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Improvements in the determination of extrapolated shorelines using Elevation Gradient Trend Propagation method.

Ismael Fernández(a), Fernando J. Aguilar(a), José L. Pérez(b), Manuel A. Aguilar(a), Antonio Mozas(b), Andrés López(b)

(a) Dept. of Agricultural Engineering, University of Almería, La Cañada de San Urbano s/n, 04120 Almería, Spain - (faguilar, ismaelf, maguilar)@ual.es
(b) Dept. of Cartographic Engineering, Geodesy and Photogrammetry, University of Jaén, Las Lagunillas s/n, 23071 Jaén, Spain – (jlperez, antmozas, alarenas)@ujaen.es

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Corresponding author:
Ismael Fernández Luque
Tel.: +34 677 629 407
Fax.:
e-mail: ismaelf@ual.es
Address: Escuela Politécnica Superior, Ctra. Sacramento s/n, La Cañada de San Urbano, 04120, Almería, Spain.

Abstract

Shoreline represents a coastal evolution indicator. Hence there is a necessity to develop new methods of shoreline mapping. Nowadays the most widely used method to compute the shoreline position is the so-called Cross Shore Profile method (CSP), which is based on computing a linear regression along different cross-shore profiles to interpolate the corresponding shoreline. However, the Mean Sea Level (MSL) datum makes difficult to get points under the datum elevation due to daily tidal variation, run-ups and waves. Therefore, it is necessary to develop a geometric extrapolation method to estimate the shoreline.

The present work aims to validate a shoreline extraction method using the Elevation Gradient Trend Propagation method (EGTP), which extrapolates the local gradient until the desired datum is reached. This validation was also carried out over the CSP method. Due to the lack of reliable vertical data around the MSL datum, the 0.4 m. contour was used as the synthetic MSL because it was the lowest contour level not presenting noise effects. Both extrapolation methods were applied from different reference elevations: 0.6, 0.8 and 1.0 m. The vertical range needed for CSP adjustment took 0.4 m. above each of the aforementioned reference elevation. Moreover, an additional method was applied to the data consisting of a mixed two steps method: first, the extrapolated Digital Elevation Model (DEM) is computed from EGTP and, second, the final shoreline is extracted by applying CSP on the EGTP extrapolated. The standard deviation of the differences between the supposed shoreline truth and the estimated shoreline over 14 homogeneous sample regions points out the accuracy of the applied method.

The results of this work showed the goodness of EGTP shoreline extraction method compared to CSP one since the corresponding extracted shoreline was significantly more accurate. Moreover, the mixed method turned out to be very close to the original EGTP except in a few areas where it was proved the influence of profile orientation in CSP method. Finally, the influence of the starting extrapolation elevation was also proved, showing that the highest errors clearly matched the highest vertical differences between reference datum and starting extrapolation elevation.

1 Introduction

The coastal strip represents one of the more influential natural systems over economy and the style of living. More than half of the global population lives within 60 km. of the shoreline [1]. Specifically in Mediterranean Sea, coasts are being degraded progressively due to they constitute areas with a high dynamic economic activity that provides high profits from the tourist industry. Therefore, this provokes the need of a big amount of infrastructures [2]. On the other hand, health of coasts is vital to environment. In fact, they are one of the richest and changeable, but also fragile, systems. As a result, degradation and conservation of coast are being studied by international organizations like UNEP/MAP (United Nations Environment Programme, Mediterranean Action Plan) [2]. The high vulnerability and fragility make the development of monitoring techniques essential to understand their morphological processes in order to mitigate the pernicious effects that are carried out over the coasts. One of the most important indicators to understand the coast behavior and evolution is the shoreline, which is defined as the physical interface between land and water [3]. The detailed analysis of shoreline evolution is the basis for modeling of what will happen in future, trying to mitigate the negative effects introduced by human activities. The long-term or medium-term change shoreline rates studies are one of the widest applications in order to extrapolate the results [4], [5] and [6]. The lack of a unique and stable method to extract the shoreline makes difficult a regional-national coastal comparison. In this work, a new approach and its validation are introduced.

The geomatic techniques, such as photogrammetry and remote sensing, have been widely employed in order to extract the shoreline [4] and [8]. Digitalization has been the most usual method, by identifying the visual land-water border over aerial images or orthoimages [4], [9] and [10]. Recently, the set of methods has been increased as a result of the development of new technologies like digital image analysis or ALS (Airborne Laser Scanning). Three groups of indicators to extract a functional shoreline are commonly established [4]: indicators that are visible for human eye –identification of high water line–, tidal datum by DEM intersection –digital elevation model– and a specific tidal elevation and linear features extracted by image or DEM analysis [11], [12] and [13]. The use of DEMs in order to extract the shoreline has been increased by ALS techniques [15] development, which has allowed the acquisition of highly dense and accurate DEMs [15]. Thus, shoreline can be extracted from some approaches like contouring [16] or profile regression to intersect a DEM with a tidal datum [17] and [18] –called Cross Shore Profile (CSP)–. ALS techniques enable other kind of applications, especially when bathymetric LIDAR is applied [14], [15] and [16]. Other approaches to prepare the DEM can be required, e.g. elimination of water returns [20] and the additional processing has to be standardized.

