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A New Approach for the Study of the Coast Indentation Index

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ABSTRACT

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The indentation index, which is the ratio between the real length of a coast and its Euclidean length, is a parameter applied to characterize rock coasts and to study their evolution. Rather than subjectively selecting two or more sectors of a rock coast, the method proposed in this paper considers analyzing the indentation index on the same coastline previously split into several adjacent tracts with equal Euclidean length. By digitizing the coastline in a GIS environment, it becomes possible to test several Euclidean length values on the same coastline, obtaining a different spatial variability of the indentation index with each trial. The best length values that maximize the spatial variability of the indentation index are those that determine an indentation index pattern characterized by high variance and low spatial autocorrelation. The spatial distribution of the indentation index can eventually be analyzed considering known littoral forces acting on the studied coast. When more than one Euclidean length value is found to maximize the variability of indentation index within the same coast, it is likely that there are one or more littoral forces acting or interacting differently at different scales.

ADDITIONAL INDEX WORDS: *Rock coast, indentation index, littoral forces, geostatistics, Liguria, Italy.*

INTRODUCTION

Although rock coasts cover 80% of the world coast length (Emery and Kuhn, 1980), depositional and anthropogenic coasts have traditionally represented the main topics of scientific coastal publications. Among the exceptions are studies focused on the stability of coastal cliffs (Bird, 1976; Davies, 1972; King, 1972; Zenkovich, 1967) as well as those focused on coastal platforms (Sunamura, 1982; Trenhaile, 1987). More recently, the growing interest in coasts has focused on rock coast dynamics, morphometry, and erosion. In particular, different researchers have pointed out how (i) weathering processes and related rock weakening, (ii) inheritance of relict landforms related to times with a sea level similar to today's, and (iii) wave energy all represent important agents and controlling factors in the development of rocky coastal landforms (Blanco Chao *et al.,* 2003, 2007; Dickson, Kennedy, and Woodroffe, 2004; Moura *et al.,* 2006; Rundgren, 1958; Stephenson and Kirk, 2000a, 2000b; Trenhaile, 2000).

In general, rock coast morphologies can be considered as effects of the interactions between several processes known as littoral forces (Guilcher, 1954) whose origins can be both endogenetic (tectonics, seismicity, and volcanism) and exogenetic (atmospheric, hydrospheric, biospheric, and cryospheric processes). An early attempt (Trenhaile, 1987) of directly linking coastal morphology with climate, lithology, and structure highlighted the complexity of the relationship among these forces. In fact, it is the different intensity of each force and their simultaneity that determines the overall morphology of a rock coast (Griggs and Trenhaile, 1994). This is well shown in the works of Sunamura (1982, 1992), in which the author quantifies various critical thresholds of the erosive power of waves and rock resistance to compression. Above or below these thresholds, a coast will tend to evolve toward the formation of a platform or a cliff.

The morphology of a rock coast and how various littoral forces act on it are in many cases scale dependent. Some endogenetic forces, mostly structure and tectonics, have a great influence on the development of coastal megaforms (Cortemiglia, 1993). In some cases though, the morphometry of catchment basins intersecting the coastline (*e.g.,* stream order) has been proved to have a direct relationship with the size of embayments (Bishop and Cowell, 1997). Other factors, such as marine conditions and lithology, have a greater influence on the meso- and microforms (Thornton and Stephenson, 2006). As an example, Blanco Chao *et al.* (2003), in a study on the controlling factors of the Galicia (NW Spain) coast morphologies, highlighted a relationship between tectonics and macroforms on one side and a relationship between lithology/climate and micro/mesoforms on the other side. In particular, they showed the direct control of tectonics in the development of the rias, the large fluvial valleys now flooded by the sea, whereas meso- and microforms were prov-

