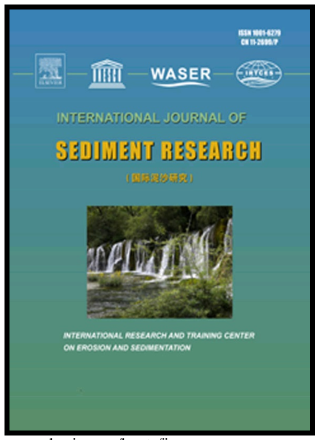

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Depth of closure: New calculation method based on sediment data

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Abstract

Obtaining depth of closure (DoC) in an accurate manner is a fundamental issue for coastal engineering, since good results for coastal structures and beach nourishment depend mainly on DoC. Currently, there are two methods for obtaining the DoC, mathematical formulations and profile surveys. However, these methods can incur important errors if one does not take into account the characteristics and morphology of the area, or if one does not have a sufficiently long time series. In this work the DoC is obtained from the break in the trend of the sediment with the depth, that is, in general with the increase of the depth a decrease in the size of the sediment takes place. However, at one point this tendency changes and the size increases, and then decreases again. When comparing the point where the minimum sediment size occurs before the increase, it is observed that the error incurred is small compared to other methods. If the Standard Deviation of Depth Change (SDDC) method is considered as the most accurate method, the error incurred by the proposed method is less than 7%. In addition, it can be seen that the dispersion of the sediment method always occurs outside the zone of bar movement. Whereas in the methods of profiles survey (using 2 cm precision profiles), sometimes the DoC is obtained within the active zone of bar movement. In addition, where the relative minimum of the median sediment size is found, and the sizes of 0.063 and 0.125 mm predominate in the composition of the sample. Therefore, this new method allows the precise location of the DoC to be obtained in a fast and simple way. Furthermore, this method has the

advantage that it is not affected by the modifications that may be experienced by both the study area and the cross-shore beach profile.

Keywords: *Depth of Closure; Median sediment size; Profile surveys; Profile change; GIS.*

1. Introduction

A key concept in beach morphodynamics is the Depth of Closure (DoC). The depth of closure has several definitions depending on the field of application: i) an empirical measurement of the seaward limit of significant cross-shore sediment transport on sandy beaches (Kraus et al., 1998), so it is not a real sediment limit (Aagaard, 2014; Stive & de Vriend, 1995). ii) An offshore transition zone in which the influence of waves on bed stresses, and, hence, sediment transport, is significantly lower than within the surf or high shoreface zone (Ortiz & Ashton, 2016). iii) Geological transition zone (Wallace et al., 2010). This research focuses on the DoC according to the first definition, widely used in coastal engineering as an empirical measure of the maritime limit of the significant cross-shore transport of sediment of sand beaches (Kraus et al., 1998), and is applied in: i) estimation of coastal sediment balance (Hands, 1983); ii) the definition of the active zone to supply material for beach nourishment (Hands & Allison, 1991); iii) numerical modelling of coastal change (Kraus & Harikai, 1983); and iv) beach nourishment and coastal defense structure design (Avila-Serrano et al., 2009; Davison et al., 1992; Ghazali & Hisham, 2007; Jiménez & Sánchez-Arcilla, 1993; Stauble et al., 1993; Stive et al., 1992).

At present, several methods are available to obtain the DoC, namely, the analytical calculation and the repetitive profile surveying methods. The only analytical method to obtain the DoC was proposed by Hallermeier (1978, 1981), who proposed an equation using extreme wave conditions. This equation was proposed, after the study of laboratory and field data, as the outer limit of the littoral zone when the envelop between profiles is less than 0.30 m (operational precision of the data). This equation was later modified by Birkemeier (1985), using a greater number of profiles and reducing the difference between profiles at 3 cm. However, the most accurate method is the study of different profile surveys, in this case, the DoC is marked as the depth beyond which seabed changes are not significant (Nicholls et al., 1996).

Fixed Depth Change (FDC) and Standard Deviation of Depth Change (SDDC) are two notable criteria for DoC calculation. The SDDC criterion (Kraus & Harikai, 1983) defines the closure depth as the point at which the standard deviation reaches a constant, non-zero tail, which often coincides with the accuracy of the survey profile measurement. This is a simple method, effective when dealing with large data sets and capable of removing distortion generated by atypical values when using fixed criteria (Hinton & Nicholls, 1998).The FDC criterion (Nicholls et al., 1996) defines the DoC as the point at which, for two profiles from the same location, the depth variation is equal to, or less than, a preselected criterion, which is often associated with the measurement accuracy of the profile surveys. Other less commonly used methods are mathematical models (de Vriend et al., 1993a, 1993b; Hanson & Kraus, 1989; Larson & Hanson, 1996; Walstra et al., 2001; Zheng & Dean, 1997) or those that take into account the deviation between the real profile and the balance profile (Dean & Dalrymple, 2002; Dean et al., 1993).

The closure depth obtained by the current methods will vary according to the time scale over which the study is performed (Capiobianco et al., 1997; Nicholls et al., 1996, 1998), the quality or accuracy of the measurement elements (Capiobianco et al., 1997), the morphological changes in the area and the energy of the incident wave (Anfuso et al., 2001; Carter, 1988). Therefore, an approach that is influenced as little as possible by morphological changes and time scale should be sought. In this regard, marine sediments can be found , whose distribution on the seabed has been extensively studied by several authors and mainly depend on currents and incident waves (Bayram et al., 2001; Beach & Sternberg, 1988). In addition the sedimentation of the particles occurs as the energy decreases (Guillén & Hoekstra, 1996; Niedoroda et al., 1985) which decreases in the sea as depth increases (Putnam & Johnson, 1949). Thus, most studies on sediment distribution on the bottom conclude that the mean sediment size decreases from the coastline to offshore (Anthony & Leth, 2002; Barusseau & Braud, 2014; Su et al., 2016; Zuo et al., 2016). On the other hand, waves with higher energy (higher wave height) will be able to move thicker sediments and deposit them at greater depths, and the regular waves will be unable to move them back to the coast.

Normal waves will move the thinner sediments seaward to a depth at which there is no affect due to the waves, while extreme waves will move thicker sizes accumulating them beyond that point. That is, if distribution of the sediment along the profile is observed, a decrease in the median sediment size will be observed towards the bottom until this tendency is broken and the size increases and decreases again. Taking into account the definition of the DoC, the point where the minimum size of sediment (prior to the increase) is located, must match the DoC. Therefore, the objective of this paper is to obtain the depth of closure by identifying this point of change in sediment size. However, since sedimentological sampling is complex and costly, a methodology for the determination of the DoC is developed using the fewest possible samples. The obtained DoC will be compared with that obtained from the different methods available in the literature.

2. Materials and methods

This section describes, firstly, the methodology followed for the sampling and survey of profiles. Second, the process to perform the statistical and spatial analysis of the sedimentological data using a Geographical Information System (GIS) is presented, in order to obtain the DoC from the change produced in the sediment characteristics. Third, the methodology for comparison of the new method with the results obtained by the profile survey method of the SDDC and FDC criteria and the analytical formulas of Hallermeier (1978) and Birkemeier (1985) is presented.

2.1. Study area

The study area is located on the Spanish Mediterranean coast and comprises a section of coast from 5.3 km to the north to 13.2 km to the south of the Port of Valencia (Fig. 1). Port and Carraixet Ravine border the northern area, where the beaches of Malvarrosa-Cabanyal (P1N), Patacona (P2N and P3N), and Port Saplaya (P4N) are located. In the southern area can be found the beaches of (from north to south) Pinedo (P1S and P2S), Saler (P3S and P4S), and Dehesa (P5S).