The use of tidal indicators has been extended [4] since are a long-period average elevation instead of instantaneous tidal conditions. Moreover, they are official elevation datum such as MHW (Mean High Water) in the USA [21] or MSL (Mean Sea Level) in Spain. The second one has been chosen to carry out this work. The difficulty of extract the 0 m level contour –official MSL in Spain– by ALS data in a microtidal environment and the noisy data caused by waves run-up have required a DEM extrapolation from a higher elevation in order to extract the shoreline [5]. This work applies the extrapolation method in a higher datum to be able to validate the approach by comparing with the "ground truth" DEM. Additionally, the most common method, that is CSP, has been also applied in order to compare both extrapolation methods for extracting the shoreline.

2 Methodology

In order to validate the proposed method and the CSP one, ALS data over a Mediterranean area in the Almeria province in Spain was used. These data were properly processed to their registration in ETRS89 system. The orthometric vertical datum was chosen based in Spanish official network REDNAP [22]. The area covers around 12 km long and 1 km cross coastline. The data were collected with a density of approximately 1.6 points/m^2 comprising four overlapping strips. As a result, a one meter resolution DEM was extracted with a vertical accuracy of 0.084 m computed on a set of 33 DGPS check points.

The aforementioned DEM was used to extract the shoreline through geometric methods. One of them was the Cross Shore Profile method based on linear regression over the profile point data [17]. On the other hand, a new method proposed by the authors, named Elevation Gradient Trend Propagation (EGTP), was applied. It is based on the extrapolation of the local gradient in the foreshore in order to reach the shoreline position [5].

2.1 Shoreline extraction methods.

2.1.1 Cross Shore Profile method.

CSP method has been widely used to extract the shoreline by linear interpolation over a set of elevation profiles which are previously extracted from a DEM [16], [17], [18]. The behavior of this method in the extrapolation case will be tested. In a previous work [5] has been deduced the theoretical accuracy of CSP method:

$$\sigma_{XY\ TOTAL} = \sqrt{\sigma^2_{XY\ DEM} + \sigma^2_{XY\ regressi\ on}}; \qquad (1)$$

$$\sigma^2_{XY\ DEM} = \sigma^2_Z / \hat{a}^2; \qquad (2)$$

$$\sigma^2_{XY\ regression} = \frac{\sigma^2_a \left(m - \hat{b}\right)^2}{\hat{a}^4} + \frac{\sigma^2_b}{\hat{a}^2} + 2\sigma^2_{ab}\frac{\left(d - \hat{b}\right)}{\hat{a}^3}; \qquad (3)$$

where $\sigma_{XY\ DEM}$ represents horizontal accuracy due to vertical uncertainty, $\sigma_{XY\ regressi\ on}$ is the estimated accuracy due to the least squares adjustment –general theory of errors propagation [24]–; σ_Z is the DEM vertical accuracy derived from check points. $\hat{a}$ and $\hat{b}$ represent the slope and intercept respectively and their corresponding variance values are given by σ^2_a and σ^2_b, obtained from the variance-covariance matrix as a result of a typical least squares adjustment (regression line). Finally, d is the datum in which the shoreline is defined, that is, the MSL or orthometric elevation 0 m in this particular case.

Vertical range (m)	median r^2	median σ_{XY} (m)	data points σ_{XY} <5 m.
A (0.8-0.2)	0.853	1.166	1952 (76%)
B (0.8-0.4)	**0.964**	**0.982**	**2095 (82%)**
C (1.0-0.2)	0.860	1.216	2065 (81%)
D (1.0-0.4)	**0.960**	**0.966**	**2074 (81%)**
E (2.5-0.2)	0.716	1.460	1303 (51%)
F (todos)	0.736	3.989	1109 (43%)

Table 1. ***r^2 of CSP regression adjustment and estimated accuracy for several data ranges.***

The profiles used in extracting the shoreline were coincident with the profiles or transects from which the shorelines were compared. Therefore an interpolation process between profiles was not required.

It should be noted that the data range used to carry out the adjustment is significant. In usual applications, it is recommended to choose a range of 0.50 m above and below the desired datum (1 m altogether, e.g. [17]). A simple simulation (tab. 1) carried out over the dataset to extract the MSL shoreline can show that the range of data should be quite lesser since the best results are from the range of 0.4 to 0.8 m, that is a range of only 0.40 m. This short range implies a less number of points for each profile and highlights the presence of noisy data under the 0.40 m. contour.

