Process-based indicators to assess storm induced coastal hazards

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Storms are responsible for several hazards (e.g. overwash, erosion, inundation) in coastal areas, leading to the destruction of property and loss of life in populated areas. Various indicators are used to express potential storm impact and describe the associated hazards. The most commonly used indicators include either forcing parameters (e.g. wave height, sea level) or coastal morphologies (e.g. dune height or berm width). Whereas they do not represent the processes associated with storm induced hazards in coastal areas. Alternatively, a hazard could be better characterised if process-based indicators are used instead. Process-based indicators express the result of the forcing mechanisms acting over the coastal morphology and reflect both hydrodynamic and morphological characteristics. This work discusses and synthesizes the most relevant process-based indicators for sandy shores subject to overwash, erosion and inundation promoted by storms. Those include: overwash depth, potential and extent; shoreline, berm or dune retreat; vertical erosion; and inundation depth and extent. The selection of a reduced set of process-based indicators to identify coastal hazards induced by storms in sandy coasts will facilitate comparison of different coastal behaviours for distinct storm return periods, and help to optimise coastal management plans, thereby contributing to the reduction of coastal risks.

Process-based indicators to assess storm induced coastal hazards on sandy coasts

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Keywords: indicators; hazards; storms; overwash; inundation; erosion

1. Introduction

Storms impacting sandy coastal areas produce hazards such as erosion and inundation that, in turn, promote risk to life and property damage in occupied areas, and the alteration and/or fragmentation of habitats. Recent examples include the severe coastal erosion and associated destruction of property caused by Hercules storm (January 2014) that impacted the southwest coasts of France and England (Castelle et al., 2015; Masselink et al., 2016a,b); the inundation and loss of life caused by the Xynthia storm (February/March 2010) in western France (e.g. Bertin et al., 2012); the vast destruction caused by the superstorm Sandy (October/November 2012), in the coastal mid-Atlantic states of the USA (Bennington and Farmer, 2015; Clay et al., 2016), or by hurricane Katrina (August 2005), at the Golf coast of the USA (Link, 2010; Kantha, 2013). Potential coastal damages and risks are expected to increase in the near future not only in association with climate change (e.g. sea level rise, change in frequency and magnitude of storms) but also due to increasing human occupation in coastal areas (Neumann et al., 2015).

Indicators, as a metric for coastal state, dynamics, behaviour or hazard, are a straightforward way to express complex data and information and can therefore be an important tool in the dialog among stakeholders (Carapuço et al., 2016). They are often based on a parameter that is used to characterise a coastal area. Coastal hazard indicators are commonly used to express the potential storm impacts in coastal areas, helping to identify and prioritise vulnerable regions (Nguyen et al., 2016). Storm related hazards have been expressed in the literature by a large number of different indicators that have been recently synthesised by the review works of Carapuço et al. (2016) and Nguyen et al. (2016). For coastal erosion and flooding hazards Carapuço et al. (2016) identified (and recommended) the use of several geoindicators, like *shoreline/baseline position*, *shoreline evolution*, *beach/barrier elevation* or *beach slope*. Nguyen et al. (2016) synthesized the existing indicators in literature related to storm surge-driven flooding and coastal vulnerability and included geoindicators (e.g. *coastal slope*, *geomorphologic characteristics*), hydrodynamic indicators (e.g. *wave height*, *tidal range*, *surge height*) and coastal evolution indicators (e.g. *erosion rate*, *shoreline/coastline position*). The aforementioned indicators, which represent a summary of the ones that have been widely used and referred to in the international literature, include forcing/driver parameters, coastal morphology characteristics and even coastal evolution. It is, however, not clear how to select the most representative parameter for a given hazard. The most commonly used parameters describe either the driving mechanisms or the coastal morphology, rarely integrating both or fully representing the processes associated with storm induced hazards in coastal areas. Moreover, these indicators hardly differentiate relevant time-scales (or return periods) and/or values that are averaged over time, which can cause difficulties (and exaggerated simplicity) in their application.

To fully characterise a coastal hazard it is necessary to use a set of indicators that combines the forcing mechanism and its effect on the coastal morphology, i.e. process-based indicators. The majority of the indicators found in the literature cannot be considered process-based. Process-based indicators can only be obtained from the application of models that incorporate physical forcing mechanisms and that include realistic coastal morphology elements, resulting in a parameter or set of parameters that express the effects of the processes acting on the coastal system.

This work reviews and synthesizes the most relevant process-based coastal indicators that can be applied for sandy coasts subject to storm-induced coastal hazards. The main hazards assessed are: overwash, inundation, and erosion. The main goal is to propose a set of process-based indicators that can serve as a reference for coastal hazard studies on sandy shores. The rationale for using process-based indicators is described in section 2. The definition, discussion and selection of indicators for each analysed coastal hazard are detailed in section 3. Section 4 provides a synthesis of the proposed indicators and their applicability, based on the use of simple parameters highly representative of coastal hazards. Final considerations on current limitations and future use of process-based indicators at sandy coasts are discussed in section 5.

