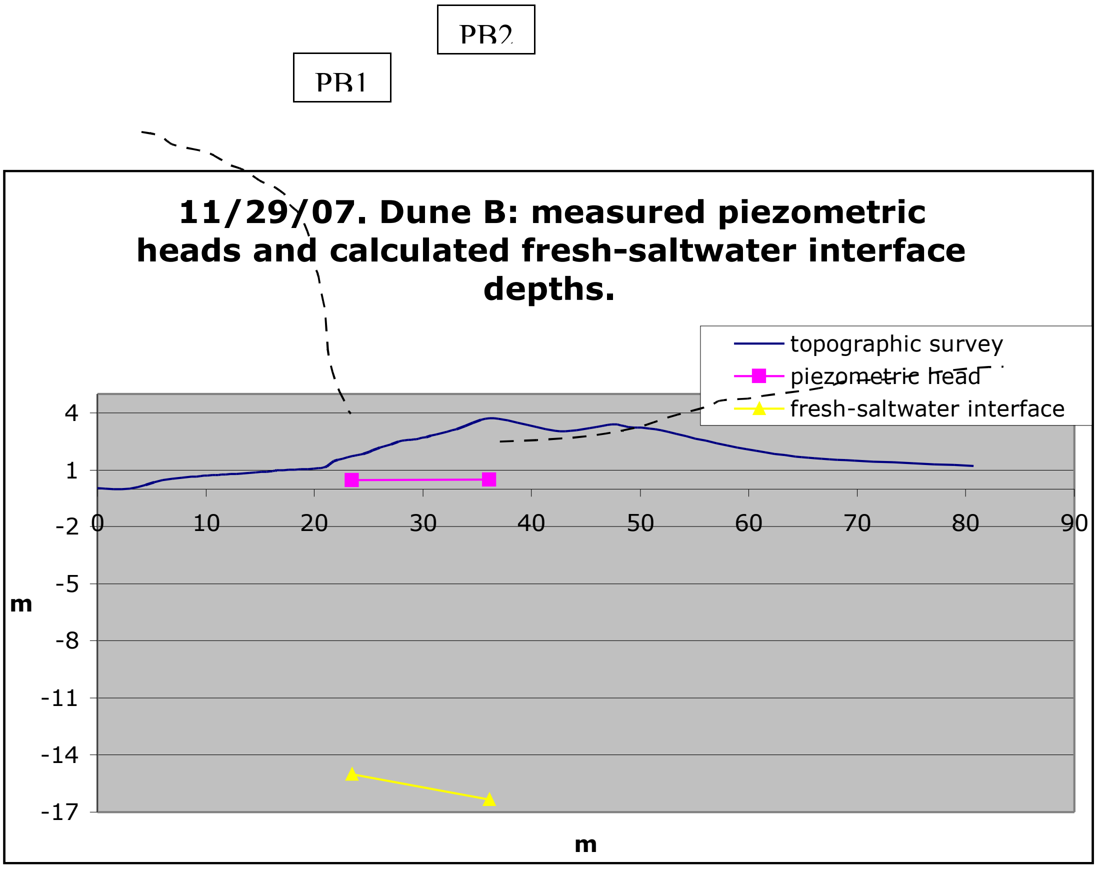
Table 3.1.4.1: piezometric head above sea level and fresh-saltwater interface depth at each piezometer.

It is evident that values can change even in as little as a few days. The very contrasting data for the last two last days of measurements (7th September 2006 and 29th September 2006) are plotted in figures 3.1.4.6 and 3.1.4.7


11/7/07. Dune A: measured piezometric heads and calculated fresh-saltwater interface depths.
topographic survey
piezometric head
fresh-saltwater interface
PA1
PA2
4
1
-2
-5
-8
-11
-14
-17
m
0
10
20
30
40
50
60
70
80
90
m


11/29/07. Dune A: measured piezometric heads and calculated fresh-saltwater interface depths.
topographic survey
piezometric head
fresh-saltwater interface
PA1
PA2
4
1
-2
-5
-8
-11
-14
-17
m
0
10
20
30
40
50
60
70
80
90
m


11/7/07. Dune B: measured piezometric heads and calculated fresh-saltwater interface depths.
topographic survey
piezometric head
fresh-saltwater interface
PB2
PB1
4
1
-2
-5
-8
-11
-14
-17
m
0
10
20
30
40
50
60
70
80
90
m


PB2
PB1
11/29/07. Dune B: measured piezometric heads and calculated fresh-saltwater interface depths.
topographic survey
piezometric head
fresh-saltwater interface
4
1
-2
-5
-8
-11
-14
-17
m
0
10
20
30
40
50
60
70
80
90
m

Fig

Resistivity data were interpolated to obtain a reconstruction of the freshwater lens laying beneath the dune ridge which runs from Lido di Classe to the Bevano River Mouth (fig 3.1.4.8). Thickness and shape variations follow a north-south gradient. At the southernmost part of the dune ridge (profile 1), the freshwater lens is at its thickest (more than 4 m, figg 3.1.4.3 and 3.1.4.8), whereas, heading northward, the freshwater lens becomes progressively thinner.

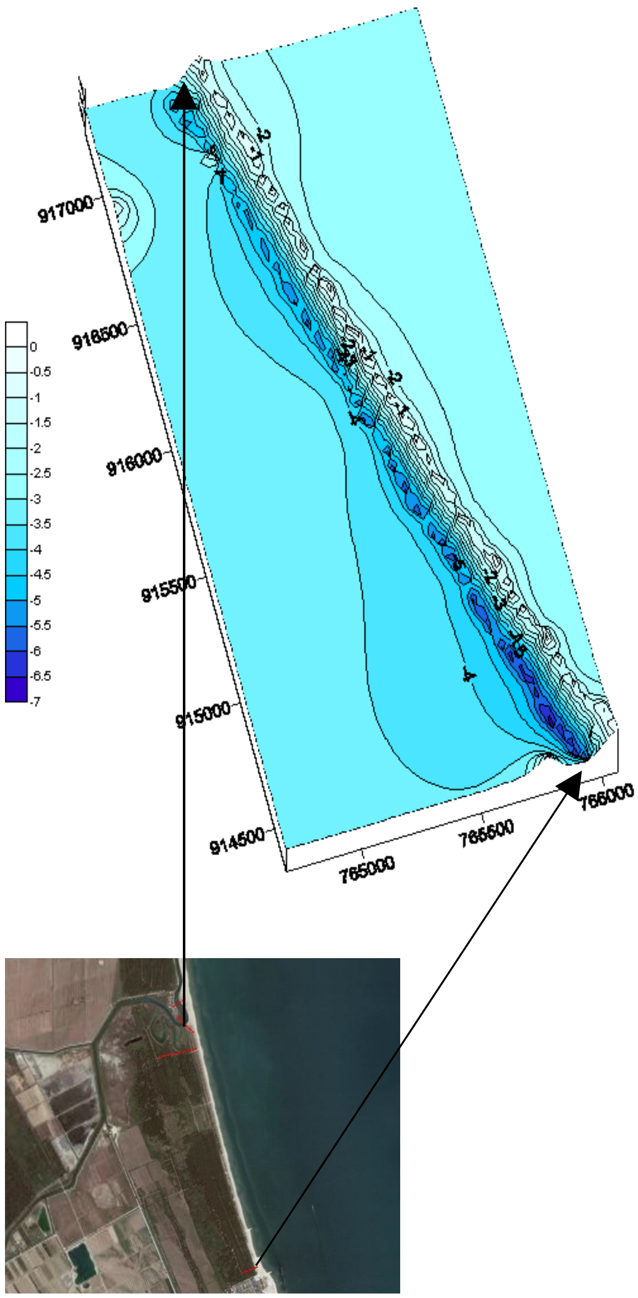


Fig 3.1.4.8: Resistivity data interpolation (nearest neighbour, Surfer 8).