2.1.2 Elevation Gradient Trend Propagation method.

EGTP method is introduced against CSP as an approach based on the extrapolation of the local elevation gradient from a foreshore specific elevation until the desired datum is reached. As a resume of [5], the stages of the approach are the following:

1) The DEM must be cleaned up for LiDAR sea-points, but at the same time assuring the absence of noise due to the presence of waves and run-ups. So it is necessary to select an appropriate reference elevation (i.e. the lowest possible height but avoiding the effects of waves and run-ups). The final result should be a non-noisy DEM.

2) Gradient calculation in both directions X and Y by means of a gradient filter applied over the DEM. Sobel filter was used [25] since it preponderates the nearest cells to the central one within a 3x3 window.

$$G_x \cong DEM \otimes \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}; \qquad G_y \cong DEM \otimes \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}; \qquad (4)$$

where G_x, G_y are, respectively, the gradient in X and Y direction applied over the cleaned-up DEM. ⊗ represents convolution operator. The variance of the gradient is expressed in eq. 5.

$$\sigma^2_{SDEGx} = \sigma^2_{SDEGy} = \sum_{i=1}^{6} \left(\frac{1}{4 \cdot 2 \cdot r}\right)^2 \sigma^2_{Zi} = \frac{3}{16 \cdot r^2} \sigma^2_Z; \qquad (5)$$

where σ^2_{SDEGx} and σ^2_{SDEGy} are the variances of the gradient computed along X and Y directions, r is the DEM spatial resolution and σ_Z is the DEM accuracy.

3) The previously estimated gradient is extrapolated, in both X and Y directions, towards the adjacent empty cells. The inverse distance weighted was used in order to extrapolate the gradient. This operation will cause an uncertainty over the extrapolated gradient (eq. 6).

$$\sigma^2_{extr\,G_x} = \frac{1}{\left(\sum_{i=1}^{n} {}^{1}/_{di}\right)^2}\left(\frac{1}{{d_1}^2}\sigma^2_{Gx1} + \cdots + \frac{1}{{d_n}^2}\sigma^2_{Gxn}\right);$$
$$\sigma^2_{extrG\,y} = \frac{1}{\left(\sum_{i=1}^{n} {}^{1}/_{di}\right)^2}\left(\frac{1}{{d_1}^2}\sigma^2_{Gy1} + \cdots + \frac{1}{{d_n}^2}\sigma^2_{Gyn}\right); \qquad (6)$$

where $\sigma^2_{extr\,G_x}$ is the variance caused by extrapolation, di is each horizontal distance between the central cell and the others and σ^2_{Gxi}, σ^2_{Gyi} is the gradient for the adjacent cells.

4) The Z coordinate is estimated by the elevation of adjacent cells and their appropriate gradients. This step makes the process iterative, estimating only the positions for which the gradient is negative –the aim is to continuously reduce the elevation–.

5) The iterative extrapolation process is locally stopped in those cells where Z coordinate is under the desired shoreline datum.

6) The last step is the shoreline extraction from a grid DEM, that is mapping the estimated shoreline through those points presenting elevations slightly above or below the desired datum. The variance or uncertainty originated from this linear interpolation is given by eq. 7.

$$\sigma^2_m = \frac{1}{m^2}\left(G^2_x\,\sigma^2_{G_x} + G^2_y\,\sigma^2_{G_y}\right);$$
$$\sigma^2_{xy} = \frac{1}{m^2}\left(\frac{(Z_i - slope)^2}{4}\,\sigma^2_m + \sigma^2_{Zi}\right); \qquad (7)$$

Being m the slope corresponding to the current cell –or slope–, Z_i is the last positive elevation and σ^2_{xy} is the variance of horizontal position.

7) Finally, an additional interpolation is carried out in order to calculate the final shoreline positions within each reference transect. This process is carried out by the intersection between the estimated shoreline and every transect. The variance of these interpolated points can be expressed as $1/3(\sigma^2_i + \sigma^2_j)$ [26], being both i and j shoreline points between which the point within the transect is interpolated.

2.1.3 Mixed extrapolation method.

A third approach tested in this work was the use of both aforementioned methods in order to obtain the shoreline following two steps: i) The

DEM is extrapoled by means of the EGTP method without the transect intersection extraction. ii) The final shoreline is extracted by applying CSP over the extrapoled DEM.

It is important to notice that the CSP method will be only applied over the DEM extrapolated area.

This approach should be able to identify what additional factors may affect the CSP method accuracy.

2.2 Validation of extrapolation methods.

The high performance of established methods like CSP to extract shorelines by interpolating data is well-known. However, the DEMs extrapolation is a process whose performance must be tested. Linear regression by least squares adjustment has been proved as a robust method within the known data limits [27]. But it is not necessarily true for data outside the sample area. Therefore, a linear regression process is expected to be a suitable method to interpolate the datum position within a profile, but not in the case of extrapolation since the beach profile may be unpredictably changeable in the data range close to land-water interface.

