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Earth Observation in Support of EU Policies for Urban Climate Adaptation

A Deep Dive Assessment of the Knowledge Centre on Earth Observation

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Abstract

Urban areas as major population centres are inherently exposed to high and compound climate risks, impacting across a socioeconomic, ecological, financial, and political nexus. The EU policy landscape recognises the critical importance of urban climate adaptation, as encompassed by the European Green Deal, EU Climate Adaptation Strategy, and European Climate Law. A key aspect of achieving the policy objectives is using knowledge and intelligence derived from Earth Observation (EO) to enable smarter, faster, and more systemic adaptation.

This report presents the findings of the second deep dive assessment of the Knowledge Centre on Earth Observation (KCEO), focusing on how EO products and services can support EU policies on urban climate adaptation. Components of the assessment include the needs of policy and Horizon Europe Missions; a consolidated set of EO-relevant urban climate adaptation indicators; and a series of use cases spanning urban heat islands, urban greening, water management, urban coastal risks and adaptation, and urban development in Africa co-developed with several European Commission Directorates-General. A common set of adaptation measures is represented by the Key Type Measures approved by European Environment Agency.

Whilst EO provides valuable information for urban adaptation needs, uptake and impact could be significantly improved through higher value intelligence offerings, tailored for decision-making. Relevant recommendations include the development of policy-focused risk and outcome indicators, a greater range of combined risk and change detection services, and city-based adaptation scenario capabilities; enabling user networks of adaptation intelligence communities; and integrating higher spatial resolution products.

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- And the constructive feedback received from EU Member States both in the context of the workshop as well as through the Copernicus User Forum.

Finally, the uptake of Copernicus in EU policy is enabled by the Core Services through their Entrusted Entities. They have provided invaluable input throughout the whole process, including the Copernicus Climate Change Service (Carlo Buontempo, Cristina Ananasso, and Samuel Almond), the Copernicus Land Monitoring Service (Usue Donezar Hoyos, Andrus Meiner, and Ana Maria Ribeiro de Sousa), the Copernicus Marine Environment Monitoring Service (Muriel Lux), and the Copernicus Emergency Management Service (Thomas Kemper and Peter Salamon).

Executive summary

The European Commission's Knowledge Centre on Earth Observation (KCEO) seeks to enhance the use of Copernicus products and services to support EU policies across various sectors. Its main goal is to translate policy needs into specific requirements for products and services while facilitating exchanges among Entities involved in Copernicus. Among the strategies used by KCEO to increase the integration of EO into EU policies is the deep dive assessments, which focus on the needs and applications of EO in specific policy domains.

This report is the result of a deep dive assessment conducted by KCEO on urban climate adaptation, examining how EO products and services can assist in urban climate adaptation policies. The deep dive evaluates the requirements of EU policies regarding urban climate adaptation, determines how well existing EO products and services address these needs, identifies gaps, and suggests directions for future developments of Copernicus products and services.

Policy context

The report addresses the policy- and decision-making needs of the 2021 EU Adaptation Strategy, European Green Deal, European Climate Law, the National Adaptation Plans of Member States, and local actions under e.g., the Covenant of Mayors Framework. It is a collaboration with relevant Directorates-General (DGs) of the European Commission and Copernicus Entrusted Entities, particularly the European Environment Agency (EEA).

Addressing climate adaptation in urban environments is a critical challenge, with high stakes and an immediate need for actions informed by optimised, dynamic intelligence. The EEA estimates an adaptation investment of ± €100 B per annum for a 2 °C global temperature rise ([1]). EO, and thus the Copernicus programme, can strongly support the policies across multiple commitments and rapidly and substantially improve the knowledge base needed to optimise the ongoing adaptation investment.

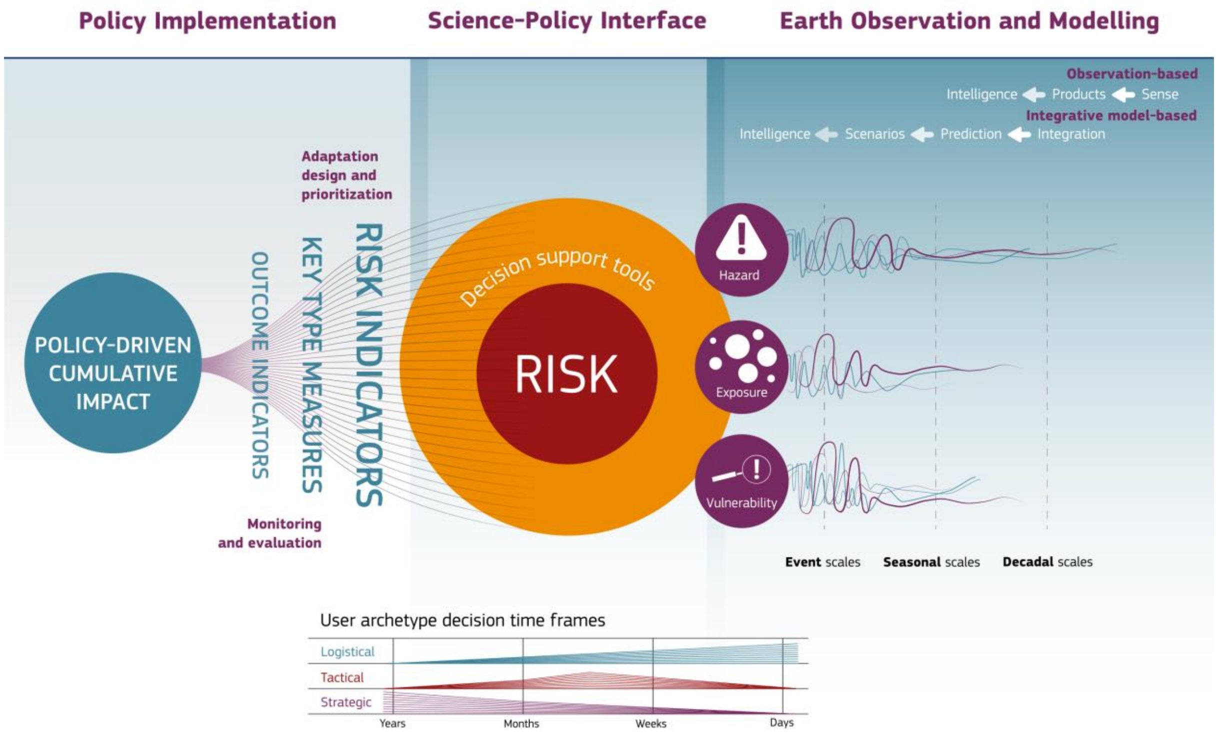
Key conclusions and main findings

Earth Observation already plays an important role in informing urban adaptation, but it is significantly under-exploited due to an underdeveloped value chain and could be used to much greater effect in the design, monitoring, and evaluation of European and global adaptation actions. Substantial ongoing European adaptation investments would greatly benefit from the improved availability of EO-derived, standardised, actionable intelligence tools and policy-facing compound indicators that address national and municipal scales, complemented by actions to improve community uptake and user-based intelligence optimisation.

A key innovation presented here is the Earth Observation Value Chain shown below, illustrating how intelligence can be derived and synthesised using a hazard-vulnerability-exposure nexus to address a variety of user needs, culminating in cumulative policy impact. The Value Chain shows the importance of moving beyond the current emphasis on climate hazard information, foregrounding vulnerability and exposure metrics as key dynamic continuum parameters and providing intelligence focusing on derived combined risk or more highly synthesised compound indicators addressing outcomes and adaptation impact.

([1]) https://www.eea.europa.eu/publications/assesing-the-costs-and-benefits-of

Earth Observation Value Chain



From the perspective of the Earth Observation Value Chain, recommendations relevant from policy to EO and modelling include:

1. Enabling policy-focused use of standardised, quantitative EO-derived adaptation indicators for legislative uptake in Member States and the European Commission

   It is recommended that the European Commission, together with the Copernicus Entrusted Entities, build on the current Core Services to derive highly synthesised EO-derived compound indicators.

2. Developing & supporting an adaptation intelligence community

   It is recommended that the relevant Commission DGs take action to enable the best EO-derived Intelligence through the Mission processes

3. Development of highly synthesised intelligence services providing actionable information to key user archetypes

   It is recommended that the European Commission supports the necessary research and innovation activities needed to increase the effectiveness of climate-focused decision support systems.

4. Establishment of a Thematic Hub for Urban Climate Adaptation

   It is recommended that the European Commission and Entrusted Entities include a Thematic Hub on urban issues on the roadmap for future consideration.

5. Facilitate and implement capabilities for city-based adaptation scenario modelling

   It is recommended that the relevant Commission DGs (DEFIS, CNECT) consider how the combined contributions from Copernicus and Destination Earth programmes can help to support this effort.

6. Provision of automated change detection products and services to identify combined risk changes

   It is recommended that the Commission and Entrusted Entities consider a systematic and consistent approach to change detection across Copernicus Services and further develop existing relevant change detection products in the Copernicus services.

7. Facilitate the use of Destination Earth to develop more actionable intelligence and cater for policy-relevant audiences with “last-mile” applications

8. Provision of dynamic hazard-specific combined risk products and services across a range of time scales

   It is important to highlight the importance of providing vulnerability and exposure metrics as dynamic continuum parameters. It is recommended that the relevant Entrusted Entities consider this, e.g., more frequent, lower latency updates in vulnerability-related services across C3S, CEMS, and CLMS.

9. Optimised integration of EO-derived intelligence with Eurostat and socioeconomic data

10. Expansion of Copernicus urban-relevant services to global

11. Systematic acquisition and integration of very high-resolution optical imagery for urban area intelligence

    It is recommended that the European Commission (DG DEFIS) and the European Space Agency take this into consideration in future planning for the Copernicus Contributing Missions programme element and that the Commission and Member States consider this for future space segment evolution planning.

The new Value Chain presented above represents considerable innovation, and the implementation of relevant recommendations will reduce the risk of sub-optimal adaptation planning and monitoring, improving the effectiveness of the substantial European adaptation investment. There are still significant knowledge gaps and uncertainties around changing risk magnitudes and adaptation needs in a world rapidly approaching 2 °C of global heating, but the dynamic intelligence structures recommended here represent an effective means of dealing with these and should substantially improve the levels of uncertainty around climate impact.

Related and future JRC work

The Deep Dive Assessment on Urban Climate Adaptation is the second of a series of thematic assessments that started in 2022 with the Biodiversity Deep Dive. A third deep dive assessment is ongoing and focused on compliance assurance, as outlined in a roadmap established with the KCEO's Steering Group. The outcomes of this work will guide the last-mile policy applications developed in KCEO.

Quick guide

The Urban Climate Adaptation Deep Dive report is organized as follows:

- Chapter 1 sets the stage for the report by presenting the main concepts of the deep dive assessments.
- Chapter 2 provides the main definitions related to urban climate adaptation and explains the role of EO.
- Chapter 3 outlines the EU and international policy context on urban climate adaptation.
- Chapter 4 discusses the relevance of EO intelligence to Horizon Europe Missions in the context of urban climate adaptation.

- Chapter 5 presents the methodological approach used for consolidating policy-relevant urban climate adaptation indicators ([2]).
- Chapter 6 explores use cases related to different DGs and thematic domains. For each use case the following topics are discussed: policy context; description of the use case; application needs; technical assessment; value chain analysis; fitness for purpose of existing EO products and services; gap analysis; monitoring risk, adaptation and outcome; and recommendations.
- Chapter 7 presents key conclusions and recommendations.

([2]) Access to the full dataset is available through https://data.jrc.ec.europa.eu/dataset/41fdfea8-0199-4fc9-83e0-1f960aead367.

1 Introduction

The European Commission Knowledge Centre on Earth Observation (KCEO) provides a central coordination mechanism inside the Commission to maximise the uptake of products and information from Copernicus to support EU Policies ([3]) in various sectors and to establish best practices in efforts to translate policy needs into concrete requirements for products and services. It also aims to provide a forum for dialogue with the technical implementing entities associated with Copernicus to enhance the exploitation on Copernicus throughout the policy cycle.

The 2016 Space Strategy for Europe ([4]) further reinforced by the Space Programme Regulation ([5]) mandates the Commissions Copernicus Programme to encourage the uptake of Earth Observation (EO) methods for EU policy. Specifically, "The Commission will encourage the use of space services, data and applications in EU policies whenever they provide effective solutions [...] the Commission will promote the uptake of Copernicus EGNOS and Galileo solutions in EU policies, where justified and beneficial".

The KCEO, created in 2021 and co-chaired by the Joint Research Centre (JRC) and Directorate-General for Defence Industry and Space (DG DEFIS), responds to the necessity of a dedicated mechanism to support the uptake of EO in support of EU policy, using the Copernicus Programme to its full potential.

Within the broader Copernicus uptake framework, a number of key actors are involved:

- Member States (MS): Copernicus User Forum (in Space Programme Regulation), MS needs (Core Users)
- Copernicus Entrusted Entities/Services: addressing uptake in their own thematic areas of expertise and through the National Collaboration Programmes.
- European Union Agency for the Space Programme (EUSPA) and the Cassini Space Entrepreneurship Initiative: Uptake by Other Users (private sector)
- KCEO focus on EU Policy uptake: Core Users inside the Commission, namely the policy DGs

The KCEO makes use of a number of tools to address policy uptake at the EU level. Among these are the Deep Dive assessments on the specific needs and use of EO in specific policy areas. The main objective of Deep Dives in the KCEO is to analyse EU policy needs in a defined policy area; to verify how and to what extent existing EO products and services meet these needs; to highlight existing gaps; and to provide recommendations on future evolution of Copernicus products and services to address these needs. To structure the deep dive assessments, EU policies were grouped according to thematic domains, also broadly keeping in mind the type of EO support the different policies may entail. The result is a list of 28 policy areas ([6]). Deep Dives, each addressing a specific policy area, shall follow a common methodological protocol (see below) and imply interactions mainly with relevant policy DGs; with pools of external experts; with Copernicus technical implementing entities and partners. This selection of broad topics, involving the numerous relevant policy DGs, also foster the use of EO and Copernicus in addressing issues of policy coherence. The policy areas are selected and prioritised according to a roadmap agreed with the Steering Group of KCEO. The KCEO also ensures that the policy uptake of products and information from Copernicus

([3]) https://knowledge4policy.ec.europa.eu/earthobservation_en

([4]) COM(2016) 705 final

([5]) Regulation (EU) 2021/696

([6]) https://knowledge4policy.ec.europa.eu/earth-observation/eu%C2%A0policy-areas_en takes advantage of the latest state-of-the-art research and innovation. It uses these emerging policy needs as a basis for establishing a longer-term Strategic Research and Innovation Agenda for Earth Observation (Rixen et al., 2024).

The KCEO's second Deep Dive exercise selected by the policy DGs is on Urban Climate Adaptation, aiming to enhance EO policy uptake related to climate change adaptation in urban areas. Urban Climate Adaptation is an area of particular importance in the current EU and international policy landscape. Climate change has affected built-up areas, as much as – if not more – than other land cover types. Higher temperatures observed in urban areas in comparison to rural areas, the so-called urban heat island (UHI) effect; more frequent and severe heat waves; disruption of coastal ecosystems; sea level rise; exacerbated rainfall flooding, droughts, storms, and wildfires; and increased vector-borne diseases lead to economic losses; decreased public health, quality of life, and the provision of essential services such as transport, water supply, housing, health care, and social services in urban areas. With more than a quarter of the EU territory directly affected by urban land use, and the rising number of people expected to live in cities and suburbs, the management of urban areas is now a key component of sustainable EU climate adaptation policy.

DEEP DIVE METHODOLOGY ([7])

The primary objective of the KCEO Deep Dive is to identify and analyse policy needs in a specific policy area that EO products currently support or have the potential to support but are underutilized, highlighting existing gaps and providing recommendations. As a preliminary step, the Deep Dive identifies relevant policy DGs and key actors to be involved in the Deep Dive process and the following steps are then carried out.

1. Analysis of the policy context and needs

An analysis of policy context and needs is conducted through workshops, questionnaires, and interviews with the selected policy DGs for the specific topic of the Deep Dive. This first step is key for understanding the maturity and preparedness of EU policymakers in using EO data. The use cases defined through the assessment of the policy needs, later expounded on through expert knowledge, constitute the key component of the Deep Dive methodology, investigating specific policy domains and legislative elements to understand the current utilisation of EO data, products, and services.

2. Application needs

The application needs (ANs) are the outcomes of the needs identified from the consultation with the DGs. The ANs consist of qualitative characteristics that an application should have for satisfying the policy needs described in the previous step. They consist of indicators, tools/ interfaces (e.g., report, dashboard, chart, map, web portal), that are needed by the policy without considering the technical constraints and existing products and services.

3. Translation of needs into technical requirements

The user needs identified through use cases are then translated into technical requirements for EO products and services. The parameters of the technical requirements include geographical area of interest, spatial resolution, time of year, temporal frequency, latency, continuity of time series, uncertainty, accuracy, thematic detail/granularity, and semantic needs, i.e. how users gain understanding

4. Earth Observation value chain

This step consists in conducting a value chain assessment for the selected use cases in order to illustrate the key dependencies of user needs and their translation them into quantitative information requirements. Moreover, the value and traceability of specific EO data in the use cases is determined, and existing practices reviewed for the four key steps (Decide-Apply-Data Production-Sense) of the EO value chain.

5. Fitness for purpose

This step consists in reviewing existing EO products, services, infrastructure, and capacities to ensure they meet expressed needs and technical requirements. This included considering products beyond Copernicus from other space agencies/providers. The assessment focuses mainly on technical specifications such as spatial, temporal, thematic and semantic features. Uncertainty, accuracy, and overall quality ratings require extensive analysis beyond the Deep Dive's scope. Overlaps, complementarities, and synergies with existing products must be considered. This represents a first-order fitness-for-purpose assessment and subsequent in-depth analyses addressing data quality and uncertainty may be required.

6. Gap analysis and recommendations

This last step consists in summarizing current gaps and shortfalls in observation and value chain capacities and formulating recommendations. Priority requirements are highlighted and improvements are suggested for ground and space segments, services, infrastructure, and R&I investment.

([7]) For more details see Camia et al. (2023).

2 Urban climate change adaptation and Earth Observation

2.1 Definition of urban climate adaptation

Urban centres possess the capacity to serve as pivotal drivers of change in the execution of recent global agreements such as the UNFCCC 2015 Paris Agreement ([8]), the 2030 Sustainable Development Agenda ([9]), the New Urban Agenda ([10]), and the Sendai Framework for Disaster Risk Reduction ([11]). Initiatives undertaken at the municipal level to tackle climate change through adaptation play a crucial role in supporting national endeavours to meet international commitments. This significance is particularly pronounced against the backdrop of rapid urban population growth, with projections indicating that 70% of the world's population will be residing in cities by 2050 (UN-Habitat, 2022). As the climate and environment undergo transformations, cities must adapt to ensure their continued liveability, functionality, and prosperity. Urban adaptation entails the process of adjusting to current or anticipated climatic conditions and related hazards in urban settings, with the overarching goal of mitigating adverse impacts and capitalizing on favourable opportunities ([12]).

Urban climate adaptation from an EO perspective involves leveraging satellite, airborne, and in-situ data and relevant technologies to monitor, analyse, and respond to climate-related challenges in urban environments, ultimately contributing to the development of resilient and sustainable cities. Copernicus links space observations to airborne, marine, ground-based, and underground data collection and processing, providing operational services in the fields of environment, ground infrastructures, civil protection, and security, supporting the implementation of a large number of sectorial and transversal public policies. Six thematic Core Service areas are identified within the Copernicus programme for EO, namely land (Copernicus Land Monitoring Service - CLMS), sea (Copernicus Marine Environment Monitoring Service - CMEMS), atmosphere (Copernicus Atmosphere Monitoring Service - CAMS), climate change (Copernicus Climate Change Service - C3S), emergency management (Copernicus Emergency Management Service - CEMS), and security (Copernicus Security Service - CSS). Urban systems are analysed primarily as a part of the land monitoring service thematic area, but require fundamental contributions from all other services i.e. climate change, marine, atmosphere, emergency and security, this is particularly true in the context of urban climate adaptation.

This assessment focuses on the policy-driven requirements and potential capabilities to address urban climate adaptation from an EO perspective, as detailed in the summary boxes below.

([8]) Paris Agreement (OJ L 282, 19.10.2016, p. 4–18)

([9]) Transforming Our World: The 2030 Agenda for Sustainable Development

([10]) https://habitat3.org/wp-content/uploads/NUA-English.pdf

([11]) Sendai Framework for Disaster Risk Reduction 2015-2030

([12]) Climate ADAPT: Sharing knowledge for a climate resilient Europe

Cross-cutting aspects

Monitoring and assessment: In planning for future urban expansion, there is a need to document and quantify the impacts of climate change on urban areas and to map the full range of co-benefits of adaptation. EO can provide valuable intelligence for monitoring both climate-related risks, and the ongoing implementation and impact of adaptation measures. This intelligence can play an important role in assessing urban hazards, vulnerability and exposure associated with parameters such as increasing temperature and precipitation, sea level rise, and land use changes.

Integration of observations, data, modelling and scenarios: To fully understand how cities are impacted by climate change, and the potential effectiveness of adaptation measures, it is important to have observations, models and scenarios at relevant spatial and temporal scales. EO data can be integrated into climate models and simulations to predict future climate scenarios and their potential impact on urban areas. Providing information that is spatially and temporally relevant to the EU and city-level actors requires the development of observation frameworks, advances in climate modelling and evaluation, and the development of scenarios at the city scale (Cleugh & Grimmond, 2012).

Decision support systems developments: EO-derived intelligence is used to develop decision support systems that provide real-time information to urban planners, policymakers, and emergency responders, facilitating informed decision-making in response to climate-related challenges (Chrysoulakis et al., 2023).

Stakeholder engagement: EO-derived intelligence can be used to raise awareness among stakeholders about climate change impacts and adaptation issues. Visualisation of appropriately synthesised EO - derived intelligence can help communicate complex environmental changes in an accessible way.

Topic-specific aspects

Urban Heat Island (UHI) analysis: EO helps in assessing the highly detrimental effects of UHI – a phenomenon where urban surfaces and the structure of the built environment result in air temperatures significantly higher than their immediate rural surroundings. Understanding UHI patterns aids in designing strategies to mitigate heat-related impacts.

Urban and land use planning: Urban planning is crucial for addressing change adaptation in cities, bringing together different sectors. It is increasingly important for both researchers and decision-makers to understand how urban micro-climates integrate into urban planning and design to simultaneously improve urban environmental outcomes, reduce risk and address the need to adapt to climate change. EO-derived intelligence aids in understanding changes in land use and land cover, supporting urban planners in developing climate-resilient land use strategies. Current and future patterns of urban growth will determine emissions, vulnerabilities, and adaptation options for the future. It is increasingly important to explore the role of urban and spatial planning in reducing vulnerability and enhancing adaptation to climate change for both formal and informal settlements.

Vegetation and green spaces monitoring and planning: Monitoring green spaces and vegetation through EO helps in evaluating the urban ecosystem's resilience and supports the planning of green infrastructure to combat climate change effects.

Extreme events detection: The complexities of climate change pose multifaceted threats to human health, encompassing both direct impacts and those mediated by natural and human systems. In urban environments, these risks are frequently heightened due to factors such as dense populations, inherent vulnerability, interconnected systems, and the heightened potential for flooding and inundation in coastal and low-lying regions. EO-derived intelligence can be used to detect and monitor extreme weather events like floods, heatwaves, and storms. This information is crucial for developing early warning systems and emergency response plans.

Sea level rise and coastal changes monitoring: Impacts of sea level rise and other effects are distributed unequally across cities' populations, often concentrated in regions with existing social vulnerability. For coastal cities, EO-derived intelligence is essential for monitoring sea level rise, shoreline changes, and coastal erosion. This information assists in planning and implementing strategies to protect coastal urban areas (Friess & Grémaud-Colombier, 2021). Further intelligence-driven support is needed to address the dynamics of adaptation alternatives for coastal urban settings.

Infrastructure resilience assessment: Essential urban services, including shelter, mobility, thermal comfort, communication, illumination, sanitation, and protection, rely heavily on infrastructure. Addressing the infrastructure gap is a vital element in delivering these crucial urban services, mitigating vulnerability, and facilitating adaptation to climate change within the framework of sustainable development. EO technologies contribute to assessing the vulnerability of critical urban infrastructure such as transportation, energy, and water supply systems to climate-related risks. It will also be necessary to understand how blue/green infrastructure itself is vulnerable to future climate change, including the increase in temperatures, changes in precipitation patterns and more frequent and intense weather events such as storms and hurricanes, and how to enhance resilience and reduce maintenance costs of the blue/green infrastructure solutions. Research on how adaptation approaches could support decision-making in terms of future infrastructure priorities is crucial to address climate change in urban settings.

2.2 Monitoring and evaluating urban climate change adaptation

While methodologies are well-defined for the monitoring of mitigation, they remain less qualified and fragmented for adaptation. Development of methodologies for monitoring and evaluation (M&E) of adaptation across time and geographic scales, i.e., scalable intelligence, has been hampered by its intrinsic complexity, its context- and location-specific nature and the absence of comprehensive and reliable datasets (Michetti et al., 2021). There is no formal standardised set of indicators, covering both the risk and adaptation ([13]) aspects, that has been adopted at the EU nor the international level, even though multiple attempts have been made focusing on various aspects (Eklund et al., 2023; GIZ & EURAC, 2017; Rouleau et al., 2022). There is however a de facto standardised framework of adaptation measures in the form of the European Environment Agency's Key Type Measures (KTMs) (Leitner et al., 2021). Standardised indicator and KTM frameworks are critical structures to provide a basis from which EO product and service providers (such as Copernicus) could direct efforts in producing fit-for-purpose intelligence.

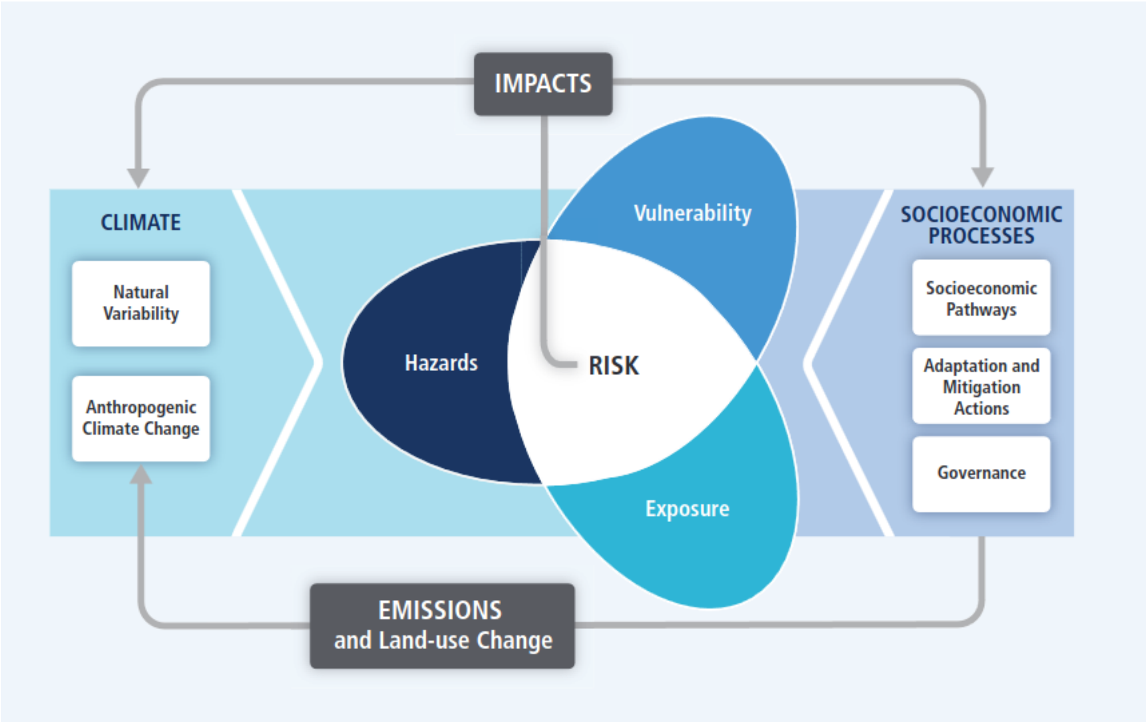
Currently, urban climate change adaptation action plans are mostly implemented at a local scale through various networks such as the Global and European Covenant of Mayors (GCoM and CoM), C40 Cities, Resilient Cities Network (RCN) and Local Governments for Sustainability (ICLEI). However, a shared set of indicators and an accompanying methodology for determining the M&E of risk components and the outcome of adaptation actions have not been defined across the urban areas that are in such networks.

The knowledge platform of the EU Strategy on Adaptation to Climate Change, Climate-ADAPT, considers the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6) as the foundation of its knowledge base. However, the risk concept defined as a function of hazard, exposure and vulnerability in the IPCC's Fifth Assessment Report (AR5) is considered sufficient in this assessment (Figure 1), even though it slightly diverges from the one defined in AR6. The risk of climate-related impacts results from the interaction of climate-related hazards with the vulnerability and exposure of human and natural systems. Changes in both the climate system and socioeconomic processes, including adaptation and mitigation, are drivers of hazards, exposure, and

([13]) Adaptation indicators are called outcome indicators in this assessment.

vulnerability (IPCC, 2014). Adaptation planning in human systems (as opposed to natural systems) generally entails a process of iterative risk management (IPCC, 2022), typically by reducing vulnerability and in certain cases also exposure (GIZ & EURAC, 2017).

Figure 1. Illustration of the core concepts surrounding risk in IPCC AR5.



Source: IPCC WGII AR5, 2014.

2.3 The role of Earth Observation

Earth Observation (EO) in this assessment refers to a science domain dealing with technologies and methods of collecting, analysing and realising value from observations and models about the different spheres (geosphere, atmosphere, hydrosphere, cryosphere, biosphere, anthroposphere) of the Earth. The collection of the observations may be through remote sensing technologies that include satellites (as the dominant systematic source) and aircraft (including drones) or in-situ devices. This collection may be performed through spaceborne, airborne, marine, ground-based or underground sensors. The massive amounts of data generated via various means, including EO, can inform climate change adaptation research and decision-making. The data that can be used alongside EO data may be generated via cell phones and social media. In addition, useful data may be produced through citizen science initiatives or crowdsourcing, which depending on the use of sensors can be categorized as EO. These data together may be referred to as “big data” (Ford et al., 2016) relevant in this assessment, which in the literature is defined in various ways, yet characterized by high levels of volume, velocity and variety (Sagiroglu & Sinanc, 2013). However, to which extent EO data in combination with these other data can be used to effectively track long-term policy objectives in the context of adaptation is understudied (Michetti et al., 2021). In addition, the adaptation community often prefers small-scale studies for developing in-depth and context-specific insights on adaptation, typically through mediums such as co-design workshops, interviews and ground-based surveys. The data collected in this manner may be called “small data”. “Big data” can enable identifying trends and certain locations for conducting more qualitative studies relying on “small data” to understand adaptation choices and responses, effectively bringing together the two approaches (Ford et al., 2016).

The use of EO in the urban climate adaptation domain has been demonstrated in various studies (Cresswell et al., 2023; De Ridder et al., 2015; Demuzere et al., 2022; Gidhagen et al., 2020; Giuliani et al., 2021; Kuffer et al., 2023; Pappalardo et al., 2023; Tzortzi et al., 2023; Vavassori et al., 2022) and many efforts in recent EU research Framework Programmes (Horizon 2020 & Horizon Europe) have been made, such as in the projects Copernicus for Urban Resilience in Europe (CURE) ([14]), HARMONIA ([15]), and REACHOUT ([16]), yet the methodologies developed have not been mapped to a set of encompassing indicators and the gaps have not been identified.

EO is crucial for comprehending environmental systems and evaluating feedback loops and impacts. Satellite data have the potential to close the massive gaps that exist in aerial and ground-based datasets, especially in data-scarce regions (Kansakar & Hossain, 2016), and provide long time series for the entire Earth (Yang et al., 2016). Even though satellite data provide such significant contributions, there are still notable gaps in integrating in-situ observations from different domains and the urban context is currently not optimally addressed. There is a pressing need to enhance the capacity to assess cross-domain impacts, create and validate intricate models and develop forecasting applications (Balsamo et al., 2018).

Adaptation pathways provide a dynamic, highly intelligence-informed and policy-driven process to implement climate adaptation. EO data, in combination with predictive and scenario modelling, can play a valuable role in building and optimising adaptation pathways (Hamlington et al., 2023). Intelligence derived from EO can provide consistently derived indicators, routinely available across wide ranges of time and space, scalable from a building scale to a national scale. In combination with a necessary range of socioeconomic data, such information is critical to identifying technical and social signpost indicators and assessing adaptation tipping points (Barnett et al., 2014; Ramm et al., 2018) (Figure 2).

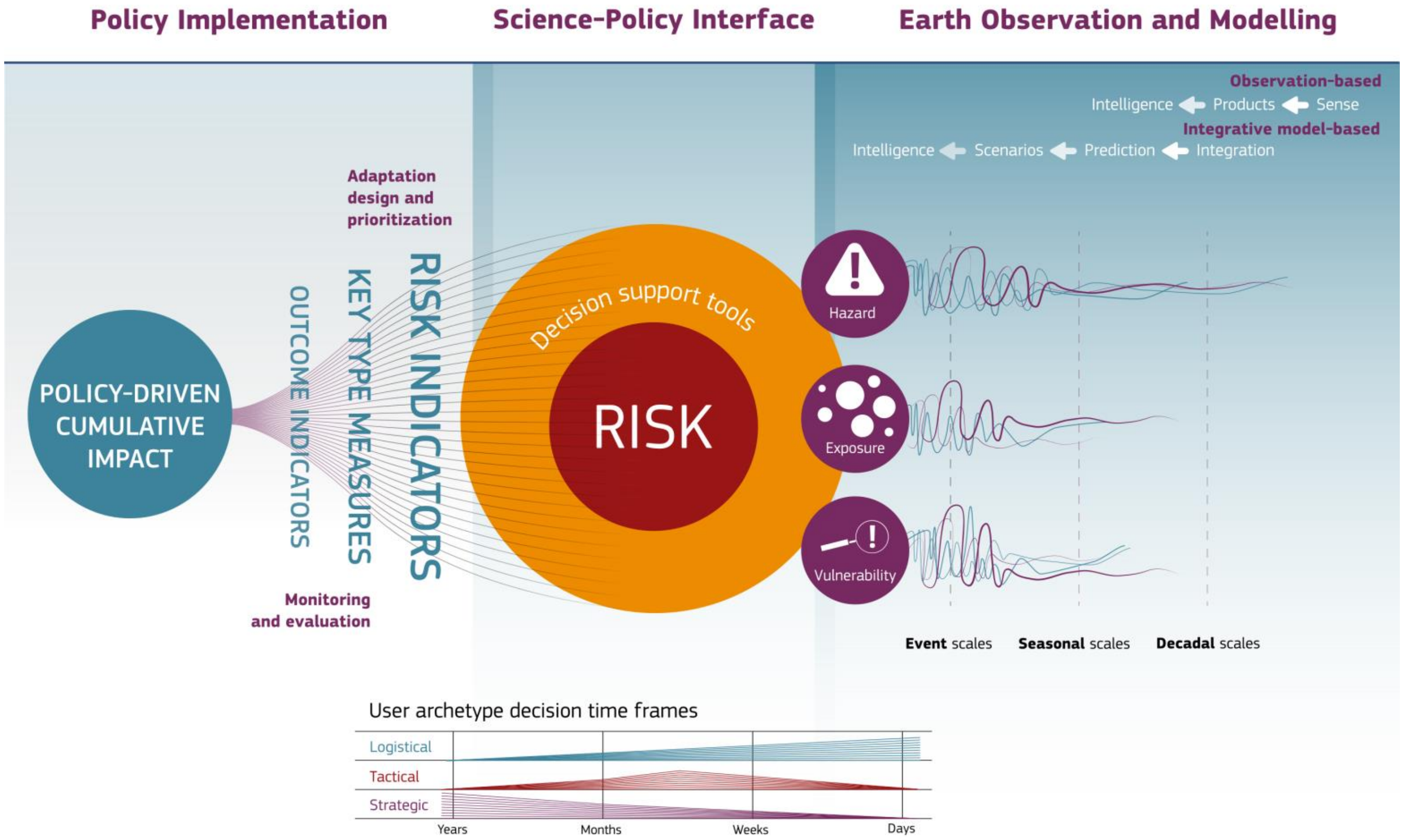
Examining the current effectiveness of the use of EO and other data and information to enable urban climate adaptation applications, the primary constraint with regard to their use in the policy cycle is the inability of administrators and other users to understand or process EO data. From a value chain perspective, this is reflected as a lack of sufficiently synthesised EO-derived intelligence, actionable to policy-relevant user archetypes. To ensure more effective use of EO in policy-making, the EC, needs a range of expert services, ideally developed through an iterative co-design process. Policy officers should be able to bring forward specific questions around their decision-making process, and EO experts should be able to offer an iterated vision of optimised, relevant and actionable EO-derived intelligence. Such a process should also offer the ability to identify the requirements for other user archetypes, e.g., across national to municipal governments of Member States. The lack of technical expertise in most administrations renders the efficient use of EO data very difficult.

