

Monitoring seasonal morphobathymetric change of nearshore seafloor using drone-based multispectral imagery

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Abstract

Short-term changes in shallow bathymetry affect the coastal zone and therefore their monitoring is an essential task in coastal planning projects. This study provides a novel approach for monitoring shallow bathymetry change based on drone multispectral imagery. Particularly we apply a shallow water inversion algorithm on two composite multispectral datasets being acquired five months apart in a small Mediterranean sandy embayment (Chania, Greece). Initially, we perform radiometric corrections using proprietary software and following we combine the bands from standard and multispectral cameras resulting in a six-band composite image suitable for applying the shallow water inversion algorithm. Bathymetry inversion results showed good correlation and low errors ($< 0.3\text{m}$) with sonar measurements collected with an uncrewed surface vehicle (USV). Bathymetry maps and true-color orthomosaics assist in identifying morphobathymetric features representing crescentic bars with rip channel systems. The temporal bathymetry and true-color data reveal important erosional and depositional patterns, which were developed under the impact of winter storms. Furthermore, bathymetric profiles show that the crescentic bar appears to migrate across and along-shore over the 5-months period. Drone-based multispectral imagery proves to be an important and cost-effective tool for shallow seafloor mapping and monitoring when it is combined with shallow water analytical models.

1. Introduction

The shallow coastal seafloor is constantly under the influence of waves and currents thus its surface changes rapidly over different spatio-/temporal scales. At the same time, shallow seafloor covers a wide area globally where major economic and other activities take place. Consequently, mapping and monitoring of shallow seafloor bathymetry is a fundamental strategy for several projects including but not limited to: maritime safety, coastal vulnerability (Davidson et al., 2007; de Swart and Zimmerman, 2009; van Dongeren et al., 2008) and coastal planning (Jackson et al., 2022; Misra and Ramakrishnan, 2020; Toodesh et al., 2021). However, obtaining bathymetry data at the coastal zone is not as straightforward as it is in continental shelf mapping. This is owing to the fact that: a) shallow seafloor changes quickly and thus bathymetry collected today is no longer valid even after a short period of time, and b) traditional sonar surveying is unable to provide full coverage at high spatial resolution (< 1 m) in a time- and cost-effective way. Therefore, new techniques were introduced for efficient shallow bathymetry mapping, covering broad shallow areas with sufficient temporal resolution (Gao, 2009; Salameh et al., 2019). These techniques include active or passive optical sensors deployed on airborne or satellite platforms. Such data is suitable for mapping areas with increased water transparency where seafloor is visible (Gao, 2009; Lee et al., 2007). In the case of turbid waters, bathymetry inversion based on wave geometry and celerity has also been applied as an alternative technique to sonar mapping (Bergsma and Almar, 2018; Collins et al., 2021). The most recognized optical technique for shallow seafloor mapping is light detection and ranging (LIDAR). LIDAR sensors have been widely applied in shallow seafloor mapping studies due to their increased spatial resolution and data density along with their extensive coverage (Costa et al., 2009; Klemas, 2011; Taramelli et al., 2020). Particularly, airborne bathymetric LIDAR is the leading technology for studying nearshore bathymetry, providing meter-scale horizontal accuracy and centimeter-scale vertical accuracy over large areas of coastal seafloor (Brock and Purkis, 2009; Klemas, 2011). However, the cost of LIDAR sensors and the costs and logistic effort for acquiring bathymetric LIDAR data are often limiting factors (Freire et al., 2015) that hinder the accessibility of this kind of technology to low-budget projects. Applications based on multi- or hyperspectral imagery are considered as an alternative to LIDAR for shallow bathymetry retrieval. Deriving shallow bathymetry using passive optical imagery is a field of ongoing research, which has been greatly expanded in recent years as it provides extended scale coverage and at relatively low-cost compared to LiDAR or sonar surveying. Consequently, the technique of satellite-derived bathymetry (SDB) has seen significant growth with plentiful applications including mainly the models suggested by Lyzenga (1978) and Stumpf et al. (2003). These are implemented in various contexts (Geyman and Maloof, 2019; Gholamalifard et al., 2013; Ma et al., 2014; Traganos et al., 2018; Wei et al., 2021) and rely on the availability of ground-truth depth measurements for model calibration compared to the analytical methods. The empirical methods do not necessarily require absolute radiometric and atmospheric corrections (Gholamalifard et al., 2013; Kibele and Shears, 2016) and depending on

model performance, they can be applied on datasets with similar seafloor types (Caballero and Stumpf, 2019). In contrast, analytical methods account for any seafloor type included as model input (Dekker et al., 2011; Klonowski, 2007; Kutser et al., 2020; Leiper et al., 2014). The analytical algorithms have been developed using in-situ calibrated spectral data which are fitted with radiative-transfer models (Dekker et al., 2011; Lee et al., 1999; Mobley et al., 2005). These algorithms are considered more suitable for imagery with increased radiometric resolution across a wide range of the visible and near infrared (NIR) spectra (Dekker et al., 2011). Analytical algorithms do not require input of a priori depth information and they account for the inherent optical properties (IOPs) of water and bathymetric uncertainty as well, in contrast with the empirical methods. Although several studies exist about the development and performance of various SDB algorithms, there is still a limited number of studies exploiting SDB products on specific geospatial applications. For example, Capo et al. (2014) utilized medium resolution SPOT-1/5 satellite imagery in order to monitor the evolution of subtidal inlets over the course of 26 years. Freire et al. (2015) applied multi-temporal SDB for identifying zones with high dynamic behavior, while Bolaños et al. (2018) derived bathymetry from Sentinel-2 imagery and applied it to wave modelling for baseline studies for offshore wind farm installations. In addition, Misra and Ramakrishnan (2020) utilized SDB from medium resolution Landsat-8 multi-spectral imagery for monitoring coastal geomorphology and Alevizos et al. (2021), applied SDB on high-resolution World View imagery for mapping geomorphological features at the wider coastal area of Chania (Crete, Greece). Though openly available Landsat and Sentinel-2 imagery have been applied successfully in large scale mapping of shallow seafloor (Caballero and Stumpf, 2019; Misra and Ramakrishnan, 2020; Pacheco et al., 2015), their spatial resolution is not sufficient for resolving morphobathymetric features and changes at landscape scale. Moreover, multi-temporal bathymetry mapping with satellite imagery is limited by atmospheric factors such as cloud cover and the increased cost of very high-resolution, commercial satellite image acquisitions that required for monitoring nearshore bathymetric features at fine spatial and temporal scales.