A validation method has been carried out in order to check the accuracy of the tested methods to extract the shoreline by extrapolation.. It is assumed the 0.4 m contour as the reference datum since is the lowest elevation maintaining a low level of noisy data.

The accuracy of the extrapolation method is given by the standard deviation of the differences between the ground truth –contour of 0.4 m from DEM– and the shoreline extracted by extrapolation. Those differences will be referenced to the transects system. Moreover, the reference elevation is defined as the least height from which the DEM is extrapolated and the extrapolated amplitude is the difference between the reference elevation and the desired datum. The difference between the reference elevation and the highest height used in profile adjustment, in the CSP method, is the data range.

In order to measure the accuracy of the methods and test the effect of the extrapolated amplitude, three reference elevations have been employed: 0.6, 0.8 and 1.0 m, which have meant the amplitudes of 0.2, 0.4 and 0.6 m, respectively. A data range of 0.4 m has been used in all CSP cases.

With the purpose of deriving a suitable sample to evaluate the performance of the methods, 14 subareas within study area have been extracted. Those samples represent places that are either constant morphology beaches or more complex shapes like berms. The samples size was variable but it was tried to maintain a minimum number of transects –observations– near to 100, in order to have enough population for the analysis. The transects spacing was set up 5 m.

2.2.1 Shoreline comparation

The observed variable is not the shoreline position, but the differences between the estimated shoreline and the ground truth along each transect. Thus, some aggregated results such as mean, mean of absolute value and standard deviation of differences could be extracted for each sample area.

The widely known 3 sigma rule [28] was applied to remove anomalous values or outliers in differences and shoreline accuracy. That is an essential step to make suitable the reading of the results. Besides, the number of anomalous observations could be significant to report about the level of noise produced by every method.

2.2.2 Systematic error and accuracy.

As the extrapolated gradient –estimated by EGTP or CSP method– could not be the true gradient, an unknown error could arise. This systematic difference could become into an offset or bias error to be taken into account.

According to fig. 1, the values of extrapolated and true gradients are given by the following expression:

$$G_{ext} = {}^{D_Z}\!/_{D_{X_{ext}}} \; ; \; G_{trut\,h} = {}^{D_Z}\!/_{D_{X_{trut\,h}}} \; ; \qquad (8)$$

From eq. 8 can be extracted that the differences between both D_X corresponds to:

$$E_d = D_{X_{ext}} - D_{X_{trut\,h}} = D_Z \left({}^{1}\!/_{G_{ext}} - {}^{1}\!/_{G_{trut\,h}} \right) \; ; \qquad (9)$$

So the extrapolated shoreline could be estimated by:

$$D_{X_{ext}} = D_Z \left({}^{1}\!/_{G_{ext}} - {}^{1}\!/_{G_{trut\,h}} \right) + D_{X_{trut\,h}} ; \qquad (10)$$

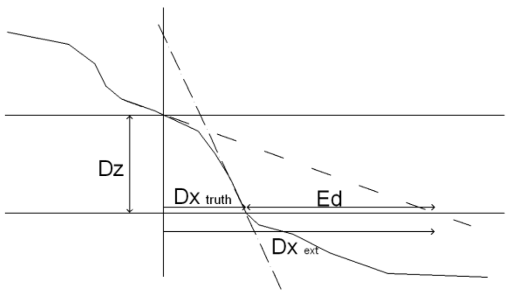

Figure 1. Systematic error or offset.

Note that the mentioned offset between the true shoreline and the extrapolated shoreline depends on the extrapolated amplitude (D_Z), as well as the difference between the inverse gradients (eq. 9).

In order to perform a simulation of the estimated shoreline accuracy regarding to the extrapolated amplitude one can follow the variance propagation theory over eq. 9 and 10:

$$\sigma_{\Delta_D}^2 = \frac{D_Z^2}{G_{Ext}^4} \sigma_{G_{Ext}}^2 + \frac{D_Z^2}{G_{trut\,h}^4} \sigma_{G_{trut\,h}}^2 ; \qquad (11)$$

$$\sigma^2_{D_{X_{Ext}}} = \sigma^2_{\Delta_D} + \sigma^2_{D_{X_{trut\,h}}} \; ; \qquad (12)$$

being $\sigma^2_{\Delta_D}$ the variance of the difference between the true shoreline and the estimated one.

In fig. 2 it is shown the influence of the differences between real gradient and extrapolated one, as well as the influence of the extrapolated amplitude over the performed offset (eq. 9). The sample 10 has a mean extrapolated gradient of 0.105 and the true gradients used were from 0.050 to 0.250, while the gradient in sample 3 was 0.233 and the true gradients used were from 0.100 to 0.300.