([14]) https://cure-copernicus.eu/

([15]) https://harmonia-project.eu/

([16]) https://reachout-cities.eu/

Figure 2. The typical components and scales of an EO value chain focused on climate adaptation. Note the importance of providing a range of user-specific intelligence using a combined approach based on EO and modelling, across a wide range of historical, real-time, short to medium term and future scenario-based timescales.



Source: Internal European Commission Knowledge Centre on Earth Observation (EC KCEO)-Joint Research Centre (JRC).

3 EU and international policy context

3.1 EU context: 2021 Adaptation Strategy & mainstreaming of adaptation into other policies

The 2013 Adaptation Strategy marked a milestone in the EU Adaptation policy landscape. The evaluation Report of the 2013 Strategy ([17]) highlights the objective of the Strategy to “contribute to a climate resilient Europe enhancing the preparedness and capacity to respond to the impacts of climate change at local, regional, national and EU levels, developing a coherent approach and improving coordination” and stressed the role of cities in EU adaptation policy areas.

Under the European Green Deal (EGD) ([18]), the European Climate Law ([19]) has already incentivised many EU countries to implement climate adaptation measures within their national legislation. With the new 2021 Adaptation Strategy ([20]), the EU has launched an ambitious and comprehensive strategy to promote climate adaptation on all governance levels. The EU has been active in promoting and issuing plans to address urban climate adaptation, and there is now a momentum for more EO data policy uptake.

The new Strategy’s accompanying Impact Assessment Report ([21]) proposes actions, novelty actions, drivers, problems and objectives where geospatial and modelling data, obtained through the Copernicus programme and the international exchanges of best practices e.g., via the European and Global Covenant of Mayors, could significantly enhance EU action for urban adaptation. The Commission Staff Working Document focuses on closing the climate protection gap ([22]) and the 2030 Climate Target Plan highlight that Adaptation policies will benefit from the EU Space programmes such as Copernicus, whose monitoring capabilities can be used as rapid analysis tools to inform climate adaptation targets.

EO could support the 2021 Adaptation Strategy’s calls for action, promotion, and mainstreaming of climate change adaptation in several cross-sectorial EU policy files and international commitments such as the National Adaptation Plan (NAP) process and the Paris Agreement. The Kunming-Montreal biodiversity agreement, the Zero Pollution Action Plan, the Biodiversity Strategy for 2030, and the Nature Restoration Law include key targets to protect, depollute and restore nature and biodiversity in cities by mainstreaming green urban planning, increasing green urban areas, green urban infrastructures and nature-based solutions across the EU. Member States need strategic adaptation guidelines to develop and review their strategies under a standard framework in line with the 2021 Climate Adaptation Strategy.

Additionally, the use of geospatial data could contribute to strengthening cultural heritage resilience for climate change in cities, and to identify and prevent disaster risks and urban vulnerabilities. In the context of a growing population under climate change, urban farming and gardening will further enhance cities' adaptive capacities. Maritime and land-based activities are connected via complex interactions: the progressive urbanisation of the coastline exerts pressure on marine and coastal ecosystems, while coastal cities face issues such as sea level rise and salt intrusion. EO-derived

([17]) SWD(2018) 461 final
([18]) COM(2019) 640 final
([19]) REGULATION (EU) 2021/1119
([20]) COM(2021) 82 final
([21]) SWD(2021) 25 final
([22]) SWD (2021) 123 final

intelligence could further support EU urban climate adaptation policy overseas and in neighbouring countries in the context of the Global Gateway ([23]) and the Strategic Corridors.

3.2 International context

International policy frameworks for urban climate adaptation provide guidelines and strategies to help cities worldwide become more resilient to the impacts of climate change. These frameworks are established by various international treaties and agreements, each with its specific focus and scope.

The Paris Agreement emphasizes the importance of enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change. This is achieved through the Nationally Determined Contributions (NDCs) where countries must outline their climate adaptation and mitigation plans, and the Global Stocktake which regularly reviews of collective progress, including adaptation efforts.

The Sendai Framework for Disaster Risk Reduction includes specific targets and priorities that focus on reducing exposure and vulnerability in urban areas. These include Priority 2: Strengthening disaster risk governance to manage disaster risk and Priority 3: Investing in disaster risk reduction for resilience.

The New Urban Agenda integrates climate adaptation into urban planning and development policies, emphasising inclusive, safe, resilient, and sustainable cities, and encouraging participatory urban policy and planning processes.

The UN-Habitat Quality of Life Initiative is a global effort by the United Nations Human Settlements Programme (UN-Habitat) to assess, monitor, and enhance the well-being of people living in cities and human settlements. It aims to provide data-driven insights into urban quality of life and help local governments make informed decisions for sustainable, inclusive urban development.

The Global Covenant of Mayors for Climate & Energy, supports cities in setting ambitious adaptation and mitigation targets and implementing relevant policies, encourages data sharing and collaboration among cities and provides a platform for cities to report on progress and share best practices. The ICLEI (Local Governments for Sustainability) global network of more than 2500 local or regional subscribed partner governments in over 125 countries also provides an extensive platform for urban sustainability actions.

As mentioned above, the National Adaptation Plans are a fundamental part of the Paris Agreement NDC and Global Stocktake process. Data and services provided by the Copernicus programme can be extensively used by UNFCCC parties in developing their NAPs. The information from EO can enhance the quality, accuracy, and comprehensiveness of NAPs, facilitating better-informed decision-making and policy formulation. Specific areas addressed through the NAP process which EO could support, include:

- Vulnerability and Risk Assessments
- Water Resources Management
- Infrastructure and Urban Planning
- Public Health and Safety
  Engagement and Capacity Building

([23]) JOIN(2021) 30 final

In addressing these specific areas, optimum EO uptake could be enhanced by undertaking the following steps:

Data Collection and Analysis: Collect relevant EO/Copernicus data and perform geospatial analysis to derive appropriate intelligence to identify vulnerabilities, risks, and adaptive capacity across different sectors.

Stakeholder Engagement: Share intelligence derived from Copernicus with stakeholders, including government agencies, local authorities, and communities, to ensure inclusive and participatory adaptation planning.

Scenario Planning and Modelling: Use Copernicus Services for climate modelling and scenario planning to anticipate future climate impacts and develop robust adaptation strategies.

Policy Formulation: Incorporate findings from Copernicus analysis into policy recommendations, ensuring that adaptation measures are data-driven and evidence-based.

Monitoring and Reporting: Establish a monitoring framework using Copernicus to track the progress of adaptation measures and report to the UNFCCC as part of the National Communications and Adaptation Communications.

Integrating Copernicus products and services into National Adaptation Plans enhances the ability of UNFCCC parties to design effective, evidence-based adaptation strategies. The comprehensive, high-resolution data provided by Copernicus supports robust vulnerability assessments, informed policy-making, and continuous monitoring, ensuring that adaptation efforts are both effective and sustainable.

In more recent developments, the UNFCCC Global Goal on Adaptation (GGA) was established as part of the Paris Agreement. It aims to enhance adaptive capacity, strengthen resilience, and reduce vulnerability to climate change, thereby contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal of limiting global warming to well below 2°C, preferably to 1.5°C above pre-industrial levels. The GGA emphasizes:

Enhancing Adaptive Capacity: Improving the ability of communities, ecosystems, and economies to adjust to climate change impacts.

Strengthening Resilience: Building the resilience of societies to withstand climate-related shocks and stresses.

Reducing Vulnerability: Minimizing the exposure and sensitivity of people and assets to the adverse effects of climate change.

At present there is an ongoing process to define a common set of indicators for the GGA. It will be of considerable added-value to investigate how EO and Copernicus can contribute to these indicators in providing a systematic, sustainable and ongoing source of intelligence for indicator derivation.

As with many other areas of climate policy, for urban climate adaption there are strong synergies between the opportunities to use EO and Copernicus at the EU and International level in addressing policy needs. That said, specific recommendations can be formulated for the global scale efforts:

1. Copernicus Services to consider suitably packaged data, products and services to support Parties in the commitments to the various international treaties (e.g. NAP reporting)

2. The Commission to work with the European Environment Agency (EEA) to proactively assess where EO/Copernicus can provide input for the GGA Indicators, as part of the ongoing indicator definition phase.

3. The Commission and Entrusted Entities to continue cooperation through the Group on Earth Observations (GEO), Committee on Earth Observation Satellites (CEOS), and World Meteorological Organization (WMO) to establish coordinated support to Parties on EO products and services to support urban climate adaptation (e.g. as a dedicated NAP guidance, through the EW4ALL process, or in sustaining Essential Climate Variable (ECV) climate data records)
4. In building on the recommendation on the need for a Copernicus Urban Thematic Hub, the Commission and Entrusted Entities to consider that the Hub could/should also have a global dimension supportive EU climate policy outside of EU and in providing support to partner 3rd countries.
5. The Commission (DG INTPA & DG DEFIS) can consider mechanisms for support and capacity building in 3rd countries for the uptake for Copernicus products and services in their reporting, monitoring and action needs for international agreements.

4 EU Missions (Adaptation and Smart Cities)

Extending the Earth Observation Value Chain: Relevance to the Horizon Europe Missions

The Adaptation to Climate Change and Climate-Neutral and Smart Cities Missions provide a clear demonstration of both the need and potential value for greater actionable intelligence on adaptation – intelligence that Earth Observation, in combination with existing sources, can provide. The missions show that the nexus between mitigation and adaptation is important, particularly in an urban context, with climate change scenario analysis and associated potential socio-economic impacts identified as key intelligence capabilities.

It is evident that Earth Observation already plays an important role in informing urban adaptation – however the current emphasis is on climate hazard information, and exposure to a lesser degree, with little evident use of vulnerability, derived combined risk, or more highly synthesised compound indicators. In particular the indicators from this study - representing the most policy-relevant end of the Earth Observation intelligence chain - provide a currently under-exploited ability to monitor and evaluate the outcome of adaptation measures. There is clear value to the missions, and their representative longer-term objectives, in the provision of a rigorous, standardised, scalable, geospatial, independently-produced set of products and indicators for climate change-related monitoring and evaluation. Earth Observation, especially in the framework of Copernicus and European agencies, can bring an important level of operational maturity and standardization of the necessary services. There is considerable potential added value that Earth Observation could bring to the missions by enhancing and complementing existing mission tools - for example the adaptation dashboard, or the design, implementation and monitoring of climate city contracts.

4.1 Missions pertinent to the Deep Dive

The Missions were introduced in the Horizon Europe (HE) programme (2021-2027), offering a means of implementation regarding the Commission's priorities, such as the European Green Deal, Europe fit for the Digital Age and the New European Bauhaus. They have been gradually maturing over the last three years with their respective knowledge bases becoming more substantial, the involved stakeholders more numerous and the call for synergies between the Missions more pronounced. Already, the HE programme moves way from its predecessors in reflecting a more systemic perspective on climate change mitigation and adaptation and not making rigid distinctions between the two. Cluster 5 of the Work Programme, comprising the climate action part, aims at developing mitigation as well as adaptation strategies and policies tackling the global climate crisis.

By design, echoing the need for synergies, three Missions fall under this Cluster:

- Adaptation to Climate Change ([24]): ("Adaptation Mission" henceforth)
- Climate-Neutral and Smart Cities by 2030 ([25]) ("Cities Mission")
- Restore our Ocean and Waters by 2030 ([26]) ("Restore Mission")

A clear case for the interplay between the first two Missions has already been established. The nexus between mitigation and adaptation is important, particularly in an urban context, with climate

([24]) EU Mission: Adaptation to Climate Change

([25]) Climate-Neutral and Smart Cities by 2030

([26]) Restore our Ocean and Waters by 2030 change scenario analysis and potential socio-economic impacts a key consideration. Greater Mission synergy, and the availability of actionable intelligence on adaptation, has been identified by both DG CLIMA and DG RTD as key to incentivising cities to adopt adaptation measures. Prime candidates for this more integrated approach are of course the common cities between the two Missions, as evidenced by the Climate City Capital Hub initiative ([27]).

Apart from this growing need of convergence, the above Missions are also the most pertinent to this assessment as is evident from the Use Cases themselves and the following chapter on Adaptation Indicators. Below, the Missions' knowledge bases are viewed through the Earth Observation (EO) lens of this study to identify existing links but also to bring out potential EO applications that could benefit the objectives of the Missions and of their intersection. Whilst the Restore Mission is also addressed in the Use Cases, most specifically the Coastal DG MARE case, it is not considered in greater detail here.

4.2 Adaptation Mission: emerging use of Earth Observation intelligence

The Adaptation to Climate Change Mission is of course of direct relevance to this assessment. A key instrument for implementing the Adaptation Mission is the Mission Implementation Platform for Climate Adaptation - MIP4Adapt ([28]). Its website is part of Climate-ADAPT and is delivered in partnership with EEA and the European Commission. MIP4Adapt is well aware of the potential value of existing and emerging Earth Observation service implementations in supporting the Mission. This assessment is informed by these user needs which include: data on hazards, data on vulnerability (socio-economic data on people and infrastructure, geospatial accounting of climate risks), data to quantify the amount and types of adaptive measures needed (such as the discussions on Key Type Measures in Chapter 5) and, similarly to the needs of DG CLIMA, data quantifying the effectiveness of the measures.

The knowledge base of MIP4Adapt further identifies existing and practical EO applications that already serve as exemplars for the Adaptation Mission. Several Mission Stories ([29]) include some form of EO, such as a) the adaptation to extreme heat in the city of Toulouse and Zagreb where EO provided monitoring and also evaluation of adaptation options before actual implementation b) nature-based solutions in the coastal Municipality of Cascais against heat and flooding events where *in situ* measurements provide intelligence on the effectiveness of nature-based solutions in reducing flood risk c) the integration of EO data with other open source variables, such as those from the Buildings and Cadastral Parcel of the INSPIRE directive in the city of Salamanca for promoting the green heritage concept. Many of the Mission Stories show that EO is widely used as regards climate hazard. The Valencian Mission Case Study ([30]), one of the most mature attempts at officially bringing together the two Missions, utilizes EO for climate hazard estimates, including future projections so as to prioritize challenges and actions.

4.3 Adaptation Mission: extending the Earth Observation value chain

It is evident that Earth Observation already plays a crucial role in urban adaptation, especially on providing data on climate hazards and exposure. The Indicators from this study (Chapter 5),

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([27]) https://netzerocities.eu/capital-hub/

([28]) https://climate-adapt.eea.europa.eu/en/mission/the-mission/about-mip4adapt

([29]) https://climate-adapt.eea.europa.eu/en/mission/solutions/mission-stories

([30]) https://climate-adapt.eea.europa.eu/en/mission/solutions/mission-case-studies/valencian-multi-level-collaboration-space representing the most policy-relevant end of the value chain, are likely to be of highest interest to DG CLIMA as the mission co-ordinator, as they provide, among others, the ability to capture the outcome of adaptation measures. It is telling that the Adaptation Dashboard ([31]), a key tool for the Mission's Regions and cities undergoing constant improvement, has adopted the JRC's EU-wide vulnerability framework (Eklund et al., 2023), which also forms part of the contributing indicator frameworks assessed in Chapter 5.

The connection with the Use Cases presented here is also apparent, as these describe the current fit-for-purpose but also the future EO directions required to cover unaddressed and emerging needs. The Adaptation Mission ecosystem can both benefit from, and crucially also provide insights to, this assessment. The Adaptation Mission provides real-world regions and cities in need of information for climate challenges and potential solutions - in essence providing (e.g. through the Mission's Community of Practice) the much sought after user perspective. These are highly illuminative in guiding the extension of the EO Value Chain: both with regard to more dynamic and impactful combinations of hazard, vulnerability and exposure products to realise more holistic EO risk intelligence services as well as the further synthesis and uptake of policy-relevant indicators derived from this intelligence.

The signatories of the Mission rely substantially on the aforementioned Adaptation Dashboard – an emerging capability in ongoing development by the EEA. Apart from the integration of the JRC Vulnerability Indicators, new metrics will be included including, among others, green area accessibility and water quality. The Indicators from this assessment (Kilsedar et al., 2024), most specifically those derived primarily from EO, can directly serve this ongoing development activity. Moreover, as shown in the following chapters, EO is currently significantly under-exploited as concerns the use of Vulnerability products, e.g. regarding proxy-based estimations of sectorial activity, a link that was less pronounced or almost absent in the above Mission mapping. To this end, the KCEO and EEA can work together in enriching the inventory of available intelligence that better exploits both the Vulnerability- and Exposure-related components of the Dashboard. This is a key aspect of the EO value chain extension, most importantly with regard to providing systematic and quantitative support for the Just Resilience component of adaptation.

Under a more strategic view, a growing consensus exists in providing more accessible climate adaptation solutions – actionable intelligence - for less specialized stakeholders. This is very much part of a growing accord within the Commission, Copernicus and both public and private Earth Observation/climate services communities, as evidenced by the new Group on Earth Observation paradigm of Earth Intelligence (within the post-2025 Strategy ([32])). Climate-ADAPT's 2022-2024 strategy ([33]) explicitly calls for creating an entry point to DestinE's digital twin on climate change adaptation (DT2) for users which include of course the Mission signatories. Similarly, the Adaptation Modelling Framework DE372 of DestineE aims to offer "non-technical end-users" access to advanced modelling capabilities in support of the adaptation planning process. This democratization process is emerging through the Climate-ADAPT platform and other more focused knowledge hubs such as the Climate Data Explorer, the European Climate and Health Observatory, the Urban Adaptation Map Viewer and the newly launched Copernicus Thematic Hubs (including Health ([34])) , Coastal ([35]), Energy ([36]). Whilst there is already substantial EO contribution to this process, its role

([31]) https://climate-adapt.eea.europa.eu/en/mission/knowledge-and-data/data-dashboards

([32]) https://earthobservations.org/storage/app/media/documents

([33]) https://climate-adapt.eea.europa.eu/en/about/climate-adapt-strategy-2022-2024-final.pdf

([34]) https://health.hub.copernicus.eu/

([35]) https://www.coastal.hub.copernicus.eu/

([36]) https://energy.hub.copernicus.eu/

should be enriched, going beyond climate hazards and into vulnerability as well as accentuating the modelling aspects, e.g. projections, early warning, forecasts, scenario-analysis, and evaluation of adaptation measures. The latter is a prerequisite for serving the climate resilient development pathways, a key component in the systemic approach of climate adaptation. EO, and especially Copernicus, also bring an important level of harmonization/standardization of services, monitoring and evaluation, and reporting processes across Europe. This is actively pursued by the Climateurope2 ([37]) and CLIMAAX project ([38]), which advocates standardised flexibility, and should be considered an important development for the Mission's ecosystem.

4.4 Cities Mission: emerging use of Earth Observation intelligence

Turning to Climate Change Mitigation, the Climate-Neutral and Smart Cities Mission comprises 100 cities coming from all 27 Member States, with 12 additional cities coming from Horizon Europe associated countries. The NetZeroCities Portal ([39]) is the equivalent to the MIP4Adapt platform as it represents the knowledge repository of the Cities Mission, and, importantly for this study, the nexus between mitigation and adaptation, the systemic perspective of the Horizon Europe Programme and the call for deeper synergies as previously discussed.

A central element that stands out in the Cities Mission is the Climate City Contract (CCC). The 112 selected cities are invited to develop CCCs, which include an overall plan for climate neutrality across all sectors such as energy, buildings, waste management and transport. The Mission Platform provides support in the co-creation of CCCs with local stakeholders and citizens. While not legally binding, these contracts represent a clear and highly visible political commitment. The CCC comprises three interlinked components: Commitments, an Action Plan, and an Investment Plan. These components need to be evaluated for a city to be awarded a Mission Label - at the time of writing ±33 have received such a label, with only 10 awarded CCCs to be found in the NetZeroCities Portal.

The Action Plan offers the most direct links with Earth Observation. The Plan complements actions detailed in existing plans (e.g. SECAP- Sustainable Energy and Climate Action Plan, SUMP-Sustainable Urban Mobility Plan, CEP-City Energy Plan) in order to realise climate neutrality and the key variable is of course Greenhouse gases (GHG) emissions broken down per sector, differentiating between municipality-controlled emissions and not. This climate neutrality juxtaposes a baseline state ("2030 Climate Neutrality Action Plan Guidance and Explanations V2.1" ([40])) against sectorial emissions (reduction), each sector containing a corresponding indicator (Module B-3 Indicators for Monitoring, Evaluation and Learning). The MyCovenant ([41]) and CDP-ICLEI Track ([42]) platforms, which are already utilised by a host of cities across Europe, are completely integrated in this monitoring system and cities can continue reporting in this way and be fully aligned with the Mission's requirements. Moreover, the Info Kit for Mission Cities ([43]) proposes a plentitude of relevant tools and guidance documents (under Annex 1 - Guidance and tools for cities), either horizontal (e.g. Google Environmental Insights Explorer) or sectorial.

([37]) https://climateurope2.eu/about-us/about-the-project

([38]) https://www.climaax.eu/

([39]) https://netzerocities.app/signin

([40]) https://netzerocities.app/file-228499b55310264a8ea0e27b6e7c6ab6

([41]) https://mycovenant.eumayors.eu/site/landing

([42]) https://www.cdp.net/en/cities

([43]) https://research-and-innovation.ec.europa.eu/system/files/2021-11/ec_rtd_eu-mission-climate-neutral-cities-infokit.pdf

It is worth briefly considering the Earth Observation potential in supporting the preparation and monitoring processes during the Action Plan's implementation with respect to GHG. A non-exhaustive overview of the tools listed in the Info Kit for Mission Cities suggests that EO is not a standardized tool in the cities' arsenal regarding GHG estimations. At the risk of being over-simplistic, these tools are mostly "1-D" in scope and derive information from socio-economic datasets (e.g. aggregated data on gasoline usage). On the other hand, the published CCCs imply the need for some form of geospatial disaggregation of GHG information, e.g. when public buildings are set as targets for mitigation measures or particular neighborhoods are set aside as climate neutral zones. Additionally, it is advised that cities report on the implementation of their Climate Neutrality Actions via indicators every two years to track progress on the Action Plan implementation. These requirements should be properly explored through an EO lens – namely the ability to provide a rigorous, standardised, scaleable, geospatial and independent set of products and indicators for monitoring and evaluation.

Copernicus and especially the Atmospheric Monitoring Service, offer direct pertinent services including direct observations of greenhouse gases (also considering the forthcoming CO2MVS ([44]), gridded anthropogenic emission inventories, and monitoring of fluxes. These may be somewhat coarse for some CCC requirements - nevertheless, they could be used as a validation for reported GHG emissions from cities (over an aggregated area). Sentinel-5P or similar satellites (e.g. GHGSat) amongst others can identify methane hotspots thus addressing waste aspects of the CCC. Solar energy potential and implementation has mature Earth Observation-driven applications, scaling from the building level which could surely benefit the renewables provisions of a CCC. Building stock models increasingly utilise a mix of traditional socio-economic data and EO data to enhance the result and production speed for building the model. Lastly, the reporting frequency, and ease of reporting through automated monitoring, can also be greatly enhanced through EO. Whilst this is a preliminary mapping analysis, it appears that there is considerable potential added value that EO could bring to both the design and implementation of the CCCs, complementing the tools that currently serve the Mission.

4.5 Cities Mission: co-benefits and extending the Earth Observation value chain

The mitigation-focused GHG aspects of the Cities Mission present a modus operandi largely agnostic to Earth Observation – whilst already identified as a design and implementation gap this appears to be deemed sufficient for the current needs of the Mission and the CCCs in particular. This does not apply however to the so-called co-benefits of climate action. As discussed in the Info Kit for Mission Cities, air quality and adaptation are heavily featured as co-benefits of the GHG-focused mitigation action. The Info Kit proposes that priority should be given to so-called "multiple-benefit" measures, such-as nature-based solutions or green roofs that help reduce emissions and cool buildings with an indirect benefit to pollutants' emissions (e.g. NO_2, $PM_{2.5}$ from residential heating in winter) and consequently, air quality. The 2030 Climate Neutrality Action Plan Guidance and the Mission Theory of Change framework (from the NetZeroCities Pilot Cities Programme Guidebook ([45]) similarly emphasises direct monitoring of GHG, in combination with data collection on co-benefits in order to more fully assess impact pathways. The awarded CCCs reflect this as they unanimously acknowledge co-benefits and link them with particular mitigation actions as well as propose particular indicators.

([44]) https://atmosphere.copernicus.eu/ghg-services

([45]) https://netzerocities.eu/wp-content/uploads/2022/06/Pilot-Cities-Guidebook.pdf

However, the monitoring framework for these co-benefits is not clear, at least in the CCCs found in the Mission Platform. Indicatively, several co-benefits are recorded in the Impact pathways of the CCC of Valencia (a frontrunner in the Mission) e.g. thermal comfort improvements because of building renovations that target GHG emissions. Even though improvement of air quality as a co-benefit is registered across all sectors, there does not seem to exist a systematic air quality monitoring framework either for creating a baseline or impact monitoring (apart from environmental sensors on-board buses, which, while consistent with a smart city, are inadequate for monitoring air quality). At the same time, established limits (both EU limit values and WHO Guidelines) are acknowledged in Table "B-3.0-b: List of proposed Green City Accord indicators".

This overall gap may be partly attributed to the fact that explicit co-benefits and complementing indicators were only recently provided by the Mission Platform under the Pilot Cities Programme. Establishing more comprehensive monitoring requirements and capabilities, there are now requirements for city indicators to analyse progress towards direct impacts (like net-zero GHG emissions) and indirect impacts (co-benefits), as well setting up tools and infrastructure for monitoring these indicators. This requirement (from the NetZeroCities Pilot Cities Programme Guidebook) is supported by a table providing an overview of the wide range of direct and indirect co-benefits and their categorization (Climate Mitigation/Adaptation, Public Health & Environmental Impacts, Social Inclusion, Democracy & Cultural, Economic Development, Resource Efficiency, Biodiversity). These minimum requirements can guide the city which can also add its own indicators. The indicators proposed by the Mission Platform can be found in Figure 3.

Figure 3. Proposed indicator set (46) for Monitoring & Evaluation of the Pilot Cities Programme of NetZeroCities (47) (3rd Cohort), slightly edited for visual clarity. In bold, the subdomains that can be partly or wholly supported by EO.

	GHG Emissions/Impact Domain	Impact Subdomain	Indicator
1	Greenhouse Gas Emissions (GHG)	**Total GHG emissions**	Total greenhouse gas emissions per year
2		**Stationary energy**	GHG emission per year from stationary energy per year
3		**Transport**	GHG emission from transport per year
4		**Waste**	GHG emission from waste per year
5		**Industrial processes and product use**	GHG emission from industrial processes and product use per year
6		**Agriculture, forestry and land use (AFOLU)**	GHG emission from agriculture, forestry and land use per year
7		Grid supplied energy	GHG emission from grid supplied energy per year
8		**Energy Consumption**	Change in the total energy consumption per year
9		**Energy Efficiency**	Change in energy efficiency over the lifetime of the project
10		Share of Renewable Energies	Change in the energy mix over the lifetime of the project
11		**Carbon capture and residual emissions**	Amount of permanent sequestration of GHG within city boundary
12		**GHG emissions**	Change of the greenhouse gas emissions per sector during the lifetime of the project
13	Public Health and Environment	**Air quality**	Improved air quality
14		**Noise**	Reduction of noise pollution
15		**Health**	Improved physical and mental wellbeing
16		**Quality of life**	Perceived change in the quality of life
17	Social Inclusion, Innovation, Democracy and Cultural Impact	Citizen & Communities Participation	Improved citizen participation
18		Capacity of the public administration	Improvement in skills and awareness
19		Social cohesion	Affordability of housing and energy
20		Digitalisation	Improved acceptance of digital solutions
21		Social Innovation	Number of participative activities implemented per stakeholder group
22		Scientific or Communication Outreach of the project	Scientific publications, social campaigns etc
23		Upscaling & Replication	Number of follow-up projects or districts
24	Digitalisation and Smart Urban Technology	Green ICT and Smart Metering	% of households and buildings with reduced energy consumption as a consequence of installing smart energy metres
25		Green ICT and Smart Metering	% of households and buildings with reduced water consumption as a consequence of installing smart water meters
26		Green ICT and Smart Metering	% of municipal buildings equipped with building energy management systems
27		EGovernment	% of city services available online
28		Access to information	Business-to-Government (B2G) data sharing
29		Urban Data Platforms	Usage of Urban Data Platforms
30	Economy	Investment in R&I	Improved investments in climate change action
31		Skilled Jobs & Employment	Newly created sustainable jobs
32		Technological readiness	Number of solutions suggested for implementation in local strategies
33		Local Entrepreneurship & Local Businesses	Creation of Start-ups, accelerators or tech innovation
34		Increase in Efficiency	Savings in working time achieved
35		Revenues generated	Revenues generated by the project
36	Finance and Investment	Public Spending	Public Capital Invested in Climate Action Projects
37		External Financing	Capital Attracted and Invested in Climate Action Projects from External Finance
38		Capital Efficiency	Emission Reductions Return on Invested Capital
39	Resource Efficiency	**Waste management and efficiency**	Urban waste reduction; Biowaste recovery
40		**Circular Economy**	Re-use of material during construction or renovation
41		**Water Management**	Improved water management
42		**Land use management**	Improved land use management practices (e.g. urban greening)
43	Biodiversity	**Urban Forestry Plantation and Improved Plant Health**	Percentage of tree canopy within the city
44		**Non-Invasive Species and Pollinators**	Change in the number of species of birds in built-up areas
45		**Ecological Habitat Connection**	Structural connectivity of green spaces

Source: NetZeroCities.

It is clear that the 45 Indicators for the Cities Mission (above), strongly echo the Adaptation Indicators presented in Chapter 5 across all impact domains. It is estimated that at least 21 of these indicators can be provided to a large extent through standardised, automated EO services – the majority other than those from the domains of Economy, Digitalisation and Smart Urban Technology and Finance and Investment as well as Social Inclusion, Innovation, Democracy and Cultural Impact. Earth Observation has a major role to play in the rest of the domains and beyond e.g. public health and heat-relevant indicators. Earth Observation therefore has significant – and currently largely under-exploited potential – to offer a framework for the monitoring and evaluation activities of the CCCs, both with regard to the mitigation-focused direct impact indicators on sectorial GHG reductions, and the adaptation-focused or otherwise "co-benefits".

Earth Observation could also directly benefit the Mission Cities on the issue of carbon sequestration. The 2030 Climate Neutrality Action Plan Guidance considers two relevant indicators: "Amount of

(46) https://netzerocities.eu/wp-content/uploads/2024/02/NZC-PCP-Cohort-3-Indicator-Set-UPDATED.xlsx

(47) https://netzerocities.eu/pilot-cities-programme/

permanent sequestration of GHG within city boundary" and "Negative emissions through natural sinks". "Natural sinks" refer to e.g. the planting of trees or other conversion of land use. Here, cities are allowed to account for negative emissions, through the enlargement or enhancement of natural sinks (accounting for all changes in the carbon stock). Earth Observation and the numerous green Indicators identified in this study offer direct support in this direction. Interestingly, the Info Kit for Mission Cities explicitly mentions Earth Observation for this particular domain of climate action: "The monitoring of the development of urban sinks could in the future be supported by satellite imagery (like the Global Human Settlement Layer - GHSL), including development of a new metric in itself (covering the change in urban built areas and additional or enhanced carbon sinks)".

4.6 Missions: ongoing convergence of adaptation and mitigation and the EO role

The two knowledge repositories of the Missions offer a glimpse of the growing, pragmatic convergence of adaptation and mitigation action. The interplay between the actual measures, consideration of direct and indirect impacts, and the corresponding indicators for monitoring and evaluating adaptation or mitigation action all fall under the umbrella of city climate action or more encompassing and appropriate terms such as urban resiliency. The Cities Mission explicitly considers adaptation as a co-benefit of mitigation. Cooling trees ([48]), Nature Based Solutions and Green Infrastructure Mapping ([49]), Green corridors for active and cooler mobility ([50]) underscore the adaptation value against heat and floods, the biodiversity and air quality co-benefit but also the natural sink capacity regarding GHG. City water resilience assessments (CWRAs[51]) are also discussed from the point of view of the embedded carbon life-cycle (e.g. footprint of grey infrastructure), constructed wetlands ([52]) which sequestrate carbon with several co-benefits, like rain gardens ([53]). This integrated viewpoint is elegantly exemplified in the so called "Concepts" of the Mission Platform. A city-user, already on the mitigation pathway, can achieve a deeper understanding of the pragmatic convergence with adaptation though concepts such as Urban green space ecology ([54]), Carbon Dioxide Removal (CDR) / Negative emissions ([55]) as well as Nature-based Solutions and Carbon sinks ([56]). Similar findings, albeit less codified as "co-benefits", can be found in Climate-ADAPT platform and the Mission Stories of the Adaptation Mission which provide several examples of mitigation as a co-benefit of adaptation.

Recent Horizon Europe Call-activities in support of the missions – focusing on mitigation, resilience and adaptation through urban greening – further testify to denser Mission intersections between adaptation and mitigation, and recognition of vulnerability and resilience as dynamic, quantifiable parameters.

The role of Earth Observation in serving this dynamic intersection becomes more evident when cross examining some of the recent Horizon requirements: "operationalisation of collaborative climate mitigation and adaptation urban planning approaches" through "innovative monitoring

([48]) https://netzerocities.app/resource-1268
([49]) https://netzerocities.app/resource-1863
([50]) https://netzerocities.app/resource-1278
([51]) https://netzerocities.app/resource-1738
([52]) https://netzerocities.app/resource-1378
([53]) https://netzerocities.app/resource-1388
([54]) https://netzerocities.app/resource-3308
([55]) https://netzerocities.app/resource-3248
([56]) https://netzerocities.app/resource-2644

frameworks and key performance indicators"; gauging the impact of "the deployed solutions regarding climate mitigation, adaptation and regeneration against a well-defined baseline"; ensuring "cross-scalar (city/region) compatibility and coherence of the urban/regional climate mitigation and adaptation plans". EO's inherent geographic scalability and standardisation – combined with the ability to deal with both holistic risk/resilience through highly quantified hazard, vulnerability and exposure parameters, in addition to more highly synthesised policy-facing indicators - makes it of very high potential value. It could be argued that EO is agnostic to the particular emphasis a city/Region puts on climate action, be it adaptation or mitigation. EO already is and can further contribute to the universal prerequisites of overall climate action in cities: a Risk and Vulnerability Assessment, a Greenhouse Gas Emissions Inventory, capacity for scenario-analysis, design and implementation of a Climate Action Plan (attached to a CCC or otherwise). However, in order to fully exploit this potential, awareness, guidance coordination is needed with the Mission Communities – actions for which this assessment is well placed to provide.