The recent developments in drone technology provided new opportunities for the development of novel geospatial applications. Drones are becoming increasingly popular in remote sensing studies since they are low-cost platforms; they provide a centimeter-scale spatial resolution that is suitable for observing objects and/or processes in unique detail; they require negligible logistic effort, allowing for frequent deployment on demand, thus increasing the temporal resolution of imagery; they operate in close range without being influenced by clouds or other atmospheric effects (Alevizos, 2019; Román et al., 2021; Rossi et al., 2020). Until recently, there have been a few recent studies applying SDB algorithms on drone-based multispectral imagery (Alevizos et al., 2022b; Kabiri et al., 2020; Parsons et al., 2018; Rossi et al., 2020; Slocum et al., 2020; Starek and Giessel, 2017) showing relatively good results with up to 40 cm vertical errors. Furthermore, there have been studies applying structure-from-motion (SfM) techniques on drone imagery for bathymetry retrieval (Agrafiotis et al., 2019; Dietrich, 2017). SfM produces significant results with

low errors only in cases where the seafloor surface is texture-rich so that the SfM algorithm can identify corresponding matching points on the images. Thus, the SfM method is suitable for bathymetry extraction over rocky or rugged seafloor areas. However, significant morphobathymetric changes occur mainly in smooth (texture-less) seafloor comprising of soft sediments types, which are more susceptible to hydrodynamic activity than rocky areas. Consequently, monitoring shallow bathymetric changes over smooth seafloor areas is not an applicable field for drone-based SfM approaches.

Considering the particular limitations of satellite imagery regarding monitoring shallow bathymetry at high spatio-temporal resolution, along with the restricted application of LiDAR, we examine the application of a drone-based approach for monitoring seasonal bathymetric changes in a Mediterranean coastal site. To our knowledge, there have not been any studies published at present, focusing on bathymetry monitoring using drone imagery. Temporal bathymetry data are required as input to coastal engineering projects for decision-making about dredging or taking counter-erosion measures (Toodesh et al., 2021), wave modelling and sediment transport predictions (Biausque et al., 2022; Jackson et al., 2022). The goal of this study is to capture and quantify small-scale bathymetric features and changes occurring at seasonal scales as a result of nearshore hydrodynamic activity. In order to achieve this, we produce centimetre resolution, temporal bathymetric datasets from drone-based multispectral imagery using the approach from Alevizos et al. (2022b) and then we analyze their results using geospatial tools. The analytical approach employed here, assists in minimizing the need for in-situ data collection, which could be a limiting factor in long-term monitoring projects. Bathymetry predictions are validated using in-situ sonar measurements from an Uncrewed Surface Vehicle (USV).

Methodology

Study area and fieldwork

The wider study area (Fig. 1) is located west of Chania city (Crete, Greece) and comprises of north-facing, sandy embayments with shallow, relatively smooth seafloor, covered with rocky reefs and exposed bedrock at places. The coastline in the Chania area stretches for at least 8 km and it is highly exposed to incoming waves from the north, which is the prevailing direction in the local wind regime (Foteinis et al., 2018), while significant along-shore sediment transport is expected due to incoming waves from various incidence angles (Tsoukala et al., 2015). The Chania area is characterized by increased water transparency due to low concentrations of chlorophyll (CHL-a) and suspended particulate matter (SPM) as a result of the oligotrophic character of the eastern Mediterranean Sea (Ignatiades, 1998) and the absence of major input from adjacent drainage systems. A typical Secchi-depth for the study areas reaches at least 10 meters. In addition, the average tidal range in Crete is at the scale of 10-20 cm.

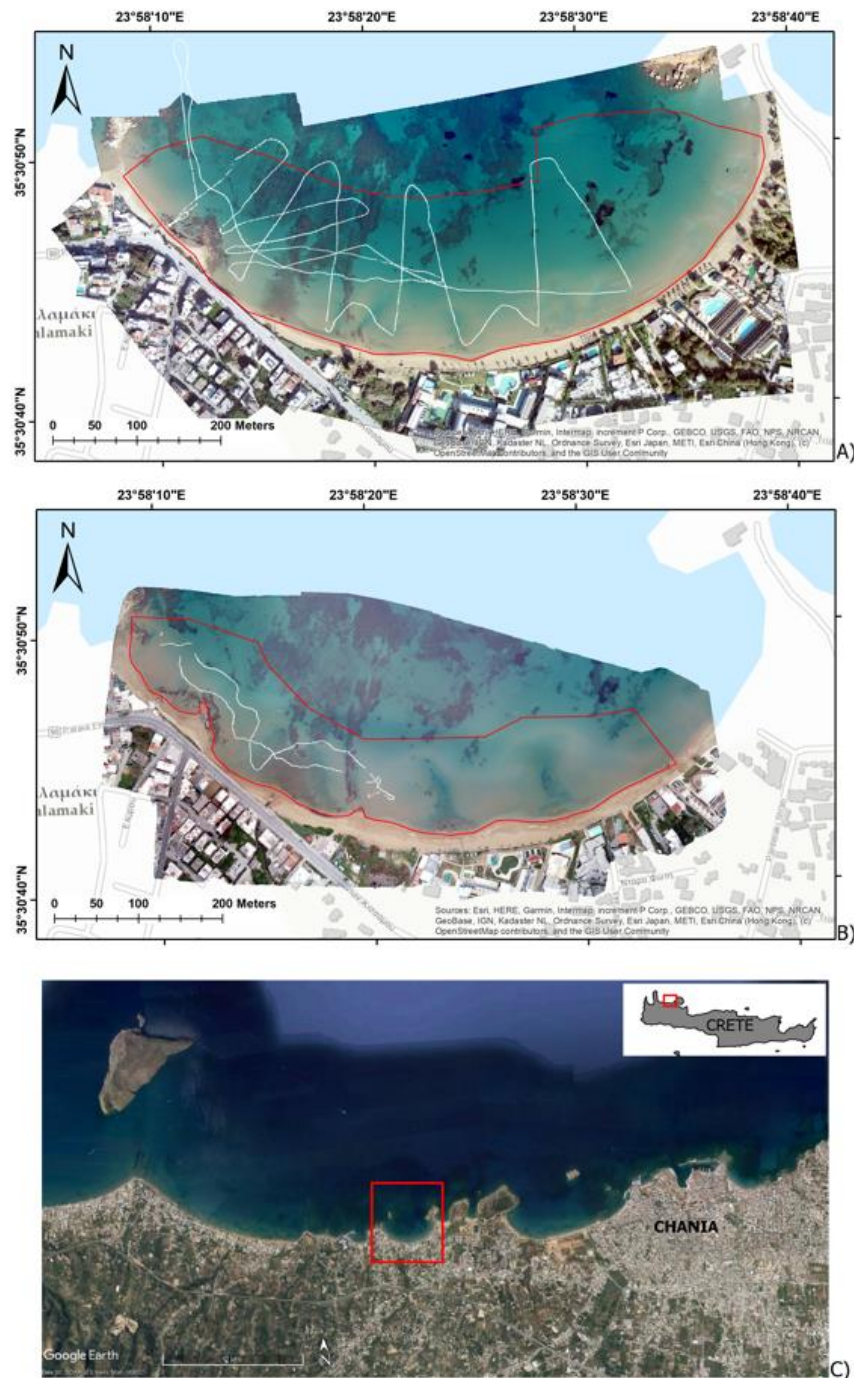


Figure 1: Temporal, true-color orthomosaics of the study area. A) Imagery acquired on 04/11/2021, B) Imagery acquired on 31/03/2022, C) Legend map of the wider study area. The red rectangles show the processing boundaries of bathymetry inversion and the white dots correspond to the track of USV sonar measurements.

