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Anthropocene Coasts

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Earth observation technologies, policies and legislation for the coastal flood risk assessment and management: a European perspective

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Abstract

The aim of this contribution is to provide a brief overview of the current and future earth observation (EO) technologies that can be used to assess and manage the EU coastal flood risk, together with the pertinent international and EU policies and legislation. The review has shown that EOs have become an indispensable technology for the assessment and management of the coastal flood risk, and their role will increase further in the future when EO information of higher resolution and accuracy become available. With regard to the relevant policies and legislation, their common thread is associated with the promotion and facilitation of the development of appropriate data and tools for high-quality and timely geo-spatial information based on EO technologies. In Europe, in particular, this development is promoted and facilitated by an array of international and supra-national (EU), interacting policies and legislation. It appears, however, that additional initiatives and technological progress in EO functionalities and the information technology are needed together with more targeted policy and legislation frameworks to provide vital information for the management of the coastal flood risk.

Keywords Coastal flood risk, Earth Observations, Flood policies and legislation, Copernicus

1 Introduction

Coastal floods and erosion have had increasing impacts on the Anthropocene natural and human ecosystems, causing coastline changes, biodiversity losses and human mortality, exacerbating poverty and health-risks, and inducing infrastructure and asset damages (IPCC 2023). Although coastal flooding and erosion affect relatively narrow strips of coastline, they can claim more victims than the other floods and incur huge economic losses (Munich Re 2021). Under climate change, both hazard and exposure are projected to increase (Almar et al. 2021). Driven by global warming, the frequency of extreme events is projected to highly increase, exposing anually a large part of the global coastline to the current 1 in a 100 years Extreme Sea Level by the end of the century (Vousdoukas et al. 2018). In Europe, the annual economic losses from coastal floods alone could amount to 0.25–0.55% of the European GDP by 2100 (JRC 2022). It appears that management plans that provide improved coastal flood prevention, preparation, response and

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recovery are urgently required. Such plans should focus on monitoring and assessing the risk, sharing information and strengthening coordination, and research and development,, including on early warning systems (EWSs) (WMO 2022).

Policies for the management of the coastal flood risk promote data collection and development and implementation of relevant tools. In addition to detailed data on the hazard, accurate information on the coastal natural and socio-economic characteristics should also be collected to assess the other determinants of the coastal flood risk, i.e., the exposure and vulnerability (UNFCCC 2020). High-quality and timely geospatial information is required, the majority of which is now provided by Earth Observation (EO) technologies. Earth observing technologies can provide large volumes of relevant information (e.g., Melet et al. 2020; Le Cozannet et al. 2020) and have been widely incorporated into the emergency management cycle, supporting, among others, early warning systems for floods (Koriche and Rientjes 2016). Earth Observations (EOs) are integrated within the models used for flood forecasting/predictions, rapid mapping for disaster response and impact assessments; thus, their quality in terms of resolution, precision and accuracy is essential for producing trustworthy information. The ever-growing efforts for greater supply of EO data are highlighted in the EuroConsult (2022) report which states that '*by 2030, the number of satellites to be launched is anticipated to be 1,700 on average per year*'.

During and after a severe flood event, information is required to evaluate impacts on populations and respond through delivering prompt assistance (Voigt et al. 2016). There have been initiatives aiming at providing such information in near real-time to support transnational disaster management and response, such as the EU Copernicus Emergency Management Service – CEMS (CEMS 2023). International cooperation in this respect is fundamental, as it allows Emergency Agencies to benefit from previously acquired, third parties' data. This is reflected, for instance, in the International Charter for Space and Major Disasters (Ito 2005) which forms a worldwide collaboration scheme through which satellite data from various sources are made available for Disaster Risk Reduction - DRR.[1]

Post-disaster response requires two different types of EO products: i) rapid damage mapping, and ii) re-assessment of hazards and risks in order to restore services and reconstruct/improve the damaged infrastructure and assets ('build back better'). The former involves severe time constraints, but has lower accuracy demands than the full assessment of hazards and risks. Damage mapping also assists in the re-assessment of vulnerability and its dynamics following disasters (Le Cozannet et al. 2020). In addition, early warning systems require geospatial information of high resolution and accuracy to: set up and force the forecasting models; map the exposure and vulnerability of the coastal natural and human systems for risk mapping and assessment; and provide post-flood assessments. The UN action plan 'EWS for all' (WMO 2022) will require expanded and improved information; thus, there is a policy drive for more and finer resolution EOs.

Against this background, the aim of the present contribution is to review the nexus of the EOs with the assessment and management of the coastal flood risk, with a focus on the European coastal zone. To this end, a summary of the relevant EOs currently available for the European coast, as well as of those that could become available in the future is presented, together with a brief overview of the EU policies and legislation pertinent to EOs used in the management of the coastal flood risk.

2 EO data and technologies: current situation and potential developments

2.1 Current situation

Earth observations can provide marine hazard monitoring, with repeated synoptic views of large areas and good spatio-temporal resolution. Nevertheless, these do not always meet the precision required by users in the highly dynamic coastal zones which are characterized by large short-scale variability (Melet et al. 2020). Coastal zones are impacted by various hazards, including the sea level rise, extreme storm events, local oceanic/atmospheric processes and land subsidence. In order to monitor and understand coastal changes and provide the requisite information for early warning and decision making various observational needs must be addressed, such as improved measurements of the coastal sea level (Benveniste et al. 2019). In Europe, EOs are used extensively in various components of the early warning and management of the flood risk, including in the EU CEMS.

Regarding the Copernicus products, marine and land related EO data from multiple sources are used. The Coastal Zone LC/LU dataset allows for the determination of bed roughness, an important parameter in the modeling of the flood flow and extent as it controls the water flow attenuation on land (Papaioannou et al. 2018; Melet et al. 2021). In addition, EOs have made feasible the mapping of coastal topography at large spatial scales. Digital Elevation Models (DEMs) derived from EOs with varying resolutions have been used in flood risk assessments, including the Copernicus 10 m COP-DEM EEA-10 (Le Gal et al. 2023), the 90 m SRTM (Neumann et al.

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[1] https://disasterscharter.org/en/web/guest/home

