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Research Article

Spatial distribution of sand dunes along the Bulgarian Black Sea Coast: inventory, UAS mapping and new discoveries

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Abstract

Coastal sand dunes are amongst the world's most sensitive and dynamic landforms. Unfortunately, during the last thirty years, heavy anthropogenic alterations have been observed, encompassing the greater part of the Bulgarian Black Sea coast (BBSC), which has changed the land-sea interactions significantly. As a consequence, the depositional coast has shrunk to 131 km or 25% of the aggregate Bulgarian Black Sea shoreline length. Although our research reveals that 86% of BBSC dunes are included in the Natura 2000 network of protected sites established under the Habitats Directive (Council Directive 92/43/EEC 1992), they are often heavily modified, subjected to environmental vandalism and destroyed due to mismanagement or lack of accurate information and prevention. These facts were the main reason for carrying out an inventory of the Bulgarian Black Sea coastal dune systems in 2021-2022. Our research aimed to identify all dune systems/sand dunes, update their spatial distribution and classify the observed coastal sand dunes landforms along the BBSC. The article demonstrates a successful methodology for combining unmanned aerial systems (UAS), Structure-from-Motion (SfM) photogrammetry, in situ sediment sampling, video imaging and verification and GNSS-RTK ground control points for coastal mapping. As of June 2022, over 97% of the Bulgarian shoreline has been surveyed with this technique, excluding military areas and national security sites. Based on the acquired data, as of 2021, the shoreline length was estimated to be 518.7 km at a scale 1:5000. The integrated UAS approach includes using Digital surface models (DSM), raster orthophotomosaics (OM) and 3D models, based on SfM photogrammetry to analyse the coastal topography, detect dune forms and update their spatial distribution. Throughout the inventory, 46 beach-dune systems were identified along the BBSC, which were divided into 62 dune sectors. The area of coastal dune systems was estimated at 988.21 ha (0.0089% of Bulgaria) and a total length of 73 km (14% of the shoreline). A comprehensive geomorphological analysis of the relationships between landforms morphology, aeolian and morphodynamic processes, vegetation density and type was the basis for the coastal dune landforms (CDLs) or dune systems to be classified into primary (312 ha; 32%) and secondary (676 ha; 68%). Additionally, the CDLs were classified according to Natura 2000 habitats: fixed (grey) dunes (546.27 ha; 55.28%), wooded dunes (222.61 ha; 22.53%), shifting (white) dunes (150.30 ha; 15.21%), embryonic dunes (68.3 ha; 6.91%) and humid dune slacks (0.94 ha; 0.09%). The highest positioned CDLs on the Balkan Peninsula were registered at perched Sozopol Sand Dunes (61 m a.s.l.) and cliff-top dunes at Arkutino (50.2 m a.s.l.). The multi-temporal analysis of photogrammetric DSMs and raster OMs showed the permanent loss of five dune systems in the Pomorie-Burgas-Rosenets coastal sector. The accrued UAS data approach allowed us to identify and map eight dune systems for

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the first time: Zlatni Pyasatsi (Panorama), Asparuhovo (Varna), Byala, Atanasovska Kosa, Central Beach (Burgas), Chernomorets, Kavatsite (partly) and Rezovo-Kastrich. A high anthropogenic footprint was registered on 50.7 ha (5.1%) of the entire dune surface. In the final stage of the study, human interventions that caused degradation and permanent loss of dunes (12 ha) over the last 15 years along the BBSC were shown. The main causes for dune degradation along BBSC have been documented, such as massive tourism development after the socialist period, road construction, recreational pressure exerted on the dunes, human trampling, lack of designated footpaths in areas with fixed and mobile dunes, off-road vehicles and parking lots (especially at camping sites), dumping of garbage and anthropogenic marine litter on the sand dunes etc.

Key words: anthropogenic pressures, Bulgarian Black Sea Coast, coastal dune landforms, drones, dune degradation, dune systems, shoreline length, unmanned aerial systems (UAS)

Introduction

Coastal dune landforms (CDLs) are common sand forms of depositional landscapes that exist along the shores of oceans, seas and other water bodies in the world, where geomorphological settings, waves and currents interact with the available sediment and psammophilous vegetation to create varieties of forms and habitats located behind the active beach (Psuty 2008; Huggett 2016, etc.). Geomorphologically, the coastal dunes were formed at various timescales, but most of them were shaped out in Holocene and modern times from sand supplied to beaches from the sea floor (notably during the Holocene marine transgression) and alongshore sources, such as cliffs or bluffs in soft sandstone or glacial drift deposits (Bird 2008).

Beach and dune definitions

Beaches, as the most dynamic component of coastal systems, offer an exposed sediment source. Luijendijk et al. (2018) assessed that 24% of the world's sandy beaches are persistently eroding at a rate exceeding 0.5 m/yr over the study period (1984–2016), while 27% are accreting. About 16% (18%) of sandy beaches are experiencing erosion (accretion) rates exceeding 1 m/yr. Hence sandy beaches are often enclosed by some dune forms, produced by sand transported by wind activity and deposited at the vegetated landward section of the beach (Davidson-Arnott 2009). CDLs range from small forms, less than a metre in height, a few metres in width and along shore extents on small rocky embayments to much greater geomorphological features that may be 100 m or more in height, extending for tens of km alongshore, on sandy barrier systems or in low coastal plains (Davidson-Arnott 2009). Most of the sediments transported from the backshore are initially trapped by vegetation colonising the beach area, just landwards from the limit of storm wave action, leading to the development of a foredune ridge parallel to the shoreline (Davidson-Arnott 2009). In addition, Davidson-Arnott (2009) generalises some facts in terms of coastal sediment budgets. Essentially, beaches are the source, while dunes represent the sink. As fine sediments are generally scarce on active sandy beaches, coastal dune deposits have very small amounts of sediment with < 0.15 mm grain size. Likewise,

because of the small air density compared to water, particles > 1 mm are selectively left on the beach during deflation and are also generally scarce. Bird (2008) summarises that dune sands have similar characteristics to the beach sands from which they derive and generally consist of quartz, feldspar and calcareous particles (including foraminifera, bryozoa, comminuted shells and corals), sometimes also containing heavy minerals, such as rutile and ilmenite.

Although the CDLs are unique aeolian landforms, their evolution is closely related to the vegetation's role in reducing wind speed and facilitating the deposition of sediments (Masselink et al. 2011) and represent habitats of important environmental and landscape values. Moreover, dunes form natural coastal defences because they act as a sand reserve and a physical barrier protecting landward territories (Fryberger et al. 1979; Jay 1998; Sabatier et al. 2009; Harley and Ciavola 2013). Geomorphologically, dunes are classified into primary (foredunes and embryonic dunes) and secondary, with different morphological and morphodynamic characteristics, each one modified by different processes (Psuty 1989; Davidson-Arnott 2009; Masselink et al. 2011 etc.). The morphodynamics of secondary dunes are similar to terrestrial (desert) dunes, but primary dunes are fundamentally different. Sherman and Bauer (1993) consider primary dunes to be essential coastal forms because they are strongly coupled to the nearshore processes on the fronting beach. By appearance and morphology, dunes can be differentiated into foredunes, parabolic, blowouts, transgressive sheets and dune fields (Hesp 1991, 1999, 2002, 2011; Bird 2008) and are associated with ridges, mounds, terraces and low-lying swales, formed by different geomorphological processes over the years (Bird 2008).

Brief reference on sand dunes inventories in Europe and Bulgaria

Early publications on sand dunes over the European Union include a Council of Europe Report and a wide-ranging study in a special Catena publication (Géhu 1985; Bakker et al. 1990). In Sand Dune Inventory of Europe (Doody 1991), the Coastal & Marine Union (EUCC) has promoted dune conservation on European coasts and nowadays (with a total area of more than 5300 km^2), they have acquired high importance for the community and nature preservation. The inventory also provides a brief description of the dune formation types, size of the overall resource, vegetation, important dune sites, comments on conservation issues and a list of references (Delbaere 1998; Doody 2008). Doody (2013) makes a retrospective analysis of the significant steps in the scientific activity of dune inventories in Europe. Recently, Jackson et al. (2019) and Gao et al. (2020) have provided a comprehensive analysis of stabilisation trends of coastal dunes by utilising a larger temporal window and more dedicated dune sites. In the context of increasing coastal urbanisation, climate change and associated sea-level rise, shorelines have become more vulnerable to overdevelopment, dune erosion and dune vanishing, especially mobile sand dunes. They are suggested to have a much higher ecological diversity and species richness, while stabilised sand dunes could be more tolerant to future sea-level rise.

At the European level, coastal dunes have a conservation significance as natural habitats and are meant to be protected from negative human impacts (Council Directive 92/43/EEC 1992; Martinez and Psuty 2004; European Commission 2008; Doody 2013; Janssen et al. 2016). The coastal sand dune

habitats are considered conservationally important at the national level, pursuant to Appendix 1 of the Biological Diversity Act (BDA 2002). The coastal dunes are also included in Volume 3 (Natural Habitats) of the Red Data Book of Bulgaria (Tzonev 2015a, 2015b, 2015c, 2015d; Tzonev and Gussev 2015). In addition, Gussev and Tzonev (2015) summarise that a substantial part of the total dune area in Bulgaria is included in the Natura 2000 network: 58% of embryonic dunes (ED), 73% of white (shifting) dunes (WSD), 89% of grey (fixed) dunes (GD), 100% of wooded dunes (WD) and 67% of humid dune slacks (HDS).

Human activities and anthropogenic pressures on coastal dunes

Human intervention is critical when discussing dune mobility alterations, their stabilisation and re-mobilisation. Therefore, in the near future, it will be necessary to increase scientific and public awareness, as well as to take careful actions to preserve or possibly even restore the dune mobility and balance the ecosystem services that coastal dunes offer. Failure to address the degradation and loss of dunes could result in hazardous consequences (Gao et al. 2020). Naturally, the distribution and ecological state of the dunes was not always excellent. The degradation and loss of coastal dunes come as a consequence of different activities performed on the coast by humans. These actions can be categorised into six groups and, to a major or minor extent, all of them affect coastal dunes: housing and recreation, industrial and commercial use, waste disposal, marine litter, agriculture, aquaculture and fisheries, military activities etc. Gómez-Pina et al. (2002) define the main dune management problems in Spain, which are unfortunately valid for dune fields all over the world: massive tourist development, road and boulevard construction, dune mining, littoral drift interruption, dune recreational pressure, inadequate waterfront construction, human trampling, off-road vehicles and parking lots, agricultural practices and afforestation, garbage dumping, water extraction, civil engineering works and military use (Martínez et al. 2013; Vallés and Cambrollé 2013 etc.).

The second half of the 20th century saw the beginning of specific anthropogenic processes primarily represented by urbanisation, industrialisation and tourism. These processes have significantly altered the natural and environmental state of many coastal and river ecosystems, resulting in intense erosional processes and the destruction of numerous dune systems (Aguilera et al. 2020; Zhai et al. 2020 etc.). In reality, 30% of the world's coastlines are eroding, while dune systems have reduced by 70% in Europe alone (Luijendijk et al. 2018; Mentaschi et al. 2018; Vousdoukas et al. 2020 etc.). Furthermore, by causing sea level rise, climate change can expedite these processes (De Figueiredo et al. 2018; Forgiarini et al. 2019; Reguero et al. 2019; FitzGerald et al. 2020). As an integral part of coastal systems, threats affecting European dune systems, such as urbanisation, extraction of materials, recreational seashore activities (including mechanical impact caused by trampling, campsites etc.), pollution, invasive species and natural system modifications (Defeo et al. 2009; Malavasi et al. 2014).