Fig. 1. Map of the study area showing beaches, precision profiles, sediment samples collected by transects including the validation set, the bathymetry (in m below Mean Sea Level) and average wave flow direction, with SIMAR (high-resolution modeling system) nodes used for calculation. **(no color is needed)** .

The study area has undergone several morphological changes over time due to the expansion of the Port of Valencia and the nourishment carried out on the beaches of Pinedo and Cabanyal-Malvarrosa. Therefore, to analyze and interpret the results it is necessary to place them in their temporal context, identifying and taking into account all processes that have taken place during the period of study. This is why, in the first place, the historical evolution has been investigated by the comparison of high-resolution georeferenced orthophotos taken in the years 2000, 2004, 2006, 2008, 2010, and 2012 (Fig. 2). From the analysis of historical orthophotos, a number of important factors are observed, such as longitudinal and transverse transport of sediment or if the studied beach is in recession or accretion, which can influence on the depth of closure to be analyzed. The historical evolution, thus, obtained, is verified with the profiles of precision of the study of profiles done by the Universidad Politécnica de Valencia (UPV).

Fig. 2. a) Detailed aerial view of the Malvarrosa-Cabanyal Beach. Shoreline position evolution shows the accretion from 2004 to 2012. **b, c)** Aerial view of Port of Valencia evolution, showing the successive enlargements of the northern breakwater. **(no color is needed)**

Table 1. Beach area balance in the area of study (2000-2012), showing accretion (positive) or erosion (negative), and associated wave parameters. $H_{s,12}$ is the wave height surpassed only twelve hours a year. H_{max} is the maximum wave height produced during the study period.

As can be seen in the North, there is longitudinal sediment transport in a North-South direction, where Malvarrosa-Cabanyal (P1N) is the only beach in the northern zone that increases its area (Table 1). An accretion of 83,628.5 m^2 was detected, but only 43,458.5 m^2 can be attributed to the Malvarrosa-Cabanyal beach nourishment in 2006. The total volume of sand contributed was 135,000 m^3, whose median sediment size (D_{50}) before nourishment was 0.171 mm and after 0.172 mm. Once the construction work had been completed, some stability in the northern zone beaches was detected, but not in the southern zone beaches. The reasons for this difference are the changes in the incident directions sector on each beach due to the port expansion. The port expansion provides additional shelter to the northern beaches -and southern beaches to a lesser extent - which did not exist prior to this expansion (Table 2).

Table 2. Incident directions (degrees from north) on each beach before and after the Valencia Port expansion.

Incident swell was characterized with data provided by Departamento de Clima Marítimo de Puertos del Estado. The information was extracted from the analysis of wave data provided by nodes belonging to the SIMAR network, in particular, SIMAR 2081114 (northern zone) and SIMAR 2081113 (southern zone) points (Fig. 1). The dominant storms in the area, selected by their higher wave height and frequency, are those of direction east-northeast (E-NE) ($H_{s,12}$ = 3.77 m and $T_{s,12}$ = 12.3 s; where $T_{s,12}$ is the period associated with wave height $H_{s,12}$), followed by direction E ($H_{s,12}$ = 2.4 m and $T_{s,12}$ = 11.1 s). However, due to the location of the Port of Valencia and the southern beaches, there are some swells from the southeast (SE) ($H_{s,12}$ = 1.6 m and $T_{s,12}$ = 9.85 s) which, despite being less energetic, are more frequent in this area. The mean flow direction is 81.35°N, which creates a net longshore transport in the North-South direction (Ecolevante, 2006). Swell can explain the specific behavior of the northern and southern zones (Table 1). In 2000-2004 and 2008-2010 the highest values of wave height $H_{s,12}$ in the NE direction occur (Table 1) at 5.39 and 5.37 m, respectively, as well as the highest maximum wave height (6.6 m and 5.7 m). Taking into account that the waves coming from the ENE and NE are the most frequent, longshore transport should be expected, but in addition, there is a great erosion in the whole area. It follows that when certain values of wave height are exceeded a change occurs from longshore to cross-shore sediment transport.

Finally, it should be noted that the tides have astronomical amplitudes between 20 and 30 cm, i-e. are small or microtidal tides, although occasionally the sum of the astronomical and meteorological tides reach 1 m (Ecolevante, 2006).

2.2. Data collection

In this work, bathymetry and seabed sediment data provided by Jefatura Provincial de Costas de Alicante were used, as well as precision profiles made by the Universidad Politécnica de Valencia (UPV). Bathymetry comes from "Estudio ecocartográfico de las provincias de Valencia y Alicante, (Ecolevante, 2006)". This bathymetry was obtained using two multibeam and a single-beam probe from the coastline to a depth of –40 m, with an accuracy of ±15 cm (Ecolevante, 2006).

Sediment sampling, done in the summer of 2006, was carried out along 35 transects perpendicular to the shoreline and distributed along the study area (Fig. 1), taking 337 samples. Each transect has at least 9 sampling stations at the beach at depths ranging from 0 to -15 m.

A Van Veen dredger collected sediment samples. The contents of the dredge are deposited in buckets for subsequent labelling and introduction into bags. The labelled bags are placed in ice coolers and sent to the laboratory, where the granulometric tests were done(Ecolevante, 2006). The grain size distribution of sediment was determined according to the techniques of Folk and Ward (1957), and sediment was classified according to Wentworth (1922), Shepard (1954), and Hobson (1977). For each sample the median sediment size (D_{50}), mean, sorting, skewness, and kurtosis, as well as the percentage of material retained in each sieve that made up the sample were determined.

Finally, precision profiles were obtained using the method denominated Beach Profiler (BP) (Serra Peris & Medina, 1996). The BP is a high precision and low-cost beach profiling system. The specially designed element to measure the level of the sea bottom was a self-floatable aluminum bar, on the top the infra-red reflectors are fixed covering all directions and an articulated led plate at the bottom.

Neither continuous mean water level measurements nor calibration due to changes in water temperature or density are required during surveys. The BP eliminates these elements of uncertainty reaching a high precision measurement (error < 2 cm).

Along the 17.7 km of studied shoreline, 159 surveys were done at 9 representative points (Fig. 1). Surveys were collected in two time intervals, from 1992-1995 to 1997 and 2005-2008 to 2014. The Valencia Beach Monitoring Program done by the UPV established the control interval for each profile. When the beach is located in an interesting position (e.g., nourished areas, in apparent erosion, or close to infrastructure), the profile is considered to need intense control, therefore, surveying was done every two or three months. However, if the area was considered stable, the surveys were done every six months.

2.3. Interpolation of sedimentological data by GIS

Due to the separation between the sediment samples, an interpolation of the data was done to improve the interpretation of the sediment distribution and to better determine the location of the DoC. There are several ways to derive a prediction for each location but there are two main groupings of interpolation techniques: deterministic and geostatistical. The deterministic interpolation methods assign values to locations based on the surrounding measured values and on specified mathematical formulas that determine the smoothness of the resulting surface. The deterministic methods include IDW (Inverse Distance Weighted), Natural Neighbor, Trend, and Spline. Geostatistical interpolation techniques (Kriging) utilize the statistical properties of the points measured.