Drone images were collected on November 4, 2021 and March 31, 2022 using a DJI Phantom 4 Pro drone. The drone was mounted with a 1-inch, 20-megapixel CMOS sensor and a MicaSense RedEdge-MX[®] multispectral camera. Both sensors were set to collect images at nadir with two seconds intervals and along parallel flight tracks at 150 m altitude above sea level. Although the MS sensor records five spectral bands simultaneously (Blue, Green, Red, Red edge and Near infrared) in this study we only considered the Blue, Green and Red bands from the visible spectrum. These bands are more favourable in optical bathymetry studies (Albert, 2004; Marcello et al., 2018) and their spectral characteristics are complementary with the built-in Red-Green-Blue (RGB) sensor of DJI Phantom 4 (Fig.2A; Table 1, Appendix). Depth measurements (Fig.A3, Appendix) were acquired on the same date of each drone survey, using an Ohmex BTX single-beam sonar with an operating frequency of 235 kHz. The sonar is integrated with a Real-Time Kinematics (RTK) GPS sensor for collecting attitude-corrected bathymetry points at 2 Hertz rate. The RTK-GPS measurements provide high spatial accuracy (< 10 cm) which is essential in processing drone-based imagery with a pixel resolution of a few centimetres. The sonar data acquired with a remotely controlled USV. The USV depth measurements were used for validating the outputs of bathymetry inversion by: a) calculating the coefficient of determination (R^2) as a measure of agreement between the sonar data and the predicted depth; b) calculating the mean average error (MAE) and the root-mean-square error (RMSE) as metrics of the spread of the residuals and c) comparing the corresponding bathymetric profiles at each area.

Pre-processing of drone-based imagery

The overall processing steps of drone images followed in this study are described in Alevizos et al. (2022). Initially, we produced one orthomosaic for each RGB and MS band (six in total) by applying RTK-GPS measurements of seven onshore ground-control points and by performing the following radiometric and geometric corrections in Pix4D[®] software. Alevizos and Alexakis (2022) suggest that radiometric corrections of drone RGB imagery are required for improving shallow bathymetry results. Both RGB and MS images were adjusted for radial lens distortion using the respective camera models included in the Pix4D[®] software. The MS sensor was integrated with an external Downwelling Light Sensor (DLS-2) module which records sun illumination parameters (i.e.: angle, radiance) that are stored in the image metadata. These recordings are required during radiometric correction processing of multispectral imagery in Pix4D[®] software. In addition, the DLS-2 module provides GPS and attitude information for each acquired image, assisting the georeferencing and orthomosaicking of processed imagery using the Pix4D[®] software. Initially, the pixel values are compensated for sensor bias such as sensor black-level, sensitivity, gain and exposure settings, and lens vignette effects and then they are converted to radiance values (i.e.: in units $\text{Wm}^{-2}\text{sr}^{-1}\text{nm}^{-1}$, meaning watts per square meter per steradian per nanometer). Following,

the radiance values are converted to spectral reflectance for each band, by incorporating the information from the reflectance panel and the DLS-2 sensor (available only for the MS images). In order to convert the pixel values to reflectance values, we acquired images of a spectral calibration panel which is specifically provided for the MS sensor and has a known reflectance coefficient for each band. The reference reflectance panel was also used for radiometric calibration of RGB images. A reference reflectance value of 0.51 was set for all bands (both RGB and MS) considering that this value accounts for all wavelengths in the visible spectrum (MicaSense©, personal communication by email, 03/11/2020). In this way, the final processed data are suitable for quantitative analysis. After the pre-processing stage, both RGB and MS reflectance orthomosaics were resampled at 15 cm pixel size and stacked together resulting in a six-band composite cube. The cube was converted to ENVI standard format for processing with the open-source WASI software. In this study, atmospheric correction of drone-based imagery was not performed. This is due to the fact that the drone surveys took place at significantly low altitude and with optimal weather conditions, thus atmospheric effects on recorded reflectance are minor. Following shallow water inversion (see next section) the output bathymetry maps were adjusted for tidal offsets by using tidal information from the Poseidon forecast website ("Poseidon System," n.d.).

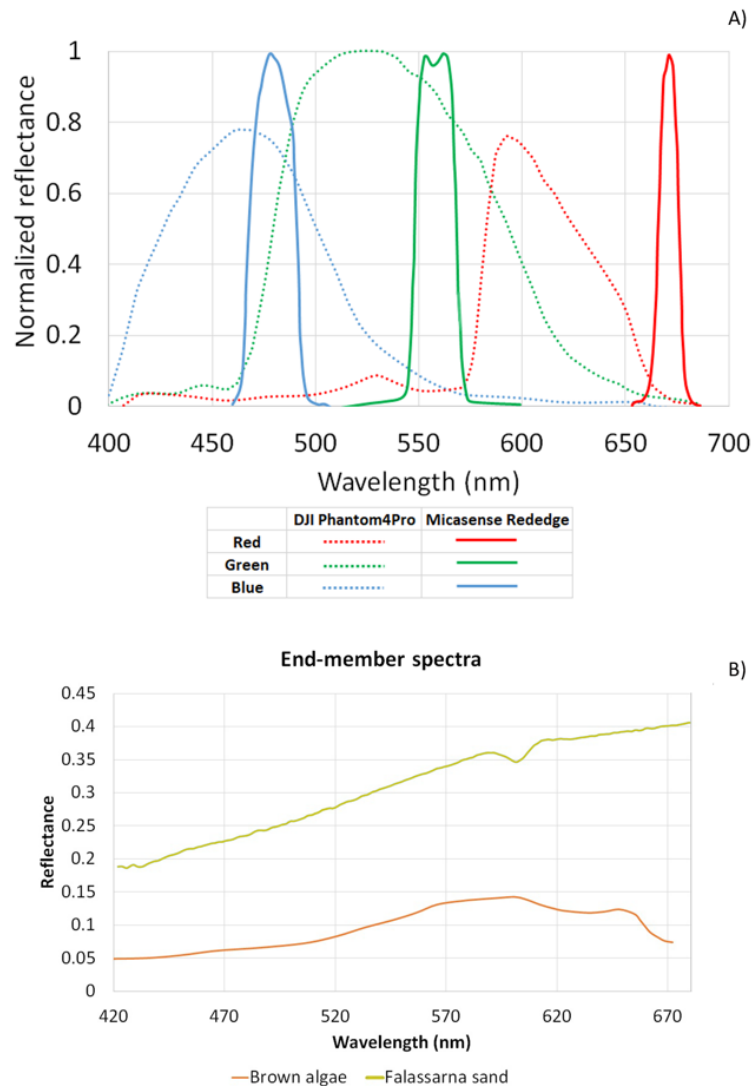


Figure 2: A) Spectral responses of both RGB and MS sensors (modified from Tagle Casapia (2017); Burggraaff et al. (2019)); B) Spectral signatures of the two end-member spectra used for bathymetry inversion.

