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Assessment of overwash-induced flooding at two beaches along the southwest Algarve, Portugal

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ABSTRACT

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At the Algarve south coast overwash-induced floods are a frequent and destructive phenomenon. In this study return periods for overwash potentials are estimated for two beaches located at the southwest coast of the Algarve (Carvoeiro and Salema) based on runup calculations for the period 1995-2017 after applying two well validated empirical formulations. Results show that overwash potentials are high even for small return periods. Additionally, the suitability of two different indicators (overwash potential and overwash depth) has been tested to represent the flood extent. Results suggest that the flood extent derived from the overwash depth presents several limitations and cannot realistically represent observations, while the flood extent given by the overwash potential (using a simple bathtub approach) fairly represents the overwash-induced flood, even though it can over/underestimate the flood extent for gentle/steep inland slopes. Flood extents derived from the overwash potential, for return periods of 10- and 100-year, show that occupied areas are potentially flooded for both return periods. It is therefore necessary to define appropriate adaptation measures for both beaches, preferably based on detailed risk assessment.

ADDITIONAL INDEX WORDS: *runup, return periods, overwash potential, overwash depth*

INTRODUCTION

Enhanced development at the worlds' coastal zones has led to an increased coastal vulnerability towards storm-induced hazards and to a consequent increase of the potential risk at coastal areas. One particular storm-induced hazard, with a high potential to cause damages on beaches backed by infrastructures, is overwash. Overwash is here considered according to the definition provided by Sallenger (2000), occurring when the maximum runup level exceeds the height of the dune, berm crest or landward beach limit (in absence of dune crest). In the case of urbanised beaches, extreme overwash events can cause severe floods leading to damage on coastal properties and infrastructure (Silveira *et al.*, 2016). Assessing how prone these urbanised beaches are towards wave-induced floods is essential to estimate the potential damage associated to extreme overwash. Overwash and associated impacts have been studied mostly on barrier islands or low-lying beaches (Donnelly *et al.*, 2006; Matias *et al.*, 2013; Morton and Sallenger, 2003; Plomaritis *et al.*, 2018; Rodrigues *et al.*, 2012), or on gravel barriers (Matias *et al.*, 2012; McCall *et al.*, 2012). Studies of their effects on urbanised beaches, and on pocket/embayed beaches are still scarce.

The Algarve south coast is one of the European coastal areas facing intense urban development due to fast growing tourism. Even though it is relatively sheltered from strong wave action, storm waves can induce intense overwash and shoreline retreat. The dense touristic development near the beaches increases the risk levels at this coast.

The wave runup height is an essential parameter to estimate overwash and to predict storm effects, and has been parameterised by several studies with various approaches (Battjes, 1974; Holman, 1986; Stockdon *et al.*, 2006). Such parameterisations use as main factors the beach face slope $\tan\beta$, the deep-water wavelength L_0, and the deep-water significant wave height H_S. For determining maximum runup levels, the wave setup and the storm surge are added to the sea level at the time of the storm. The main goals of this study are to compute overwash potentials and corresponding return periods at two urbanised beaches from the south coast of the Algarve, southern Portugal. The latter were used to estimate associated flood extents to illustrate the potential impact associated to overwash at the selected sites.

STUDY AREA

The southwestern part of the south facing coastline of the Algarve, southern Portugal, is characterised by sea-cliffs interrupted by small embayments with sandy pocket beaches. The mean tidal range is 2.2 m, reaching 3.5 m during spring tides (mesotidal regime). The mean offshore significant wave height is about 0.9 m and the mean peak period 8 s. Circa 71 % of all waves arrive from W-SW directions, while 23 % are from E-SE (Costa *et al.*, 2001). As a consequence, two main storm directions dominate,

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with about 2/3 coming from W-SW and 1/3 from E-SE directions (Oliveira *et al.*, 2018). To capture overwash-induced flooding by both dominant wave directions, the selection of the beaches depended on their wave exposure (W-SW and S-SE).