Table 1 Characteristics of the EOs used in the Copernicus land data sets

Sensor	Function/Role	Ground sample distance	Temporal Coverage & Resolution	Reference
SPOT-5	Topography, Vegetation	2.5–5 m (PAN) 10 m (MS), 10 m (Stereoscopic for DEM)	2002–2015 26 days cycle Revisit: 2–3 days	earth.esa.int/missions/spot-5
SPOT-6	Land Surface, Vegetation	1.5 m (PAN) 6 m (MS)	2012–2023 26 days cycle Revisit: 1–3 days	earth.esa.int/missions/spot-6
SPOT-7 (Azersky) (ceased operations in April 2023)	Land Surface, Vegetation	1.5–4 m (PAN) 6 m (MS)	2014–2024 26 days cycle Revisit:1–3 days	earth.esa.int/missions/spot-7
Pleiades	Land Surface, Topography, Vegetation	0.5 m (PAN) 2 m (MS)	2011–present 26 days cycle Revisit: 1 day for Constellation	earth.esa.int/missions/pleiades
Worldview-2	Vegetation & crop types, wetlands, security	0.5 (PAN) 1.8 m-2.4 (MS) (2 m)	2009–2022 Revisit:1.1 days	earth.esa.int/missions/worldview-2
SUPERVIEW-1	Land management, Land Surface, defence/security	0.5 (PAN) 2 m (MS)	2016–present Revisit:2 days	eos.com/find-satellite/superview-1
KOMPSAT-2	Urban planning, Agriculture, defence, engineering	1 m (PAN) (2 m) 4 m (MS)	2006–present 14 days cycle	earth.esa.int/missions/kompsat-2
Planet Dove	Land Surface Vegetation	Dove-C: 3–4 m Dove-R: 3–4.1 m SuperDove: 3.7 m (MS)	2021–present Revisit: 1 day	satimagingcorp.com/satellite-sensors/dove-3m/
Deimos-2 (GEOSAT-2)	Vegetation measurements	0,75 m (PAN) 4 m (MS)	2019–2029 Revisit: 4 days	eoportal.org/satellite-missions/deimos-2
TripleSat-1	Urban Planning Land Surface	0.8 m(PAN) 3.2 m (MS)	2015–2022 Revisit: 1 day	satimagingcorp.com/satellite-sensors/triplesat-satellite
RapidEye	Land Observation	5 m (MS bands)	2008–2020 Revisit:12 days for one, 6 days for 2 constellations	earth.esa.int/eogateway/missions/rapideye
Sentinel 1	Land Monitoring	5 m – 20 m regarding the mode	2014–present Revisit: 2–3 days	sentinel.esa.int/web/sentinel/missions/sentinel-1
Sentinel 2	Land Monitoring	10 m (MS)	2015–present Revisit: 10 days for one constellation 5 days for 2 constellations	sentinel.esa.int/web/sentinel/missions/sentinel-2
LANDSAT-8	Land Monitoring	15 m (PAN) 30 m (MS)	2013–Present	https://www.usgs.gov/landsat-missions/landsat-8
FormoSat-2	Vegetation	2 m (PAN) 8 (MS)	2004 -2016 1 day cycle	eoportal.org/satellite-missions/formosat-2

Key: *PAN* Panchromatic band, *MS* Multispectral band

2015; Kulp and Strauss 2018) and the 100 m EU-DEM (Paprotny et al. 2019). Copernicus population data sets, such as the Global Human Settlement Layer (GHSL) (Melchiorri and Kemper 2023), are also exploited for the estimation of flood exposure (Ieronymidi and Grigoriadis 2021).

Concerning the land data sets, different sensors have been used in the creation of the Coastal Zone Land Use/Land Cover (LU/LC) product (reference years 2012 and 2018), whereas feature delineation has been mainly based on different available Very High Resolution (VHR) optical images (Table 1). For example, the SPOT-5 mission (2002–2015, French Space Agency) aimed to provide observations for topographic and vegetation applications, had a revisit time of 2–3 days and provided images in panchromatic and multispectral modes with resolutions of 2.5 m (used in Copernicus) and 10 m, respectively.

SPOT-6 and SPOT-7 (renamed 'Azersky', ceased operations in April 2023) had been planned to be operational till 2024, had revisit times of 1–3 days, operated in panchromatic and multispectral modes, with resolutions of 1.5–4 m (used in Copernicus) and 6 m, respectively; their main applications involve the monitoring of the land surface/vegetation. The Pleiades mission for environmental information involves the satellites 1A and 1B, and has delivered high resolution optical data since 2011

(0.5 m and 2 m on the panchromatic and multispectral modes, respectively). With a similar spatial resolution and a revisit time of 2 days, the Chinese SUPERVIEW-1 mission aimed, among others, to provide information for land and forestry management and accuracy mapping.

The WorldView-2 (USA), provided EOs with a 0.5 m panchromatic and 1.8–2.4 m multispectral band resolutions (2 m resolution used in Copernicus), targeting observations on land cover types including the mapping of wetlands, crop types and plant habitats and species. The Korean satellite KOMPSAT-2 has been delivering panchromatic images of 1 m spatial resolution (used in Copernicus) and multispectral images with 4 m resolution; its main applications are related to agriculture and land and urban planning. TripleSat-1 and Deimos-2 (renamed GEOSAT-2) offer a 4 m spatial resolution in the multispectral mode (used in Copernicus), while in the panchromatic band they achieve resolutions of 1 m. Finally, the Planet Dove operates solely in the multispectral mode (3.7 m resolution) (Table 1).

Additional EO VHR data used in the Coastal Zone LU/LC dataset originate from the RapidEye satellite which delivered multispectral images (5 m resolution). Time series of the freely available Sentinel and Landsat-8 products are used to fill gaps in the data sets. Various data sets derived mainly from Sentinel-2 observations (multispectral band, 10 m resolution), were utilized for the creation of the Coastal Zone LU/LC dataset. Imperviousnes Density (IMD) and Impervious Built Up (IBU) data indicate the soil impermeability through mapping of sealed surfaces; they were used to establish the boundaries between the different urban fabric classes of the Coastal Zone LU/LC. Tree Cover Density (TCD) and Grassland (GRA) data sets, provide the tree- and grassland-coverage and can be used in certain occasions to classify agricultural land uses. For the IMD, IBU and GRA layers, Sentinel-1 radar images were processed, whereas for the TCD, aerial ortho-photos and VHR optical data were used as reference. The European Settlement Map (ESM) and the Coastline (EU - Hydro Coastline) layers were generated by processing VHR data sets by SPOT-5 and SPOT-6The ESM and the EU-Hydro Coastline having a 2.5 m resolution.

In Europe, EO data sets used for data assimilation/validation in marine products are collated in the Thematic Assembly Centres of the Copernicus Marine Environment Monitoring Service (CMEMS)[2] containing several oceanographic parameters. These products facilitate coastal flood risk estimation in many ways, including ocean forcing for flood forecasting schemes in regional (Oliveira et al. 2020) and Pan European scale (Irazoqui Apecechea et al. 2023), estimation of trends and extremes in sea level rise through satellite observations and reanalysis (Prandi et al. 2021) that can be used also for validation purposes, and the monitoring of polar ice melting (von Schuckmann et al. 2016). Although the main sources of data are the Sentinel missions (S3A/B, S6A), there are also contributing missions supplying additional information streams, including altimeters for Sea Level Anomaly such as the HY-2B/C, Saral – Altika and Topex/Poseidon (Table 2).

As described in van Dongeren et al. (2017), efficient modeling of coastal floods and their impacts at local levels require detailed forcing information, including storm surge and wave fields. From an operational point of view, CMEMS forecasts appear suitable for the provision of reliable open boundary conditions and several local and regional European modeling systems use the CMEMS forecasts for this purpose (Pérez-González et al. 2017; Capet et al. 2020; Umgiesser et al. 2021). In the recently developed Pan European Coastal Flood Awareness System – ECFAS (Le Gal et al. 2023), coastal flood forecasting is also driven by CMEMS total water level (TWL) forecasts.

The lack of updated and realistic coastal topography is often a limiting factor on the precise prediction of coastal flooding, erosion and barrier overwash (van Dongeren et al. 2017; Jimenez et al. 2017; Ciavola and Coco 2017)). LIDAR data can be used as an alternative in order to capture efficiently pre- and post-storm morphology (Matias and Masselink 2017). Considering that in an operational mode, the limit between subaqueous and subaerial parts should be often updated for the flood extent calculation, satellite derived shoreline (SDS) methods can be used while also allowing for post impact assessments. Mapping of flood extent with SAR images combined with a LANDSAT- derived mosaic allowed for the assessment of urban damages during the Katrina hurricane (Klemas 2009). Sentinel-1 observations of flood extent have been used for validation of coastal flooding simulations (Kiesel et al. 2023) including also compound flooding (Eilander et al. 2023), while Makris et al. (2023) calculated the NDWI on Sentinel 2 images for the delineation of storm surge affected areas in order to validate their coastal flood model.