Aim of the study

In accordance with the definition by numerous authors (Bird 2008; Psuty 2008; Davidson-Arnott 2009; Masselink et al. 2011; Huggett 2016), in this article,

the Bulgarian Black Sea coastal dunes are considered as sand landforms, a fundamental element of the coastal system. In Bulgaria, the spatial register of beaches, dunes and other coastal features is maintained as an integral thematic module of the Cadastral-Administrative Information System (CAIS) of the Republic of Bulgaria (https://kais.cadastre.bg/en) which should be up-to-date. This online-accessible webGIS-based information system is administered by the Geodesy, Cartography and Cadastre Agency (GCCA) to the Bulgarian Ministry of Regional Development and Public Works (MRDPW-Bulgaria). These duties of GCCA are in line with the Black Sea Coast Spatial Development Act and the related Ordinance No. 1/ 16 September 2008, that regulates the creation, maintenance and data update of the specialised maps and registers of the coastal features illustrated (i.e. beaches, dunes, coastal lakes, estuaries, lagoons, wetlands, hydro-technical structures etc.) (Ordinance 2020). Currently, however, CAIS fails to reflect all coastal dunes and sites in the country.

Due to the mobile nature of ED and WSD, they often shift their locations and boundaries. Hence, they change their size and position, which has not been systematically reflected in the specialised maps and dedicated thematic module on coastal features in CAIS over the years. Such geodata gaps lead to various issues concerning beach management and respective measures by local authorities, relevant ministries and executive agencies. Moreover, a large number of unidentified and unclassified dune areas and forms have been found during the dune inventory over the years and described herein.

Last but not least, throughout the last 15 years, the number of hydrotechnical facilities and ports along the BBSC has grown significantly, resulting in the formation of new beaches and, in some places, new dune areas (MSPRB 2021; UASME 2021). It was precisely the cited data discrepancies between the thematic coastal module of CAIS and the actually observed features in situ that, in 2020, led to the decision to launch an inventory of all beach-dune systems along the BBSC by a research team affiliated with the Institute of Oceanology – Bulgarian Academy of Sciences (IO-BAS).

The objectives of the presented study herein are: **(1)** a spatially explicit inventory of beach-dune systems (dune landforms) and preparation of an up-to-date list of dune systems locations along the BBSC; **(2)** detailed mapping of newly identified dune systems at a scale of 1:1000; **(3)** data update on the spatial distribution of coastal dune landforms; **(4)** assessment of the aggregate dune area affected by anthropogenic alterations; **(5)** assessment of the area and type of dunes lost over the past 15 years.

Materials and methods

Study area

Geomorphology of the Bulgarian Black Sea Coast

The geomorphological settings along the western Black Sea coast provide excellent conditions for the formation of coastal sand dune landforms. Tătui et al. (2019) report that 68% of the shoreline is morphodynamically stable (change between -1 m/yr and 1 m/yr) and 13% is dominated by accumulative processes (over 1 m/yr), which allows for the formation of local beach-dune systems

in some low-lying coastal sectors of Bulgaria, Romania, Ukraine, Russia and Turkey (Bird 2010).

The relief of the Bulgarian coastal region is a result of intricate interactions amongst tectonics, neotectonic movements and exogenous weathering and accumulation processes, such as erosion, abrasion, aeolian transport and deposition (Popov and Mishev 1974; Cheshitev et al. 1989; Keremedchiev 2001; Krastev 2002; Peychev 2004; Peychev and Peev 2006; Filipova-Marinova 2007; Keremedchiev and Stancheva 2007; Aleksiev 2012; Filipova-Marinova et al. 2013; Dimitrov et al. 2023). Over the years, zonation of the Bulgarian coastal area has been carried out on the basis of different criteria, for example, morphostratigraphic specifics (Lilienberg 1966), morphostructural properties (Popov and Mishev 1974), morphodynamic systems (Peychev and Andreeva 1998), morphometric parameters (Keremedchiev 2001), morphodynamic activity (Keremedchiev and Stancheva 2007), morphographic settings (Dimitrov et al. 2023) etc. In this regard, the authors of this paper consider that the dune systems analysis should correlate with the following six morphographic subdivisions on the Bulgarian Black Sea coastal zone (Fig. 1): Northern zone - Dobrudzha and Franga-Avren sectors; Central zone - Lower Kamchiya (Kamchiya) and Stara Planina (East Balkan Mts.) sectors; Southern zone - Burgas and Medni Rid-Strandzha sectors.

Bulgarian Black Sea beach-dune systems

In Bulgaria, the beach-dune systems are a valuable recreational resource and the most frequent landforms created in coastal depositional environments, making their preservation crucial. The accumulative forms comprise more than 70 beaches along the Bulgarian coast, including a total of 19 beach-dune systems (Stancheva 2010; Stanchev et al. 2013). They are prevalent along the southern Bulgarian Black Sea coast (Popov and Mishev 1974), but this information will be updated in the study presented herein. Most of the beach-forming substrates along the coast of Bulgaria are of terrigenous origin. Once eroded from the nearby coastal source areas, they are subsequently transported by rivers and surface streams and eventually deposited and redistributed in the littoral zone. As a result, estuaries, lagoons, inlets, bays, gullies and ravines are essentially linked to the spatial distribution of beach-dune systems. Furthermore, due to overlapping characteristics of the coastal morphodynamics (sand strips) and the aeolian transport (dunes), beach-dune systems are characterised by rather intense spatio-temporal variations (Popov and Mishev 1974; Krastev 2002; Keremedchiev and Cherneva 2003; Peychev 2004; Stancheva 2010; Stancheva et al. 2011; Kotsev et al. 2020; Prodanov et al. 2021b etc.).

Coastal landforms differ as to the degree of influence by morphodynamic processes that predominate in the littoral zone. They also exhibit notable differences in terms of their origin. However, in recent years, the anthropogenic activity or anthropogenic load has become yet another significant factor regarding coastal change (Stancheva et al. 2011; Stanchev et al. 2013; MSPRB 2021; UASME 2021), which applies with full force to the dune fields: Nessebar (Stancheva et al. 2011) and campsites, for example, Kavatsi, Smokinya, Gradina etc. (Stancheva 2010; MSPRB 2021). Over the years, dunes along the

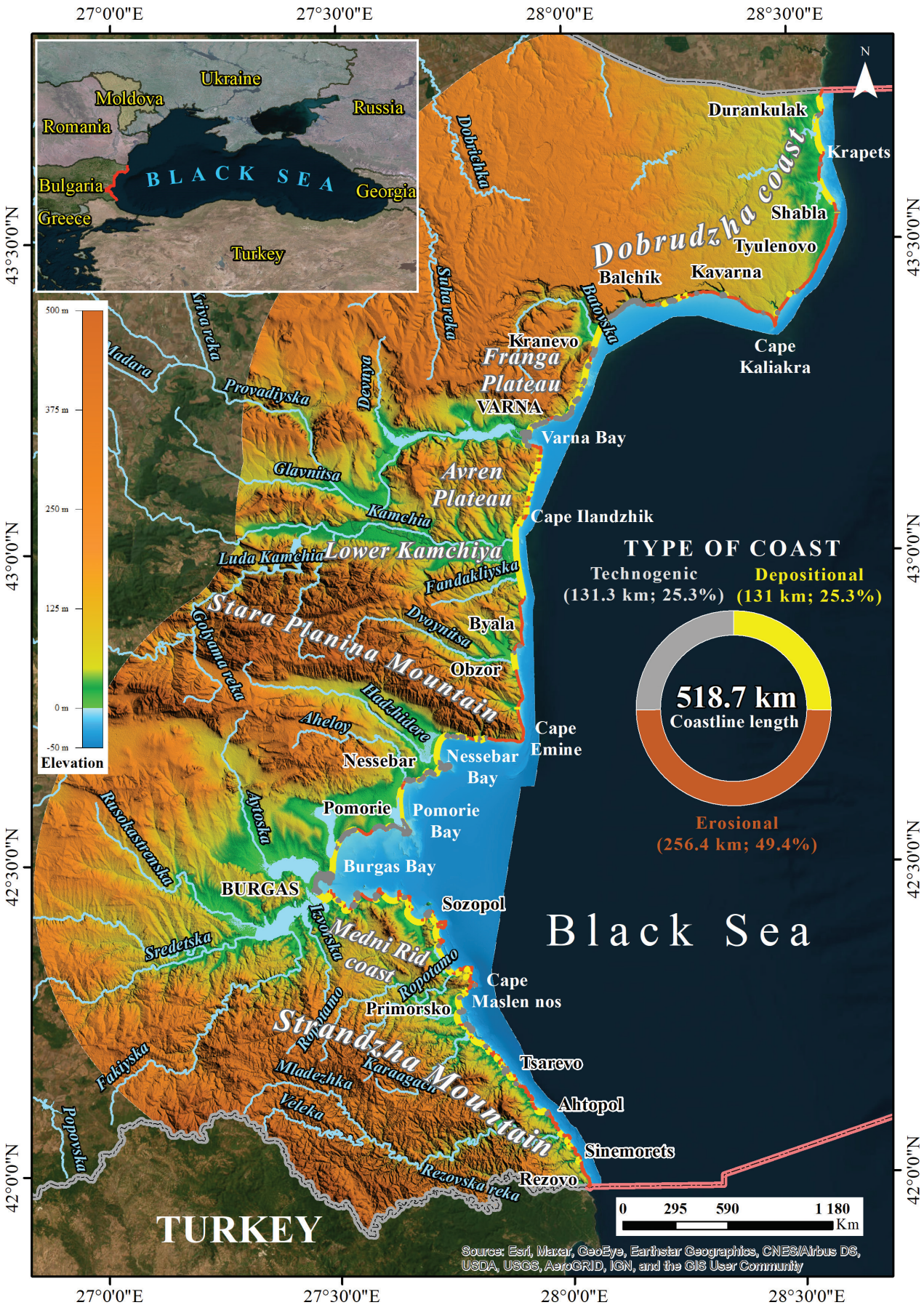

Figure 1. Bulgarian Black Sea shoreline and spatial distribution of depositional, erosional and technogenic coastal types.

Bulgarian coast have been relatively understudied in geomorphological, morphodynamic (Passports of the Bulgarian Beaches 1994; Kenderova et al. 1999; Prodanov et al. 2019a, 2020b, 2021a; Kotsev et. 2020; Prodanov 2023) and geological aspects (Petrov 2013; Valchev 2014, 2015; Sinnyovsky and Sinnyovska 2016, 2017) or as Natura 2000 Habitats. Dunes of the first row at the back of a beach's active portion are termed foredunes (corresponding to the so-called embryonic and mobile/white dunes) (Tzonev 2015a, 2015b), while these located further landwards are known as stabilised (grey) dunes, which may also be covered by arboreal vegetation (vegetated dunes) (Gussev and Tzonev 2015; Tzonev 2015c, 2015d). The negative, often moist depressions located amongst dune ridges are termed dune slacks (Tzonev 2015d). Gussev and Tzonev (2015) summarize that a substantial part of the Bulgarian coastal dune areas is included in the Natura 2000 Network: 58% of embryonic dunes (ED), 73% of white (shifting) dunes (WSD), 89% of grey (fixed) dunes (GD), 100% of wooded dunes (WD) and 67% of humid dune slacks (HDS). In recent years, an increase in non-psammophytes, grass and shrubland species has been observed, probably due to tourist activity and technogenic pressure, which should be addressed as an issue in the future (Valcheva et al. 2019, 2020, 2021).

Climate of the Bulgarian Black Sea coast. Prevailing winds, aeolian transport and dune formation

Redistribution and accumulation of sand through aeolian transport represent the essence of dune formation. Dune locations are indivisibly related to the beach exposure towards the prevailing strong winds direction. For the BBSC, threshold values for aeolian transport are assumed to be 15 m/s (Popov and Mishev 1974). The prevailing eastern and north-eastern winds are of utmost significance, although such coming from the west quarter are also important concerning aeolian transport and subsequent dune formation. At beaches open towards the east and prevailing strong north-easterly winds, dunes form in the middle, especially in the southern section of the beaches. Accordingly, at sand strips exposed towards the north, dunes are formed in the middle and western beach sections (Popov and Mishev 1974).

