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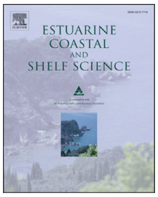

# Study of wave runup using numerical models and low-altitude aerial photogrammetry: A tool for coastal management

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## ABSTRACT

Monitoring the impact of sea storms on coastal areas is fundamental to study beach evolution and the vulnerability of low-lying coasts to erosion and flooding. Modelling wave runup on a beach is possible, but it requires accurate topographic data and model tuning, that can be done comparing observed and modeled runup. In this study we collected aerial photos using an Unmanned Aerial Vehicle after two different swells on the same study area. We merged the point cloud obtained with photogrammetry with multibeam data, in order to obtain a complete beach topography. Then, on each set of rectified and georeferenced UAV orthophotos, we identified the maximum wave runup for both events recognizing the wet area left by the waves. We then used our topography and numerical models to simulate the wave runup and compare the model results to observed values during the two events. Our results highlight the potential of the methodology presented, which integrates UAV platforms, photogrammetry and Geographic Information Systems to provide faster and cheaper information on beach topography and geomorphology compared with traditional techniques without losing in accuracy. We use the results obtained from this technique as a topographic base for a model that calculates runup for the two swells. The observed and modeled runups are consistent, and open new directions for future research.

## 1. Introduction

The administrative Region of Liguria (Italy, NW Mediterranean) is often hit by severe storms (Parodi et al., 2012; Rebora et al., 2013; Fiori et al., 2014), that are usually associated with high waves, or sea storms, hitting the coastline (Orlandi et al., 2008; Pasi et al., 2011). As most of the coastal urban development in the Region happens near the shoreline with few physical barriers to stop wave runup, the main damages caused by extreme wave events are due to sea waves hitting infrastructures such as roads and railroads or commercial properties, such as beach resorts that are kept on the beach also during the winter season. This scenario is common to the majority of Italian and Northern Mediterranean coastal areas (Jiménez et al., 2011). Here, one need of coastal managers is to assess the impact of extreme wave events in the immediate aftermath of a storm or, more adequately, to be able to predict to some extent the areas more vulnerable to runup of extreme swells (Ruggiero et al., 2001). To do this, it is necessary to have on one side accurate and timely data on coastal topography, geomorphology and impact of the swell. On the other side, models calculating the maximum runup of swell waves can be implemented if the coastal topography and wave parameters are known with sufficient accuracy.

The main tools that can be employed to obtain reliable topographic and geomorphological data in coastal areas are LIDAR or aerial surveys (e.g. White and Wang, 2003). In a large effort to provide reliable topographic data for the Italian coastlines, the Italian ministry of Environment is performing coastal LIDAR surveys along the national coasts, and recently made available coastal

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orthophotos from its web portal (www.pcn.minambiente.it). Airborne techniques have the advantage of providing wide coverage and accurate topography (point cloud and orthophotos), but their high cost and the necessity to deploy an aircraft to obtain such data makes virtually (and economically) impossible to perform surveys repeated regularly in time or each time that a sea storm hits the shoreline of interest. The solution is therefore to adopt surveys on the ground (Morton et al., 1993; Cariolet and Suanez, 2013), that are more repeatable in time, renouncing to the detail that a point cloud and an orthophoto can give.

In an ideal situation, if the topography of a beach is known with sufficient detail and wave data are available from an offshore buoy, it is possible to implement a model that simulates the runup along transects on the shore. Varying the intensity and direction of the swell, one could perform pre-event assessments of the runup, which are the information ultimately necessary to coastal managers to assess the expected damages due to incoming waves. The weak point of such workflow is that before being used in this way, a validation process that uses observations to tune model parameters for the specific area is necessary.

In order to validate a runup model for an area, one needs accurate topographic data of the beach and the evaluation of the runup elevation repeated for a different set of sea storms with different wave height, period and direction. The ideal setting would be to repeat LIDAR and orthophoto surveys after each event to detect the maximum wave runup and compare it with the modeled one to perform a best-fitting analysis and ultimately tune the model parameters in the area of interest. To do this, either costs are too high or one needs to abandon the synoptic view and rely on ground surveys, which can cover smaller areas.

In this paper we show a workflow that, starting from rapid surveys performed with Unmanned Aerial Vehicles (UAVs), allowed us to obtain accurate beach topography and information on observed wave runup for two sea storms in the Ligurian Sea, NW Mediterranean. We then set up a modeling chain, which includes concatenated wave and runup models, and compare modeled and observed runup values. We conclude that this workflow is rapid, low-cost and effective, and can be exported in other Mediterranean areas.

## 2. Methods

As outlined in the introduction, in this paper we propose a workflow to obtain runup observations and compare them with modeled runup values. The workflow is summarized in different steps hereafter, while in the next sections we describe more in detail the study area and the different aspects of the methodology employed.

1) We collected aerial photos of the study area immediately after two swell events.
2) From the first set of aerial pictures and a set of ground control points surveyed with high-accuracy GPS we obtained orthophotos and Digital Elevation Models using photogrammetric techniques.
3) We merged the beach topography with bathymetric datasets, then we extracted topographic transects that were used as an input to a runup model. From the orthophotos, we extracted the position of the maximum wave runup.
4) We retrieved wave data (specifically period, direction and height) from an offshore buoy, and we took into account all the processes affecting wave propagation implementing a wave model.
5) Using the outputs of the wave model in our study area and the topography calculated from step 4 we ran a runup model with the parameters set after literature studies and a sensitivity test conducted comparing the modeled values against observed data.