3.1.5 Discussion

Piezometric data gathered at both dunes A and B are important since they directly whitness the presence of the freshwater lens beneath the dunes and its height above the sea level. These data are essential in determining, indirectly, the depth of the fresh-saltwater interface in the static case, by applying the Ghyben-Herzberg principle (paragraph 1.2.1). Data collected during this thesis highlight the importance of several factors. 1) Rainfall influences the thickness of the freshwater lens far more than seasonal factors. 2) Changes in the height of coastal foredunes had an affect on the thickness of the freshwater lens, which followed a topographic gradient. Thus, a higher and well developed dune (site B) is more effective at accumulating freshwater than a lower one (site A). The presence of the Bevano River Mouth (whose salinity is rather high, 22 g/l, in its final tract) affects the shape and the thickness of the freshwater lens, which lays beneath dune A.

Recharge and the evolutionary state of dunes are very influential factors on the fresh-saltwater lens depth (Ranjan et al., 2005), thus rainfall frequency and the maturity of coastal foredunes play an important role. Comparisons made between data collected at sites A and B confirmed that dunes can be effective at contrasting saltwater intrusion provided that they are well developed and that recharge is sufficient. It is worth noting that, at the crest of dune B, the piezometric head never gave a reading below sea level (tab 3.1.4.1). This fact means that freshwater was always present below that dune, though at times there was only a very thin layer (2 m). Contrastingly, during other periods, the fresh-saltwater interface depth beneath dune B went as low as 16 m below sea level. Nevertheless, this level is not low enough to defend landward areas. Resistivity techniques enabled us to extend groundwater measurements to a larger area. Results confirmed that beneath the dunes analyzed there is a freshwater lens, but it is localized only in the area occupied by the dunes. In the landward area, in correspondence to the pine forest, groundwater is salty (point 3, 6 and 7; fig 3.1.4.3 and 3.1.4.4).

The saltwater, along the inlet, pushes and tends to infiltrate both from the sea and from the river, whose salinity values, in its terminal stretch, are very high (22 g/l). The push caused by salt water coming both from the sea and from the river induces a thinning of the freshwater lens. This phenomenon did not occur more southward, where there is no influence produced by the river.

Moreover the shape of the freshwater lens laying beneath the dune ridge that runs from Lido di Classe to the Bevano River meander seemed to follow a North-South gradient. In the southernmost part, it is thicker and more confined whereas going further north it becomes thinner and less confined. The thinning of the freshwater lens seemed to be induced by the proximity of the river and the geomorphological features of the area. In fact, along the inlet, saltwater creates pressure and tends to infiltrate both from the sea and from the river, whose salinity values, along its final tract, are very high (22 g/l). Hence, the pressure caused by both seawater and salty river water produces a thinning of the freshwater lens. This phenomenon did not occur further South, where the river has no influence. With regards to the freshwater lens shape, data suggest that, in the southern part of the ridge, its landward profiles were steeper whereas in the northern part of the ridge the freshwater profile became gentler. It is remarkable that, at profile 1 (fig 3.1.4.3), a thicker freshwater lens is also more confined. This abnormal freshwater lens shape could be due to the close proximity of some extraction withdrawal. But in this case, since there are no water withdrawals in the vicinity, this unnatural shape might be explained by the presence of the pine forest. Pines may act as a water withdrawal net which causes saltwater upconing. Taking this into account, it is worth mentioning that the only backdune area where a layer of freshwater was found was at profile 3, where, at the back, there is no pine forest. Furthermore, given its close proximity to the salty meander (fig 3.1.3.1), profile 3 should have been the saltiest one. It was, however, the only profile where fresh groundwater was found at the backdune. This is evidence of the way the presence of the pine forest, artificially planted by man, may affect the hydrological coastal equilibrium. The only plausible reason which can explain the presence of saltwater in landward areas is that, at some point in time, pumping occurred. Since there are no water withdrawal wells in the pine forest, it is evident that other features must have had the same effect. The pines could be such features, as they have great water extraction capacity due to their transpiration (Lammerts, 1999). The artificial pine forest, which lays behind the dunes, has a negative impact on saltwater intrusion,

3.1.6 Conclusions

My results highlight that, even in a protected area, the influence of human alterations of the landscape is very strong. These impacts had brought about a system, which is less effective in contrasting saltwater intrusion. At the Bevano River Mouth Natural Reserve, in fact, coastal foredunes seem to be effective only at limited spatial and temporal scales. Dunes accumulate fresh groundwater, but this phenomenon is highly localized. Just at the backdune, there was no evidence of freshwater accumulation. The peculiar thickness and shape of the freshwater lens (3.1.4.8), which lays beneath the dune ridge from *Lido di Classe* to the Bevano River Mouth, is due to the presence of the pine forest. Thus firstly, coastal foredunes efficacy in accumulating freshwater can differ very much, depending on their height, integrity and maturity (as for site A and B of the study area analyzed). Then, depending on landward area use, coastal dune effectiveness in contrasting saltwater intrusion can be reduced. In the case of the Bevano River Mouth Natural Reserve, the landward presence of the artificial pine forest has a very negative impact on the system. Nevertheless, our results highlight the effectiveness of well protected coastal foredunes in defending landward areas against saltwater intrusion. However, it is worth noting that this is possible only provided that the environmental conditions had not been altered by human activities.

3.2 The influence of Human activity on coastal areas

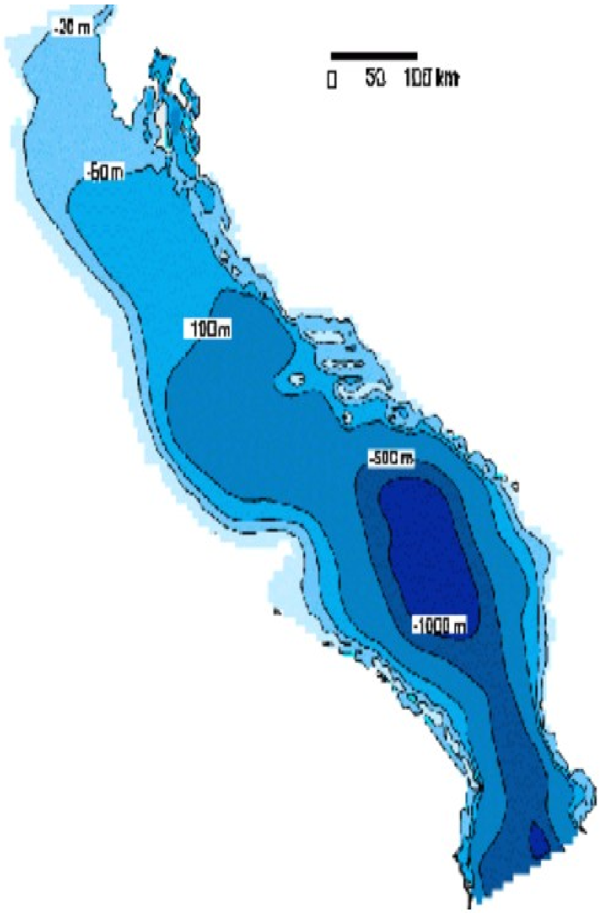
3.2.1 Introduction: goals achieved and future steps in international research