The beach of Salema is located at the western part of the Algarve south coast, close to Cape St. Vincent (Figure 1) and is oriented towards S-SE. The beach has a variable length of 600 m to 1100 m, being laterally constrained by headlands and vertically by a rocky shore platform. It is a reflective to intermediate beach, with an average beach face slope of 0.11 (Bon de Sousa, 2016), often presenting a low tide beach terrace (Loureiro *et al.*, 2013). It is composed of a thin layer of medium to coarse sand, overlying cobble and boulder layers. As Salema faces S-SE, waves of the dominant SW swell, as well as waves coming from SE directions reach this beach (Loureiro *et al.*, 2012). Salema is backed by an urbanised area. At the western part, a seawall marks the limit of the beach, while at the eastern part restaurants and houses spread along a narrow low-lying promenade adjacent to the beach.

The beach of Carvoeiro, located eastwards, between Portimão and Albufeira (Figure 1), faces southwest and is protected from the SE waves by a headland. Carvoeiro is a small pocked beach (ca. 150 m-long), backed by sea-cliffs cut into biocalcarenites from the Miocene. The beach is composed of fine to coarse sands, and has an average beach face slope of 0.15 (Bon de Sousa, 2016), corresponding to a reflective beach. Carvoeiro is densely populated with infrastructures and buildings extending from the top of the cliffs to the valley where a promenade, more buildings and a car parking space contact with the adjacent beach.

Figure 1: The southwest coast of the Algarve, southern Portugal, with the two studied beaches, Salema and Carvoeiro (Source: Google Earth). The red line (wall) indicates the area under analysis.

METHODS

The two main indicators reflecting overwash induced hazards are: overwash potential (OP) and overwash depth (h_c) (Ferreira *et al.*, 2017). OP is defined as the vertical difference between the potential wave runup (along an imaginary extended beach/dune slope) and the dune/beach crest elevation (Matias *et al.*, 2012). h_c can be defined as the water depth at a point (dune crest or back-barrier) during an overwash event. To estimate OP, h_c and the corresponding return periods for Carvoeiro and Salema, the runup was calculated by applying and comparing two different empirical formulations for all storms identified between 1995 and 2017. The offshore wave parameters (significant wave height, H_s, peak period, T_p and direction) were obtained from the wave buoy from the Portuguese Hydrographic Institute, located off Faro, while the sea level (tide + storm surge) was obtained from the tide gauge of Huelva (belonging to Puertos del Estado, Spain), for the considered time span. Wave data were available at 3-hour time intervals, and at 30 min during storm conditions, while sea level data was available at each 5 minutes. The tidal levels of Huelva, referenced to the mean sea level (MSL) in Alicante (southern Spain), were corrected for the Portuguese MSL. Storms were defined as independent wave conditions of $H_s > 2.5$ m for at least 3 h (Oliveira *et al*., 2018). A database was created joining all wave and sea level data along all storm periods, at intervals of 30 minutes (or 3 h when data were not available with higher frequency). Moreover, conditions where $T_p >$ 15 s were also integrated in the database, since overwash can also occur for non-storm conditions with long waves (Matias *et al.*, 2010). For Salema, waves coming from both directions, SE and SW, were considered, here referred as SalemaSE and SalemaSW. Since Carvoeiro is only directly exposed to SW waves, only the SW wave directions were considered for the analyses.

Runup

The two selected approaches to calculate runup R are the ones of Holman (1986) and Vousdoukas *et al.* (2012; equation 13, including tidal effect). Both formulations have been widely applied to calculate runup and are well validated (Atkinson *et al*., 2017). According to Almeida *et al.* (2012), Holman's approach is a better predictor of runup for the Algarve than Stockdon *et al.* (2006) while Vousdoukas' equation was derived specifically for beaches along the south coast of the Algarve.

The final computation of the runup level was performed by adding R to the sea level (tide + storm surge) for all storm (and T_p > 15 s) conditions at the database, considering waves arriving from SE and SW quadrants separately.

Overwash potential, overwash depth and flood cartography

Estimating OP requires elevation data to define a threshold value to be exceeded by runup. These values were obtained by taking elevations with a DGPS/GNSS system along the inland beach limit (see red lines in Figure 1). This border consists of low-lying walls, separating the beaches from the adjacent infrastructures. Considered threshold values represent the average of the elevation data obtained along each measured transect and therefore the average elevation of the boundary beach/occupation. The computed elevation thresholds are 5 m for Carvoeiro and 4.46 m for Salema.