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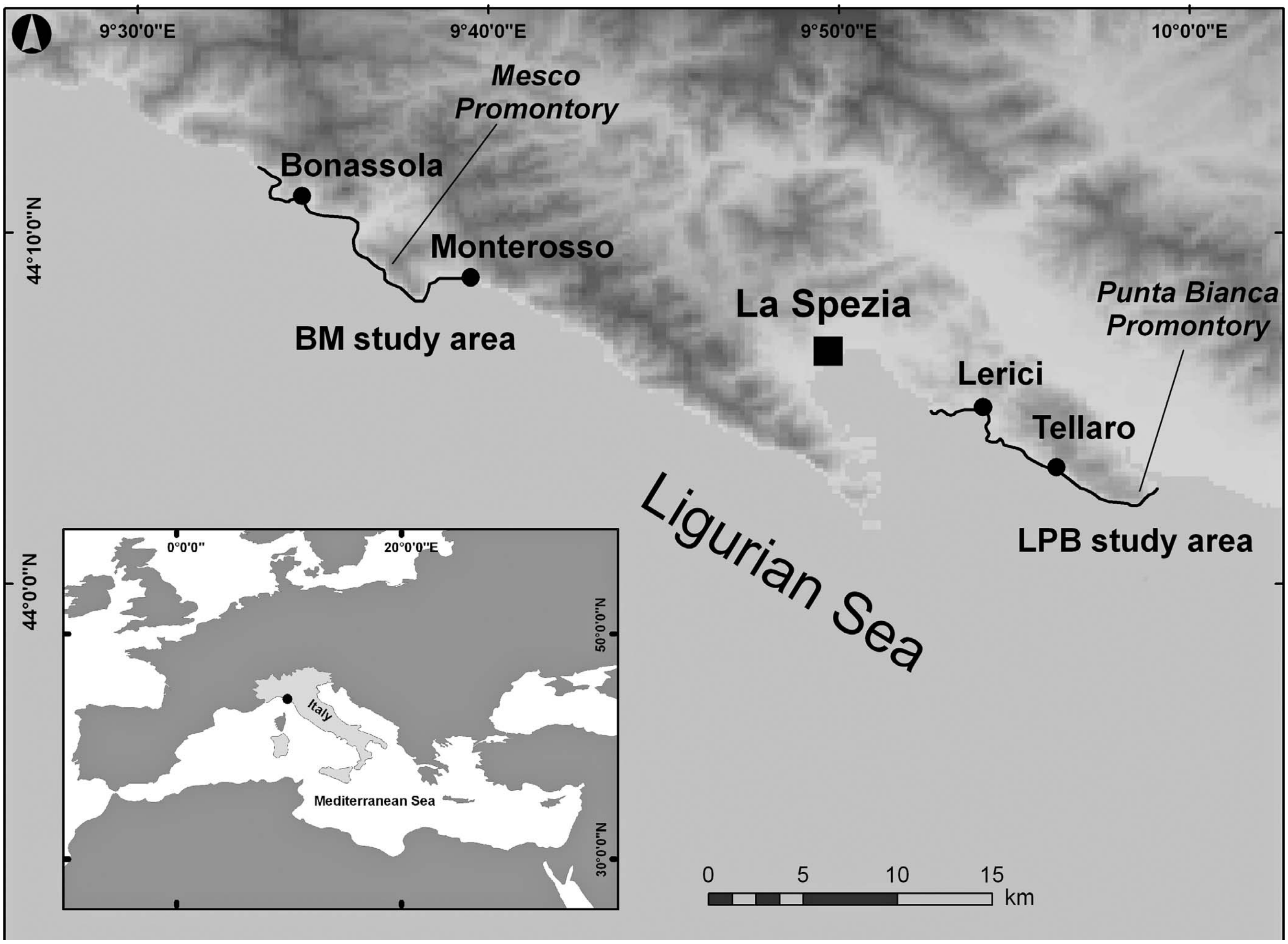

Figure 1. The two study areas in NW Italy (Liguria): Bonassola-Monterosso (BM) coastline and Lerici–Punta Bianca (LPB) coastline. The main promontories and villages, together with the town of La Spezia are shown.

en to be more directly dependent on lithology, meteomarine climate, and inherited morphology.

Among the various morphological approaches that can be used to analyze a rock coast, those based on the analysis of altitudinal profiles of coastal slopes are prevailing. Nevertheless, some studies have dealt with the planar geometry of the coastline (Bellotti, Caputo, and Del Monte, 2005; Jiang and Plotnick, 1998; Mastronuzzi, Palmentola, and Sansò, 1992a, 1992b, 1992c), considering it clearly sensitive to the influence of various littoral forces that are present in a certain area.

Table 1. *A synoptic table of abbreviations found in the text.*

Abbreviation	Meaning
LPB	Lerici–Punta Bianca coast
BM	Bonassola-Monterosso coast
If	Indentation index
L	Length measured along the coastline
D	Euclidean length

In the present work, we focus in particular on coastline linearity, with a quantitative approach that can be applied to both very small and very large portions of a coast. A simple look at any topographic map of a coast is enough to conclude that only a few portions of a coast, namely the depositional or those related to a recent active fault displacement, are characterized by regular rectilinear development (Bird, 1988), whereas most rock coastlines present tortuous and indented geometry.

The parameter that best quantifies the level of linearity of a coastline is the indentation index (Mastronuzzi, Palmentola, and Sansò, 1992a). So far the indentation index has been evaluated to compare two coastlines, sometimes even of different lengths, to link their overall indentation value to known differences in rock types or other littoral forces (Mastronuzzi, Palmentola, and Sansò, 1992b). The indentation index has also been considered a good proxy for the steady state reached by a coastline (Maracchione *et al.*, 2001): the less indented a coast, the more it is in balance with littoral forces and thus the closer to a steady state.