Inventory data source

Archive of IO-BAS

At the end of the 1970s, IO-BAS carried out the first scientific studies on the BBSC for mapping the beach-dune systems. For a decade, in-situ campaigns were carried out to map all sand beaches and coastal dunes (as landforms) and determine their morphodynamic properties. Unfortunately, the results of these studies were kept confidential during Bulgaria's socialist period and, currently, only the beach and dune locations are available in the IO-BAS archives. After 1991, at the beginning of the democratic period, IO-BAS resumed systematic studies of the Bulgarian coast. The most detailed records of beach-dune systems on the BBSC date from that time (Passports of the Bulgarian Beaches 1994).

Cadastral-Administrative Information System of the Republic of Bulgaria (CAIS): Thematic module for the Bulgarian Black Sea coast

The webGIS-based information system for cadastral data and services - CAIS comprises several components containing and visualising thematic geospatial data, amongst which is a module dedicated to coastal features (i.e. beaches, dunes, estuaries, lagoons, wetlands, coastal protection infrastructure etc.), as listed in Article 6, paragraphs 4 and 5 of the Black Sea Coast Spatial Development Act (BSCSD 2008). However, despite being a highly valuable (and openly available) data source, the cited thematic module of CAIS fails to represent the up-to-date locations and boundaries of all the above-mentioned coastal features. Amongst the reasons for these drawbacks are certain peculiarities of data updates on behalf of the GCCA, cadastral parcel-based approach in delineating contours of the cited features, discrepancies in the coastal classifications used, delayed in-situ surveys on behalf of the authorities in charge, resulting property rights issues due to the legal status of the cited coastal features etc.

Methods

The study combines various techniques, such as spatio-temporal GIS-aided analysis of archival data, drone mapping, sedimentological analysis and visual observations, integrated into a GIS database. For the accuracy of our research, field geodetic GNSS measurements were performed at each beach-dune system (Fig. 2).

UAS mapping and field surveys

The use of drones for photogrammetric surveys is widespread in studies of beach-dune systems around the world (Papakonstantinou et al. 2016; Suo et al. 2017; Laporte-Fauret et al. 2020, 2022; Fabbri et al. 2021). In the last five years, drones have become the most efficient and inexpensive method for environmental monitoring, habitat and vegetation mapping and analysis of geomorphic processes/changes (Turner et al. 2016; Choi et al. 2017; Madurapperuma et al. 2018; Guisado-Pintado et al. 2019; Pagán et al. 2019; Prodanov et al. 2019a, 2019b; Suo et al. 2019; Kotsev et al. 2020; Prodanov 2023). Scientific UAS surveys in Bulgaria are focused on the SfM-derived georeferenced data for different purposes, such as geomorphological or landscape mapping (Dimitrov and Savova 2019; Prodanov et al. 2019a, 2019b, 2021a, 2021b; Kotsev et al. 2020; Tcherkezova et al. 2020; Dinkov et al. 2021; Tcherkezova 2021; Trendafilova and Dechev 2021; Prodanov 2023), landslide processes (Atanasova and Nikolov 2021; Pashova et al. 2021; Nankin et al. 2022), geoarchaeological mapping (Peev and Prodanov 2020; Prahov et al. 2020; Tzvetkov 2020; Vajsov et al. 2020) etc. The cited references prove the wide range of digital results obtained, making drones a suitable mapping tool for beach-dune systems along the BBSC.

Since 2018, IO-BAS has been using Phantom 4 Pro, Phantom 4 RTK and WingtraOne drones (Figs 2, 3). As of June 2022, over 97% of the Bulgari-

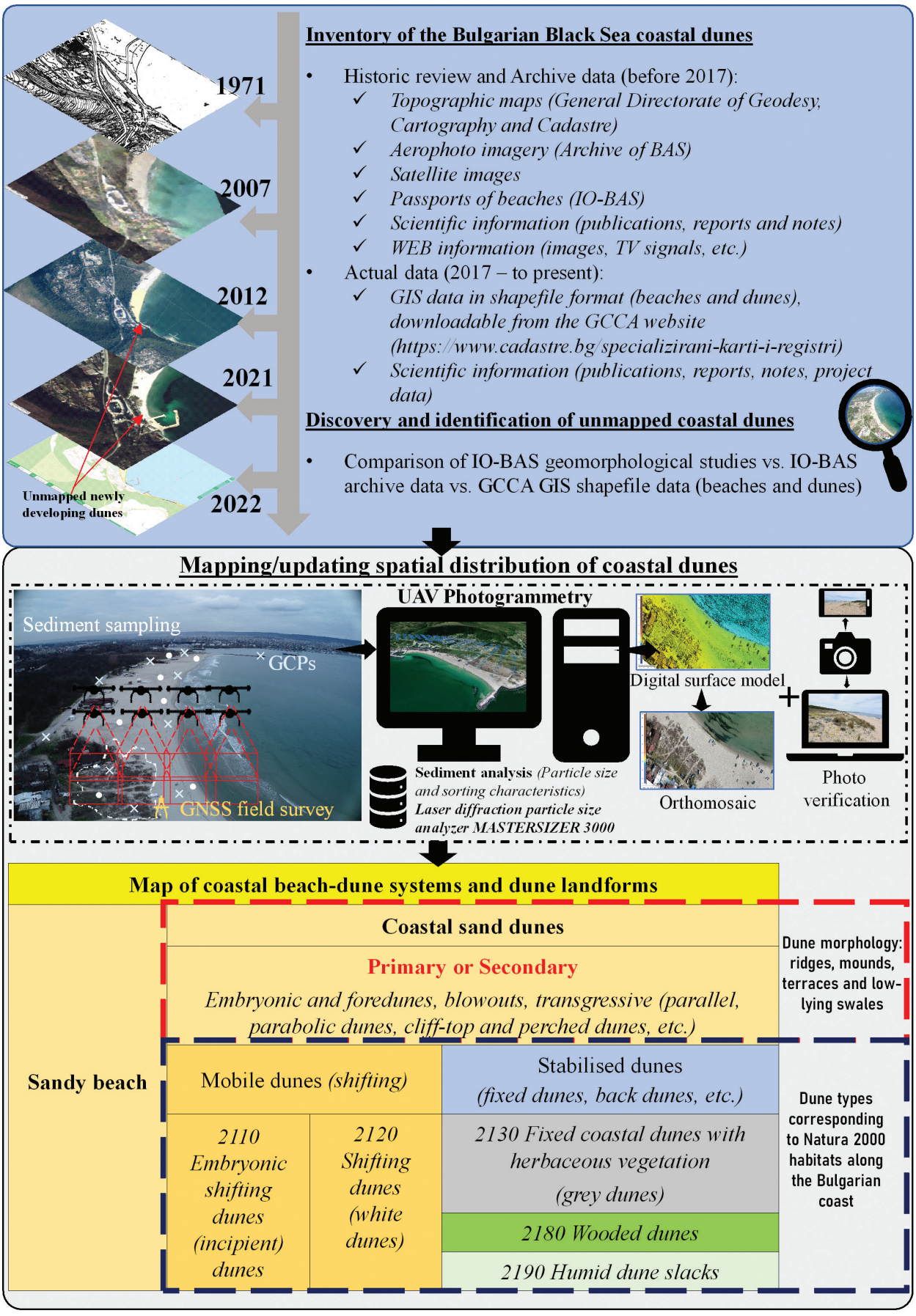

Figure 2. Methodology for inventory and mapping of coastal sand dune landforms along the Bulgarian Black Sea Coast.

an coast has been surveyed using these UAVs, excluding military areas and national security sites (Prodanov et al. 2020a etc.). Furthermore, geodetic GNSS surveys were performed to physically trace dune landforms in wooded areas (such as the Koral coastal area, town of Kiten) and to locate 2316 ground control points (GCPs) in order to increase the accuracy of the UAV photogrammetric measurements. In addition, photo verification of landforms and plant species within the range of beach-dune systems was performed at over a thousand locations (Figs 2, 3). Flight data were processed by specialised photogrammetric software, such as Agisoft Metashape, Pix4D and Global Mapper. The digital surface models (DSMs) were brought to the Baltic Height System. All vector and raster files representing survey results were combined into a coherent geodatabase, with WGS 1984/UTM zone 35N as a spatial reference.

Grain-size sampling and analysis of beach-dune sediments

Sediment sampling was performed by the IO-BAS team within each beach-dune system along the BBSC. Samples were taken at 1632 stations between February 2018 and May 2022 along morpho-lithologic transects and distinct locations on the CDLs (Fig. 3). Sands were collected from the beach face, beach face crest, summer berm, high beach winter berm, seaward dune slope, the crest and lee slope of the primary dune, a transition zone between primary and secondary dunes, middle sections of secondary dunes and the end of the secondary dunes. Sediment characteristics were determined using a Mastersizer 3000 Laser Diffraction Particle Size Analyzer in the Laboratory of Lithodinamics and Sediment Analysis at IO-BAS. The study used a grain-size distribution and statistics package for the analysis of unconsolidated sediments by sieving and laser granulometry (Blott and Pye 2001). The sediment stations were classified according to the Wentworth grain-size scale (Wentworth 1922) and Gradistat (Blott and Pye 2001).

Beach-dune systems and hierarchical subordination of sectors

For CDLs, two main levels of hierarchical subordination were used. Primarily, they correspond to **(I)** beach-dune systems - they represent unified beach and dunes in a geomorphological sense often named on their localities (Fig. 4, Suppl. material 1). The secondary level is **(II)** beach-dune sectors compliant with the coastal thematic module of CAIS (Suppl. material 1).

Identification and classification of coastal dune landforms

The geomorphological field surveys were conducted systematically outside the tourist season and low level of anthropogenic influence on dunes. In the present study, the spatial distribution of CDLs was based on morphometric analyses of the DSMs, visual analyses of the OMs or 3D photorealistic models, as well as in situ verification. From a geomorphological point of view, the division of CDLs into primary (embryonic and foredunes) vs. secondary (blowouts, transgressive, parabolic, cliff-top, perched etc.) or fixed vs. mobile dunes is important for the study of land-sea interactions and coastal natural resources.

Figure 3. Example of field surveys and UAS mapping of coastal dune landforms using WingtraOne and DJI Phantom 4 RTK drones at Kavatsite-Smokini beach-dune system (Location on Fig. 4).

The vegetation field observation (verification) was conducted systematically in the summer (July -August) of 2021 and 2022. In the light of the Natura 2000 European ecological network and the EU Habitats Directive, the inventory of CDLs carried out and newly mapped dunes were classified according to their characteristics in the sense of the Red Data Book of Bulgaria (Tzonev 2015a, 2015b, 2015c, 2015d; Tzonev and Gussev 2015). Furthermore, field observation of the vegetation type and anthropogenic influence on the dunes was conducted within the active touristic period in the summer seasons of 2021 and 2022. As a result, the CDLs were divided into shifting/mobile dunes (embryonic and white dunes) and relatively stabilised dunes (fixed grey dunes, wooded dunes and humid dune slacks) - Suppl. material 1.

Results

Spatial distribution of dune systems along the Bulgarian Black Sea coast

The results presented herein summarise the field study of the IO-BAS team in the period between 2018 and 2022. The combination of UAS (drone) mapping, DSM-based morphometric analysis, sediment sampling, visual recognition (verification) and plant reconnaissance allowed the identification of 46 beach-dune systems along the BBSC (Fig. 4, Suppl. material 1). The coastal dune systems consist of 14% of the Bulgarian shoreline (total length of 73 km) with an aggregate area of 988 ha (0.0089% of Bulgaria). A comprehensive analysis of the relationships between local morphology, aeolian and morphodynamic processes and stabilization by density vegetation was the basis for dune classification into two broad types: primary and secondary.