2. Process-based indicators

The vast majority of recommended coastal hazard related indicators in the literature (see reviews by Bush et al., 1999; Carapuço et al., 2016; Nguyen et al., 2016) only take into account: (i) the characteristics of the physical/morphological features of the coastal system, or (ii) the driving mechanism. Combinations between both, representing the processes and the consequent hydrodynamic or morphological results (process-based indicators), are not commonly used and have not yet been the subject of a synthesis. Process-based indicators are directly related to hazard and represent the interaction between driving mechanisms and the coastal morphology. The process-based indicators are therefore obtained by using formulations or models (from simple to complex) that will combine the driving mechanisms (e.g. storm parameters like wave height, wave period, storm duration or sea level) and the coastal system morphology (such as beach face slope, dune height, berm width, grain size or bathymetry) (Figure 1, steps 1 and 2). The result will be an impact (e.g. erosion, overwash occurrence) that can be expressed through an indicator that has a physical meaning (e.g. flood depth, shoreline retreat). Overall, results can be reclassified into new classes that express different levels of hazard according to stipulated limits/thresholds allowing an illustrative mapping of the hazard (Figure 1, steps 3 and 4). These thresholds can be defined locally or regionally, allowing a comparison of the hazard intensity within a specific coastal area and also between different coastal areas. Furthermore, such indicators can often be used to estimate (or to indicate) the extent of the hazards, allowing the representation of the spatial distribution of the coastal hazard. However, it is worth mentioning that the thresholds depend on the hazard receptor-type (e.g. dunes, salt marsh, houses, infrastructure), defined according to the Language of Risk (Gouldby and Samuels, 2005) and, therefore, comparisons should be restricted to similar receptors. These indicators are comparable in concept to the Coastal State Indicators (CSI), introduced by van Koningsveld et al (2005). CSI are defined as "issue-related parameters that can simply, adequately and quantitatively describe the dynamic-state and evolutionary trends of a coastal system" (Davidson et al., 2006, 2007). The use of process-based indicators can therefore include alongshore and cross-shore variability as well as time-dependency (e.g. inclusion of time-scales or return periods). The indicators must, however, remain simple on application and expression to ensure their applicability by most coastal managers. Examples of commonly used process-based indicators (e.g. Wright and Short, 1984 or Masselink and Hegge, 1995) include beach morphodynamic state indicators such as the surf scaling parameter (Guza and Inman, 1975) and the surf similarity parameter (Battjes, 1974). However, these are not commonly applied to indicate the degree of coastal hazard. In fact, widely accepted process-based indicators to represent storm hazard at sandy coasts have not yet been defined and used.

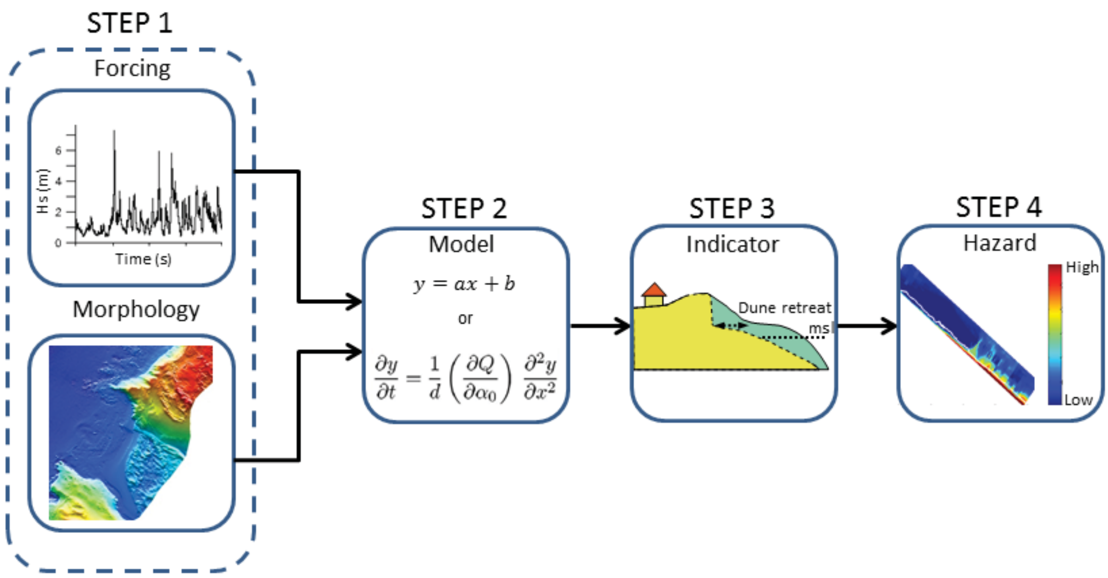

Figure 1. Scheme representing the steps needed to obtain a process-based indicator, and its use for hazard assessment. Driving mechanisms and coastal morphology (Step 1) are integrated in numerical models (from simple to complex) to produce a process-based indicator (step 3) that can be used to express the hazard degree (step 4).

Two possible approaches can be used to obtain the indicator's variability through time: event approach and response approach (see Divory and McDougal, 2006; Bosom and Jiménez, 2011; Ferreira et al., 2016). The *event approach*, also called deterministic, uses the extreme probability distribution of the physical forcing parameter and the present day coastal morphology (or any simulated condition) to determine the process-based indicator. The storm parameter (e.g. wave height) for a given return period is obtained from the corresponding extreme distribution. A formulation/model (Step 2 on Figure 1) is then applied for the dominant (or other) morphological condition and the process-based indicator is obtained (e.g. overwash depth, shoreline retreat) for that return period. In this approach the obtained indicator is then associated with one value of a storm parameter, for a given return period, losing significant information on the natural variability of the process (Sánchez-Arcilla et al., 2009). The *response approach*, also called the probabilistic approach, uses the entire forcing parameter time-series (e.g. water level, wave height, storm duration) to obtain the indicators for all known conditions (e.g. runup, erosion) through time. A probability distribution of extremes must be fitted to the obtained indicator time-series and the indicator associated with a given return period will be computed from its own probability distribution. This method is particularly recommended when the forcing variables are poorly correlated or statistically independent (Bosom and Jiménez, 2011).