Figure 2. A typical landscape for the NW sector of the Lerici–Punta Bianca coastline

The aim of this study is to define a procedure, as objective as possible, that can best highlight spatial variations of the indentation index within the same coastline without having to select *a priori* segments of a given length or known littoral forces. With the recent development of GIS software, particularly useful for morphometric analysis, together with the growing availability of digital cartographic data, it is now possible to automatically derive the indentation index from a digitized coastline of any given length in a relatively short time. The GIS-based methodology we suggest in this paper includes a statistical approach for defining the length for coastline segmentation to automatically evaluate the indentation index. The method has been tested on two sample areas of the Ligurian coast in Italy.

SAMPLE AREAS

The sample areas are two portions of the western Ligurian coast (NW Italy, Figure 1): the southeastern promontory of La Spezia Gulf, between the village of Lerici and the promontory of Punta Bianca, and the coast between the villages of Bonassola and Monterosso, 30 km away to NW of La Spezia Gulf. The first coastal area is characterized by a linear extension of 18.9 km, and 21.8 km in the second coastal area.

The overall morphology and geology of these two areas are known (ABBATE, 2005; AROZARENA, 2005; GIAMMARINO *et al,* 2002; TERRANOVA, 1987). The Lerici–Punta Bianca area (LPB from now on, Table 1) represents the southern limit of the rock coasts of Liguria (Figure 2). Morphologically, the LPB area can be distinguished into two portions. Between the Punta Bianca promontory and Tellaro, the extensive outcrop of at-dipslope limestone belongs to a rather homogeneous formation and determines a steep coastal slope evolving mainly through gravitational processes (AROZARENA, 2004). Moving to the NW, between Tellaro and Lerici, a complex structural assemblage of alternating calcareous and metamorphic rocky formations is associated with a morphology characterized by the succession of small capes and bays, with sandy beaches in the bays and complex rock morpholo-

Figure 3. A typical landscape for the Mesco promontory, along the coastline of Bonassola-Monterosso

gies in the capes, such as raised platforms, and ramps (Arozarena, 2006).

The second sample area (Figure 3), between the two villages of Bonassola and Monterosso (BM from now on, Table 1), is characterized by an extensive outcrop of ophiolites, with the exception of the main promontory (the Mesco promontory), which is modeled into sandstone and claystone. In the NW tract, slope-over-wall profiles are the dominant morphologies, with cliff tops exceeding 50 m a.s.l. in height. Only the lower part of this cliff is currently modeled by sea action, whereas the upper part is affected by gravitational collapse. Similar morphology is displayed in the tract of the Mesco promontory stretching NW–SE, where the steeply dipping arenaceous layers constrain to lower angles at the basal part of the slope. The coastal tracts stretching NE–SW and the bays inlets, instead, display stripes of gravelly beach, nourished by the littoral drift and by gravitational processes along the slopes.

METHOD

Indentation Index and the Definition of a Common Scale

The linearity of a coast can be quantified by a parameter known as the indentation index (Mastronuzzi, Palmentola, and Sansò, 1992b). The indentation index of a segment of coast is defined as:

$$\mathrm{If} = L/D$$

where If is the indentation index, L is the length measured along the segment of coast, and D is the Euclidean length of the same segment, which is the length of the straight line that joins the first and the last point of the segment (Figure 4 and Table 1). From a geometrical point of view, the indentation index is the equivalent of the sinuosity index usually measured on rivers.

The same coastline digitized at different scales easily gives different and not comparable values of If, because the greater

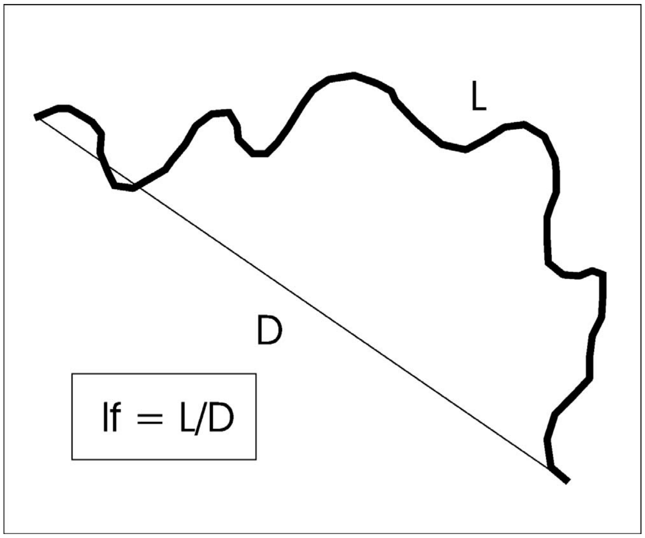

Figure 4. How to calculate the indentation index (If): *D* represents the Euclidean length; *L* is the length measured along the coast segment.