5 Indicators

Extending the Earth Observation Value Chain: The Synthesis of Policy-Relevant Indicators

The EU Strategy on Adaptation to Climate, European Climate Law, and the European Green Deal lay down a powerful legislative framework for Climate Adaptation in Europe. A key component of this framework is the need for fit-for-purpose adaptation monitoring, reporting and evaluation systems, using a harmonised framework of standards and indicators. There are currently no formalized EU-standard or consolidated set of adaptation indicators, especially when addressing the vulnerability dimension of climate-change or -adaptation actions. Current evaluation capabilities are immature, with challenges that include: a lack of indicators; immature reporting implementation; calls for improved methodologies; and compilations of existing best practices.

Over 140 indicator frameworks, from the EEA and other authoritative sources, were used here to provide a broad-ranging and thematically-encompassing corpus of city-relevant indicators. Several critical components were then used to refine this corpus into a manageable, urban-focused compilation of descriptive indicator frameworks, including: Earth Observation potential; Socio-economic data requirement; Key Type Measures applicability; Risk components of hazard, exposure and vulnerability; Climate Change Impact; and Adaptation Action Outcome. The incorporation of a well-structured, clearly-recognised typology of adaptation actions is critically important – these effectively represent core user decision-making from an intelligence value chain perspective. Key Type Measures (KTMs) were used here to represent these adaptation actions, in synergy with the EEA.

This synthesis resulted in an inventory of eight frameworks providing 511 indicators, ranging across domains and thematic perspectives regarding Climate Change Adaptation. Over 200 of these indicators are in some way addressed by Earth Observation, with ±100 of these only approachable through EO, with the majority of indicators strongly and unsurprisingly addressing Vulnerability. This inventory, intended as descriptive rather than prescriptive, provides a clear pathway to extending the adaptation-relevant intelligence value chain, and the significant role that EO can play in this value chain.

Independent, standardized, observation-based, actionable indicators should be a central tenet of the monitoring and evaluation process. These will also greatly facilitate adaptation design in 1) providing a clearly quantified expression of risk (and therefore risk reduction) through the hazard/vulnerability/exposure nexus, and 2) allow the setting of appropriate adaptation targets based on routine monitoring of this risk nexus. The indicator approach and inventory provided here shows the potential value and ability to move beyond process-related indicators – highlighting the importance of vulnerability and exposure as dynamic continuum parameters, and compound indicators as the interface between intelligence and policy. Earth Observation is currently poorly exploited for climate adaptation due to an under-developed value chain, and - through such indicator frameworks - has a critical role to play in the monitoring, evaluation and reporting needed for more effective adaptation design and impact.

5.1 Towards a necessary and standardized component of climate adaptation

The EU Strategy on Adaptation to Climate Change ([57]) and European Climate Law constitute the reference policy and legislation for all things related to Climate Adaptation in Europe. The Strategy acknowledges the power of conveying messages through the utilisation of indicators regarding both climate hazards, e.g. “frequency and severity of climate and weather extremes is increasing” and

([57]) COM/2021/82 final

climate change impacts, e.g. “economic losses from more frequent climate-related extreme events are increasing”. The 2021 Strategy builds on the previous 2013 Adaptation Strategy which, among others, has solidified the Climate-ADAPT platform of the EEA as a key reference for knowledge on adaptation in Europe.

Both the Strategy and Law call for Member States and the Union to enhance their adaptive capacity, strengthen resilience and reduce vulnerability to climate change, as provided for in Article 7 of the Paris Agreement. The need for adopting “plans based on robust climate change and vulnerability analyses, progress assessments and indicators” is underlined. While climate adaptation has matured over the last decade and now enjoys a firmer policy framework, the Strategy nonetheless sets, as one of the Commission’s implementing actions, the upgrading of adaptation monitoring, reporting and evaluation by using a harmonised framework of standards and indicators (a direction pursued among others by the Climateurope2 ([58]) and CLIMAAX projects). The immature status of monitoring, reporting and evaluation is evident in the majority of the Member States as is evident in the December 2023 Commission’s “Assessment of progress on climate adaptation in the individual Member States”, under the European Climate Law. Mature practices are seen to exist in only a small minority of Member States (e.g. France, Finland). The challenges include lack of indicators; immature reporting implementation; calls for improved methodologies and compilations of existing best practices. Moreover, the Strategy, in sync with the European Green Deal, further highlights the dangers of inequitable adaptation, as unequal exposure and vulnerability to climate impacts may exacerbate pre-existing socio-economic inequalities, particularly in urban areas (EEA, 2018).

Global proceedings closely parallel this European state-of-play. The Conference of the Parties (COP) 27 initiated the development for the Global Goal on Adaptation framework ([59]). COP28 set the adaptation Targets, adopted the Framework for Global Climate Resilience ([60]) and launched the two-year UAE–Belém work programme aimed to develop indicators and potential quantified elements for measuring progress towards the Targets. Europe is engaging in this SDG-like process primarily through the EEA. Given the explicit policy drivers and the inherent interplay of quantitative climate change components - hazards, impacts, vulnerability, adaptive/coping capacity, resilience - it is clear that an equivalent approach necessitates mapping these components in an indicator space. The mainstreaming of Earth Observation into the climate adaptation information space has made great strides over the last fifteen years and a key aim of this assessment is to facilitate their inclusion in the overall Global Goal on Adaptation Process.

5.2 Using the existing knowledge base and practice of city networks

There is currently no formalized EU-standard or consolidated set of adaptation indicators, especially when addressing the vulnerability dimension of climate change or climate adaptation action in cities. The Adaptation Strategy’s default knowledge platform, Climate-ADAPT ([61]), is therefore taken to offer the state-of-the-art in the urban dimension of climate adaptation. The platform considers the IPCC’s Sixth Assessment Report (IPCC, 2022) as the foundation of the knowledge base which is also the case for the European Climate Risk Assessment (EUCRA) (EEA, 2024a). Therein, the risk components are delineated: hazards, exposure, and vulnerability which further breaks down to sensitivity, coping and adaptive capacity. The approach presents some departures from the AR5

([58]) https://climateurope2.eu/

([59]) https://unfccc.int/topics/adaptation-and-resilience/workstreams/gga

([60]) https://unfccc.int/sites/default/files/resource/cma5_auv_8a_gga.pdf

([61]) https://climate-adapt.eea.europa.eu/en report (see "Risk in IPCC assessment through time") but, for the purposes of this assessment, AR5 nomenclature/approach is deemed adequate (See Figure 1 in Section 2.2).

The Risk Supplement to the Vulnerability Sourcebook (GIZ & EURAC, 2017), another Climate-ADAPT resource, considers adaptation measures as a means for reducing risk by reducing vulnerability and in certain cases also exposure, if possible. Vulnerability can in turn be reduced either by decreasing sensitivity or by increasing capacity. The Sourcebook also introduces the concept of the 'impact chain' as a key tool in risk assessment. While impact chains are necessarily hazard-specific and can reach highly intricate levels of detail that go beyond the scope of this assessment, they offer a theoretical framework that is instrumental in providing a methodology for Indicator derivation. Categorization across the risk components, and the provision of criteria for quality indicators, e.g. begin with the hazard, provide clear direction/sign, consideration of both adaptive and coping capacities etc. Lastly, and very importantly, the Sourcebook's perspective on monitoring and evaluation (M&E) is that is valid not only for risk but also adaptation - every adaptation effort (be it a specific adaptation measure, plan or policy) aims at decreasing vulnerability (through decreasing sensitivity or increasing capacity) or – in very specific circumstances – decreasing exposure. This underlines the primary EO-focused concept that routine, quantified standardized vulnerability and exposure parameters, contextualized through key hazards, are critical to monitoring adaptation.

Climate-ADAPT further maps key city networks that lead the way in climate adaptation in Europe such as the EU Covenant of Mayors for Climate & Energy (CoM, ~ 9000 cities and towns across the EU), Local Governments for Sustainability (ICLEI Europe), C40 Cities and the Resilient Cities Network (RCN). These networks feature their own knowledge bases and reports. A common denominator of these networks is that they do not point to a definitive set of indicators for monitoring and evaluating climate action. Climate action plans are central to ICLEI Europe and C40 but both encourage cities to define their own indicators for these plans rather than offering pre-existing ones (except for some suggestions ([62]). The Urban Adaptation Support Tool ([63]), as part of the CoM knowledge base, constitutes an integrated tool for assisting cities, towns and other local authorities in developing, implementing and monitoring climate change adaptation plans.

For the CoM cities, the guidelines for monitoring and evaluation are defined in the Global Covenant of Mayors Common Reporting Framework (CRF) and accompanying Guidance Note ([64]). Signatories are urged to report how they are planning to track progress toward the achievement of the adaptation goal ideally, but not necessarily, through an indicator. Even more importantly, while the signatory city is obliged to regularly monitor progress in implementing the action plan, this mostly refers to 'process-monitoring' and corresponding process-based indicators as opposed to indicators regarding the risk components. The Covenant of Mayors: 2022 assessment (Melica et al., 2022) offers a sobering perspective on the reporting status. As the "adaptation goals" lack specific references with defined quantitative targets, data include different levels of information, data from submitted templates show unclear goal descriptions, and only a minor number are linked to reducing the risk of climate hazards through reduction of exposure and/or vulnerabilities. Additionally, the quantitative component of the goal is often incorrectly filled in. Overall, the last step "Monitoring and evaluating adaptation" of the Urban Adaptation Support Tool, remains, by far, the most unimplemented step according to the scoreboard according to the assessment.

Again, these issues very clearly point to a significant gap in current adaptation planning and implementation – the lack of independent, standardized, quantitative, observation-based (as opposed to process-based), appropriately synthesized indicators that should be a central tenet of

([62]) C40 Knowledge Hub

([63]) https://climate-adapt.eea.europa.eu/knowledge/tools/urban-ast/step-0-0

([64]) Explanatory Note accompanying the Global Covenant of Mayors Common Reporting Framework the monitoring and evaluation process. This intelligence gap also results in sub-optimal adaptation design in that: 1) it precludes a clearly quantified expression of risk (and therefore risk reduction) through the hazard/vulnerability/exposure nexus, and 2) precludes the setting of appropriate adaptation targets based on routine monitoring of this risk nexus. Targets must be set based around an available and robust set of measurements and derived intelligence, particularly so for the highly complex and multi-dimensional urban adaptation space. "When you can measure what you are speaking about…you know something about it; but when you cannot measure it…your knowledge is of a meagre and unsatisfactory kind" (Kelvin, 1889).

5.3 Consolidating frameworks of climate adaptation indicators in synergy with the European Environmental Agency

Following the validation of the gap in established adaptation practices and indicators, this assessment has sought synchronization with EEA as the entrusted entity that is the de facto adaptation body in Europe. These gaps were acknowledged, and EEA has parallel, ongoing activities in the Urban Adaptation Map Viewer ([65]) and the Adaptation Dashboard ([66]), also following the Risk structure and nomenclature discussed above. The Dashboard in particular, an integral tool for the Regions/Cities of the Mission on Adaptation, testifies to the cross-relevance between the Indicators and the EU Missions discussed in the previous chapter. The gap spectrum is also critical in monitoring outcomes of climate action such as in implementations of Nature Based Solutions. While the increase of green areas is relatively straightforward, monitoring and documentation of the consequent impacts on heat and air quality is less so.

One of the most important components in further developing standardized adaptation indicators is a clear focus on the spectrum of adaptation actions and pathways under consideration. These adaptation actions represent the core user decision making from an EO value chain perspective, and the incorporation of a well-structured, clearly-recognised framework or typology of adaptation actions is critically important. The synergy with EEA therefore introduces Key Type Measures (KTMs) ([67]), utilised in reporting climate adaptation action in the EEA member countries (Leitner et al., 2021). KTMs are not obligatory yet - only 8 EU Member countries reported back for 2021 as part of their obligations under the Energy Union Governance Regulation ([68]). The KTM methodology was developed to provide a standardised way of communicating adaptation measures to better support adaptation policy process across the EU - but it comes with caveats. Reporting KTMs and Sub-KTMs as such does not convey any information on the progress in implementing these measures. Reporting on the state of implementation is also not mandatory and the methodology focuses on the "what is being done" and not on the "what is being achieved" with respect to the risk components such as vulnerability. Nevertheless, EEA considers KTMs as a critical component of adaptation reporting, to increase in significance over the next reporting period. Given their importance - across the value chain, impact and policy dimensions - this assessment has accommodated KTMs in the Indicators methodology below and, partly, in the Use Cases themselves (as depicted in the illustrative examples).

Of pertinence to the emerging indicator development and application, EEA engaged in a bottom-up process to inventory indicators found in individual local action plans of cities (more than 70 plans) which was utilised in the Urban adaptation section in the "Europe What works?: implementing

([65]) https://climate-adapt.eea.europa.eu/en/knowledge/tools/urban-adaptation

([66]) https://climate-adapt.eea.europa.eu/en/mission/knowledge-and-data/data-dashboards

([67]) https://climate-adapt.eea.europa.eu/en/metadata/publications/using-key-type-measures-to-report-climate-adaptation-action-in-the-eea-member-countries

([68]) Regulation (EU) 2018/1999

climate action in European cities" publication (EEA, 2024b). Such an inventory offers potential to move beyond process-related indicators and should be extremely useful in realising some of the aims expressed here in the longer term. This assessment was able to exploit another available inventory of more than 130 indicator frameworks identified by the EEA, from both EU and global sources. In synergy with the EEA, this resource was consolidated in this assessment. In light of the currently identified gap in standardized adaptation monitoring, it is hoped that the intersection and likely convergence of these bottom-up and top-down approaches will prove beneficial both for the appropriate entrusted entities and broader adaptation-relevant communities.

5.4 Methodology

An initial inventory of more than 130 indicator frameworks from the EEA, with additional frameworks from authoritative sources to ensure appropriate thematic coverage, were filtered to yield a manageable, urban-focused indicator compilation. The final indicator framework set (Table 1) encompasses a broad corpus of city-relevant indicators that echo the inherent complexity of the urban environment, and the multi-dimensional interplay between climate change and vulnerability.

Table 1. Different frameworks ultimately considered in this assessment, providing city-relevant adaptation indicators.

Framework	**Provider**
Key Performance Indicators for Smart Sustainable Cities [69]	United for Smart Sustainable Cities (U4SSC)
Sustainable cities and communities — Indicators for resilient cities ISO 37123:2019 [70]	International Organization for Standardization (ISO)
Repository for Adaptation Indicators [71]	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, German Federal Ministry for Economic Cooperation and Development
Urban Vulnerability Indicators - A joint report of ETC-CCA and ETC-SIA [72]	European Topic Center (ETC) on Climate Change Impacts, Vulnerability and Adaptation / ETC on Spatial Information and Analysis
The Lancet Countdown on health and climate change	Romanello et al. (2022)
Indicators for European cities to assess and monitor the UN Sustainable Development Goals (SDGs) [73]	European Topic Center ETC/ULS - Urban, Land and Soil systems
Towards a European wide vulnerability framework	Joint Research Centre (Eklund et al., 2023)
The climate and ocean risk vulnerability index: Measuring coastal city resilience to inform action	Rouleau et al. (2022)

Source: Internal EC KCEO.

These indicators were then categorized with regard to relevance for: Earth Observation potential; Socio-economic data requirement; Directorates-General (DGs) applicability; Key Type Measures and

[69] Key Performance Indicators for Smart Sustainable Cities

[70] Sustainable cities and communities — Indicators for resilient cities ISO 37123:2019

[71] Repository for Adaptation Indicators

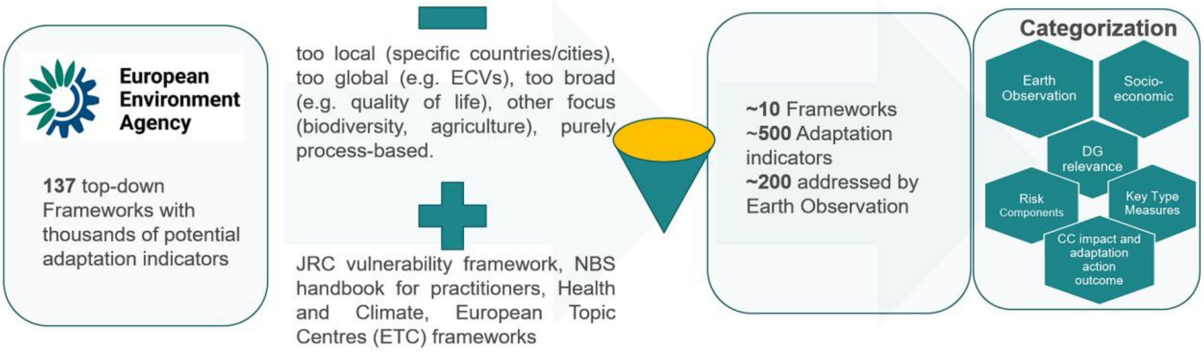
[72] Urban Vulnerability Indicators - A joint report of ETC-CCA and ETC-SIA

[73] Indicators for European cities to assess and monitor the UN Sustainable Development Goals (SDGs)

sub-KTMs; Risk components of hazard, exposure and vulnerability; Climate Change Impact; and Adaptation Action Outcome. Impact is considered as the realization of the Risk, and Outcome as the results of climate action, i.e. implementation of sub-KTMs. The Outcome is limited to the most attributable results, e.g. the green area indicator is suitable for describing the outcome of Green options measures (D1 sub-KTM) but the costs of heat-related mortality (which green areas reduce) is not as it involves several other parameters and it is difficult, if not impossible, to attribute the effect of the particular adaptation measure.

The main steps of the consolidation and categorization process can be seen in Figure 4, with additional source details and technical descriptions in Appendix 1.

Figure 4. Consolidation process of top-down indicator frameworks provided by the European Environment Agency. Filtering based on the objectives of this assessment and additions of pertinent authoritative frameworks led to a corpus of approximately 500 indicators. These were then categorized based on whether they are addressed by Earth Observation and are relevant to the Use Cases, their KTM relevance as well as their connection to Risk components.



Source: Internal EC KCEO.

5.5 Climate change adaptation: examining the indicators

The output of the consolidation process yielded 8 frameworks hailing from different domains and points of view regarding Climate Change Adaptation, comprising in total 511 Indicators that have been categorized (Kilsedar et al., 2024). More frameworks were considered with hundreds of indicators which have not been categorised. Whilst the DG-relevant Use Cases of the following chapters were accounted for in the categorization aspect, the frameworks themselves are agnostic to them, and thus, the compilation is applicable elsewhere. This list of frameworks should not be considered exhaustive but rather a comprehensive starting point regarding indicators for climate change adaptation. Collaboration and convergence with the EEA activities is important in this regard. There are several of the 511 indicators which are identical or very similar to each other - these have been preserved to add legitimacy and weight when a particular indicator is featured in disparate frameworks (e.g. green area related indicators or loss and damage ones). A sample of the spreadsheet file is presented in Figure 5.

Figure 5. A sample of the spreadsheet file (edited for visual clarity) containing the consolidated frameworks of climate change adaptation indicators along with their categorization per: Source Type, DG Relevance in the Deep Dive (edited out), Key Type Measures of the Regulation on the Governance of the Energy Union and Climate Action (A: Governance and Institutional, B: Economic and Finance, C: Physical and Technological, D: NBS and Ecosystem Approaches, E: Knowledge – Behavioural change), Risk Component (Hazard, Exposure, Vulnerability), Climate Change impact or Adaptation Action Outcome.

FRAMEWORK	INDICATOR	Source Type			Key Type Measure					Risk component			Impact/Outcome	
		Earth Observation (brief reasoning)	EO Scale	Socio-economic	A	B	C	D	E	Hazard	Exposure	Vulnerability	Climate Change Impact	Adaptation Action Outcome
Key Performance Indicators for Smart Sustainable Cities	Disaster Related Economic Losses	Loss and damage official EEA indicator. Risk Data Hub of JRC. Ultimately	2											
Key Performance Indicators for Smart Sustainable Cities	Population Living in Disaster Prone Areas	Overlaying historical datasets (e.g. EEA's flood viewer-	1											
Sustainable cities and communities — Indicators for resilient cities	Electricity supply capacity as a percentage of peak electricity demand													
Sustainable cities and communities — Indicators for resilient cities	Annual expenditure on green and blue infrastructure as a percentage of total city budget													
Sustainable cities and communities — Indicators for resilient cities	Annual percentage of the city population directly affected by natural hazards	By overlaying the right layers. Disaster information is EO-derived, trends and per event. Gridded population data is	1											
The Lancet Countdown on health and climate change	Change in labour capacity	Need for integration with socio-economic datasets. The hazard itself is	2											
The Lancet Countdown on health and climate change	Premature mortality from ambient air pollution by sector	Sectorial breakdown of pollution is possible through source apportionment from in situ	2											
The climate and ocean risk vulnerability index: Measuring coastal city resilience to	Percent of National Economy Based in Port and Shipping Industries													
The climate and ocean risk vulnerability index: Measuring coastal city resilience to	Percent of Low-Income Housing in Relation to Flood Zones	Need for integration with socio-economic data. Disaster information, risk-related and historical, is EO-	2											
The climate and ocean risk vulnerability index: Measuring	Percent of people living below 5 Meters above Sea Level	CMEMS for trend: https://marine.copernicus.eu/ocean-	1											

Source: Internal EC KCEO.

Out of the 511 Indicators, 217 (42%) are in some way addressed by Earth Observation (following the expansive definition of this assessment that includes for example geospatial data or modeling outputs). 97 (19% of the total) of these are only monitored/approachable through EO and 120 can also be addressed through socio-economic means (i.e. data not from EO sources) or in necessary conjunction with EO, e.g. 'Accessibility to public recreation sites'. Some EO-addressed indicators may indeed strike odd to the reader. As an example, the "Income inequality (GINI coefficient)" is usually attributed to the socio-economic realm. Nevertheless, research exploring the link of economic activity or inequality with NO_2 satellite retrievals or night light imagery exists (Xu et al., 2015). Some distinction was therefore introduced for the EO-indicators (See EO Scale parameter in Kilsedar et al. (2024)). An EO Scale value of 1 was attributed when EO alone addresses entirely or almost entirely the indicator and does not need integration with other sources (gridded population datasets do not count as this is considered EO and play role in many indicators). An EO Scale value of 2 was attributed when EO is rather utilised as a proxy or has a complementary or indirect link to the indicator. 139 indicators thus are deemed to be entirely addressed via EO (albeit with some similar indicators), and 78 to have a softer link to the indicator. The KCEO brief and exhaustive reasoning is also included that enables further exploration by the reader. 294 (57%) indicators are solely reliant on socio-economic approaches.

Regarding the Risk Components, out of the 511 (217 EO addressed) indicators, 58 (11%) (49) refer to Hazard, 105 (20%) (80) to Exposure and 399 (78%) (118) to Vulnerability. The latter indicators are the more numerous, in line with the increased importance of this component in the Risk Assessment domain. Earlier chapters have highlighted that there is often a greater stress on the Hazard components (and Exposure to a lesser degree), perhaps due to their comparatively easier monitoring. It is noteworthy that some indicators are relevant to more than one component – albeit with different signs - and this increases the added value of the indicator and potentially merits more effort for its monitoring. This preliminary categorization is binary however and does not capture the degree to which each indicator is relevant to a Risk component or across components. As an example, "Percentage of the workforce in informal employment" is important for exposure as the nature of this work often carries higher risk, but the uninsured and dangerous/unregulated conditions at work increase vulnerability to an, arguably, larger degree.

Regarding the Key Type Measures, Table 2 maps the indicators against the sub-KTMs and captures the role of Earth Observation in monitoring the presence, in designing and in monitoring the outcome of such climate adaptation measures. While EO can strongly support some sub-KTMs, socio-economic data have an inescapable role to play for several of these. This is to be expected because of the nature of the sub-KTMs that entails aspects of human interaction/activity (e.g. A1 Policy, A3 Coordination and E2 Capacity Building) are simply unapproachable by EO. Green and blue options are, as expected given the strong environmental capabilities of EO, the most prevalent type where EO can fully support sub-KTMs but can also be utilised for monitoring climate action outcomes (with half the EO indicators being solely reliant on EO). EO can also potentially support Management and planning (A2), especially as the mainstreaming of EO progresses and touches upon the operational modus operandi of cities. But these are first order generalisations, and the Use Cases can assist in illuminating the complexity of particular implementations of EO that can support more socio-economic inclined measures (e.g. 'Industrial/commercial area affected by the risk of flooding' and how this connects with financing instruments: B1 and the EU Sustainable Finance Taxonomy ([74]) or 'Percentage of city area covered by publicly available hazard maps' that directly feeds into E1: Information and awareness raising as well as A2: Management and planning).

Table 2. Number of indicators relevant to sub-KTMs based on their reliance on Earth Observation.

Sub-KTM	**EO-addressed indicators ([1])**	**Socio-economic indicators**	**EO-addressed outcome of climate action**
A1: Policy instruments	1 (0)	13	0
A2: Management and planning	77 (28)	123	26
A3: Coordination, cooperation and networks	1 (0)	17	1
B1: Financing and incentive instruments	30 (6)	79	2
B2: Insurance and risk sharing instruments	35 (14)	46	2
C1: Grey options	61 (24)	67	6
C2: Technological options	15 (7)	34	1
D1: Green options	123 (62)	93	42
D2: Blue options	130 (64)	125	43
E1: Information and awareness raising	19 (8)	58	2
E2: Capacity building, empowering and lifestyle practices	11 (2)	37	1

([1]) in brackets the solely reliant on EO, i.e. Scale 1

Source: Internal EC KCEO.

As regards Climate Change Impact - 33 indicators in total are relevant with 27 being addressed by EO, 21 of which are EO Scale 2, meaning that EO cannot exclusively support the production of the indicators. As regards Adaptation Action Outcome, 160 indicators are relevant. It is of interest to note that several of these indicators (e.g. "Demonstrate a steady reduction in water closures of at least 2% annually") imply that a monitoring system is in operation that can produce trends over time. This is consistent with the monitoring and evaluation frameworks discussed above and the repeatability needs of Risk assessment. While not all components necessitate annual or bi-annual

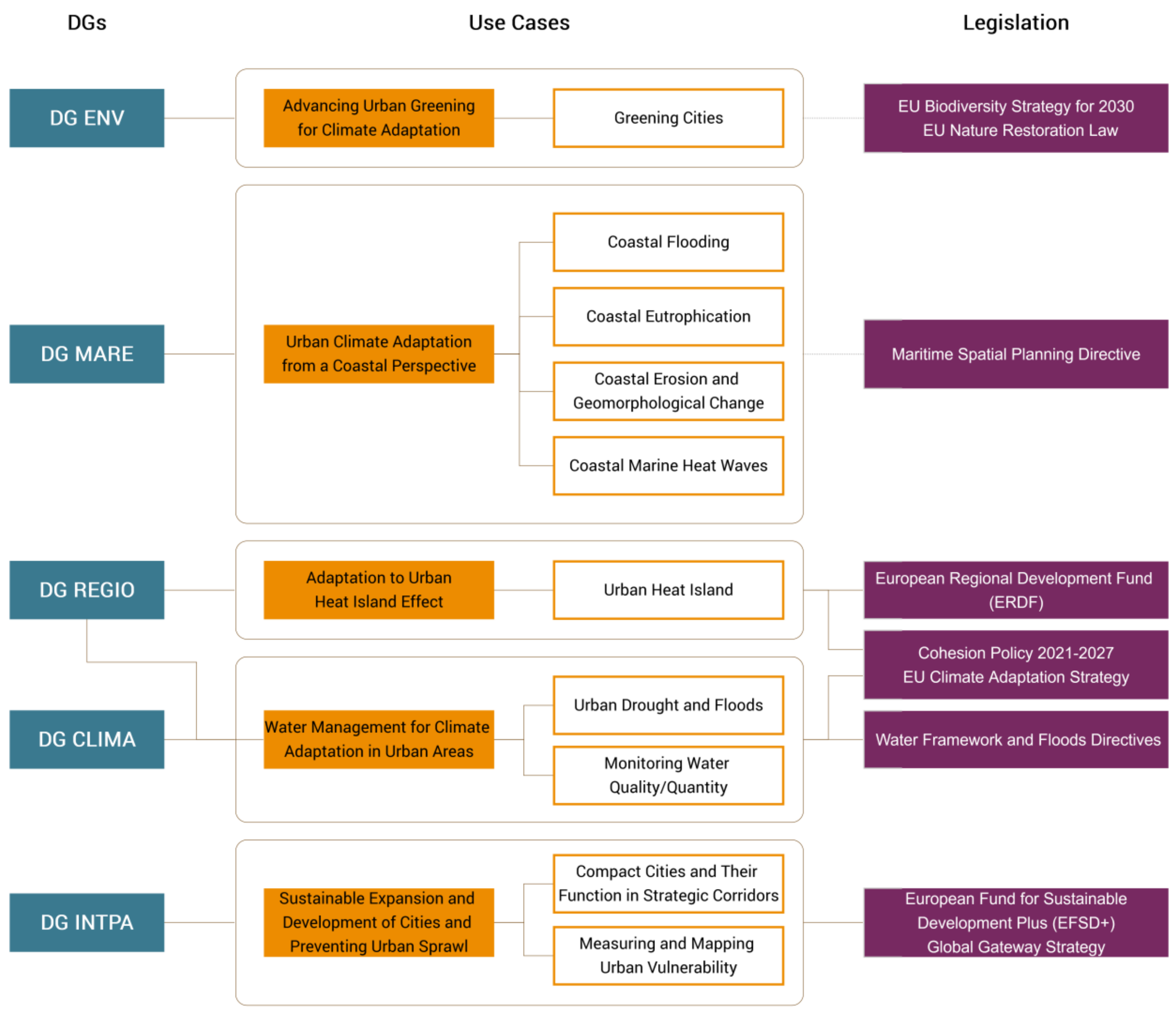
([74]) https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en updates (e.g. exposure is less likely to change rapidly), in order to capture the signal of climate action some assessments may require more frequent updates and, quite possibly, historical trends. 96 out of the 160 are solely reliant on socio-economic data, a reminder of the steady value of such data which are present in all 8 categorised frameworks. 64 are EO addressed with, 51 at EO Scale 1. Indicators entailing some form of Green Area metric are the majority (30, albeit some are quite similar) and are included in all the frameworks bar one. Land cover/Land take indicators are also heavily present (8) and found across three frameworks. Imperviousness/erosion related indicators follow (5) across five frameworks. The rest of the indicators pertain to monitoring pollution (water, air) and to certain aspects of disaster/adaptation management.

6 Description of the use cases

6.1 Introduction to the use cases

The use cases are a key part of the Deep Dive methodology, which is summarized in the Deep Dive Methodology Box. They represent the translation of expressed needs by policy DGs into use cases. An overview of the main use cases addressed in this Deep Dive, the main DGs involved and the related legislation is presented in Figure 6.

Figure 6. Use cases overview.



Source: Internal EC KCEO.

The definitions of the technical terms used in this chapter (e.g., spatial/temporal/spectral resolution, temporal extent, etc.), can be found in the KCEO Glossary ([75]).

While temporal resolution and temporal extent are defined for each use case separately and can be found at the beginning of each use case, a set of spatial resolution definitions valid for all the use cases are inherited from the Copernicus Contributing Missions (CCM) ([76]). Therefore, these definitions are as follows:

Spatial Resolution
VHR1: Very High Resolution 1, where resolution < =1 m **VHR2:** Very High Resolution 2, where resolution >1 m and < =4 m **HR1:** High Resolution 1, where resolution >4 m and <=10 m **HR2:** High Resolution 2, where resolution >10 m and <=30 m **MR1:** Medium Resolution, where resolution >30 m and <=100 m

([75]) https://ec-jrc.github.io/KCEO-Glossary/

([76]) https://spacedata.copernicus.eu/web/guest/ondemand-dataset

6.2 Advancing Urban Greening for Climate Adaptation (DG ENV)

Earth Observation Use Case: Advancing Urban Greening for Climate Adaptation

The European Biodiversity Strategy seeks to improve urban resilience to flood, drought and heat risks through ambitious urban greening and nature-restoration goals. Green and ecosystem-based adaptation actions, in combination with soft- and accommodation-focused measures, are shown to have significant potential to reduce heat, flood and drought impacts across European cities. Earth Observation intelligence has much potential to meet key applications needs such as accessible green cover dynamics, extreme heat information, vulnerability and exposure mapping, and the use of models and indicators to guide greening and ecosystem restoration activities. Many of the necessary products and services are available in an emerging sense through Copernicus and other European services – although not all in an optimal form for the required applications. There is a clear need to bridge gaps in both temporal and spatial observation resolution for urban applications; and semantic gaps through the development of Decision Support Tools offering actionable information in appropriate metrics. The value of scenario modelling to guide spatial and biodiversity-related adaptation implementation is also highlighted. Earth Observation has a valuable potential role across a significant set of the Key Type Measures that represent a formalised spread of adaptation activities: most obviously Green, Blue, and Grey but also across Management-, Financial- and Information-related measures.

Key recommendations include the development of operational land surface temperature models; more time-extensive and frequently updated EO services; enhanced automated change detection products; integration of sub-metric EO data from Copernicus Contributing missions; more widespread use of adaptation scenario models and compound indicators; and a range of activities to bridge the “last mile” of the EO value chain and provide actionable intelligence to a range of user archetypes.

6.2.1 Policy context

The Biodiversity Strategy to 2030, advocates promoting and supporting cities in greening their urban areas / new developments, integrating green infrastructure and using nature-based solutions to adapt to the inevitable impacts of climate change. Copernicus can support urban planners in identifying risks, and understanding options for using nature to reduce them - i.e. detailed green land use mapping, heat mapping, flood risk assessment and trends over time.

In response to the growing challenges of urbanisation and the heightened risks of floods and droughts, the European Union has embarked on a transformative journey outlined in its Biodiversity Strategy to 2030. This strategy not only addresses the urgent need to protect and restore Europe's natural ecosystems but also emphasises the critical role that urban areas play in building resilience against climate-related hazards. At its core, the strategy recognises that urban greening is not just a trend but a fundamental component of sustainable and resilient urban development, including managing flood and drought risks.

Additionally, the Nature Restoration Law includes Urban ecosystems – no net loss of green urban space by 2030; a 3% increase in the total area covered by green urban space by 2040; and a 5% increase by 2050; a minimum of 10 % urban tree canopy cover; and a net gain of urban green space that is integrated into existing and new buildings and infrastructure developments.

Urban Resilience and Climate Change

The European Biodiversity Strategy to 2030 sets ambitious goals aimed at reversing biodiversity loss and restoring nature's resilience. One of its key pillars is the commitment to allocate at least 30% of European land and sea to protected areas while strictly protecting primary and old-growth forests. These actions contribute significantly to safeguarding biodiversity. However, the strategy also recognises that cities and urban areas, often concentrated in flood-prone or drought-vulnerable regions, need dedicated attention to address these specific challenges.

Managing Flood Risk in Urban Areas

Urbanisation increases the risk of flooding due to the expansion of impermeable surfaces, altered hydrological patterns, and increased runoff. To address this, the European Biodiversity Strategy emphasises:

- Green Infrastructure: Developing green infrastructure networks in urban areas to absorb excess rainwater, reduce flooding, and enhance urban resilience.
- Floodplain Restoration: Restoring and preserving natural floodplains within and near urban areas to act as buffers during floods.
- River Restoration: Implementing measures to rehabilitate urban rivers, improving their capacity to handle heavy rainfall and mitigate flood risks.