Generally, the data currently in use in the Copernicus systems do not have the appropriate resolution at a pan-European scale to support high spatial resolution forecasts for various products, although some of these issues could be addressed in the future. For example, the coarse resolution and, especially, the vertical inaccuracies of the EU Digital Elevation Models - DEMs do not support modelling of fine-scale morphodynamic processes.

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[2] https://marine.copernicus.eu/about/producers/sl-tac

Table 2 Characteristics of the EOs used in the Copernicus marine data sets

Sensor	Function	Spatial resolution	Operation & cycle time	Reference
ERS-1	SIT, MGA	10–30 m	1991–2000 3- or 35-day cycle	https://www.eoportal.org/satellite-missions/ers-1
ERS-2	SIT, MGA	30 m	1995–2011 3- or 35-day cycle	https://www.eoportal.org/satellite-missions/ers-2
TOPEX/Poseidon	SLA, MGA	7 km	1992–2005 10-day cycle	https://www.eoportal.org/satellite-missions/topex-poseidon
GFO	SLA	N/A	1998–2008 17-day cycle	https://www.eoportal.org/satellite-missions/gfo
Jason 1	SLA, MGA	N/A	2001–2013 10-day cycle	https://www.eoportal.org/satellite-missions/jason-1
Jason 2	SLA, MGA	70 km	2008–2019 9.9-day cycle	https://www.eoportal.org/satellite-missions/jason-2
Jason-3	SLA, MGA	70 km	2016–Present 10-day cycle	https://www.eoportal.org/satellite-missions/jason-3
SARAL-ALTIKA	SLA	40–50 km	2013–2023 35-day cycle	https://www.eoportal.org/satellite-missions/saral
CRYOSAT	SIT	300 m	2010–Present 369-day cycle	https://www.eoportal.org/satellite-missions/cryosat-2
Sentinel 3A/3B	SSH & SST	300 m	2016–Present 27-day cycle Revisit: 4 days	https://www.sentinel.esa.int/web/sentinel/missions/sentinel-3
Sentinel 6A	SSH	35 km	2020–Present 10-day cycle	https://www.eoportal.org/satellite-missions/copernicus-sentinel-6-michael-freilich
CFOSAT	Wave, Wind Characteristics	50 km	2018–Present 13-day cycle	https://www.eoportal.org/satellite-missions/cfosat
NOAA AVHRRs 7, 9, 11, 14, 16, 17,18	SST	1.1 km	Various, from 1981, 2009–Present	https://www.avl.class.noaa.gov/release/data_available/avhrr
ENVISAT AATSR	SST	1 km	2008–2012 10-day cycle	https://www.earth.esa.int/eogateway/instruments/aatsr
HY - 2B	SLA, MGA	0.25°	2018–Present 14- & 168-day cycle	https://www.aviso.altimetry.fr/en/missions/current-missions/hy-2b
HY - 2C	SLA, MGA	0.25°	2020–Present 10-day cycle	https://www.aviso.altimetry.fr/en/missions/current-missions/hy-2c

Key: *SSH* Sea Surface Height, *SLA* Sea Level Anomaly, *SWH* Significant Wave Height, *SST* Sea Surface Temperature, *SIT* Sea Ice Thickness, *IST* Ice Surface Temperature, *MGA* Marine Gravity Anomaly. The list is non-exhaustive

Previous studies of flood risk on a Pan European scale have compared the EU DEM with more accurate national DEMs and revealed vertical errors greater than 2 m in some coastal zones that could have a major impact on the accuracy of the projected inundation (Paprotny et al. 2019). This discrepancy is illustrated in Fig. 1 where the EU DEM is compared with the elevation of the Greek Cadastre DEM for a barrier beach of the island of Chios (Greece). It becomes apparent that both the beach and backshore morphology as well as the coastal works are poorly resolved by the EU DEM compared to the 2×2 m national Cadastre grid.

Another major constraint is related to the bathymetric information available from the open-source GEBCO and EMODnet products (Weatherall et al. 2015; Thierry et al. 2019), the resolution of which in the nearshore areas cannot support products of high resolution at a pan-European level for different reasons. First, coastal total water levels (TWLs) comprise several contributors: the mean sea level, the astronomical tide and water circulation, and the episodic coastal water level rise due to storm surges and wave setups; their interactions can affect the TWLs at several spatio-temporal scales (e.g., Melet et al. 2018, 2020). The magnitude of the storm surges in deep waters is mainly controlled by the atmospheric pressure, while during storm propagation to the nearshore the effects of the wind surface stress and water transport become dominant due to the shoaling seabed (Bertin et al. 2017). Wave setup, a significant contributor to the TWL, is sensitive to the nearshore bed slope and habitats (CEM 2002; Dodet et al. 2019; Da Silva et al. 2020). The combination of wave refraction, shoaling and breaking over the (mostly complex) inshore seabed and interactions with wave-generated flows under storms

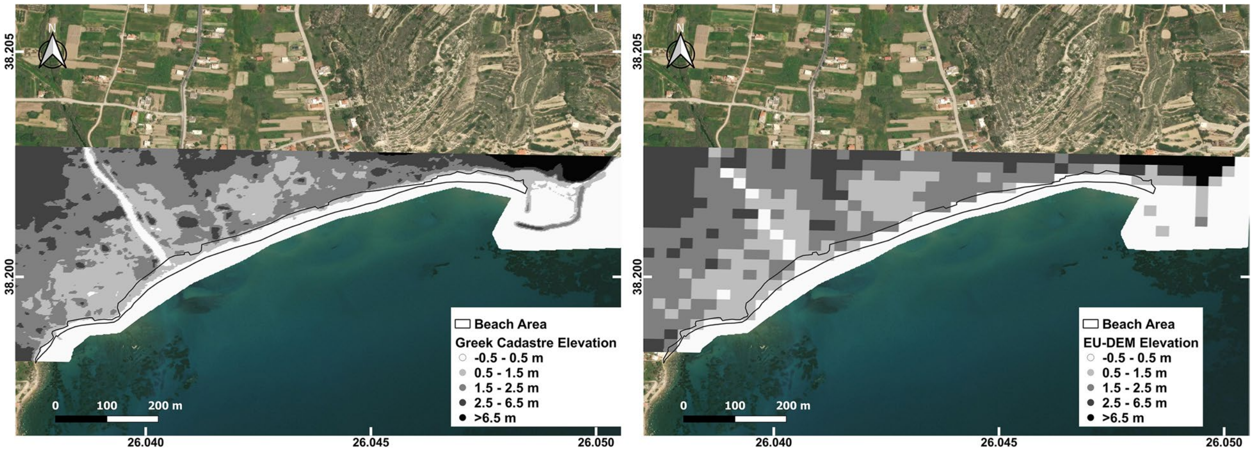

Fig. 1 Greek Cadastre Topography (left) compared with the EU DEM topography (right) for the Komi coastal zone (Chios, Greece). The much finer resolution of the Greek Cadastre DEM (2 × 2 m) is apparent, resolving in greater detail the coastal works in contrast to the EU DEM. **Figure 1** has been created in QGIS (project layout)

(Roelvink and Reniers 2012), generate further uncertainties in the estimation of the wave setup, particularly in the absence of coastal bathymetric/topographic data of high resolution and accuracy (CEM 2002). This is the reason why in large scale studies (e.g., Vousdoukas et al. 2018), a generic approximation is used (wave setup set at 0.2 of the SWH).