Shallow bathymetry inversion in WASI-2D

The WASI software is one of the few open-source tools for analyzing the spectral properties of aquatic environments. The WASI tool was initially designed for studying the water properties of fresh water environments and it has been applied on a limited number of bathymetry studies, mainly in lake environments so far (Gege, 2014a; Dörnhöfer et al., 2016; Niroumand-Jadidi et al., 2020) while recently Alevizos et al. (2022a) applied WASI on PRISMA data from two Caribbean sites. The software is based on earlier bio-optical models developed by Albert (2004), Albert &

Mobley (2003), and Gege & Albert (2006). These models are applied on optically deep waters for estimating water-column constituents such as CHL-a and SPM, while they are also applied on optically shallow waters (i.e.: where the influence of the seafloor is apparent) for deriving seafloor cover and water depth. WASI supports atmospherically-corrected radiance and reflectance spectra and it uses a down-welling irradiance model for estimating the effect of sun-glint and sky reflectance on the spectral signatures (Dörnhöfer et al., 2016). WASI includes a 2D module that allows for image analysis on a per-pixel basis (Gege, 2014b). This is particularly useful for analyzing imagery from multi- or hyper-spectral sensors. Regarding bathymetry retrieval, the WASI tool considers the influence of water-column constituents along with combinations of end-member seafloor reflectance spectra on water-leaving reflectances. For the current study, we applied the end-member spectra of sand and brown algae (Fig.2B), which are more representative of the seafloor types that occur in our area than the default, end members provided by WASI. The sand spectrum was measured at Falassarna beach (50 km west of the study area) using a hand-held spectroradiometer (Alevizos & Alexakis, 2019, unpublished dataset). This type of sand consists of medium-sized, white grains with colored foraminifera fragments and it can be found in various coastal areas in the region of Chania. The brown algae spectrum was extracted from the project report of Mouquet and Quod (2010). In their work, they measured underwater spectra using a spectroradiometer and a reference reflectance panel at various coastal locations in the southwest Indian Ocean. Suitable initial values of geometric (i.e.: sun zenith angle) and irradiance model parameters are required for accurate fitting of the spectral signatures. Regarding datasets from both dates we applied 0.1 mg/l for CHL-a and SPM concentrations and a sun zenith angle of 40 degrees. Ideally, in-situ water column data should be applied for tuning these parameters however collecting such data was not practical in this study. Once the model is tuned, the depth and seafloor type are fitted using the least squares method iteratively. The modelled spectral signature showing the lowest residual with the observed signature is used to determine the depth and seafloor type for each pixel. A detailed description of the WASI tool can be found in Gege (2014). The remote sensing reflectance in WASI is modelled according to the equations of Albert and Mobley (2003) and Albert (2004):

$$R_{rs}^{sh-}(\lambda) = R_{rs}^{deep-}(\lambda) * [1 - A_{rs,1} * \exp\{-(K_d(\lambda) + K_{uW}(\lambda)) * Z_b\}] + A_{rs,2} * R_{rs}^b(\lambda) * \exp\{-(K_d(\lambda) + K_{uB}(\lambda)) * Z_b\} \quad (1)$$

The superscript *sh* indicates shallow water, *deep* deep water, *b* bottom, and the symbol λ indicates the wavelength. The first term on the right-hand side is the contribution of water column with depth z_b , the second term represents the contribution of the bottom albedo. Light attenuation is described by the attenuation coefficients K_d for down-welling irradiance, K_{uW} for upwelling radiance originating from the water layer, and K_{uB} for upwelling radiance from the bottom surface. These three coefficients are calculated as a function of the sun zenith angle, viewing direction and the concentrations of water constituents using equations also derived by

Albert and Mobley (2003) and Albert (2004). Ars_1 and Ars_2 are empirical constants. The WASI algorithm iterates the spectral signatures on per pixel basis trying to fit an optimal spectrum given the constant values of model parameters. Inverse modeling takes place by approximating the remote sensing reflectance (R_{rs}) spectra (of each pixel) with suitable WASI spectra for different depths. The best fit with the observed image spectrum is obtained by minimizing a cost function that calculates the correlation between the R_{rs} and the WASI spectra. The inversion algorithm employs the absolute difference function in order to identify an optimal set of fit parameters (depth and seafloor type), which minimize the residual of the cost function (Gege, 2014b; Gege and Albert, 2006; Niroumand-Jadidi et al., 2020).

Results

Bathymetry validation

The bathymetry inversion outputs were validated with in-situ sonar measurements from the USV platform. We compared the predicted versus the actual depth (tidally corrected) at each temporal dataset and produced linear regression scatterplots from which the overall R^2 , mean average error (MAE) and root-mean-square-error (RMSE) were calculated as useful metrics for assessing the accuracy of each bathymetry dataset. The bathymetry inversion results show excellent agreement with in-situ sonar measurements and thus a temporal change analysis can be further performed. Specifically, the scatterplot for November-2021 dataset (Fig.4B) shows optimal correspondence between the predicted and actual depths with $R^2=0.94$, and low error (MAE= 0.22m; RMSE=0.30m). There are only a few instances of localized errors and these are related to some seagrass patches the depth of which was significantly overestimated by the WASI algorithm (Fig.4A). Regarding the March-2022 dataset it shows a very good correlation coefficient between the predicted and the measured depth is $R^2=0.93$, and low error as well with MAE= 0.18m and RMSE=0.21m (Fig.4D). We further examined the bathymetry residuals as per depth category (Table 2). The residual statistics show a slight increase of the error with increasing depth; however, this never exceeds 10% of the depth at each depth category. The predicted bathymetry datasets show nearshore bedform features matching those identified by (Alevizos et al., 2021) in the same area using high-resolution World View-3 imagery. These features appear somewhat clustered, forming a continuous “chain” along the coastline in the November-2021 bathymetry. In contrast, these features appear more interrupted in the March-2022 bathymetry dataset (Fig.4 A,C).