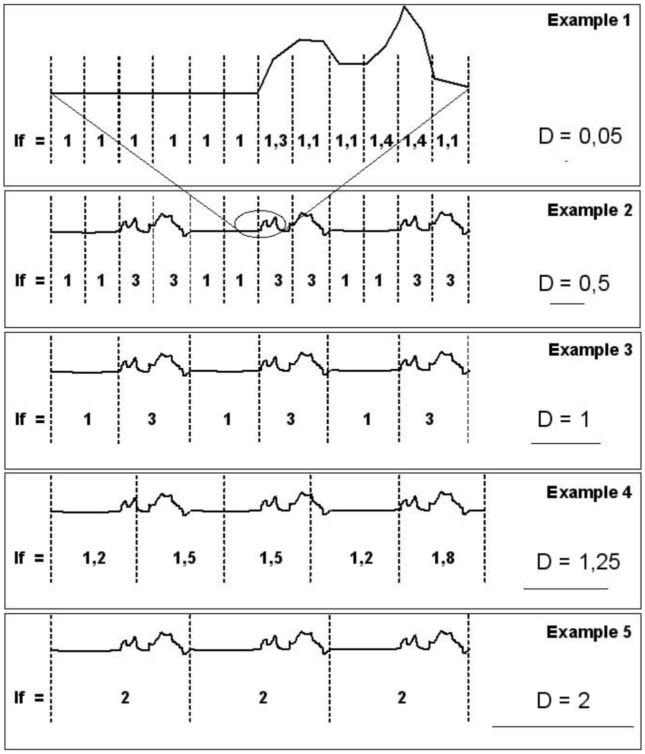

Figure 5. Variation in the values of the indentation index (If) depending on the size of the segment (*D*) into which an ideal coastline is split

the scale, the longer the *L* value of the equation. Thus, it is very important to define a common working scale. Usually it is the cartographic, possibly digital, availability that determines the scale at which certain analyses can be carried out. In the sample area of western Liguria, topographic maps at the 1:5000 scale of the Regione Liguria were available as raster files already georeferenced. The coastline was digitized on a computer screen at a scale of 1:2500, an adequate enough scale to accurately follow the coastline drawn in the cartographic map. To avoid possible subjectivity of the digitizing process, the same operator digitized both the 18.9-km LPB coastline and 21.8-km BM coastline.

Classic and New Method

Once the proper scale is defined, there are two possible ways of measuring the indentation index. In the "classic" method (MASTRONUZZI, PALMENTOLA, and SANSÒ, 1992b), the one applied so far in the literature, researchers know *a priori* that two or more coastlines are characterized by different basic constraints or littoral forces that affect the grade of indentation. Thus, with the aim of quantifying this grade, the effective lengths (*L*) of two or more coastlines are divided by their measured Euclidean lengths (*D*).

In the new method, the focus is on the variation of If measured for several adjacent segments of equal *D* along the same coastline. With GIS techniques, different values of *D* can be tested easily on a coastline, and only those that best highlight differences of If within the selected coastline are taken into account. In other words, only those *D* values that maximize the spatial variability of If along the coast will be taken into account. When the littoral forces acting on the coastline are well known, it becomes possible to give a genetic interpretation of the results. In particular, the variation of If values along the coastline, also dependent on the values of *D* adopted each time, can suggest which littoral forces are dominant within each segment.

By testing different values of *D,* which means splitting the same coastline into a variable number of segments, we can look at coastline indentation at different wavelengths or scales. To split a 10-km-long coastline into 100 small segments or simply five very large segments will result in completely different analysis perspectives, although in both cases, it is possible to achieve high spatial variability of If. The reason more than one value of *D* can maximize the variability of If is related to the different littoral forces that influence the shape of a coastline at different wavelengths. For instance, variation in the density of joins can determine a high variability of If when looking at small segments, whereas variation in lithology could determine high variability when analyzing large segments. More generally, if a coastline shows different high If variability in relation to the different values of *D* adopted, morphologically this could be the result of (i) the same littoral forces acting variously at different wavelengths, (ii) two or more different forces acting variously at two or more different wavelengths, or (iii) two or more different forces interfering with one another variously at different wavelengths.

Identification of *D* Values that Maximize the Variability of If

In general, extreme values (too high or too small) of *D* result in low variability of If along a coastline. In the ideal case