Primary dunes are located closest to the shoreline. They are significantly affected by wave processes (e.g. overwashing, storm erosion) and are in a dynamic interrelationship with the beach. Primary dunes include embryonic dunes on the backshore and foredunes on the seaward edge of the dune system. Their area amounts to 311.9 ha (32% of the total dune area). As a result of coastal progradation, secondary dunes (dune systems) are found further inland, where they are no longer affected by wave processes. These dunes encompass various landforms, including blowouts, dune fields, parabolic dunes, transgressive dunes, mature foredune ridges and cliff-top (perched) dunes. These distinct types of coastal dune landforms collectively span an area of 676.3 ha, accounting for 68% of the total dune area.

According to Natura 2000 Habitats, the most widespread is the stabilized grey dunes (546.47 ha, 55.28% of the total dune area). They are typical for the entire BBSC. The white dunes are mainly confined to the foredune zone and have an area of 150.30 ha (15.21% of the total dune area). The shifting embryonic dunes are common in front of foredunes, with a total area of 68.30 ha (6.91%). Wooded dunes are characteristic of the backwardmost parts of the beach-dune systems. In nearly all cases, they mark the outer end of the dunes and their area is 222.61 ha (22.53% of the total dune area). The least widespread type is the dune slacks, with an aggregate area of barely 0.94 ha (0.09% of the total dune area).

Dunes along Dobrudzha coast (Cape Sivriburun - Batova River Mouth)

Four beach-dune systems have been identified and mapped along the northern Bulgarian coast: Durankulak, Krapets, Ezerets-Shabla and Bolata (Fig. 4, Suppl. material 1). Examples of well-formed primary and secondary dunes are observed in the Durankulak-North coastal sector. The first row represents foredunes of medium sand and the wide beach strip provides conditions for the formation of embryonic dunes. Secondary dunes in the section are flat-to-undulating sand sheets to sand sheets that rise in elevation downwind and end up in a slip face, for which we will use the term ramp dunes. After the construction of the Durankulak Fishing Port (Fig. 5), the geological conditions and the exposure of the coast to wind waves (Valchev et al. 2014) have contributed to the accumulation of a narrow beach and adjacent embryonic dunes have been formed (Fig. 4, Suppl. material 1).

Figure 4. Spatial distribution of sand dune systems along the Bulgarian Black Sea coast.

Figure 5. 3D model of newly identified coastal sand dune landforms north of Durankulak Fishing Port from 2018 (see location on Fig. 4).

Dunes accumulated over barrier beaches attached to the land at both ends are characteristic of the Dobrudzha coast. Mobile white and stabilised grey dunes separate Durankulak, Ezerets and Shabla lakes from the Black Sea. The average width of the dune systems is approximately 60 m. South of Cape Shabla, the erosional morphology dominates. The coast consists of karstified rock platforms or vertical cliffs without sand beaches. A small sand-dune system exists in the area of Bolata Cove. The dunes are small in size and close to the shoreline (Prodanov et al. 2019b). Although they are protected by an old dilapidated military port, they have been subjected to high anthropogenic pressure and are almost completely destroyed. Sediment profiles show the presence of coarse sand in the active beach area, passing into medium sand within the primary and secondary dune areas. The finest sands occur at the end of the secondary dunes located immediately next to lakes or backwoods at Durankulak - North.

Dunes along Franga-Avren coast (Batova River Mouth - Cape Paletsa)

The Franga-Avren coast is also known as the Varna coastal region (Fig. 4). Coastal dune landforms were identified and mapped in the following sectors: Batova River Estuary, Zlatni Pyasatsi Panorama Resort (Fig. 6), Asparuhovo quarter (Varna) – Fig. 7 and Pasha Dere Ravine. South of the Batova River Estuary, the specific geological and geomorphological conditions do not allow the formation of long beach-dune systems. Most beaches are narrow and heavily altered by the thriving tourism along the Varna coast. Beaches have been exploited and groomed for many years, which does not allow the formation of dunes on them. In some places, small embryonic dunes were found that did not exceed the minimum mapping unit and were, therefore, not reflected in Suppl. material 1.

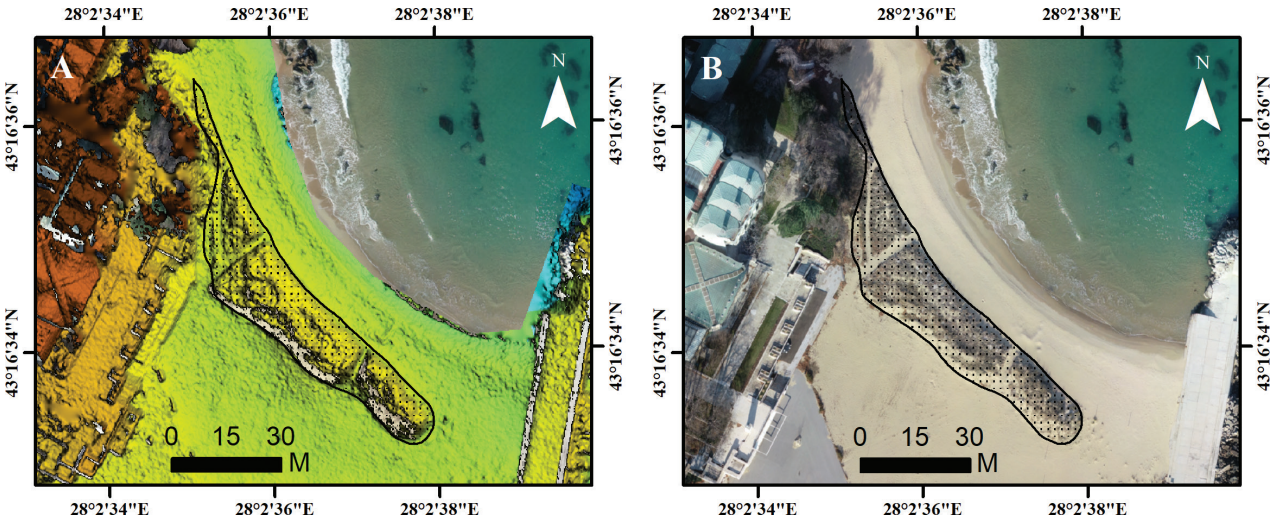

Figure 6. Newly identified coastal sand dune landforms at Riviera Beach, Zlatni Pyasatsi Resort (**A** digital surface model **B** orthophotomosaic from 2022) - (see location on Fig. 4).

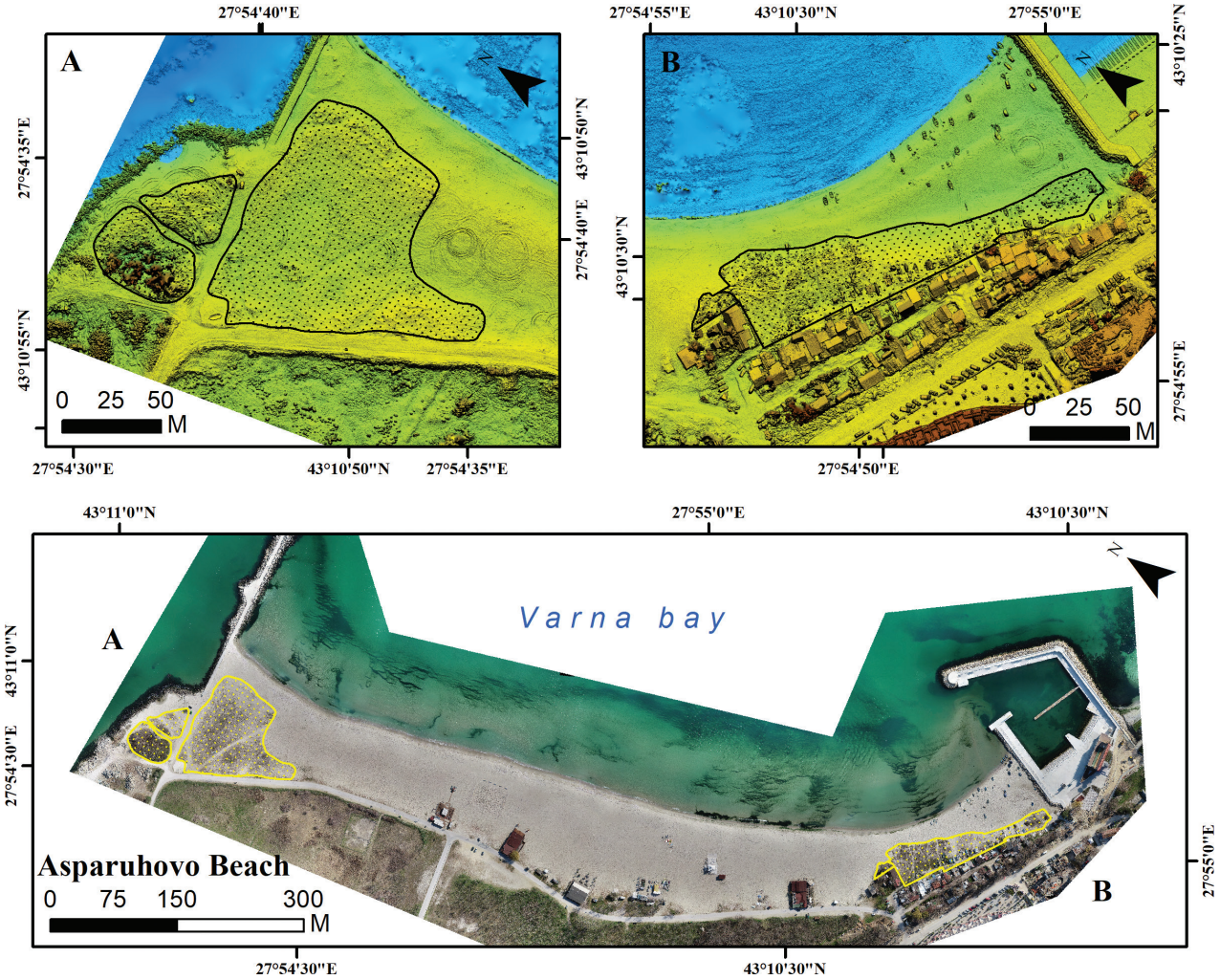

Figure 7. Newly identified coastal sand dune landforms (embryonic, grey and wooded dunes) at Asparuhovo Beach in the southern part of Varna Bay (**A** digital surface model **B** orthophotomosaic from 2022) - (see location on Fig. 4).

In the second half of the 20th century, a period of mass industrialisation, the Varna coast was heavily armoured by hydrotechnical facilities – groins, seawalls etc. To a large extent, these constructions have changed land-sea interactions. These help for dune formation at some urban and resort sectors of the Varna coast by the deposition of sea sand after the construction of the T-groins (Fig. 6) and Karantinata Fishing Port (Fig. 7). A few remnants of the large dune field separating Varna Lake from the Black Sea remained under the landscaped part of Asparuhovo District. South of Cape Galata, the development of embryonic dunes positioned in front of the Pasha Dere Ravine was reported.

Dunes along Kamchiya coast (Cape Paletsa – Cape Karaburun)

Kamchiya coast is emblematic of the BBSC. The shoreline between Capes Paletsa and Karaburun is 12.9 km long, which makes Kamchiya-Shkorpilovtsi the longest beach on the Bulgarian coast. Over 90% of it is a well-formed beach-dune system with an area of 326 ha, comprising five different sectors: Kamchiya – North (Romantika Campsite), Kamchiya River Mouth, Kamchiya-South (Novo Oryahovo Village), Shkorpilovtsi and Shkorpilovtsi-South (Samotino Village). Dunes in the five sectors differ due to variations in the vegetation types, geological and geomorphological processes that affect them. North of the Kamchiya River mouth, low, up to 1–1.5 m high embryonic dunes were formed along the entire beachfront (Prodanov et al. 2021b). Immediately next to the river mouth, in a small area between the flood terrace and the road, stable wooded dunes are present (Fig. 4, Suppl. material 1). The low-lying relief is a precondition for the different nature of the dunes near the villages of Novo Oryahovo and Shkorpilovtsi. In some areas, the secondary (wooded) dunes reach up to 1 km inland, where the sand is still medium-grained. Along the flattened central dune fields, prevalence of grey dunes was established. Their stabilised sand ridges vary between 1.5 and 3 m in height. The foredunes are mainly white (mobile), at places armoured by embryonic mobile dunes of small size up to 25–40 cm high, formed by medium-grained sand.