For both used formulations the response approach (Bosom and Jiménez, 2011) was applied, meaning that the entire forcing parameter time-series was used to compute runup time-series for Carvoeiro, SalemaSW and SalemaSE. To obtain all overwash events, a peak over threshold analysis was applied. Thereby, only runup values that exceeded the identified elevation thresholds (5 m for Carvoeiro and 4.46 m for Salema) were selected. The maximum OP of all overwash events during each storm was extracted and considered as the representative OP of the storm (or event with T_p > 15 s). To obtain the OP probability distribution, a Generalised Pareto Distribution (GPD) was fit to all storm representative OP for each beach and wave direction separately. The return period is the inverse of the calculated probability.

A digital terrain model (DTM) of the Algarve south coast with a horizontal resolution of 2 m, obtained by LiDAR in 2011 (data from Direção Geral do Território), was used to create flood maps, in which the flood extent is represented by the landward extension of the overwash derived from the OP or h_c approaches. Note that the DTM does not include buildings, and thus the maps show a theoretical extent, as if buildings would not exist. The overwash extent associated with h_c was calculated after Plomaritis *et al.* (2018, eq. 7):

Table 1: Overwash potential (OP) for selected return periods (in meters).

		Carvoeiro		SalemaSW		SalemaSE	
	Return period	Holman (1986)	Vousdoukas *et al.* (2012)	Holman (1986)	Vousdoukas *et al.* (2012)	Holman (1986)	Vousdoukas *et al.* (2012)
1995-2017	10 year	2.00 m	1.98 m	1.76 m	1.78 m	1.18 m	1.54 m
	25 year	2.58 m	2.36 m	2.12 m	2.06 m	1.58 m	1.74 m
	50 year	2.98 m	2.56 m	2.32 m	2.20 m	1.88 m	1.86 m
	100 year	3.34 m	2.70 m	2.50 m	2.30 m	2.20 m	1.94 m

$$h(x) = h_c exp(-a * x/u_c) \qquad (1)$$

where a is the proportionality constant for infiltration, u_c is the flow velocity at the barrier crest and $h(x)$ the overwash depth at distance x. To determine the maximum flood extent, a minimum $h(x) = 0.05$ m was considered, following Plomaritis *et al.* (2018). The computation of h_c and u_c were performed applying the formulations proposed by Donnelly (2008). The infiltration constant was tested for both values proposed in literature (0.01 for impermeable surfaces and 0.12 for sandy areas). The results obtained for $a = 0.01$ were unrealistic and thus a value of 0.12 was assumed, although the flood areas are partially impermeable. The value of the tangent of the runup lens was computed by using a linear interpolation from the values presented in Plomaritis *et al.* (2018; Table 1), for the beach face slopes at the study sites. When considering h_c, the flood extents were computed as simple distances (x) from the wall that separates the beaches from the occupation. For the OP indicator the flood extents were computed using a simple bathtub approach in ArcMap. Flooded areas were then calculated with the assumption that all cells below the OP elevation and above the elevation threshold (walls) are temporarily flooded (Seenath *et al.*, 2016).

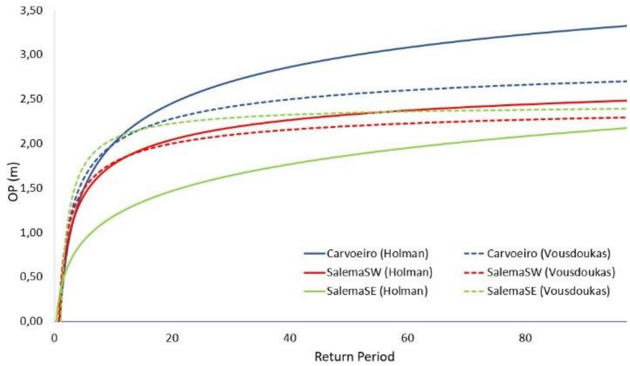

Figure 2. Return periods of the overwash potentials for both beaches and wave directions, calculated using Holman (1986) and Vousdoukas *et al.* (2012) equations for the period 1995-2017.

RESULTS

Overwash return periods

The OP values have been calculated for different return periods by using the equations of Holman (1986) and Vousdoukas *et al.* (2012) and afterwards compared (Table 1; Figure 2). Carvoeiro shows higher OP values for the same return periods, as a function of the higher beach face slope. SalemaSE (waves from SE) has always smaller OP values than SalemaSW (waves from SW) since the SE storm regime generically has lower energy than the SW one.