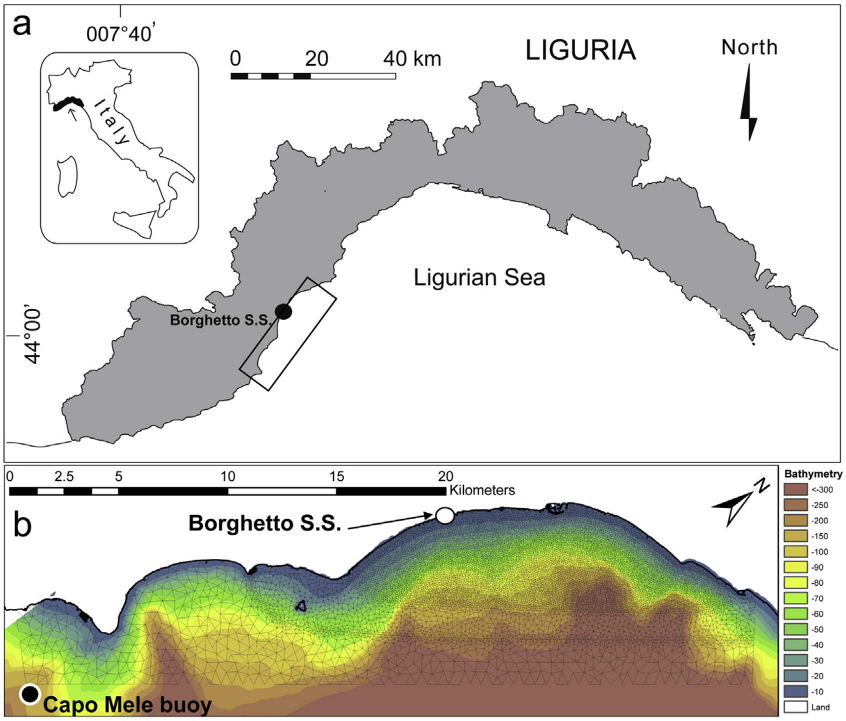


**Fig. 1.** a) Location of the town of Borghetto S.S. (Black dot) in Italy and in the Liguria Region. The small rectangle represents the area detailed in b); b) Area where the MIKE21 Spectral Wave (SW) model has been implemented. The figure shows the bathymetry and mesh used.

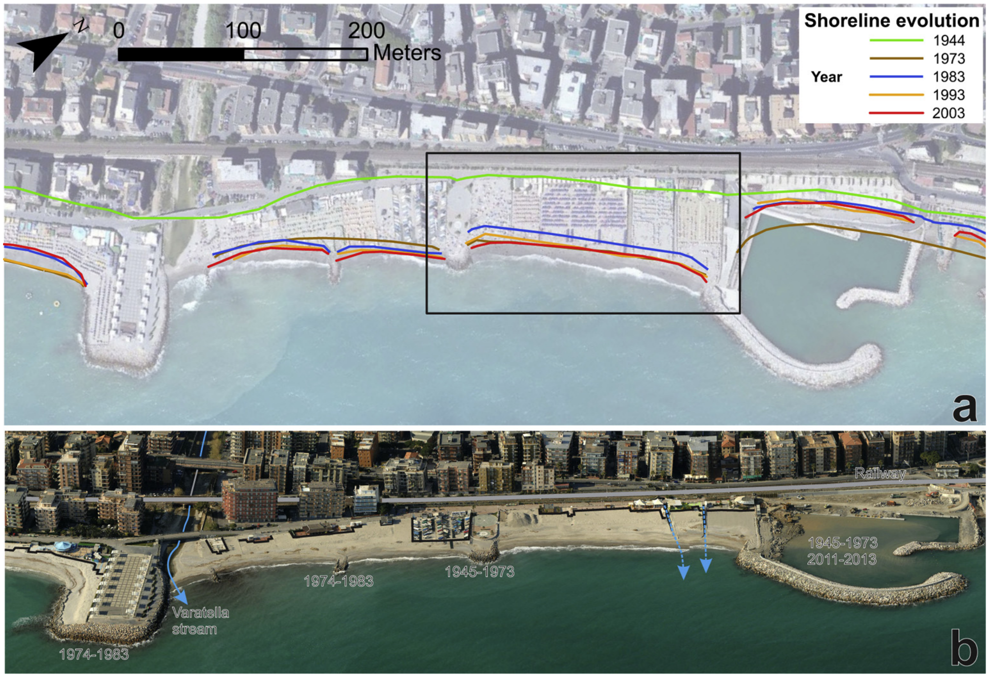


**Fig. 2.** a) Long-term shoreline evolution in the proximity of the study area. Shoreline data were derived from the official coastal cartography of Regione Liguria (http://www.cartografiarl.regione.liguria.it/SiraWebGis/IndiceCarte_PT.asp?idCanale=SICOAST); black box indicates the study area where UAV surveys were performed and wave runup was calculated b) Perspective photography (Courtesy Regione Liguria) showing the same area of a). Blue arrows indicate the sources of major (continuous) and minor (dashed) sedimentary inputs. The black solid line indicates infrastructures on the coast, which remain also during the winter season. Years of construction of the main defensive structures are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 2.1. Study area

The study area is located in Italy, in the Liguria Region, Province of Savona, in the municipality of Borghetto Santo Spirito (Fig. 1a). Borghetto is a town with about 5000 residents, which nearly triplicate during the summer season since the town is a touristic destination for summer holidays. As a consequence, in this area the pressures on the coast are high: in some parts of the municipal territory, infrastructures and living areas are located less than 50 m from the shoreline (Rovere et al., 2010, 2014). The municipality of Borghetto has a waterfront that extends for ~1.7 Km. The coastline is composed by a large beach, whose sediments are provided mainly by the Varatella river (Figs. 2a,b) and by other small watercourses.