Passing south from the mouth of the Fundakliyska River, the beach-dune system becomes narrower and the existing grey dunes are limited by a road that marks the northern border of the Balkan Mountains. This narrow strip is an example of misclassified dunes in CAIS. It is important to note that a wide strip of wooded dunes was recorded in the Shkorpilovtsi - South (Samotino) sector. During the field surveys in the Cape Karaburun direction, it was established that the narrow sand-dune system of embryonic and grey dunes passes over steep cliffs covered by cliff-top wooded dunes (Fig. 4, Suppl. material 1).

Dunes along the Balkan Mountains coastal area (Cape Karaburun – Aheloy)

In this sector, there are steep flysch cliffs all along the shoreline with narrow beach strips at the cliff bases, formed mainly by eroded and abraded material. In the southern part, the cliff descends almost to sea level at the Hadzhiyska River Mouth and the low cliff sections between the towns of Nessebar and Aheloy. The depositional relief is represented by stable beach-dune systems

at Kara Dere Ravine, the town of Byala, Irakli Protected Area, Slanchev Bryag (Sunny Beach) Resort and the town of Nessebar (Figs 4, 8, Suppl. material 1).

Small embryonic dunes (0.287 ha) were identified and mapped during the field surveys. These dunes have formed after the construction of the Byala fishing port that has created a sheltered environment from the eastern storm processes, facilitating aeolian and deposition processes. Over the past three years, the dunes have progressively transitioned into white (shifting) dunes. It is important to pay attention to their preservation in the future, as they are in an area with strong anthropogenic pressure, such as fishing activities, boat launching etc. In Kara Dere, Vaya River Mouth and Irakli sectors, an extension of the embryonic dunes and some newly formed ones have been discovered (Fig. 4, Suppl. material 1).

The most significant beach-dune systems along central parts of BBSC are observed in the coastal sectors of Slanchev Bryag Resort and the town of Nessebar (Fig. 4, Suppl. material 1). The low-lying relief and abundance of sand material at Slanchev Bryag Resort are the main reasons for the presence of coastal dune landforms inside the resort complex. Over the years, many secondary dunes have been formed. Embryonic dunes, white (shifting) dunes, grey (fixed) dunes (GD) and wooded dunes (WD) with a total area of 46.98 ha were identified. The comparative spatio-temporal analysis of coastal dune dynamics showed that 14.80% of their area was subjected to strong anthropogenic pressure as a consequence of expanding tourism (Fig. 4, Suppl. material 1).

The Nessebar dunes are distributed between the Nessebar Sand Dune Field and Nessebar – South coastal segments (Fig. 8). Their area is almost twice as large as those of Slanchev Bryag. Again, the local geomorphological conditions are the leading factor in shaping out their modern boundaries. At the Nessebar Sand Dune field, dunes are 100% secondary, formed under conditions of intense aeolian transport in the past. The sediment nourishment of the Nessebar grey and wooded dunes nowadays is rather limited due to increased distance from the source province (the beach of Nessebar - South) as well as the presence of primary foredunes and vegetation cover posing an effective barrier to aeolian transport. Another coastal issue at the Nessebar Sand Dune Field in terms of sand nourishment is the urbanisation and large-scale development of the Mladost residential area of Nessebar in the 1960s that altered the wind flow from the north side of the dunes at Slanchev Bryag - South and the associated aeolian sand transport (Fig. 4, Suppl. material 1).

Dunes along the Burgas coast (Aheloy – Chernomorets)

Pomoriyska Sand Spit, Pomorie, Sarafovo, Burgas (Central), Burgas (South), Kraymorie, Vromos and Chernomorets beach-dune systems have been identified and the dunes on Atanasovka Sand Spit were mapped for the first time (Fig. 4, Suppl. material 1). Over the years, numerous factors have had an impact on the coastal spatial pattern of Burgas and Pomorie Bays. Similar to Durankulak Lake, Pomoriysko and Atanasovsko Lakes are separated from the sea by sand strips known as Pomoriiska and Atanasovska sand spits. Geomorphologically, they also represent barrier beaches attached to land at both ends and covered with well-formed foredunes with a maximum height of 3.7 m (Suppl. material 1). Over the years of development, the sand spits have been colonised

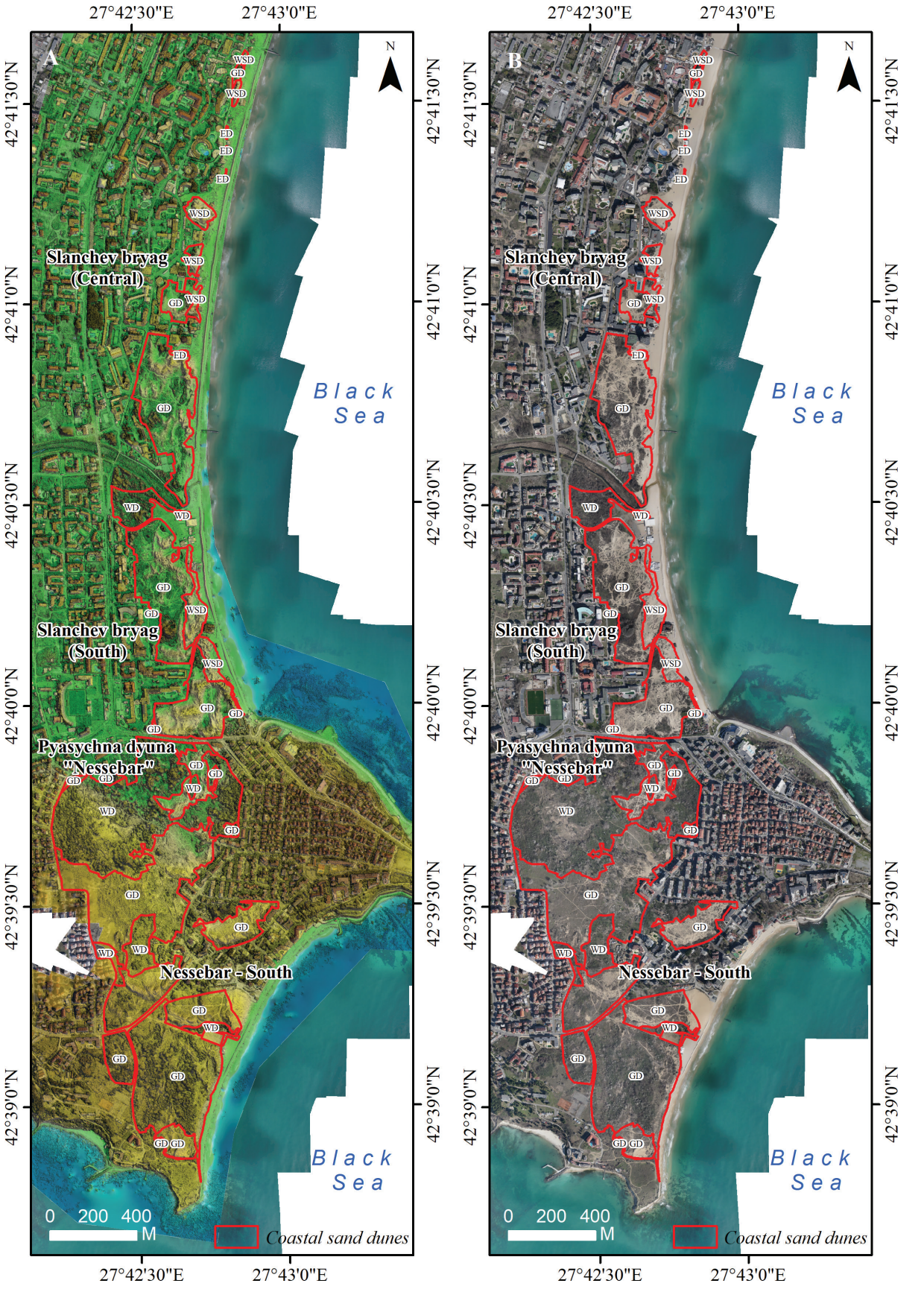

Figure 8. Coastal sand dune systems at Slanchev Bryag Resort and Nessebar coastal sectors - embryonic dunes (ED), white (shifting) dunes (WSD), grey (fixed) dunes (GD), wooded dunes (WD) **A** UAV photogrammetric DSM from 2022 **B** UAV orthomosaic from 2022 (see location on Fig. 4).

by specific psammophilous species characteristic of grey dunes, for example, sand cornflower (*Centaurea arenaria* M.Bieb. ex Willd.), white-stemmed musk (*Jurinea albicaulis* subsp. *kilaea* (Azn.) Kožuharov), Euxinian campion (*Silene euxina* (Rupr.) Hand.-Mazz.), milkweed (*Cionura erecta* (L.) Griseb.) etc. (Tzonev 2015c). In the Sarafovo beach-dune system, grey dunes also predominate over white ones. Dunes composed of medium-grained sand have been developing unhindered within the Burgas (Central) Beach for many years. Although moderately exposed to wave action (Valchev et al. 2014), positive sediment balance and weak, but constant accretion have contributed to the formation of mobile embryonic and white dunes (Fig. 9, Suppl. material 1). Our research team mapped these dune landforms for the first time at the beginning of 2022. Unfortunately, as of October 2022, they still do not appear in the thematic coastal module of CAIS, necessitating an immediate update of the relevant coastal geodatabase of GCCA.

Strong anthropogenic pressure on these dune systems was registered in the last years of field surveys. South of the City of Burgas, the dunes undergo even more significant human alterations, affecting up to 65–70% of their area in the Burgas (South) and Burgas (Pobeda quarter) depositional sectors (Fig. 4, Suppl. material 1). The permanently lost beach-dune systems were established along the Burgas coast: Pomorie (East), Europa Campsite, Lahana-West, Lahana-East and Rosenets (West) at Cape Chukalya (Fig. 4).

Dunes along Medni Rid - Strandzha coast

The largest number of beach-dune systems (25) have been identified along the Medni Rid - Strandzha coast. Out of 157 km of shoreline between the town of Chernomorets to the north and the Village of Rezovo to the south, approximately 32 km represent depositional relief comprising the following beach-dune systems: Gradina Campsite (Sozopol Bay), Sozopol, Harmani and Kavatsite-Smokini Beaches (Fig. 10), Alepu and Arkutino Lagoons (Fig. 11), Ropotamo River mouth, Primorsko (Stamopolu – Perla Beach), Primorsko – South Beach, Atliman Bay, Kiten, Koral Beach and Yug Campsite, Lozenets, Oasis, Arapya, Tsarevo (Popski plazh), Nestinarka and Ahtopol Beaches, Veleka and Butamyata River mouths (Fig. 12), Lipite and Listi Beaches, Silistar River mouth and Rezovo-Kastrich Beach (Suppl. material 1). Generally, the systems consist of well-formed primary dunes, including foredunes and incipient dunes. Usually, the first row is represented by 7–9 m in high white/grey dunes and armoured by embryonic dunes (Kavatsite, Smokini, Arkutino etc.). In rare cases, as at Butamyata Beach, the dune field is further shaped out by the small estuary. However, in the last ten years, dunes have evolved from small embryonic to grey ones and occupy a much larger portion of the beach. Unfortunately, this beach-dune system has been systematically destroyed every year by excavation, trampling and grooming as part of the beach preparation for the summer season because a significant portion of them is not reflected in the coastal thematic module of CAIS. In this sense, the Kavatsi Dune Area is an example of strong anthropogenic pressure on the dunes (Valcheva et al. 2022). Therefore, an urgent update is required of the relevant geodatabase of GCCA in order to protect them (Suppl. material 1).