Managing Drought Risk in Urban Areas

Conversely, droughts in urban areas can strain water resources, threaten ecosystems, and disrupt daily life. The strategy addresses this through:

- Drought-Resilient Landscaping: Encouraging the use of drought-resistant native plants in urban landscaping to conserve water resources.
- Water Efficiency Measures: Promoting water-efficient technologies and practices in urban design and infrastructure.
- Water Recycling: Supporting the implementation of water recycling and rainwater harvesting systems in urban areas to reduce dependence on external water sources.
- Public Awareness: Raising public awareness about water conservation in cities and the importance of reducing water waste.

By integrating these flood and drought resilience measures with urban greening initiatives, the European Biodiversity Strategy acknowledges the multifaceted challenges faced by urban areas. It emphasises that urban green spaces, when strategically designed and managed, can serve as natural buffers against the impacts of climate change, reducing both flood and drought risks. These actions not only improve urban quality of life but also contribute to the overall goal of protecting and restoring biodiversity in urban environments.

In summary, the European Biodiversity Strategy to 2030 recognises the vital role of urban greening in building resilience to flood and drought risks within cities. By embracing nature-based solutions and sustainable urban planning, Europe is not only striving to protect its natural heritage but also ensuring the safety and well-being of its urban populations in an era of climate uncertainty.

Urban Heat Islands and the Role of Greening Cities

The Urban Heat Island (UHI) effect refers to a distinct urban climate characterised by higher temperatures in densely built-up areas compared to their surroundings. This phenomenon is primarily caused by human activities altering the natural environment, such as constructing buildings and impervious surfaces. These alterations result in increased heat capacity, trapping more energy and radiation, leading to temperature rises. Urban layout and morphology also play a role by intensifying the absorption of shortwave radiation and trapping longwave radiation, further increasing heat storage in cities. Anthropogenic activities like heating and transportation contribute to higher heat emissions in urban areas compared to natural landscapes.

Global warming and urban expansion are expected to worsen the UHI effect and its associated health risks, impacting not only extreme heatwaves but also more frequent, moderate temperature increases. To address this, green infrastructure, including urban vegetation, has a cooling effect that can mitigate UHI.

Recommendations, such as the Nature Restoration Law, suggest a minimum of 10% tree canopy cover, while others propose 30% to enhance microclimates, air quality, and public health.

6.2.2 Description of the use case

Definitions
For the purpose of this use case, we will refer to the following definitions: **Temporal resolution** Very High Resolution (VHR): < daily High Resolution (HR): >= daily and < monthly Medium Resolution (MR): >= monthly and < seasonal Low Resolution (LR): >= seasonal **Temporal extent** Short Extent (SE): < 10 years Medium Extent (ME): >= 10 years and < 30 years Long Extent: >= 30 years

The objective of this use case is to describe how Copernicus data, services and derived products can be used to monitor greening cities.

Abstract
Impact Pathways: wealth decrease; economic losses; reduced productivity; social, financial and political instability; disease & public health risks. **Key Adaptation Activities:** Hard (green roofs, green walls, tree and green areas), soft (incentives, planning), accommodation (technical, social, knowledge), ecosystem based (natural and protected areas). **Potential EO Value:** Physical monitoring of the green cover dynamics (optical, SAR, models). Hazard products both predictive, near real time and historical. Vulnerability products including land cover, green and natural areas, impervious surfaces, topography, flood hazard (optical, SAR, models). Exposure products and inventories (optical, SAR, models). **Key Risk/Adaptation Indicators:** Percentage of new green areas, accessibility to public recreation sites, variation rate of the municipality surface area covered by protected areas.

A recent paper by Marando et al. (2022) explored the role of urban green infrastructures in mitigating UHI effects in 600 European cities. The study found that urban vegetation has an average cooling effect of 1.07 °C, up to 2.9 °C, but in order to achieve a 1 °C drop in urban temperatures, a tree cover of at least 16% was required. Overall, the authors found cities with low cooling (0-1 °C) concentrated in southern regions, other than Belgium, Netherlands and Poland. Cities with an intermediate degree of cooling (1-2 °C) were more widespread in continental Europe. Furthermore, cities with a high degree of cooling (>2 °C) were in most continental areas and Italy along the Apennines.

Similar studies confirm the beneficial increase of urban vegetation. For example, D'Isidoro et al.(2023) showed how urban vegetation affects meteorological variables, such as temperature, relative humidity, and wind speed, in Bologna, Milano, and Madrid. The investigation described that vegetation in urban areas reduces temperature and wind speed and increases relative humidity. Geletič et al. (2022) studied the impact of green cover on the human physiological response to the thermal environment. The study reported a reduction of the Universal Thermal Climate Index (UTCI) of 4.1 K under tree crowns and 0.6 K on average in the neighbourhood as a day-time average, peaking at about twice these values near midday. Moreover, the authors emphasised trees' highly localised microclimate effects for pedestrian thermal exposure reduction (with temperature reductions of more than 5 K in some locations under trees and neighbourhood-average air temperature reduction of up to 0.3 K). They concluded that combining green walls and roofs yielded negligible results regarding UTCI reduction and only minor air temperature effects. Similarly, the previous work by Tsiros (2010) demonstrated that urban trees could significantly mitigate sweltering summers with light winds in urban areas. The author described an average cooling effect in Athens up to 2.2 °C in streets with high tree-shaded areas and minimal traffic load.

On the effects of greening cities, Lungman et al. (2023) proposed a quantitative health impact assessment for the summer of 2015. The authors found that 6,700 premature deaths in 93 European cities could be attributed to the effects of UHI. They also estimated that increasing tree coverage to 30% in all cities would have produced an average cooling effect of 0.4 °C, thus preventing 2,644 premature deaths, corresponding to roughly 1.8% of all summer deaths in the cities considered in the study. Lungman et al. (2023) also found that cities with the highest mortality attributable to UHI effects were in southern and eastern Europe (Spain, Italy, Hungary, Croatia, and Romania). In contrast, those with the lowest mortality attributable to UHI effects were mainly in northern Europe (Sweden, Estonia, the UK, and northern France). A similar pattern was noted for mortality that could be prevented by increasing tree coverage.

6.2.3 Application needs

The Biodiversity Strategy to 2030 and the Nature Restoration Law set ambitious goals for sustainable urban green planning by increasing cities' climate resilience with green cover and other permeable surfaces.

The policy context sets clear indicators and thresholds to measure the progress over time, such as:

- No net loss of green urban space by 2030;
- Increase in the total area covered by green urban space: 3% by 2040, 5% by 2050;
- Net gain of urban green space integrated into existing and new buildings and infrastructure developments;

All the targets mentioned above can be monitored with today's EO systems.

Generic application needs:

Application Need 1: [Vulnerability, Exposure] An explicit, standardised vulnerability and exposure products for all European cities, based on the existing Copernicus products/services and Eurostat statistics, would be extremely valuable. Alternatively or in addition tools that facilitate users to derive suites of vulnerability and exposure products would have high value.

Application Need 2: [Vulnerability, Exposure] Availability of a routinely calculated geospatial change product over time, for both vulnerability and exposure components, would be of high user value. Automated change detection in both risk components, on an ongoing basis, would greatly facilitate adaptation monitoring and the implementation of adaptation pathways.

Application Need 3: [Risk] Combined risk indicators need to be made routinely available across the necessary spatiotemporal and value-added intelligence ranges, as detailed below. These cascade from geospatially-explicit, hazard-specific risk indicators; combined geospatially-agnostic, hazard-specific risk indicators; composite geospatially-agnostic, hazard-agnostic risk indicators & frameworks.

Application Need 4: [Risk] Risk indicators need to be made available in an appropriate range of metrics for key user archetypes, e.g. potential or realised economic damage; public health risks and other suitable key indicators.

Application Need 5: [Semantics] Users frequently cannot access appropriate information, or struggle with information that they are uncertain of how to use. A key aspect of the EO value chain is the last part – the interfaces that users interact with to gain understanding and knowledge. Realising full value of the EO knowledge offering requires the ongoing development of community-driven, iterative, aspirational, enabling Decision Support systems, driven by strong user co-design. Creating a strong two-way dialogue between providers and users aids in identifying the best solutions, speeds development, and results in much increased uptake (Virapongse et al., 2020).

Specific application needs:

Application Need 1: [Hazards] Green cover dynamics need to be made available to policy makers and investors in a simple and timely manner.

Application Need 2: [Hazards] Extreme heat information in urbanized areas needs to be made available on a historical, phenological basis, e.g. as a climatology/anomaly; as a component of a predictive short term Early Warning System; and as a component of future climate scenarios.

Application Need 3: [Vulnerability, Exposure] Easy access to data, information and models at the regional and municipality levels needs to be made available to help identify effective long-term solutions to different climate risks.

Application Need 4: [Semantics] Indicators should be able to support the mapping of areas prone to natural hazards that could benefit from a greener landscape (e.g., floods, droughts, heat).

Application Need 5: [Semantics] Indicators should be able to suggest where to place new/regenerated urban green areas.

Application Need 6: [Semantics] Indicators should be able to encourage the use of drought-resistant native plants in urban landscaping to conserve water resources.

Given the abovementioned objectives, the application should focus on a local (sub-municipality) scale, with analyses at high spatiotemporal scales over a long period (Table 3).

Table 3. Objectives, spatiotemporal resolution, and user archetype intelligence dimensions.

Objectives	Spatial dimension	Temporal dimension	User archetype
Evaluation of green urban spaces net gain by 2030, 2040, and 2050 Developing green infrastructure networks in urban areas to absorb excess rainwater and reduce flooding Restore and preserve natural floodplains within and near urban areas to act as buffers during floods	Municipality level (main) Regional level (secondary) National level (secondary) EU level (secondary)	Short-term (secondary) Medium-term (main) Long-term (main)	Strategic: interannual policy-focused (primary) Tactical: intra-annual (secondary) Logistical: event to seasonal (secondary)

Source: Internal EC KCEO.

6.2.4 Technical assessment

The application should support the evaluation of progress in the greening of EU cities up to 2050 and in developing green infrastructures and natural floodplains to mitigate flooding. Ideally, the application should also support the reconstruction of the past evolution, predict future scenarios and evaluate local adaptation measures by integrating Copernicus products and services, thus maximising the added value of existing information sources and future operational services from EU-funded research when relevant.

The main indicator is green vegetation cover. Since urban and peri-urban green areas are often patchy, fragmented, and small-sized, their estimation requires very high-resolution data. This requirement implies a considerable commitment of resources to meet the application needs but is feasible from a technical point of view by integrating data imaged from satellites, aircraft, drones and street views.

That information should be integrated with very high-resolution layers on impervious surfaces and built-up obtained using EO data from visible or microwave sensors and supplemented with general land cover at high resolution. Moreover, topography (elevation) is linked with climate change resilience and vegetation development, and the proximity to natural and protected areas is another critical aspect, especially for flooding mitigation. This additional information can be derived from EO data as well.

Air quality and climate variables (precipitation, temperature, wind speed, and direction) are monitored with EO at low spatial resolution and impact both vegetation and human health. Besides, climate variables are also needed to project future scenarios.

In terms of temporal resolution, the evaluation should be carried out with a frequency appropriate to the nature of the observed indicators. For instance, the estimated vegetation cover should be ideally updated annually. The land cover, such as impervious surfaces, street networks, and transitions from impermeable to permeable surfaces, should be ideally updated with the same frequency.

The occurrence of natural hazards (floods) and the damage caused, instead, should be available more frequently.

Regarding the availability of time series, historical EO data are needed to evaluate progress against a reference baseline, and future projections are instead required to model long-term effects.

Finally, the overlapping of vegetation cover with climate variables, impervious surfaces, natural areas and socio-economic indicators such as statistics on demography, poverty and social exclusion, health, or population living in floodplain areas at a suitable scale should help monitor the respect of policy goals and, more broadly, adaptation to climate change.

Table 4 describes parameters of the environmental, climate and socio-economic dimensions derived from the specific application needs, along with the main physical parameters. Their minimum technical requirements on spatial resolution, temporal resolution, and time series length are also provided. This information was used to identify suitable existing EO services and products.

Table 4. Parameters and minimum technical requirements. (n/a = not applicable)

Parameter	**Spatial resolution**	**Temporal resolution**	**Temporal extent**
Main physical parameter			
Green cover	Very High Resolution 2	Medium-Low Resolution	Long Extent
Environmental dimension			
Land cover	High Resolution 2	Low Resolution	Medium Extent
Street networks	Very High Resolution 2	Low Resolution	Medium Extent
Impervious surfaces	High Resolution 1	Low Resolution	Medium Extent
Topography	Medium Resolution	Low Resolution	n/a
Flood hazard	High Resolution 2	Medium-Low Resolution	Medium Extent
Natural areas	Medium Resolution	Low Resolution	Medium Extent

Climate dimension			
Climate variables	Medium Resolution	Medium Resolution	Long Extent
Air quality	Medium Resolution	Medium Resolution	Long Extent
Socio-economic dimension			
Demographic statistics	DEGURBA (1)	Medium Resolution	Medium Extent
Poverty and social exclusion statistics	DEGURBA	Medium Resolution	Medium Extent
Health statistics	DEGURBA	Medium Resolution	Medium Extent
Population living in floodplain areas	DEGURBA	Medium Resolution	Medium Extent

(1) Applying the degree of urbanization (European Commission: Eurostat, 2021)

Source: Internal EC KCEO.

6.2.5 Value chain analysis

The use case focuses on policies that want to promote localised changes in the urban structure. Therefore, the spatial domain is the sub-municipality scale, and this assessment will consider the minimum technical requirements to achieve these goals.

In many cases, the products and services described in the next section provide parameters at a high spatial resolution suitable to produce aggregated indicators at the regional, national, or EU level but not at the primary sub-municipality scale. The reason is the patchy and fragmented nature of small urban green plots.

Breaking down the risk components to evaluate impacts and adaptation to climate change into hazard, exposure and vulnerability, the main hazards are:

- Occurrence and magnitude of floods: driven by extreme precipitation, wind, and impervious land cover, but mitigated by green cover and natural areas.

All the physical forcing phenomena can be evaluated and monitored using EO data. From a value-add perspective, hazard information should be available both for short term early warning, reanalysis of historical floods events, and future scenarios across a range of climate-driven forcing conditions and adaptation scenarios. Besides, the green cover development has additional impacts on drought and urban heat islands, which can be evaluated and monitored using EO data.

From an exposure and vulnerability perspective, we have parameters like:

- Population density;
- Availability, distribution and accessibility to green areas (public spaces, protected natural areas and recreational facilities);
- Use of drought-resistant native plants in built-up areas;
- Urban development and spatial planning;
- Population share living in flood-risk areas;
- Percent of low-income housing in flood-risk areas.

All exposures and vulnerabilities can be evaluated and monitored using EO data or by assimilating EO data with other socio-economic information. Critical aspects of vulnerability parameters should be closely linked to primary adaptation actions as given by the key type measures, including grey options such as physical flood defences, and green options such as rehabilitation of natural flood defences.

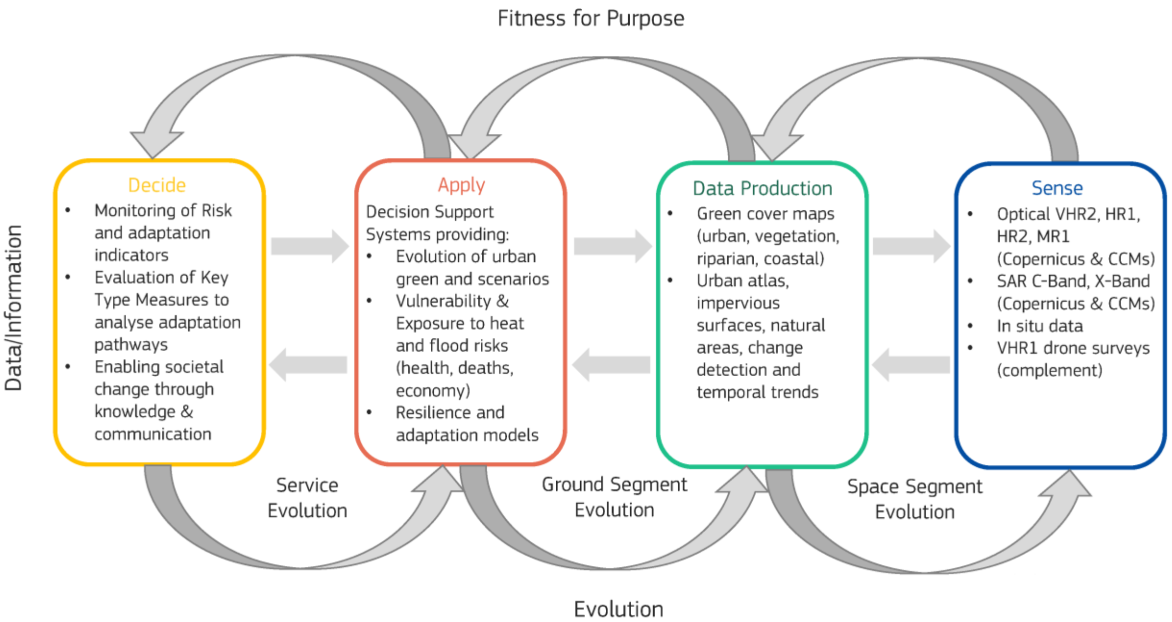
Hazard related impacts can be quantified, both for adaptation scenarios and extreme events, as:

- Impacts of climate change
    - Flood-related economic losses (number of residential and commercial properties flooded);
    - Reduced work productivity due to floods (number of people permanently displaced from homes);
    - Number of floodings-related mortality;
- Impacts of climate change adaptation
- Percentage of brownfield/grayfield redevelopment;
- Variation rate of the municipality surface area covered by Natura 2000 protected areas.

With many other indirect impacts available through a combination of EO and socio-economic data (Kilsedar et al., 2024).

Figure 7 shows the Earth Observation value chain (SAR=Synthetic Aperture Radar; CCMs= Copernicus Contributing Missions).

Figure 7. Earth Observation value chain for Greening cities.



Source: Internal EC KCEO.

6.2.6 Fitness for purpose of existing products and services

The fitness for purpose discussed below is based on the technical assessment (spatial resolution, temporal resolution, time series length), the products/services' thematic content, and fitness to application needs. The critical aspects of uncertainty and accuracy, as well as ratings of the overall quality of EO products/services, were not considered since they would require extensive analysis beyond the scope of this assessment.

Table 5 shows a summary of the results, andSource: Internal EC KCEO.

Table 6 summarises the fit to application needs of all technical requirements.

Table 5. Examples of EO-derived products and services that could contribute to the assessment. (n/a = not applicable, n/d = not defined)

Parameter	Service(s)/Product(s)	Spatial resolution	Temporal resolution	Temporal extent
Main physical parameter				
Green cover	Urban Atlas Street Tree Layer	500 m^2	6 years	2012, 2018
	High Resolution Layer Tree Cover Density	10 m, 20 m, 100 m	3 years	2012, 2015, 2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
	Vegetation	10m, 300 m	1 year	2014-present
	Small Woody Features	10 m, 100 m	3 years	2017-present
	Riparian Zones	0.5 ha	6 years	2015-2018
	Coastal Zones	0.5 ha	6 years	2012, 2018
Environmental dimension				
Street networks	OpenStreetMap	Undefined	Continual	n/a
Impervious surfaces	High Resolution Layer Imperviousness	10 m, 20 m, 100 m	3 years	2006-2018
	High Resolution Layer Impervious Built-up	10 m, 100 m	3 years	2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
Topography	EEA-10	10 m	Continual	Continuous
	GLO-30	30 m	Continual	Continuous
	SRTM	30 m	Continual	2000
Flood hazard	Copernicus Emergency Management Service	2500 m^2	On demand	2012-present
	JRC River flood hazard maps for Europe and the Mediterranean Basin region	100 m	n/a	>100 years return period
Natural areas	Natura 2k	0.5 ha	6 years	2006, 2012 and 2018
Climate dimension				
Climate variables	Precipitation (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present
	Wind speed and direction (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present

	CLMS Temperature (77)	5 km	1 hour, 10-day composite	from 2009, 2016, or 2017 depending on products
	CAMS global reanalysis (EAC4)	0.75°	3 hours	2003-2023
	Urban Heat Island Intensity for European Cities	100 m (downscaled)	1 hour	2008-2017
	CURE LST (78)	100 m (downscaled)	~3 days	2018-2019
Air quality	AIR-Portal (79)	100 m (downscaled)	n/d	n/d
Socio-economic dimension				
Population/population density	Eurostat data	DEGURBA	1 year	Different by region
Population grid	Global Human Settlement Layer (GHSL)	100 m, 1 km, 3 arcsec, and 30 arcsec	5-year intervals	1975-2020 (and projections to 2025 and 2030)
Demographic statistics	Eurostat data	NUTS3	1 year	Different by region
Poverty and social exclusion statistics	Eurostat data	NUTS2	1 year	Different by region
Health statistics	Eurostat data	NUTS2	1 year	Different by region
Population living in floodplain areas	European Environment Agency	WS04 subcatchment	n/d	n/a

Source: Internal EC KCEO.

Table 6. Fit for application needs. (n/a = not applicable, n/d = not defined)

Parameter	**Service(s)/Product(s)**	**Fit to application needs**
Main physical parameter		
Green cover	Urban Atlas Street Tree Layer	Spatial resolution: is unsuitable for monitoring the green cover at the tree level. Temporal resolution: does not fit the application's needs.

(77) CLMS temperature products: https://land.copernicus.eu/en/products/temperature-and-reflectance

(78) The CURE portal, funded by H2020 grant No.870337, provides services for urban resilience implemented in the Wekeo Copernicus Data and Information Access Services (DIAS). The Local Scale Surface Temperature Dynamics product generates daily land surface temperature maps for urban areas exploiting the Copernicus Sentinel-3 thermal acquisitions and detailed dynamic information on the land surface from Sentinel-2 and land cover/land use information from the CLMS and the atmosphere information from C3S. CURE provides a dense time series of intra-urban surface temperature variations (up to 4 maps per day) at a medium spatial resolution of 100 m.

(79) https://business.esa.int/projects/air-portal

		Temporal extent: does not fit the application's needs.
	High Resolution Layer Tree Cover Density	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
	Urban Atlas Land Cover/Land Use	Spatial resolution: is unsuitable for monitoring the green cover at the tree level Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
	Vegetation	Spatial resolution: most of the datasets fit the application's needs, and some datasets are sub-optimal. Temporal resolution: fits the application's needs. Temporal extent: fits the application's needs.
	Small Woody Features	Spatial resolution: fits the application's needs, even if the constraints on linear and patchy features might be sub-optimal. Temporal resolution: fits the application's needs. Temporal extent: does not fit the application's needs.
	Riparian Zones	Spatial resolution: is sub-optimal for the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
	Coastal Zones	Spatial resolution: is sub-optimal for the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
Environmental dimension		
Street networks	OpenStreetMap	Spatial resolution: cannot be assessed; Temporal resolution: fits the application's needs; Temporal extent: n/a.
Impervious surfaces	High Resolution Layer Imperviousness	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: the available time series is suitable for assessing short-term trends. However, long-term analyses and assessments of urban adaptation to policies require observations over a more extended period.
	High Resolution Layer Impervious Built-up	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs (new product). Temporal extent: does not fit the application's needs (new product).

	Urban Atlas Land Cover/Land Use	Spatial resolution: is unsuitable for monitoring the green cover at the tree level Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
Topography	EEA-10 GLO-30 SRTM	Spatial resolution: all products fit the application's needs. Temporal resolution: n/a. Temporal extent: n/a.
Flood hazard	Copernicus Emergency Management Service	Spatial resolution: fits the application's needs, but the spatial extent might not be sufficient for large-scale events. Temporal resolution: the temporal resolution is not pre-defined. Products are made on demand. Temporal extent: does not fit the application's needs.
	JRC River flood hazard maps for Europe and the Mediterranean Basin region	Spatial resolution: fits the application's needs. Temporal resolution: n/a. Temporal extent (return period): fits the application's needs.
Natural areas	Natura 2000	Spatial resolution: is sub-optimal for the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs. However, it is close to that of Copernicus Emergency Management Service.
Climate dimension		
Climate variables	Precipitation (C3S Agrometeorological indicators) Wind speed and direction (C3S Agrometeorological indicators) Temperature (C3S Agrometeorological indicators)	Spatial resolution: all products do not fit the application's needs; Temporal resolution: all products fit the application's needs; Temporal extent: all products fit the application's needs.
	Land Surface Temperature (LST)	Spatial resolution: does not fit the application's needs. Temporal resolution: fits the application’s needs. Temporal extent: does not fit the application's needs.
	CAMS global reanalysis (EAC4)	Spatial resolution: does not fit the application's needs. Temporal resolution: fits the application’s needs. Temporal extent: the available time series is suitable for assessing medium-term trends. However, observations over a longer time are needed for long-term analyses.
	CURE LST	Spatial resolution: fits the application needs. Temporal resolution: fits the application needs.

		Temporal extent: doesn't fit the application needs.
	Urban Heat Island Intensity for European Cities	Spatial resolution: fits the application needs. Temporal resolution: fits the application needs. Temporal extent: doesn't fit the application needs.
Air quality	AIR-Portal	Spatial resolution: fits the application's needs; Temporal resolution: fits the application's needs. Temporal extent: n/d.
Socio-economic dimension		
Population/population density	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Population grid	Global Human Settlement Layer (GHSL)	Spatial resolution: data have different spatial scales. Overall, they do not fit (or are sub-optimal for) the application's needs. Temporal resolution: is sub-optimal for the application's needs. Temporal extent: fits the application's needs.
Demographic statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Poverty and social exclusion statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Health statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs.

		Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Population living in floodplain areas	European Environment Agency	Spatial resolution: is sub-optimal for the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.

Source: Internal EC KCEO.

6.2.7 Gap analysis

Operational EO products/services and additional socio-economic statistical data useful for the assessment are already available. Nevertheless, there are still some significant gaps to meet the applications' needs.

It is to be mentioned that the uncertainty and accuracy of EO products could not be considered and are beyond the scope of this assessment. Thus, no recommendations can be made in this respect.

Spatial resolution

- The main limitation in monitoring the policy goals related to greenifying cities is that all the existing products on green areas mapping (Urban Atlas Street Tree Layer, Urban Atlas Land Cover/Land Use, Small Woody Features, Riparian Zones, and Coastal Zones) do not have enough spatial detail to map individual trees. Some others (e.g. Natura 2000) are sub-optimal for the use case. Besides, Urban Atlas products need to cover all cities, towns and suburbs in the EU.
- Integrating satellite-based layers with sub-metric data from Copernicus Contributing Missions (e.g. WorldView-3, Pléiades Neo, Vision-1) and drone surveys will increase the mapping capabilities of vegetation inside cities, thus enhancing the green cover net gain assessment;
- Climate variables are much too coarse for the application's needs. However, some variables (e.g. air quality or temperature) are available with a finer spatial detail through services that use downscaling methods;
- OpenStreetMap's spatial accuracy changes from one place to another and cannot be evaluated. Nevertheless, some studies show its overall quality is pretty good [a, b, c]; for that reason, OpenStreetMap is the most used Volunteered Geographical Information;
- Socio-economic indicators are essential for evaluating exposure and vulnerability to climate change, and Eurostat delivers valuable information. Nevertheless, even if some Eurostat data is being gridded at 1 km spatial resolution, the standard territorial units for their statistics are defined by the average population size and not on a geospatial scale. A closer match between Eurostat's spatial extent and EO-derived products' spatial resolution will significantly improve the analysis at the municipality scale;

Temporal resolution

- Similarly to spatial resolution, all the existing products on green areas mapping (Urban Atlas Street Tree Layer, Urban Atlas Land Cover/Land Use, High Resolution Layer Tree Cover Density, Small Woody Features, Riparian Zones, and Coastal Zones) do not have enough temporal resolution to follow the greening dynamics. Also, additional land cover layers (High Resolution Layer Imperviousness and High Resolution Layer Impervious Built-up) are not updated frequently enough. Ideally, an annual update is desirable to monitor periodic changes in green cover.

Temporal extent

- The limited temporal extent of all land cover products is insufficient for reliable trend analyses today.

Spectral resolution

- Concerning the additional goal of encouraging the use of drought-resistant native plants in urban landscaping, one technological limitation is the spectral resolution of data. The supplement of hyperspectral surveys from low-altitude aircraft, drones and (future) satellite missions will increase the diagnostic capabilities of vegetation health and pave the way for new products on plant species layers.

Final remarks

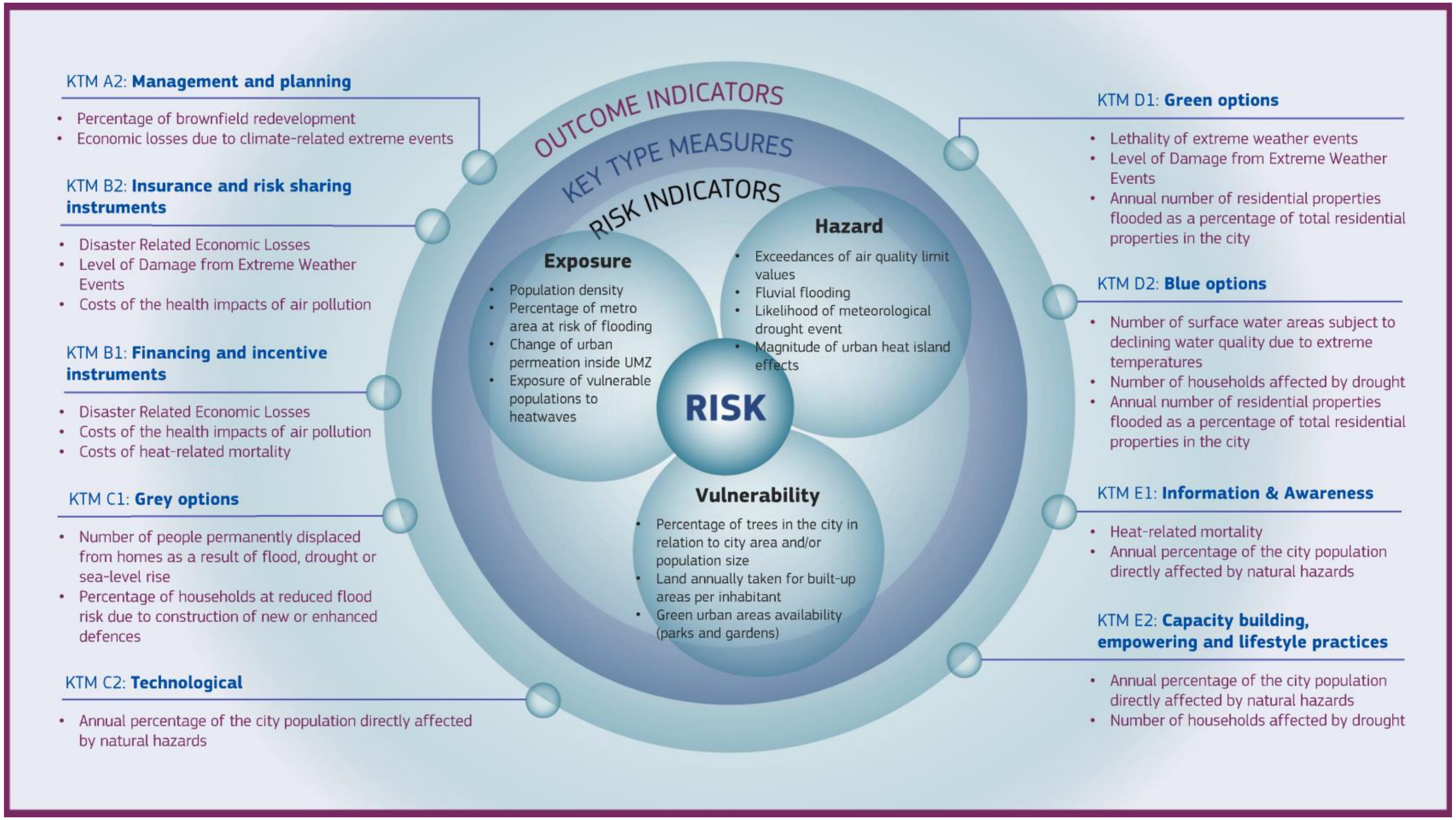
It is to be mentioned that any information, product, map or analysis should be made readily available to managing authorities in a user-friendly dashboard. Digital twins can be another tool to support local authorities with little knowledge of geospatial sciences in decision-making.

It is also to be mentioned that for EO data and services to help assess the effects of climate change adaptation policies, ensuring the continuity of the products and services reviewed for at least the policies' time horizon is necessary. In the present use case, policies set goals for 2030, 2040, and 2050. Thus, data continuity should be provided until 2050.

6.2.8 Monitoring risk, adaptation and outcome

Figure 8 shows an illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators. The schematic aims to bring out the applicability of Earth Observation in the Climate Adaptation aspects of Risk Assessment (comprising the components of Hazard, Exposure and Vulnerability); of the climate action reporting framework of Key Type Measures; and the outcome of this action through pertinent indicators (all indicators within are EO-addressed). Moreover, it aims to encapsulate the discussion in the Indicators chapter and link it with each Use Case through an illustrative example of a particular hazard, a traditional starting point for Risk Assessments and identification of adaptation measures, in essence presenting the Earth Observation ‘value proposition’ to the adaptation cycle (e.g. contributing to steps 2 till 6 in Climate-ADAPT’s Adaptation Support Tool). The schematic does not aim to paint Earth Observation as a cure-all. Dozens of indicators and KTMs are solely dependent on socio-economic data and many will remain unapproachable by EO alone. Nevertheless, the schematic, as does this assessment as a whole, advocates for the Earth Observation potential in direct monitoring (the bane of most adaptation frameworks) of the above but also in overall support through contributing in e.g. monitoring the presence of KTMs, designing KTMs and allowing for more harmonized and more frequent risk assessments.

Figure 8. DG ENV – Greening cities. Illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators.



Source: Internal EC KCEO.

This use case featured in the DG ENV use case on greening cities has no specific risk. Nevertheless, urban greening is paramount in mitigating several hazards; thus, this illustrative example focuses on extreme heat, droughts and floods.

When it comes to the risk factors, Earth Observation provides a straightforward approach: satellite observations supplemented by in situ measures, climate projections, and modelling, deliver time series of risk indicators at different spatial and temporal scales. Estimation of vulnerability and exposure require integrating socio-economic datasets with hazard maps and landscape attributes. The former, among other things, are mainly provided by Eurostat, while the latter, among other things, are provided primarily by the Copernicus products and services reviewed in the previous sections. Again, Earth Observation plays an essential role in supporting their quantification.

Turning to sub-KTMs and their outcome, only those in which Earth Observation has a potential role are here represented:

- Green options (D1) & Blue options (D2): Green options (D1) & Blue options (D2): these measures are vital for mitigating extreme temperatures (both heat waves and cold spells) and droughts. Earth Observation provides instruments for directly monitoring the policy's outcomes over time (e.g., new percentages of green cover and their spatial patterns) and evaluating urban adaptation to climatic risks. For instance, the lethality of extreme weather events, the level of damage from extreme weather events, or the annual number of residential properties flooded as a percentage of total residential properties in the city. Or provide information on the number of surface water areas subject to declining water quality due to extreme temperatures, the number of households affected by drought, or the annual number of residential properties flooded as a percentage of total residential properties in the city.
- Grey options (C1): this measure is not relevant to the primary use case objective but to the related hazards. Again, Earth Observation can provide valuable insight in estimating the number of people permanently displaced from homes as a result of flood, drought or sea-level rise, or the percentage of households at reduced flood risk due to construction of new or enhanced defences.
- Management and planning (A2): incorporating Earth Observation can add value, for instance, in estimating economic losses due to climate-related extreme events, or the percentage of brownfield redevelopment.
- Financing and incentive instruments (B1) & Insurance and risk sharing instruments (B2): in incentives/insurance domains, Earth Observation can help estimate the level of damage from extreme weather events, thus disaster-related economic losses, costs of the health impacts of air pollution, and costs of heat-related mortality.
- Information & Awareness (E1) & Capacity building, empowering and lifestyle practices (E2): in this case, Earth Observation can significantly contribute to the production of hazard maps and evaluating heat-related mortality, the annual percentage of the city population directly affected by natural hazards, or the number of households affected by drought.