Since 1870, when the railroad was constructed, the coastline in our study area has suffered severe erosion problems, which caused the shoreline to retreat until it started to endanger the position of the railway in 1944 (Fig.2a). The situation of erosion was exacerbated by the fact that, to build the railway, sands and boulders were also extracted from the Varatella river, therefore decreasing the (already low) sedimentary input (Fierro et al., 2010). Since 1944, the coastline has been affected by engineering works aiming at the protection of the coast from marine erosion (Fig. 2b). Since the 60s, the shoreline has been object of several interventions of beach nourishment and coastal engineering (Fierro et al., 2010). As an example, the entire beach of Borghetto has been renourished in 2003 and 2007 with a total amount of ≈2000 cubic meters of sand.

Our study area is located in the westernmost part of the municipality of Borghetto S. Spirito. This area is the only one that still receives sediments from the Varatella river. Here a small touristic harbor has been recently constructed (Figs. 2a,b, right) exploiting a pre-existing jetty that was built and modified over the period 1945–1973 (Fig. 2b). The large jetty located in proximity of the river (Figs. 2a,b) and the new harbor create a quasi-closed littoral cell, that has very few sediment exchanges with the nearby areas.

### 2.2. Unmanned aerial vehicles

In this work we used two different UAVs to collect aerial photographies of the study area. The first is a Mikrokopter Okto XL mounting a Canon G11 camera. This kind of system has already been successfully employed in different studies (e.g. Niethammer et al., 2010, 2012; Colomina and Molina, 2014). The second UAV we used is a DJI Phantom, a smaller quadrocopter that we fitted to mount a Canon PowerShot SD940 IS. The SD card of the camera was Canon Hack Development Kit (http://chdk.wikia.com/wiki/CHDK), a firmware that allows implementing a customized intervalometer script to command the camera to take photographs at user-specified time intervals (Koh and Wich, 2012). A picture showing the two UAVs employed in this study is available in the Supplementary materials.

We flew both UAVs at heights of ~80 m above ground in conditions of calm winds. We did two flights on the study area immediately after two sea storms: the first flight was the 15th April after the low-intensity sea storm of the 13th April 2013 and was done with the Mikrokopter while the second flight was done with the DJI phantom the 27th December right after the high-intensity sea storm of the 25th-26th December 2013. As a reference, we highlight that, in the Ligurian Sea, a significant wave height of ~7 m has a return time of about 50 years (Corsini et al., 2006). Each flight resulted in a total of ~130 photos shot at ~90° angle (i.e. the camera pointing almost perpendicular to the ground). Excluding blurred or moved pictures and the areas where less than 9 pictures overlapped, we ended up having ~90–100 pictures for each flight as input for the software workflow.

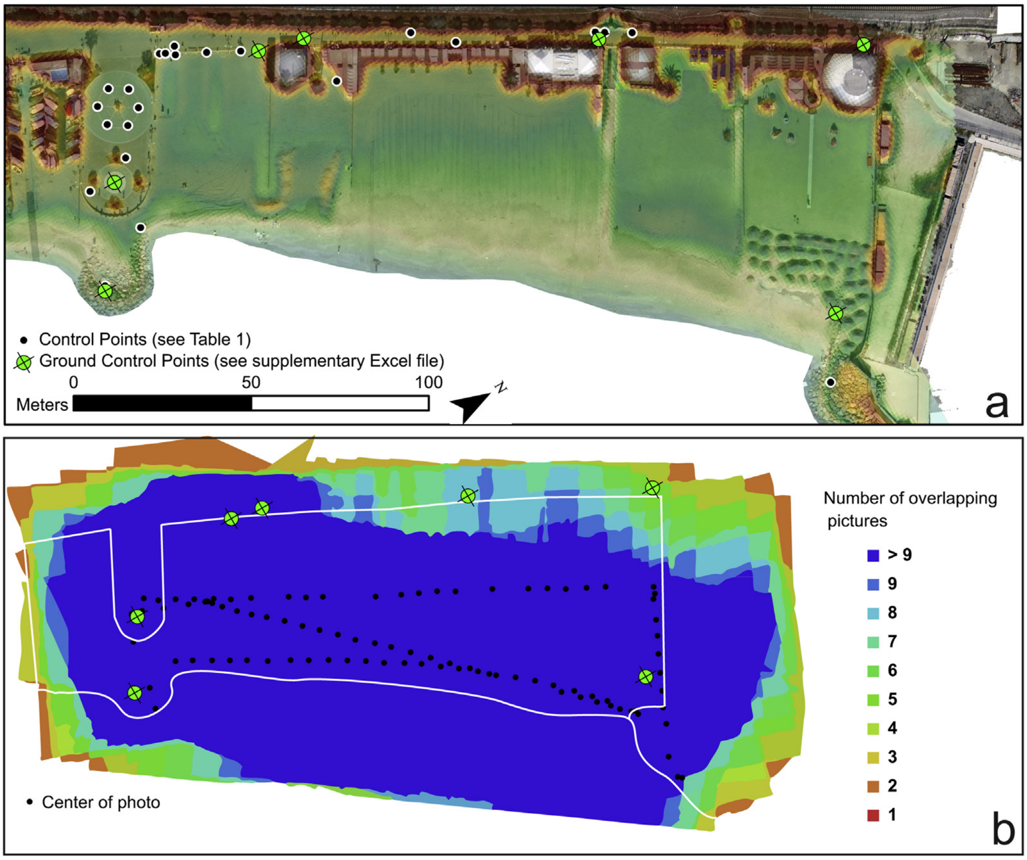
### 2.3. Beach orthophotos and digital elevation models

In order to generate ortho-rectified images (orthophotos) and digital elevation models from photos acquired with our UAVs we used Agisoft Photoscan (a photogrammetry suite tailored to UAV image processing, http://www.agisoft.ru) and ArcGIS. In coastal zone surveys, most pictures are partially occupied by the sea, which needs to be excluded from the beach topography because of unwanted reflections on the water surface. To remove the sea from the calculation of the point cloud, we used the Photoscan mask function.