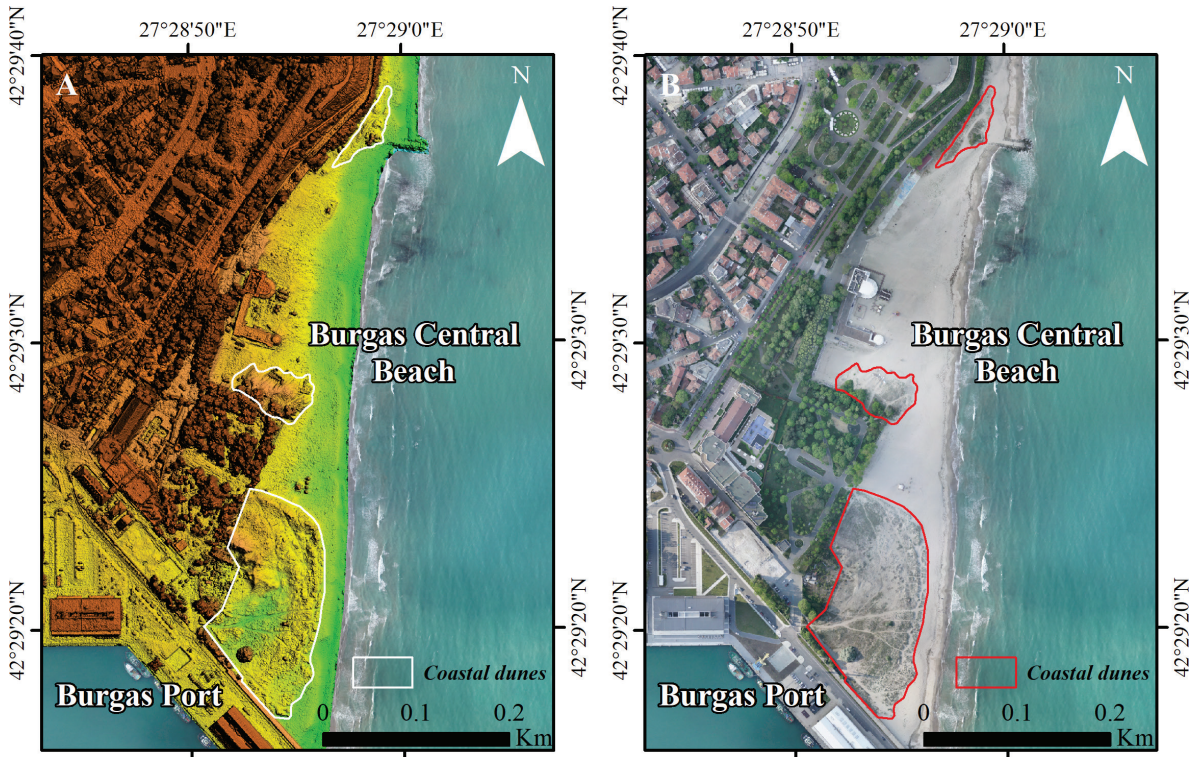

Figure 9. Newly identified coastal dune system at Burgas (Central) Beach - embryonic dunes (ED), grey (fixed) dunes (GD) **A** UAV photogrammetric DSM from 2022 **B** UAV orthomosaic from 2022 (see location on Fig. 4).

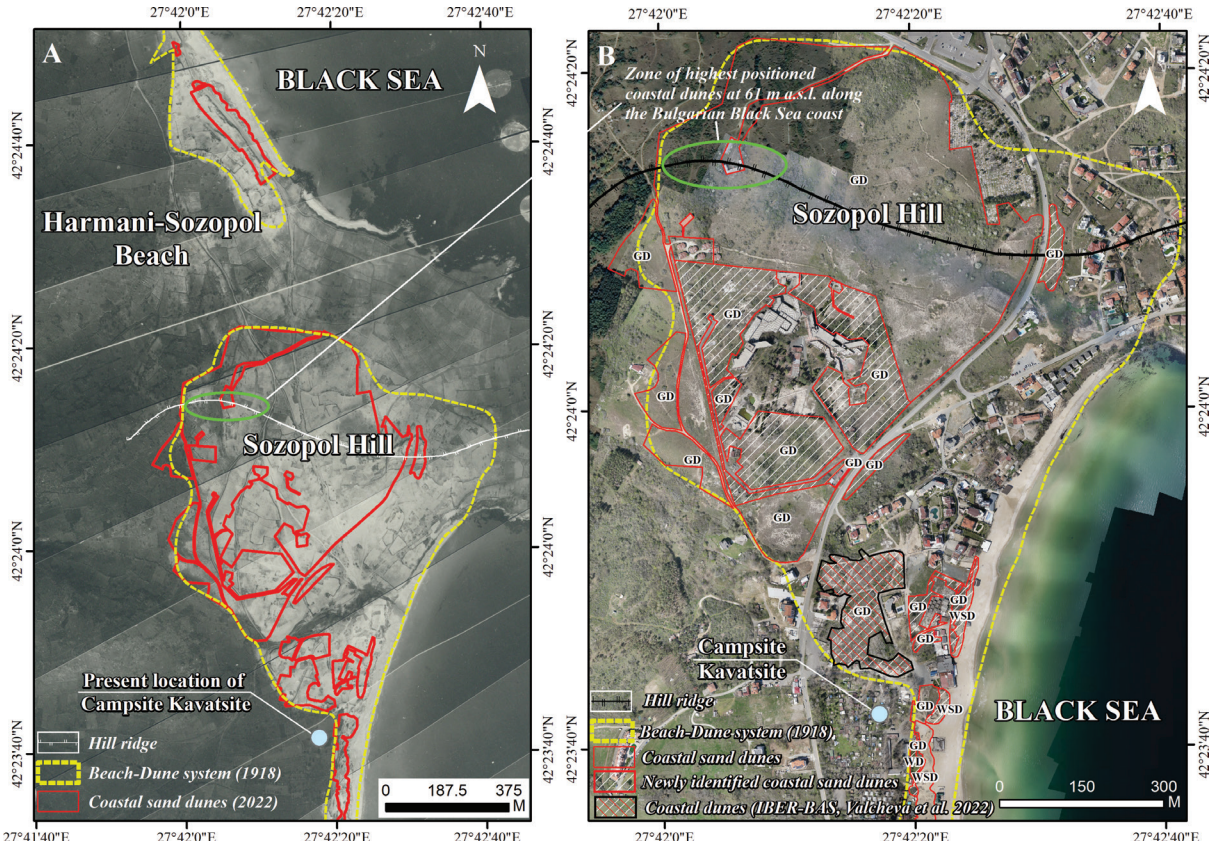

Figure 10. Coastal sand dune systems at Kavatsite Beach, Sozopol - embryonic dunes (ED), white (shifting) dunes (WSD), grey (fixed) dunes (GD) and wooden dunes (WD); **A** spatial distribution of beach-dune systems in 1918 (Aerial Photomosaics 1918) **B** UAS orthomosaic from 2022.

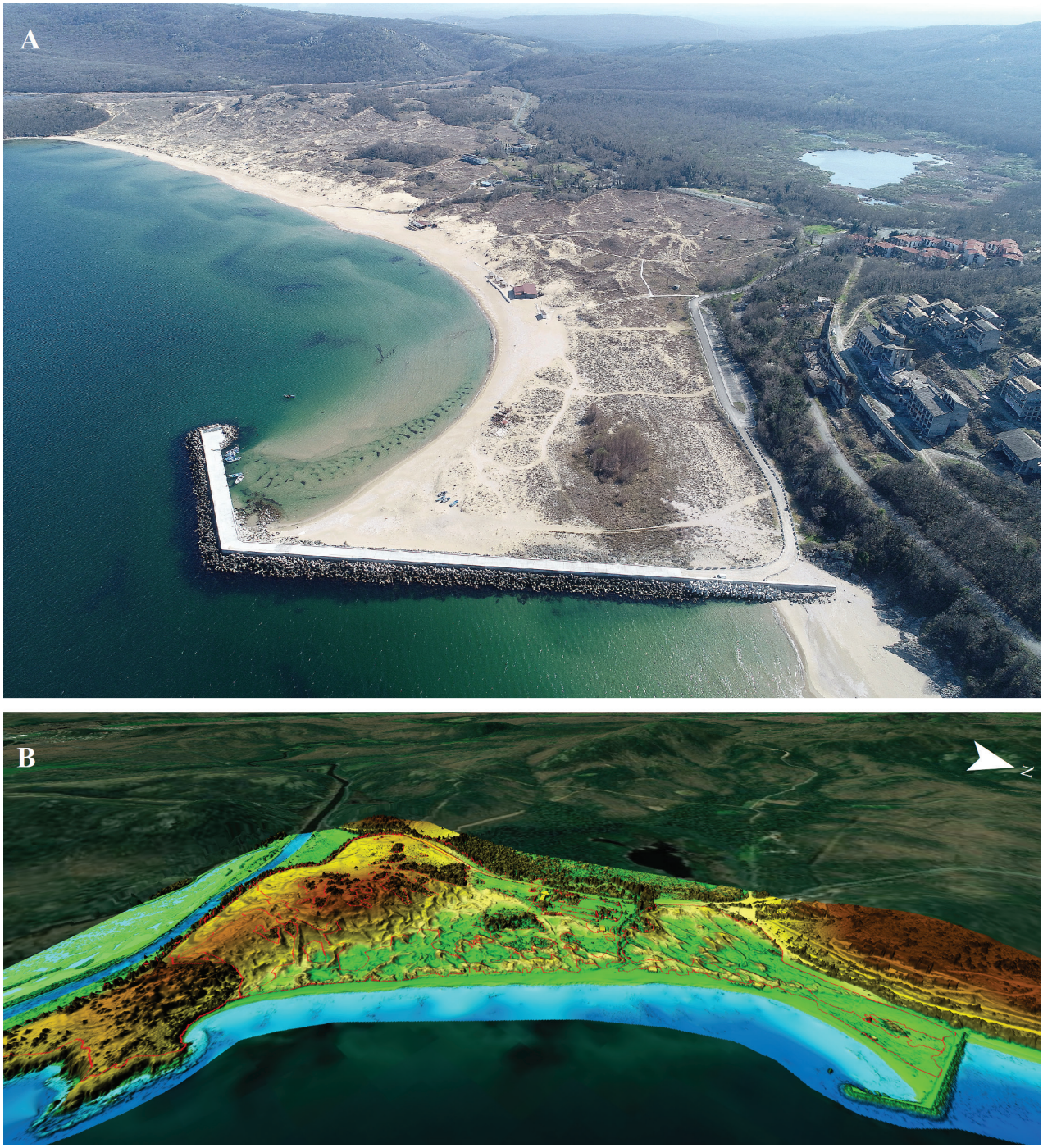

Figure 11. A an aerial view of the Arkutino beach-dune system from 2022 (photography of Dr. Bogdan Prodanov) **B** UAV digital surface model of the Arkutino sector with the second highest positioned coastal dunes (50.2 m a.s.l.) along the Bulgarian coast from 2022 (see location on Fig. 4).