For a 10-year return period, the computed values do not differ much between equations for the same beach/wave conditions, with a minimum difference of 2 cm at Carvoeiro and SalemaSW and a maximum of 36 cm at SalemaSE (Table 1; Figure 2). The longer the return period, the higher the discrepancies of the estimated OP between both formulations, with Holman (1986) always giving higher values. The differences for the 100-year return period range between 20 cm in SalemaSW and 64 cm in Carvoeiro. For SalemaSE the results of the two equations differ more for short return periods than for longer return periods. This is probably an artifact from the GPD adjustment (Figure 2) due to the lower number of overwash events obtained for SE conditions.

Flood cartography

Due to the relatively small differences in the results for both formulations (Holman and Vousdoukas) and being Vousdoukas *et al.* (2012) validated for a beach close to the study area, this equation was used to produce flood maps and flood projections for Salema and Carvoeiro. The flood extent was calculated using the OP and the h_c indicators for both beaches. To compare the differences between them, the 10-year return period was chosen as an example (Figure 3).

In Salema, the flood extent associated with h_c is bigger than the one given by OP (Figure 3, upper panel). The h_c extent indicates that a vast part of the occupation is flooded. According to witness's observations and statements, the Emma storm (March 2018; return period between 15-20 years) caused overwash-induced floods, which reached 27 m inland until an elevation of approximately 8 m, impacting the first rows of houses after the promenade and the road behind them. The h_c method gave 45 m of overwash extension for a 10-year return period, suggesting an overestimation of the extent by this indicator. The OP method gives a total runup elevation of 6.8 m for a 10-year return period (below the 8 m observed for Emma storm, with a higher return period), which seems to provide results in agreement with the observations.

At Carvoeiro (Figure 3, bottom right image) the flood extent given by the h_c indicator is much smaller (53 m) than the maximum extent given by OP (230 m) for the 10-year return period. A direct comparison between recorded flood events and theoretical computations was done by using videos from storm Hercules (January 2014). During this storm, overwash flooded the promenade and the road, reaching approximately 80 m inland, until an elevation of ca. 5.4 m. For the same storm, the runup calculations with Vousdoukas *et al.* (2012) reached a height of 5.56 m (OP of 0.56 m; a reasonable adjustment) and thus an extent of 85 m. The longer extent of the OP indicator results from the small inland slope, with the bathtub approach leading to overestimation of the overall flooded area. Nevertheless, the OP indicator was considered a better predictor for both Salema and Carvoeiro and was chosen as a best fit (for this coastal area) to estimate overwash induced flood projections for different return periods.

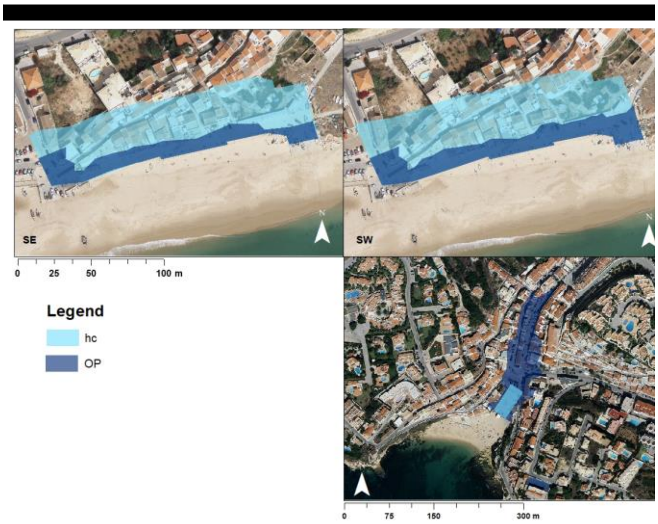

Figure 3. Overwash induced flood computed for the overwash depth (h_c) and the overwash potential (OP) indicators for a 10-year return-period. The upper panel shows SalemaSE and SalemaSW (the scale is valid for both images). The bottom panel shows Carvoeiro.

Overwash-induced flood projections were estimated for several return periods, with the ones of 10-year and 100-year return periods being presented in Figure 4. At SalemaSE/SW (Figure 4, upper image) the flood for a 10-year return period reaches a maximum inland extent of 16/25.3 m, measured from the wall (Figure 1), while the 100-year extent reaches 25/26.9 m. For Carvoeiro (Figure 4, bottom image), the OP flood extent for a 100-year return period reaches a maximum inland extent of 300 m inland against 230 m computed for the 10-year return period.