6.2.9 Recommendations

One critical goal of this assessment is to support DG ENV in promoting and supporting greening European urban areas in the framework of the Biodiversity Strategy to 2030 and the Nature Restoration Law. Specifically, this strategy both addresses the protection and restoration of natural ecosystems, and the critical role of urban areas in building resilience against climate-related hazards.

In this context, Earth Observation is essential for comprehending environmental systems and evaluating feedback loops and impacts in urban and peri-urban areas.

Usable intelligence derived from Earth Observation data has advanced significantly. However, gaps still exist, and the analysis has identified the following areas where improvements might facilitate the uptake of EO products and services for urban climate adaptation at the European, national and local scales.

On the evolution of Copernicus, recommendations include the promotion of:

- Further development and integration of temperature modelling, such as the UrbClim or CURE models, bringing them to operational products and services into the Copernicus ecosystem. This is crucial for building better interpretative and predictive models.
- Further processing/re-processing of high/very-high resolution data collected before Copernicus from the Member States' national and international programs to build a more extended time series. This is crucial for creating more reliable retrospective analyses and for extrapolating future trends.
- Further development of Copernicus Urban Atlas and high-resolution land cover and green cover products (e.g. Small Woody Features, Riparian Zones, Coastal Zones, Urban Atlas Street Tree Layer, Urban Atlas Land Cover/Land Use), with the ideal goal of annual update cycles (plus one-year latency). This is crucial for enhancing the description of the land cover dynamics and, thus, improving the estimation of the Vulnerability and Exposure components.
- Further development of all relevant change detection products (e.g. Tree Cover Change Mask, Urban Atlas Land Cover/Land Use Change, Imperviousness Change, Imperviousness Classified Change), with the ideal goal of annual update cycles (plus one-year latency). This is crucial for highlighting hot spots and fast land changes, thus focusing and prioritizing high/very-high resolution data collection.
- Further integration with Eurostat statistical data and ask the statistical institute to produce data with a finer granularity. This is crucial for bringing the socio-economic dimension into the models and better evaluating the Vulnerability and Exposure components.
- Further integration of sub-metric data from Contributing Missions (e.g. WorldView-3, Pléiades Neo, Vision-1) into Copernicus products and services. This is crucial for improving the mapping capabilities within cities, thus enhancing the overall monitoring capability. Moreover, small-scale drone surveys might supplement mapping at the single-tree level. However, the cost-benefit of such action has to be carefully evaluated, but this is beyond the scope of the deep dive.
- Integration of future Copernicus Expansion Missions (e.g. Copernicus Hyperspectral Imaging Mission for the Environment, Copernicus Anthropogenic Carbon Dioxide Monitoring). This is crucial for improving the main physical variables observed.

On the risk side, recommendations include the promotion of:

- Advanced adaptation scenario modelling capacity for all European cities, under a range of KTM-classified adaptation and hazard scenarios.
- Indicators that could be used across different use cases (e.g. urban heat island, drought and floods in European cities).
- Combined risk indicators for key user archetypes (e.g. potential or realised economic damage, population affected, public health risks) (Kilsedar et al., 2024).

On the policy-making side, recommendations include the promotion of:

- User-friendly web-based dashboards that integrate available information into specific, quantitative, measurable, and standardized indicators. This would provide give policymakers and local authorities, non-EO experts, simple effective tools to make better decisions and evaluate *ex post* impacts of their policies. In this regard, Destination Earth could be an appropriate platform to provide a common framework for the provision of such indicators and services. The Destination Earth digital twins, specifically the climate adaptation digital twin and weather-induced extremes digital twin, in conjunction with information from the European Data Spaces ecosystem provide significant potential to realise the necessary extension of the EO value chain. The identification of user needs – most specifically around key type measure focused decision making - is an important first step in supporting the co-design of tailored services for EC policymakers.
- Increased use of EO-derived indicators within Member States' national legislation. This is crucial to accelerating Copernicus information, products, and services uptake.
- Further use, in future policy documents, of specific and quantitative indicators that can be measured with Earth Observation or are EO-based, as evaluation metrics. This is crucial to have *ex ante* measurable parameters.
- Dissemination to politicians, national authorities and local administrators of the potential of Earth Observation and geodata. This is crucial as a whole.
- It is also worth noting that to help assess the effects of climate change adaptation policies, continuity of the products and services reviewed is necessary for at least the policies' time horizon. In the present use case, since the Nature Restoration Law sets goals up to 2050, data continuity should be provided until 2050.

6.3 Urban Climate Adaptation from a Coastal Perspective (DG MARE)

Earth Observation Use Case: Urban Climate Adaptation from a Coastal Perspective

The Marine Spatial Planning Directive (MSPD) is a crucial instrument for promoting and managing sustainable development of marine areas and coastal regions. Whilst the MSPD does not provide policy obligations around urban climate adaptation, it does pertain to coastal urban growth and development in the context of the Green Deal, the Climate Adaptation Strategy, and the Sustainable Blue Economy approach. Coastal cities, facing ocean, terrestrial, atmospheric and hydrological climate-related hazards, are inherently exposed to high climate-compounded risks, manifesting in a complex, interactive web across ecological, financial and political issues. Critical adaptation issues, under the MSPD and associated policy frameworks, include integrating land-sea planning, promoting climate resilience in coastal urban areas, and the adoption of ecosystem-based approaches to protect both urban development and the natural coastal environment.

The priority coastal hazard addressed here is urban flooding, with additional short syntheses on eutrophication, erosion and marine heat waves. Earth Observation - based intelligence has much potential to meet key application needs such as coastal and compound flood inundation and potential damage across historical, scenario and early warning circumstances; dynamic vulnerability and exposure mapping coupled with change detection; and the use of models and indicators to guide nature-, knowledge-, and infrastructure-based adaptation. Many of the necessary products and services are available in an emerging sense through Copernicus and other European services – although not all in an optimal form for the required applications. The availability of local scale data (such as Digital Elevation and Terrain Models) for flood inundation mapping in urban areas is an important technical consideration.

There is a clear need to bridge gaps in both temporal and spatial observation and model resolution for urban applications; and semantic gaps through the development of Decision Support Tools offering actionable information in appropriate metrics. The value of exploratory scenario modelling with damage metrics to guide spatial adaptation planning is also highlighted. Earth Observation has a valuable potential role across a significant set of the Key Type Measures that represent a formalised spread of adaptation activities: most obviously Green, Blue, and Grey but also across Management-, Financial- and Information-related measures.

Key recommendations include the development of a range of key hazard products across a range of time scales; increased availability of more dynamic and hazard-specific vulnerability, exposure and automated change detection products; greater availability of standardised, operational risk indicators; more widespread use of adaptation scenario models and compound indicators; and the development of a coherent coastal adaptation planning community using actionable intelligence to exploit a greatly extended Erath Observation value chain.

6.3.1 Policy context

The Commission's 'Marine Knowledge 2020' Communication ([80]), provided a policy platform for DG MARE to further develop Marine Knowledge, a priority area that is relevant to Urban Climate Adaptation. The European Marine Observation and Data network provides harmonised *in situ* marine

([80]) Marine knowledge 2020 – Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – Marine knowledge 2020 marine data and observation for smart and sustainable growth – COM(2010)461 data which are relevant to the subject ([81]). Additionally, DG MARE, co-manages together with DG RTD the Mission Restore our Ocean and Waters by 2030 and is deeply engaged on the development of the European Digital Twin of the Ocean (DTO) core public infrastructure. In the framework of the DTO, there will certainly be requirements for the development of applications and scenarios relevant to Urban Climate Adaptation, utilising Earth Observation intelligence, including modelling capabilities and a range of management tools.

Maritime Spatial Planning (MSP) is recognized as an important instrument for promoting the sustainable development of marine areas and coastal regions, contributing to the restoration of Europe's seas to environmental health. The escalating competition for maritime space, driven by diverse activities like renewable energy production, oil and gas exploration, maritime shipping, fishing, ecosystem conservation, biodiversity preservation, raw material extraction, tourism, aquaculture installations, and underwater cultural heritage, poses a pressing need for an integrated planning and management approach. The EU MSP Directive, adopted by the European Parliament and the Council of the European Union in 2014, establishes a framework for MSP and lays down a set of minimum common requirements ([82]), and requires 22 coastal MS ([83]) to produce MSPs for the marine waters under their jurisdiction. The Directive is embedded in the EU Integrated Maritime Policy (IMP) designed to develop coordinated, coherent and transparent decision-making in relation to EU's sectorial policies affecting the oceans, seas, islands, coastal and outermost regions and maritime sectors. The Directive identifies MSP as a cross-cutting policy tool, which enables public authorities and stakeholders to apply a coordinated, integrated transboundary approach (Friess & Grémaud-Colombier, 2021). MSPD lays down the obligation to establish a maritime planning process, which should consider land-sea interactions, public consultation requirements, the use of best available data, and cross-border cooperation with non-EU countries. In line with the subsidiarity principle, it focuses on processes while leaving content largely in the hands of the Member States, which have the responsibility to provide the format and content of the resulting MSPs, including any allocation of maritime space to various activities and uses.

The Common Fisheries Policy (CFP) and the Marine Spatial Planning Directive (MSPD) refer exclusively to marine waters, with no direct reference to land and particularly urban environments, other than through inexplicit synergies with coastal zone management – and no policy obligations. Although there is no explicit reference to urban settings and urban climate adaptation in the definition of the plans, urban issues within the MSPD pertain to strategies and considerations for accommodating urban growth and development along coastal areas in the context of more recently communicated EU policy frameworks and related missions. Of particular importance are the Green Deal (2019), the Climate Adaptation Strategy (2021), and the Sustainable Blue Economy approach (2021). Three of the five EU Missions are also very relevant here: Mission 1 – Adaptation to Climate Change; Mission 4 - 100 Climate-Neutral and Smart Cities by 2030; and Mission 3 – Restore our Ocean and Waters by 2030. This last mission is of particular importance to DG MARE, and directly addresses nature-based solutions (NbSs) for enhanced coastal resilience, emerging platforms such as the DTO, and many other multi-dimensional pressures and conflicts relating to the MSP process and coastal climate resilience.

The minimum requirements for Member States (cf. In particular Articles 4-7, 10-12 of the Directive) include:

- Involvement of stakeholders

([81]) Commission Staff Working Document evaluation of the European Marine Observation and Data Network (EMODnet) - SWD(2023) 281 final

([82]) Directive 2014/89/EU

([83]) The MSP Directive does not apply to landlocked Member States.

- Apply an ecosystem-based approach
- Organise the use of the best available data and share information
- Account for land-sea interaction
- Promote the co-existence of activities and coherence between maritime spatial planning and the resulting plan(s) and other processes, such as the integrated coastal management or equivalent formal or informal practices
- Develop cross-border cooperation between Member States
- Promote cooperation with third countries

Three points could explain where urban climate adaptation could fit in the context of the MSPD:

1. Integrated Land-Sea Planning: The Directive encourages Member States to adopt an integrated approach to MSP, taking into account both land-based and sea-based activities. Urban adaptation involves considering how coastal cities and urban areas interact with adjacent marine environments. This can include mapping out urban expansion areas, setting guidelines for sustainable urban development near the coast, and identifying areas at risk from coastal hazards like sea-level rise and storm surges.

2. Climate Resilience: Urban adaptation within the directive emphasizes the need for coastal cities to adapt to the impacts of climate change. This includes measures to increase the resilience of urban infrastructure, such as designing coastal cities to withstand rising sea levels, more intense storms, and other climate-related challenges. The directive encourages Member States to incorporate climate resilience and adaptation strategies into their maritime spatial plans to protect urban areas along the coast.

3. Ecosystem-Based Approach: The directive promotes an ecosystem-based approach to maritime spatial planning, which considers the interconnectedness of marine and terrestrial ecosystems. In the context of urban adaptation, this means safeguarding coastal ecosystems and habitats that provide natural buffers against coastal erosion and flooding. It also involves implementing green infrastructure solutions within urban areas, such as the creation of coastal wetlands or dunes, to enhance urban resilience while preserving natural environments.

In addition, this assessment has the potential to add significant value around the process- and platform-pertinent aspects of the MSP directive, particularly given the post-2014 emergence of both climate-relevant policy frameworks and new EO-based knowledge streams. Relevant MSP articles are: the involvement of stakeholders; best available use of data and shared information; the promotion of the co-existence of activities and coherence between maritime spatial planning and the resulting plan(s) and other processes; and cross-border cooperation between Member States.

Finally, the Member States are required to review the plans at least every 10 years (Art. 6). The Directive mandates that EU Member States formulate MSPs by 31 March 2021. These plans are expected to delineate current human activities in their marine waters and outline the most efficient spatial development for the future. However, there are some challenges to using the current MSPs as the sole policy context driver, beyond those already discussed around the lack of explicit climate-related policy obligations and the emergence of more recent climate-focused policy frameworks. Four Member States (Croatia, Cyprus, Greece and Italy) are under infringement procedures by the European Commission for their failure to implement MSPs by 2021. Few MSPs have content relating to climate adaptation, and there is very little focus on urban climate adaptation ([84]). Several WWF reviews of the completeness of the MSPs at the basin scale (WWF 2022A – C, WWF 2023) also highlighted additional challenges and points of leverage for the ongoing MSP process from the perspective of this assessment:

- The integration of multiple policies, directives, frameworks and missions was identified as a significant challenge in MSP development, especially in a retrospective sense. This highlights the need and difficulties of addressing the Green Deal, Climate Adaptation, and Sustainable Blue Economy policy frameworks from an MSP perspective.
- Implementation of the MSP directive was generally recognised as being extremely challenging, particularly with regard to conflict in maritime spatial use.
- All the WWF studies identified poor cross-boundary cooperation apart from the Baltic – this cross-boundary approach and basin scale MSP coherence was identified as critically important to effective MSP implementation
- The continued absence of an ecosystem-based approach (EBA) in the majority of the MSPs makes it difficult for the EU and neighbouring regions to address the impacts of climate change. The general lack of EBA mechanisms greatly limits the regional ability to deal with scenarios addressing the spatial and temporal uncertainties of climate change, and potential negative impacts on the sustainable management of ecosystem goods and services.

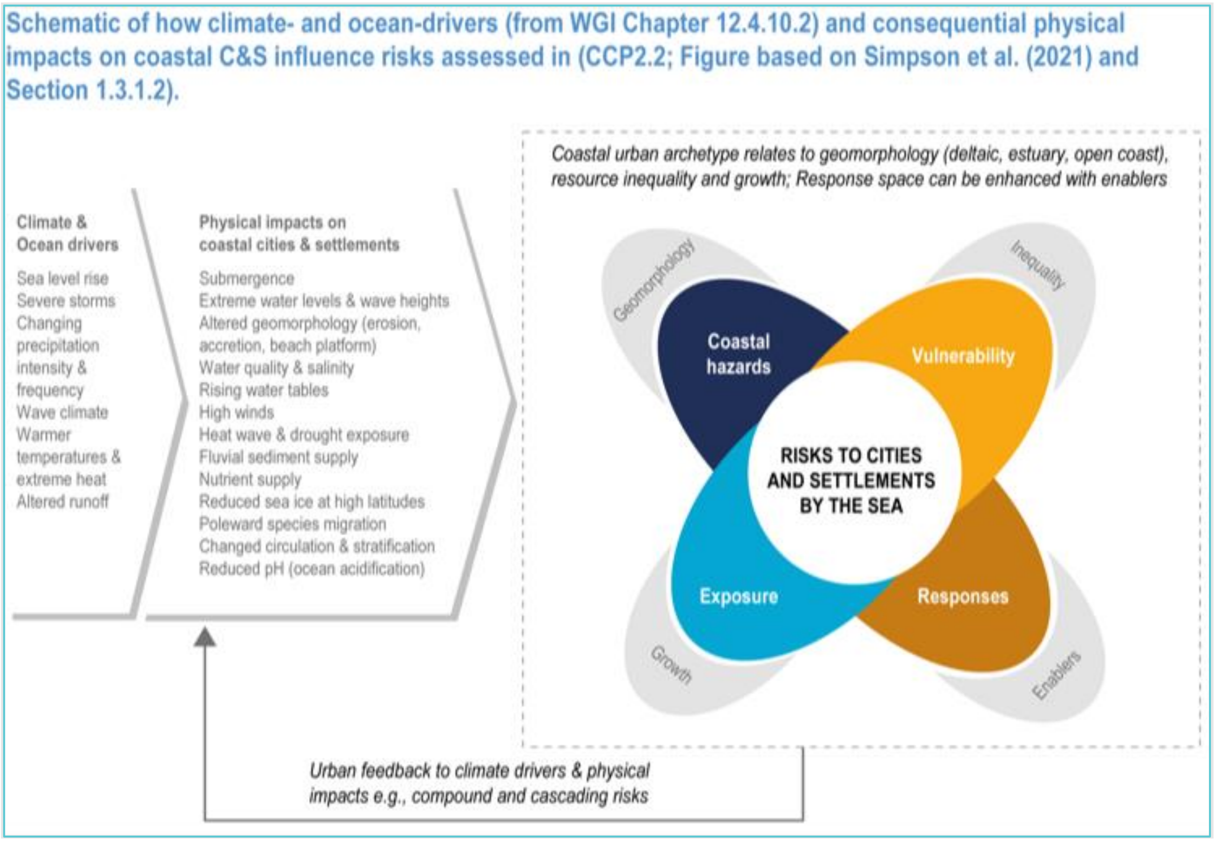
Urban climate adaptation in the MSPD primarily involves integrating land-sea planning, promoting climate resilience in coastal urban areas, and facilitating the adoption of an ecosystem-based approach to protect both urban development and the natural coastal environment. EU countries are obligated to utilize the most accurate and up-to-date economic, social, and environmental data in this process, using shared and collaborative intelligence platforms. This assessment will focus on these primary obligations, also informed by the subsequent three climate-relevant policy frameworks already discussed, assessing the EO value chain necessary for policy-driven impact.

6.3.2 Description of the use cases

A critical aspect of the use case is a clear understanding of how climate-related risk, resilience and adaptation can be understood and classified from a climate-hazard perspective, and systematically quantified from EO and other products. Figure 9 below offers insight into the range of climate and ocean drivers, their associated combined hazards, and the typical approach to deriving risk based on a combination of hazard, vulnerability and exposure.

([84]) CINEA: European Climate, Infrastructure and Environment Executive Agency annual Activity Report

Figure 9. Coastal climate-related combined risks and drivers from an IPCC perspective.



Source: IPCC WGII AR6, 2022.

It is clear that there are a suite of complex, interactive ocean and coastal drivers, resulting impacts, and associated hazards and risks for coastal urban centres. Examples of combined climate-related risk frameworks for coastal cities (Roukounis & Tsihrintzis, 2022; Rouleau et al., 2022) also present a complex, interactive web of risks, typically across ecological, financial and political thema. Coastal cities and settlements are inherently exposed to some of the highest climate-compounded risks, facing ocean, terrestrial, atmospheric and hydrological climate-related hazards. Physical ocean drivers include extreme sea level, increased severity of storm and wave events, changing ocean hydrodynamics and circulation, and marine heat waves. Associated changes in ocean acidification and ecosystem function will lead to significant changes in biodiversity, affecting all coastal ecosystem services, impacting on food security and coastal vulnerability as examples. These in turn lead to risks to maritime and industrial ocean and coastal activities, including shipping, energy and extractive services – and to cultural services such as tourism and recreation. These in turn compound and cascade into a wide range of economic, social and political risks (Chapter 5, Rouleau et al. (2022)).

Many such risks are not uniquely coastal or marine/maritime specific and can be found across a multitude of climate risk frameworks (Chapter 5), and many of the coastal risks are driven somewhat indirectly from an urban perspective, e.g. loss of food security due to changes in offshore fishing productivity. Given this assessment's focus on urban climate adaptation, the first order analysis here will be driven by a detailed analysis of coastal and compound flooding, with a short overview of a smaller set of the most common coastal hazards with a more direct urban impact. However, it is also important to understand that whilst this hazard-driven approach is necessary to illustrate the EO value chain through thematic use cases, the adaptation focus of the assessment places a very strong emphasis on understanding vulnerability as a dynamic geospatial variable.

Adaptation has an intrinsic complexity, is highly context- and locale-specific, and the absence of appropriate datasets has been clearly identified as a barrier to the required scalable intelligence (Michetti et al., 2021). As previously discussed in Section 2C, adaptation pathways, primarily addressed here through the use of the European Environmental Agency's Key Type Measures (Leitner et al., 2021), play an important role in analysing the Earth Observation value chain.

Use Case 1: Coastal Flooding

Coastal Flooding
Impact Pathways: loss of life; damage to property, infrastructure and services; displacement and loss of habitation; loss of economic capability; social, financial and political instability; disease & public health risks…
Key Adaptation Activities: Hard (built infrastructure), soft (rehabilitation and nourishment), accommodation (technical, social, knowledge), ecosystem based (nature based solutions), managed retreat (Bongarts Lebbe et al., 2021)
Potential EO Value: Physical hazard drivers of extreme sea level (altimetry, tide gauges, models), storms & waves (scatterometers, SAR, altimetry, optical, models). Flood hazard products, both predictive (storm surge & scenario models) and near real time/historical surface flood extent (SAR, optical, models). Vulnerability sub-product ranges, e.g. land cover, impervious surfaces, topography (optical, SAR, lidar, models). Exposure products and inventories (optical, SAR, models)

Risk Overview

Climate induced coastal flooding presents significant risks to populations and infrastructure in low lying coastal areas, with estimates of >700 million people and US$13 trillion of economic assets exposed (Kirezci et al., 2023). Major contributing processes affected by climate change are extreme sea levels (ESL); and storm, circulation, tidal and wave induction patterns – with complex non-linear interactions and potentially compounded by anomalously heavy precipitation and riverine overflow (ibid.). In addition, many natural coastal flooding defences are under threat or degraded by climate change or unsustainable development, increasing vulnerability of coastal settlements and infrastructure. Coastal flood risks in 2100, with no additional adaptation measures in place, are considered to be 2-3 times higher than present (Glavovic et al., 2022). Estimates of affected people in 2100 range up to 246 million globally (increasing from 34 million in 2015), with analogous annual damage estimates of 2.9% of global GDP (increasing from 0.3% global GDP in 2015) (Kirezci et al., 2023). Informed adaptation is critical e.g. substantial and appropriate increases in coastal defences could halve the number of affected people, and reduce economic damage by almost a third to ±1.1% of global GDP (ibid.)

Role of Earth Observation: Existing Use Case Examples

Destination Earth aims to build high resolution digital twins for climate services, and provides a comprehensive, leading-edge example of compound flood hazard modelling ([85],[86]). Both early warning (deterministic) and scenario modelling (probabilistic) are focused on with, with the latter providing the important ability to assess the potential impact of specific adaptation measures, e.g. as categorised by the EEA's Key Type Measures. The service integrates local weather forecasts, existing climate projections, wave datasets and discharge datasets. The deterministic hazard

(85) ECMWF 2023
(86) https://www.intertwin.eu/intertwin-use-case-deploying-floodadapt-a-digital-twin-for-flood-impact-modelling-anywhere-on-earth

products use a wide variety of Copernicus (ECMWF, ECFAS/GLOFAS, ERA5), Member State (MeteoFrance, UK MetOffice, KNMI) and international capabilities (CMIP, CORDEX, GFS, Wavewatch III). Aiming to ultimately use forcing data at 2km resolution to provide flood maps at 30m resolution, the study highlights the need to consider pluvial, fluvial and coastal flooding in a compound manner, and highlights the need for high resolution Digital Elevation Models (DEM). Early warning system examples (ECMWF 2023) focus primarily on hazard aspects, with additional and critical risk components of vulnerability and exposure not explicitly considered, as the users considered have significant technical expertise in this regard. Scenario-focused probabilistic examples (interTwin), specifically the FloodAdapt capability, allow the explicit combination of hazard, exposure and vulnerability parameters, producing damage and loss metrics, typically based on flood inundation and depth -damage parameterisations. Enabling the analysis of what-if scenarios, e.g. potential impacts of new flood defences or more extreme hazards, these capabilities can quantitatively guide the implementation of adaptation measures. It is important to note the critical role that satellite data from a range of sensors, and *in situ* data from tide & river gauges and other field stations, play in the calibration and validation of the suite of Destination Earth models.

Addressing both disaster management and climate hazards, the European Copernicus Coastal Flood Awareness System (ECFAS ([87])) showcases similar flood risk modelling capability, with additional impact quantification. Vulnerability sub-components include impact layers such as the exposed population, potential damage to building and infrastructure, and the exposure of other elements such as vulnerable ecosystems and land use classes. The existing information provided by different Copernicus Services was used extensively for the project implementation: the Coastal Zone layer from the Land Monitoring Service; products from CMEMS; ERA5 forcing from the Climate Change Service; and various EFAS capabilities from the Emergency Management Services. Additional altimetry and Very High Resolution (VHR) satellite data, and *in situ* data, were also used in different system components. Whilst the current focus is on the development of short-term forecasts, the approach also includes total water level (TWL) thresholding for varying return periods and can be used to model extreme scenarios. These capabilities, in combination with the emerging impact/vulnerability quantification based on the Coastal Zone Layer and other information, will be extremely valuable to coastal flood adaptation. As per the Destination Earth case above, critical calibration and validation for the predictive capability relies on a suite of appropriate satellite and *in situ* data.

Exploratory scenario modelling has been identified as a critical part of adaptation pathway design (Hamlington et al., 2023; Ramm et al., 2018). Examples for extreme sea level scenarios under CMIP6 low and high emissions scenarios, in the form of the amplification of 1-in-100-year flood events, are showcased at a Pan-European level ([88]). The planning of coastal defences, and other adaptation measures and pathways, will certainly require more detailed and higher resolution analyses, e.g. based on the data provided by the European advances on CLImate Services for Coasts and SEAs (ECLISEA) project (Acevedo et al., 2018). The Key Type Measures (KTMs) of the European Environmental Agency (Leitner et al., 2021) are the most useful formal structures for characterising adaptation actions in this regard.

From an emerging policy-driven research perspective, the PROTECT, CoCliCo and SCORE H2020 projects have provided a joint policy brief focusing on adaptation recommendations for coastal flooding (Le Cozannet et al., 2023). As shown in Figure 10, this provides a succinct overview on the necessary adaptation pathway process, focusing on the co-design and development process to establish operational climate services in response to sea level rise. Encompassing both flooding and

([87]) European Copernicus Coastal Flood Awareness System: the ECFAS project

([88]) EEA: Projected change in the frequency of historical 1-in-100 year coastal flooding events by 2100 erosion, key considerations include critical infrastructure, coastal landfills and soil contamination, conservation of cultural heritage, and critical coastal habitats.

Figure 10. "Engaging with adaptation to the range of sea-level rise possibilities: an ongoing process with priorities for today".

Source: Le Cozannet et al., 2023.

Ideal adaptation tools for coastal flooding will quantitatively combine hazard, vulnerability and exposure information to build risk assessment frameworks, and an excellent example of this is the Coast-RiskBySea (COASTal zones RISK assessment for Built environment bY extreme SEA level) (Clemente et al., 2022). Focusing on Naples for demonstration purposes, the case study exploits the Copernicus Coastal Zones database available through the Land Monitoring Service to derive both exposure and vulnerability. Hazard in the form of Extreme Sea Levels (ESL) values are considered as a combination of mean sea level plus high tide water levels and fluctuations due to extreme events such as wind-waves and storm surges (ibid.). These ESL data are available as a JRC database (Vousdoukas et al., 2018). The output risk maps from this combined approach are very user-friendly, important from a semantic perspective. The cellular approach used also has semantical appeal, with each cell containing potential economic damages in euros, elevation, land use and other user-critical information.

Other valuable aspects of the interTwin, Clemente et al. (2022) and the ECFAS studies are 1) that the damage is presented in an economic loss-and-damage metric, giving significant political traction and allowing first-order estimates of adaptation economic value, 2) a wide range of hazard (and implicitly mitigation) scenarios can be assessed, 3) the methods used are entirely scalable and based on available European open source data, with dependency on the availability of appropriate regional Digital Terrain Models (DTM). The DTM used in the Clemente et al. (2022) study has a spatial resolution of 1 m and an altimetric accuracy of ± 15 cm, derived from airborne LIDAR – an important consideration. In contrast to the necessarily very sophisticated modelling employed in the Destination Earth (ECMWF) and ECFAS studies, primarily focused on short term early warning application on the event scale, the approach employed by Clemente et al. (2022) uses a simplified and scalable approach (primarily based on pre-existing data) that is extremely well suited to adaptation scenario modelling. Both the ECFAS and the Coast-RiskBySea case studies showcase the high value of the Copernicus Coastal Zones product for vulnerability and exposure derivation, indicating that this is suitable for scaled Pan-European application. Plans by CLSM to increase the re-analysis frequency to 3 years (from the existing 6 years) should make the product even more broadly valuable.

Crowd sourcing and citizen science approaches can also offer emerging and innovative ways to address adaptation (Michetti et al., 2021). Other emerging data driven approaches, such as the use of mobile phone traffic intensity to derive quantitative, highly dynamic maps of exposure (Balistrocchi et al., 2020), also offer significant potential value.

6.3.3 Application needs

There is a clear need for highly synthesised flood-related intelligence, designed to facilitate user uptake with a minimum of additional overhead, as the above case studies indicate. This typically is achieved through the integration of a suite of models, integrated with highly synthesised satellite and *in situ* products. This places an onus on intelligence and product providers to clearly understand the needs of various user archetypes, including those of a semantic nature, and appropriately resolve the many technical complexities associated with the use of multiple sensors, algorithm types, analytics and product merging.

<u>Application Need 1:</u> [Hazards] Coastal flooding information needs to be made available in a highly synthesised manner as coastal and compound flood inundation, e.g. from Total Water Levels (TWL) or Extreme Sea Levels (ESL) values as a combination of mean sea level plus high tide water levels and fluctuations due to extreme events such as wind-waves and storm surges.

<u>Application Need 2:</u> [Hazards] Flooding information needs to be made available on a historical, phenological basis, e.g. as a climatology/anomaly under varying return periods; as a component of a predictive short term Early Warning System; and as a component of future climate scenarios under a variety of return periods.

<u>Application Need 3:</u> [Vulnerability] An explicit, standardised Pan-European vulnerability product based on the existing Coastal Zone product & classes would be extremely valuable. Alternatively, or in addition, tools that facilitate users to derive suites of vulnerability product would have high value.

<u>Application Need 4:</u> [Exposure] An explicit, standardised Pan-European exposure product based on the existing Coastal Zone product & classes would be extremely valuable. Alternatively, or in addition, tools that facilitate users to derive suites of exposure product would have high value.

<u>Application Need 5:</u> [Vulnerability, Exposure] Availability of a routinely calculated geospatial change product over time, for both vulnerability and exposure components, would be of high user value. Automated change detection in both risk components, on an ongoing basis, would greatly facilitate adaptation monitoring and the implementation of adaptation pathways

<u>Application Need 6:</u> [Risk] combined risk indicators need to be made routinely available across the necessary spatiotemporal and value-added intelligence ranges, as detailed below. These cascade from geospatially-explicit, hazard-specific risk indicators; combined geospatially-agnostic, hazard-specific risk indicators; composite geospatially-agnostic, hazard-agnostic risk indicators & frameworks (Chapter 5)

<u>Application Need 7:</u> [Risk] Risk indicators need to be made available in an appropriate range of metrics for key user archetypes, e.g. potential or realised economic damage; population displacement; public health risks and other suitable key indicators (Chapter 5)

<u>Application Need 8:</u> [Semantics] Users frequently cannot access appropriate information, or struggle with information that they are uncertain of how to use. A key aspect of the EO value chain is the last part – the interfaces that users interact with to gain understanding and knowledge. Realising full value of the EO knowledge offering requires the ongoing development of community-driven, iterative, aspirational, enabling Decision Support systems, driven by strong user co-design. Creating

a strong two-way dialogue between providers and users aids in identifying the best solutions, speeds development, and results in much increased uptake (Virapongse et al., 2020).

Coastal flooding is often a combination of storm surge, pluvial and fluvial flood phenomena, and the application needs should be considered in synergy with the DG REGIO flood risk use case. As shown in Table 7, it is important to provide intelligence or products at 1) a range of temporal and spatial scales from the decadal to the event scale to the predictive, and 2) a range of value-added intelligence from highly synthesised combinations of adaptation risks for strategic user archetypes, to event scale products for logistical user archetypes addressing situational awareness.

Table 7. Objectives, spatiotemporal resolution, and user archetype intelligence dimensions.

Objectives	**Spatial dimension**	**Temporal dimension**	**User archetype**
Monitoring of flood risk Analysis of the impact of existing climate adaptation initiatives	Municipal scale (primary) Regional scale (primary) National scale (secondary) Pan European scales(secondary)	Interannual to decadal (primary) Seasonal to annual (secondary) Event-scale to monthly (secondary)	Strategic: interannual policy-focused (primary) Tactical: intra-annual (secondary) Logistical: event to seasonal (secondary)

Source: Internal EC KCEO.

6.3.4 Technical assessment

Definitions
For the purpose of this use case, we will refer to the following definitions: **Temporal resolution** Very High Resolution (VHR): < daily High Resolution (HR): >= daily and < monthly Medium Resolution (MR): >= monthly and < seasonal Low Resolution (LR): >= seasonal **Temporal extent** Short Extent (SE): < 10 years Medium Extent (ME): >= 10 years and < 30 years Long Extent: >= 30 years

The application need is primarily for appropriately synthesised flood-related intelligence, available across a wide range of time scales. These should include short term early warning systems; hindcast/reanalysis of flood impact across both actual and hypothetical adaptation scenarios; and future scenarios across a range of climate-driven hazard conditions and adaptation scenarios. This range of flood-related intelligence options is typically achieved through the integration of suites of models, integrated with highly synthesised satellite and *in situ* products. Focusing on the two key application domains of early warning and probabilistic impact analysis, typical model suites will incorporate the following components (interTwin, ECFAS):

- Hydrological models [Hazard], producing hydrological fluxes based on a wide range of climate, topography, surface and land use data. These include static data such as global flow & surface water, land cover/land use, soil properties, ice and glacier distributions, gauged discharge data. Dynamic forcing data include ERA5 atmospheric, ocean and land surface information; catchment-based seasonal hydrological forecasts; station-based meteorological data; and global precipitation.
- Coastal inundation models [Hazard], producing both deterministic and probabilistic flood maps. These are built on static data including elevation, bathymetry, land use, infiltration and structures: and dynamic data such as global tide and surge forecast and reanalysis, wave models, and meteorological forecast and reanalysis data. It is important to note that the satellite-derived Global Flood Monitoring service (Sentinel 1) has critical use here in calibrating and augmenting inundation model output.
- Impact/damage models [Vulnerability, Exposure], explicitly combining hazard, exposure and vulnerability parameters, producing asset- or grid-based damage and loss metrics, typically based on water depth and ranges of depth -damage curves. This model component is critical to analysis of adaptation, and is of particular value in assessing probabilistic adaptation scenarios. Exposure parameters are typically calculated from a variety of building footprint and classification geospatial data, vulnerability from existing depth damage curves (Huizinga et al., 2017), and hazard from the above inundation models.
- Resilience and Adaptation models [Vulnerability, Exposure] producing maps of risk and resilience for critical infrastructure, based on explicit geospatial exposure and vulnerability parameters.

Whilst these modelling approaches enable global application, sensitivities to local scale data are noted in particular to: the vertical uncertainties for Digital Elevation Models (DEM), with preferred accuracy of < 30cm as opposed to the 1-10m of the Copernicus DEM; and to the spatial resolution of global DEMs, typically 30-90m, whereas <10m resolution is considered more appropriate. Table 8 provides a breakdown of the required intelligence components.