The highest positioned coastal dunes along the Bulgarian coast were registered at the perched **Sozopol Sand Dunes** (grey dunes), located at Sozopol Hill at an impressive height of 61 m above sea level in coordinates: 42°24'16.5907"N, 27°42'00.0501"E (Fig. 10). It is noteworthy to mention that, in the past, prior to the high level of anthropogenic impact on the Sozopol Hill and Budzhaka Locality, these dunes have been nourished with sand through aeolian transport from two sources simultaneously - the Harmanite Beach (from the northern direction) and

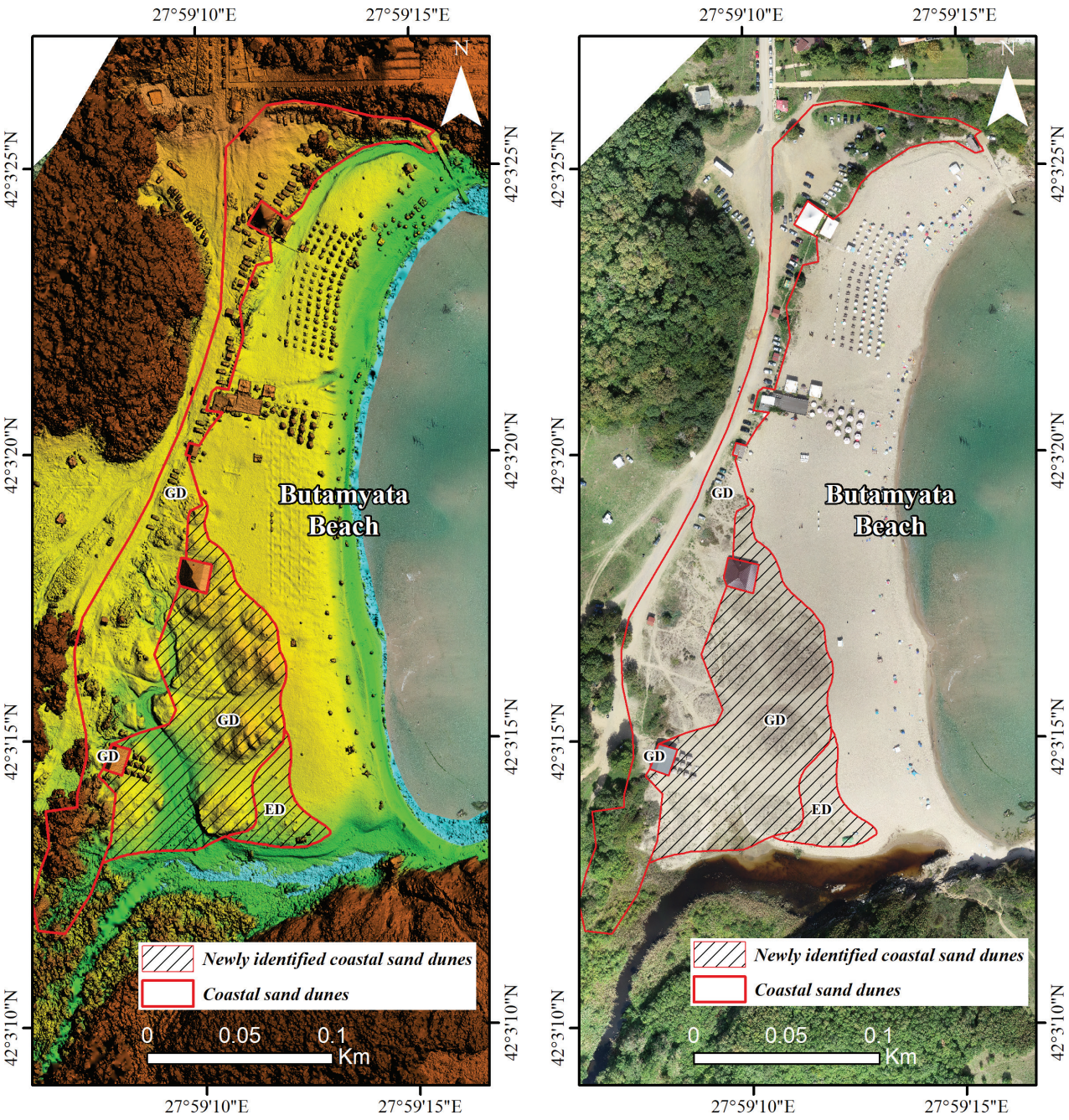

Figure 12. Coastal sand dune system at Butamyata Beach (Sinemorets) - embryonic dunes (ED) and grey (fixed) dunes (GD) **A** UAV photogrammetric digital surface model from 2022 **B** UAV orthomosaic from 2022 (see location on Fig. 4).

the Kavatsite Beach (from the southern direction) (Fig. 10, Suppl. material 1). The Sozopol cliff-top dunes have been formed by wind activity, which has transported medium to fine sand from the aforementioned beaches. However, over the last two decades, construction activities in the northern part of Kavatsi and the southern part of Harmani have discontinued the supply of sand to this secondary dune system (Fig. 10A). These dunes have had a chance to remain relatively undisturbed from human intervention, allowing for the colonisation and stabilisation of psammophyte vegetation on their sandy surfaces. The sediment analysis of seven stations taken within these dunes exhibits an extremely poor sorting, indicating a low intensity of morphodynamic processes of the dune sand at this hypsometric level.

The second highest positioned dunes were registered in Arkutino coastal sector. The system is composed of a long row of frontal dunes, discontinued by small-size blowouts, followed inland by mosaics of parabolic and cliff-top dunes, which reach a height of 50.2 m a.s.l at coordinates: 42°19'32.6673"N, 27°44'10.2816"E (Fig. 11). In many sections of the Medni Rid - Strandzha coast, the embryonic dunes have been colonised by psammophytes that are characteristic of white dunes, slowly increasing their area. As a result, 63% of the dunes are stabilised and, over the years, together with the wooded dunes, have preserved their area of 45 ha (12%). Most beach-dune systems consist of secondary dunes. They were classified as parabolic and cliff-top dunes, blowouts, sand sheets (dune fields) that rise in elevation downwind and end up as a slip face (Arkutino, the Sozopol Sand Dune Area etc.).

Discussion

General morpho-sedimentological profile of dune systems along the Bulgarian Black Sea coast

At this point, we have discussed some correlations and relationships in dune morphology and the spatial distribution of beach-dune sands. The analyses of available data show that 88% of the active beaches on the Bulgarian coast are mainly composed of medium-grained sand and the remaining 12% consist of coarse-grained sand. In rare cases, sediments from external sources were found during the surveys, but these were not included in the summary results. Sedimentological analyses from all sediment stations in the period 2020 – 2022 showed fine to coarse sands (from 0.131 mm to 0.78 mm diameter) deposited in the Bulgarian Black Sea beach-dune systems. Accumulative and aeolian processes have contributed to the formation of progradation beaches with alternating embryonic/white and stabilised/grey or wooded dunes (Fig. 13).

Kavatsite-Smokini beach-dune system is an excellent example, in which the general cross-shore profile shows a complex distribution of dunes subjected to intensive anthropogenic pressure due to tourist development and human trampling (Figs 14–17). A correlating cross-shore diagram of the grain-size distribution ($\mathbf{D_{50}}$) and sorting of sediments is added to the general morpho-sedimentological profile and shows decreasing grain size diameter in the landward direction. Analyses of sand from the beach face, beach face ridge, summer berm and high beach winter berm at each beach identify that moderately well-sorted coarse sands (greater than 0.5 mm in diameter) dominate the seaward slope of the main dunes and the active beach that is influenced by wave processes. Foredune morphology continues to evolve as foredune ridges develop through a combination of reduced sediment supply and increased surface stabilisation by plant species. As a result, they are mostly composed of well-sorted to moderately well-sorted medium sands. An inverse relationship was established for the Bulgarian Black Sea dune systems - as the distance from the ridge of the primary front dune to the land increases, the diameter of the sediment decreases within the average size of the sand, while its sorting increases to well-sorted (Fig. 13).

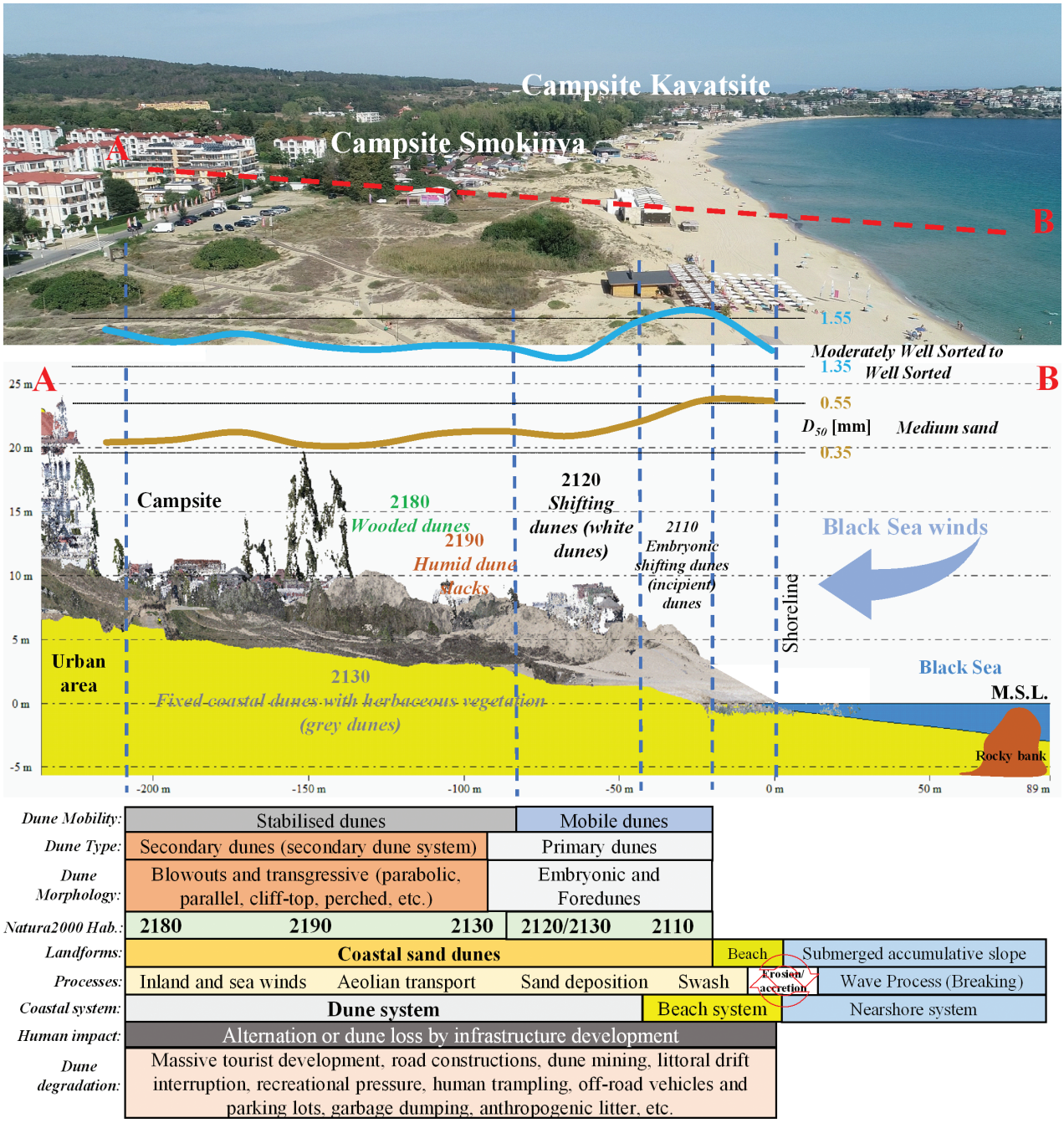

Figure 13. A general geomorphological profile of the beach-dune systems along the Bulgarian Black Sea coast (example of the Kavatsite-Smokini beach-dune system).

Alteration, degradation and loss of coastal dunes due to human activities

The most important issue to be addressed is the increasing anthropogenic pressure on dune formations. The Bulgarian Black Sea coastal dune landforms have always been of interest to tourists and holidaymakers during the summer season. The development of tourism and the adjacent beach-dune infrastructure are the main reasons for the large altered area of 50.72 ha (5.1% of the total area of dunes). An extremely high degree of human intervention and dune degradation (over 50% of their area) was registered at seven dune systems: Byala, Burgas (South), Burgas (Pobeda), Asparuhovo (Varna),

Kamchiya River mouth and Bolata Cove, Kavatsite and Smokinya campsites (Fig. 4, Suppl. material 1).