The photogrammetric software has two outputs: one is the ortho-rectified aerial image, while the second is a cloud point representing triplets of XYZ data of the area covered by the survey. These two outputs need to be georeferenced in the 3D space using points measured on the ground with high-accuracy GPS. In our study area, we collected a total of 30 GPS points (Fig. 3a) using a Trimble® GPS system equipped with ProXRT® receiver and Zephyr® antenna, Terrasync® software centimeter edition and Trimble GeoXh® data collector. We postprocessed our survey using the 1-s data of the GNSS base station 'Istituto G. Falcone' (http://www.gnssliguria.it/postprocessing.html), which is located ~0.5 Km from the study area. Thanks to the proximity of this base reference station, the final accuracy of our GPS data is ±1 cm (horizontal) and ±3 cm (vertical). We referred our data to the EGM 2008 geoid model and our horizontal positioning (XY) data to UTM32-WGS84.

As targets for GPS points on the ground, we used fixed structures that can be recognized in different set of photos taken at different times (e.g. the centre of sewer covers, edges of structures or stones located on the jetties). This allows to georeference each set of photos using the same set of points and therefore avoiding to re-perform a GPS survey after every flight. An alternative method is that of placing mobile targets for the time of the flight, such as rectangular coloured sheets (Mancini et al., 2013).

We used 7 of our GPS points as Ground Control Points (GCPs), that have been employed to georeference our point cloud and ortophotos with the ground control point toolset of AGISOFT photoscan. The remaining 23 GPS points (Control Points, CPs), were used to evaluate the vertical accuracy of our final Digital Elevation Model (DEM) (Fig. 3a). The validation analysis was performed using Root Mean Square Deviation (RMSD) between the CPs and the values extracted from the DEM at the same location. The results show that the vertical accuracy of our DEM is within ±12 cm (see Supplementary excel file for GPS position and calculation of RMSD). In Fig. 3b we show the results of the Agisoft workflow and the



Average Flying altit 83.1421 m
Ground resolution: 0.0258921 m/pix
Coverage area: 0.0418231 sq km
Tie-points: 105976
Projections: 560910
Error: 0.791181 pix

| Camera Model | Resolution | Focal Length | Pixel Size | Precalibrated |
|---|---|---|---|---|
| Canon PowerShot G11 (6.1 mm) | 3648 x 2736 | 6.1 mm | 2.03311 x 2.03311 um | No |

**Fig. 3.** a) spatial distribution of GPS data collected in this study (for raw dataset see supplementary material) overlapped on Digital Elevation Model obtained from the UAV flight done the 15th of April; b) number of overlapping pictures and center of camera for the 98 pics used to build the DEM the 15th of April. The parameters at the bottom of the figure indicate the main results of the photogrammetric procedure.

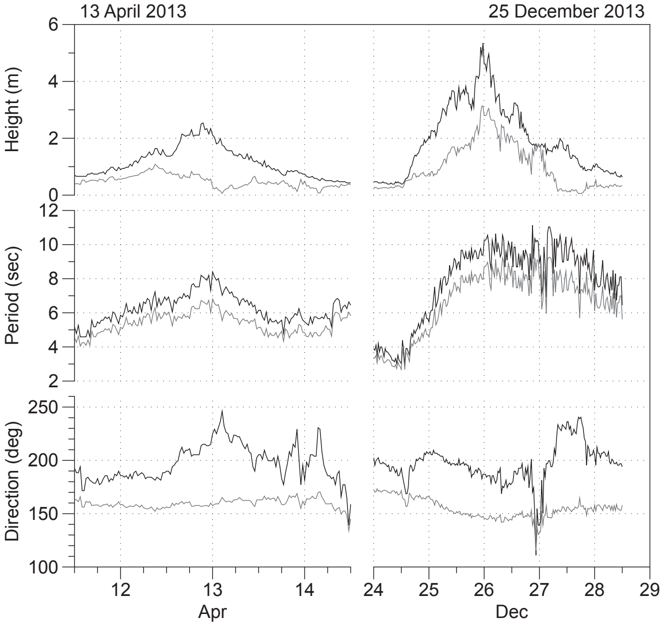


**Fig. 4.** Significant wave height, peak period and mean wave direction for the two swells occurred immediately before our UAV surveys. The black line represents the Capo Mele buoy measurement (see Fig. 1b for location), while the gray line represents the values modeled by MIKE 21 SW model in our study area. MIKE 21 SW model output represents the wave parameters 500 m offshore the area of Borghetto S.S., in a location with coordinates 44° 6'46.96“N 8°15'9.73”E.

overlapping of aerial pictures that defines the accuracy of our cloud point within the study area.

The point cloud obtained from photogrammetric techniques was then imported into ArcGIS to be interpolated into a continuous DEM and merged with the multibeam data of Regione Liguria (2012). To calculate the DEM from the orthophoto, we used the Topo to Raster tool of the ArcGIS spatial analyst extension, which is an interpolation method specifically designed for the creation of DEMs, and is based on the ANUDEM program developed by Hutchinson 1988, 1989. The resulting DEM is shown in Fig. 3a (only the onland part) and in Fig.5a (merged with multibeam data).

### 2.4. *Topography for runup model*

The topographic inputs needed for the runup model are beach profiles extending from the shoreward end to the seaward end of the beach (Kobayashi, 2009). As from the two flights we obtained two DEMs, the ideal approach would have been to calculate the topographic transects on a mean ± standard deviation of the two DEMs, that represent different states of transient equilibrium of the beach. Unfortunately, the beach after the swell of the 27th of December was covered by debris left by the waves (also visible in Fig. 5c as a brown deposit on the beach), which was in some zones up to 1 m thick, veneering irregularly the real beach topography. Therefore, we adopted the compromise of calculating the topography from the DEM obtained from the flight done the 15th of April 2013 merged with multibeam data (Fig. 5a). From the merged profiles, we extracted topographic transects using the 3D Analyst® ArcGIS extension in the form of profile length/elevation that was then given as input to the runup model.