3. Proposed process-based indicators

A large number of the indicators that are currently used are frequently poorly defined (Carapuço et al., 2016). The existing lack of standardization of concepts and assumptions restricts the comparability between indicators and among different coastal areas (Nguyen et al., 2016). The use of different indicators may even result in significantly different hazard estimates, requiring greater caution in the selection of the appropriate indicators (Hanslow, 2007). All above expressed shortcomings call for a standardized approach, with clear guidelines for the determination and applicability of hazard indicators. Indicators should, therefore, be as simple as possible, unambiguous, reproducible in different coastal regions, and based on a consistent methodology that enables comparison between sites (see Carapuço et al., 2016; Nguyen et al., 2016). Moreover, they should be suitable for defining the morphodynamic and hydrodynamic state of sedimentary coasts, in support of coastal zone management (Davidson et al., 2006).

The indicators analysed in this paper are process-based and therefore describe the dynamic interaction between the coastal morphological states and the driving mechanisms of the particular hazard. The computation of the proposed indicators for existing (or hindcast) data time-series, and subsequent probabilistic analysis of the indicators' distribution, will allow their use in association with return periods. Since the selected indicators are applicable to sandy coastal areas and can be associated with a given probability of occurrence, they allow direct comparisons or ranking of the hazard intensity between different coastal areas. For each indicator a set of thresholds can be established (at local, regional or international level) that can be used to classify and rank the hazard. Those limits will not be the subject of detailed analysis in this paper, although application examples will be mentioned after the physical description of each indicator.

Overwash indicators

Overwash occurs when wave induced runup overtops the foredune ridge or the highest beach/barrier elevation if the dune is absent. Following Matias and Masselink (2017) the overwash is a discontinuous flow of seawater and sediment over the dune/beach crest, which will propagate inland for a given extent (distance to the initial dune/beach crest position). The two main indicators reflecting overwash induced hazards are: *overwash potential* and *overwash depth*. Overwash potential is defined as the vertical difference (in meters) between the potential wave runup (along an imaginary extended beach/dune slope) and the dune/beach crest elevation (Matias et al., 2012, 2016; Figure 2). Overwash depth can be defined (adapted from Donnelly, 2008) as the water depth (in meters) at a point (dune crest or backbarrier) during an overwash event. Overwash depth decreases with the distance across the backbarrier until reaching a zero value at the maximum inland overwash extent (Figure 2). Computation of both indicators requires the use of empirical equations to predict the runup (e.g. Holman, 1986; Stockdon et al., 2006; see Matias et al., 2012 for a review on formulations) and a digital terrain model. For complex environments, such as partially engineered coastlines or areas with a complex geomorphological framework, process-based models should be used to determine such indicators.

Both indicators (overwash potential and overwash depth) state a vertical difference between a water level associated with the overwash and the terrain (Figure 2). The overwash potential is easier to use because of its computational simplicity since it compares the result of a runup formulation with the height of the dune/berm crest. The overwash depth needs extra formulations to determine the effective water lens depth at the crest and its cross-shore variability (see Donnelly, 2008). However, the overwash depth has the advantage of being physically representative of the actual process as it can be applied not only at the dune/beach crest but also at the backbarrier up to the maximum extent of the overwash (Figure 2). The computation of the overwash depth can be performed using the formulations proposed in Donnelly (2008), relating the overwash depth with infiltration and the velocity of the overwash flux. However, this approach has not been calibrated for all grain-sizes and assumes a simplified morphology. Overwash depth values at the back of the dune can be estimated by using an exponential decay that varies according to infiltration and lateral expansion of the flow. This also allows the definition of a maximum *overwash extent* which represents the total cross-shore extension of the overwash and can be applied as an indicator of the area prone to be flooded (e.g. Garcia et al., 2010; Ferreira et al., 2016; Christie et al., 2017). The inclusion of processes like infiltration and lateral expansion increases the applicability of the method by providing free parameters that can be set to local conditions and used as calibration parameters. A more effective (but also more complex and computationally demanding) way to compute the overwash depth is to use 1D or 2D numerical models. Other potential indicator to state the overwash hazard (for expected damages) is the overwash velocity. This is currently obtained (with limited field validation) by using models and it is therefore of restricted application. Alternatively, the overwash velocity can be estimated as a function of the overwash depth at the dune crest, as determined by Donnelly (2008) and Matias et al. (2016).

Existing studies mostly use the overwash depth and the overwash potential to determine the possibility of overwash for a given event. Negative values of these indexes are associated with swash or collision states, according to the storm impact scale proposed by Sallenger (2000), while positive values imply overwash (e.g. Almeida et al., 2012; Rodrigues et al., 2012) or higher hazard levels such as inundation (e.g. Bosom and Jiménez, 2011). Several researchers have applied the overwash potential indicator in order to find a storm threshold for morphological changes (e.g. Stockdon et al., 2007; Almeida et al., 2012; Armaroli et al., 2012; Del Río et al., 2012; Haerens et al., 2012; Trifonova et al., 2012). The use of the overwash depth is still limited (e.g., Ferreira et al., 2016; Poelhekke et al., 2016; Valchev et al., 2016; Christie et al., 2017) since it is not directly obtained by the most commonly used formulas (e.g. Holman, 1986; Stockdon et al., 2006) and has been rarely measured in the field, leading to lack of validation. However, it has to be stated that overwash depth is a measurable value in the field in contrast with the overwash potential. For gravel barriers and laboratory conditions, such measurements have been obtained by Matias et al. (2011) as a result of the Bardex Project (Williams et al., 2009). Future application of the overwash depth and overwash potential values should be based on severity scales, to be developed at local, regional or even international levels, as a function of the potential hazard associated with each overwash level. Specific depth damage curves can then be obtained to assess the risk associated with overwash such as already exists for riverine floods.