Coastal zones are highly affected by a past and present mentality of overexploitation, which has brought about extensive, unrepairable damage. In some areas of the world, this process started many years ago and is still continuing. Human intervention has affected the distribution of fresh and saline water in the ground. Reclamation of coastal areas, impoldering, extraction of groundwater, artificial recharge of groundwater, lowering of groundwater tables, irrigation and drainage, construction of canals, mining etc. have all led to changes in the hydrogeological regime. The response of the groundwater system is to reach a new state of equilibrium, with a different distribution of fresh and saline groundwater. This may last decennia or even centuries, as groundwater flow is, in general, a very slow process. This fact means that once an unwanted effect is observed, it will also take a long time before countermeasures become effective. Worldwide, excessive overpumping of especially coastal aquifers is the most important anthropogenic cause of salt water intrusion. In coastal aquifers, saline groundwater is nearby and upconing of saline groundwater can easily occur. Exploiting and mining of groundwater regularly take place to mitigate droughts or supply irrigation projects, especially in (semi)arid areas. Fossil and non-renewable??? groundwater basins are utilized for domestic, industrial and agricultural water supply. Furthermore, reducing recharge areas to develop touristic activity causes a decreasing outflow of fresh groundwater, inducing an inland shift of the salt water wedge. Lowering of piezometric heads caused by excessive overpumping can also induce a severe land subsidence. In some areas, land reclamation (e.g. in the Netherlands from about the seventeenth century on) caused a lowering of piezometric heads, and subsequently, sea water has rapidly invaded the coastal aquifer even since. In fact, sea level rise is basically the same as equally lowering the land surface and thus the piezometric heads. Nowadays, lowering of the piezometric heads due to overpumping already occurs in many aquifers around the world. It is obvious that, for those systems, the impact of a (relatively small) sea level rise (e.g. 50 cm per century) on the aquifer will be of marginal importance compared to the effect of an increase in extraction rate (Oude Essink, 2001a). Beukeboom (1976) and Bakker (1981) demonstrated that, due to coastal resources overexploitation, lowest groundwater table depth dropped to *c.* 2 m in some dune slacks along the Dutch coast and up to *c.* 10 cm in some slacks of the inhabitated Wadden Sea islands. Vegetation plays a very important role in this phenomenon. Ranjan et al. (2005) demonstrated that deforestation reduces evapotranspiration even though it favours runoff, thus deforestation leads to increase groundwater recharge in arid areas. In many areas of the world, increasing evapotranspiration due to growing pine plantations have led to lower groundwater levels (Lammerts, 1999). This, in Countries such as the Netherlands, stimulated the replacement of specific dune slack plants by more common and highly productive species. Today, forestry on the Dutch islands aims at replacements of pine trees by broad leaved trees (Lammerts, 1999). Many studies were carried out on Dutch dunes (Grootjans et al, 1996; Lammerts, 1999; Lammerts et al, 2001; Oude Essink 2001b), due to their economical importance. In fact, in the Netherlands, groundwater withdrawal for drinking water started in 1950s. Nowadays, the tendency in the NL has been inverted, and drinking water production companies have made great efforts to restrict impacts due to dune-water catchments: by completely stopping or greatly reducing groundwater withdrawal or by using alternative locations and methods. Since the early 1990s, many field studies have provided valuable information on the occurrence of saltwater intrusion observed in freshwater aquifers along the coasts. Location and movement of saline water in coastal aquifers have been described by Reilly and Goodman (1985) and by Bear et al (1999). Several geochemical (Reilly, 1993; Jones et al, 1999; Stewart, 1999) and geophysical (Gnanasundar and Elango, 1999; Stewart, 1999; Galgaro, 2000) techniques are used to directly and indirectly monitor the presence and level of saltwater in coastal aquifers. The physical processes governing seawater intrusion in coastal aquifers are well understood and governing equations of flow and salinity transport in coastal aquifers have been developed and solved numerically using different methods (Huyakorn et al., 1987; Andersen et al., 1988; Essaid, 1990; Bear et al., 1999; Gambolati et al., 1999; Oude Essink, 2001b). A common approach for simulation of seawater intrusion in coastal aquifers is based on the sharp interface approximation and the Ghyben–Herzberg relation (Bear, 1979; Essaid, 1990; Bear et al., 1999; Essaid, 1999). Emch and Yeh (1998), Cheng and Ouazar (1999), Cheng et al. (2000) and Mantoglou (2003) presented coastal aquifer management models based on the sharp interface approximation. Strack's (1976) flow potential is used in order to trace the toe of sea water lens (Cheng and Ouazar, 1999; Mantoglou, 2003). More complex seawater intrusion models consider the transport processes that occur in the mixing zone (Das and Datta, 1999; Gordon et al., 2000). Future steps in the international research aim at improving the seawater intrusion models by including more variables related to environmental conditions.

3.2.2 The North Adriatic coast: features and the impact of human activity

The Adriatic Sea is the biggest semi closed basin in the Mediterranean Sea. It is orientated SSE-NNW, its maximum extension is 800 km whereas its minimum extension is 200 km. Thus it is a narrow basin with a north-south depth gradient: the southern part is deeper while, going further north, the basin becomes shallower.

Fig 3.2.2.1: Bathymetric reconstruction of the Adriatic Sea (CENAS, 1997)



The North Adriatic coast is one of the most densely populated and developed areas of Europe. In such an area, as in other very developed coastal zones, the natural balance between freshwater and saltwater in coastal aquifers is negatively influenced by groundwater withdrawals and other human activity that lower groundwater levels, reduce fresh groundwater flow to coastal waters, and ultimately cause saltwater to intrude coastal aquifers (Kumar, 2000). Saltwater intrusion can occur in many different ways, depending on hydrogeologic features, sources of saline water and activity of groundwater withdrawals and freshwater drainage along the coast. In the Province of Ravenna, where this thesis has been carried out, problems related to subsidence are very serious. In fact, past offshore extraction of natural gas led to an extremely deteriorated coastal system. This activity, carried out in an area where natural subsidence was already occurring, was very damaging and it has now been restricted. Since this activity ceased, the subsidence rate has been reduced. Past subsidence rates reached 11 cm/y in the 70s, whereas nowadays subsidence is about 3-4 mm/y. By lowering the land surface level, the piezometric heads also become lower, and this effect is worsened by the rising sea level. Thus, in this area, problems related to saltwater intrusion are affected not only by fresh groundwater withdrawal, which is now restricted, but also by subsidence and the rising sea level. Before the great boom in tourism, which occurred in the 1960s, dunes on the North-West Adriatic coast used to be a very common feature of the littoral. Since then, however, they have slowly disappeared due to overdevelopment and nowadays they occupy only in limited areas. In the Province of Ravenna alone, coastal dunes that have disappeared during the last 50 years have been calculated to be 75% of the initial coverage (Caruso et al., 2005). Their disappearance, which is due to the construction of many bathing establishments, where once only dunes were situated, and to the indiscriminate use of their sand as cheap construction material has caused many serious environmental problems. One of these problems is related to coastal dune efficacy in contrasting saltwater intrusion. In fact, dunes have a great infiltration capacity, so they can accumulate fresh groundwater. This watertable, laying above sea level, acts as a hydrostatic control on saltwater intrusion, by contrasting the seawater density head. The fresh-saltwater interface is 30 to 40 times deeper than the freshwater hydraulic head (Ghyben-Herzberg principle, paragraph 1.2.1). Hence, by decreasing the freshwater hydraulic head by 1 m, it causes a 40 m interface upconing. This capacity of coastal dunes is very important to protect landward areas, since dunes can accumulate beneath them a freshwater lens that contrast the saltwater intrusion. In some cases, if the piezometric head is well above sea level, the fresh-saltwater interface can reach the clay basement. When this occurs, landward areas are completely protected against the saltwater intrusion phenomenon. This capacity of coastal dunes to protect landward areas against saltwater intrusion is mainly influenced by recharge and topographic features. A higher and more mature dune, in fact, is more effective at contrasting saltwater intrusion than a lower and younger one (chapter 3.1). On the North-West Adriatic coast, the height of coastal dunes ranges from 2 to 8 m. Obviously, in very damaged areas, the length of dunes is discontinuous because of the presence of many bathing establishments and the height of dunes is often lower than in protected areas. Aiming at assessing the efficacy of damaged coastal foredunes in contrasting saltwater intrusion, we chose a very touristic stretch of coast, where dunes are eroded and isolated by buildings constructed around them.

3.2.3 Coastal dunes on developed coasts: are they still effective in contrasting saltwater intrusion?

Very little is known about the efficacy of dunes on developed coasts in contrasting saltwater intrusion. It is well known that, it is possible for them to accumulate a fresh groundwater lens (Oude Essink, 2001a). The Badon Ghijben-Herzberg principle was originally formulated for situations where the transition zone between fresh and saline groundwater is only a small percentage of the thickness of the saturated freshwater body (thus, usually in the order of several meters). Under these circumstances, a fresh-salt interface should be considered. This situation occurs in untouched natural sand-dune areas or (coral) islands, where the freshwater lens evolves by natural groundwater recharge (Oude Essink, 2001a). Obviously, when human activity carried out in coastal zones (groundwater extraction, construction of buildings on the dune line, plantation of non autochthon species) is intense, the freshwater lens does not evolve in the same way. Recharge is one of the most important factors in determining the formation of the freshwater lenses (Ranjan et al, 2005). It is remarkable that in a natural situation, where there are no buildings or cement pathways, recharge is not reduced by the presence of artificial obstacles. Moreover, it is worth noting that dunes on very developed beaches are smaller (Nordstrom, 2000). Their size is a very influencing factor on their capacity to accumulate a freshwater lens, which stands above sea level. Results obtained in this thesis highlight the importance of coastal dunes in contrasting the saltwater intrusion phenomenon, even in a very stressed situation as that observed at Marina Romea beach. Nevertheless, human impact in this area hardly affected dune effectiveness, which has been highly reduced. This is one of the earliest studies regarding the efficacy of a coastal foredune system in contrasting saltwater intrusion on a developed coast.