The influence of error estimation in gradient is much bigger in slow-sloped areas, e.g. the area 10, than in high-sloped areas (e.g. the area 3). Moreover, both cases show the influence of extrapolated amplitude. As a result, the bigger the amplitude is, the bigger the shoreline estimation error.

In order to estimate the shoreline accuracy, eq. 11 and 12 have been used, assuming the same value in true gradient accuracy and estimated gradient accuracy. The horizontal accuracy of the real shoreline is the vertical DEM accuracy –expressed as standard deviation– divided by simulated true gradient.

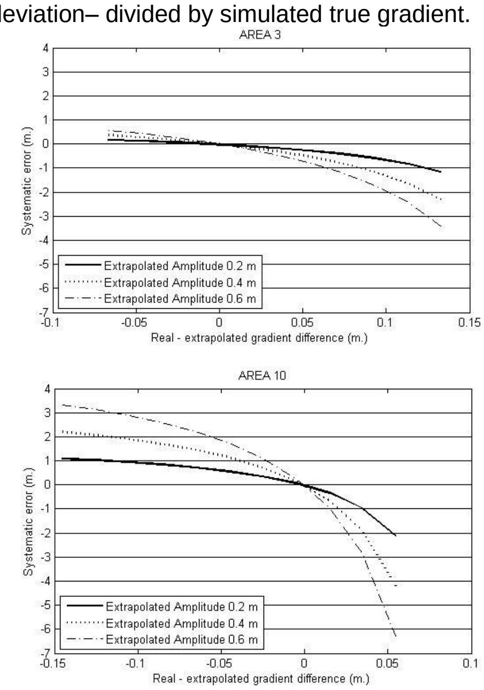

Figure 2. Systematic error (Y axis) vs. true gradient difference (X axis) in areas 3 and 10.

Fig. 3 points out to the slope as the variable which has the most important influence over shoreline accuracy. In addition, it is noted the influence of the estimated gradient in area 10, in which the accuracy variation is about 2 m, being only about 0.50 m in area 3. Thus, if the estimated gradients were the same than the real ones, there were no systematic errors but the shoreline estimated accuracy would mainly depend on both extrapolation amplitude and estimated slope.

The previous results could be quantitatively questionable since the mathematical models could result too simples. However, an evident relation between the estimated shoreline offset and the theoretical difference between the real gradient and the extrapolated one has been highlighted qualitatively. That could be called as 'information loss' [29] since an extrapolation is being applied over previous information, without an exact knowledge about the DEM behavior in that area.

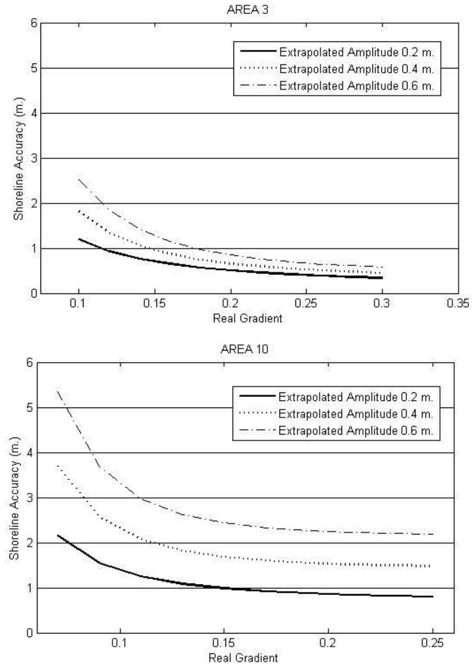

Figure 3. Estimated acuracy (Y axis) vs. Real gradient (X axis) in m. Areas 10 and 3.

3 Results and discussion

The results related to the comparisons between estimated shorelines and the well-known contour of 0.4 m is introduced in the next subsections. The main result, or observed variable, is the standard deviation of the differences. In addition, the mean of those differences represents the systematic offset, which could also be a relevant result. The number of outliers is also a parameter under analysis.

3.1 Experiment design

Every comparison carried out for each elevation reference and within each area is shown in tab. 2. In all, 126 observations were obtained.

Method	Reference elevation (m.)	Data range (m.)	Alias
EGTP	0.6	-	EGTP06
EGTP	0.8	-	EGTP08
EGTP	1.0	-	EGTP10
CSP	0.6	1.0 – 0.6	CSP06
CSP	0.8	1.2 – 0.8	CSP08

CSP	1.0	1.4 – 1.0	CSP10
CSP-EGTP	0.6	0.7 – 0.0	CSP_EGTP06
CSP-EGTP	0.8	0.9 – 0.0	CSP_EGTP08
CSP-EGTP	1.0	1.1 – 0.0	CSP_EGTP10

Table 2. Resume of experiment carried out for each one of the 14 sample areas.