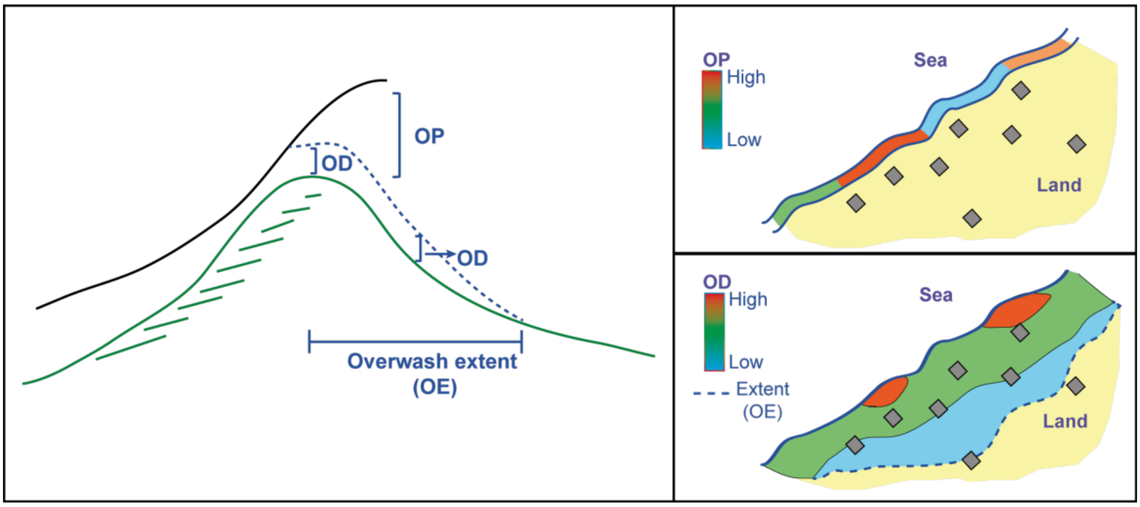

Fig 2. Cross-shore and plan view representing the concept and application of overwash indicators. Grey squares represent the location of the hazard receptors (e.g. houses). OD – overwash depth; OP – overwash potential; OE – overwash extent.

Inundation indicators

Inundation, which is here defined according to the concept proposed by Sallenger (2000), occurs when the storm related still water level (tide + surge) is sufficient to completely and continuously submerge a barrier (i.e. the dune crest or the highest barrier elevation). Inundation should not be confused with overwash, were an intermittent runup level overpasses the barrier for short periods (seconds), and must be treated separately as different time (hours to days) and spatial (larger areas and depths) scales are involved. Important processes for tide/surge interactions that can affect the water level (surge height) are surge propagation during the tidal cycle and wind forcing. The continental shelf depth and width are important factors on the amplification (mainly for shallow and wide shelves) of both processes (see Fortunato et al., 2016). Finally, the storm trajectory and the timing of the storm affect the total water level (Bertin et al., 2012). For small areas, the total water level can be assumed constant but when the inundation affects very large areas a variable level could be applied (Breilh, et al., 2014).

The extent of the inundation can be determined through several methods with different degrees of complexity. A simple bathtub model approach can be used for areas with low morphological complexity (Figure 3). In this method, a given area becomes inundated if its elevation is less than the water level (Poulter and Halpin, 2008) while a vertical water depth can be computed at each point. The method does not account for infiltration, roughness or shear stress and therefore it can lead to overestimation. An adaptation can be performed in order to reduce the level of error on the estimation of the inundated area and water depth by using a tilted water surface (Figure 3) along a sloping plane (see Sekovski et al., 2015) based on historical information and cartography. Problems arise from the application of this simple methodology when the total inundated area is large and therefore the time needed to achieve complete inundation is too long when compared with the actual flooding time. This is particularly valid in inundation areas subjected to tides, where the inundation level can occur for just a few hours. In such cases, more complex methods, such as the flood intensity index (Dottori et al., 2016) should be applied. This index reproduces flooding processes using as theoretical background the 1D uniform flow equation, and considers the vertical differences between the water level at a given source of the flow and the elevation of the adjacent terrain. Inundation models, such as LISFLOOD (De Roo et al., 2000), which can account for lateral connectivity and permeability, can also be used to better represent the inundation area and depth. The main indicator to be used on hazard assessment should be the *flood depth* (see Figure 3) at each hinterland position, which expresses the intensity of the hazard and its variability along each considered coastal region. Other useful indicators worth of mentioning are the *total flood extent* (see Figure 3) from a given reference point (e.g. the shoreline), and the *percentage of flooded area per coastal sector* (from the shoreline to a given previously defined hinterland limit). The *overflowing discharge volume* can also be used. This indicator is a function of the overflow depth at the crest of a dune or dyke multiplied by its length and integrated over time using the rectangular weir discharge equation of Kindsvater and Carter (1957). The extension of the overflowing discharge volume can be calculated by a step by step increase in the water level until the total volume is reached. Similarly, the volume can be used in combination with the tilting bathtub method to compare inundation volumes.