3.2.4 The case of Marina Romea beach (Ravenna).

The work carried out at Marina Romea beach aims at describing the function of dunes along a developed stretch of coast where dunes act as a natural defense against storms, erosion and wave attack; but they also have a very important role in defending landward areas against saltwater intrusion. The Province of Ravenna is particularly affected by subsidence, which causes the lowering of already depressed areas and worsens the saltwater intrusion phenomenon. Furthermore, past policies of bad coastal management have brought about a very damaged system, where dunes are often stressed or even absent. Along this coast, the remaining dunes are the only elements that lay above the ground. Moreover, dunes have a great infiltration capacity (Tsoar, 2005) and they can accumulate fresh groundwater by contrasting the seawater density head. We evaluated the influence of dunes in minimizing saltwater intrusion by comparing different data related to groundwater table height and salinity.

3.2.4.1 Study area

The study site is located south of the Lamone river mouth, Ravenna, Italy (fig. 3.2.4.1.1).

Fig 3.2.4.1.1: Location of the study area.

Over the last few decades, this beach has been strongly eroded by the sea (fig 3.2.4.1.2).

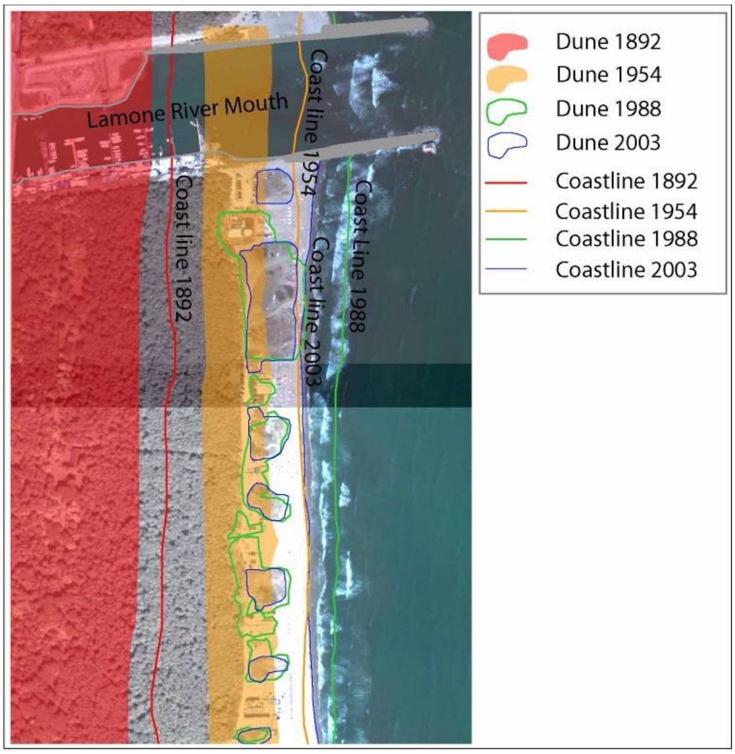


Fig 3.2.4.1.2: Coastline and dune evolution at the study area

Today the beach is very narrow (less than 20 meters) and, since dominant winds come from NNE and SSE, the dune development potential (DDP) calculated is less than 5. This means that there is a poor potential of coastal dune formation (Bezzi and Fontolan, 2003). Dunes are damaged by the presence of tourist establishments that have been built directly on them and by strong erosion. Now, the dunes appear as cliff-shaped relieves, which are more than 5 m high and are isolated by buildings constructed around them (Fig 3.2.4.1.3).

Fig 3.2.4.1.3: the study site in November 2005.

It is worth noting that the Marina Romea coastal area lays below sea level and landward areas are occupied by a wetland (Piallassa Baiona, fig 3.2.4.1.4). Thus, dunes become even more important because they are the only element, which stands above sea level. And this is fundamental for fresh groundwater accumulation. The vegetation found on the dune is typical of that of a backdune area since the dune crest and the dune front are absent because of erosion.

Fig 3.2.4.1.4: reconstruction of the area obtained by LIDAR data (2005). Blue zones lay below sea level. Piallassa baiona location is indicated.

3.2.4.2 Methodology

In order to monitor the state of the groundwater table, 9 piezometers were constructed and positioned at different locations (Fig 3.2.4.2.1). P2C was positioned about 1 km south of the others piezometers, in a control area where the littoral is even more developed and there are no dunes. Another piezometer, P4B, was positioned about 500 m landward, to determine whether saltwater intrusion reached that area or not. Three piezometers were positioned in correspondance to dune 1, the biggest dune of the area (its perimeter is about 350 m and its area 7000 m^2). P1A was located at the dune foot, P2A at the backdune and P3A in the pine forest. Another piezometer, PC, was positioned in the pine forest, in correspondance to a littoral zone where there are no dunes, but only a bathing establishment. Three piezometers were positioned in correspondance to dune 2, a very small dune limited by two bathing establishemnts. PD was located at the dune foot, P2B at the backdune and P3B in the pine forest.

Figure 3.2.4.2.1: An aerial image of the study area (2003). Piezometers location.

The PVC piezometers used were about 5 m long, had a 5 cm diameter and 9 holes at one end covered by a finely meshed fabric. Watre table deptha and salinity readings were taken using a phreatimeter and a conducimeter,. Each piezometer's elevation was computed using a DGPS. Moreover, to characterize the morphology of the biggest dune of the area (dune 1, Fig 3.2.4.2.3), an altimetric survey has been made with Real Time Kinematic Techniques (RTK), using a couple of receivers Topcon GB500 (Base and Rover), which guarantees a centimetric precision of measurements (Fig 3.2.4.2.2).

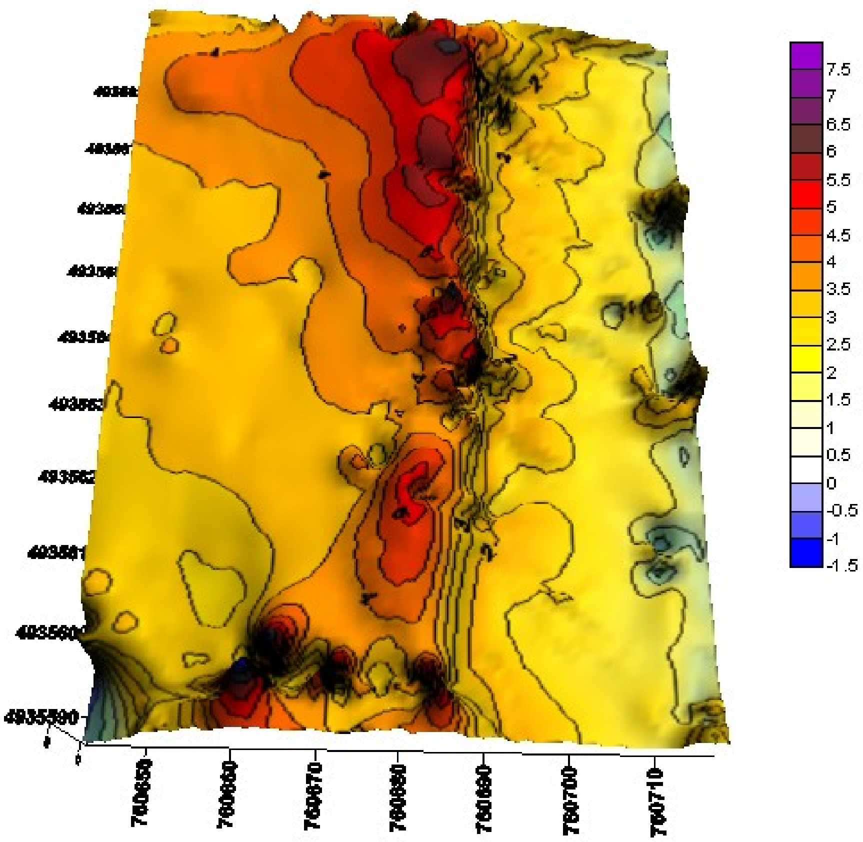


Fig 3.2.4.2.2: Altimetric survey of dune 1(Topcon GB500)

Aiming at describing the historical evolution of the study site, a GIS database has been created as a support in aerial imagery analysis (Fig 3.2.4.1.2). As at the Bevano beach, both methodologies, piezometric and resistivity techniques, were used. Several resistivity measurements were taken along the AA' transect (fig 3.2.4.2.3).