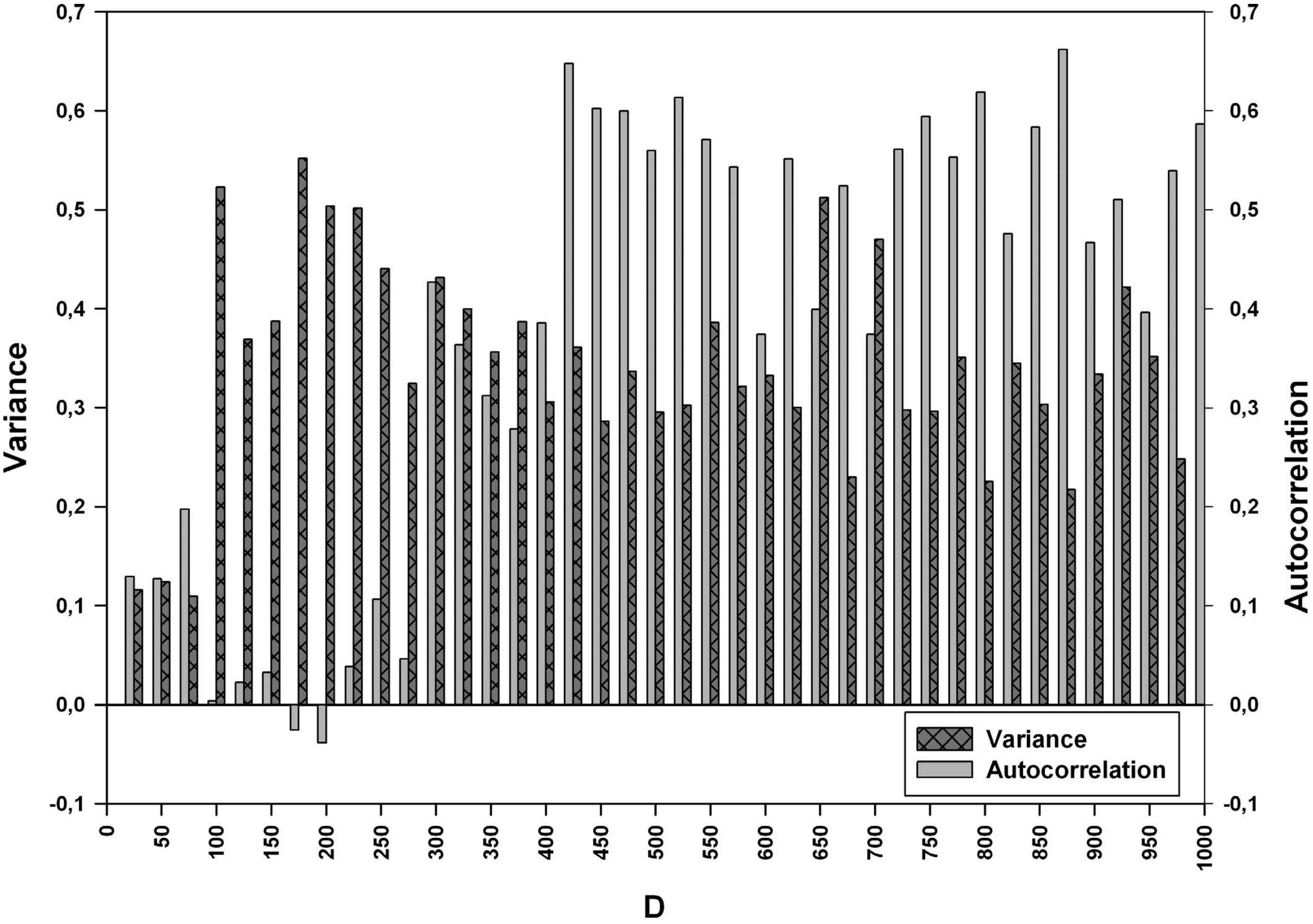

Figure 6. Change in variance and autocorrelation of the indentation index (If) at various values of Euclidean lengths (*D*) in the Lerici–Punta Bianca (LPB) coastline

in Figure 5, the best *D* is that of example 3, to which a symbolic value of 1 is assigned. If the value of *D* is reduced (<1), the coastline is split into smaller and smaller segments, but the resulting If values accordingly become more and more similar to one another, thus reducing the general If variability of the analysis and the morphological characterization of the coast that can be deduced from it. At some point, if *D* becomes too small, all coastal segments will become almost identically long; If will become progressively lower, tending to the minimum value of 1; and, overall, If values will show very poor variability along the coastline. Analogously, too high a value of *D* will result in a low or null variability of If.

In the theoretical case of Figure 5, only one *D* value gives the highest variability of If along the ideal coastline taken into account. The reality is usually more complex, and in most cases, there is more than one value of *D* in which the variability of If is maximized, with the already-mentioned implication that various littoral forces control the morphology of a coastline at different wavelengths.

To define which values of *D* best maximize the variability of If, various statistical indexes were taken into account. Among others, spatial autocorrelation and variance were thought to be the best indexes in quantifying the variability of If along a coastline. On one hand, variance quantifies the variability of If, taking into account all segments of a subdivided coastline. On the other hand, spatial autocorrelation is the correlation of the variable If with itself through space and is a way to highlight the presence (or absence) of a systematic pattern in the spatial distribution of If along the coastline. Thus, autocorrelation quantifies how each segment of coast differs (in terms of If) from the two adjacent segments: the one that follows it and the one that precedes it. The higher (positive) the autocorrelation, the more frequently neighboring coastal segments are characterized by a similar value of If, thus suggesting that the value of *D* that generated that specific subdivision of coastal segments is not adequate to enhance the variation of If along the coastline. When autocorrelation is 0, there is no relationship between the value of If of one segment and that of the adjacent segments (random pattern). Finally, when autocorrelation is negative, it means that high and low If values alternate in adjacent segments (neighboring segments are unlike), which is a result that it