Secondly, forecasts of the wave runup (i.e., the time-varying position of the shoreward water edge) are fundamental for assessing beach erosion and corresponding damages (e.g., Dean 2002; Jimenez et al. 2012; Vitousek et al. 2017; Chatzipavlis et al. 2019). Wave runup variability also provides critical information for the legal delimitation of the beach and the 'set-back' zones for the purposes of the 2008 Integrated Coastal Zone Management (ICZM) Protocol and the national legislation of several EU Member States (Velegrakis et al. 2021). Wave runup (and overtopping) forecasts require detailed and accurate nearshore bathymetric/topographic information (Da Silva et al. 2020; Almar et al. 2021).

Notwithstanding the above constraints, GIS based on EO-derived information have been proven useful tools for the assessment of the coastal flood extent and impacts. First, GIS-based methods have been developed to improve the estimation of flood water depth in remote sensing studies of coastal flooding (Cohen et al. 2019). Secondly, there are GIS-based 'bath-tub' approaches for the estimation of the flood extent/depth, which are based on the comparison of the coastal Extreme Sea level – ESL (the hazard) to the coastal DEM assuming flooding in each DEM cell with an elevation lower than or equal to the flood water level. Although such approaches do not account for dynamic evolution of the coastal floods during storms, as well as for other hydraulic considerations (e.g., bed friction), they are often used in rapid flood risk assessments (Seenath et al. 2016; Williams and Lück-Vogel 2020). Thirdly, GISs facilitate flood vulnerability assessments by spatial comparisons between the estimated flood extent and GIS information concerning populations, infrastructure/assets, cultural heritage and habitats (Ferreira et al. 2021). Finally, EO-derived GIS information is also required for the deployment of dynamic flood models, such as the LISFLOOD (Bates et al. 2005).

Regarding improvements, further options of EO data should be explored, either those being available from already launched missions or becoming available in the next few years from announced missions. Generally, information from already existing EOs might be utilised to a better effect.

COSMO – SkyMed is a constellation operated by the Italian Space Agency (ASI) consisting of 4 satellites launched in 2007–2010. Each satellite is equipped with a SAR-2000, a multi-mode instrument operating on different swath ranges and resulting in varying spatial resolution. SAR technology can substantially contribute to product improvements due to its capability to retrieve data under the severe weather conditions (cloud, rain, haze) during coastal floods. The highest resolution achieved by COSMO - SkyMed is 1 m, but there are also additional resolutions: Spotlight - 1 m; Stripmap HIMAGE- 3 m; Stripmap PING PONG - 15 m; ScanSAR Wide - 30 m; and ScanSAR Huge- 100 m. Although access to the highest-resolution images (1 m) is restricted, the remaining modes might be available to public authorities and for research purposes upon request. Three different system operative modes have been defined (routine, crisis and very urgent) allowing responding to different needs in terms of the required programming latency.[3]

TanDEM-X is based on the German TerraSAR-X's twin Synthetic Aperture Radar (SAR) satellite(s), implemented by the German Aerospace Centre (DLR) and the EADS Astrium (now Airbus Defence and Space). TanDEM-X satellite mission flies two satellites in a closely controlled formation, which allowed the generation of WorldDEM global digital elevation models starting in 2014.[4] It has revisit times of 2.5–11 days, depending on imaging mode, and the missions can operate in the modes: Map (SM), resolution 3 m, scene size 30 × 50 km^2 (up to 30 × 1650 km^2); SpotLight (SL), resolution 2 m, scene size 10 × 10 km^2; Staring SpotLight (ST), resolution 0.25 m, scene size 4 × 3.7 km^2; High Resolution SpotLight (HS), resolution 1 m, scene size 10 × 5 km^2; ScanSAR (SC), resolution 18 m, scene size 100 × 150 km^2 (up to 100 × 1650 km^2); Wide ScanSAR (WS), resolution 40 m, scene size 270 × 200 km^2 (up to 270 × 1 500 km^2).

ALOS-2 satellite mission, launched by the Jaxa Japanese Space Agency, is equipped with an imaging microwave radar, PALSAR-2 (Phased Array type – L-band SAR) and among its mission goals is the disaster monitoring. The mission has a revisit time of 14 days and operates in SL mode for increased resolution of 1 × 3 m (25 km observation width). Observations on conventional modes of Stripmap (3 m / 6 m/ 10 m resolution, 50–70 km width) and SC (60/100 m resolution, 350/490 km) are also provided.

SAR could play a particularly important role in flood mapping, due to its proven near all-weather/day-night capabilities and its effectiveness to detect inundation beneath vegetation canopies (e.g., Ormsby et al. 1985; Alsdorf et al. 2000; Horrit et al. 2003). A most important advantage of SAR EOs is that the boundary between land and water can be easily distinguished; it appears that further utilisation of Cosmo,TerraSarX and ALOS-2/PALSAR-2 EOs data could improve the analysis regarding the spatio-temporal extent and patterns of flood inundation and the flood map resolution. Because X band penetration of the vegetation canopy is limited compared to other SAR bands, opportunities could emerge from the simultaneous use of Cosmo and/or TerraSarX and TandemX with other missions such as Saocom[5] operating in the L band and Radarsat and Sentinel 1 operating in the C band. Although the spatial and temporal resolution of these missions are lower than the previously mentioned satellite constellations, the combined use of different SAR sensors may allow to fill the gap. L and C bands in particular have highest penetrations and, thus, may be able to better detect flood extent in dense vegetation areas. For example, the combined use of Sentinel 1 and ALOS-2/PALSAR-2 allowed for accurate rapid flood assessment on both urban and rural areas in India (Venama et al. 2021).

Flood risk assessment, management and early warning could benefit from the use of hyperspectral sensors such as those of the PRISMA mission. PRISMA (Hyperspectral PRecursor of the Application Mission) is a medium-resolution hyperspectral imaging satellite (Agenzia Spaziale Italiana- ASI) launched in March 2019. The HYC sensor is a prism spectrometer for two bands with a total of 237 channels: VIS/NIR (Visible/Near Infrared) and NIR/SWIR (Near Infrared/Shortwave Infrared). Its primary objective is the high-resolution hyperspectral imaging of land, vegetation, inner waters and coastal zones.[6] The second sensor module (PAN) is a high-resolution optical imager, co-registered with HYC data to allow testing of image fusion techniques. The HYC module has a spatial resolution of 30 m while the PAN module a spatial resolution of 5 m. Its applications regarding the mapping of the surficial characteristics in coastal zones include the provision of detailed land and coastal cover maps and extraction of coastal bathymetry information (Alevizos et al. 2022; Poursanidis and Chrysoulakis 2021).

Lastly, land subsidence which can be a critical important parameter for the assessment of the flood exposure, especially in the urbanised coastal areas (Nicholls et al. 2021), can be also estimated by EO based techniques that offer coverage of large areas compared to the traditional ground topographic surveys (Melet et al. 2020). GRACE-FO[7] and its predecessor GRACE have been utilized together with SAR- based interferometric techniques for the estimation of land subsidence due to groundwater depletion (Pranjal et al. 2021). GRACE-FO mission is operated by NASA and DLR and consists of two satellites equipped with multiple instruments including a Microwave Instrument and a Laser Ranging Interferometer for the precise measurement of variations in the gravitational field of Earth. The mission has relatively coarse spatio-temporal resolution (150 km^2, and one month, respectively).