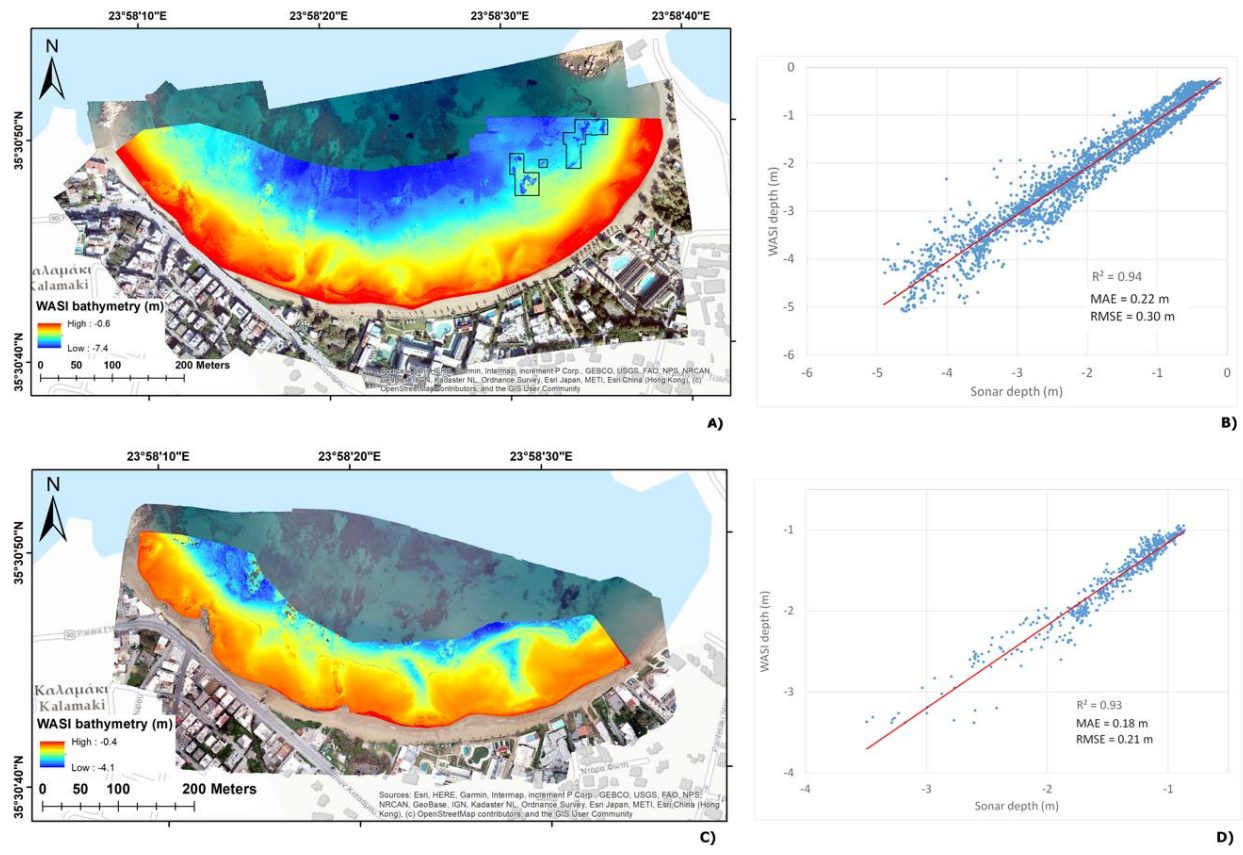


Figure 4: Bathymetry inversion output for the November-2021 dataset. Black polygons indicate erroneous results due to the presence of seagrass patches; B) Linear regression between modelled and measured depth for the November-2021 datasets; C) Bathymetry inversion output for the March-2022 dataset; D) Linear regression between modelled and measured depth for the March-2022 datasets. The red line in the regression plots indicates the linear trend of the correlation.

04-Nov-21	0-1m	1-2m	2-3m	3-4m	4-5m
Samples	498	573	597	423	177
MAE (m)	0.13	0.22	0.21	0.29	0.38
RMSE (m)	0.16	0.27	0.29	0.37	0.45
St.dev. (m)	0.16	0.26	0.28	0.35	0.40
31-Mar-22	1-2m	2-3m	3-4m		
Samples	434	113	14		
MAE (m)	0.16	0.24	0.29		
RMSE (m)	0.18	0.29	0.39		
St.dev. (m)	0.10	0.19	0.30		

Table 2: Descriptive statistics of bathymetry residuals per depth category.

Seasonal bathymetric changes

The temporal drone imagery captured significant shallow seafloor changes that occurred within a five-month period. Bathymetric changes greater than the threshold of 0.25 meters (that corresponds to the average prediction error) are considered valid, and these changes are apparent both on the RGB orthomosaics, and on the differential bathymetry map (Fig.5). The differential bathymetry map was created by subtracting the March-2022 dataset from the November-2021 dataset (Fig.5A). In this way, we obtain a better idea of how bathymetry changed over this short period. The most prominent features on the bathymetric difference map are the development of two “channels” that are perpendicular to the coast (Fig.5E). They correspond to areas of intense erosion resulting in uncovering of coarse seafloor sediments, which are not apparent in the RGB orthomosaic of November-2021 dataset (Fig.5D). These features have an average width of 20 meters, they are approximately 70 meters long and they are approximately 100 meters apart. Further erosional features are observed in the west part of the scene close to a gravelly shoal (Fig.5 B, C) where a larger portion of underlying seafloor is revealed in the March-2022 orthomosaics. A comparison of temporal bathymetric profiles along and across these erosional features shows 0.5-1 m differences within five months Fig.6. Moreover, the along-shore profiles (Fig.6B) indicate that the rip channels are shifted ca.25 meters to the west parallel to the shore over the five-month period.