From the orthophotos obtained with photogrammetry it is possible also to extract the position and elevation of the maximum wave runup, since it is clearly detectable as wet line on the orthophotos of the area surveyed immediately after the event. The wet line was digitized manually in ArcGIS.

### 2.5. *Wave model and model set-up*

To achieve the information on the wave data near the study area we implemented MIKE 21 Spectral Wave (SW) model developed by DHI (former Danish Hydraulic Institute). MIKE 21 SW is based on unstructured meshes which allows for different spatial resolution in the same domain and it simulates wave growth by action of wind, non-linear wave–wave interaction, dissipation due to white-capping, dissipation due to bottom friction, dissipation due to depth-induced wave breaking, refraction and shoaling due to depth variations and wave–current interaction. MIKE 21 SW model is appropriate for both off shore and near shore wave modelling since it includes two different formulations: a directional decoupled parametric formulation and a fully spectral formulation of the wave action. In this work we used the first formulation that is suitable for coastal applications and relatively small spatial domains. This formulation is based on parameterisation of the wave action conservation equation (Holthuijsen et al., 1989). The full description of the formulations is included in the ‘Scientific documentation’ of the software, DHI (2012).

In this work, the simulated area covers about 150 km$^2$ of near shore zone in the Northwestern Mediterranean, from the longitude of 8°10'50''E to 8°24'52'' (Fig.1b). The coastline was extracted from the databases available in the Italian Ministry of Environment cartographic portal (www.pcn.mianmbiente.it). Bathymetric data have been obtained from the Istituto Idrografico della Marina (the Italian National Hydrographic Institute) and, near the coast, from multibeam data by Regione Liguria (the dataset has been published in Rovere et al., 2014). The spatial resolution of the model spans from 500 m offshore to 100 m nearshore (Fig.1b). The Southeast corner of the domain is located at 43°55'18''N 8°10'50''E where a buoy registers every 30 min the state of the sea. The buoy is part of the Ligurian buoy network (http://servizi-meteoliguria.arpal.gov.it/boacapomele.html) and is managed by the regional environmental protection agency (Agenzia Regionale per la Protezione dell'Ambiente Ligure, ARPAL).

The data we retrieved from the buoy are significant wave height, mean wave direction and peak period for the two different swell events (Fig.4). We used these data to compute the time series imposed to the boundary offshore of the domain of the MIKE SW model. Data from the buoy have been transposed to the Northeast corner of the domain using the formulation of De Girolamo et al. (1998), then an interpolation along the offshore boundary, between the data at the Southeast corner (buoy location) and the transposed data at the Northeast corner, have been done to achieve the information to impose on the offshore boundary of the domain varying in time and along the boundary during the sea events simulated. The sea state information provided by the model outputs at about 500 m offshore of the study area have been used as input conditions to the wave runup model.

### 2.6. *Wave runup model and model setup*

Wave runup is specifically defined as the landward extent of wave uprush measured vertically from the still water level (Stockdon et al., 2006; Melby et al., 2012). Runup is a function of nearshore wave transformation and wave breaking across the surf zone. Runup on beaches is influenced by local bathymetry, beach granulometry, beach steepness, wave steepness, beach permeability, groundwater elevation, and infragravity waves.

In this work, the model used to compute wave runup is a phase-averaged cross-shore model, CSHORE (Kobayashi, 1999; Kobayashi et al., 2008; Kobayashi, 2009). For the purpose of this paper we chose a phase-averaged model since it is less time consuming and more stable than a phase-resolving model. The CSHORE model