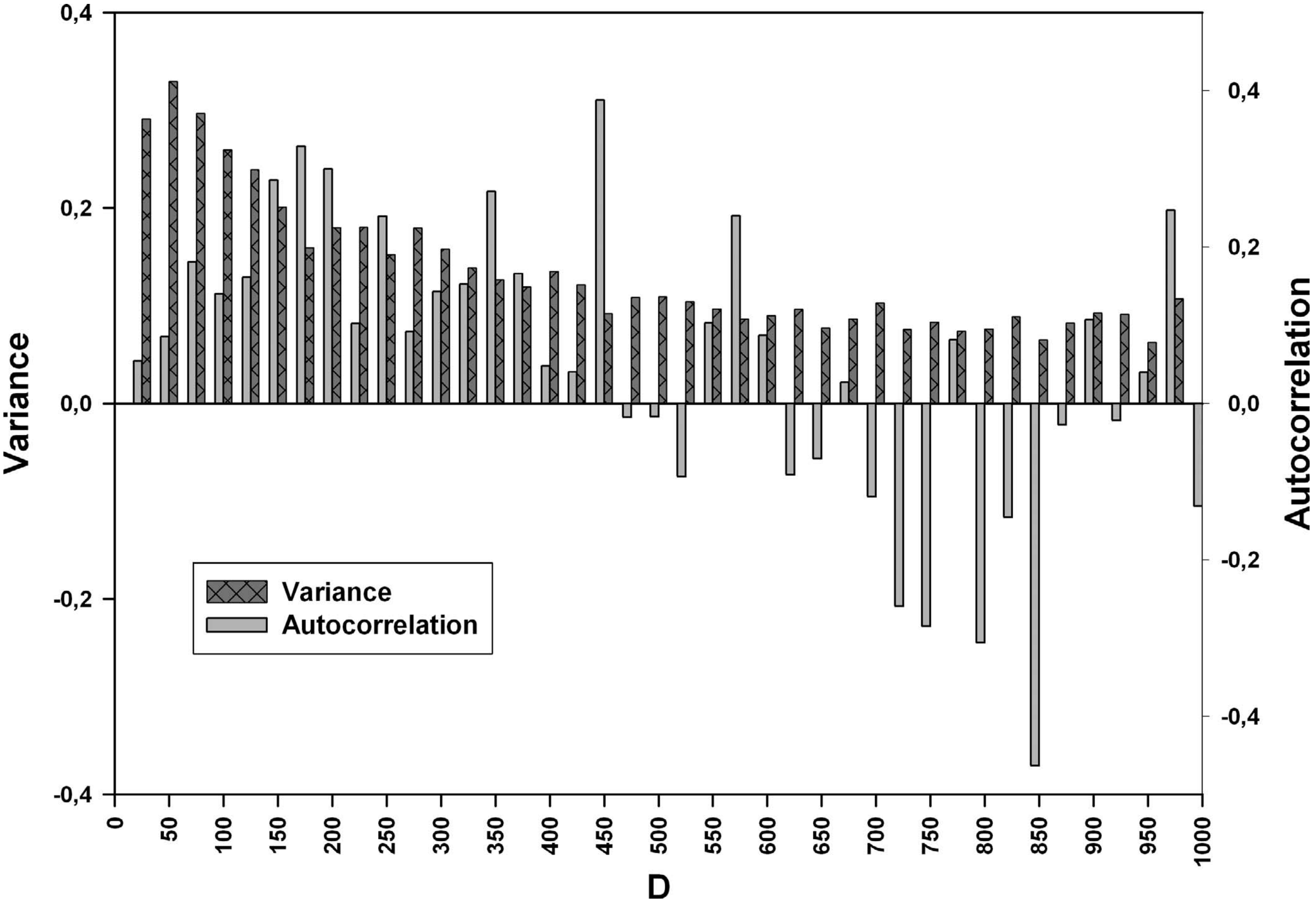

Figure 7. Change in variance and autocorrelation of the indentation index (If) at various values of Euclidean lengths (*D*) in the Bonassola-Monterosso (BM) coastline.

worth taking into account. In general, values of autocorrelation near zero or negative are good indicators of high variability of If along a coastline.

In the extreme case of an infinitesimal *D* value, which will make the If values of most segments tend to 1, variance is very low and autocorrelation very high. The ideal value of *D* is the one that will split a coastline into segments with resulting If values showing high variance and low (near zero or negative) autocorrelation. These two statistical parameters are not necessarily correlated to one another; thus, it could be useful to consider more than one value of *D*. In particular, for the final interpretation of the results, those *D* values characterized by a combination of low autocorrelation and high variance of If should be considered. This should be done together with the *D* value that makes the variance the highest, possibly related to a low value of autocorrelation, and the *D* value that makes autocorrelation the lowest, possibly related to a high value of variance.