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[3] https://www.asi.it/wp-content/uploads/2019/08/COSMO-SkyMed-Mission-and-Products-Description_rev3-1.pdf

[4] https://www.intelligence-airbusds.com/imagery/reference-layers/worlddem/

[5] https://earth.esa.int/eogateway/missions/saocom

[6] https://www.eoportal.org/satellite-missions/prisma-hyperspectral#mission-capabilities

[7] https://www.eoportal.org/satellite-missions/grace-fo#eop-quick-facts-section

2.2 Potential developments

The Copernicus program will expand its current capabilities with six new satellite missions.[8] More specifically, the CHIME (Copernicus Hyperspectral Imaging Mission) starting from 2025 is expected to complement Copernicus Sentinel-2 for applications such as land-cover mapping, providing routine hyperspectral observations to increase the capabilities, accuracy and spatial resolution of current products. The CHIME mission will consist of two satellites (CHIME-A and CHIME-B) providing systematic hyperspectral images to map changes in land cover and aid sustainable agricultural practices; it will be launched in 2028. The satellite will operate with Visible (VIS), Near Infrared (NIR), and Short-Wave Infrared (SWIR) spectrum at a spectral bandwidth less than 10 nm, with a spatial resolution of 30 m with a revisit time of 10–12.5 days. Compared to multi-spectral missions, both satellites will have more (narrow) spectral bands in the visible-to-shortwave infrared range allowing for more accurate determination of biochemical and biophysical variables. In addition, the availability of a continuous spectrum makes algorithms more effective in a variety of marine environments with different water depths and seabed reflectance (Giardino et al. 2020). The spatial resolution obtained from these satellites will also be beneficial to capture the fine spatial features typical of inland and coastal waters and, thus, to improve the land use and cover (LU/LC) maps for flood risk assessments.

Another hyperspectral mission under development that could be relevant to coastal flood risk assessment and management, is the SBG (Surface Biology and Geology) NASA mission. The SBG mission envisages to acquire global, high spatial resolution EOs at a sub-monthly basis over terrestrial, freshwater, and coastal marine habitats relating to: visible to shortwave infrared (VSWIR, 380–2500 nm, about 30 m pixel resolution); hyperspectral (imaging spectroscopy); and multispectral mid-wave and thermal infrared (MWIR. 3 – 5 μm; TIR., 8–12 μm, about 60 m resolution) (Cawse-Nicholson et al. 2021). Together with the other two hyperspectral missions, SBG would provide important information through the development of the TIR range of the spectrum at a higher resolution than the one currently available. To implement EU policies for the management of natural resources and climate change adaptation, as well as to achieve the objectives outlined by NASA's Decadal Survey (NASEM 2018), high fidelity imaging spectroscopy data with global coverage and high spatial resolution are required. This is why synergies between CHIME and SBG have been already envisaged and implemented (Boccia et al. 2021). A complementary multi-mission approach appears to be more suitable for improved spatio-temporal resolutions than single missions.

IRIDE is a large low orbit space program and will consist of a constellation of 36 satellites of various types, combining SAR, optical, panchromatic, hyperspectral and infrared sensors.[9] The constellation will be built in Italy and completed by 2026 with the support of the European and Italian Space Agency. IRIDE will be able to provide information for applications related to coastal protection and the monitoring of critical infrastructure. The configuration of the mission is still under development, but is foreseen that will provide for two SAR, two multispectral and one hyperspectral constellations, together with TIR and VHR missions which will allow daily revisits over the globe and fine spatial resolution (<3 m).

Finally, new promising technologies have been suggested, based on communication satellite transmissions that can be re-utilized as illumination sources in a bistatic radar configuration, for measuring coastal sea level (Signals of Opportunity - SoOp). As this technology requires only receiver technology to be placed in orbit, small satellite platforms could be used, enabling constellations to achieve high spatio-temporal resolutions for coastal sea levels (Benveniste et al. 2019).

Regarding existing information, progress has also been made in the bathymetric products of GEBCO and EMODnet, due mostly to an apparent increase in the number of survey data sets fed by data providers. For example, while the 2015 EMODnet bathymetry product used in the Copernicus Marine Service to set up the hydrodynamic models had tiles of 1/8 arc min, the 2018 and 2020 DTMs achieved a resolution of 1/16 arc min. The potential for further improvement is manifested by the rising number of supplied bathymetric data sets (from about 9400 in 2018 to more than 16,000 in 2020). Nevertheless, these products constitute static data sets which might not capture the shallow inshore bathymetry and its dynamics with the detail needed for wave runup forecasts.

In recent years, several algorithms for shoreline detection have been developed, using EOs from multispectral satellites that can provide information with high spatio-temporal resolution for coastline detection through image processing techniques; shoreline detection at sub-pixel level has been achieved using available open-source multi-spectral images from the Landsat and Sentinel constellations (Souto Ceccon et al. 2021a) and hyperspectral

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[8] https://sentinels.copernicus.eu/web/sentinel/missions/copernicus-expansion-missions

[9] https://researchitaly.mur.gov.it/en/2022/06/07/__trashed-8/

PRISMA images (Souto Ceccon et al. 2021b). Satellite derived shorelines (SDSs) from the analysis of optical imagery have also shown promising results (Pardo-Pascual et al. 2018). Thus, tools for shoreline analysis/extraction should be developed to evaluate the coastal storm impacts along large sectors of the (EU) coast, through automated extraction of pre- and post-storm SDS from EOs collected within the Copernicus and Copernicus Contributing Missions programs (Palomar-Vázquez et al. 2023).

Satellite Derived Bathymetry (SDB) techniques have also emerged that use high resolution EOs to retrieve coastlines and nearshore bathymetry (Ashphaq et al. 2021) for, amongst others, to set up wave models (Bolanos et al. 2018). Usually relatively coarse (10 m) imagery is appropriate for larger scale mapping, with finer resolutions used at local scale applications. SDB algorithms are based either on multispectral or on hyperspectral images and they can cover large areas of shallow waters (usually < 15 m depth) even at regional scales (Baba et al. 2021). However, empirical SDB techniques (Traganos et al. 2018) require field data for model calibration (e.g., Pacheco et al. 2015) and, thus, their resolution relies also on 'ground truthing', an inherent limitation for large scale applications.

Nevertheless, analytical techniques based mainly on hyperspectral imagery that can model the optical properties of water column appear more suitable for large scale applications. It is noteworthy that PRISMA imagery analysed by SDB methods using pan-sharpened images maximised spatial resolution to 5×5 m and improved accuracy (Alevizos et al. 2022). Due to the constraints posed by increased shallow water turbidity from suspended sediments, however, such analytical techniques may be only suitable for coastal areas of low turbidity (e.g., the Mediterranean), but not optimal for other coastal areas such as the open Atlantic coast. In addition, there could be high computational and data storage costs for mapping the nearshore bathymetry at high resolution at a pan-European scale.

In order to alleviate data deficiency, alternative remote sensing EOs have been used. One example is the Airborne LiDAR Bathymetry (ALB) which has been widely used for terrestrial and shallow water mapping (Oliveira et al. 2021; Klemas 2011; Agrafiotis et al. 2020). Airborne Lidar Bathymetry can collect high resolution depth measurements quickly over large areas, although with high costs and logistical difficulties, by mounting lasers on manned (MAVs) and, increasingly, unmanned airborne vehicles (UAVs). Generally, ALB is considered as an effective approach for shallow bathymetric surveys, since it offers good accuracy (~0.2 m) and grid resolution (1 m) through clear water and for depths up to tens of metres (for powerful LIDARs, Mandlburger (2020)). However, these observations are weather-constrained (e.g. strong winds/waves, and water column clarity). A main advantage of LiDAR data sets is that they can capture morphological changes and estimate seabed slopes with the resolution/accuracy required for the wave transformation and runup modelling (Guimaraes et al. 2015; Chalazas et al. 2023). There are also EU Member States that have used (mostly sub-aerial) LiDAR data in the production of coastline and flood maps.[10] Finally, it is noted that the rapidly evolving unmanned aerial vehicles (UAVs) with the appropriate sensors (e.g., Mandlburger 2020), can provide coastal topographic/bathymetric data sets of very high resolution, albeit at limited spatial scales.