Emblematic examples of dune mismanagement are within the resort towns of Sunny Beach, Nessebar and the campsites around Sozopol (Gradina, Kavatsite and Smokinya) - (Figs 14–17). In the last 15 years, the loss of coastal dunes along the Bulgarian Black Sea Coast due to various human activities has been estimated at 12.5 ha. The inventory found a permanent loss of 3.2 ha at five dune systems: Pomorie (East), Evropa Campsite, Lahana, Lahana (West) and Rosenets (West) near Cape Chukalya. The losses fall entirely within the Burgas coast. Shoreline exposure of the northern Burgas Bay coast and the impact of storm processes have resulted in necessary additional wave break construction and fortification to protect the Pomorie-Burgas Road. On the southern shore of Burgas Bay, during the construction of the port and the tourist complex at Cape Chukalya, 0.03 ha of white dunes have been wiped out (Fig. 4).

Human interventions that have caused the degradation of 50.72 ha (5.1% of dune areas) and 12 ha of permanent dune losses along the BBSC can be identified as a consequence of massive tourist development after the socialist period, road construction, dune recreational pressure, human trampling, lack of walkways over fixed and mobile dunes, off-road vehicles and parking lots (especially at campsites), garbage dumping and marine litter on CDLs. The above-mentioned losses of dune systems in the last 15 years are outside designated Natura 2000 sites, which directs the discussion towards their conservation beyond the boundaries of the European ecological network. Another issue remains the illegal effacement of dunes (mostly grey dunes) inside privately-owned land behind the beaches designated for real estate

Figure 14. Sand dunes breaching (degradation) from off-road vehicles and beach cleaning techniques at Veselie campsite, September 2022.

Figure 15. Beach bar on the white dunes at Smokinya Beach, South Bulgarian Black Sea coast, September 2022.

Figure 16. Destruction of the protective fence of "Pyasachna Liliya" Reserve by off-road, poor dune management and walkways, Southern Bulgarian coast, September 2022.

development. Coastal dunes within the limits of such cadastral parcels are often trampled and subsequently covered artificially with a soil layer in order to disguise the action, with the owners almost always stating that no dunes have ever existed on their property.

Figure 17. Example of recreational construction on the coastal sand dune landforms of Kavatsite Campsite, Southern Bulgarian Black Sea coast, September 2022.

Adequacy of protected areas boundaries in the light of CDL conservation: "Pyasachna liliya" Managed Reserve, Kavatsite Dune Area

A disturbing fact emblematic of coastal mismanagement concerning dune preservation is the current boundaries of "Pyasachnata liliya" (The Sea Daffodil) Managed Reserve at Kavatsite Area (Fig. 18). In fact, subject to preservation are three spatially separate dune polygons that are artificially united into a single protected area. Squeezed amongst adjacent campsites and recently established beach bars and nightclubs, the boundaries literally "slice" through the existing CDL ridge in the southern part of the Reserve. Such a "delineation approach" runs counter to fundamental principles of nature conservation when designing the extent of a given protected area, for example, spatial coherence, ecological connectivity and landscape-scale consistency of the boundaries.

Accordingly, ludicrous decisions of this kind towards an environmentally sensitive area raise questions regarding the adequacy of management decisions taken on behalf of the public environmental authorities, as well as towards the employees' expertise who are in charge of coastal nature conservation. Additionally, Fig. 18 demonstrates an example of the negative anthropogenic influence of rake-up (cleaning) of beach sand, causing physical destruction/loss of embryonic dunes in front of the Managed Reserve.

Long-term legal preservation of coastal dune landforms in Bulgaria

As of today, the network of protected areas preserving coastal dune landforms in Bulgaria remains inadequate. Nevertheless, it is crucial to note that dunes are granted special legal protection according to the BSCSD (2008). Currently, a common approach in Bulgaria involves designating coastal dune areas as natural landmarks, compliant with the Protected Areas Act of the Republic of Bulgaria (PAA 1999).

Figure 18. Coastal dune landforms at "Pyasachna liliya" Managed Reserve, Kavatsite Area: embryonic dunes (ED), white (shifting) dunes (WSD), grey (fixed) dunes (GD), wooded dunes (WD). An example of physical rake-up/cleaning of beach sand, causing degradation of embryonic dunes.

In light of the existing situation, the authors of the study herein strongly advocate for necessary legal actions to be initiated by the Ministry of Environment and Water. Their proposal is to designate all remaining dune areas along the Bulgarian coast as natural landmarks, aligning with the provisions stated in the above-cited act. This step, on behalf of the relevant authorities, would significantly enhance the protection of these ecologically valuable coastal landforms.

Data adequacy of CAIS, thematic module for the Bulgarian Black Sea Coast

Results of our surveys revealed several weaknesses and data discrepancies of the coastal thematic module (shown in Suppl. material 1) discussed herein, amongst which:

- Obsolete data, incorrect classification and erroneous cartographic representation (i.e. spatial and thematic) of coastal beaches and dunes and incorrectly illustrated spatial extents of beaches and dunes;
- Incorrectly depicted contours (boundaries) of geomorphological features (i.e. coastal beaches, dunes, estuaries, lagoons, wetlands etc.).

The above drawbacks dictate the necessity for rapid measures aimed at data accuracy improvement of the specialised maps maintained by GCCA and the related geospatial files of the coastal geomorphological features in CAIS. Amongst these, improvement of the coastal surveying approaches, including the use of UAVs as equivalent to the geodetic survey on the ground, mandatory participation of experts with proficiency in coastal geomorphology and dune phytocoenology in the mapping campaigns, as well as the willingness of the executive authorities in charge to collaborate with academia is highly recommendable and in line with the recently-amended legislation in the field of coastal spatial development (Ordinance No.1/Art.6 2020). Furthermore, designing a scientifically sound national programme for mapping and monitoring the geomorphological features and hydrotechnical facilities along the BBSC should be amongst the priorities of the MRDPW in Bulgaria. Finally, such a national programme should naturally include scientifically sound guidelines for mapping with clear (non-ambiguous) definitions of dunes of all types and dune fields/systems in morphological and habitat aspects and subsequent cartographic representation of the results, based on good practices from other littoral EU Member States.

Conclusions

The integration of remote sensing methods in geomorphological mapping and monitoring dune formations and anthropogenic changes is demonstrated in the study presented. The identification of a significant number of previously unknown dune landforms within a span of two years was made possible by the easy utilisation of unmanned aerial systems. Based on our UAS surveys, the Bulgarian Black Sea shoreline length was estimated to be 518.7 km at a scale 1:5000, stretching between Cape Sivriburun and Rezovo Village. The sand beaches encompass 131 km (25%) of the Bulgarian coastline. The coastal dune systems consist of 14% of the Bulgarian shoreline (total length of 73 km) with a total area of the Bulgarian coastal sand dune landforms at 988.21 ha (9.8 km^2), 0.0089% of Bulgaria, differentiated into 46 beach-dune systems.

The primary dunes along the Bulgarian coast are significantly influenced by wave processes and have a dynamic interrelationship with the beach, but it is essential not to forget their coastal flood defence role. The area of primary dunes (foredunes and embryonic dunes) is 311.9 ha (31%) and their distance to the shoreline varies from 12 m to 80 m for wide beaches. Within the BBSC, secondary dunes (676.3 ha; 69%) prevail over the primary ones. These secondary dunes are positioned further inland, where the effect of the wave process was not observed. Given their mobile character, embryonic dunes rarely exceed 1.5 m in height, while the foredunes in places reach 7 m at Arkutino dunes, 9 m at Kavatsite-Smokini dunes and 4–5 m at Durankulak and Krapets, but in general, they are a long ridge with average heights of 3.5–4.2 m along the Bulgarian Black Sea Coast.

The different natures of dunes are determined by morphodynamics and, subsequently, stabilisation by vegetation. As we have already noted, most foredunes are presented by shifting (white) dunes – 150.3 ha (15.2%) and "armoured" by embryonic dunes - 68.3 ha (6.9%). Generally, CDLs are dominated by grey (fixed) dunes - 546 ha (55.3%) and wooded dunes - 222 ha (22.5%), which reach 1 km inland between Kamchiya River Mouth and Shkorpilovtsi Resort. Dune slacks are minimised and observed in the context of enclosing dunes – 0.94 ha (0.09%).

The largest mapped dune systems, such as Kamchiya-Shkorpilovtsi (326 ha), Nessebar (98 ha), Arkutino (94 ha), Kavatsi-Smokini (59 ha), Gradina (57 ha), Slanchev Bryag (47 ha), include mature foredune ridges, blowouts and transgressive dunes. In addition, they comprise cliff-top dunes, perched dunes, flat, vegetated plains and interdune slacks. The cliff-top or "perched" dunes are relatively uncommon, in general, but in some cases, such as Nessebar, Sozopol, Kavatsite, Krapets, Durankulak, Arkutino, Koral, Ahtopol etc., the geomorphological settings and dominant wind direction predispose the migration of sand inland over the bedrock or, in some cases, over loess surfaces as of Krapets and Durankulak. The highest positioned coastal dune landforms on the Balkan Peninsula were found at "perched" Sozopol Sand Dunes (61 m a.s.l.) and Arkutino dunes (50.2 m a.s.l.).

Massive tourist development and poor dune management (regulation, restriction, actual data about spatial distribution, lack of short-term monitoring of dune integrity) have caused destruction and dune surface changes on 50.7 ha in 5.1% of dune areas (see Table 1). For example, the inventory shows permanent losses of five beach-dune systems (12 ha) for the last 15 years along the Burgas coast, located outside Natura 2000 sites. Within this research, we identified and mapped eight dune systems for the first time: Zlatni Pyasatsi – Panaroma, Asparuhovo – Varna, Byala, Atanasovska kosa, Burgas – Central Beach, Chernomorets, Kavatsite (partly) and Rezovo-Kastrich. A stunning fact is that 16.8% of the dunes identified are outside the Natura 2000 network, mainly around the cities and resorts along the Bulgarian Black Sea coast.

Table 1. General information of coastal dune landforms, anthropogenic area and permanent loss of dune systems along the Bulgarian Black Sea Coast up to 2022.

CDL area	Anthropogenic area of CDLs		Morphological type of CDLs, [ha]		CDLs, corresponding to Natura 2000 habitats, [ha]					Permanent loss of CDLs
[ha]	[ha]	[%]	Primary	Secondary	ED 2110	WSD 2120	GD 2130	WD 2180	HDS 2190	[ha]
988.21	50.04	5.06	311.9	676.3	68.30	150.15	546.41	222.61	0.94	12
Percentage, %			32	68	6.91	15.19	55.29	22.53	0.09	five dune systems

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

B.P. conceptualised research, inventory, geomorphological and GIS analysis; B.P., R.B., T.L. designed and performed the UAS surveys, SfM processing, generating of DSMs and OMs; B.P., R.B. performed sedimentological sampling and analysis, maps, tables, graphics and appendix; B.P., I.K., L.D. analysed the coastal dune forms. I.K., R.B., L.D. assisted with the landscape analysis, vegetation observation and refinement of the overall text in English; I.K. analysed the relevant Bulgarian legislative acts on coastal planning and development; L.D. supervised the accuracy of ground geodetic measurements and dune characterisation and provided critical notes.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

List of identified beach-dune systems along the Bulgarian Black Sea coast

Authors: Bogdan Prodanov

Data type: word file

Explanation note: ED – embryonic dunes, WSD – shifting (white) dunes, GD – fixed (grey) dunes, WD – wooded dunes and HDS – humid dune slacks.

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