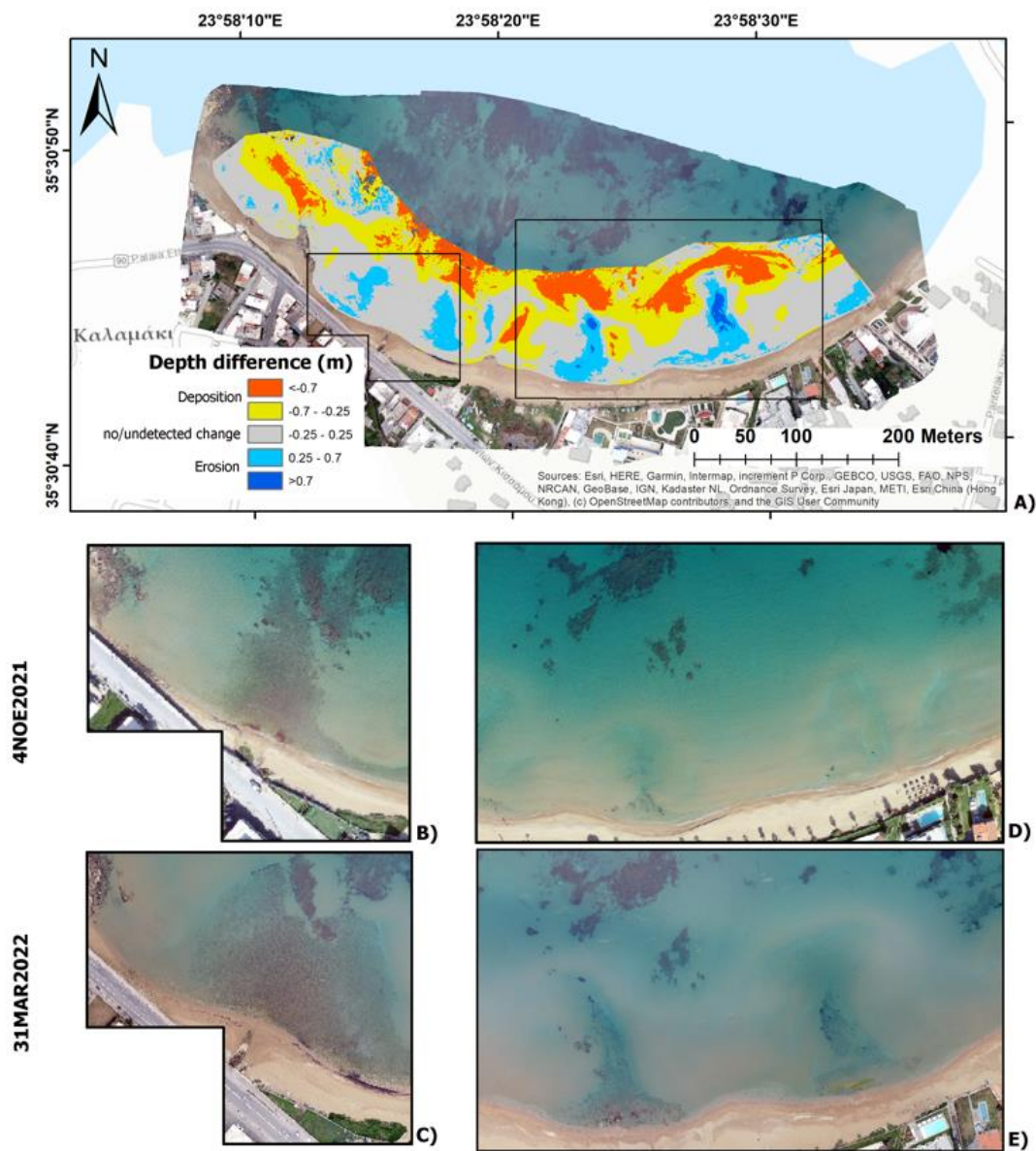


Figure 5: A) Bathymetric difference map (November-2021 minus March-2022). B) & C) True-color orthomosaic subsets showing the temporal changes within the left polygon area; D) & E) True-color orthomosaic subsets showing the temporal changes within the right rectangle area.

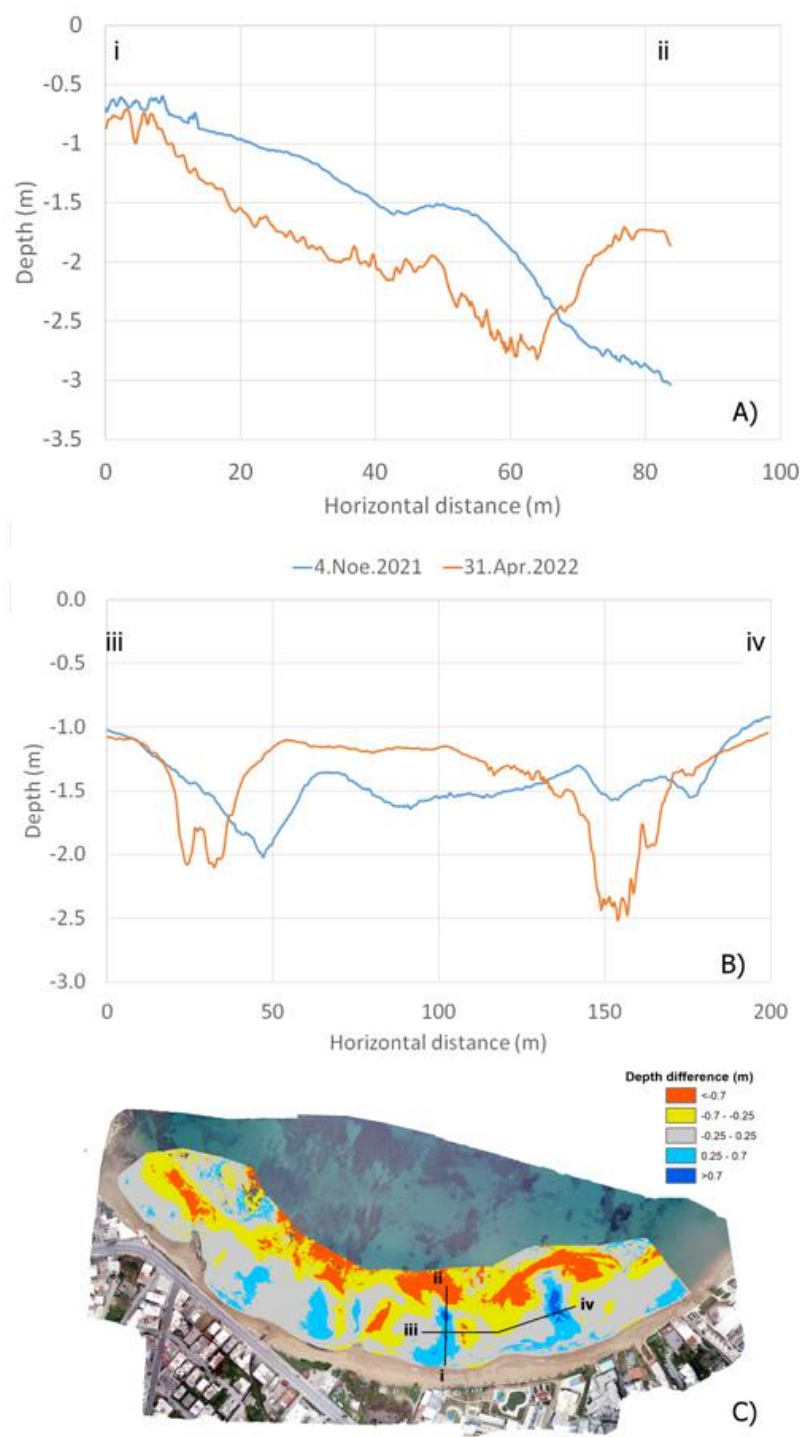


Figure 6: Temporal bathymetric profiles A) across-shore and B) along-shore. C) Legend map showing the profiles on the bathymetry difference map.