3.2 Results depending on the observed area.

The results are changeable depending on the sample data area. The qualitative study has been subdivided in several parts depending on the evaluated variable.

3.2.1 Rocky and high-sloped areas

Areas 1 and 2, in the North, and 14, in the South, have been included in this set of samples. These areas correspond with rocky shores with some beaches within them.

Generally, the standard deviation values indicate a low divergence between estimated shorelines and the ground truth. The best results are reached by EGTP method (0.5 – 2.0 m standard deviation). Differences between EGTP and mixed method are noted only in area 1 (fig. 4a and b) due to the transects orientation does not match the maximum slope orientation.

CSP method clearly offers the worst accuracy results (1.0 – 4.0 m. standard deviation). This fact is due to changes in gradient trend along the data range used in extrapolation regression. On the other hand, the local gradient used in EGTP is more similar to the real one.

As a result, EGTP method seems to be more suitable in this type of shores because the applied gradient will be close to the real one since the variability in rocky areas data can substantially affect the CSP adjustment.

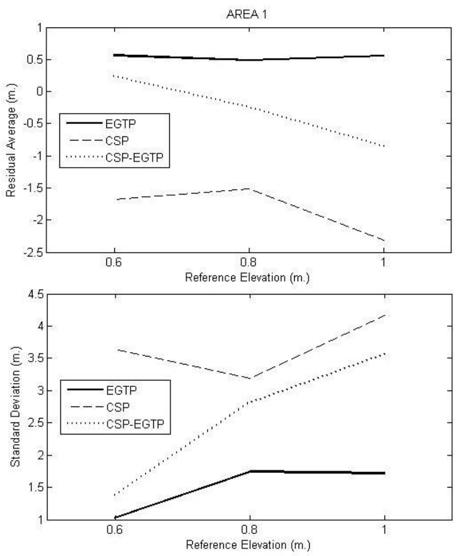

Figure 4. a- Standard Deviation (S.D.) and b- Residual Average (R.A.) corresponding to area 1.

3.2.2 Sandy and moderate-sloped beaches areas

The areas included were the 3 and 13 ones. The sample 3 is currently under an important erosive process which is currently unaffected of artificial regeneration, in contrast to other areas in the study site. The sample 13 is located at the South and its morphology is characterized by a soft beach and a strong slope in the water-sand interaction face, which could indicate a high erosive process.

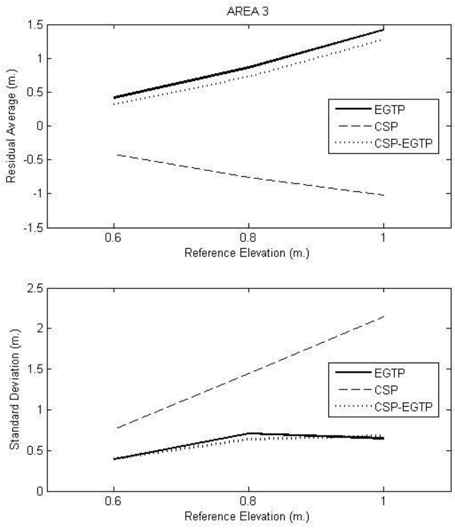

Figure 5. a- Standard Deviation (S.D.) and b- Residual Average (R.A.) corresponding to area 3.

The EGTP and mixed method results are very similar but not for the CSP case, which shows a considerably higher standard deviation (fig. 5a). Sample 3 yields better results in accuracy (0.3 – 2.0 m.) than sample 13 (0.5-5-0 m.) since area 13 presented a more variable slope. Moreover, the transects orientation did not influence in EGTP-mixed method differences.

The finer results in CSP, especially for sample 3, are due to the lack of significant slope changes within the diverse adjusted range of data. Note that in uniform slope beaches, EGTP accuracy is similar from every reference elevation (fig. 5a).

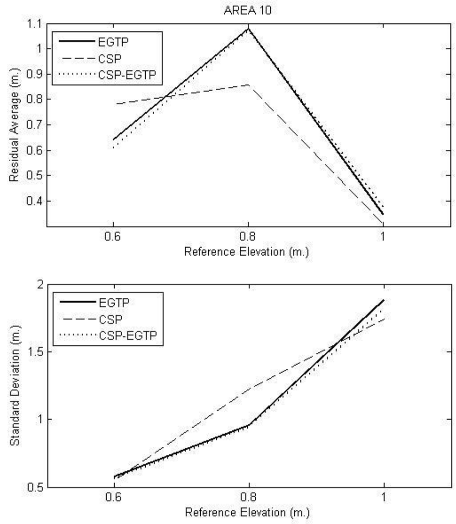

Figure 6. a- Standard Deviation (S.D.) and b- Residual Average (R.A.) corresponding to area 10.