IDW interpolation assumes that the characteristics of the surface are driven by local variation (Watson & Philip, 1985). It works best if the sample points are evenly distributed throughout the area and are not clustered. This is an exact interpolator, where the maximum and minimum values in the interpolated surface can only occur at sample points. The IDW tool uses a method of interpolation that estimates cell values by averaging the values of sample data points in the neighborhood of each processing cell. The closer a point is to the center of the cell being estimated, the more influence, or weight; it has in the averaging process. This method assumes that the variable being mapped decreases in influence with distance from its sampled location. This is an exact interpolator, where the values on the interpolated surface agree with the sample points, which is an advantage over other methods that predict the whole surface.

With the ArcGIS Spatial Analyst extension, a continuous surface, or map, can be created. So, IDW was used to produce a grid of interpolated values of parameters like D_{50} (Fig. 3), and percentage of sediment retained by sieves, as well as textural parameters such as asymmetry, standard deviation, and kurtosis. For the creation of a continuous surface, or map, from measured sample points stored in a point feature layer, firstly, samples were divided into two subsets, so 285 samples were used to create the interpolated maps (training set) and 52 were retained for validation. These samples were selected using a randomized approach so that the validation set contained the same beach and sea sample proportion as the training set (Table 3). Several outputs were generated to adjust the model parameters (power, which controls the surface smoothness; cell size, based on sample spacing). Results were validated by applying the samples from the validation set (Fig. 4).

Fig. 3. Median sediment size, D_{50}, map produced using the IDW interpolation tool. Tool parameters are Power = 3 and Cell size = 50. **(no color is needed)**

Table 3. Sample stations by area and division into training and validation sets.

Fig. 4. Observed versus predicted median sediment size, D_{50}, of the 52 validation set samples. The best-fit line is dashed. The coefficient of determination (R^2) is 0.9652 and the Root Mean Square Error (RMSE) is 0.0027. **(no color is needed)**

2.4. Results validation

The results obtained using the new methodology are compared with the DoC obtained from: i) the formulation proposed by Hallermeier (1978), ii) the formulation proposed by Birkemeier (1985), iii) the FDC criteria using 2 cm precision profiles, and iv) the SDDC criterion using the criterion of 30 cm. Given the extensive data collection period available for both precision profiles and wave data, the DoC was obtained for periods of more than 5 years.

3. Results

First, the behavior of the point samples is studied. Thus, it is observed that the D_{50} follows a downward trend from dry beach to deep water, however, between depths of -4 m and -6 m there is a change in the trend (Fig. 5a and b), which recovers again, i.e., the size decreases again after this change. Something similar occurs with the distribution of the fraction of each sample, particles greater than 0.125 mm decrease with depth to a relative minimum (DoC), and then begin to increase. The opposite happened with the 0.0039 and 0.063 mm fractions. For instance, in the northern zone, the 0.063 mm fraction increases to a 48% relative maximum in the depth range -5 to -6 m, while the 0.125 mm fraction has, at that depth, a relative minimum (38.85%). If sediment data were grouped by beaches, the sorting of the D_{50} from backshore to the DoC is evident (Fig. 5c). At backshore the sand size varies from very fine gravel to very fine sand. However, at the DoC very fine sand always is detected.

Fig. 5. Grouped sediment samples by depth range. D_{50} and individual grain-size fractions of **(a)** northern and **(b)** southern zones. **(c)** Sediment samples grouped by beaches, showing the dispersion in the D_{50} by depth. The change in trend of sediment size is marked as the DoC. **(no color is needed)**

Therefore, using the samples a location zone of the DoC can be obtained, however, the range in which it is located is too wide, reaching in some areas at almost 3 m (Fig. 6). However, by applying GIS interpolation, a continuous sediment distribution profile can be created using side profile samples, so that the DoC coordinates (distance and depth) can be obtained and the value of the D_{50} can be estimated with less uncertainty (Fig. 6). In total, 35 sediment transects perpendicular to the coast have been examined, nine of which coincide with the precision profiles taken by the UPV. For example, if only the sediment samples are taken for the 3S profile, the change occurs between sizes 0.235 mm (-3.2 m) and 0.145 mm (-7.1 m), which implies a DoC location range of almost 4 m (Fig. 6). While with the new method (sample interpolation), the DoC will be at -4.8 ± 0.5 m, with a D_{50} of 0.121 mm (Fig. 6). In addition, as it is also possible to represent the percentage retained by the sieves that compose the sample, it is observed that beyond the DoC there is a predominance of size fraction 0.063 mm (Fig. 5).

Fig. 6. The DoC adjusted by GIS system from the sedimentological data in the profile, and comparison with other methods for the 3S profile. **(no color is needed)**

Finally, the results of the DoC estimated by the sedimentological method were compared with the DoC estimated by the method of profile surveys with its two criteria and the analytical formulations. Figure 7 shows that there are great differences in the results among the different methods used. It is observed that the depths obtained by the analytical formulations are located at greater depths, with the DoC obtained by the formulation of Hallermeier (1978) always yielding a greater depth (~ -7.7 m to the North, and ~ -8.7 m to the South) than that obtained by the formulation of Birkemeier (1985) (~ -5.8 m to the North, and ~-6.6 m to the South). The average DoC obtained with the SDDC and FDC criteria have a similar value (Fig. 7), given the accuracy of the profiles (± 2cm), but the DoC yielded by the SDDC criterion is generally deeper than that of the FDC criterion. However, some of the values obtained by these criteria are within the zone of bar movement, so that although they meet the criteria set by the methods they do not meet the definition of the DoC, as they are within the breaker bar zone. However, the values obtained by the sediment profiles, although obtaining values similar to those obtained by the SDDC method, always fall (including the dispersion) outside the zone of bar movement.

Fig. 7. Comparison of the results of the DoC obtained by each of the different methods and location of the zone of bar movement. **(no color is needed)**

On the other hand, the SDDC method has been considered the most accurate method among the existing methods for estimating the DoC because the criterion to obtain the DoC is the difference between envelopes must be less than 2 cm. Fig. 8 shows the results of the other estimation methods, and it is observed that the biggest error is yielded by the formulation of Hallermeier (1978) with values that oscillate between 40 and 90%. The Birkemeier (1985) formulation yields estimates with errors values ranging from 6 to 44%. The sediment method with interpolated samples yields closest results to the value given by the SDDC criterion (error of 7.5% in the North and 6.2% in the South).

Fig. 8. Error yielded by each of the methods compared to the SDDC method of precision profile survey (2 cm). **(no color is needed)**

Finally, the sediment method with interpolated samples has been validated in other study areas (Points in red Fig. 1). As can be seen in Fig. 9, the change in sediment trend occurs independently of the orientation and size of the sediment at the shore. This change occurs generally between -4 and -6 m, being located to greater depth for those beaches with a bigger grain size and a greater energy of the incident waves.

Fig. 9. a) Dorado beach, orientation ENE, D_{50} = 0.463 mm. **b)** Los Locos beach, orientation SSE, D_{50} = 0.195 mm. **c)** El Arenal beach, orientation ENE, D_{50} = 0.259 mm. **d)** Beach located in the Gulf of Tunis (Data taken from Saïdi et al. (2014)) orientation E, D_{50} = 0.26 mm . **(no color is needed)**

4. Discussion

The concept of DoC, understood as the theoretical depth from which sediment transport is very small or nil, is key in coastal engineering, since, to a great extent, the volumes of material necessary for nourishment and coastal protection depend on it (Avila-Serrano et al., 2009; Davison et al., 1992; Ghazali & Hisham, 2007; Jiménez & Sánchez-Arcilla, 1993; Stauble et al., 1993; Stive et al., 1992). Therefore, precise determination of the DoC can reduce costs and ensure the success of the project. In this research, sediment samples were used for the determination of the DoC, and to improve the interpretation of the results a GIS was used to interpolate the data (IDW algorithm), which enables the creation of a sediment distribution map covering the entire study area. Since IDW does not provide a prediction of interpolation errors (as an exact interpolator which uses all the samples available), to justify the results a subset of samples randomly retained for validation were compared with the predicted values. The coefficient of determination (R^2) of this relation is 0.9652 (Fig. 4). This great correlation validates the results obtained from the interpolated data. Cross-shore sections overlapping the interpolated rasters of median sediment size, D_{50}, the individual grain-size fractions, and bathymetric data can be generated (Fig. 7).