3 Relevant policy and legislation

The growing importance of Earth Observations (EOs) is manifested in a variety of policy imperatives and legal requirements. Not only are they referred to in many policy and legal instruments relevant to coastal flood risk assessment and management, but EOs now form inherent components of most DRR phases and activities, including the monitoring to assess progress in policy implementation.

3.1 International instruments

The Sendai Framework for Disaster Risk Reduction (SFDRR 2015), highlights the importance of the implementation and coherence of tools (paras 19 h and 28b) and embraces a multi-hazard approach (paras. 15 and 19 g). Its priorities for action include: 1) '*understanding the disaster risk - in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics* and *the environment*'; 2) '*strengthening disaster risk governance to manage disaster risk*'; 3) '*investing in disaster risk reduction for resilience*'; and 4) '*enhancing disaster preparedness*' for effective response, and to '*build back better*' in the recovery, rehabilitation and reconstruction DRR phases. Coastal flood risk assessments, mapping, and associated EWSs and EOs are indispensable tools for these SFDRR priorities and the availability of and accessibility to EWSs and disaster risk information and assessments are explicitly referred to in its implementation roadmap (paras 24–34).

In terms of legislation, there are a number of international Agreements of relevance that entail binding obligations for EU Member States that have ratified/acceded to these instruments (Velegrakis et al, 2022).

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[10] https://www.dutchwatersector.com/news/fugro-to-map-northern-irelands-coastline

The 1992 UN Framework Convention on Climate Change (UNFCCC 1992) sets out obligations to establish, implement and update national and regional programmes to facilitate adequate adaptation to climate change (Art. 4.1b). The commitments of the Parties to integrated coastal zone management and the protection/rehabilitation of areas affected by floods (Art. 4.1e), impact assessments (Art. 4.1 g) and cooperation/promotion of scientific research, systematic observation and climatic data archiving (Art. 4.1 g) are of direct relevance to the EO collection/analysis. In a UNFCCC policy brief (UNFCCC 2020), focusing on technologies for averting, minimising and addressing loss and damage in coastal zones, the development/improvement of EO technologies features prominently. The 2015 Paris Agreement (UNFCCC 2015) prescribes, among others, international action to improve climate resilience. Of particular interest in the EO and EWS context is the commitment of the Parties to enhance cooperation including, among others, with regard to '*strengthening scientific knowledge on climate, including research, systematic observation of the climate system and early warning systems ....*' (Art. 7.7c).

At the regional level, the 2008 ICZM Protocol to the 1995 Barcelona Convention (UNEP 2008) is also highly relevant. The Protocol has been ratified by only some of the Mediterranean EU Member States (Croatia, France, Malta, Slovenia and Spain) as well as the EU (EU 2010a, b). It promotes ICZM and prescribes a range of actions/measures to monitor and protect the coastal human and natural environment (Arts. 9, 10, 11 and 13), as well as actions related to the development of monitoring and observation mechanisms (Art. 16). It deals with the 'risks affecting the coastal zone', and includes detailed provisions setting out obligations in respect of natural hazards (Art. 22), coastal erosion (Art. 23) and response to natural disasters (Art. 24), including '*coordinated use of the equipment for detection, warning and communication*'. Importantly, the ICZM Protocol prescribes the introduction of a 100 m 'set-back' zone '*as from the highest winter waterline ... where construction is not allowed*' subject to limited exceptions (Art 8). Monitoring and understanding the coastline dynamics associated with coastal flooding, erosion and extreme wave runups (highest winter waterline) are critical for the determination/implementation of the 'set-back' zones. High resolution EOs can facilitate the necessary coastal mapping and provide crucial information for the assessment of marine incursion - wave runup under extreme events; thus, they can assist in the delimitation of 'set-back' zones for the purposes of the ICZM Protocol, as well as of the relevant national legislation (Velegrakis et al. 2021).

3.2 EU instruments

The 2021 EU Climate Change Adaptation Strategy (EU CCA) (EU 2021a) envisages that by 2050 '*...EU will be a climate-resilient society, fully adapted to the unavoidable impacts of climate change*'. It links to the global agenda such as the SFDRR, the Paris Agreement and the 2030 Sustainable Development Agenda (UN 2015), as well as EU legislation such as the Union Civil Protection Mechanism - UCPM (EU 2021b) and the 2021 EU Climate Law (EU 2021c). It also relates to EU initiatives like the Horizon Europe Mission on Adaptation to Climate Change (EC COM 2021a) and highlights the need for synergies with the DRR policies and legislation (e.g., the UCPM and the SFDRR).

The EU CCA highlights the need for Earth Observations (EOs), smart weather stations, artificial intelligence and high-performance computing to underpin decision making. It details wide-ranging actions of particular relevance to the coastal flood risk management, such as: development of *state-of-the-art* tools for adaptation modelling; risk assessments/management – towards 'asset-level modelling'; and actions aiming at more, and better risk and loss data. It advocates for actions to close knowledge gaps on climate impacts and resilience through Horizon Europe, Digital Europe, Copernicus and EMODnet. It also recognizes the increasing demand to translate the available information into customised, user-friendly tools, noting that: all data from EU scientific lighthouses such as Copernicus and EMODnet should be freely and openly available to users; and the Copernicus Climate Change Service (C3S) should advance data usability and develop additional services, such as extreme event attribution.

The EU Action Plan on the SFDRR (EC SWD 2016) offers a coherent agenda across different EU policies to strengthen resilience to risks, shocks and disruptions. Monitoring to assess progress and support disaster (coastal flood) preparedness and response through satellite mapping and early warning and monitoring services are also emphasised; these activities are linked with the SFDRR Priorities 1 and 4 (Section 3.1). The importance of improved data for DRR, including in respect of coastal flooding, is reflected throughout the activities and outputs listed; for example, Activity 2.3, focuses on the review/update of flood risk assessments under the EU Flood Directive (FD) (EU 2007a), and Activity 1.1 on identifying gaps and possible solutions in disaster loss data required for monitoring. Of particular relevance is also the Implementation Priority Actions 20.1 - develop and better integrate transnational detection and multi-hazard early warning and alert systems through the EU Civil Protection Mechanism, and 20.2 - continue provision through the CEMS of timely geo-spatial information (satellite-based maps) for disaster preparedness, emergency response and recovery.

The UCPM (EU 2021b), the main operational EU mechanism for disaster risk reduction, response and recovery, highlights the need for '*comprehensive risk management approaches that underpin prevention and preparedness …*' (Preamble, para. 12) and envisages the establishment of a '*Union Civil Protection Knowledge Network to aggregate, process and disseminate knowledge and information relevant to the Union Mechanism, based on a multi-hazard approach and including relevant civil protection and disaster management actors, centres of excellence, universities and researchers*' (Art. 13.1). It also mandates work on a range of issues, including the development of '*transnational detection and early warning systems of Union interest in order to mitigate the immediate effects of disasters*'; and improved integration of '*existing transnational detection and early warning systems based on a multi-hazard approach, with a view to minimising the lead time to respond to disasters*' (Art. 8c, 8i and 8ii). These activities require coordinated collection/analysis of appropriate EOs.