3.2.3 Sandy and slow-sloped beaches areas

Samples 10 and 4 have been included in this samples typology in which the beach slope is approximately constant in the adjustment data range.

The similarity between CSP and iterative extrapolation methods, both in standard deviation and residual average (offset), is shown in fig. 6a and 6b.

Every applied method can be deemed as highly accurate in this case (standard deviation below 2m. in every case). Moreover, the offset value results in barely 1 m.

3.2.4 Non-classified areas

Generally, the shore areas included in this study site present typical berm morphology in the sandy beaches areas. When the adjusted data are computed over these areas, the estimated gradient becomes quite erroneous, especially in the case of CSP method application.

As explained above, EGTP method extrapolates the gradient towards negative values cells. Because of that, areas showing peak positive values affect seriously the extrapolated shoreline, which can be deduced from the low number of effective transects.

The biggest differences between CSP and EGTP methods are shown in this sort of samples. As a general rule, CSP method yields an irregular behavior since the differences respect to the ground truth are not fine enough. The standard deviation results are much bigger than those supplied by EGTP method.

A special mention is deserved by sample 11, which comprises around 600 m long coastline and has a high variable morphology and certain data noise due to run-ups. The shorelines yielded by CSP method within every range data results inadmissible in spite of applying the outliers removal based on 3-sigma rule (standard deviation 30-300 m.).

3.3 Results by method

3.3.1 EGTP results.

Standard deviation results show the high accuracy of EGTP method and how it is affected by the reference elevation (fig. 7). At reference elevation of 0.6 m., the accuracy is over 1 m. and quite stable. At 0.8 m. the results are between 1 and 2 m. Note that in 1.0 m. reference level, the areas number 8 and 12 have been removed since the extrapolation turned out to be erroneous (positive local gradient). It is shown that the CSP values are similar until area 5, whereas from sample 6 the results are clearly distinguishable. The offset value clearly growths with the reference elevation.

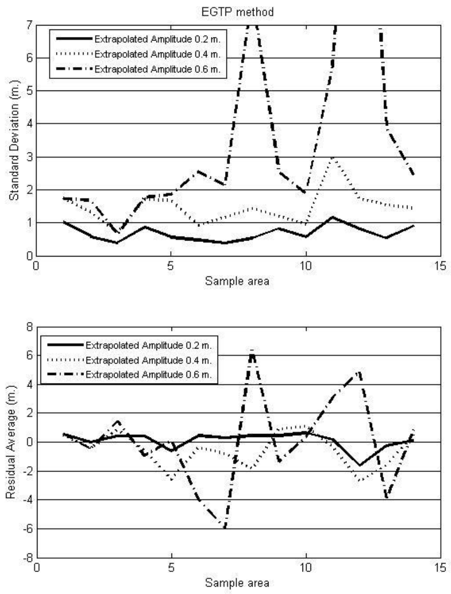

Figure 7. a- Standard deviation y b- Residual average of the EGTP method

According to the results, it can be concluded that the EGTP accuracy depends on the extrapolated amplitude. It was shown that the results agree properly in nearest distances (0.2 m) whereas the deviations are greater for farther distances (0.6 m) depending on the discrepancy between the modeled morphology and the true one. The offset values proved that the gradient varies depending on the selected reference elevation. Thus, it is proved that the best reference elevation should be the nearest as possible to the desired datum, in order to minimize the difference between the true gradient and the extrapolated one.

3.3.2 CSP results

As it is shown in fig. 8a and 8b, the best accuracy is yielded by CSP for the lowest reference elevation (0.6 m) with a general standard deviation of 2 m. It could be explained because the foreshore situation is within the data range adjustment (0.6 – 1.0 m) approximately. In fact, that result is proved in the other reference elevations, where the berm areas looked like different from the other ones. This behavior is also stepped up by the offset results.

Therefore, the reference elevation has been underlined as the main parameter for the CSP method application since the beach areas have a significant variation in those elevation ranges.

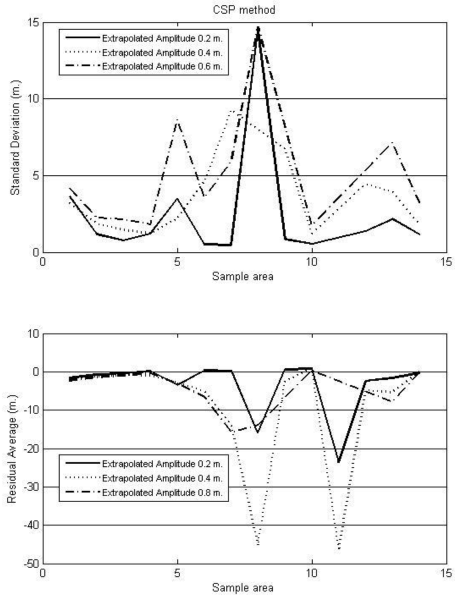

Figure 8. . a- Standard deviation y b- Residual average of the CSP method

3.3.3 CSP-EGTP mixed method results

The results for mixed method are similar to the EGTP ones, excluding the sample 8 for the reference 1.0 m, where is found an atypical value (too high standard deviation). A higher level of offset is detected for the reference elevation of 1.0 m which will be examined in the section 3.4.