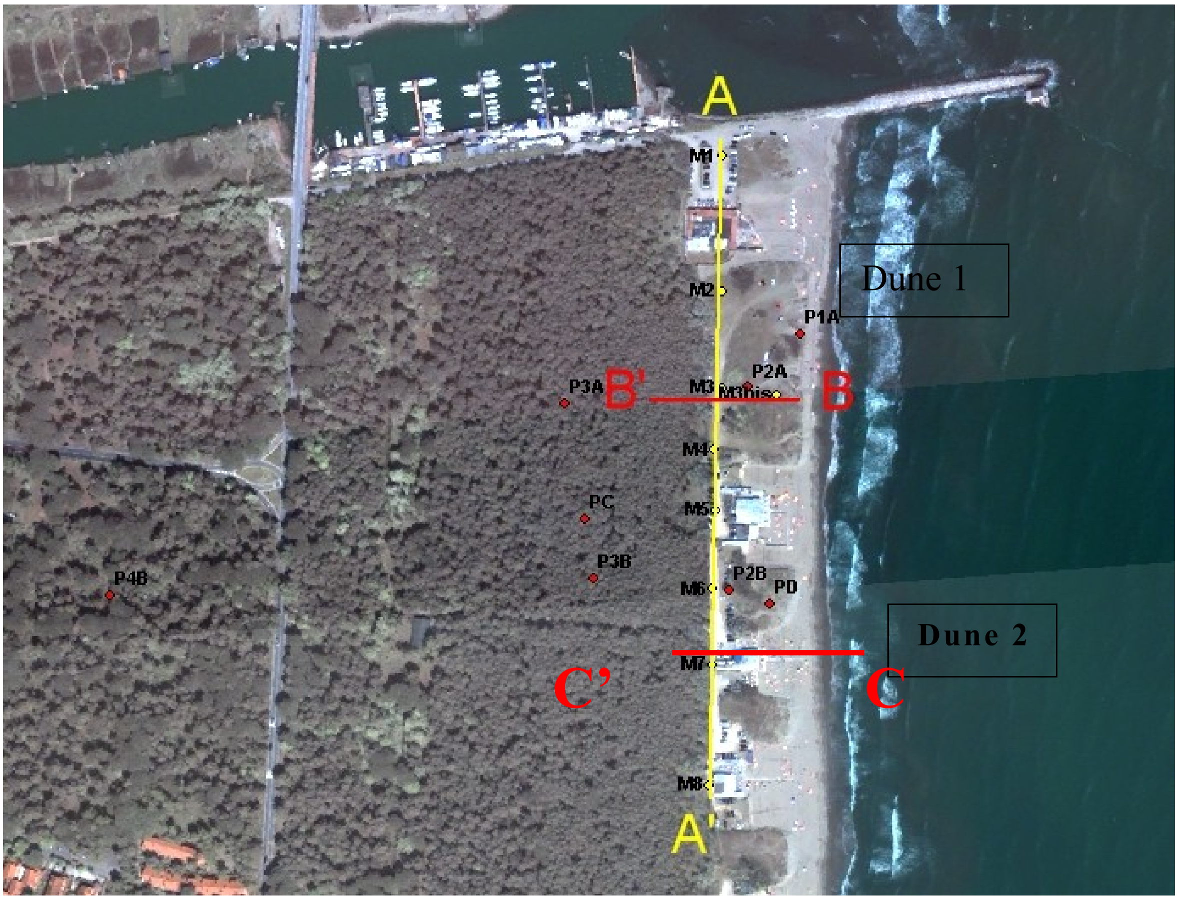


Fig 3.2.4.2.3: An aerial image of the study area (2003). Resistivity measurements (M1 to M8) location is highlighted in yellow. Piezometers are highlighted in red: P1A, P2A, P3A, PC, PD, P2B and P3B. Three transects (AA', BB' and CC'), which will be analyzed further on, are highlighted.

In order to monitor the state of the groundwater table in correspondence to the biggest dune of the area, two piezometers were constructed and positioned along dune number 1 (Fig 3.2.4.2.3), at the foot (P1A) and in the backdune (P2A). Moreover, several measurements were taken along another transect (AA', see Fig 3.2.4.2.3) using electrical resistivity methods. The methodology is completely similar to that adopted in the Bevano case study (see paragraph 3.1.3). Resistivity data were collected along AA' transect (Fig 3.2.4.2.3) located in the backdunes. Measurements were taken at approximately the same elevation above sea level. Measurements M1, M2, M4, M5, M6 and M7 were obtained at 2 investigation depth (3 and 6 meters), while M3 and M8 are more detailed and relate to 4 investigation depths (3, 4, 5,and 6 m). Since lithologic composition of the study area is homogeneous (sand) at the depths analyzed (Carta Geologica Regionale), variations in resistivity can indicate the presence of water. A very rapid variation in resistivity could be explained by the presence of a salt-freshwater interface.

3.2.4.3 Results

The GIS was very useful in managing the data regarding the changes the study area underwent over time. Significant coastal erosion is evident as well as an increase in the number of beach establishments (Fig 3.2.4.3.1 and fig 3.2.4.1.2).

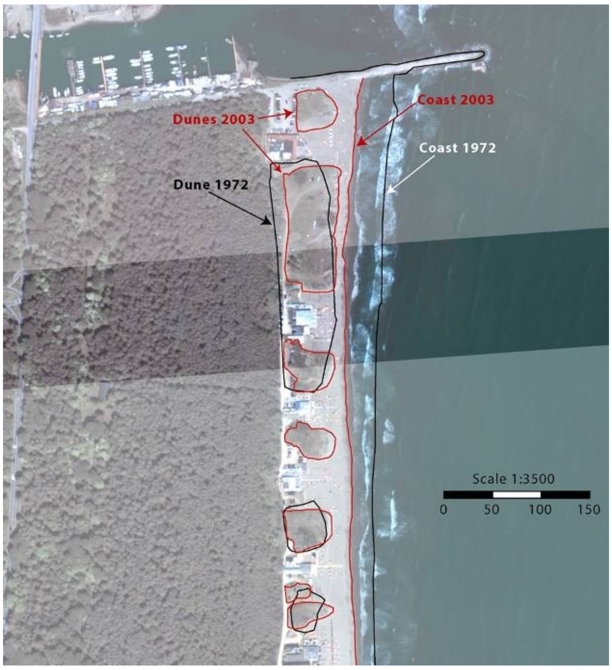


Figure 3.2.4.3.1: Beach-dune system evolution from 1972 to 2003

Data regarding groundwater depth and salinity in piezometers 1 and 2 are resumed in Fig 3.2.4.3.2. These data are integrated with data obtained using the electrical resistivity methodology at point M3 and at point M3BIS. Data are presented along a topographic survey obtained using a DGPS.