RESULTS AND COMMENTS

The new method was applied (separately) to two sample areas in Liguria. In both cases, the coastline was digitized on screen at a scale of 1:2500. At first, the two coastlines were split into a very large number of segments by applying a particularly low *D* value ($D = 25$ m). With this value of *D,* 645 consecutive segments of coast were obtained in the LPB area and 716 along the BM coastline. This procedure was done with the use of specific GIS tools that allows the user to take a digitized and georeferenced coastline and split it into *n* segments of a given Euclidean length. Eventually, each segment's along-coast length (*L*) was derived, and If (*L*/*D*) was evaluated. Specific statistical tools were applied to evaluate the variance and autocorrelation of the resulting If values, taking into account all segments. This was then repeated for $D = 50, 75, \ldots, 1000$ m in 25-m increments. With $D = 1000$ m, LPB coastline was split into just 11 coastal segments and the BM coastline into 13 segments. Every time, the relative autocorrelation and variance of If was evaluated (Figures 6 and 7).

For the LPB coastline, variance was low for $D = 25$, 50, and 75 m. For $D > 75$ m, variance varied between 0.2 and 0.6. Higher values of variance were reached at $D = 175$ and 100 m. Spatial autocorrelation was relatively low for $D < 300$ m, high for $D > 400$ m, and intermediate in between. It was

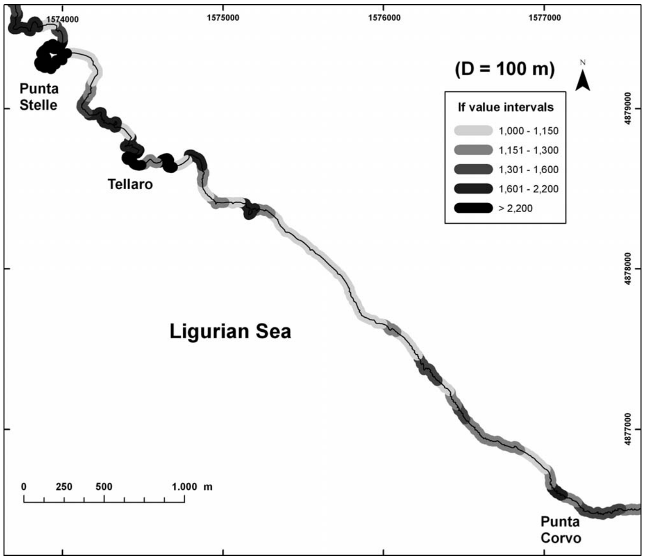

Figure 8. Geographical variation of the indentation index (If) along the Lerici–Punta Bianca (LPB) coastline by applying a value of Euclidean length (D) equal to 100 m.

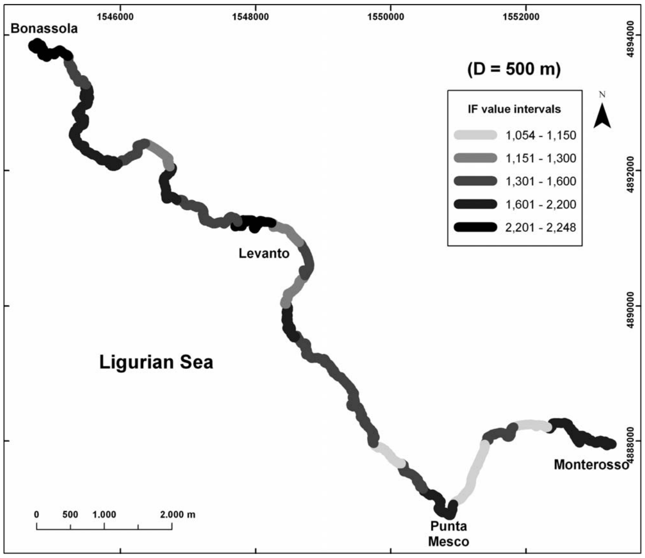

Figure 9. Geographical variation of the indentation index (If) along the Bonassola-Monterosso (BM) coastline by applying a value of Euclidean length (D) equal to 500 m.

negative only when $D = 175$ and 200 m, with values very close to 0. The lowest autocorrelation value was reached for $D = 100$. Overall, by combining both statistical parameters, the two best D values for splitting the LPB coastline into segments for If analysis were $D = 100$ and 175 m.

In the BM area, the situation is rather different, with variance regularly decreasing from lower to higher values of D. The higher value of variance was reached at $D = 50$ m. The lower value was that of $D = 950$ m. On the other hand, spatial autocorrelation was very irregular, with values near 0 or very negative for $D = 450$ and 475 m and for 625 m $< D <$ 925 m. The autocorrelation values closest to 0 were found at $D = 475$ and 500 m. The most negative autocorrelation was for $D = 850$ m, the most positive autocorrelation at $D = 425$ m. Overall, this seems to be one of those cases in which the combination of the two statistical parameters, variance and spatial autocorrelation, does not point to a unique value of D. In fact, the best approach would probably be to consider more values of D. In particular, three values were taken into account here: $D = 50$ m (the highest variance and a relatively low spatial autocorrelation), $D = 500$ m (the spatial autocorrelation closest to 0), and $D = 850$ m (the most negative spatial autocorrelation).