The analysis of the parameters of the sediment samples as a function of depth shows that there is a tendency, according to which the median sediment size decreases with increasing depth, and in addition, the samples become better classified, that is, the number of fractions that compose the sample decreases. All this confirms what has been observed by many other authors in different parts of the world (Anthony & Leth, 2002; Bascom, 1959; Horn & Walton, 2007; López et al., 2016; McLaren, 1981; Su et al., 2016). However, when a certain depth is reached this tendency is broken and the D_{50} increases, decreasing later again (Figs. 5 and 6). In this transition zone is where it has been verified that the DoC is located, coinciding with the smaller D_{50} and the larger proportion of sediment in the 0.063 mm size fraction of the sample (Figs. 5 and 6). This confirms that the DoC is a morphodynamic boundary instead a transport limit, since during storms the waves of greater energy can move larger sediment outside this limit, which are impossible to return in times of calm due to the depth and weight of these particles (Guillén & Hoekstra, 1996; Niedoroda et al., 1985; Putnam & Johnson, 1949). However, it is not the median sediment size itself that marks the DoC, but the change in the trend produced in the sample composition (which implies a variation in the tendency of the D_{50} itself). As it has been observed (Fig. 9), median sediment size at the same depth is different depending on the place studied. Thus, in areas with intense erosion and in the longshore transport direction (in the study area from north to south), the D_{50} at the same depth is finer (Fig. 5), which indicates that the distribution of the sediment along the profile depends both on the local granulometry and on the swell in the area.

On the other hand, the new methodology (with and without data interpolation) has been compared with the current methods (comparison of profiles and analytical formulas), among which the SDDC method is considered one of the most accurate methods for obtaining the DoC. However, the accuracy of these methods (SDDC or FDC) depends mainly on two factors, the accuracy or error during the profiling and the period covered by those profiles. In the current case, the accuracy of the profiles is ± 2 cm, which have been taken biannually for more than 20 years. Thus, it has been verified that for the same profile depending on the methodology used, there may be variations of up to 3 m for periods of more than 5 years (Fig. 7). Whereas if smaller periods are taken these dispersions increase, and the variations of the profile in response to the variations of the profile due to the variations of the climatic wave are much more affected on the small scale (Capiobianco et al., 2002). If the analysed criteria are compared, it is observed that analytical formulas usually always result in deeper DoC values than the methods based on profile surveys. In addition, using the SDDC criterion, the DoC obtained has a greater depth than that obtained with the FDC criterion, while the new methodology is always within the range established by the SDDC criterion of 2 cm with errors of 15.9 ± 8.1% for the sediment samples and 6.8 ± 5% for the interpolated sediment method.

Although the methods of profile surveys are considered the most accurate, it can be observed that depending on the period of study or profiling important errors can be made. Fig. 7 shows that both the range of values for the SDDC method and the FDC method occur many times within the range of motion of the active bars in the study zone, but this does not occur with the sediment methods. It can be said that while for profile survey methods' variations in coastal and profile morphology (erosion, accretion, bar movement, etc.) and anthropogenic actions (nourishment, breakwaters construction, etc.) modify or distort the results (more likely for the FDC criterion), the new proposed method allows the DoC to be obtained in a precise way without the influence of these elements. This improved precision is probably the result of the different sensitivity of the two methods (precision profiles versus sediment) to changes in hydraulic and/or morphologic conditions. Profiles are affected immediately by any morphological or energy change during the period analyzed, while sediment needs more important changes than those that have acted within the study area in the analyzed period (> 20 years) to modify the sedimentological distribution. This is an advantage in favor of the sediment methods, since the probability of error in choosing the DoC by the coastal engineer will be lower.

While it is true that the accuracy of the DoC that can be achieved by the sediment methods depends on the number of samples taken, the results show that a large number of samples are not necessary to obtain satisfactory results. Therefore, although sediment sampling is expensive, when compared to the methods of profile surveys, it is concluded that to obtain a large-scale DoC it would be cheaper and faster to perform sediment sampling. Since a single sediment sampling would be sufficient, whereas the method of profile surveys would have to take the profiles for at least 5 years to obtain valid long-term data. In addition, it has been shown that the sediment beyond the DoC remains relatively stable, as observed by Anthony and Leth (2002) the composition of the seabed seems to be relatively stable despite the passage of a cyclone with a return period of 100 years and diverse storms between two sediment sampling periods.

It is, for all the foregoing reasons, that the particle size distribution and the consideration of the variations in its distribution to estimate the DoC really adds a new dimension to morphodynamics. At the engineering level, the sediment methods provide a reduction of the time to obtain a reliable DoC, when being calculated from field data. This has a great impact on the cost and the time needed to obtain reliable information, since although it requires a greater initial economic investment than other methods it does not require an extended time of profiles surveys, which is economic. In addition, accurately calculating the DoC allows better adjustments of the depth to which coastal defense structures must be located or the lower limit of the equilibrium profile to obtain the necessary volumes for beach regeneration, thus, avoiding errors that modify the projected beach width.

5. Conclusions

In this paper, a new methodology has been developed to obtain the depth of closure from the transverse distribution of the sediments, which is valid at least for periods of less than 20 years (validation period). This new method has several advantages: i) High precision, because it allows establishing with accuracy the location of the DoC with results close to the average obtained from profile surveys. ii) Simplicity, both in the taking of data and in its interpretation. iii) The observed pattern in the sediments is extended to other areas of study. iv) Period of validity is good, since with a single sediment sampling, the same results are obtained as with 20 years of profile surveys. v) Less sensitivity to anthropic actions (nourishment, construction of breakwaters, etc.) that modify the environment, waves, and morphology, but not the DoC. On the contrary, these changes imply that the methods based on the profile surveys experience greater variation in the results or even cannot yield a value for the DoC, since the cross-shore profiles are morphologically so diverse that they do not coincide, or come close enough to obtain a valid result. While the most important limitation of the method from the sedimentological change is the spatial separation between samples in each transect. This limitation is corrected by tools such as GIS, allowing accurate results with adequate planning in the spatial distribution of sampling and the use of advanced interpolation methods.

The results obtained cannot be more encouraging as they provide a simple method, which can be quickly implemented and applied. Since sediment is the element that interacts with waves, it provides information about changes that occur in the coastal environment, information provided by the median sediment size, D_{50}, and its textural parameters. Moreover, complex zones should be examined with a different approach than the traditional ones, using tools such as GIS, which can analyze the changes in three dimensions (spatial and temporal). Thus, mathematical models can be proposed from this research. These models should be validated and compared with the current methods, incorporating the essence of local samples and environmental conditions.