Table 8. Decision supporting intelligence, with optimal spatial, temporal and user expertise requirements. User expertise is indicative of the level of specialist expertise required to use the intelligence, where: technical indicates a requirement for significant technical expertise, e.g. in hydrological flood modelling or further manipulation of Earth Observation products; domain indicates no detailed technical expertise but a requirement for domain knowledge, e.g. understanding urban risks & relevant climate policies; and citizen indicates no requirement for specialist knowledge. Grey indicates model-derived, white indicates observation-derived.

Value Chain			**Optimal Capability**			**Extent**
Decide (Risk)	Apply (Component Service)	Data Production	Spatial resolution	Temporal resolution	User expertise	
Hazard						
Compound flood extent (1,2)	Flood inundation	Hydrological model; Inundation model	10 m HR2	Variable VHR	Technical Domain	Long extent
		Static build data: flow, surface water, land cover /land use, soil properties, ice & glacier distributions, gauged discharge	10 m HR2	Variable HR	Technical	Medium Extent

		Dynamic forcing data: weather forecasts, climate projections, wave datasets, discharge datasets	200 m (3)	Variable VHR	Technical	Medium Extent
	Observed surface flood extent	Single or multi-sensor SAR & optical	<10 m HR1	2-4 days (4) HR	Technical Domain	Medium Extent
	DEM/DTM	InSAR, optical, LIDAR	1 m	5 years	Technical	Short Extent
Vulnerability & Exposure						
Loss & Damage	Flood damage	Flood damage models	<10 m HR1	Quarterly	Technical Domain	Medium Extent
	Building footprint & classification	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Quarterly	Technical	Medium Extent
Resilience	Infrastructure resilience analysis	Resilience models	<10m HR1	Quarterly	Technical Domain	Medium Extent
	Infrastructures & Asset Classes	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Quarterly	Expert	Medium Extent
Land Cover / Land Use	Risk-prone areas	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Annual	Technical Domain Citizen	Short Extent
	Land cover	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Annual	Technical Domain	Short Extent
	Green areas	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Annual	Expert Domain	Short Extent
	Impervious surface	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Annual	Technical Domain	Short Extent
	Topography	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Annual	Technical Domain	Short Extent
	Natural areas	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Annual	Technical Domain	Short Extent
Change Detection	Automated change detection for LC/LU classes	Sentinel 2 & optical	<10 m VHR1, 2, HR1	Quarterly (5)	Technical Domain	Short Extent
Socio-Economic	Demographic statistics	DEGURBA	Medium extent	Annual	Technical Domain	Long Extent
	Poverty & social exclusion statistics	DEGURBA	Medium extent	Annual	Technical Domain	Long Extent
	Tourism statistics	DEGURBA	Medium extent	Annual	Technical Domain	Long Extent
	Population living in risk areas	DEGURBA	Medium extent	Annual	Technical Domain	Long Extent

(1) Maps of Total Water Level for early warning systems and under range of return periods for hindcast and projection scenarios
(2) Leijnse et al. (2021), as the underlying basis for DELTARES FloodAdapt
(3) ECMWF 2023

([4]) Based on existing GFM Sentinel 1 only products for threshold and Tarpanelli et al. (2022) for Breakthrough.
([5]) Olteanu-Raimond et al. (2020)

Source: Internal EC KCEO.

6.3.5 Value chain analysis

Risk and adaptation to climate change affects decision making and policy implementation at a range of scales, from the municipal to the EU level. Whilst all these scales need consideration, this analysis focuses on urban adaptation and thus the municipal scale is considered the most critical. It can be argued that pan-European consideration is effectively the synthesis of cumulative events at the urban scale, reinforcing the outlook that the urban scale is most critical.

As can be seen from Table 8, the highest value intelligence is delivered through a suite of models, with a very strong dependency on a range of satellite-derived (and *in situ*) observations. Whilst the necessary modelling capabilities are emerging rather than operational, the majority of the satellite-derived products are available at an appropriate first-order spatial resolution, although the temporal resolution of both flood maps, and vulnerability/exposure sub-products, should be enhanced.

Breaking down the risk components into hazard, exposure and vulnerability, and further identifying the semantic or value-added aspect of the required intelligence, the primary hazards are:

- Coastal and compound flood inundation: driven by extreme sea levels interacting with storm, circulation, tidal and wave induction patterns, compounded by anomalously heavy precipitation and riverine overflow.

Both the primary flood inundation hazard, and the physical forcing phenomena, can be evaluated and monitored using EO data, with the proviso that the primary intelligence is necessarily model-dependent. From a value-add perspective, hazard information should be available as all of the following: short term early warning; hindcast/reanalysis of historical flood events; and flood inundation scenarios across a range of climate-driven forcing conditions and adaptation scenarios.

From an exposure and vulnerability perspective, the Copernicus Coastal Zones land cover/land use products form the core capability, with key sub-products relating to:

- Population density
- Population living in flood-prone areas
- Building footprints and building classification
- Land cover/land use types
- Green and natural areas
- Wetlands and water areas
- Impervious surfaces
- Transport, energy, health and water infrastructure

All exposures and vulnerability related geospatial parameters can be evaluated and monitored using EO data or by assimilating EO data with other socio-economic information. Critical aspects of vulnerability parameters should be closely linked to primary adaptation actions as given by the key type measures, including: grey options such as physical flood defences; and green options such as rehabilitation of natural flood defences such as wetlands.

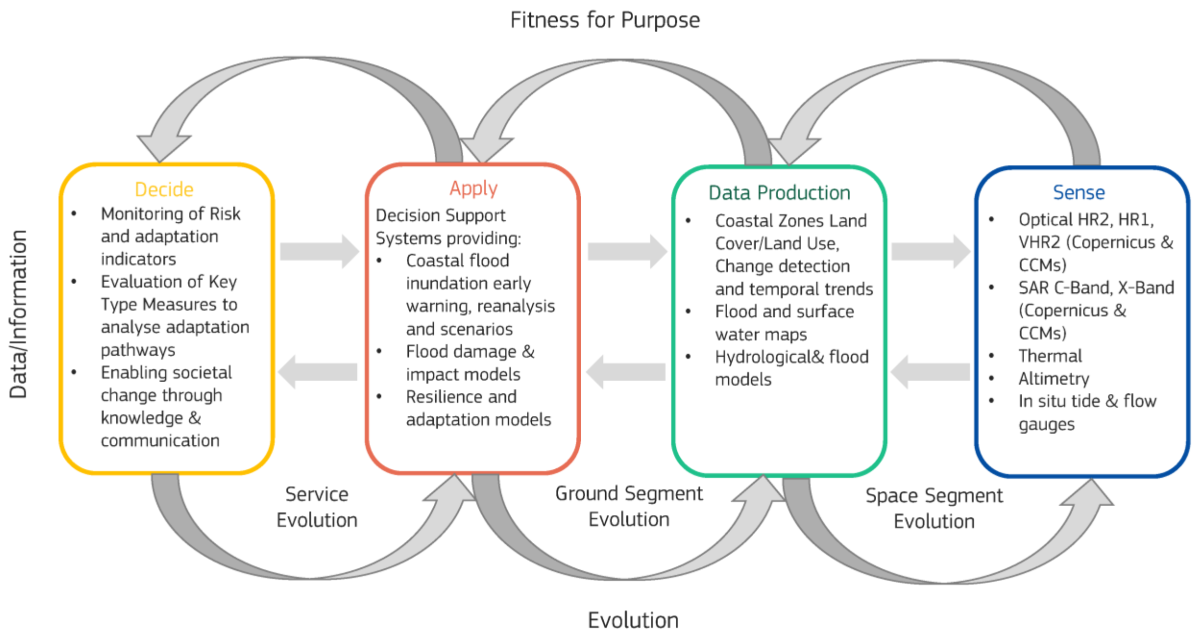
Hazard related impacts can be quantified, both for adaptation scenarios and extreme events, as:

- Economic loss and damage models providing geospatial damage and loss metrics, typically based on water depth and ranges of depth -damage curves.
- Flood related mortalities and displacement

- Flood related infrastructure damage

With many other indirect impacts, e.g. relating to food security, political and social unrest, public health, available through a combination of EO and socio-economic data (Chapter 5). Figure 11 depicts the relevant Earth Observation value chain, with the most significant development above in current capabilities in the “last mile” aspects of the Application and Decision making components.

Figure 11. Earth Observation value chain for coastal and compound flooding.



Source: Internal EC KCEO.

6.3.6 Fitness for purpose of existing products and services

The application needs and technical assessment very clearly demonstrates that the most impactful coastal and compound flooding intelligence requires a suite of hydrological, inundation, impact and resilience models. Such models have a complex and critical dependency on a wide range of products derived from satellite and *in situ* observations, in addition to other model-derived forcing variables. Quantitative assessments of the uncertainty, verisimilitude and predictive skill of these models is certainly beyond scope of the current study. However, some first order consideration of the functional fitness of the key model-based services and contributing satellite-derived products and services can be made. The semantic fitness for purpose of the primary intelligence generating services is an important consideration – effectively an assessment of how easily non-expert users can find understanding and value from these services.

The fitness for purpose discussed below is based on a technical assessment (spatial resolution, temporal resolution, time series length) given in Table 9, and the products/services' thematic content, and fitness to application needs given in Source: Internal EC KCEO.

Table 10.

Table 9. Examples of existing and emerging EO-derived products and services that could contribute to the coastal and compound flooding capability with their technical specifications (n/a = not applicable, n/d = not defined). Emerging services are indicated, otherwise services are considered operational.

Parameter	Service(s)/Product(s)	Spatial resolution	Temporal resolution	Temporal extent
Main physical parameter				
Compound flood extent (risk scenarios)	ECFAS Pan-EU Flood Catalogue	100m	n/a	n/a
	Destination Earth (Emerging)	200m	n/a	n/a
Compound flood extent (Early Warning System)	CEMS Flood delineation & modelled flood extent (on demand)	250m	NRT with 5 day latency	n/a
	ECFAS-Warning (Emerging)	100m	n/d	n/d
	Destination Earth (Emerging)	200m	n/d	n/d
Observed surface flood extent	Global Flood Monitoring Service	10m	6-7 days	2014 onwards
Precipitation	ERA-5	0.1° (about 10 km)	1 hour, 1 month	1979-present
	E-OBS	0.1° (about 10 km). 0.25° (about 25 km)	1 day	1950-present
	CORDEX	0.11° (about 10 km)	From 3 hours to seasonal	1948-2100
Environmental dimension				
Risk-prone areas	European Drought Observatory	Between 5 km and 100 km	1 month	n/a
	JRC River flood hazard maps for Europe and the Mediterranean Basin region	100 m	n/a	>100 years return period
	Copernicus Emergency Management Service (CEMS)	2500 m^2	On demand	2012-present
Land cover	CORINE Land Cover (CLC)	25 ha	6 years	1990, 2000-2018
Green cover	Urban Atlas Street Tree Layer	500 m^2	6 years	2012, 2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
	High Resolution Layer Tree Cover Density	10 m, 20 m, 100 m	3 years	2012, 2015, 2018
	Riparian Zones	0.5 ha	6 years	2012, 2018
Impervious surface	High Resolution Layer Imperviousness	10 m, 20 m, 100 m	3 years	2006-2018
	High Resolution Layer Impervious Built-up	10 m, 100 m	3 years	2018

	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
Topography	EEA-10	10 m	Continual	Continuous
	GLO-30	30 m	Continual	Continuous
	SRTM	30 m	Continual	2000
Natural areas	Natura 2000	0.5 ha	6 years	2006, 2012 and 2018
Infrastructures	Urban Atlas Building Height	10 m	n/d	2012
	OpenStreetMap	n/d	Continual	n/a
Climate dimension				
Climate variables	Water vapour (C3S Agrometeorological indicators)	0.1° (about 10 km	1 day	1979-present
	Wind speed and direction (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present
Socio-economic dimension				
Population/population density	Eurostat data	DEGURBA	1 year	Different by region
Population grid	Global Human Settlement Layer (GHSL)	100 m, 1 km, 3 arcsec, and 30 arcsec	5-year intervals	1975-2020 (and projections to 2025 and 2030)
Demographic statistics	Eurostat data	NUTS3	1 year	Different by region
Poverty and social exclusion statistics	Eurostat data	NUTS2	1 year	Different by region
Tourism statistics	Eurostat data	NUTS3	1 year	Different by region
Population living in floodplain areas	European Environment Agency	WS04 subcatchment	n/d	n/a

Source: Internal EC KCEO.

Table 10. Fit for application needs. (n/a = not applicable, n/d = not defined)

Parameter	Service(s)/Product(s)	Fit to application needs
Main physical parameter		
Compound flood extent (risk scenarios)	ECFAS Pan-EU Flood Catalogue Destination Earth (Emerging)	<u>Spatial resolution:</u> for all products, the spatial resolution is unsuitable for monitoring local variations at the municipality level. <u>Temporal resolution:</u> fit the application's needs for all products. <u>Temporal extent:</u> for all products, the available time series is suitable for assessing long-term trends (for the past) and projecting future trends.
Compound flood extent (Early Warning System)	CEMS Flood delineation & modelled flood extent (on demand)	<u>Spatial resolution:</u> for all products, the spatial resolution is unsuitable for monitoring local variations at the municipality level.

	ECFAS-Warning (Emerging) Destination Earth (Emerging)	Temporal resolution: fit the application's needs for all products. Temporal extent: for all products, the available time series is suitable for assessing long-term trends (for the past) and projecting future trends.
Observed surface flood extent	Global Flood Monitoring Service	Spatial resolution: the spatial resolution is suitable for monitoring local variations at the municipality level. Temporal resolution: the temporal resolution is sub-optimal for monitoring all relevant flood events Temporal extent: for all products, the available time series is suitable for monitoring long term variability.
Precipitation	ERA-5 E-OBS CORDEX	Spatial resolution: for all products, the spatial resolution is unsuitable for monitoring local variations at the municipality level. Temporal resolution: fit the application's needs for all products. Temporal extent: for all products, the available time series is suitable for assessing long-term trends (for the past) and projecting future trends.
Environmental dimension		
Risk-prone areas	European Drought Observatory	Spatial resolution: could be unsuitable for the application's needs at higher resolution spatial scales. Temporal resolution: fits the application's needs for all the spatial scales. Temporal extent: each indicator has a different temporal extent.
	JRC River flood hazard maps for Europe and the Mediterranean Basin region	Spatial resolution: fits the application's needs. Temporal resolution: n/a. Temporal extent (return period): fits the application's needs.
	Copernicus Emergency Management Service (CEMS)	Spatial resolution: fits the application's needs, but the spatial extent might not be sufficient for large-scale events. Temporal resolution: the temporal resolution is not pre-defined. Products are made on demand. Temporal extent: does not fit the application's needs.
Land cover	CORINE Land Cover (CLC)	Spatial resolution: fits the application's needs. Temporal resolution: is sub-optimal for the application's needs. Time series: fits the application's needs.
Green cover	Urban Atlas Street Tree Layer	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs.

		Temporal extent: is sub-optimal for the application's needs.
	High Resolution Layer Tree Cover Density	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
	Riparian Zones	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
	Coastal Zones	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
Impervious surface	High Resolution Layer Imperviousness	Spatial resolution: fits the application's needs. Temporal resolution: is sub-optimal for the application's needs. Temporal extent: the available time series is suitable for assessing short-term trends. However, long-term analyses and assessments of urban adaptation to policies require observations over a more extended period.
	High Resolution Layer Impervious Built-up	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs (new product). Temporal extent: does not fit the application's needs (new product).
	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
Topography	EEA-10 GLO-30 SRTM	Spatial resolution: all products fit the application's needs for all the spatial scales. Temporal resolution: n/a. Time series: n/a.
Natural areas	Natura 2000	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
Infrastructures	Urban Atlas Building Height	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.

	OpenStreetMap	Spatial resolution: cannot be assessed. Temporal resolution: fits the application's needs. Temporal extent: n/a.
Climate dimension		
Climate variables	Water vapour (C3S Agrometeorological indicators) Wind speed and direction (C3S Agrometeorological indicators)	Spatial resolution: all products do not fit the application's needs. Temporal resolution: all products fit the application's needs. Time series: all products fit the application's needs.
Socio-economic dimension		
Population/population density	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Population grid	Global Human Settlement Layer (GHSL)	Spatial resolution: data have different spatial scales. Overall, they do not fit (or are sub-optimal for) the application's needs. Temporal resolution: is sub-optimal for the application's needs. Temporal extent: fits the application's needs.
Demographic statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Poverty and social exclusion statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.

Tourism statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Population living in floodplain areas	European Environment Agency	Spatial resolution: is sub-optimal for the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.

Source: Internal EC KCEO.

Hazard overview: from an adaptation perspective, flood inundation scenario models are valuable. The existing ECFAS Pan EU Flood catalogue offers relevant functionality and appropriate first order spatial resolution, but is offered as a set of files and codes with no front end, and therefore requires additional expertise to offer value to outside the technical domain. The emerging Destination Earth interTwin capability will offer significant functionality and potentially relatively accessible intelligence, but is still predominantly considered an expert system from a semantic perspective. Both capabilities offer powerful links to impact models based on Copernicus-derived exposure and vulnerability products. Near real-time flood observed delineation and modelled extent mapping is available through Copernicus Emergency Management Service on a request basis, with potential emerging capabilities through Destination Earth. There is a strong dependency on the satellite-derived Copernicus Global Flood Monitoring service for calibrating and augmenting inundation model output, discussed further below.

Exposure & Vulnerability overview: The ECFAS Coastal dataset, derived from Sentinel 2 through the CLMS Coastal Zone offers significant functionality at a 10m resolution, and provides an extensive suite of products that enable quantitative risk mapping. The 3 year reprocessing interval for the CLMS Coastal Zone data may not be sufficiently dynamic to capture rapid changes to human settlements and infrastructure.

Impact overview: The ECFAS Impact Tool provides analysis of inundation impacts to population, damage to buildings, infrastructure and other assets. It is offered as code base with no front end, and therefore requires additional expertise to offer value to outside the technical domain. The emerging Destination Earth interTwin capability should offer an extensive range of impact, damage and resilience intelligence linked to comprehensive scenario modelling – creating a user community for this capability, not least through an appropriate approach to the semantic offering, will be an important aspect of the development.

6.3.7 Gap analysis

Hazards

From a hazard perspective, the most critical offerings are the coastal and compound flood inundation models, primarily scenario models that allow impact analyses under a range of climate and adaptation scenarios. Optimally, there should be a coherent user community across municipal to Pan-European user archetypes, using and sharing accessible and intuitive adaptation scenario tools. This is not the case currently, with regard to the existence of both the tools and the community. The only current offering (beyond the CEMS on-demand Reforecast capability) is the ECFAS Pan EU Flood Catalogue, coupled to the ECFAS Coastal dataset and Impacts tools. This is offered as a set of files and codes, i.e. highly technical. The emerging Destination Earth capability should offer significant functionality and potentially accessible intelligence around hazard-to-impact adaptation scenario analysis, but the need to develop and ultimately provide ongoing adaptation analysis capabilities to a community based on a range of key user archetypes should be clearly identified as necessary.

A key contributing service to the available and emerging coastal flood inundation models is the satellite-derived Global Flood Monitoring (GFM) service, which has much value as an independent tool, and has critical use in calibrating and augmenting inundation model output. The GFM service is currently based around the surviving Sentinel 1A Synthetic Aperture Radar sensor, providing an estimated revisit time in Europe of ±6 days (assuming ascending and descending acquisition). However, the average European flood duration is ±2 – 4 days, with the implication that flood monitoring using a single Sentinel 1 sensor is probably observing only 20 – 40% of occurring floods (Munasinghe et al., 2023; Tarpanelli et al., 2022). Increased revisit would enhance service value through the addition of Sentinel 1C when launched, and/or the ability to integrate optical satellites such as Sentinel 2 (with the proviso that cloud significantly reduces effective optical data acquisition in flood scenarios). There are also concerns around the optimal performance of SAR for flood mapping in urban and vegetated areas (Amitrano et al., 2024). Given the critical nature of the GFM service, a more sophisticated cost: benefit analysis of the integration of additional sensors to the GFM service would be valuable – including the option to integrate Copernicus Contributing Missions such as IceEye or Planet, and the possibility of augmenting with GNSS-Reflectometry, typical operating at much coarser spatial scales but with daily temporal coverage (Zeiger et al., 2022).

Exposure & Vulnerability

The CLMS Coastal Zone data is a valuable resource and is the basis for the most advanced available (ECFAS Coastal dataset) and emerging (interTwin) coastal exposure and vulnerability flood products. It is available through a map viewer, and as a change detection product. However, whilst the currently planned 3 year reprocess may be sufficient from a Pan-European policy monitoring perspective, it may not be sufficiently dynamic to capture rapid changes to human settlements and infrastructure.

There is also substantial value in the operational provision of automated change detection for assessing urban dynamics in human settlements (in particular informal settlements with rapid change scales), critical transport and coastal defence infrastructure, natural ecosystems providing coastal defences and other land cover/land use classes critical to quantifying exposure and vulnerability. There is considerable semantic value to automated adaptation monitoring and reporting of key Land Cover (LC) / Land Use (LU) classes, and arguably such a capability would significantly increase Copernicus value to a wide range of user archetypes. Multi-scale "tip and cue" change detection based on AI also allows for cost-effective integration of <10m spatial resolution (VHR1, VHR2, HR1) where necessary, e.g. from Copernicus Contributing Missions. Change thresholds above prescribed targets in Sentinel 2 products can trigger acquisition of small tiles of e.g. VHR1 optical data for characterisation of individual buildings, transport infrastructure, trees and green structures.

Risks and Impacts

Both the available ECFAS Impact Tool and the emerging Destination Earth provide impact and damage analyses - of inundation impacts to population, damage to buildings, infrastructure and other assets. This is of high value but it is important that these impact tools are provided in an accessible and easily used format for non-technical end users, and that they are coupled to appropriate user community building initiatives to ensure knowledge development, cross-border collaboration and expertise transfer. Realising full value of the EO knowledge offering requires the ongoing development of community-driven, iterative, aspirational, enabling Decision Support systems, driven by strong user co-design. Creating a strong two-way dialogue between providers and users aids in identifying the best solutions, speeds development, and results in much increased uptake (Virapongse et al., 2020).

Short Use Case 2: Coastal Eutrophication

Coastal Eutrophication
Impact Pathways: degraded regulating ecosystem services; damage to provisioning (food security) and cultural (tourism) ecosystem services; damage to abstraction-based infrastructure, e.g. desalination; loss of economic capability; social, financial and political instability; disease & public health risks…
Key Adaptation Activities: Hard (water and wastewater infrastructure), accommodation (technical, social, knowledge), ecosystem based (nature based solutions) (Bongarts Lebbe et al., 2021)
Potential EO Value: Physical hazard drivers of temperature, stratification and runoff (thermal, optical, river gauges, models), bloom hazard products, both predictive (coupled ecosystem & scenario models) and near real time/historical eutrophication/bloom phenology, extent, functional types (optical, thermal, models). Vulnerability sub-product ranges, e.g. cultural ecosystem service related (optical, models). Exposure products and inventories (optical, SAR, models)

Climate change is likely to increase anthropogenic nutrient loading, with significant changes to catchment nutrient dynamics affecting land use, streamflows, runoff, stratification and other ecosystem functional characteristics (Costa et al., 2023). Likely impacts include the increased severity of coastal eutrophication: development of harmful phytoplankton events, hypoxic zones, loss of coastal habitats. Such impacts are likely to be compounded by other climate-related pressures, including coastal development or rehabitation, compromised wastewater infrastructure, increases in sea temperatures, acidification, changed circulation and weather patterns, and loss of fishing and aquaculture productivity (Malone & Newton, 2020). The most critical adaptation measures must include enforced, ecosystem-based management of both point and diffuse sources of nitrogen and phosphorus (Wells et al., 2020). This accommodation-focused adaptation, based on technical, social, and knowledge components (Bongarts Lebbe et al., 2021), needs holistic and sustained research, monitoring and predictive assessment of eutrophication components, including nutrient loading and impacts. The productivity, composition, phenology and geographic range of phytoplankton assemblages will all be affected by physical and biogeochemical water column changes, in addition to land-sea nutrient fluxes (Wells et al., 2020), but there is substantial uncertainty on how these will manifest at local and regional scales.

Earth Observation offers significant value to the monitoring, analysis and prediction of water quality and eutrophication in coastal and estuarine systems. Considerable multi-sensor capability, with a strong focus on Sentinel-2 and -3, has been demonstrated for harmful algal bloom applications (IOCCG, 2021) and water quality applications (IOCCG, 2018) across coastal, estuarine and freshwater systems. The use of Earth Observation for desalination planning and operations, likely to increase substantially with changing climate, has been extensively demonstrated (Anderson et al., 2017). Eutrophication scenario modelling under a range of IPCC scenarios has been demonstrated at river basin (Raimonet et al., 2018) and sea basin scales (Bossier et al., 2021). Knowledge systems for risk management at European scales (West et al., 2021) highlight the semantic aspects through "*the salience, legitimacy, usefulness, and usability of this knowledge for decision-making.*"

Short Use Case 3: Coastal Erosion and Geomorphological Change

Coastal Erosion
Impact Pathways: damage to property, infrastructure and services; displacement and loss of habitation; degraded regulating ecosystem services; damage to provisioning (food security) and cultural (tourism) ecosystem services; loss of economic capability; social, financial and political instability **Key Adaptation Activities**: Hard (built infrastructure), soft (rehabilitation and nourishment), accommodation (technical, social, knowledge), ecosystem based (nature based solutions), managed retreat (Bongarts Lebbe et al., 2021) **Potential EO Value:** Physical hazard drivers of extreme sea level (altimetry, tide gauges, models), storms & waves (scatterometers, SAR, altimetry, optical, models). Erosion hazard products, both predictive (circulation & scenario models) and near real time/historical land loss (optical, models). Vulnerability sub-product ranges, e.g. land cover, impervious surfaces, topography (optical, SAR, lidar, models). Exposure products and inventories (optical, SAR, models)

The combination of physical drivers leading to increased coastal flooding risks are also likely to lead to increased risk of coastal erosion and changes to coastal geomorphology, with substantial environmental and socioeconomic impact. In many cases loss of land and habitat through erosion can compound coastal flooding risks. European combined economic loss to flooding and erosion are estimated at up to €17B per annum under RCP4.5 (COACCH, 2018). Soft-sediment, i.e. beach, coastal ecosystems are considered highly vulnerable to erosion, with potential for large projected loss of habitat and cultural ecosystem services under future climate scenarios. In regions with significant beach-based economic activity such as tourism, erosion is considered one of the most important climate risks (Laino & Iglesias, 2023). Urban coastlines, with limited ability for landward beach transgression and coastal squeeze, are particularly susceptible. Impacts from increased erosion rates include loss of beaches and dunes, damage to infrastructure and settlements, loss of habitat and reduced biodiversity, subsequent increased vulnerability to flooding, saline intrusion and other compounded flood impacts. However, there are a wide range of adaptation (KTM) measures that can be implemented, including coastal protection structures, beach re-nourishment, dune restoration, setback and manged retreat, and ecosystem-based approaches (Johnson, 2023). Appropriate adaptation measures, such as mangrove restoration, could promote relatively stable coastline morphology in estuarine and delta systems (Glavovic et al., 2022).

Earth Observation offers significant value to the monitoring, modelling, process understanding and impact modelling of coastal erosion. From a physical driver perspective, much of the EO or Metocean observation and modelling capability used for coastal flooding intelligence is also relevant to coastal erosion. Analyses of coarse-scale (30-m resolution) global Earth Observation data estimate that 15% of tidal flats (including beaches) have been lost since 1984 (Murray et al., 2019). Shoreline and waterline changes can be monitored and assessed very effectively using SAR and optical data such as those from Sentinel-1 and -2, e.g. the CLMS Coastal data. Other geomorphological hazards such as subsidence (which can have substantial effect on flood inundation) can be effectively monitored using interferometric SAR (Melet et al., 2020). Whilst there is a certain overlap with the coastal flooding intelligence requirements on the semantic and community development requirements, there is an explicit need for morphological model suites for both deterministic and probabilistic shoreline change modelling (Ranasinghe, 2020), and operational shoreline/waterline satellite derived products, such as those piloted in the ESA Coastal Change from Space project.

Short Use Case 4: Coastal Marine Heat Waves

Coastal Heat Waves
Impact Pathways: degraded regulating ecosystem services; damage to provisioning (food security) and cultural (tourism) ecosystem services; loss of biodiversity & natural coastal defences; loss of economic capability; social, financial and political instability; disease & public health risks…   **Key Adaptation Activities**: accommodation (technical, social, knowledge), ecosystem based (nature based solutions) (Bongarts Lebbe et al., 2021)   **Potential EO Value:** Physical hazard drivers of temperature, stratification (thermal, models), hazard products, both predictive (coupled hydrodynamic/ecosystem & scenario models) and near real time/historical Sea Surface Temperature phenology (thermal, models). Vulnerability sub-product ranges, e.g. cultural, regulating, provisioning ecosystem service related (optical, models). Exposure products and inventories (optical, SAR, models)

Sea surface temperature in European basins are expected to increase by 2-6°C by 2100 under the IPCC high emissions scenario ([89]), exacerbating the already observed increase in the magnitude and frequency of marine heatwaves (MHW). Increased sea surface temperatures lead to increases in atmospheric water vapour over the sea, in turn influencing macro-scale weather systems and effectively part of a negative feedback loop into global warming. Physical impacts can include amplification of terrestrial heatwaves, extraordinary precipitation or hail events (Martín et al., 2024) and intense extratropical cyclones. Ecological impacts can include increased likelihood of harmful algal blooms and/or invasive species, with attendant risks to human health, coastal mangrove and seaweed ecosystems, coral bleaching, aquaculture, faunal mortalities, biodiversity and tourism (ibid.) This can cause massive disruption to ecosystem services and attendant socioeconomic impacts, with potential economic damage of several billion US$ (Smith et al., 2021). These latter impacts are of most direct consequence to urban coastal adaptation. Adaptation is primarily centred on accommodation through knowledge systems, e.g. new management practises for MPAs and fisheries, diversification of target species, aquaculture site and stock selection, changes to processing infrastructure (ibid.). There is thus a considerable need for Earth Observation-based, ecosystem-focused intelligence systems – as these are critical to one of the only credible adaptation measures for this hazard class.

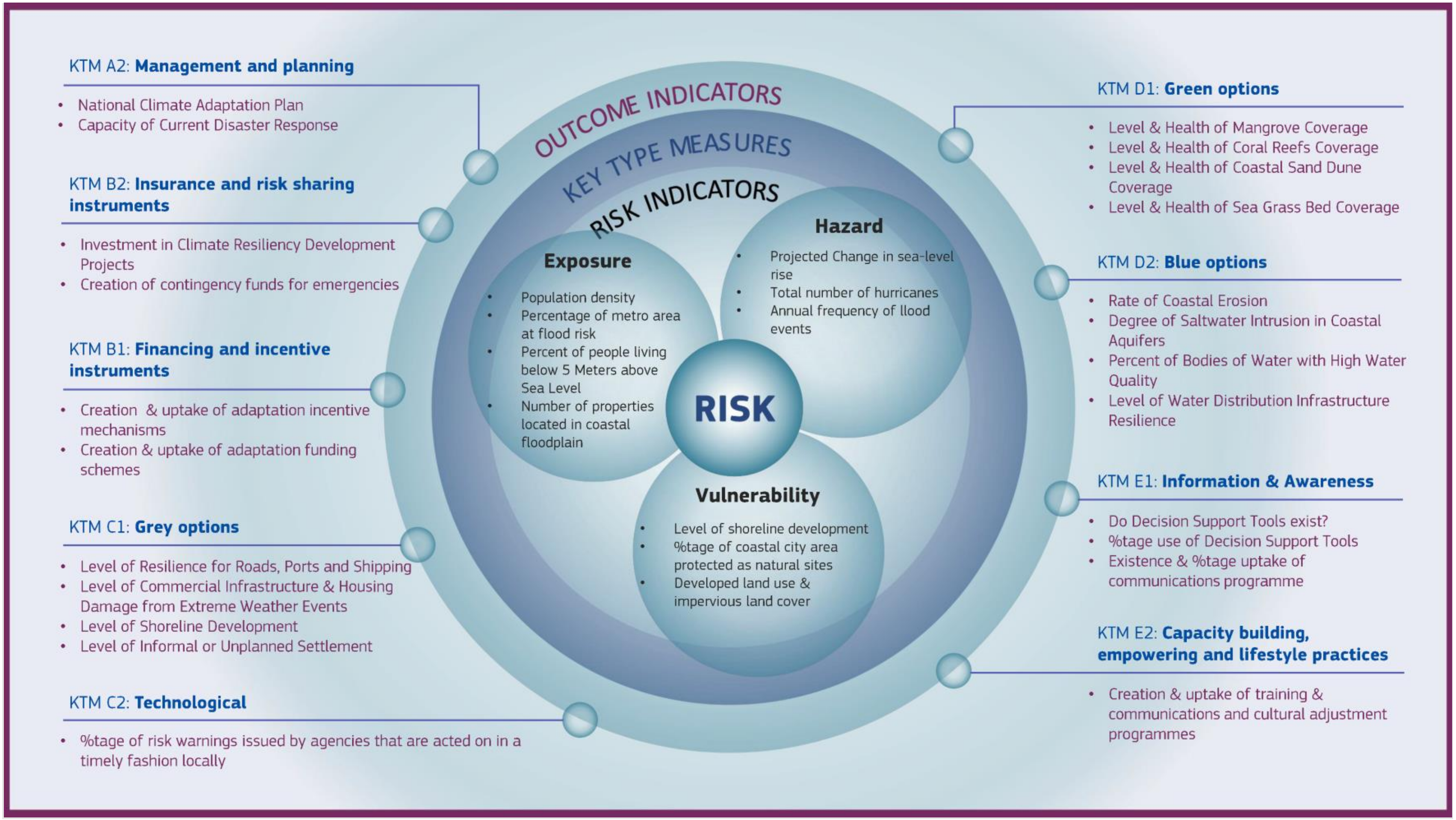
Earth Observation intelligence systems therefore have a significant role to play, and there are many valuable capabilities to build optimised intelligence systems. Satellite measured SST are critical primary observations, with demonstrated insight from over 40 years of data (Androulidakis & Kourafalou, 2022) ([90]) and well evolved operational services including the Copernicus Marine Services Ocean Monitoring Indictors. The ability to observe the primarily biotic and ecological impacts of MHW are well established through Sentinel-2 and -3 and other sensors, with appropriate products and services available through Copernicus Marine Services and other platforms. A range of models for adaptation scenario planning are available through Copernicus and the research community (Qiu et al., 2021; S. Wang et al., 2022). Application needs are likely to focus on the need to more cohesively exploit the comprehensive available intelligence, providing an enhanced capability to explore adaptation options.

([89]) European sea surface temperature

([90]) Mediterranean Heat Waves Monitoring Service

6.3.8 Monitoring risk, adaptation and outcome

Figure 12. DG MARE - Coastal flooding. Illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, Horizon Missions and pertaining indicators.



Source: Internal EC KCEO.

The schematic in Figure 12 aims to bring out the applicability of Earth Observation in the Climate Adaptation aspects of Risk Assessment (comprising the components of Hazard, Exposure and Vulnerability); of the climate action reporting framework of Key Type Measures; and the outcome of this action through pertinent indicators (all indicators within are EO-addressed). Moreover, it aims to encapsulate the discussion in the Chapter 5 and link it with each Use Case through an illustrative example of a particular hazard, a traditional starting point for Risk Assessments and identification of adaptation measures, in essence presenting the Earth Observation 'value proposition' to the adaptation cycle (e.g. contributing to steps 2 till 6 in Climate-ADAPT's Adaptation Support Tool). The schematic does not aim to paint Earth Observation as a cure-all. Dozens of indicators and KTMs are solely dependent on socio-economic data and many will remain unapproachable by EO alone. Nevertheless, the schematic, as the Deep Dive as a whole, advocates for the Earth Observation potential in direct monitoring (the bane of most adaptation frameworks) of the above but also in overall support through contributing in e.g. monitoring the presence of KTMs, designing KTMs and allowing for more harmonized and more frequent risk assessments.