An example of the application of the tilted bathtub method can be found in Sekovski et al. (2015). The authors used both the flood depth (total water level at a given point) and the flood extent to evaluate present-day and future flood hazards at coastal cities from Emilia-Romagna (Italy). An inter comparison of the above methods to assess the inundation caused by the Xynthia storm to La Faute-sur-Mer is provided by Breilh et al. (2013) and Vousdoukas et al. (2016). Furthermore, Vousdoukas et al. (2016) applied the above indicators to assess the flood hazard along the entire European coast. Poulter and Halpin (2008) used and improved the bathtub method by incorporating the hydrological connectivity between grid cells by considering that only cells that have a connection with the open sea or with nearby cells are considered flood-prone. Perini et al. (2016) used the tilted bathtub approach and the Cost Distance tool of ArcGIS to produce a least-path cost analysis and to remove isolated areas without hydrological connectivity in order to improve the final flood maps.

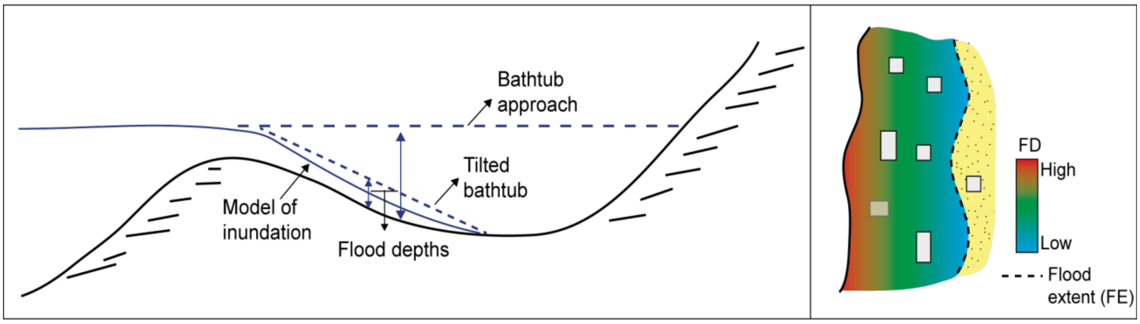

Fig 3. Cross-shore and plan view representing the concept and application of the inundation indicators. White polygons represent the location of the hazard receptors (e.g. houses, hotels). FD – Flood depth; FE – Flood extent.

Erosion indicators

Erosion in this paper simply refers to short-term (episodic) effects driven by storm events or storm groups effecting coastal areas, excluding continuous erosion caused by persistence of sediment scarcity. Storm-induced erosion can be observed as a vertical lowering of the beach/dune system (or by scarp or bluff formation, including subsequent dune avalanching) or as a horizontal inland displacement of the coast (e.g. barrier rollover). The erosion associated with storms will not necessarily result on an overall and definitive displacement of the shoreline since the coast can recover to its original configuration if there is enough sediment available. However, the promoted vertical and horizontal shifts are capable of producing destruction and damages if occupation or other receptors are present. Three main indicators can be proposed: *shoreline/berm retreat*, *dune foot retreat*, and *vertical erosion* (all in meters) at a given point (e.g. dune foot, dune crest, at the infrastructure) (Figure 4). The shoreline/berm retreat and the dune foot retreat represent the horizontal displacement produced by the storm at a given coastal feature (Figure 4), and can be directly compared with occupation to assess vulnerability. The use of the shoreline/berm retreat versus the dune foot retreat as indicators depends very much on the exposed elements to be assessed. For coastal areas with infrastructure located on the beach berm or on the beach face (e.g. bars, amenities) the shoreline/berm retreat should be used, which can then be transformed (or not) into a remaining beach width or into a distance to occupation. For coastal areas where development and infrastructure (e.g. houses, roads) are located on the dune or at the hinterland, the dune foot retreat should be applied. This can also be transformed into a remaining distance to the developed area when necessary/applicable. The use of the shoreline/berm retreat versus the dune foot retreat also depends on the coastal morphology; at sandy coasts without a dune the shoreline/berm retreat should be used. The vertical erosion corresponds to the vertical difference between the original morphology and the computed/observed morphology during and after the storm (Figure 4). Vertical differences can result in potential damage for the existing development on the beach. This indicator can be equally used on the berm, dune or backbarrier, for any storm and given morphological characteristics, allowing the cross-shore determination and comparison of the vertical erosion indicator. The retreat/erosion indicators can be computed by using relatively simple analytical models, such as the convolution model (Kriebel and Dean, 1993), Larson's method (Larson et al., 2004), the erosion structural function (Mendoza and Jiménez, 2006), or the ShoreFor behaviour model (Davidson et al., 2013), among many others. These models use relatively simple analytical formulations that integrate driving mechanisms (such as wave height, storm duration and sea level) jointly with the morphological and sedimentological characteristics of the coastal area (e.g. dune height, berm width, beach slope or grain size) to determine coastal erosion (volume or retreat) induced by each storm. All the above methods deal with swash and collision conditions but not with overwash and inundation. For the later regimes, the erosion processes are different and generally more complex. Process-based models, like XBeach (Roelvink et al., 2009), can also be employed to determine the same indicators, for all regimes and with greater detail but requiring a higher level of computational complexity and available data for model calibration. Process-based models like XBeach reproduce the processes occurring at coastal areas during a storm, containing the essential physics of dune erosion, overwash, avalanching, swash, infragravity waves and wave groups (Roelvink et al., 2009). Finally, if LIDAR (Light Detection and Ranging) or similar resolution/quality data (e.g. from UAVs or satellite imagery) exists for pre- and post-storm conditions the erosion indicators can also be computed based on direct measurements (for example by comparing pre and post storm digital terrain models) and for all storm impact regimes following the method of Stockdon et al. (2007).