Moreover, the Regulation establishes an Emergency Response Coordination Centre (ERCC) which: a) '*shall ensure 24/7 operational capacity, and serve the Member States and the Commission in pursuit of the objectives of the Union Mechanism*'; and b) '*shall in particular coordinate, monitor and support in real-time the response to emergencies at Union level*' working '*in close contact with national civil protection authorities and relevant Union bodies to promote a cross-sectoral approach to disaster management'* (Art. 7.1). The Copernicus Emergency Management Service - CEMS can play an important role, as it provides information for early warning and emergency response as well as prevention, preparedness, response and recovery activities. To this end, the CEMS support to the ERCC '*in the various emergency phases from early warning and prevention to disaster response and recovery*' is highlighted in para. 17 of the preamble of the UCPM Regulation ((EU) 2021/836).

The adoption of the 2021 EU Climate Law (EU 2021c) is also of relevance in the context of EOs. The Law envisages strong action on climate change adaptation and resilience-building (Art. 5), and prescribes related stocktaking, assessments and reviews (Art. 6) all of which depend on the availability of appropriate EOs. The EU institutions and Member States must ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, thereby making relevant actions a legal requirement as a matter of the supra-national (EU) legislation.

The Floods Directive (FD) (EU 2007a) imposes a duty to EU States to assess the coastal flood risk, map the flood extent, assets and humans at risk and take adequate management measures. It requires comprehensive flood hazard and risk maps - FHRMs and flood risk management plans - FRMPs in recurring implementation cycles; its effective implementation rests on the availability and accessibility of good quality EOs. Another legislative instrument relevant to coastal flood risk is a proposed Regulation (EC COM 2021b) to amend guidelines for the development of the trans-European transport network (TEN-T). Among others, the proposed legislation will require Member States to give due consideration to improving resilience to climatic hazards and environmental disasters in their infrastructure planning. The proposed amendments further envisage '*climate proofing*' of the new network infrastructure based on latest available best practice and guidance. Ports and other coastal transport infrastructure are vital network components and, as such, their resilience to coastal foods should be assessed and improved in line with the detailed technical EC guidance (EC COM 2021c). 'Climate proofing' of new coastal infrastructure is also prescribed by the EU Environmental Impact Assessment Directive 2014/52/EU. EOs of appropriate resolution/accuracy provide indispensable data for the assessment of the exposure and vulnerability of coastal zones (UNECE 2020).

Worth highlighting in this context is also the EU INSPIRE Directive (EU 2007b), through which the EU envisaged to enable access and re-use of geo-spatial data and information across all levels of government and borders. The Directive lays down general rules aimed at '*the establishment of the infrastructure for spatial Information in the European Community*' (INSPIRE) for the purposes of '*Community environmental policies, and policies or activities which may have an impact on the environment'*. INSPIRE shall build upon the spatial data infrastructures (SDIs) established and operated by the Member States (Art. 1). The Directive addresses 34 spatial data themes needed for environmental applications, with key components specified through technical implementing rules.[11] Most of these data themes (set out in 3 Annexes) refer to Earth Observations, including: geographical grid systems, elevation, land cover/use, ortho-imagery, hydrography, oceanographic features, habitats/biotopes, protected sites, population, administrative units, transport networks, buildings, and utilities. To ensure that the Member States' SDIs are compatible/usable in the EU and in a transboundary context, INSPIRE requires common binding Implementing Rules (IRs) in e.g., metadata, data specifications, network services, data/service sharing, monitoring and reporting) (see also EU (2021a)). In

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[11] https://inspire.ec.europa.eu/Themes/Data-Specifications/2892

addition, Regulation (EU) 2019/1010 (EU 2019a) on the alignment of reporting obligations in the environmental legislation requires annual summary reports (Art. 21) and alignment of the reporting (Art. 23). INSPIRE presents the world's largest coordinated effort to establish a Spatial Data Infrastructure (SDI), currently holding more than 150,000 (mostly geo-spatial) data sets which are made increasingly available, i.e., discoverable, viewable and downloadable (e.g., Cetl et al. 2019).

The Open Data Directive (EU 2019b), which aims at full exploitation of the public sector information, acknowledges INSPIRE as a good practice and explicitly refers to the high potential of the re-use of the massive (and increasing) amount of data and tools produced. Such activities require good data management practices, guided by the Findability, Accessibility, Interoperability, Reusability (FAIR) principles (Wilkinson et al. 2016). It should be noted that the INSPIRE Directive supports open governance and data initiatives, but does not specify a common data policy; this has resulted in variable licensing procedures by the EU Member States (Kotsev et al. 2020). It is worth noting that the the increasing usage of the rapidly evolving EO technology, such as the UAVs with their very high resolution sensors may also pose challenges in terms of their regulation which differs across the globe; this regulation is dictated by the balance in the national approaches between new technology promotion and safety (Jones 2017). In Europe, Regulation (EU) 2019/945 (EU 2019c) sets out the features and capabilities that UAVs (drones) must have in order to be flown safely and classifies types of operations (open, specific and certified). Relevant is also Section VII of Regulation (EU) 2018/1139 (EU 2018) which prescribes authorization procedures for UAVs. As there is no common data policy, there are various licensing procedures in the EU Member States.

The new Regulation (EU) 2021/696 (EU 2021d) on the EU space programmes, including the Copernicus programme (EC 2023a, b) is of paramount significance. The Regulation focuses on different aspects of the EU EOs, including their scope, budgetary contributions/mechanisms, financial provisions, governance and security. In its preamble, it reiterates the principles established in the previous Copernicus Regulation (EU) 377/2014 to '*…maintain state-of-the-art systems, to upgrade them to meet evolving users' needs…*'. It mandates Union support for '*…research and development activities relating to applications and services based on the systems established under the programme…*' and declares that '… [Copernicus] *evolution should be based on …. evolving user needs, including those related to implementation, and monitoring of Union policies which require the continuous, effective involvement of users…*' (Preamble para. 75). It also states that '*…it is important to ensure the continuity of the infrastructure and services already in place, whilst adapting to the changing user needs…*' (Preamble para 76). The commitment to providing good quality EOs is also found in various Articles, such as: '[Copernicus] …to *deliver accurate and reliable Earth observation data, information and services….to support the formulation, implementation and monitoring of the Union and its Member States' policies and actions based on user requirements…*' (Art. 4.3b); and to deliver '*data and information building on the needs of the Copernicus users…*' (Art. 49.2). Moreover, the Regulation prescribes an emergency management service to provide information '*…in support of and in coordination with public authorities concerned with civil protection, supporting civil protection and emergency response operations (improving early warning activities and crisis response capacities), and prevention and preparedness actions…*' (Art. 51.1b).

Copernicus shares objectives with other EU programmes, such as Horizon Europe (EU 2021e), the InvestEU Programme (EU 2021f), the European Defence Fund (Regulation (EU) 2021/697) (EU 2021g), as well as with various sectoral (funding) instruments including on EU regional development, cohesion, the maritime and fisheries/aquaculture industries, migration and integration. This impressive array of interacting, recently adopted EU legal instruments shows the growing significance and mainstreaming of the EOs as well as overarching policy for synergies and integration.

4 Discussion and conclusions

EOs form the basis of most data sets involved in the assessment of the coastal flood risk. Earth observing technologies have been widely incorporated into the emergency management cycle, as they can deliver massive information on the hazard, exposure and vulnerability determinants of the flood risk. This review has shown that marine and land EO data from multiple sources are (and can be) utilised for these purposes. These data sets provide, in most cases, land information with a resolution acceptable to users; in comparison, the resolution of the marine products (e.g., TWL forecasts) is lower than that preferred by end-users (Alves et al. 2022). This is mainly due to the resolution of the EO products used (e.g., of the nearshore bathymetric information). In the future, some of the resolution/accuracy issues could be addressed by either the re-use and re-analysis of information from already launched EO missions, or new data of higher accuracy/spatial resolution which will become available from planned missions.