The hazard in focus for this example is Coastal flooding, featured in the DG MARE Use Case. Earth Observation is straightforward regarding the Risk components. Climate projections, *in situ* instruments and satellites with accompanying time-series deliver indicators regarding the actual Hazard at different time frames. Estimations of exposure necessitate some kind of integration of gridded population (or properties) datasets with hazard maps, the former are provided by, among others, the Copernicus EMS and are already an integral part of Disaster Risk Reduction and climate adaptation. The connection of riparian tree planting, shoreline buffers etc. with exposure implies the use of e.g. inundation modelling. A range of modelling capabilities (climate, Early Warning Systems, forecasts, scenario analysis etc.) is of course an inherent part of Earth Observation. Vulnerability indicators are not as straightforward in this example, however, Earth Observation can certainly support estimations of shoreline development (e.g. Urban Atlas, LC/LU) and provide valuable information (extent, condition) for protected natural areas, thus informing vulnerability. Turning to sub-KTMs, their outcome included, only those where Earth Observation has a potential role are depicted. Green and Blue options (D1, D2), as expected, offer the most traction. Earth Observation has a direct role in establishing baselines (for identification of hotspots necessitating action, e.g. a shoreline in high flood risk, riparian tree line in poor condition) but also monitoring the implementation of Nature-based solutions, importantly, over time. Grey options (C2) were not as prominent, although modelling can however provide analyses on their positive impact through risk assessment(s). Regarding the more 'process based' sub-KTMs, local hazard warnings are undeniably dependent on Earth Observation (of appropriate resolution, timeliness). Unlike the Policy sub-KTM, Management and Planning (A2) has much to benefit from integrating Earth Observation in operational procedures. Spatial planning and coastal natural areas information can also strongly benefit from Earth Observation intelligence. Lastly, E1: Information and awareness can directly benefit from hazard maps (produced among others by Copernicus EMS). It is evident that some indicators are common between the Risk components and the sub-KTMs, this was to be expected because of the intertwined nature of climate adaptation, especially in an urban locale.

6.3.9 Recommendations

Some of the key aims of this assessment are to support DG MARE in the implementation of the EU Integrated Maritime Policy (IMP), most specifically the Maritime Spatial Planning (MSP) Directive. MSP is seen as a cross-cutting policy tool, enabling public authorities and stakeholders to apply a coordinated, integrated transboundary approach to planning and decision making. Relevant key implementation mechanisms, co-managed by DG MARE, are the European Marine Observation and Data Network (EMODNET); Copernicus services with specific regard to CMEMS and CLMS; the Mission Restore our Ocean and Waters by 2030; and the European Digital Twin of the Ocean (DTO) core public infrastructure.

Earth Observation is crucial for comprehending environmental systems and evaluating feedback loops and impacts, particularly in vital interfaces such as the land-sea interface in coastal zones. Despite the significant contributions of satellite data, there are notable gaps in the availability of EO derived actionable intelligence, integrating observations and models from terrestrial and marine domains, and the 'urban' context is currently not addressed. There is a pressing need to enhance the capacity to assess cross-domain impacts, create and validate intricate models, and develop forecasting and scenario applications specifically for the land-sea interface. The modelling and observation capabilities outlined here should have a strong, explicit, ecosystem-based approach, allowing clear linkages between oceanic and land-based drivers, marine ecosystem response and status, near-shore ecosystem (mangroves, wetlands, sea grasses etc) response and status, and key risk indicators.

In the context of the MSPD three key components have been identified as most important to urban adaptation: Integrated Land-Sea Planning; Climate Resilience; and an Ecosystem-Based Approach to MSP. Additional cross cutting directives include the involvement of stakeholders; best available use of data and shared information; the promotion of the co-existence of activities and coherence between maritime spatial planning and the resulting plan(s) and other processes; and the cross-border cooperation between Member States. These application and community components frame the following recommendations.

On the evolution of Copernicus, recommendations include the promotion of the following.

For the Space Segment:

- Given the importance of Sentinel 1 to flood and emergency monitoring under prioritised fast track services, the planned launches of Sentinel 1C and 1D in 2024 are extremely important. Given the Sentinel 1B failure, and the need for optimal revisit and continuity (both for near real time emergency monitoring and historical data at optimal revisit for model integration), consideration should be given to the increased revisit and redundancy of operating a three satellite Sentinel 1 constellation.
- Given the critical nature of the Global Flood Monitoring service, a cost: benefit analysis of the integration of additional sensors to the GFM service would be valuable, with the aims of increasing the revisit time and veracity of the product.

For the Services Segment

- [Hazards] Further development and availability through CMEMS of key hazard climatology, phenology, near real-time and forecast products for compound flood inundation; coastal erosion and geomorphological change; coastal marine heat waves; and coastal eutrophication.
- [Hazards, Exposure & Vulnerability] Integration of future Copernicus Expansion Mission products into Copernicus services, most notably CHIME: Copernicus Hyperspectral Imaging Mission, CIMR: Copernicus Imaging Microwave Radiometer, LSTM: Copernicus Land Surface Temperature Monitoring and ROSE-L: L-band Synthetic Aperture Radar. This could significantly improve the main physical variables observed.
- [Exposure & Vulnerability] The CLMS Coastal Zone Land Cover/Land Use product is a valuable resource. The currently planned 3 year reprocess may not be sufficiently dynamic to capture rapid changes to human settlements and infrastructure, and an ideal goal of annual update cycles (plus one-year latency) is suggested.

- [Exposure & Vulnerability] There is also substantial value in the operational provision of automated change detection for assessing changes in exposure and vulnerability in critical hot spots or for critical infrastructure. There is also considerable semantic value to automated adaptation monitoring and reporting of key LC/LU classes, and arguably such a capability would significantly increase Copernicus value to a wide range of user archetypes. Multi-scale change detection based on AI also allows for cost-effective integration of <10m spatial resolution (VHR1, VHR2, HR1) where necessary, e.g. from Copernicus Contributing Missions. A cost-benefit analysis around such a capability would be of high value.

On addressing the value-added intelligence aspects of integrated risks, recommendations include the promotion of:

- The development of easily used adaptation scenario modelling capacities in coastal ecosystems and the urban coastal zones, under a range of KTM-classified adaptation and hazard scenarios, for: compound flood inundation and impacts; coastal erosion, geomorphological change and impacts: coastal marine heat waves and impacts; and coastal eutrophication and impacts. Cross-domain impacts should be considered.
- Further development of early warning modelling capacity in coastal ecosystems and the urban coastal zones for compound flood inundation and potential risk; coastal erosion, geomorphological change and potential risk: coastal marine heat waves and potential risk; and coastal eutrophication and potential risk.
- The greater availability of hazard and combined risk products, ideally using both satellite and in situ products, for the same four hazard classes, as climatology, phenology and near real-time products with appropriate user-driven analytics, e.g. hazard/risk thresholding.
- Combined risk indicators, ideally based on common metrics across all of the above capabilities, need to be made available in an appropriate range of metrics for key user archetypes, e.g. potential or realised economic damage; population displacement; public health risks and other suitable key indicators (Chapter 5).
- The further development of an active, coherent, coastal adaptation planning community; including a range of user archetypes, scientists and service providers; driven by strong user co-design principles. Realising full value of the EO knowledge offering requires both the ongoing development and uptake of community-driven, aspirational, enabling Decision Support systems, with a strong focus on the collaborative use of adaptation scenario tools.
- Standard risk/change metrics for EEA Key Type Measures: Nature Based Solutions and Ecosystem- based Approaches D1 (Green options) and D2 (Blue options) should be adopted and used as a basis for collaborative knowledge exchange and community building (Chapter 5).

On the policy-enabling and uptake side, recommendations include the promotion of:

- User-friendly web-based dashboards that integrate and assimilate all the available information into specific, quantitative, measurable, and standardized indicators. This is mandatory to give policymakers and local authorities, non-EO experts, simple (but powerful) tools to make better decisions and evaluate *ex post* impacts of their policies. In this regard, Destination Earth could be the ideal candidate to collect different end users' needs.

- Increased use of EO-derived indicators within Member States' national legislation. This is crucial to accelerating Copernicus information, products, and services uptake.
- Further use, in future policy documents, of specific and quantitative indicators that can be measured with Earth Observation or are EO-based, as evaluation metrics. This is crucial to have *ex ante* measurable parameters.
- Putting in place automated reporting mechanisms based on regular assessment of standardised indicators and evaluation metrics. This has the potential to dramatically reduce reporting overhead for both Member States and the Commission, and would also further serve to standardise the metrics used for reporting. Linking reporting to automated change detection could also be very powerful policy monitoring tool from a semantic perspective
- Dissemination to politicians, national authorities and local administrators of the potential of Earth Observation and geodata. This is crucial as a whole.
- It is also worth noting that to help assess the effects of climate change adaptation policies, continuity of the products and services reviewed is necessary for at least the policies' time horizon. In the present use case, since DG REGIO is preparing the 2028-2035 Cohesion Policy, data continuity should be provided until 2035.

Concerning future research and innovation needs, recommendations include the promotion of:

- R&I to increase the temporal resolution and veracity of satellite derived flood extent monitoring such as GFM through the integration of a wider array of sensors, including Copernicus Contributing Missions, L and X band SAR, and GNSS-Reflectometry .
- R&I to increase the effectiveness of climate-focused Decision Support Systems (DSS), developing new typologies and approaches to actionable use of climate-focused intelligence systems (e.g. Jagannathan et al. (2023). Incorporating typologies of actual quantified, characterised use into emerging DSS has potential to greatly enhance their value.

6.4 Climate Adaptation for Urban Heat Island Effect (DG REGIO)

Earth Observation Use Case: Climate Adaptation for Urban Heat Islands

The European Common Provisions Regulation under existing and emerging Cohesion Policies, and the European Regional Development Fund, allocate major expenditure for the achievement of EU climate objectives, specifically around adaptation and risk management. Key investment areas include adaptive coping with climate extremes such as heatwaves, with high-impact urban manifestation through Urban Heat Island (UHI) effects, as recognised by the EU Strategy on Adaptation to Climate Change. This investment in improved resilience requires significantly improved intelligence on UHI phenology, mapping, indicators, and multi-sectoral impacts.

Green, infrastructural, and ecosystem-based adaptation actions, in combination with soft- and knowledge -focused measures, have significant potential to reduce UHI impacts across European urban areas. Earth Observation intelligence can make a significant contribution to key applications needs such as extreme heat exposure and vulnerability information; extreme heat hazard mapping across a range of time scales and into the predictive; automated change detection around urbanisation, greening and population dynamics; and the use of models and indicators to guide resilience monitoring and adaptation activities. Many potentially valuable products and services are available in an emerging sense through Copernicus and other European services, although there are many scale, extent and resolution issues that require optimisation. There is a clear need to bridge resolution gaps in both temporal and spatial operational services for urban applications; and gaps in the value chain through the development of Decision Support Tools offering actionable information across the wide range of urban-relevant scales needed. Earth Observation has a valuable potential role across a significant set of the Key Type Measures that represent the necessary adaptation activities: Green, Blue, Planning, Risk Sharing and Awareness -related measures.

Key recommendations include the development of operational land surface temperature models for scenario analysis and prediction; more time-extensive and frequently updated EO services; automated change detection products identifying hot spots and rapid land use changes; better integration with finer granularity socio-economic statistical data; more widespread use of adaptation scenario and early warning models; and accessible dashboards offering actionable intelligence and standardised monitoring indicators.

6.4.1 Policy context

The Cohesion Policy 2021-2027 (Common Provisions Regulation - CPR ([91])) has specific climate investment targets under Article 6. The European Regional Development Fund (ERDF) and Cohesion Fund (CF) shall contribute 30% and 37% respectively of the EU contribution to expenditure supported for the achievement of the climate objectives. The intervention areas for investments listed in Annex 1 of the CPR have a specific focus on the adaptation to climate change measures and prevention and management of climate-related risks. In addition, an effective disaster management framework to promote climate change adaptation, disaster risk prevention and resilience, taking into account ecosystem-based approaches, has been identified as an enabling condition. The current programming period also has a dedicated urban policy aspect via the European Urban Initiative (Article 7.2 of the current CPR and Articles 11 and 12 of the ERDF and CF Regulation ([92]), which justifies the urban focus of this deep dive. DG REGIO is currently preparing the Cohesion Policy 2028-2035. Specific focus will be put on place-based and place-sensitive approaches to determine if it is possible to target the interventions of the future Cohesion Policy

([91]) REGULATION (EU) 2021/1060

([92]) REGULATION (EU) 2021/1058

better so that it delivers better results. This is particularly relevant for investments that make regions and cities more climate-resilient and help them cope with climate extremes, including extreme temperatures, which have a direct link to the UHI phenomenon.

Moreover, the European Urban Initiative supports urban areas with innovative actions, capacity and knowledge building, policy development and communication on sustainable urban development. The initiative works with calls for proposals. The budget comes from the ERDF. In a topic particularly focused on, Greening Cities, the impact of green roofs and walls for mitigating the UHI effects is emphasized ([93]). Similarly, the EU Strategy on Adaptation to Climate Change refers to the UHI effect and how it can be reduced using green roofs and walls. The same Strategy also references the need for a deeper understanding of the climate-related risks for health and a greater capacity to counter them and lists heat as one of the risks.

With this context during the co-design sessions DG REGIO emphasized the need for data on:

- impacts of UHI on population by age, income and class;
- impacts of UHI in terms of mortality and on infrastructure, including transport infrastructure, and vegetation;
- detailed mapping of UHI extent at the European scale and
- state and trends of UHI.

They also expressed the need for an annually updated indicator that informs about the share of people exposed to UHI and the number of days of exposure across the EU and a potential future development of a Copernicus service at the service of cities to anticipate the effects of UHI would be useful.

6.4.2 Description of the use case

Definitions
For the purpose of this use case, we will refer to the following definitions: **Temporal resolution** Very High Resolution (VHR): < daily High Resolution (HR): >= daily and < monthly Medium Resolution (MR): >= monthly and < seasonal Low Resolution (LR): >= seasonal **Temporal extent** Short Extent (SE): < 10 years Medium Extent (ME): >= 10 years and < 30 years Long Extent: >= 30 years

The objective of this use case is to describe how Copernicus data, services and derived products can be used to monitor the urban heat island in European cities.

([93]) https://www.urban-initiative.eu/innovative-actions-greening-cities

Abstract

Impact Pathways: loss of life; economic losses; reduced productivity; social, financial and political instability; disease & public health risks.

Key Adaptation Activities: Hard (energy efficiency, retrofitting), soft (incentives, planning), accommodation (technical, social, knowledge), ecosystem based (urban green, natural and protected areas).

Potential EO Value: Physical hazard drivers of extreme heat events (optical, thermal infrared, models). Hazard products (magnitude of the urban heat island), both predictive, near real time and historical. Vulnerability products including land cover, green and natural areas, impervious surfaces, topography, building characteristics and morphology (optical, Synthetic Aperture Radar, models). Exposure products and inventories (optical, Synthetic Aperture Radar, models)

Key Risk/Adaptation Indicators: Percentage of brownfield redevelopment, accessibility to public recreation sites, variation rate of the municipality surface area covered by protected areas, ratio of land consumption to population growth rate.

An urban heat island is an urban area that is significantly warmer than its rural surroundings. Human activities such as driving, warming buildings (in winter), or cooling buildings (in summer) add heat to the city. At the same time, artificial infrastructures absorb heat during the daytime and raise their temperatures, while narrow streets or tall buildings could reduce the airflow with a consequent increase in heat trapping (called the canyoning effect) and reduce solar illumination (shadowing effects). In addition, during nighttime, the release of heat retained in artificial infrastructures can lead to temperature differences between urbanised and rural areas of up to 10°C (Mentaschi et al. (2022), ([94])). On the other hand, vegetation cover has a cooling effect primarily through daytime evapotranspiration and shading (Marando et al., 2022).

In the literature, however, Urban Heat Island (UHI) and Surface Urban Heat Island (SUHI) are often used as synonyms when describing what is generally called the 'urban heat island effect'. While UHI is related to the atmosphere and refers to the microclimate conditions whereby a metropolitan area is significantly warmer than its surrounding rural areas because of differences in the energy budget (Arnfield, 2003), SUHI refers to the difference in Land Surface Temperature (LST) between an urban area and its surrounding non-urban area (Medina-Fernández et al., 2023) and is a critical component of the UHI.

In the past, several authors have reported studies on the UHI. For instance, Chen et al. (2020) analysed several algorithms to detect impervious surfaces from Sentinel-2 imagery, which could be used to monitor the dynamics of Urban Heat Island. Hidalgo-García & Arco-Díaz (2022) modelled the Urban Heat Island in the city of Granada (Spain) with Copernicus Sentinel-3 images. Reis et al. (2022) evaluated the Urban Heat Island effects in Lisbon's metropolitan area (Portugal) using the climate variables dataset from the Copernicus Climate Change Service. Pace et al. (2022) integrated the Copernicus Urban Atlas provided by the Copernicus Land Monitoring Service to map urban heat mitigation by tree cover in Naples (Italy). Marconcini et al. (2023) highlighted the current limitations for UHI mapping of the 5km Land Surface Temperature (LST) product available through the Copernicus Land Monitoring Service (CLMS). The authors also presented and tested in 10 European cities a downscaling method that generates 100m spatial resolution LST maps by integrating Sentinel-2 and Sentinel-3 images with atmospheric information from Copernicus Atmosphere Monitoring Service (CAMS) and surface cover information from Copernicus Land Monitoring Service (CLMS).

([94]) Demonstrating heat stress in European cities

In addition, some authors also described the intensification of UHI effects during heat waves (K. Chen et al., 2023; Possega et al., 2022; Zhao et al., 2018), thus linking local-scale UHI with larger-scale extreme events correlated to climate change.

Many studies and toolkits have been proposed when dealing with adaptation measures to urban heat islands. For instance, in the document 'Adapting to Urban Heat: A Tool Kit for Local Governments' (Hoverter, 2012), the author analysed how cool roofs, green roofs, cool pavements, and urban forestry can reduce the urban heat island effect, helping residents adapt to urban overheating. The author also described the benefits of these built-environment changes on public health, economy and the environment.

The authors of the document 'Urban heat planning toolkit 2021' (McAuley et al., 2009) identified several design measures to increase the city's resilience to urban heat, including rooftop solar photovoltaic systems to reduce indoor temperature, cool paving and cool roofs to reduce the amount of heat absorbed (and then released), green cover to increase the cooling effects of shadowing and evapotranspiration. The authors of the study 'Urban Heat Island's Vulnerability Assessment by Integrating Urban Planning Policies: A Case Study of Montpellier Méditerranée Metropolitan Area, France' (Técher et al., 2023) proposed mitigation solutions into urban planning for increasing resilient to heat islands by increasing permeable and green areas, improving urban ventilation and heat exchange, and decreasing anthropogenic heat generation.

All the studies and toolboxes highlight that urban vegetation cover strongly influences the landscape mosaic, modifies the microclimate conditions and reduces the difference between urban and non-urban temperatures. They also suggest that policymakers should use urban planning policies to encourage the adoption of appropriate mitigation strategies.

6.4.3 Application needs

The cohesion report describes the social, economic, and environmental state of the EU regions every three years and tracks various indicators and data sources that describe possible growing disparities between regions. Many indicators are also expressed by the degree of urbanisation, recognising the different dynamics between cities, towns, suburbs, and rural areas.

In this context EO can provide objective tools to managing authorities and intermediary bodies for investments in urban resilience to climate change impacts. For instance, the impact of the Cohesion Policy 2021-2027 will also be measured using specific climate change adaptation indicators assessing the share of the population benefitting from measures relying on Copernicus services that map both measures, such as green infrastructure and population (ERDF and CF). Unfortunately, local authorities often have little knowledge about how to use Copernicus data and little capacity to help make decisions on investments in climate change adaptation.

Generic application needs:

Application Need 1: [Vulnerability, Exposure] An explicit, standardised vulnerability and exposure products for all European cities, based on the existing Copernicus products/services and Eurostat statistics, would be extremely valuable. Alternatively or in addition tools that facilitate users to derive suites of vulnerability and exposure products would have high value.

Application Need 2: [Vulnerability, Exposure] Availability of a routinely calculated geospatial change product over time, for both vulnerability and exposure components, would be of high user value. Automated change detection in both risk components, on an ongoing basis, would greatly facilitate adaptation monitoring and the implementation of adaptation pathways.

Application Need 3: [Vulnerability, Exposure] Availability of a routinely calculated hotspots over time, showing areas of high vulnerability and exposure, would be of high user value.

Application Need 4: [Risk] Combined risk indicators need to be made routinely available across the necessary spatiotemporal and value-added intelligence ranges, as detailed below. These cascade from geospatially-explicit, hazard-specific risk indicators; combined geospatially-agnostic, hazard-specific risk indicators; composite geospatially-agnostic, hazard-agnostic risk indicators & frameworks.

Application Need 5: [Risk] Risk indicators need to be made available in an appropriate range of metrics for key user archetypes, e.g. potential or realised economic damage; public health risks and other suitable key indicators.

Application Need 6: [Semantics] Users frequently cannot access appropriate information, or struggle with information that they are uncertain of how to use. A key aspect of the EO value chain is the last part – the interfaces that users interact with to gain understanding and knowledge. Realising full value of the EO knowledge offering requires the ongoing development of community-driven, iterative, aspirational, enabling Decision Support systems, driven by strong user co-design. Creating a strong two-way dialogue between providers and users aids in identifying the best solutions, speeds development, and results in much increased uptake (Virapongse et al., 2020).

Specific application needs:

Application Need 1: [Hazards] Urban heat island information needs to be made available to policy makers and investors in a simple and timely manner.

Application Need 2: [Hazards] Extreme heat information in urbanized areas needs to be made available on a historical, phenological basis, e.g. as a climatology/anomaly; as a component of a predictive short term Early Warning System; and as a component of future climate scenarios.

Application Need 3: [Vulnerability, Exposure] Easy access to data, information and models at the regional and municipality levels needs to be made available to help identify effective long-term solutions to different climate risks.

Application Need 4: [Semantics] Indicators should be able to assist ex-post monitoring of the impacts of climate adaptation projects funded under the Cohesion Policy.

Given the abovementioned objectives, the application should address different needs, from low spatiotemporal scales for overall synthesis at the EU level to high spatiotemporal scales for detailed local analyses at the municipality (Table 11).

Table 11. Objectives, spatiotemporal resolution, and user archetype intelligence dimensions.

Objectives	**Spatial dimension**	**Temporal dimension**	**User archetype**
Evaluation of the impact of heat island on population health Evaluation of the impact of green areas on heat islands Ex-post evaluation of the impact of climate adaptation projects Evaluation of urban resilience to climate change impacts	Municipality level (main) Regional level (main) National level (secondary) EU level (secondary)	Short-term (secondary) Medium-term (main) Long-term (main)	Strategic: interannual policy-focused (primary) Tactical: intra-annual (secondary) Logistical: event to seasonal (secondary)

Source: Internal EC KCEO.

6.4.4 Technical assessment

The application should support the evaluation of urban resilience to the urban heat island, identify and map the location and extent of critical hot spots in EU municipalities, reconstruct the past evolution, predict future scenarios and evaluate local adaptation measures. Different products and services should be integrated to reach these goals, thus maximising the added value of existing information sources and future operational services from EU-funded research.

Specifically, temperature is measured with satellites sensing in the thermal infra-red with a high temporal resolution and assimilated with ground station measures. That information shall be integrated with high-resolution urban green areas, impervious surfaces, and built-up layers obtained using EO data from visible or microwave sensors and supplemented with general land cover at medium resolution. Moreover, building characteristics such as height are essential to model canyoning effects, topography (elevation) is linked with climate change resilience, and proximity to natural areas is another critical aspect. This additional information can be derived from EO data as well.

Air quality and climate variables (precipitation, water vapour, wind speed, and direction) are monitored with EO at low spatial resolution and amplify the urban heat island effects on human and vegetation health. Besides, climate variables are also needed to project future scenarios.

In terms of temporal resolution, the evaluation should be carried out with a frequency appropriate to the nature of the observed indicators. For instance, the main physical indicator temperature should be ideally measured daily (or even hourly) due to its highly dynamic nature. The land cover, such as green cover areas and impervious surfaces, has slower dynamics and monthly (for green areas) or annual (for impervious surfaces) should be an adequate trade-off. The evaluation of building characteristics and proximity to natural areas may also imply annual updates.

Regarding time series availability, historical EO data are needed to evaluate progress against a reference baseline, ideally coinciding with the policy period under evaluation.

Future projections are instead required to model long-term effects.

Finally, the overlapping of land cover maps with air quality, climate variables, and socio-economic indicators like statistics on demography, poverty and social exclusion, health, tourism, or energy consumption at a suitable scale should help monitor adaptation to climate change.

Table 12 describes parameters of the environmental, climate and socio-economic dimensions derived from the specific application needs. Their minimum technical requirements on spatial resolution, temporal resolution, and time series length are also provided. This information was used to identify suitable existing EO services and products.

Table 12. Parameters and minimum technical requirements. (n/a = not applicable)

Parameter	Spatial resolution	Temporal resolution	Temporal extent
Main physical parameter			
Temperature	Medium Resolution	High Resolution	Long Extent
Environmental dimension			
Land cover	High Resolution 2	Low Resolution	Medium Extent
Green cover	High Resolution 1	Low Resolution	Medium Extent
Impervious surfaces	High Resolution 1	Low Resolution	Medium Extent
Topography	Medium Resolution	Low Resolution	n/a
Building characteristics	n/a	Low Resolution	Medium Extent

Proximity to natural areas	Medium Resolution	Low Resolution	Medium Extent
Climate dimension			
Climate variables	Low Resolution	High Resolution	Long Extent
Air quality	Low Resolution	High Resolution	Long Extent
Socio-economic dimension			
Demographic statistics	DEGURBA	Low Resolution	Medium Extent
Poverty and social exclusion statistics	DEGURBA	Low Resolution	Medium Extent
Health statistics	DEGURBA	Low Resolution	Medium Extent
Tourism statistics	DEGURBA	Low Resolution	Medium Extent
Energy statistics	DEGURBA	Low Resolution	Medium Extent

Source: Internal EC KCEO.

6.4.5 Value chain analysis

Resilience and adaptation to climate change affect policies at different scales, from the municipal to the EU level. For this reason, the use case should partially address the different needs. However, this assessment focuses on urban areas and should provide tools to the municipality governments on local climate change risks and adaptation measures. Consequently, the assessment will consider the minimum technical requirements needed for the analysis at the municipality scale.

In some cases, the products and services described in the next section already provide parameters at a high spatial resolution and could be used directly to produce parameters at the coarser scales (regional, national, EU). That is not true when the parameters are patchy, fragmented, and small compared to the desired resolution, and higher resolution parameters should be aggregated at a coarser scale. In these cases, getting a reliable parameter estimation on the lower-resolution products might be impossible, but starting from the higher-resolution product could be done. A typical example is the urban green cover, where it is always possible to give a fractional cover estimate for every spatial scale by aggregating the information from high-resolution products. However, getting it directly from the lower-resolution products is impossible.

Breaking down the risk components to evaluate impacts and adaptation to climate change into hazard, exposure and vulnerability, the main hazards are:

- Magnitude of the urban heat island: driven by extreme temperatures interacting with water vapour and wind (speed and direction).

All the physical forcing phenomena can be evaluated and monitored using EO data. From a value-added perspective, hazard information should be available both for short term early warning, reanalysis of historical heatwaves events, and future scenarios across a range of climate-driven forcing conditions and adaptation scenarios. Besides, the magnitude of the urban heat island hazard has additional impacts on drought and water availability for different uses, which can be evaluated and monitored using EO data.

From an exposure and vulnerability perspective, we have:

- Population density;
- Availability, distribution and accessibility to green and blue areas (public spaces, protected natural areas and recreational facilities);
- Overall urban development.

All exposures and vulnerabilities can be evaluated and monitored using EO data or by assimilating EO data with other socio-economic information. Critical aspects of vulnerability parameters should be closely linked to primary adaptation actions as given by the key type measures, including green and blue options as temperature mitigation, or capacity building, empowering and lifestyle practices as public building sustainability and energy consumption for mitigating heat stress.

Hazard related impacts can be quantified, both for adaptation scenarios and extreme events, as:

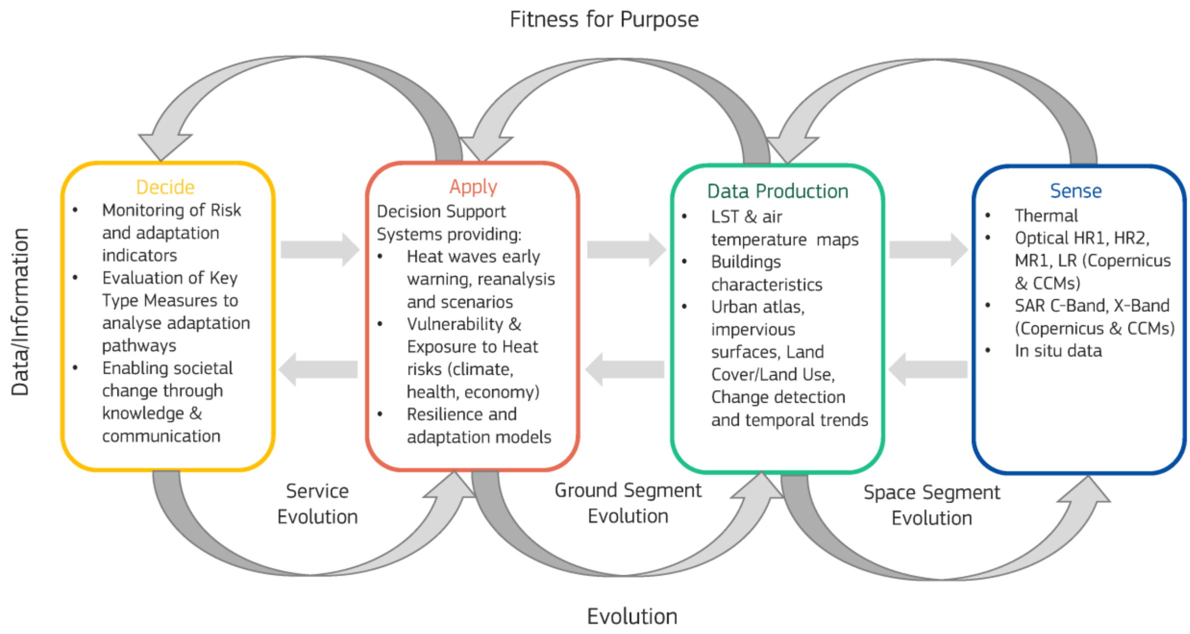
- Impacts of climate change;
- Economic losses attributable to overheating (percentage of the city's gross domestic product or any other meaningful parameter);
- Reduced work productivity due to heat stress (number of hours or percentage);
- Number of heat-related mortality.

While parameters for adaptation action outcomes can be quantified as:

- Percentage of brownfield redevelopment;
- Accessibility to public recreation sites (as distance or time);
- Ratio of land consumption to population growth rate;
- Variation rate of the municipality surface area covered by protected areas.

With many other indirect indicators available through a combination of EO and socio-economic data (Kilsedar et al., 2024). Figure 13 shows the Earth Observation value chain.

Figure 13. Earth Observation value chain for Urban Heat Island. (SAR=Synthetic Aperture Radar; CCMs= Copernicus Contributing Missions)



Source: Internal EC KCEO.

6.4.6 Fitness for purpose of existing products and services

The fitness for purpose discussed below is based on the technical assessment (spatial resolution, temporal resolution, time series length), the products/services' thematic content, and fitness to application needs. The critical aspects of uncertainty and accuracy, as well as ratings of the overall quality of EO products/services, were not considered since they would require extensive analysis beyond the scope of the deep dive.

Table 13 shows a summary of the results, and Source: Internal EC KCEO.

Table 14 summarises the fit to application needs of all technical requirements.

Table 13. Examples of EO-derived products and services that could contribute to the assessment and their technical specifications. (n/d = not defined)

Parameter	Service(s)/Product(s)	Spatial resolution	Temporal resolution	Temporal extent
Main physical parameter				
Temperature	CLMS Temperature and Reflectance (Land Surface Temperature)	5 km	1 hour	2010-present
	E-OBS (temperature)	0.1° (about 10 km)	1 day	1950-present
	Urban Heat Island Intensity for European Cities	100 m (downscaled)	1 hour	2008-2017
	CURE LST	100 m (downscaled)	~3 days	2018-2019
Environmental dimension				
Land cover	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
	CORINE Land Cover+ Backbone	10 m	3 years	2018
Green cover	High Resolution Layer Tree Cover Density	10 m, 20 m, 100 m	3 years	2012, 2015, 2018
	Urban Atlas Street Tree Layer	500 m^2	6 years	2012, 2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
	CORINE Land Cover+ Backbone	10 m	3 years	2018
Impervious surfaces	High Resolution Layer Imperviousness	10 m, 20 m, 100 m	3 years	2006-2018
	High Resolution Layer Impervious Built-up	10 m, 100 m	3 years	2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
Topography	EEA-10	10 m	Continual	Continuous
	GLO-30	30 m	Continual	Continuous
	SRTM	30 m	Continual	2000
Building characteristics	Urban Atlas Building Height	10 m	n/d	2012

	EUBUCCO [95]	Vector (n/d)	n/d	n/d
	GHSL	Variable	Variable	Variable
Proximity to natural areas	CORINE Land Cover (CLC)	25 ha	6 years	1990, 2000-2018
Climate dimension				
Climate variables	Precipitation (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present
	Water vapour (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present
	Wind speed and direction (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present
	CERRA-Land	5.5 km	1 day	1984-2021
Air quality	AIR-Portal	Downscaled to 100 m	n/d	n/d
	CAMS	Variable	Variable	Variable
Socio-economic dimension				
Population/population density	Eurostat data	DEGURBA	1 year	Different by regionPartial match
Population grid	Global Human Settlement Layer (GHSL)	100 m, 1 km, 3 arcsec, and 30 arcsec	5-year intervals	1975-2020 (and projections to 2025 and 2030)
Demographic statistics	Eurostat data	NUTS3	1 year	Different by region
Poverty and social exclusion statistics	Eurostat data	NUTS2	1 year	Different by region
Health statistics	Eurostat data	NUTS2	1 year	Different by region
Tourism statistics	Eurostat data	NUTS3	1 year	Different by region
Energy statistics	Eurostat data	NUTS3	1 year	Different by region

Source: Internal EC KCEO.

(95) EUBUCCO is a scientific database of individual building footprints for 200+ million buildings across the 27 European Union countries and Switzerland, together with three main attributes – building type, height and construction year – included for respectively 45%, 74%, 24% of the buildings. EUBUCCO is composed of 50 open government datasets and OpenStreetMap that have been collected, harmonized and partly validated.