According to Ciavola et al. (2015) dune erosion volume, berm retreat or dune height reduction can be used directly or against thresholds to identify areas prone or resistant to erosion hazards. Nevertheless, the use of process-based erosion indicators is not widespread, with trend indicators such as shoreline position, high water line, vegetation line or scarp location (see Hanslow, 2007) being the most widely used. The sub-aerial beach and dune volume are also used as coastal indicators (Hanslow, 2007; Armaroli et al., 2012) but not necessarily as process-based indicators, with exceptions such as the use of the erosion resistance index by Judge et al. (2003), the eroded volume and the beach retreat (e.g. Mendoza and Jiménez, 2006), and the dune stability factor by Armaroli et al. (2012). Examples of use of process-based erosion indicators also include the distance between the dune and the shoreline or the comparison between the momentary coastline position and a given landward boundary, such as the dune foot (see Davidson et al., 2006).

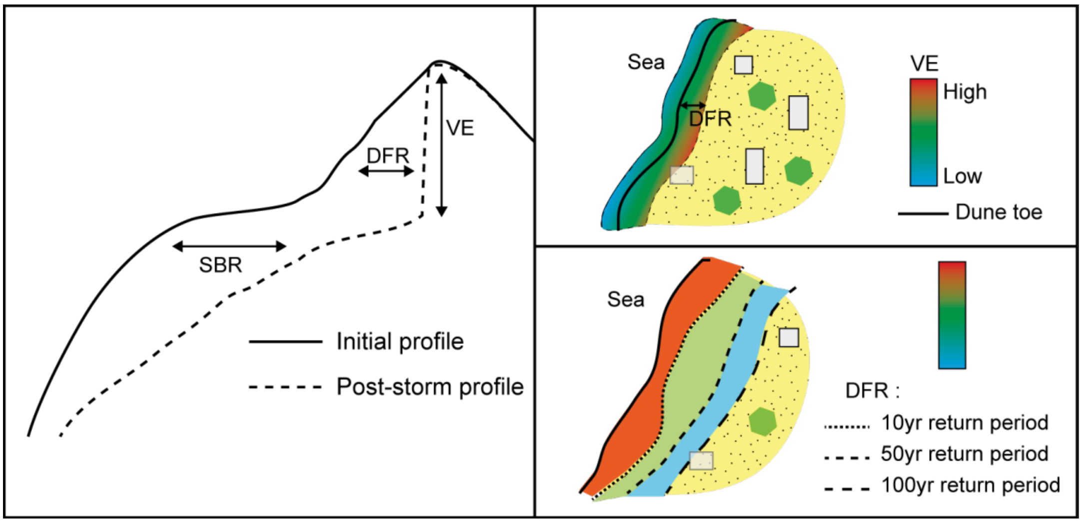

Fig 4. Cross-shore and plan view representing the concept and application of the erosion indicators. White polygons represent the location of the hazard receptors (e.g. houses, hotels). SBR – Shoreline/Berm retreat; DFR – Dune foot retreat; VE – Vertical erosion.

4. Summary of indicators and discussion of use

A synthesis of the reviewed and proposed indicators for three main analysed hazards (overwash, inundation and erosion), on sandy shores, can be found in Table I. The proposed process-based indicators are all simple in concept and refer to a measurable distance, permitting a cartographic expression of the hazard (see figures 2 to 4). Several indicators report a vertical difference to the initial topographic surface (overwash depth, overwash potential, flood depth, vertical erosion) representative of an interaction between driving processes (e.g. water level, runup) and such surface (as is the case for overwash depth, overwash potential and flood depth) or the result of the morphodynamic process measured as a difference between pre and post-event surfaces (vertical erosion). Others (overwash extent, flood extent, shoreline/berm retreat, and dune foot retreat) register the cross-shore extent of the hazard. The alongshore integration of both (vertical and horizontal indicators) allows, in most cases, for an overall three-dimensional cartography of the hazard, including the potentially affected areas and the vertical level of action. That is, for instance, the case of the joint use of the overwash/flood depth and the associated extent. The vertical erosion indicator, since it is immediately associated with an inland position, allows a direct three-dimensional representation of the hazard when expressed alongshore.

The here-reviewed and proposed indicators can be applied on natural sandy (or gravely) beaches with or without dune systems or backbarriers. Although the indicators are not necessarily limited in their use, some of the proposed approaches are, and they can only be applied to coastal areas with low morphological complexity. This includes the case of the determination of the flood depth/extent by using a bathtub (or tilted bathtub) approach. Most of the existing formulations and models are also not completely adapted to heavily developed hinterlands (e.g. dominated by impermeable surfaces) and will require some adaptation. Previous knowledge of the dominant processes during storms will also help to correctly select the methods and indicators to use in the most cost-effective way.