Discussion

Interpretation of nearshore bathymetry change

Change analysis between the temporal bathymetry datasets revealed geomorphological patterns that are typical for sandy coastal areas exposed to wave action from normal incidence angles (Castelle et al., 2010; Ribas et al., 2015). These patterns are characterized as crescentic bar systems and they are linked to processes that distribute large volume of sediments in the nearshore seafloor. Crescentic bars are apparent in both temporal RGB orthomosaics and bathymetry outputs (Fig.4; Fig.5) and the bathymetry difference map highlights the paths of bar reorganization under the influence of enhanced wave and current activity during the winter months. Bathymetry data (Fig.4A, C) show that crescentic bars with secondary channel systems cover the entire nearshore part of the beach. Castelle et al. (2010) and Ribas et al. (2015) have reported that the development of the crescentic bar, is linked to a self-organizing mechanism that depends on the feedback between the seafloor geometry and the distribution of wave energy. Thus, we created a conceptual model representing coastal hydrodynamic activity based on the bathymetry difference map (Fig.7). The bathymetry difference map indicates two narrow corridors (rip channels) within which intense erosion occurred. The perpendicular orientation of the channels relative to the coastline suggests that the prevailing incidence angles of waves were directly from the north. This pattern of erosion process corresponds to rip-current action, which is part of the wider coastal cell circulation (Castelle et al., 2016) (Fig.7). Rip channels are developed under the combination of wave focusing (due to refraction) and nearshore bathymetric variability (Castelle et al., 2010; Ribas et al., 2015). The transported sediment is redeposited following the rhythmic pattern of the crescentic bar. Sediment deposition is controlled by the depth-averaged sediment concentration profiles (Ribas et al., 2015). Persistent rip-current action removes large volumes of sediments from the surf zone and deposits them further offshore (Andreeva et al., 2021) as shown in Fig.5E. Using the two bathymetric datasets, we estimated the volume of sediment that was eroded through the rip channels and found that more than 1500 cubic meters were removed during the 5-month period. The shape of nearshore bedforms is further controlled by the geometric characteristics of the beach (i.e.: length) (Holman et al., 2006) and the occurrence of hard seafloor areas that influence sediment deposition.

It has been suggested that the crescentic bar oscillates between straight and crescentic form at various time scales depending on the intensity and incidence angle of waves (Garnier et al., 2013). Such a behavior was not observed in the duration of the study. However, the crescentic bar appears to be moved further offshore in March-2022 bathymetry dataset, while in November-2021 bathymetry dataset appears to be closer to the coastline. It is hypothesized that wave action during the winter storms resulted in dissociation of the “summer” structure of the bar and a slow build-up of the deeper part of the bar as it usually happens with typical beach profiles (Dean,

1991). The only difference here is that this change occurs on a crescentic bar instead to a standard straight bar. This type of across-shore migration has also been reported in the studies of Biauxque et al. (2022) and Andreeva et al. (2021). The bathymetric profile comparison in Fig.6 provides evidence that there is also a lateral migration of the crescentic bar (i.e.: along shore). Drone-based bathymetry with high temporal resolution should assist in further understanding of the along-shore displacement of the crescentic bar.

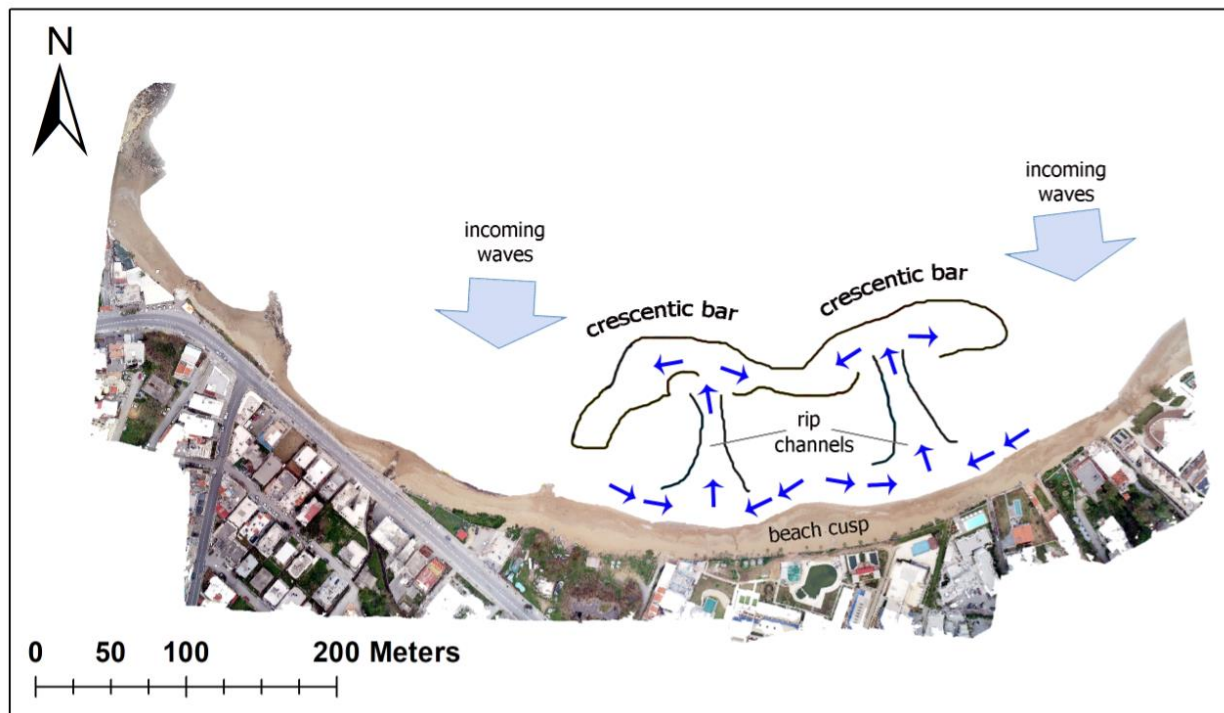


Figure 7: Conceptual model about coastal circulation and corresponding geomorphology features occurring at the study area. This model resulted from an adaptation of the bathymetric difference map (Fig.5). The thin blue arrows indicate the direction of nearshore currents.