3.4 Results by reference elevation

A better understanding about the behavior of every method can be achieved examining the accuracy results regarding the reference elevation. The results of standard deviations in each reference elevation are shown through fig. 9a, b and c.

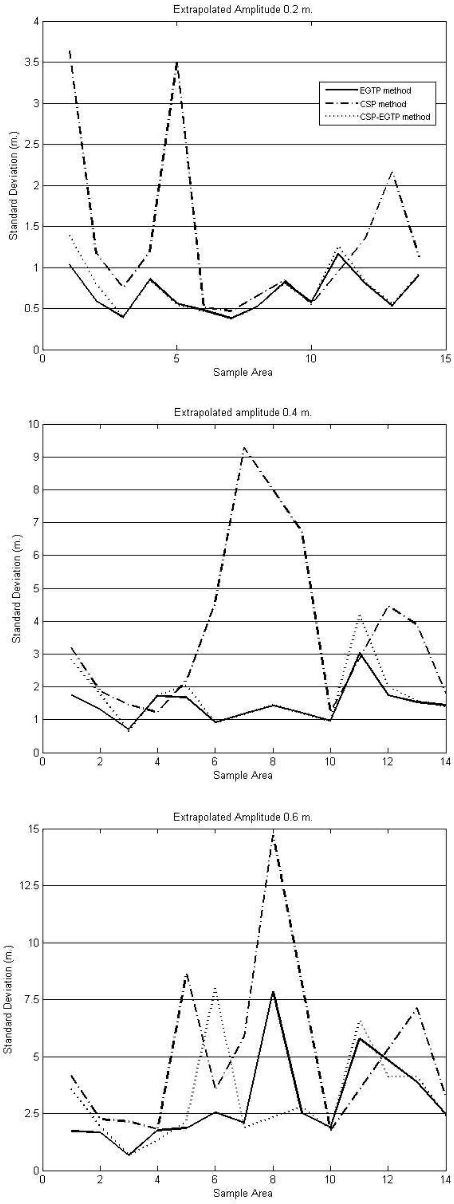

Figure 9. Accuracy (standard deviation) for every extrapolated amplitude.

According to the results depicted in the figures, the EGTP method has proved to be the more suitable in every reference elevation. On the other hand, CPS seems to be much more dependent on the used data range since the results are, generally, less accurate than EGTP. However, it could be noted that the results are still appropriate for the 0.6 m reference because they are not been affected by the berm effects. On the contrary, the results became worse when higher reference levels were used, especially in berm areas. Finally, the results are quite similar for EGTP and mixed method comparison, excepting for samples 1 and 6 where mixed method presented less accuracy mainly due to the orientation of transects.

4 Conclusions

The previous sections have proved the satisfactory results yielded by the local gradient extrapolation methods in order to estimate the shoreline where the interpolation methods cannot be used. Thus, the accuracy results depend mainly on the extrapolated amplitude. The higher the amplitude, the higher the standard deviation is found. There have been some areas in which the method was not suitable since the local gradient was found positive for the higher tested reference elevation of 1 m.

The CSP method was found much more dependent on the terrain morphology (e.g. berms) and reference elevation. The differences between the true gradient and the estimated one are much more obvious where a sharp variation of local gradient occurs. While the application from reference elevation of 0.6 m. turned out to be similar to the EGTP method, for upper reference elevations the berm areas appear strongly distinguishable since they yield a higher standard deviation.

The third method has been the mixed method or CSP-EGTP, which offers very similar results to the original EGTP, excepting for some areas where the transects orientation and the buffer size seem to play an important role. Anyway, it is out of the scope of this work.

It should be taken into account that the used datum was a synthetic one (0.40 m.), since the desired datum is the MSL (0 m.). This fact implies that the errors found in this work related to the case of CSP applications could change when a 0 m. reference datum was used, since the berm effect has been proved to start from a certain elevation (0.8 m. approximately). Therefore, meanwhile the employed data range was below the berm, results in both methods could be more similar.

On the other hand, an extrapolation method instead of an interpolation one leads to commit a general bias as it has been indicated by the offset or systematic error results. As a consequence, data capture –ALS in this case– must be done in order to be able to apply an interpolation method, or when the extrapolated amplitude is minimum and the differences between the true gradient and the estimated one are also minimum. The usage of extrapolation method could be advisable in microtidal shores as Mediterranean ones, especially when the more suitable datum is the 0 m. level.

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