A direct comparison on the applicability of selected (based on the works of Carapuço et al., 2016 and Nguyen et al., 2016) geo- and driver- based indicators against the proposed process-based indicators is expressed at Table II. Most geo- and driver-based indicators are easier to obtain since they can be directly extracted from existing cartography or field measurements (geoindicators) and from instrumental measurements or hindcast predictions (driver-based indicators) often available on-line. They are commonly converted into several simple semi-quantitative values (e.g. from 1 to 5) that are added (quantified) alongshore to permit a representation of the hazard, making them simple to use even for non-experts. They are therefore still used as a simple methodology to classify the coast according to its vulnerability (e.g. Jiménez et al., 2016). They do not, however, account for the acting processes and can therefore affect the final results as observed by Judge et al. (2003) when considering the crest height as a predictor of dune vulnerability. Process-based indicators require both geo- and driver-based information and the additional use of formulations/models, to obtain a final value. If using return periods, a statistical analysis (for either the event or response approach) is also required. This implies, from the users, a higher expertise on coastal dynamics, including the perception of the physical processes acting in coastal areas and responsible for hazards. This reduces the applicability of process-based indicators to users with sufficient background on coastal dynamics. Process-based indicators have, however, several advantages that will, most probably, increase their future use. Most indicators have the possibility of including both detailed longshore variability and cross-shore expression of the hazard, while driver-based indicators have a reduced representativeness of the longshore variability, mainly if wave propagation models are not used. Most used geo and driver-based indicators are also not able to include the cross-shore expression of the hazard (with the exception of the erosion rate).

Geo- and driver-based indicators when used alone are often site-specific and hardly comparable between coastal areas. Process-based indicators present an outcome that can be easily compared among sites. For instance, the vertical expression of a hazard (e.g. flood depth or overwash depth) can be compared between coastal regions with similar settings and a higher value of the indicator will represent a potentially higher hazard. That is not the case for driver-based indicators, for instance. A higher wave height or water level cannot be compared between coastal areas since the hazard will depend on the relationship with the coastal elevation. A lower value of a driver-based indicator can be responsible for a higher hazard if the coastal elevation is low, and the opposite is also valid. This prevents the compared use of geo- and driver-based indicators to assess the hazard for distinct coastal areas. The extensive use of process-based indicators, for different coastal regions will allow, in the future, the development of hazard levels/scales that can be internationally adopted. Since process-based indicators can be associated with a given probability of occurrence and can be directly compared between coastal regions, they can also be used to rank the hazard intensity for vast coastal areas, for equal return periods. It must however be stressed that, for the moment, no universal application of indicators exists and that there are no internationally widely accepted intervals to classify each indicator according to the potential hazard. This is still work to be performed, to be based on the lessons learned from the application of process-based indicators at a large-scale.

The here proposed process-based indicators do not integrate feedback mechanisms resulting from the interaction between morphology and forcing agents (e.g. waves, currents). That is also the case for geoindicators and for indicators solely based on driving mechanisms. The hazard and consequent risk can change as a result of feedback mechanisms. For instance, the lowering of a dune by overwash will increase the overwash potential and the overwash depth, leading to an increase in the hazard when compared with the initial (and considered) situation/morphology. The feedback mechanism can occur differently alongshore, as a function of the nearshore, shoreface and dune morphologies. In cases where feedback mechanisms may be highly relevant, these (and other indexes) may not fully reflect the impacts associated with a given event. In those cases only process-based models with high resolution topo-bathymetric grids, after validation and calibration, may be helpful to better understand the hazard in coastal areas. It must be also kept in mind that the indicators must remain simple in concept and application to ensure their use by most coastal managers. Highly complex indicators requiring extreme computational effort and a high degree of specialization will probably fail to be widely applied by most coastal end-users, including managers.

5. Conclusions, limitations and future improvements

The current use of process-based indicators is still on its infancy, being necessary to establish a set of the most relevant indicators that can better express potential hazards at sandy (and gravelly) shores:

- Overwash: overwash depth, potential and extent;

- Inundation: flood depth and extent;
- Erosion: shoreline/berm and dune foot retreat, and vertical erosion.

The future use of process-based indicators to quantify coastal hazards is recommended, mainly when compared to the most classical and commonly used geo- and driver-based indicators, since they allow:

a) better quantification of the hazard by representing the interaction between forcing mechanisms and morphology;
b) better expression of the alongshore and cross-shore (extent) variability of the hazard, including its three-dimensional representation (longshore, cross-shore and vertical); and
c) comparison between coastal areas.

The development of the process-based indicators' potential will rely on their generalised use in the future. Only an increase in their use will allow the definition of common hazard levels for distinct coastal regions and a large-scale application to vast areas (e.g. at pan-European level). A few limitations still exist that prevent the wider use of these indicators. These include:

i) limited available quality data for several regions, regarding either morphologic and hydrodynamic parameters, which is particularly relevant when long-term time-series (e.g. wave characteristics) are needed to better define return periods;
ii) restricted current use of formulations and models by end-users and namely coastal managers;

iii) reduced possibility of integrating feedback mechanisms, with the exception of the most complex process-based models.

The first limitation will be solved (with time) by the ongoing and increasing improvement on data access (and quality) worldwide, including on-line access to coastal morphology and wave/water level series. To obviate the second limitation an improvement will be needed on the transfer of knowledge from the coastal scientific community towards coastal end-users. The third limitation will be solved by integrating process-based models into user-friendly frameworks for generalised use. The improved and generalised use of process-based indicators will provide coastal managers with a highly relevant tool to evaluate coastal hazards and risks and, therefore, to better establish and implement disaster risk reduction in the future, in the most cost-effective way.