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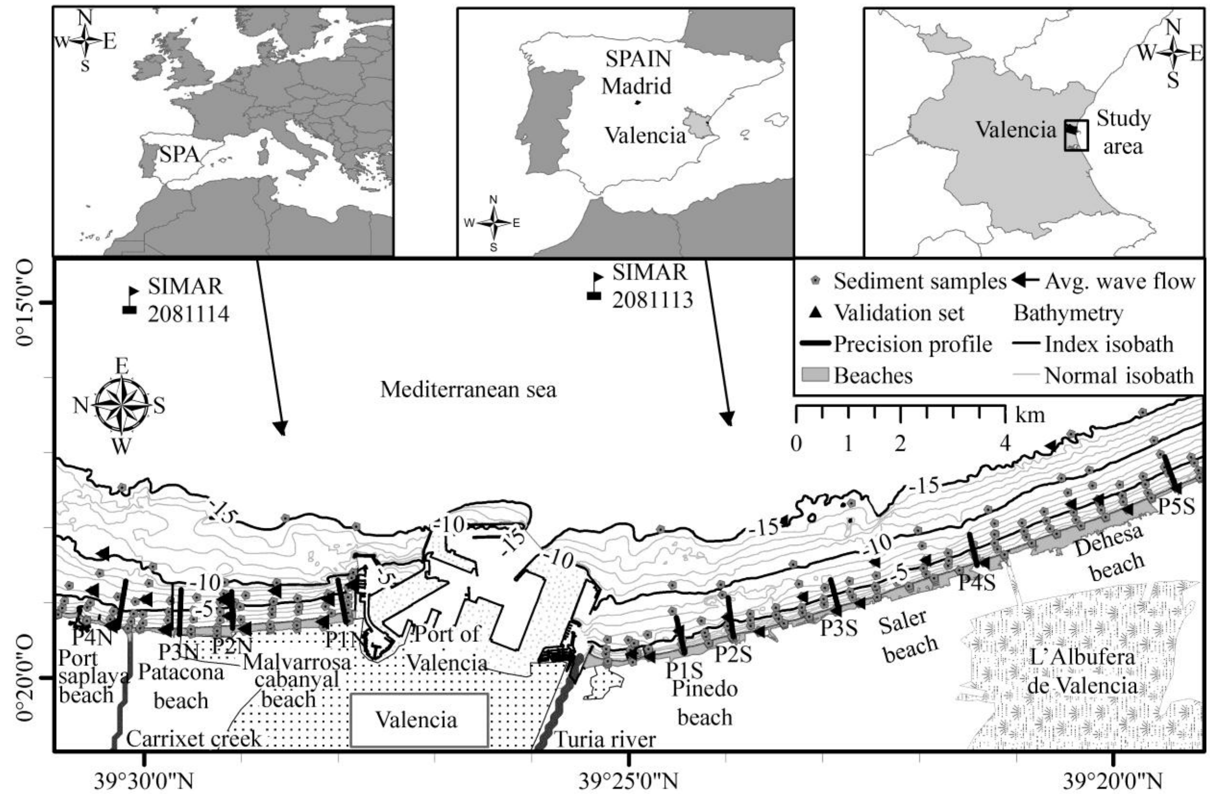


Fig. 1

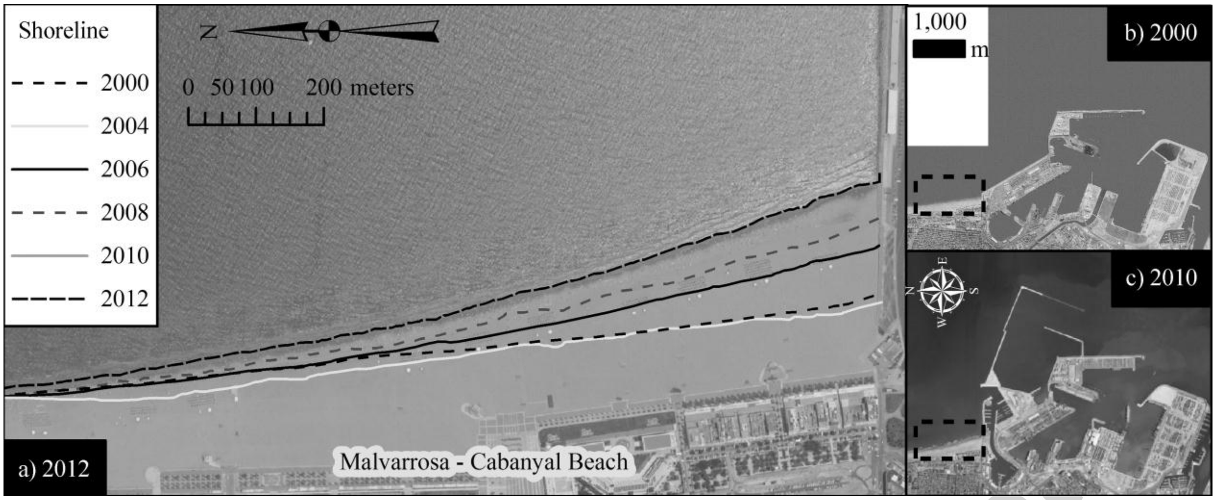

Shoreline
2000
2004
2006
2008
2010
2012
0 50 100 200 meters
Malvarrosa - Cabanyal Beach
a) 2012
1,000 m
b) 2000
c) 2010

Fig. 2

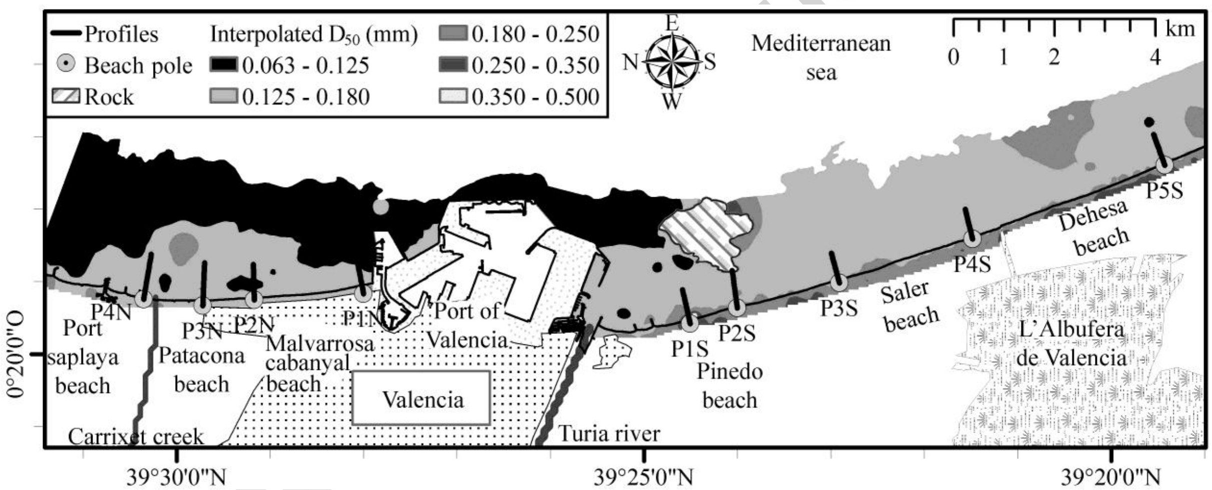

Profiles
Beach pole
Rock
Interpolated D50 (mm)
0.063 - 0.125
0.125 - 0.180
0.180 - 0.250
0.250 - 0.350
0.350 - 0.500
Mediterranean sea
0 1 2 4 km
P4N
P3N
P2N
P1N
Port saplaya beach
Patacona beach
Malvarrosa cabanyal beach
Port of Valencia
Valencia
Carrixet creek
Turia river
P1S
P2S
P3S
P4S
P5S
Pinedo beach
Saler beach
Dehesa beach
L'Albufera de Valencia
0°20'0"O
39°30'0"N
39°25'0"N
39°20'0"N