Implications in coastal seafloor monitoring

The presented study introduces a novel approach for monitoring small-scale nearshore seafloor change in areas with sufficient water transparency. This approach provides centimetre resolution bathymetry, which is sufficient for capturing fine-scale geomorphological features and short-term changes of shallow seafloor. Although the drone-based bathymetry does not achieve the vertical accuracy of a multi-beam echo-sounder, it is considered sufficient for rapid bathymetry assessment and geomorphological mapping applications where area coverage is the primary goal. In this study, we exploited the effectiveness of WASI shallow-water inversion model for producing bathymetry without utilizing input depth data. This is a very important aspect in

shallow bathymetry mapping where several studies rely on large volume of in-situ depth measurements for building accurate empirical models (Kutser et al., 2020; Salameh et al., 2019). Obtaining extensive in-situ data requires additional costs and logistical effort, which can be problematic for long-term bathymetry monitoring projects (Capo et al., 2014). The presented study shows that radiometrically-corrected, multispectral imagery from drones (with several bands in the visible range) is suitable for producing bathymetry outputs with significant detail. Thus, drone-based bathymetry provides a cost-effective approach that is suitable for shallow bathymetry change monitoring. Shallow-water inversion models work well when imagery with suitable radiometric/atmospheric corrections is used and when the model parameters (e.g.: water-column constituents, end-member spectra) are representative of the study area. A particular advantage of drone imagery over satellite/airborne imagery regarding shallow-water inversion is the fact that the first does not require atmospheric correction. The atmospheric effects on drone-based imagery are considered minor for bright targets in the visible spectrum and when images are taken from less than 150 m altitude under favorable weather conditions (Suomalainen et al., 2021). However, the use of a calibration reflectance panel is required for obtaining reflectance values adjusted for incoming radiance. Regarding water-column and seafloor spectra data for model tuning, this information can be extracted from various sources. Information about the concentration of water-column constituents according to watertype is found in current literature and can be retrieved from large-scale satellite products (e.g.: CHL-a and SPM from Copernicus missions). Seafloor end-member spectra covering various locations (e.g.: temperate, tropical) have been published as well, providing a useful alternative to collecting these data in-situ (Mouquet and Quod, 2010). This study was based on the method of Alevizos et al. (2022b) about integrating RGB and MS data into a single image-cube. Thus, we recommend that a standard type of MS sensor and data pre-processing should be developed in the future, targeting particularly shallow bathymetry applications. An ideal sensor for drone-based bathymetry mapping should comprise at least five narrow spectral bands spanning in the visible range. This type of sensor would provide the appropriate radiometric resolution that is required for shallow bathymetry inversion (Klonowski, 2007; Marcello et al., 2018). Additionally, a dedicated radiometric calibration procedure should be implemented for this particular type of sensor in order to convert pixel values to reflectance. The availability of such a sensor would enable a wider variety of shallow seafloor mapping applications to be realized. Particularly, high temporal resolution bathymetry datasets will allow to visualize better the geometric and migration characteristics of rip channel systems, and thus assist in a better understanding of nearshore seafloor change. Drone-based bathymetry is expected to cover a significant gap in coastal modelling studies (Holman and Haller, 2013) and act synergistically with other in-situ methods (i.e.: GPS drifters) for improving the knowledge about nearshore features and processes.

Conclusions

The application of shallow bathymetry inversion on drone-based imagery provided an efficient approach for mapping nearshore geomorphological features and seasonal bathymetric changes at a small sandy bay in Greece. A composite image cube with increased spectral resolution in the visible spectrum, resulting from the combination of radiometrically corrected drone-based RGB and MS orthomosaics was used for bathymetry inversion. Predicted bathymetry showed <0.3 m average errors when compared with USV sonar bathymetry. Nearshore bedforms identified on drone-based temporal bathymetry datasets are characterized as crescentic bars and rip channel systems. Evidence on differential bathymetry and true-color orthomosaics suggest that two main rip channels developed during a period of five months, driven by the impact of wave action in winter. Temporal bathymetric profiles suggest that the crescentic bar system transforms from summer to winter geometry and migrates along-shore at seasonal time-scale. In general, the drone-based bathymetry assisted in capturing the geographic boundaries of local hydrodynamic patterns. Future improvements in drone sensors are expected to lead to a greater variety of shallow bathymetry applications.

Acknowledgements

This study is part of the ACTYS project (<https://actys.ims.forth.gr/>) that has received funding from a 2020 FORTH-Synergy Grant.

Data availability statement

Data available on request from the authors

Appendix

Band name	Central wavelength (nm)	Fwhm* (nm)
Blue	462	40
Green	525	50
Red	592	25
MS-Blue	480	10
MS-Green	560	10
MS-Red	671	5

Table A1: Spectral characteristics of standard RGB and multispectral bands used for building the composite 6-band cube. *full width at half maximum.

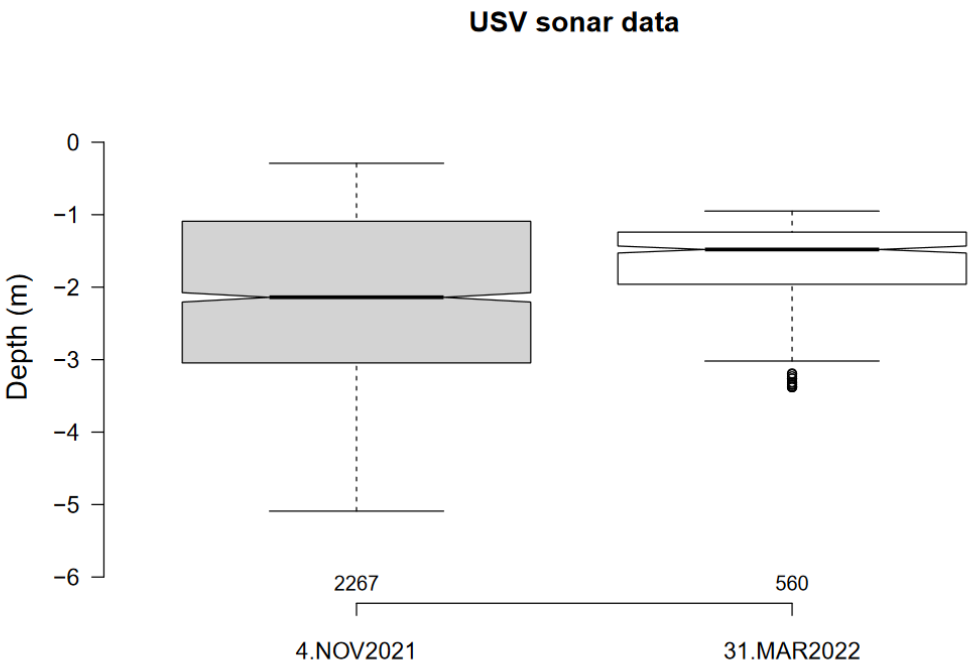


Figure A3: Boxplots of the sonar depth measurements collected at each survey. The black horizontal line inside each box indicates the median value of each sample and the numbers at the horizontal axis indicate the number of measurements.

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