Figure 4. Flood extent computed for the overwash potential with a 10-year and a 100-year return period, using Vousdoukas *et al.* (2012) for the period 1995-2017. The upper panel shows SalemaSE and SalemaSW (the scale is valid for both images). The bottom panel shows Carvoeiro.

DISCUSSION

Return periods

The return periods of the OP computed with both used formulations (Holman and Vousdoukas) vary mostly for longer return periods. This can be partly explained by the different parameters accounted for in the runup formulations. While Holman (1986) only considers wave setup and swash, Vousdoukas *et al.* (2012) additionally consider tides. The larger difference for the shorter return periods in SalemaSE can be explained by the small number of overwash events used to perform the adjustment for that wave direction, with the GPD not completely describing the runup behaviour for SalemaSE. The Chi^2 and the Kolmogorov-Smirnov tests for the fitted GPD for SalemaSE events produced small p-values. A better fitting distribution would require a larger data series.

Flood extents by overwash potential and depth

Both indicators used to represent the flood extent (OP and h_c), are rather theoretical. The OP bathtub approach does not account for processes such as flow velocity or discharge, infiltration or friction. For low inland slopes it increases the flooded area while for very steep slopes probably decreases it. The computation of the overwash extent based on the h_c indicator was originally designed for steep beaches and hard structures. For a reasonable application, several changes had to be incorporated, such as the use of infiltration, considering an inland sand substrate (which is not true for the study areas), and the adaptation of the value of the tangent of the runup lens as a function of each beach face slope.

The validation of the overwash-induced flood extent has shown that extents derived from h_c either overestimated (Carvoeiro) or underestimated (Salema) the flood extent (Figure 3) when compared to observations. This suggests the need for improvement of the formulation and parameters to be used, namely as a function of the inland slope and of the area's permeability. The extent associated to the OP (using a simple bathtub approach) results in smaller errors and the method is easier to apply. This method should only be applied at sites where the runup can keep flowing along relatively steep and impermeable areas.

Since both beaches are backed by relatively dense infrastructure (roads, promenades, car parking), the overwashed zones are mostly impermeable. In Carvoeiro, the slope of the area immediately behind the beach is rather small, which explains the computed high extents and probable overestimation given by the OP indicator. At Salema, on the other hand, the slope of the area immediately behind the beach is steeper, and the overall flood extension given by the OP indicator seems reasonable (or may even be underestimated).

Implications for occupation

The hazard areas associated with floods caused by overwash with a 10- and a 100-year return period (Figure 4) show that there is a possibility of flooding, and eventual damages to occupation, at both locations, even for the 10-year overwash event. Despite the over/underestimations in Carvoeiro/Salema the maps can be seen as a first attempt to characterise potential areas of overwash impact at these sites. They can also serve as the basis to implement adaptation measures for risk reduction. One adaptation solution would be beach nourishment, increasing the water infiltration and decreasing the runup energy before reaching the occupied area. Estimating the risk of overwash-induced floods requires a detailed risk assessment, including the incorporation of the value (economic and cultural) of the potential areas to be affected.

CONCLUSION

The present study has shown that return periods for overwash potentials could be estimated for two selected field sites, Salema and Carvoeiro, in southern Portugal, by applying simple methods, i.e. two validated empirical formulations (Holman and Vousdoukas). The analysed beaches are occupied by important infrastructures (roads, restaurants, hotel, car parking), exposed to the overwash-induced flood. The computation of a potential flood area was tested by using the extent associated to both the overwash potential and overwash depth indicators. The flood extent computed using the overwash depth indicator requires further improvement. The extent associated to the overwash potential indicator seemed to better represent the flood than the overwash depth when compared to observations, which produces an overestimation in Carvoeiro and probably an underestimation in Salema. Thus, the overwash potential indicator can be applied as a first assessment of the overwash induced flood extensions at beaches with a steep slope and impermeable areas behind.

At the study areas, human occupation is expected to be affected by overwash events with less than 10-year return periods. This situation will aggravate with sea-level rise, demanding the elaboration and implementation of adaptation measures to reduce and minimise the risk.

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