Fig. 3

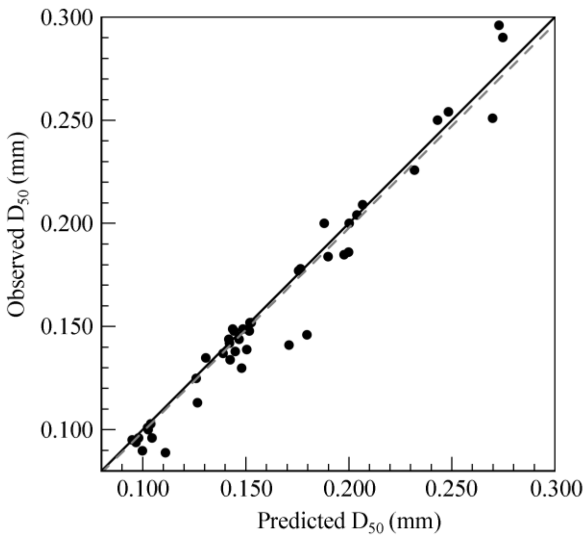
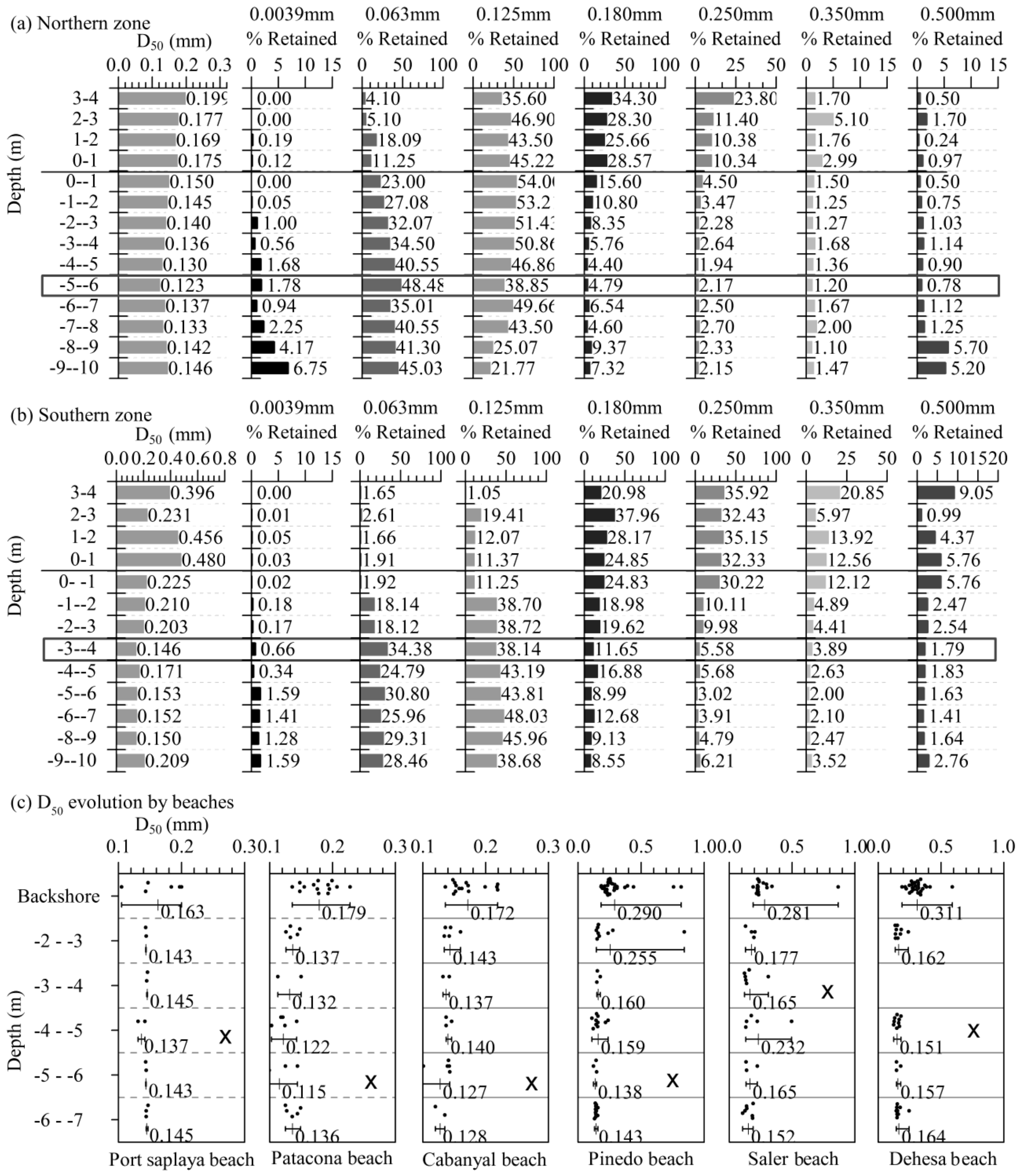
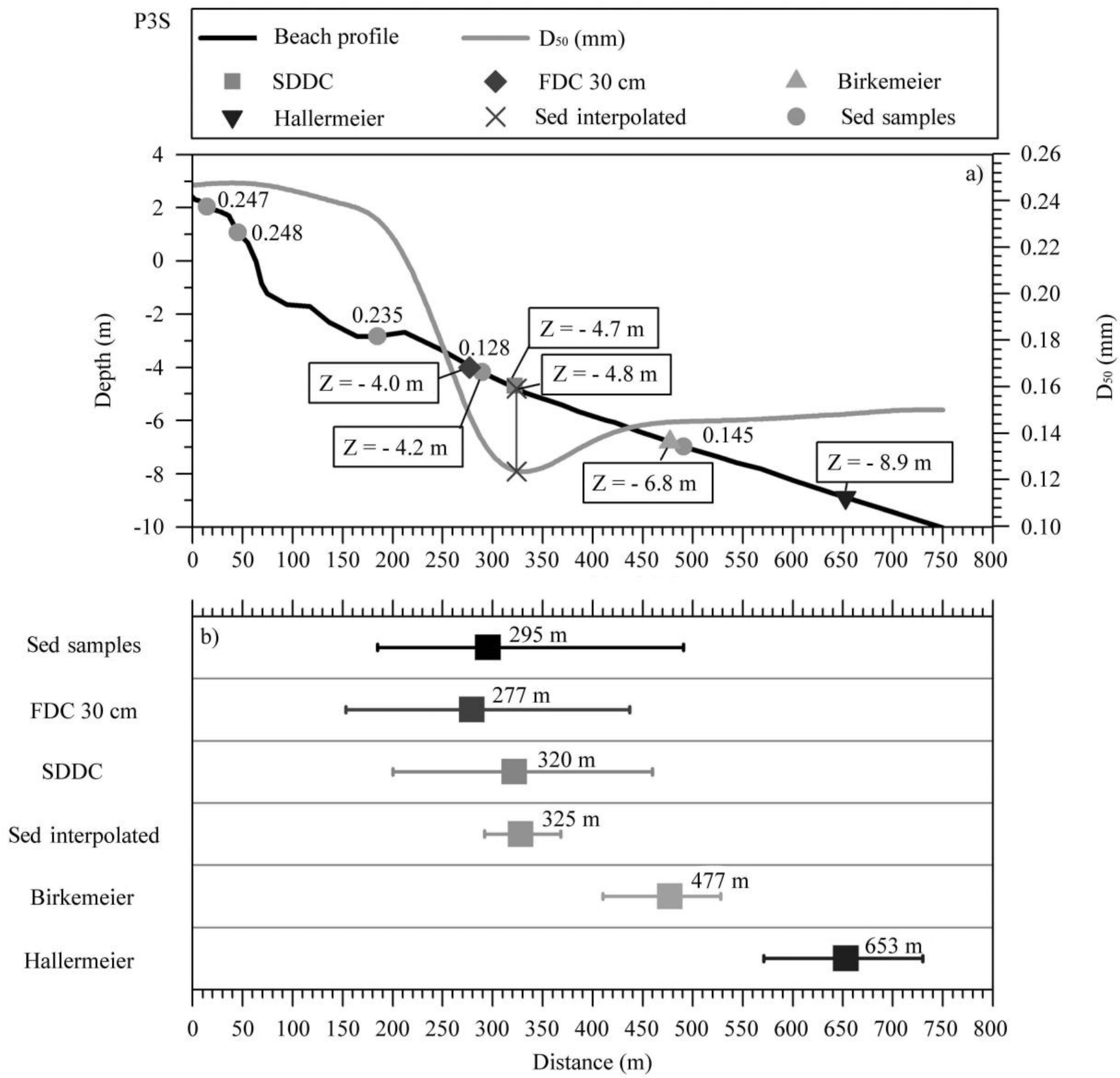