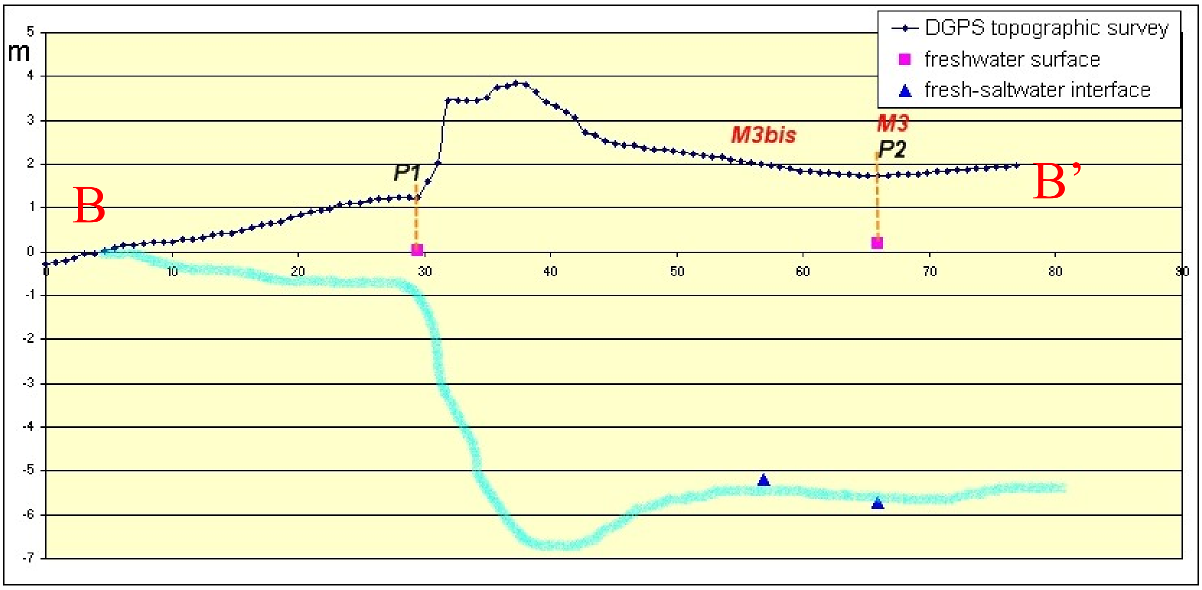


Fig 3.2.4.3.2: Topographic survey of dune 1. It is evident the freshwater surface trend beneath the ground obtained interpolating the piezometers groundwater surface values. The fresh-saltwater surface was obtained by interpolating the resistivity data.

It is worth noting that at dune 2 the piezometric head id always below the sea level (fig 3.2.4.3.3).

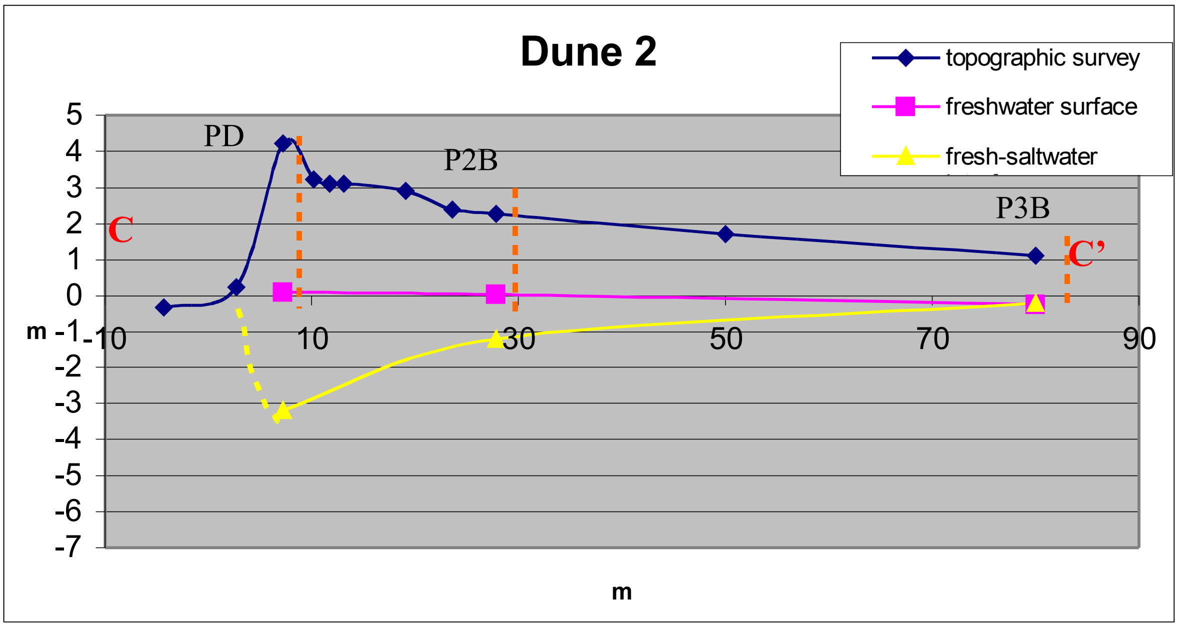


Fig 3.2.4.3.3: Topographic survey of dune 2 (blue line). The pink line is referred to the piezometric heads levels. The yellow line is referred to the fresh-saltwater interface reconstruction obtained by applying the Ghyben-Herzberg principle.

Elaboration of resistivity data obtained at transect AA’ are showed in fig 3.2.4.3.4.

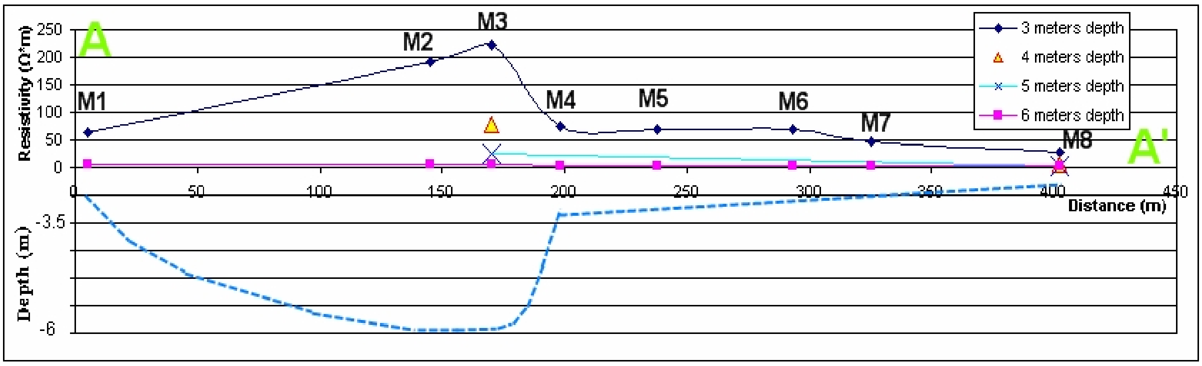


Figure 3.2.4.3.4: Resistivity values at different depth for each measure (from point A to point A', see fig 3.2.4.2.3). In the lower part of the scheme there is a hypothetical reconstruction of the fresh-saltwater interface.

Salinity values measured at the top and at the bottom of each piezometer are showed in table 3.2.4.3.1.

Piezometer	Salinity at the top of the piezometer(g/l)	Salinity at the bottom of the piezometer(g/l)
P1A	1.98	5.6
P2A	0.42	0.41
P3A	4.47	6.29
PC	4.20	8.92
P2B	0.23	0.14
P3B	3.69	7.41
P4B	0.50	3.49
PD	1.25	4.36
P2C	1.73	3.78

Table 3.2.4.3.1: salinity at the top and at the bottom of each piezometer.