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Table I. Synthesis of process-based indicators by hazard, including calculation methods, input parameters, area of application and potential visual expression. OD – Overwash depth; OE – Overwash extent; FD – Flood depth; FE – Flood extent; SBR – Shoreline/berm retreat; DFR – Dune foot retreat; VE – Vertical erosion. The numbers in brackets refer to works where the indicators application/details can be found.

Hazard	Indicator	Method	Input parameters	Application [References]	Visual expression
Overwash	Overwash potential	Runup formulation (e.g. Holman, Stockdon)	Hs, Tp, sea level, beach face slope, dune crest height	Natural beaches/dunes [1-12]	Linear (along dune crest)
	Overwash depth	Runup formulation (e.g. Holman, Stockdon) + Donnelly formulation for depth decrease	Hs, Tp, sea level, beach face slope, dune crest height, backbarrier topography, overwash lens angle, backbarrier slope	Natural beaches/dunes/backbarriers [13-15]	2D with 3D possibility in association with OE
		Numerical models (e.g. XBeach)	Nearshore wave conditions (Hs, Tp, direction); topo-bathymetry	Natural beaches/dunes/backbarriers [16, 17]	2D with 3D possibility in association with OE
	Overwash extent	Donnelly Washover extent Formulation/XBeach	Hs, Tp, sea level, beach face slope, dune crest height, backbarrier topography, overwash lens angle, backbarrier slope/Nearshore wave conditions (Hs, Tp, direction); topo-bathymetry	Natural beaches/dunes/backbarriers [13-15, 18]	2D with 3D possibility in association with OD
Inundation	Flood depth/extent	Bathtub or tilted bathtub	Total sea level (tide + surge); Topography	Coastal areas with low morphological complexity [19-26]	2D with 3D possibility in association with FE/FD
	Flood depth/extent	Numerical models (e.g. LISFLOOD) or semi-static approaches	Water discharge/level; Topography	Low to complex hinterland morphologies [19, 24, 26]	3D
	Overflowing discharge volume	Numerical models (e.g. LISFLOOD) or semi-static approaches	Water discharge/level; Topography	Low to complex hinterland morphologies [19, 26]	3D

Erosion	Shoreline/berm retreat; Dune foot retreat; Vertical erosion	Convolution model; Larson's model; Erosion structural function	Nearshore wave conditions (Hs, Tp, direction); topo-bathymetry	Natural beaches/dunes [3, 13, 27-32]	SBR and DFR - 2D; VE - 3D
		Numerical models (e.g. XBeach)	Nearshore wave conditions (Hs, Tp, direction); topo-bathymetry	Natural beaches/dunes [16, 33-35]	SBR and DFR - 2D; VE - 3D

[1] Almeida et al., 2012; [2] Armaroli et al., 2012; [3] Bosom and Jiménez, 2011; [4] Del Rio et al., 2012; [5] Duran et al., 2016; [6] Haerens et al., 2012; [7] Long et al., 2014; [8] Matias et al., 2014; [9] Rodrigues et al., 2012; [10] Silveira et al., 2017; [11] Stockton et al, 2007; [12] Trifonova et al., 2012; [13] Ferreira et al., 2016; [14] Christie et al., 2017; [15] Valchev et al., 2016; [16] Poelhekke, et al., 2016; [17] van Verseveld , et al., 2015; [18] Garcia et al., 2010; [19] Breilh et al., 2013; [20] Dottori et al., 2016; [21] Hinkel, et al., 2014; [22] Perini et al., 2016; [23] Poulter and Halpin, 2008; [24] Ramirez et al., 2016; [25] Sekovski et al., 2015; [26] Vousdoukas et al., 2016; [27] Almeida et al., 2011; [28] Callaghan et al., 2008; [29] Ciavola et al., 2015; [30] Davidson et al., 2006; [31] Jiménez et al., 2016; [32] Mendoza and Jiménez, 2006; [33] McCall et al., 2010; [34] Smollegan et al., 2016; [35] van Verseveld et al., 2015.

Table II. Comparison between computation type, longshore variability, comparability among coastal areas and cross-shore expression for selected geo, driver and process-based indicators.

Indicator type	Indicator name	Computation type	Longshore variability	Hazard comparability between coastal areas	Cross-shore hazard expression
Geoindicators	Shoreline position	DM/CE	Yes	Reduced	No
	Barrier/beach elevation	DM/CE	Yes	Reduced	No
	Beach/coastal slope	DM/CE	Yes	Reduced	No
	Erosion rate	CE/F/M	Yes	High	Yes
Driver-based indicators	Wave height	I/H	Reduced/Yes [a]	Reduced	No
	Tidal range	I/H	Reduced	Reduced	No
	Surge height	I/H	Reduced	Reduced	No
Process-based indicators Overwash	Overwash depth	F/M	Yes	High	Yes
	Overwash potential	F/M	Yes	High	No
	Overwash extent	F/M	Yes	High	Yes
Process-based indicators Flood	Flood depth	F/M	Yes	High	Yes
	Flood extent	F/M	Yes	High	Yes
Process-based indicators Erosion	Shoreline/berm retreat	F/M	Yes	High	Yes
	Dune foot retreat	F/M	Yes	High	Yes
	Vertical erosion	F/M	Yes	High	Yes

[a] requires wave propagation models to include detailed lonsghore variability near the coastline;
DM – direct measurement; CE – cartographic extraction; I – instrumental; H – hindcast; F – formulation; M – model.