0.300
0.250
0.200
0.150
0.100
Observed D_{50} (mm)
0.100
0.150
0.200
0.250
0.300
Predicted D_{50} (mm)

Fig. 4



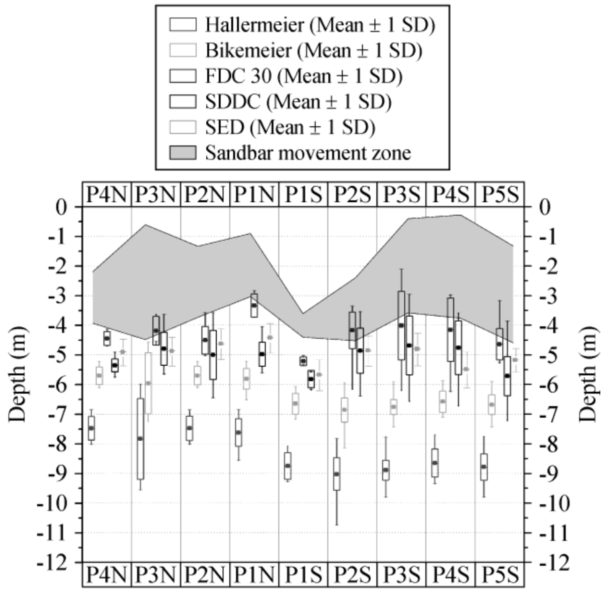
(a) Northern zone
D50 (mm)
0.0039mm % Retained
0.063mm % Retained
0.125mm % Retained
0.180mm % Retained
0.250mm % Retained
0.350mm % Retained
0.500mm % Retained
Depth (m)
3-4 0.199 0.00 4.10 35.60 34.30 23.80 1.70 0.50
2-3 0.177 0.00 5.10 46.90 28.30 11.40 5.10 1.70
1-2 0.169 0.19 18.09 43.50 25.66 10.38 1.76 0.24
0-1 0.175 0.12 11.25 45.22 28.57 10.34 2.99 0.97
0--1 0.150 0.00 23.00 54.00 15.60 4.50 1.50 0.50
-1--2 0.145 0.05 27.08 53.2 10.80 3.47 1.25 0.75
-2--3 0.140 1.00 32.07 51.4 8.35 2.28 1.27 1.03
-3--4 0.136 0.56 34.50 50.86 5.76 2.64 1.68 1.14
-4--5 0.130 1.68 40.55 46.86 4.40 1.94 1.36 0.90
-5--6 0.123 1.78 48.48 38.85 4.79 2.17 1.20 0.78
-6--7 0.137 0.94 35.01 49.66 6.54 2.50 1.67 1.12
-7--8 0.133 2.25 40.55 43.50 4.60 2.70 2.00 1.25
-8--9 0.142 4.17 41.30 25.07 9.37 2.33 1.10 5.70
-9--10 0.146 6.75 45.03 21.77 7.32 2.15 1.47 5.20
(b) Southern zone
D50 (mm)
0.0039mm % Retained
0.063mm % Retained
0.125mm % Retained
0.180mm % Retained
0.250mm % Retained
0.350mm % Retained
0.500mm % Retained
Depth (m)
3-4 0.396 0.00 1.65 1.05 20.98 35.92 20.85 9.05
2-3 0.231 0.01 2.61 19.41 37.96 32.43 5.97 0.99
1-2 0.456 0.05 1.66 12.07 28.17 35.15 13.92 4.37
0-1 0.480 0.03 1.91 11.37 24.85 32.33 12.56 5.76
0- -1 0.225 0.02 1.92 11.25 24.83 30.22 12.12 5.76
-1--2 0.210 0.18 18.14 38.70 18.98 10.11 4.89 2.47
-2--3 0.203 0.17 18.12 38.72 19.62 9.98 4.41 2.54
-3--4 0.146 0.66 34.38 38.14 11.65 5.58 3.89 1.79
-4--5 0.171 0.34 24.79 43.19 16.88 5.68 2.63 1.83
-5--6 0.153 1.59 30.80 43.81 8.99 3.02 2.00 1.63
-6--7 0.152 1.41 25.96 48.03 12.68 3.91 2.10 1.41
-8--9 0.150 1.28 29.31 45.96 9.13 4.79 2.47 1.64
-9--10 0.209 1.59 28.46 38.68 8.55 6.21 3.52 2.76
(c) D50 evolution by beaches
D50 (mm)
Depth (m)
Backshore
-2 - -3
-3 - -4
-4 - -5
-5 - -6
-6 - -7
Port saplaya beach 0.163 0.143 0.145 0.137 0.143 0.145
Patacona beach 0.179 0.137 0.132 0.122 0.115 0.136
Cabanyal beach 0.172 0.143 0.137 0.140 0.127 0.128
Pinedo beach 0.290 0.255 0.160 0.159 0.138 0.143
Saler beach 0.281 0.177 0.165 0.232 0.165 0.152
Dehesa beach 0.311 0.162 0.151 0.157 0.164

Fig. 5



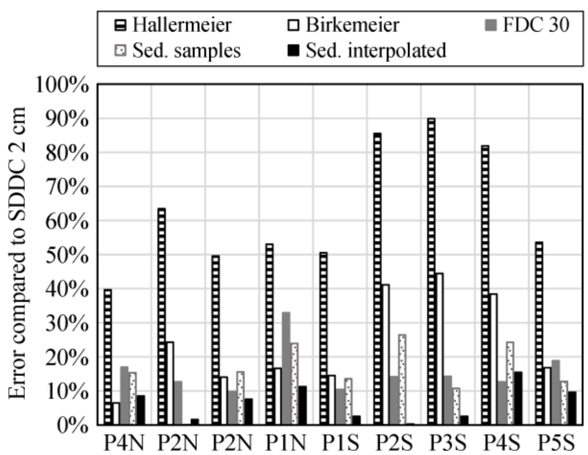
P3S
Beach profile
D50 (mm)
SDDC
FDC 30 cm
Birkemeier
Hallermeier
Sed interpolated
Sed samples
a)
Depth (m)
D50 (mm)
0.247
0.248
0.235
0.128
0.145
Z = - 4.7 m
Z = - 4.8 m
Z = - 4.0 m
Z = - 4.2 m
Z = - 6.8 m
Z = - 8.9 m
b)
Sed samples
295 m
FDC 30 cm
277 m
SDDC
320 m
Sed interpolated
325 m
Birkemeier
477 m
Hallermeier
653 m
Distance (m)