3.2.4.4 Discussion

Data obtained from aerial images and from topographic DGPS surveys highlight the erosive trend of the last decades. These dunes continue to be a buffer against erosion but they have lost their dynamism and they are doomed to disappear in several years or decades. Very encouraging data are those which regard groundwater table level and salinity in the study area. Resistivity data indicate the presence of a deeper fresh-saltwater interface beneath the largest dune of the area (Fig 3.2.4.3.4: M2, M3, M4). Going further south, resistivity values are lower and this (considering the homogeneous lithologic composition of the area) could be explained by the presence of a very thin layer of fresh groundwater. Since the lithological composition of the area is homogeneous (sand), when resistivity values become lower this is due to the presence of a shallower fresh-saltwater interface. This fact is confirmed by watertable depth data gathered at dune 2 (fig 3.2.4.3.3). By comparing data collected during the same field campaign day (May 15th 2006), it is evident that dune 1 effect is much greater than dune 2's (fig 3.2.4.3.2, 3.2.4.3.3 and 3.2.4.3.4). Moreover, P2C salinity data (tab 3.2.4.3.1) highlight the presence of a very thin or even inexistent freshwater lens compared to that measured at P2A and at P2B. This is evidence of the effect caused by the total absence of dunes. In the area of dune 2, dunes are very small and damaged. They are cliff-shaped just as the biggest dune of the area, but they are considerably smaller. This is due to the presence of several touristic establishments built around them. Our results highlight that an eroded dune can still be effective against the saltwater intrusion provided that it is wide enough to create a freshwater lens. It is worth noting that near the edge of dune 1, i.e. near the beach establishment (M4: Fig 3.2.4.3.2 and 3.2.4.3.4), there is a rapid decrease in resistivity values. Looking at the positions of M5, M6, M7 and M8, their resistivity values have a trend that can be attributed to the succession of touristic establishments and small dunes. Anyhow, differences in resistivity between M5, M6, M7 and M8 are quite low. Thus, in this area, there aren't significant differences in resistivity between backdunes and buildings because these dunes are so small and damaged that they cannot have a hydrostatic control on saltwater intrusion. On the contrary, in correspondence to dune 1, there was a 6 m deep freshwater lens, whose effects were evident also in the pine forest. In fact, by observing data showed in figure 3.2.4.3.5, it is possible to understand the effectiveness of coastal dunes in contrasting saltwater intrusion on this stretch of coast. At the three piezometers located in the pine forest (P3A, PC, P3B), salinity values are quite high (Tab 3.2.4.3.1). At the top values are very similar, ranging from 3,7 to 4,5 g/l. Nevertheless, it is remarkable that, at the bottom, the lowest value is referred to piezometer P3A.This is a very important result because, if there were no dunes in this area, it would have been reasonable to expect P3A to be the saltiest point because of its proximity to the Lamone river mouth, whose salinity is very similar to that of the sea. But data referred to each piezometer indicate a different situation. The piezometer located in correspondence to dune 1 had the lowest salinity values at its bottom. This datum is even more significant because of the northward vicinity of the Lamone river mouth. It is evident that, on this developed stretch of coast, the only dune, which had an affect on saltwater intrusion, was the biggest. However, it is remarkable that its effectiveness was strictly localized in correspondence to the dune itself, since the effects that dune 1 produced on landward areas were slightly visible. It is worth noting that, in the pine forest, the lowest salinity value was the one referred to piezometer P3A. But, nevertheless, it was still quite high (table 3.2.4.3.1). The pine forest salinization could be explained by assuming that Marina Romea dunes produce a sort of island effect. This means that they create a freshwater lens, which was not thick enough to effectively contrast the landward push operated by the seawater. So, seawater can infiltrate below the freshwater lens and reach landward areas. However, the same effect could also be due to the presence of the artificial pine forest. In fact, as demonstrated at the Bevano study case (paragraph 3.1.5), pines act as a water withdrawal net which causes saltwater upconing. This phenomenon is described also by Lammerts (1999), who indicates that forestry on the Dutch islands now aims at replacements of pine trees by broad leaved trees. Thus, the pine forest impact is very serious and can reduce the effectiveness of coastal dunes. Our results, however, confirm the effectiveness of coastal dunes in contrasting saltwater intrusion, provided that they are wide enough to accumulate a freshwater lens and they are not disturbed by human influence. Another condition to take into account is the state of the coastal environment where dunes act. Coastal dunes effectiveness is highly dependent on the presence of water withdrawals. Every human induced activity related to water extraction can negatively affect dunes effectiveness in contrasting saltwater intrusion. Anyhow, even in a very stressed area, as that here analyzed, dunes demonstrated to be a very important feature of the coast. Their effect can be observed even in an area below sea level, as the pine forest (tab 3.2.4.3.1). Thus, since a deeper fresh-saltwater interface can guarantee a more effective control on saltwater intrusion, dunes represent a resilient factor for coastal dynamic equilibrium. This fact is confirmed by data showed in figg 3.2.4.3.2, 3.2.4.3.3 and 3.2.4.3.4. Furthermore, it has to be considered the conservation state of the beach. This stretch of coast is highly eroded and overexploited. Dunes are cliff shaped and very damaged. In such an environment, low salinity values at the foot of the dunes have an even more important significance. This is evidence of the way dunes can represent an irreplaceable protective feature of the coast.

3.2.4.5 Conclusions

Our analysis of piezometric and geo-electric data, shows that dune integrity is important in controlling saltwater intrusion. This study has been carried out on a particularly overdeveloped coast. In this area, where the dunes are wider (northern part of the study area), the interface between saltwater and freshwater is deeper (6 m), whereas it is shallower (3.5 m) where the dunes have been almost completely destroyed (southern part of the study area). Thus, dunes size is a very important factor in determining freshwater accumulation, even on stretches of coast where dunes are very stressed and eroded. The effectiveness of the biggest dune of this stretch of coast in protecting landward areas has been demonstrated. Although it could not completely avoid the saltwater contamination, there are evidences of its mitigation capacity. This result assumes an even more important value, because it was obtained in a very damaged area. This stretch of coast is overexploited by tourism development and by erosion; but there is another factor, which had a very strong affect in reducing dune effectiveness in contrasting saltwater intrusion. In fact, the pine forest presence is damaging with respect to the salinization of this area, since pines act as water withdrawal points (Lammerts, 1999). Every human induced activity related to water extraction (including the pine forest plantation) can negatively affect dunes effectiveness in contrasting saltwater intrusion. Anyhow, dune effect has been observed even on a very developed coast, as Marina Romea. Thus, since a deeper fresh-saltwater interface can guarantee a more effective control on saltwater intrusion, dunes represent a resilient factor for coastal dynamic equilibrium.

3.3 General Conclusions

One of the main purposes of this part of the thesis was to describe the effectiveness of coastal dunes on the North-West Adriatic coast in protecting landward areas against saltwater intrusion and to identify the most influencing factors on this capacity. This very important feature of coastal dunes was described in fundamental hydrogeology manuals (Fetter, 2001; Bear 1999), but there is a lack of specific experimental work which focuses on this topic along the Adriatic coast (see paragraph 1.2.2). Two case studies were developed. The first is located in a coastal area where human disturbance is low (Bevano river mouth Natural Reserve) was chosen and almost the entirety of this thesis is related to such study. Whereas, aiming at determining whether a more damaged dune system is still effective in contrasting saltwater intrusion, another experiment, on a more developed stretch of coast (Marina Romea, Ravenna), was carried out. The methodology used in the Bevano River Mouth case study was similar to that used in the Marina Romea one, as both were based on the use of a piezometric network and resistivity measurements. In both the case studies, results highlight the great influence of coastal dunes in minimizing the saltwater intrusion phenomenon, provided that they are still of a reasonable size. Hence, if the dunes are of a sufficient size (the one we analyzed was 7000 m2) and the use of landward areas is compatible with the conservation management of freshwater resources, they are capable of effectively contrasting saltwater intrusion. Nevertheless, before starting to analyze the main results obtained, it is very important to emphasize some preliminary remarks. Both the case studies were analyzed using the same methodology, but sample designs were different. Anyhow, it is worth noting that in both case studies, results highlight that coastal foredunes are actually the only elements which can effectively oppose and mitigate saltwater intrusion. This is a very important result, particularly if we consider the strong impact of saltwater intrusion on this stretch of coast, which lays below sea level. In both case studies, fresh groundwater was always found in correspondence to dunes. This is evidence of the way coastal dunes can have an influence on the hydrologic equilibrium of coastal systems. But it is also worth pointing out that their effect is not always capable of protecting landward areas. Theoretically, they could protect landward areas if the piezometric head were high enough to push down the fresh-saltwater interface as low as the clay basement (bottom of the unconfined aquifer). This could occur if the piezometric head were higher than 60 cm above sea level, since basement depth is about 30 m in these zones (see paragraph 1.2.1). This did not actually occur in any of the analyzed transects, neither at the Bevano nor at Marina Romea beach. However, it is worth noting that the only transect where freshwater was found not only in correspondence to dune crest but also at the backdune was the only transect (profile 3, fig 3.1.3.1) where there was no pine forest. Furthermore, it is worth mentioning that, given its close proximity to the salty meander, profile 3 should have been the saltiest one. It was, on the contrary, the only profile where fresh groundwater was found at the backdune. This is proof of the way the presence of the pine forest, artificially planted by man, negatively affects hydrological coastal equilibrium. In fact, pines act as a water withdrawal net which causes saltwater upconing, given that they have great water extraction capacity due to their transpiration (Lammerts, 1999). This is the only plausible reason, which can explain the presence of saltwater in all the landward areas analyzed except for profile 3, which, surprisingly, was expected to be the saltiest. As well as the pine forest there are others important factors, which can reduce dune effectiveness. In fact, dunes efficacy in accumulating fresh groundwater can differ very much, depending on their height, integrity and maturity. At the Bevano river mouth, it was possible to compare values of piezometric heads levels and salinity at two different aged foredunes. The most mature dune had the thickest freshwater lens beneath it. This was due to its topography, which was more developed than the young dune, but it could also be due to other factors, as the presence of the river in the lee side of the young dune. However, considering the presence of a salty wetland, on the lee side of the most mature dune, topography should be considered as the most influencing factor on differences between the two dunes analyzed. Furthermore, our results highlight that, even in a protected area, the impact of human alterations of the landscape was very strong. And these impacts had brought about a system, which is less effective in contrasting saltwater intrusion. In fact, at the Bevano beach, coastal foredunes seem to be effective only at limited spatial and temporal scales. This is due to the presence of the artificial pine forest, which lays behind the dunes and has a negative impact on saltwater intrusion. Another important factor in determining freshwater accumulation is dunes extension, even on stretches of coast where dunes are very stressed and eroded. The effectiveness of the biggest dune analyzed at Marina Romea beach in protecting landward areas has been demonstrated. Although it could not completely avoid the saltwater contamination, there are evidences of its mitigation capacity. This result assumes an even more important value, because it was obtained in a very damaged area. This stretch of coast is overexploited by tourism development and by erosion; but there is another factor, which had a very strong effect in reducing dune ability to contrast saltwater intrusion, that is the presence of the pine forest. Anyhow, it is remarkable to have an evidence of dune effectiveness even in such an area.