The growing importance of the EOs in the assessment and management of the coastal flood risk is manifested in various policy imperatives and legal requirements. A common thread of the pertinent policy instruments is the promotion/facilitation of the development of appropriate data and tools, such as high-quality and timely geo-spatial information; most of this information is now provided by EO technologies. In Europe, the 2021 EU CCA Strategy notes that better coherence in practices, standards, guidance, targets, resources and knowledge is needed, which should be achieved through closer coordination at national, EU and international levels. In addition, translation of the massive data sets available into customised, user-friendly information/tools is required, which should be available from the EU Scientific Lighthouses. The EU CCA Strategy also promotes use of artificial intelligence and high-performance computing in the analysis of EOs. Similarly, the EU Action Plan on the SFDRR highlights the role of EOs in supporting disaster (coastal flood) preparedness and response through satellite mapping and early warning and monitoring services. It appears that EOs not only are they referred to in many policy instruments, but they now form inherent components of most DRR phases and activities, such as rapid mapping (RM). For example, the EU CEMS on-demand service for (other) disaster risks[12] offers RM services based on satellite information on on-going events upon request by authorised users. If such services could be provided also for coastal flood events that could be a much needed policy development,

The effective implementation of EU legislation relevant to the coastal flood risk also depends on the availability and accessibility of quality EOs, as is the case for the construction of the FHRMs and FRMPs prescribed by the Flood Directive. In this context, the INSPIRE Directive which promotes access and re-use of geo-spatial data and information across all levels of governance and borders through pertinent SDIs is also of high significance. Integration of the INSPIRE SDIs in a broader framework of EU initiatives is, however, required, as well as higher coherence in data licencing and coordination with the EU Space Programme (Regulation (EU) 2021/696) and the Open Data Directive 2019/1024/EU that aims towards full exploitation of the public sector information (Kotsev et al. 2020).

It appears that EOs could address many information gaps, as they have a global coverage and can provide much of the spatio-temporal information required for the historical analysis and mapping of the coastal floods. However, the translation of EO data into global information layers in a consistent and systematic way and their effective utilisation/uptake presents technical, methodological and policy challenges which should be addressed. First, the EOs' massive and increasing data sets ('big Earth data') test the (increasingly) web-based workflows used by analysts and end-users (Sudmanns et al. 2020). Secondly, there have been differences between the objectives of the EO information community who promotes integrated applications and those of the stakeholders/users who require standardised products and services and actionable risk information in accessible, credible, and useful formats (e.g., Lorenzo-Alonso et al. 2019). Thirdly, there are infrastructure and capacity deficiencies (particularly in a global context), little and patchy 'ground truthing,' problems with product accuracy and accessibility, increased costs and institutional acceptance issues (e.g., Politi et al. 2019). Finally, the evolving technological ecosystem, particularly with regard to the increasing role of private-owned sensors, EO platforms and proprietary algorithms, challenges the traditional role of the public sector as the main producer/owner of EO-based geo-information.

Future satellite missions also present challenges. The development of small satellite technology/systems, designed, manufactured, and launched at much lower costs, has resulted in an 'explosion' of small satellite deployment by private operators. The greatly increasing deployment and traffic present new problems related to: frequency allocations and interference, satellite removal/de-orbiting at end of life, space situational awareness and space traffic control, and other concerns related to the safety of space systems in Earth orbit (Freeland 2020). These issues could only be addressed by new 'fit-for-purpose' international policies and legislation, as those instruments in place (e.g., the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, UN (1966)) cannot deal effectively with the radically changed EO ecosystem. At the EU level, the Space Programme Regulation (EU) 2021/696 has recognised these problems and prescribes enhancement of '*… the safety, security and sustainability of all outer space activities pertaining to space objects and debris proliferation…*' (Art. 4.1e).

Generally, this work has shown that EOs have become an indispensable technology for the assessment and management of the coastal flood risk. Their role is expected to increase further in the future when EO information of higher resolution and accuracy becomes available. In Europe, in particular, these developments are promoted and facilitated by an array of international and supranational (EU), interacting policy and legislation instruments. Additional initiatives and technological progress in EO functionalities and the information technology are, however, needed together with more targeted policy and legislation frameworks to provide the information

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[12] https://emergency.copernicus.eu/mapping/ems/rapid-mapping-portfolio

required for the effective reduction/management of the coastal flood risk.

Abbreviations

ALB	Airborne Lidar Bathymetry
ASI	Agenzia Spaziale Italiana
C3S	Climate Change Service
CCA	Climate Change Adaptation Strategy
CEMS	Copernicus Emergency Management Service
CMEMS	Copernicus Marine Environment Monitoring Service
CHIME	Copernicus Hyperspectral Imaging Mission
DEM	Digital Elevation Model
DRR	Disaster Risk Reduction
EO	Earth Observation
EOs	Earth Observations
ERCC	Emergency Response Coordination Centre
ESM	European Settlement Map
EWS	Early Warning Systems
FAIR	Findability, Accessibility, Interoperability, Reusability
FD	Flood Directive
FHRMs	Flood Hazard and Risk Maps
FRMPs	Flood Risk Management Plans
GRA	Grasslands
HS	High Resolution Spotlight
IBU	Impervious Built Up
ICZM	Integrated Coastal Zone Management
IMD	Imperviousness Density
INSPIRE	Infrastructure for Spatial Information in the European Community
IRs	Implementing Rules
IST	Ice Surface Temperature
LU/LC	Land Use/Land Cover
MAVs	Manned Airborne Vehicles
MS	Multispectral
MWIR	Multispectral mid-wave infrared
NDWI	Normalized Difference Water Index
NIR	Near Infrared
PAN	Panchromatic
RM	Rapid Mapping
SAR	Synthetic Aperture Radar
SBG	Surface Biology and Geology
SC	ScanSAR
SDB	Satellite Derived Bathymetry
SDIs	Spatial Data Infrastructures
SDSs	Satellite Derived Shorelines
SFDRR	Sendai Framework for Disaster Risk Reduction
SIT	Sea Ice Thickness
SL	SpotLight
SoOp	Signals of Opportunity
SSA	Sea Surface Anomaly
SSH	Sea Surface Height
SST	Sea Surface Temperature
ST	Staring Spotlight
SWH	Significant Wave Height
SWIR	Shortwave Infrared
TCD	Tree Cover Density
TEN-T	Trans – European Transport Network
IR	Thermal Infrared
TWL	Total Water Level
UAVs	Unmanned Airborne Vehicle
UNFCCC	United Nations Framework Convention on Climate Change
UCPM	Union Civil Protection Mechanism
VHR	Very High Resolution
VIS	Visible
VSWIR	Visible to shortwave infrared
WS	Wide ScanSAR

Authors' contributions

Article conception and design were conducted by A.F. Velegrakis, D. Chatzistratis, T. Chalazas and C. Armaroli. Review on existing and future satellite sensors were conducted by T. Chalazas, D. Chatzistratis, E. Schiavon, D. Grigoriadis and E. Ieronymidi. Review on alternative EO techniques was performed by D. Chatzistratis and T. Chalazas. Review on legislation and policies was conducted by A.F. Velegrakis, T. Hasiotis, C. Armaroli and B. Alves. The first draft of the manuscript was written by A.F. Velegrakis, D. Chatzistratis and T. Chalazas and all authors commented on previous versions of the manuscript. All authors read and approved the final version of the manuscript.

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Availability of data and materials

The data sets generated or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare that they have no conflict of interest.

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