Fig. 6



Hallermeier (Mean ± 1 SD)
Bikemeier (Mean ± 1 SD)
FDC 30 (Mean ± 1 SD)
SDDC (Mean ± 1 SD)
SED (Mean ± 1 SD)
Sandbar movement zone
P4N P3N P2N P1N P1S P2S P3S P4S P5S
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12

Fig. 7



Hallermeier
Birkemeier
FDC 30
Sed. samples
Sed. interpolated
Error compared to SDDC 2 cm
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
P4N P2N P2N P1N P1S P2S P3S P4S P5S

Fig. 8

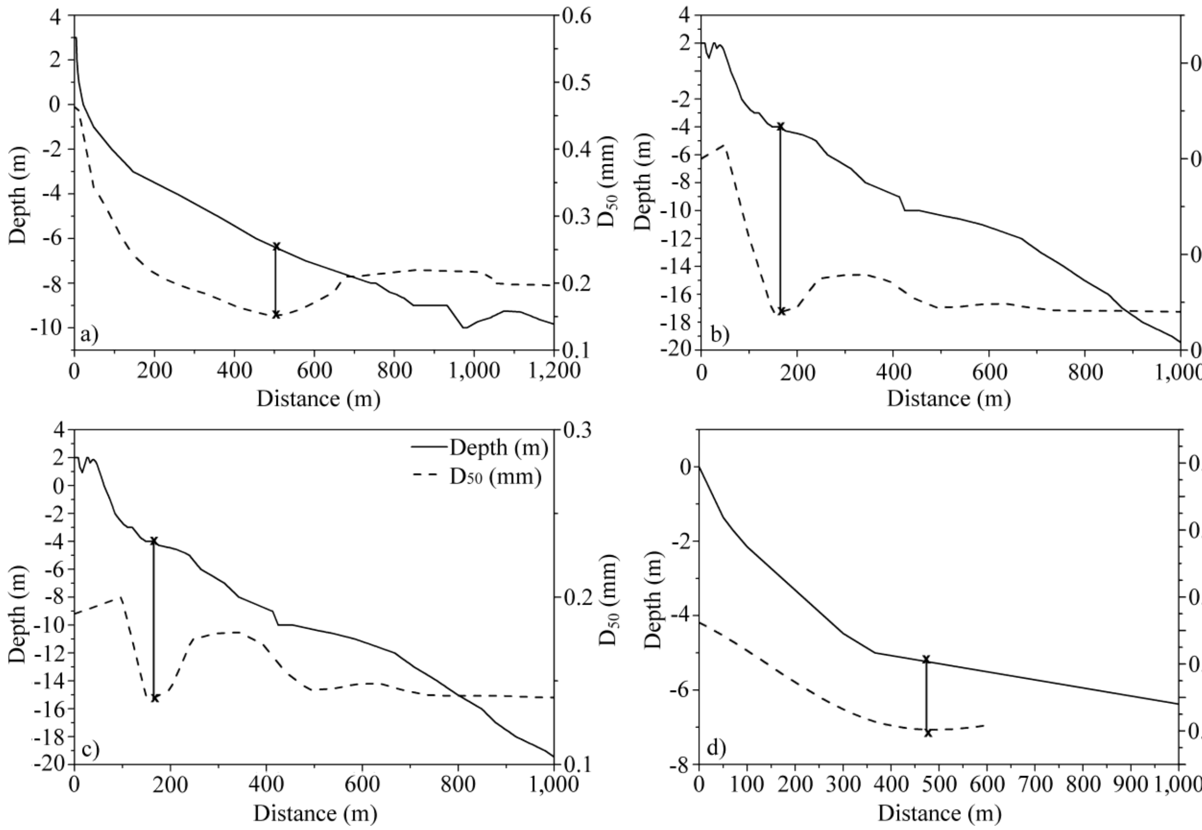


Fig. 9

Table 1. Beach area balance in the area of study (2000-2012), showing accretion (positive) or erosion (negative), and associated wave parameters. $H_{s,12}$ is the wave height surpassed only twelve hours a year. H_{max} is the maximum wave height produced during the study period.

	Area variation (m^2)	2000-2004	2004-2006	2006-2008	2008-2010	2010-2012	2000-2012
	Port Saplaya Beach	-14,109.89	-1,152.85	-1,949.25	-4,561.86	12,030.89	-9,832.96
	Patacona Beach	-33,289.38	-13,332.81	-3,288.57	-24,110.07	41,418.23	-32,602.59
	Malvarrosa-Cabanyal Beach	-17,284.29	43,458.09	13,808.81	-3,635.43	47,281.28	83,628.46
	North zone total	**-64,683.56**	**28,972.44**	**8,570.98**	**-32,397.36**	**100,730.40**	**41,192.91**
	Pinedo Beach	-46,963.50	-2,570.84	8,544.35	-10,572.27	1,693.00	-49,869.27
	El Saler Beach	-34,612.23	-5,590.52	-18,517.00	-10,301.97	-6,281.91	-75,303.64
	La Dehesa Beach	-21,857.16	-1,761.97	-7,662.85	-18,591.26	14,625.71	-35,247.52
	South zone total	**-103,432.90**	**-9,923.34**	**-17,635.50**	**-39,465.50**	**10,036.81**	**-160,420.43**
Swell	ENE and NE direction frequency	0.4527	0.4711	0.4581	0.3654	04132	0.3856
	SSE and SE direction frequency	0.1841	0.2257	0.1871	0.2642	0.3121	0.2454
	NE direction $H_{s,12}$ (m)	5.39	3.16	3.72	5.37	4.4	3.64
	H_{max} (m)	6.6	3.2	4.1	5.7	4.5	6.6

Table 2. Incident directions (degrees from north) on each beach before and after the Valencia Port expansion.

Beach	Profile	Direction range before expansion	Direction range after expansion
Port Saplaya Beach	P4N	43-175	43-161
Patacona Beach	P3N	41-171	41-159
Patacona Beach	P2N	40-164	40-144
Malvarrosa/Cabanyal Beach	P1N	36-124	36-114
Pinedo Beach	P1S	41-159	41-159
Pinedo Beach	P2S	27-158	32-158
El Saler Beach	P3S	16-157	20-157
El Saler Beach	P4S	6-156	12-156
La Dehesa Beach	P5S	(-2)-153	4-153

Table 3. Sample stations by area and division into training and validation sets.

Samples	North zone		South zone		Total
	Beach	Sea	Beach	Sea	
Total	44	72	88	133	337
Training set	37	61	74	113	285
Validation set	7	11	14	20	52

Highlights

159 profile precision surveys during up to 22 years have been studied.

New method based on the changes in cross-shore D_{50} was developed to determinate DoC

Profile survey methods to get the DoC are strongly influenced by morphological changes