In conclusion, this thesis produced several important results in the study of hydrogeology applied to dune systems. We can affirm that dune size is one of the most important features to be considered.

The higher they are the more effective they result in accumulating fresh groundwater. And, since dune height is strictly related to their maturity, we can affirm that a mature dune is an effective resilient factor of the coast. It is evident that their protection (at any stages of their evolution) should be one of the main goals of any good coastal zone management. Another important result concerning dune size was referred to their lateral extension. Their lateral continuity is a fundamental factor in determining the creation of a freshwater lens. This factor is more important than the integrity of their topographic profile. In fact, a very damaged, overdeveloped, eroded and cliff shaped dune proved to be still effective in mitigating saltwater intrusion phenomenon. The most important condition is that it is long enough to accumulate a freshwater lens. Another very important factor is related to the use of landward areas. Any human activity related to groundwater extraction (including the artificial plantation of non autochthon species) has a very strong impact on coastal aquifers. At both our study sites, pines act as a water extraction withdrawals net. The pine forest plantation had brought about a very damaged system, where dune effects are very localized. At both sites, the most damaging factor seemed to be the presence of the pine forest. This is a very important result, because, at two very different sites, a natural reserve and a very developed beach, the strongest influence on saltwater intrusion is related to the presence of the pine forest. Moreover, at both sites, even on a very overdeveloped stretch of coast, dune effectiveness in contrasting saltwater intrusion was proved. Thus, since a deeper fresh-saltwater interface can guarantee a more effective control on saltwater intrusion, dunes represent a very important resilient factor for coastal dynamic equilibrium.

Conclusions

This thesis gave important results concerning the importance of dunes as a coastal resilient elements. To do this, the most influencing factors on dunes effectiveness in protecting coastal areas have been identified both on undeveloped and developed stretches of coast. Results obtained at the Bevano case study demonstrated that morphological maturity of dunes is a very important factor in determining differences in sand accumulation. In fact, at the old dune, morphology was a key factor in dune growth while, at the young one, changes in elevation were mostly due to vegetation coverage. The young dune was extremely affected by the presence of vegetation and by strong onshore winds activity while the old dune was unaffected by the absence of vegetation at the dune foot and by differences in the vegetation coverage at the dune crest and at the backdune. The young dune was extremely affected by erosion in unvegetated areas and generally has high deposition rates in vegetated areas. There were evidences of sediment transportation beyond the young dune, so a bit of the total accumulation was missed landward. Results obtained at the Bevano river mouth study site highlight that the older dune is characterized by a lower variability in sand accumulation and a higher resilience against erosive events. This is a result that coastal managers should take into consideration. In fact, it should be a priority to protect coastal dunes during their most vulnerable stages. Dunes laying on undeveloped coasts can reach bigger height and they are generally characterized by more continuous profiles (Nordstrom, 2000). Our results highlight that, on undeveloped coasts, mature dunes are less dependent on vegetation than during their earlier stages. This is because their morphology itself acts as a trap for sediment transport. On the contrary, at Eraclea beach, dunes are damaged and their morphology is not natural. Once again, it must be made clear that the two beaches are completely different and this is not a comparison between sites but a site internal comparison referred to different dunes laying on the same beach. Results obtained at Eraclea beach, confirm that the development rate of the beach can affect very much dune effectiveness in sediment accumulation. Thus at Eraclea beach, after nourishment, which demonstrated to reactivate beach-dune sand interchange, the most influencing factor on sand accumulation was not morphology but vegetation. The main accumulations were observed at the dune foot for both mature dunes and lower and younger ones. Nevertheless there is an evidence of sand transport even on the dune crest. At every profile (for both mature and young dunes) a very important role in inducing sediment accumulation is played by vegetation presence and density. In fact, the most irrelevant growth was observed at the foot of a dune where there was a very sparse vegetation, many unvegetated areas covered by bare sand and some little patches of vegetation. Thus, it is worth noting that at Eraclea beach, vegetation (even if artificial planted) is very effective in inducing sediment accumulation, whereas dunes morphology is a factor that has less an affect on sand accumulation. In fact, at such a location, it would be normal to expect a higher accumulation at both the mature dunes. This is evidence of the way vegetation can influence variability in sand accumulation, mostly on developed coasts. Thus, beach nourishment should be carried out on beaches where vegetation is not disturbed or where there is a plan to protect it. In conclusion, sediment accumulation at different foredunes can be highly variable, depending on morphology, vegetation and beach development. Our study highlight that vegetation is the most important factor on sand accumulation at vulnerable dunes. When dunes are young or overdeveloped, their dependence on vegetation is higher. Whereas, mature dunes grow more and even in unvegetated areas. This thesis produced several important results also in the study of hydrogeology applied to dune systems. We can affirm that dune size is one of the most important features to be considered. The higher they are the more effective they result in accumulating fresh groundwater. And, since dune height is strictly related to their maturity, we can affirm that a mature dune is an effective resilient factor of the coast. It is evident that their protection (at any stages of their evolution) should be one of the main goals of any good coastal zone management. Another important result concerning dune size was referred to their lateral extension. Their lateral continuity is a fundamental factor in determining the creation of a freshwater lens. This factor is more important than the integrity of their topographic profile. In fact, a very damaged, overdeveloped, eroded and cliff shaped dune proved to be still effective in mitigating saltwater intrusion phenomenon. The most important condition is that it is long enough to accumulate a freshwater lens. Another very important factor is related to the use of landward areas. Any human activity related to groundwater extraction (including the artificial plantation of non autochthon species) has a very strong impact on coastal aquifers. At both our study sites, pines act as a water extraction withdrawals net. The pine forest plantation had brought about a very damaged system, where dune effects are very localized. At both sites, the most damaging factor seemed to be the presence of the pine forest. This is a very important result, because, at two very different sites, a natural reserve and a very developed beach, the strongest influence on saltwater intrusion is related to the presence of the pine forest. Moreover, at both sites, even on a very overdeveloped stretch of coast, dune effectiveness in contrasting saltwater intrusion was proved. Thus, since a deeper fresh-saltwater interface can guarantee a more effective control on saltwater intrusion, dunes represent a very important resilient factor for coastal dynamic equilibrium.

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