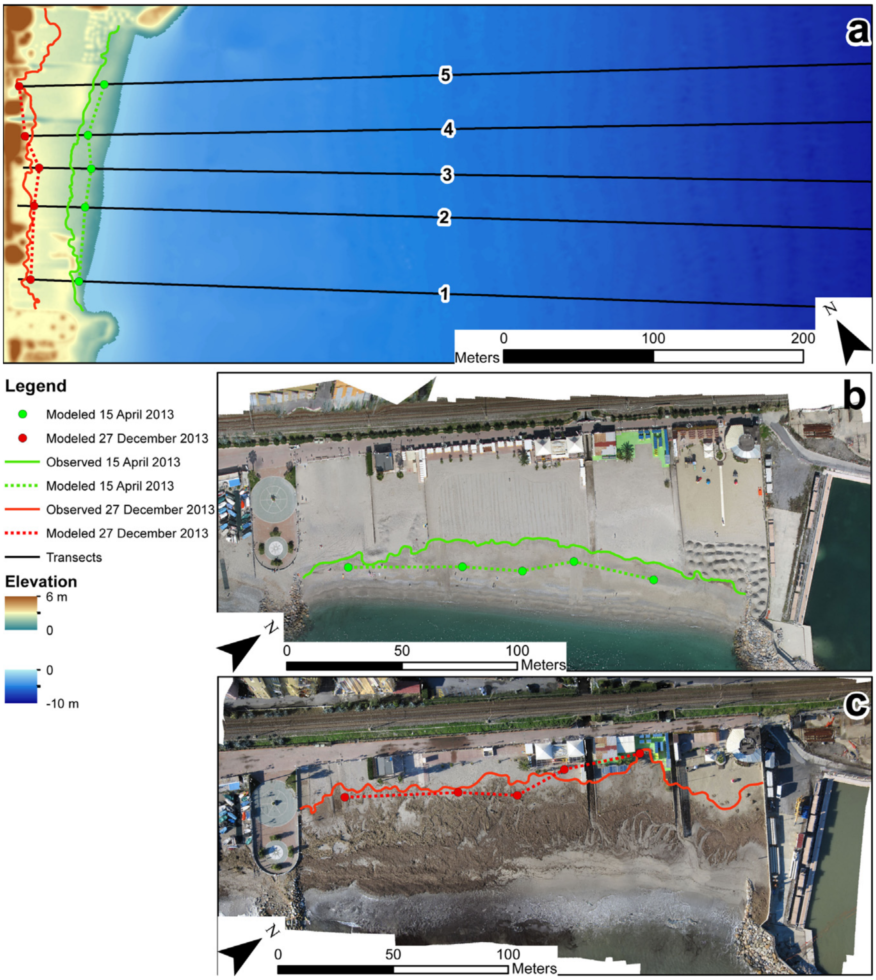


**Fig. 5.** a) DEM obtained merging the point cloud from the 15th Apr 2013 flight and Multibeam data by Regione Liguria. The figure shows also transects 1–5 used as input in CSHORE model and the observed and modeled runup for the two events. b) and c) orthophotos, modeled and observed runup of respectively 15th Apr 2013 and 27th Dec 2013. In c) the debris on the beach are still visible.

solves the time-averaged continuity, momentum, and energy equations in the region that is always wet and separately for the wet-dry region. Runup is solved as a probabilistic estimate along a runup wire in the wet-dry region assuming runups to be Rayleigh distributed. The two percent exceedance value of wave runup (R2%) is computed from this distribution. A full description of the model is included in Kobayashi (1999) (2009), Kobayashi et al. (2008), Pietropaolo et al. (2012), and Melby (2012). CSHORE proved an efficient tool to predict wave runup over a broad range of wave and nearshore profile situations including coastal structures and beaches (Johnson et al., 2012; Melby, 2012). The only limitation of the model concerns the prediction of wave runup for situations where infragravity conditions dominate, particularly on gently-sloping dissipative beaches that are typical of the northwest Pacific coast while good skills have been observed in the case of reflective beaches (Melby, 2012).

The input wave conditions for CSHORE have been obtained from the MIKE SW model output outside the surf zone offshore the beach studied. Data extracted from the wave model are significant wave height, peak wave period, and wave direction (gray lines in Fig. 4). Before using these variables as input to CSHORE, we calculated the Root-mean-square wave height, Hrms, from significant wave height, Hs, using the formulation $Hrms = Hs/\sqrt{2}$. In this work, CSHORE parameters were set according to recommendations given in Melby et al. (2012), and to estimate the runup wire height we performed a simple sensitivity test, checking which values produced more consistent results with our observed runups (Table 2). The input tidal conditions for CSHORE were extracted from the official Italian tide archives (http://www.mareografico.it/) at the Imperia station, which is located about 30 km south of the study area.

## 3. Observed and modeled runup comparison

The DEM obtained from the procedure of merging the multibeam and the point cloud from UAV photos is represented in Fig.5a. In Fig. 5b and c are shown the orthophotos with calculated and observed runup. The DEM varies from 6 m (elevation of railroad located landward) and −10 m (which is below the closure depth for Ligurian beaches, that was estimated by Vacchi et al., 2012 at 5–9 m). CSHORE model has been implemented on 5 different transects on the study area for the two different wave events. The profiles we chose extend from +6 m down to −8 m. CSHORE has been run on the 5 transects with the input conditions described in the methods section and in Table 1.

Observed and modeled runup are in good agreement for which concerns both elevations (Table 2) and geographic location (Figs. 5c,d). Maximum differences in elevation between observed and modeled runup are in accord with the values obtained by other studies using CSHORE to predict wave runup (around 20% of

**Table 1**
Set up of CSHORE parameters. CSHORE was applied using a fixed beach profile (i.e. we did not consider morphology changes).

| Parameter | Value | Explanation |
|---|---|---|
| IWCINT | 1 | We include wave–current interaction in the simulation |
| IROLL | 1 | we consider the roller effects in the wet zone |
| GAMMA, empirical breaker ratio parameter | 0.8 | Indicated for beaches (Melby et al., 2012) |
| RWH, runup wire height | 0.019 m | A range of runup wire heights have been investigated in Melby et al., 2012. Following this example we tested, for our study area, a set of values ranging from 0.0046 m to 0.022 m obtaining best matches between observed and modeled runup with 0.019. |
| DX, constant grid mesh spacing | 1 m | |
| Bottom friction factor | 0.002 | Value indicated for beaches (Melby et al., 2012) |
| IPERM | 0 | We consider an impermeable bottom |
| IOVER | 1 | We include wave overtopping at the landward end of the computation domain |
| IWTRAN | 0 | No standing water in a bay or lagoon landward of an emerged dune or coastal structure |
| IPOND | 0 | No ponding on lee side of dune or structure |
| IWIND | 0 | No wind effects |
| ITIDE | 0 | We don't consider tidal effect on current but we include tides in our simulations. Tidal data have been extract from the official Italian tide archives (http://www.mareografico.it/). |
| ILAB | 0 | We used field data. |
| D50 | 0.11 mm | From technical reports from the Municipality of Borghetto S.S. |

difference between simulated and observed values, Melby, 2012). It is worth highlighting that our modeling chain performs slightly better for the 26th December event, where the RMSD between observed and modelled runup is 0.16 m. In the case of the 13th April event, the RMSD is 0.32 m and the model underestimates the wave runup. We tentatively attribute the better performance to the major intensity of the 26th December event, which is more regular in terms of height, period and direction (Fig. 4). The wave event of the 13th of April was much less intense in our study area, and this may be the cause of the lower performance of our modeling chain, that is based, especially the CSHORE part, on ocean waves.