With the aim of showing a possible interpretative approach, some preliminary comments can be made on the distribution of If values along the examined coastlines according to the available geological and geomorphological data.

For the results from the LPB area, If was found to highlight a similar spatial pattern along the LPB coastline when applying both $D = 100$ m and $D = 175$ m (thus, Figure 8 will only show results obtained for $D = 100$). For $D = 100$ and 175 m, higher values of If are mostly located around the two areas of Tellaro and Punta Stelle (NW), whereas between Tellaro and Punta Corvo (SE), If is considerably lower (Figure 8). It is likely that this difference between the SE and the NW portions of the coastline is related to their different geological features. In particular, the SE portion is characterized by at-dipslope limestone that determines steep coastal flanks. As a result, the coast is characterized by several rock falls in which incoherent deposits, although constantly reworked by sea waves, protect the cliff, thus determining a sort of steadiness in the morphological evolution of the coastline and an overall less indented shape. In the NW sector, the situation is more complex. In fact, the tight structural constraints (FEDERICI and RAGGI, 1975; STORTI, 1995) and the presence of inherited landforms cause general unsteadiness with the present-day sea level. As a result, the morphology is characterized by a higher indentation index, and the planar geometry of the coastline displays a succession of small bays and promontories (see, for example, Figure 2). Also, the nearshore sea bottom morphology points to a difference between the NW and SE portions of the LPB coast (AROZARENA, 2005) In the coastal tract dominated by landslide morphology (SE sector), the sea bottom is shallower and waves break a few tens of meters away from the coast, whereas in connection with plunging cliffs and ramps (NW sector), they directly break onto the rock face, exerting more pressure on the rocks. Therefore, nearshore sea bottom morphology, by influencing the breaking mechanism of the incoming waves, enhances the difference in the indentation index between the two portions of the coast.

In the BM area, it is possible to comment on the If spatial pattern only for $D = 500$ and 850 m but not for a very small $D = 50$ m because the known geological and geomorphological information for this area is at a smaller scale. Applying $D = 500$ or 850 m, the If spatial variability is relatively similar, and only the results for $D = 500$ are discussed here (Figure 9). The use of a value of D (500 m) in the BM area highlights a general difference between the portions of the coastline oriented NW–SE and NE–SW (Figure 9). In the BM case though, the variability of If seems to reflect the broad distribution of erosional or depositional tracts of coast without showing any specific relationships with the known differences in rock types. In fact, the sector characterized by hard rocks (*i.e.,* ophiolites) displays values of If as high as those found in the Mesco promontory, which is modeled in soft claystone and sandstone. Although these latter rock types are more prone to landslides, as in the SW sector of the LPB coastline, in the Mesco promontory, the nearshore sea bottom bathymetry is deep (plunging cliff), and the accumulation of loose material is not possible at the cliff toe, thus preventing the development of a regular planar geometry (see, *e.g.,* Figure 3). Low If values can be found only where the shallow sea bottom bathymetry and sources of loose material (streams mouths, degradational scarps, and niches mainly along lithological contacts) permit the accumulation of a stripe of gravelly beach, which forces the coast planar geometry into a steady state.

CONCLUSION

To enhance the objectivity of the analysis of the indentation index, we proposed a method in which If is evaluated for each segment of equal D value along a coastline. For this kind of analysis, the coastline has to be digitized and acquired in a GIS environment in which several D values could be tested quickly in order to define the best values that maximize the variation of If along the coastline. The values of D that determine the lowest spatial autocorrelation, the highest variance of resulting If values, or both are those that better highlight the spatial If pattern along a coastline. Once the best D values are identified, it is possible to show on a map the variation of If along the coastline and to analyze it on the basis of known or hypothesized littoral forces that act on shaping that coastline. Sometimes, as in the case of the BM coastline, more than one D value could maximize the variation of If along the coastline. In these cases, it is possible that one littoral force might have an effect on coastline indentation at different wavelengths. Nevertheless, these could also be the result of different littoral forces working at different wavelengths or variously interfering at different wavelengths. Finally the inherited morphology, related to past littoral forces, can also be relevant in the present-day variation of If along a coastline.

The indentation index has, in the opinions of the authors of this paper, great potential as a tool for studies on coastal evolution (and in particular on rock coast landforms development), provided it can be applied objectively to any coastline. Moreover, it could be employed as a marker of coastline retreats. As such, the indentation index could be considered a relevant tool for coastal hazard assessment.

Analyses of real coastlines with littoral forces that are well known are now needed to test these hypotheses and to validate the new method suggested here.

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