**Table 2**
Comparison between the observed and modeled runup along the 5 transects shown in Fig. 5a. The maximum runup represents the elevation of the points drawn in Figs. 5b and c. The RMSD is the Root Mean Square Deviation calculated on the difference between DEM elevation and Maximum runup on the 5 transects.

| Transect | Observed runup 15th Apr (m) | Modeled runup 15th Apr (m) | Observed runup 27th Dec (m) | Modeled runup 27th Dec (m) |
|---|---|---|---|---|
| 1 | 1.1 | 0.66 | 1.48 | 1.43 |
| 2 | 1.02 | 0.73 | 1.54 | 1.52 |
| 3 | 0.99 | 0.65 | 1.56 | 1.49 |
| 4 | 0.96 | 0.69 | 1.46 | 1.80 |
| 5 | 0.97 | 0.77 | 1.38 | 1.37 |
| RMSD | | 0.32 | | 0.16 |

## 4. Final remarks and future research directions

In this study, we presented a workflow that uses field data obtained from a UAV as both source of input and setting of a modeling chain that calculates wave runup on the shore. The UAV approach allowed gathering observations rapidly and accurately (on-land DEM with accuracy of ±12 cm) and low-cost. This accuracy is in line with that obtained by other studies employing this technique, that lies in the range of 11–31 cm (Niethammer et al., 2012; Hugenholtz et al., 2013; Grenzdoerffer et al., 2008; Udin and Ahmad, 2012; Mancini et al., 2013).

We used the DEM data as topographic input in the modeling chain, and the elevation and position of runup observed on orthophotos as validation of the model results. In our study case, we also defined a set of parameters suitable for the simulation of wave runup in the Ligurian coastal area using a modeling chain composed by MIKE 21 and CSHORE models. We argue that the parameters shown in Table 1 provide a good baseline for such studies in the Mediterranean or other fetch-limited basins.

In order to improve the approach proposed here and to provide useful information for coastal managers, further research must be carried out in two directions. First, with particular reference to the study area, it is necessary to increase the number of the observed runups in time and continue the comparison with model results. This would allow improving the outcomes of the sensitivity test to model parameters and tune such parameters to obtain better fits. Second, it is necessary to increase the number of study sites in order to test the model performance in different geographic conditions, with different beach types. Despite research must be still carried out, we highlight that the use of UAV platforms applied to the study of coastal areas has the potential to improve our capability to provide reliable beach topography data rapidly and with low costs. Such data are of great value to establish the sensitivity to different parameters and ultimately assess the outputs of hydrodynamic, sediment transport and runup models.

Our methodology and the set of parameter chosen for the runup modeling (Table 1) proved efficient in obtaining model results that match the observations with high accuracy. The RMSDs between observed and modelled runup for the two events are 0.16 m and 0.32 m. The lower end of this estimate being for a higher intensity storm, which is also most critical in terms of coastal flooding risks. Although generalizing our results is premature due to the fact that we applied our workflow in a single area for only two events, we argue that the workflow we used is exportable in other areas, also outside the Mediterranean region.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2014.08.012.

## References

Cariolet, J.M., Suanez, S., 2013. Runup estimations on a macrotidal sandy beach. Coast. Eng. 74, 11–18.

Colomina, I., Molina, P., 2014. Unmanned aerial systems for photogrammetry and remote sensing: a review. ISPRS J. Photogr. Remote Sens. 92, 79–97.

Corsini, S., Inghilesi, R., Franco, L., Piscopia, R., 2006. Italian Waves Atlas. APAT-Universita degli Studi di Roma 3, Roma, p. 134 (þ).

De Girolamo, P., Contini, P., Franco, L., Noli, A., 1998. Studio degli impatti morfologici di opere costiere con modelli matematici. In: Atti VIII Convegno AIOM "Le opere di ingegneria offshore e marina e loro interazione con l'ambiente". S.Teresa (SP), pp. 75–83.

DHI, 2012. Mike21 Spectral Wave Module. Scientific Documentation. Danish Hydraulic Institute (DHI).

Fierro, G., Berriolo, G., Ferrari, M., 2010. Le spiagge della Liguria occidentale, Regione Liguria. Regione Liguria, Genova.

Fiori, E., Comellas, A., Molini, L., Rebora, N., Siccardi, F., Gochis, D.J., Tanelli, S., Parodi, A., 2014. Analysis and hindcast simulations of an extreme rainfall event in the Mediterranean area: the Genoa 2011 case. Atmos. Res. 138, 13–29.

Grenzdoerffer, G., Engel, A., Teichert, B., 2008. The Photogrammetric Potential of Low-cost UAVS in Forestry and Agriculture. In: Part B1 International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences, vol. XXXVII. ISPRS Congress, Beijing, China, pp. 1207–1213.

Holthuijsen, L.H., Booij, N., Herbers, T., 1989. A prediction model for stationary, short-crested waves in shallow water with ambient currents. Coast. Eng. 13, 23–54.

Hugenholtz, C.H., Whitehead, K., Brown, O.W., Barchyn, T.E., Moorman, B.J., LeClair, A., Riddell, K., Hamilton, T., 2013. Geomorphological mapping with a small unmanned aircraft system (sUAS): feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model. Geomorphology 194, 16–24.

Hutchinson, M.F., 1988. Calculation of Hydrologically Sound Digital Elevation Models. Paper presented at Third International Symposium on Spatial Data Handling at Sydney, Australia.

Hutchinson, M.F., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. J. Hydrol. 106, 211–232.

Jiménez, J.A., Gracia, V., Valdemoro, H.I., Mendoza, E.T., Sánchez-Arcilla, A., 2011. Ocean & Coastal Management Ocean. Coast. Manag. 54, 907–918.

Johnson, B., Kobayashi, N., Gravens, M., 2012. Cross-shore Numerical Model CSHORE for Waves, Currents, Sediment Transport, and Beach Profile Evolution. U.S. Army Corps of Engineers, Engineer Research and Developement Center, Vicksburg, MS. Retrieved from. http://www.greatlakescoast.org/great-lakes-coastal-analysis-andmapping/technical-resources/.

Kobayashi, N., 1999. Numerical modeling of wave runup on coastal structures and beaches. Mar. Technol. Soc. J. 33, 33–37.

Kobayashi, N., 2009. Documentation of Cross-shore Numerical Model CSHORE. Center for Applied Coastal Research, University of Delaware.

Kobayashi, N., de los Santos, F.J., Kearney, P.G., 2008. Time-averaged probabilistic model for irregular wave runup on permeable slopes. J. Waterw. Port, Coast. Ocean. Eng. 134, 88–96.

Koh, L.P., Wich, S.A., 2012. Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. Tropical Conserv. Sci. 5.

Mancini, F., Dubbini, M., Gattelli, M., Stecchi, F., Fabbri, S., Gabbianelli, G., 2013. Using unmanned aerial vehicles (UAV) for high-resolution reconstruction of topography: the structure from motion approach on coastal environments. Remote Sens. 5, 6880–6898. http://dx.doi.org/10.3390/rs5126880.

Melby, J., 2012. Wave Runup Prediction for Flood Hazard Assessment. U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS. Retrieved from. http://www.greatlakescoast.org/great-lakes-coastal-analysis-andmapping/technical-resources/.

Melby, J., Caraballo-Nadal, N., Kobayashi, N., 2012. Wave runup prediction for flood mapping. Coast. Eng. Proc. 1, 1–14.

Morton, R.A., Leach, M.P., Paine, J.G., Cardoza, M.A., 1993. Monitoring beach changes using GPS surveying techniques. J. Coast. Res., 702–720.

Niethammer, U., James, M.R., Rothmund, S., Travelletti, J., Joswig, M., 2012. UAV-based remote sensing of the Super Sauze landslide: evaluation and results. Eng. Geol. 128, 2–11.

Niethammer, U., Rothmund, S., James, M.R., Travelletti, J., Joswig, M., 2010. UAV-based remote sensing of landslides. Int. Arch. Photogram. Remote Sens. Spat. Info. Sci. 38, 496–501.

Orlandi, A., Pasi, F., Onorato, L.F., Gallino, S., 2008. An observational and numerical case study of a flash sea storm over the Gulf of Genoa. Adv. Sci. Res. 2, 107–112.

Parodi, A., Boni, G., Ferraris, L., Siccardi, F., Pagliara, P., Trovatore, E., Foufoula Georgiou, E., Kranzlmueller, D., 2012. The "perfect storm": from across the Atlantic to the hills of Genoa. Eos, Trans. Am. Geophys. Union 93, 225–226.

Pasi, F., Orlandi, A., Onorato, L.F., Gallino, S., 2011. A study of the 1 and 2 January 2010 sea-storm in the Ligurian Sea. Adv. Sci. Res. 6, 109–115.

Pietropaolo, J., Kobayashi, N., Melby, J., 2012. Wave runup on dikes and beaches. In: Proc. 33rd ICCE. Santander, Spain.

Rebora, N., Molini, L., Casella, E., Comellas, A., Fiori, E., Pignone, F., Siccardi, F., Silvestro, F., Tanelli, S., Parodi, A., 2013. Extreme rainfall in the Mediterranean: what can we learn from observations? J. Hydrometeorol. 14.

Regione Liguria, 2012. Indagine morfosedimentologica di dettaglio dei fondali compresi tra capo Santa Croce e capo Caprazoppa. Technical report. WaterSoil S.r.l, Ravenna.

Rovere, A., Casella, E., Vacchi, M., Mucerino, L., Pedroncini, A., Ferrari, M., Firpo, M., 2014a. Monitoring beach evolution using low-altitude aerial photogrammetry and UAV drones. Geophys. Res. Abstr. 16, 1. EGU General Assembly 2014.

Rovere, A., Casella, E., Vacchi, M., Parravicini, V., Firpo, M., Ferrari, M., Morri, C., Bianchi, C.N., 2014b. Geo-environmental map of the Albenga-Savona coastal tract (Liguria, NW Italy). J. Maps.

Rovere, A., Parravicini, V., Vacchi, M., Montefalcone, M., Morri, C., Bianchi, C.N., Firpo, M., 2010. Geo-environmental cartography of the Marine Protected Area "Isola di Bergeggi" (Liguria, NW Mediterranean Sea). J. Maps 6, 505–519.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., Beach, R.A., 2001. Wave runup, extreme water levels and the erosion of properties backing beaches. J. Coast. Res., 407–419.

Stockdon, H.F., Holman, R.A., Howd, P.A., Sallenger Jr., A.H., 2006. Empirical parameterization of setup, swash, and runup. Coast. Eng. 53, 573–588.

Udin, W.S., Ahmad, A., 2012. The potential use of rotor wing unmanned aerial vehicle for large scale stream mapping. Int. J. Sci. Eng. Res. 3 (12). ISSN: 2229–5518.

Vacchi, M., Montefalcone, M., Bianchi, C.N., Morri, C., Ferrari, M., 2012. Hydrodynamic constraints to the seaward development of *Posidonia oceanica* meadows. Estuar. Coast. Shelf Sci. 97, 58–65.

White, S.A., Wang, Y., 2003. Utilizing DEMs derived from LIDAR data to analyze morphologic change in the North Carolina coastline. Remote Sens. Environ. 85, 39–47.