Table 14. Fit for application needs. (n/d = not defined)

Parameters	**Service(s)/Product(s)**	**Fit to application needs**
Main physical parameter		
Temperature	CLMS Temperature and Reflectance (Land Surface Temperature)	Spatial resolution: is unsuitable for monitoring local variations at the municipality level. On the other hand, it is suitable for aggregated statistics at the regional, national or European levels. Temporal resolution: fits the application's needs for all the spatial scales. Temporal extent: is suitable for assessing short/very short-term trends. However, long-term analyses and assessments of urban adaptation to policies require observations over a more extended period.
	E-OBS (temperature)	Spatial resolution: does not fit the application's needs. Temporal resolution: fits the application's needs for all the spatial scales. Temporal extent: fits the application's needs for all the spatial scales.
	Urban Heat Island Intensity for European Cities	Spatial resolution: fits the application needs. Temporal resolution: fits the application needs. Temporal extent: doesn’t fit the application needs.
	CURE LST	Spatial resolution: fits the application needs. Temporal resolution: fits the application needs. Temporal extent: doesn’t fit the application needs.
Environmental dimension		
Land cover	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: partially fits the application's needs.
	CORINE Land Cover+ Backbone	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs (new product). Temporal extent: does not fit the application's needs (new product).
Green cover	High Resolution Layer Tree Cover Density	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
	Urban Atlas Street Tree Layer	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: partially fits the application's needs.
	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: partially fits the application's needs.

	CORINE Land Cover+ Backbone	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs (new product). Temporal extent: does not fit the application's needs (new product).
Impervious surfaces	High Resolution Layer Imperviousness	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: the available time series is suitable for assessing short-term trends. However, long-term analyses and assessments of urban adaptation to policies require observations over a more extended period.
	High Resolution Layer Impervious Built-up	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs (new product). Temporal extent: does not fit the application's needs (new product).
	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: partially fits the application's needs.
Topography	EEA-10 GLO-30 SRTM	Spatial resolution: all products fit the application's needs for all the spatial scales. Temporal resolution: n/d; Temporal extent: n/d.
Building characteristics	Urban Atlas Building Height	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: partially fits the application's needs.
	EUBUCCO	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: n/d. Temporal extent: n/d.
	GHSL	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: does not fit the application's needs. Temporal extent: fits the application's needs.
Proximity to natural areas	CORINE Land Cover (CLC)	Spatial resolution: fits the application's needs. Temporal resolution: fits the application's needs. Temporal extent: fits the application's needs.
Climate dimension		
Climate variables	Precipitation (C3S Agrometeorological indicators)	Spatial resolution: all products do not fit the application's needs. Temporal resolution: all products fit the application's needs. Temporal extent: all products fit the application's needs.

	Water vapour (C3S Agrometeorological indicators) Wind speed and direction (C3S Agrometeorological indicators) CERRA-Land	
Air quality	AIR-Portal	Spatial resolution: fits the application's needs for all the spatial scales. Temporal resolution: fits the application's needs for all the spatial scales. Temporal extent: n/d.
	CAMS	Spatial resolution: does not fit the application's needs. Temporal resolution: fits the application's needs. Temporal extent: does not fit (or it is sub-optimal for) the application's needs.
Socio-economic dimension		
Population/population density	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Population grid	Global Human Settlement Layer (GHSL)	Spatial resolution: data have different spatial scales. Overall, they do not fit (or are sub-optimal for) the application's needs. Temporal resolution: is sub-optimal for the application's needs. Temporal extent: fits the application's needs.
Demographic statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Poverty and social exclusion statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing

		medium-term trends. In some other cases, a more extended period is required.
Health statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Tourism statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Energy statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.

Source: Internal EC KCEO.

6.4.7 Gap analysis

Today, there are already available EO products/services and additional socio-economic statistical data that are useful for the assessment. Moreover, some new experimental products that extend the analytical capabilities are being proposed or demonstrated. Nevertheless, to date, there are still some significant gaps.

It is to be mentioned that the uncertainty and accuracy of EO products could not be considered and are beyond the scope of this deep dive. Thus, no recommendations can be made in this respect.

Spatial resolution

- The Copernicus Land Monitoring Service does not provide the temperature information (main physical parameter) at a suitable spatial resolution for monitoring variations at the municipality level. That is a severe limitation. On the other hand, new services that use downscaled temperature data to 100 m have already been demonstrated (e.g. UrbClim model or CURE portal), but they are not operational. The implementation of such products into the Copernicus ecosystem would be a game changer for the use case;

- Increasing the spatial resolution of climate variables, including both ECVs and derived datasets, will also bring benefits in modelling the heat stress in urban areas;
- Today, the spatial observation capabilities of the Sentinels are very limited in the thermal infrared region. Future Copernicus missions will fill this gap. However, including past data (e.g. Landsat 4-9) and future data from Contributing Missions will provide essential information at a higher spatial resolution;
- Socio-economic indicators are essential for evaluating exposure and vulnerability to climate change, and Eurostat delivers valuable information. Nevertheless, even if some Eurostat data is being gridded at 1 km spatial resolution, the standard territorial units for their statistics are defined by the average population size and not on a geospatial scale. A closer match between Eurostat's spatial extent and EO-derived products' spatial resolution will significantly improve the resilience analysis at the municipality scale;

Temporal resolution

- The temporal resolution of coarse temperature data is very high (hourly). Nevertheless, its spatial resolution is low (as discussed above). The processing of data from Contributing Missions will also increase the temporal resolution of finer EO-derived parameters, thus increasing the overall reliability of downscaled models;
- Regarding the land cover products, the use case would benefit from a more frequent update of the key indicators derived from the Urban Atlas, High Resolution Layer Tree Cover Density, High Resolution Layer Imperviousness, and High Resolution Layer Impervious Built-up. Ideally, an annual update is desirable;

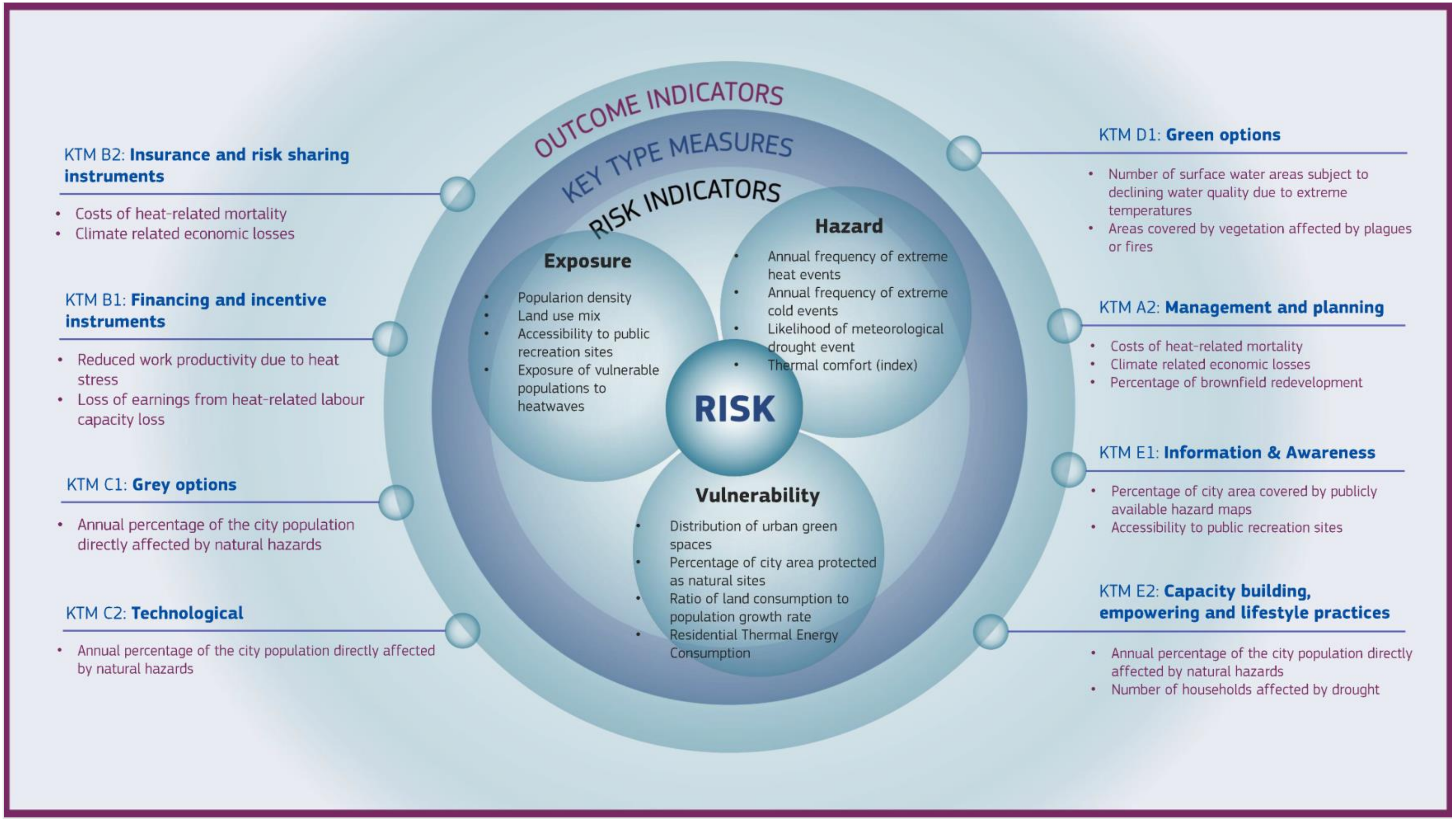
Temporal extent

- The temporal extent of all land cover products is minimal, with the exclusion of the CORINE land cover going back to 1990. That severely limits trend analyses (in the past) and thus the ability to observe the impacts of policies. An increase in the temporal extent of land cover, green cover and impervious surfaces with data from Landsat Complementary Data, even if at a lower resolution than the available Copernicus products, will partially fill this gap.

6.4.8 Monitoring risk, adaptation and outcome

Figure 14 shows an illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators. The schematic aims to bring out the applicability of Earth Observation in the Climate Adaptation aspects of Risk Assessment (comprising the components of Hazard, Exposure and Vulnerability); of the climate action reporting framework of Key Type Measures; and the outcome of this action through pertinent indicators (all indicators within are EO-addressed). Moreover, it aims to encapsulate the discussion in the Indicators chapter and link it with each Use Case through an illustrative example of a particular hazard, a traditional starting point for Risk Assessments and identification of adaptation measures, in essence presenting the Earth Observation 'value proposition' to the adaptation cycle (e.g. contributing to steps 2 till 6 in Climate-ADAPT's Adaptation Support Tool). The schematic does not aim to paint Earth Observation as a cure-all. Dozens of indicators and KTMs are solely dependent on socio-economic data and many will remain unapproachable by EO alone. Nevertheless, the schematic, as does this assessment as a whole, advocates for the Earth Observation potential in direct monitoring (the bane of most adaptation frameworks) of the above but also in overall support through contributing in e.g. monitoring the presence of KTMs, designing KTMs and allowing for more harmonized and more frequent risk assessments.

Figure 14. DG REGIO – Urban heat island. Illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators.



Source: Internal EC KCEO.

This illustrative example focuses on extreme heat waves, featured in the DG REGIO Use Case on Urban Heat Island.

When it comes to the risk factors, Earth Observation is a straightforward approach: satellite observations supplemented by *in situ* measures, climate projections, and modelling, deliver time series of risk indicators at different spatial and temporal scales. Estimation of vulnerability and exposure require integrating socio-economic datasets with hazard maps and landscape attributes. The former, among other things, are mainly provided by Eurostat, while the latter, among other things, are provided primarily by the Copernicus products and services reviewed in the previous sections. Again, Earth Observation plays an essential role in supporting their quantification.

Turning to sub-KTMs and their outcome, only those in which Earth Observation has a potential role are here represented:

- <u>Green options (D1) & Blue options (D2):</u> Earth Observation has a dual role in setting a reference for evaluating future improvements and monitoring outcomes over time. For instance, the number of surface water areas subject to declining water quality due to extreme temperatures or areas covered by vegetation affected by plagues or fires are examples.
- <u>Grey options (C1):</u> this is not among the most relevant for this use case. Nevertheless, Earth Observation can provide information such as the annual percentage of the city population directly affected by natural hazards.
- <u>Management and planning (A2):</u> incorporating Earth Observation can add value, for instance, in estimating the costs of heat-related mortality, climate-related economic losses, or the percentage of brownfield redevelopment.
- <u>Financing and incentive instruments (B1) & Insurance and risk sharing instruments (B2):</u> in incentives/insurance domains, Earth Observation can help estimate the loss of earnings from heat-related labour capacity loss, together with the costs of heat-related mortality and overall climate-related economic losses.
- <u>Information & Awareness (E1) & Capacity building, empowering and lifestyle practices (E2):</u> in this case, Earth Observation can significantly contribute to the production of hazard maps and evaluating the annual percentage of the city population directly affected by natural hazards or the number of households affected by drought.

6.4.9 Recommendations

One critical goal of this assessment is to support DG REGIO in evaluating the outcomes of the current policy and targeting better interventions for future Cohesion Policies. Specifically, intervention areas for investments in climate change adaptation include climate-related risks such as floods and landslides, fires, storms, drought, and other relevant risks.

In this context, Earth Observation is essential for comprehending environmental systems and evaluating feedback loops and impacts in urban and peri-urban areas.

Usable intelligence derived from Earth Observation data has advanced significantly. However, gaps still exist, and the analysis has identified the following areas where improvements might facilitate the uptake of EO products and services for urban climate adaptation at the European, national and local scales.

On the evolution of Copernicus, recommendations include the promotion of:

- Further development and integration of temperature modelling, such as the UrbClim or CURE models, bringing them to operational products and services into the Copernicus ecosystem. This is crucial for building better interpretative and predictive models.

- Further processing/re-processing of data collected before Copernicus from the Member States' national and international programs to build a more extended time series. This is crucial for creating more reliable analyses.
- Further development of Copernicus Urban Atlas, with the ideal goal of annual update cycles (plus one-year latency). This is crucial for enhancing the description of the land cover dynamics and, thus, improving the estimation of the Vulnerability and Exposure components.
- Further development of all relevant change detection products (e.g. Urban Atlas Land Cover/Land Use Change, Imperviousness Change, and Imperviousness Classified Change), with the ideal goal of annual update cycles (plus one-year latency). This is crucial for highlighting hot spots and fast land changes, thus focusing and prioritizing high/very-high resolution data collection.
- Further integration with Eurostat statistical data and ask the statistical institute to produce data with a finer granularity. This is crucial for bringing the socio-economic dimension into the models and better evaluating the Vulnerability and Exposure components.
- Further integration into the Copernicus products and services of higher spatiotemporal data from the Landsat programme and (future) Contributing Missions. This is crucial for improving the main physical variables observed.
- Integration of future Copernicus Expansion Missions (e.g. Land Surface Temperature Monitoring, Copernicus Anthropogenic Carbon Dioxide Monitoring). This is crucial for improving the main physical variables observed.

On the risk side, recommendations include the promotion of:

- Advanced adaptation scenario modelling capacity for all European cities, under a range of KTM-classified adaptation and hazard scenarios.
- Advanced early warning modelling capacity for all European cities.
- Indicators that could be used across different use cases (e.g. greening, drought and floods in European cities).
- Combined risk indicators for key user archetypes (e.g. potential or realised economic damage, population affected, public health risks).

On the policy-making side, recommendations include the promotion of:

- User-friendly web-based dashboards that integrate available information into specific, quantitative, measurable, and standardized indicators. This would provide give policymakers and local authorities, non-EO experts, simple effective tools to make better decisions and evaluate *ex post* impacts of their policies. In this regard, Destination Earth could be an appropriate platform to provide a common framework for the provision of such indicators and services. The Destination Earth digital twins, specifically the climate adaptation digital twin and weather-induced extremes digital twin, in conjunction with information from the European Data Spaces ecosystem provide significant potential to realise the necessary extension of the EO value chain. The identification of user needs – most specifically around key type measure focused decision making - is an important first step in supporting the co-design of tailored services for EC policymakers.
- Increased use of EO-derived indicators within Member States' national legislation. This is crucial to accelerating Copernicus information, products, and services uptake.

- Further use, in future policy documents, of specific and quantitative indicators that can be measured with Earth Observation or are EO-based, as evaluation metrics. This is crucial to have *ex ante* measurable parameters.
- Dissemination to politicians, national authorities and local administrators of the potential of Earth Observation and geodata. This is crucial as a whole.
- It is also worth noting that to help assess the effects of climate change adaptation policies, continuity of the products and services reviewed is necessary for at least the policies' time horizon. In the present use case, since DG REGIO is preparing the 2028-2035 Cohesion Policy, data continuity should be provided until 2035.

6.5 Water Management for Climate Adaptation in Urban Areas (DG REGIO/CLIMA)

Earth Observation Use Case: Water Management for Climate Adaptation in Urban Areas

The EU Strategy on Adaptation to Climate Change identifies floods and drought as major climate hazards, whilst emphasising that sustainable freshwater availability is fundamental for climate resilience. Smart, sustainable water use requires transformational changes through the engagement of the Common Implementation Strategy of the Water Framework and Floods Directives. Adaptation investment through current and emerging Cohesion Policies, the European Regional Development Fund, and the European Urban Initiative all require place-based and -sensitive targeted intervention, with a strong requirement for enhanced, dynamic, resilience-focused intelligence systems.

Infrastructural (flood defence and water supply diversification) and Blue adaptation actions, in combination with soft- , accommodation-, and ecosystem-focused measures, are shown to have significant potential to increase water resilience issues across European urban areas. The Cohesion reports used to guide and monitor investment rely on dynamic geospatial information and indicators, and Earth Observation can provide a range of objective tools to managing authorities and intermediary bodies for investments in urban climate resilience. Key applications needs include dynamic and standardised hazard, vulnerability and exposure intelligence; compounded risk and damage indicators; event-based reconstruction and predictive capabilities; and increased access to actionable intelligence across all urban scales. Many necessary products and services are available in an emerging sense through Copernicus and other European services, although there are clear needs for increased precipitation and temperature related resolution at municipal scales. A significant set of Key Type Measures can be monitored from an Earth Observation perspective, most notable Green, Blue, and Grey, Planning, and Information-related measures.

Key recommendations again include the development of operational land surface temperature models; more time-extensive and frequently updated EO services; enhanced automated change detection products; and activities designed to extend the EO value chain and provide actionable intelligence to a range of user archetypes.

6.5.1 Policy context

The sustainability of water resources is a key area identified in the EU Strategy on Adaptation to Climate Change. The Strategy emphasizes that ensuring freshwater is available in a sustainable manner is fundamental for climate resilience. Water underpins many sectors of the economy, and access to drinking water is a basic human need, but torrential rains and floods can have devastating effects on communities and infrastructure. These issues are even more exacerbated in urban areas. Europe is increasingly facing situations of either too much or too little water. Smart, sustainable water use requires transformational changes in all sectors. The Commission is prioritising these aspects through the enhanced engagement of the Common Implementation Strategy of the Water Framework and Floods Directives. Furthermore, The Strategy states that the Commission will help address storm water overflows and urban runoff as part of the revision of the Urban Waste Water Treatment Directive, and share best practices on preventing water pollution through industrial accidents caused by flooding and droughts.

Climate change also threatens water quality. A stable and secure supply of drinking water is of highest importance and it must be guaranteed. Climate change will increase the risk of contamination and acute pollution of freshwater due to impacts such as low river flows, increased water temperatures, flooding, and forest loss. It is important to include climate impacts in the risk analyses of (drinking) water management plans, develop water-monitoring technologies, and ensure minimum river flow. These will play an important role in ensuring water quality and preserving sufficient water quantity for the environment and all people. Similarly, it is important to maximise the capacity of soils to purify water and reduce pollution.

Climate water aspects are often associated with extreme events. Due to the changing climate, many European regions and cities are already facing more frequent, severe, and longer lasting droughts. Droughts can have cascading effects; for example, they reduce water levels in rivers and ground water, stunt tree and crop growth, increase pest attacks and fuel wildfires.

These aspects on extremes and the management of climate related risks are also relevant to DG REGIO in the context of current Cohesion Policy 2021-2027 (Common Provisions Regulation (CPR)). Cohesion Policy has specific climate investment targets under article 6. The ERDF and the Cohesion Fund shall contribute with 30 % and 37 % respectively of the Union contribution to expenditure supported for the achievement of the climate objectives set for the Union budget. The list of intervention fields for investments in climate change adaptation are in Annex 1:

- Adaptation to climate change measures and prevention and management of climate related risks: floods and landslides (including awareness raising, civil protection and disaster management systems, infrastructures and ecosystem-based approaches)
- Adaptation to climate change measures and prevention and management of climate related risks: others, e.g. storms and drought (including awareness raising, civil protection and disaster management systems, infrastructures and ecosystem-based approaches)
- Adaptation to climate change measures and prevention and management of climate related risks: fires (including awareness raising, civil protection and disaster management systems, infrastructures and ecosystem-based approaches)

On urban aspects specifically, the European Urban Initiative supports urban areas with innovative actions, capacity and knowledge building, policy development and communication on sustainable urban development. The initiative works with calls for proposals. The budget comes from the ERDF.

The current programming period has also a dedicated urban policy via the European Urban Initiative (article 7.2 of the CPR) and article 11, 12 of the ERDF and CF regulation.

DG REGIO is currently preparing the 2028-2034 Cohesion Policy. Specific focus goes to place-based and place-sensitive approaches. Put differently, can we target better interventions of the future Cohesion Policy so that they deliver enhanced results as well. This is particularly relevant for investments that make regions and cities more climate resilient and help them cope with droughts, floods, extreme temperatures or other climate extremes.

6.5.2 Description of the use case

Definitions
For the purpose of this use case, we will refer to the following definitions: **Temporal resolution** Very High Resolution (VHR): < daily High Resolution (HR): >= daily and < monthly Medium Resolution (MR): >= monthly and < seasonal Low Resolution (LR): >= seasonal **Temporal extent** Short Extent (SE): < 10 years Medium Extent (ME): >= 10 years and < 30 years Long Extent: >= 30 years

Use Case 1: Urban Drought and Floods

The objective of this use case is to describe how Copernicus data, services and derived products can be used to monitor drought and floods in European cities.

Abstract
Impact Pathways: loss of life; economic losses; social, financial and political instability; reduced food security; public health risks.
Key Adaptation Activities: Hard (hydraulic defence works, water supplies), soft (incentives, planning, awareness), accommodation (technical, social, knowledge), ecosystem based (urban green, natural and protected areas).
Potential EO Value: Physical hazard drivers of extreme rain and heat waves (optical, SAR, TIR, models). Hazard products (magnitude and return period), both predictive, near real time and historical. Vulnerability products including land cover, green and natural areas, impervious surfaces, topography, infrastructures, risk-prone areas (optical, SAR, models). Exposure products and inventories (optical, SAR, models)
Key Risk/Adaptation Indicators: Percentage of brownfield/greyfield redevelopment, variation rate of the municipality surface area covered by protected areas, variation rate of natural hazards-prone areas.

In the first two decades of the 21st century, drought severely affected 79 global cities (Zhang et al., 2019). The global urban population challenging water scarcity is projected to increase from 933 million in 2016 to 1.693-2.373 billion people in 2050. Over the same period, the number of cities with over a million people exposed to water scarcity may double (from 193 to 292), also including 10-20 megacities with over 10 million populations (Dąbrowska et al., 2023).

Drought and floods are climate-related hazards closely connected to high temperatures: as the average temperature increases, more evaporation occurs, thus increasing overall precipitation. Accordingly, a warming climate is expected to increase precipitation in many areas ([96]). This connection was recently quantified by Sauter et al. (2023). In their research, the authors described a compounding effect between heatwaves and extreme rainfall, with the strongest compounding in central Europe and Japan, where the likelihood of extreme rainfall after a heatwave is increased by approximately four times compared to climatology. The study concluded that heatwaves and extreme rainfall are expected to become more frequent, and the potential impacts of compounding heatwave-extreme rainfall events are also expected to increase significantly. However, even if heavy rainfall events could increase, they might not be sufficient to counterbalance the long-standing lack of rain due to the increasingly extended heat waves.

Regarding the wild weather swings from severe drought to heavy rains, which are becoming more frequent with climate change, Qing et al. (2023) studied the dynamic evolution from drought to pluvial transitions in the last 40 years (from 1980 to 2020). The authors concluded that the soil moisture-latent heat flux-precipitation causal chain is likely to trigger the rainfall following the dryness in humid regions where enhanced evaporation increases the actual atmospheric moisture, thus favouring the pluvial occurrence. And Europe is one of the seven regional hotspots where this trend worsens, according to their study.

Concerning flooding, cities often rely on grey solutions to drain urban rainwater. However, green infrastructures such as green roofs, parks, and green spaces can significantly enhance flood mitigation in urban areas. Tree branches and leaves intercept rainfall, reducing its erosive impact. Dense grass sods create a root network, making the soil more resilient to heavy rain. Overall,

([96]) United States Environmental Protection Agency increased vegetation cover increases the storage capacity and infiltration of the soil, thus reducing stormwater runoff and producing substantial improvements in the urban drainage system.

Zimmermann et al. (2016) analysed different scenarios of urban resilience towards floods in Rosario City (Argentina). The authors compared the current scenario to moderate waterproofing, severe waterproofing, and increased green infrastructures. The results show that the moderate and severe waterproofing scenarios produce an increased risk of flooding from 1.9 times to 4 times, while the increased green scenario keeps the runoff coefficient, even when considering the significant increases in population and urbanisation. Thus, the study concluded that expanding urban green is an effective adaptation strategy to climate and urban changes to cope with upcoming increases in precipitation and urbanisation. Other researchers have pointed out the limitations of small, patchy, and isolated green infrastructures. For example, Ferreira et al. (2021) concluded that the effectiveness of nature-based solutions for water management within urban areas, such as urban forests, gardens, wetlands, infiltration trenches, and green roofs, varies with their design, size, and local conditions. Furthermore, it is a network of connected nature-based solutions rather than small isolated elements that can effectively mitigate urban floods and thus enhance urban adaptation to climate change.

Regarding drought, this is a complex and not widely understood phenomenon triggered by weather, soils, climate, and human activities. It has a slow onset with cumulative effects and a large spatial extent. Moreover, the complex structure of cities and the occurrence of different types of drought (meteorological, agricultural, hydrological and socio-economic) requires monitoring based on multiple composite indicators. Nevertheless, past research mainly concerned selected elements of the city's structure or single social problems (i.e. water supply, urban blue or green infrastructure, poverty associated with climate change and disasters), while urban drought as a complex phenomenon affecting the entire urban ecosystem has not been studied enough yet (Dąbrowska et al., 2023). Many researchers are attempting to adapt the drought indices and EO methods commonly used in agricultural drought monitoring to urban conditions (Dilling et al., 2019; Miller et al., 2020; Obringer et al., 2016).

From an economic point of view, Kim (2021) studied the flooding mitigation effect of urban vegetation in Ulsan during the tropical storm Chaba that hit the southeastern part of South Korea in 2016. The research quantifies that an increase of 1 km^2 in urban green space could reduce financial insurance payments for flooding by $44,099. In addition, the author estimated that an increase in non-green space could have raised insurance payments by $691,094. The study concluded that green space inside a floodplain is about 21 times more effective ($44,099 vs. $953,755) than outside the floodplain.

What clearly emerges from the literature is that cities should be treated as a coherent ecosystem, and flood and drought risk reduction strategies should be integrated.

6.5.3 Application needs

The cohesion report describes the social, economic, and environmental state of the EU regions every three years and tracks various indicators and data sources that describe possible growing disparities between regions. Many indicators are also expressed by the degree of urbanisation, recognising the different dynamics between cities, towns, suburbs, and rural areas.

The report relies on regularly updated geospatial information, and EO can provide objective tools to managing authorities and intermediary bodies for investments in urban resilience to climate change impacts. For instance, the impact of the Cohesion Policy 2021-2027 will also be measured using specific climate change adaptation indicators assessing the share of the population benefitting from measures relying on Copernicus services that map both measures, such as green infrastructure and population (ERDF and CF). Unfortunately, local authorities often have little knowledge about how to use Copernicus data and little capacity to help make decisions on investments in climate change adaptation.

Concerning the ex-post outcomes of projects and beneficiaries of EU Cohesion Policy (2014-2020 period), the Kohesio database ([97]) maps in detail all the interventions funded. It is noted that climate change adaptation measures are often pinpointed and spread; thus, it is not easy to evaluate the actual impact on the territory. In some cases, that is possible, like for hydraulic infrastructures. In other cases, the number or density of local interventions could be related to a generic qualitative improvement in climate resilience.

Generic application needs:

Application Need 1: [Vulnerability, Exposure] An explicit, standardised vulnerability and exposure products for all European cities, based on the existing Copernicus products/services and Eurostat statistics, would be extremely valuable. Alternatively or in addition tools that facilitate users to derive suites of vulnerability and exposure products would have high value.

Application Need 2: [Vulnerability, Exposure] Availability of a routinely calculated geospatial change product over time, for both vulnerability and exposure components, would be of high user value. Automated change detection in both risk components, on an ongoing basis, would greatly facilitate adaptation monitoring and the implementation of adaptation pathways.

Application Need 3: [Risk] Combined risk indicators need to be made routinely available across the necessary spatiotemporal and value-added intelligence ranges, as detailed below. These cascade from geospatially-explicit, hazard-specific risk indicators; combined geospatially-agnostic, hazard-specific risk indicators; composite geospatially-agnostic, hazard-agnostic risk indicators & frameworks.

Application Need 4: [Risk] Risk indicators need to be made available in an appropriate range of metrics for key user archetypes, e.g. potential or realised economic damage; public health risks and other suitable key indicators.

Application Need 5: [Semantics] Users frequently cannot access appropriate information, or struggle with information that they are uncertain of how to use. A key aspect of the EO value chain is the last part – the interfaces that users interact with to gain understanding and knowledge. Realising full value of the EO knowledge offering requires the ongoing development of community-driven, iterative, aspirational, enabling Decision Support systems, driven by strong user co-design. Creating a strong two-way dialogue between providers and users aids in identifying the best solutions, speeds development, and results in much increased uptake (Virapongse et al., 2020).

Specific application needs:

Application Need 1: [Hazards] Drought and flood hazard needs to be made available to policy makers and investors in a simple and timely manner.

Application Need 2: [Hazards] Drought and flood information in urbanized areas needs to be made available on a historical, phenological basis, e.g. as a climatology/anomaly; as a component of a predictive short term Early Warning System; and as a component of future climate scenarios.

Application Need 3: [Vulnerability, Exposure] Easy access to data, information and models at the regional and municipality levels needs to be made available to help identify effective long-term solutions to different climate risks.

Application Need 4: [Semantics] Indicators should be able to assist ex-post monitoring of the impacts of climate adaptation projects funded under the Cohesion Policy.

([97]) https://kohesio.ec.europa.eu/en/

Given the abovementioned objectives, the application should address different needs, from low spatiotemporal scales for overall synthesis at the EU level to high spatiotemporal scales for detailed local analyses at the municipality (Table 15).

Table 15. Objectives, spatiotemporal resolution, and user archetype intelligence dimensions.

Objectives	**Spatial dimension**	**Temporal dimension**	**User archetype**
Management of flood risk Management of drought risk Ex-post evaluation of the impact of climate adaptation projects	Municipality level (main) Regional level (main) National level (secondary) EU level (secondary)	Short-term (secondary) Medium-term (main) Long-term (main)	Strategic: interannual policy-focused (primary) Tactical: intra-annual (secondary) Logistical: event to seasonal (secondary)

Source: Internal EC KCEO.

6.5.4 Technical assessment

The application should support the evaluation of the resilience of cities to droughts and floods, identify and map the location and extent of critical hot spots, reconstruct the past evolution, predict future scenarios and evaluate local adaptation measures. Different products and services should be integrated to reach these goals, thus maximising the added value of existing information sources and future operational services from EU-funded research.

Specifically, precipitation and temperature are measured with microwave and thermal infra-red satellites with a high temporal resolution and assimilated with ground station measures. That information shall be integrated with maps of risk-prone areas, high-resolution urban green areas, impervious surfaces, and built-up layers obtained using EO data from visible or microwave sensors and supplemented with general land cover at medium resolution. Moreover, natural areas, topography (elevation, slope and aspect), and the location of infrastructure are critical information to model potential damages. This additional information can be derived from EO data as well.

Climate variables (water vapour, wind speed and direction) are monitored with EO at low spatial resolution. They are needed to forecast extreme droughts and floods and to project future scenarios.

In terms of temporal resolution, the evaluation should be carried out with a frequency appropriate to the nature of the observed indicators. For instance, the main physical indicators, precipitation and temperature, should be ideally measured daily (or even more frequently) due to their highly dynamic nature. The land cover, such as green cover areas and impervious surfaces, has slower dynamics and seasonal (for green areas and land cover) or annual (for impervious surfaces, natural areas and infrastructures) should be an adequate trade-off. The evaluation of risk-prone areas may also imply annual (or even less frequent) updates.

Regarding time series availability, historical EO data are needed to evaluate progress against a reference baseline, ideally coinciding with the policy period under evaluation.

Future projections are instead required to model long-term effects.

Finally, the overlapping of land cover maps with climate variables and socio-economic indicators like statistics on demography, poverty and social exclusion, health, tourism, or population share living in risk areas at a suitable scale should help monitor adaptation to climate change.

Table 16 describes parameters of the environmental, climate and socio-economic dimensions derived from the specific application needs. Their minimum technical requirements on spatial resolution, temporal resolution, and temporal extent are also provided. This information was used to identify suitable existing EO services and products.

Table 16. Parameters and minimum technical requirements. (n/a = not applicable)

Parameter	Spatial resolution	Temporal resolution	Temporal extent
Main physical parameter			
Precipitation	Medium Resolution	Very High Resolution	Long Extent
Temperature	Medium Resolution	Very High Resolution	Long Extent
Environmental dimension			
Risk-prone areas	Medium Resolution	Low Resolution	Long Extent
Land cover	High Resolution 2	Medium Resolution	Medium Extent
Green areas	High Resolution 1	Medium Resolution	Medium Extent
Impervious surface	High Resolution 1	Low Resolution	Medium Extent
Topography	Medium Resolution	Low Resolution	n/a
Natural areas	Medium Resolution	Low Resolution	Medium Extent
Infrastructures	Very High Resolution 2	Low Resolution	Medium Extent
Climate dimension			
Climate variables	Medium Resolution	Very High Resolution	Long Extent
Socio-economic dimension			
Demographic statistics	DEGURBA	Low Resolution	Medium Extent
Poverty and social exclusion statistics	DEGURBA	Low Resolution	Medium Extent
Tourism statistics	DEGURBA	Low Resolution	Medium Extent
Population living in risk areas	DEGURBA	Low Resolution	Medium Extent

Source: Internal EC KCEO.

6.5.5 Value chain analysis

Resilience and adaptation to climate change affect policies at different scales, from the municipal to the EU level. For this reason, the use case should partially address the different needs. However, this assessment focuses on urban areas and should provide tools to the municipality governments on local climate change risks and adaptation measures. Consequently, this assessment will consider the minimum technical requirements needed for the analysis at the municipality scale.

In most cases, the products and services described in the next section already provide parameters at a high spatial resolution and could be used directly to produce parameters at the coarser scales (regional, national, EU), like all the land cover layers. However, that is not true for the main precipitation and temperature parameters, which must be spatially enhanced.

Breaking down the risk components to evaluate impacts and adaptation to climate change into hazard, exposure and vulnerability, the main hazards are:

- Water scarcity conditions: driven by extreme heat and wind;

- Water overflows: driven by extreme precipitation, wind, land cover, green and natural areas.

All the physical forcing phenomena can be evaluated and monitored using EO data. From a value-add perspective, hazard information should be available both for short term early warning, reanalysis of historical floods events, and future scenarios across a range of climate-driven forcing conditions and adaptation scenarios.

From an exposure and vulnerability perspective, we have parameters like:

- Population density;
- Population share living in natural hazards-prone areas;
- Urban development and spatial planning;
- Green and natural areas.

All exposures and vulnerabilities can be evaluated and monitored using EO data or by assimilating EO data with other socio-economic information. Critical aspects of vulnerability parameters should be closely linked to primary adaptation actions as given by the key type measures, including grey options such as physical flood defences, green options such as rehabilitation of natural flood defences, and blue option for mitigating drought.

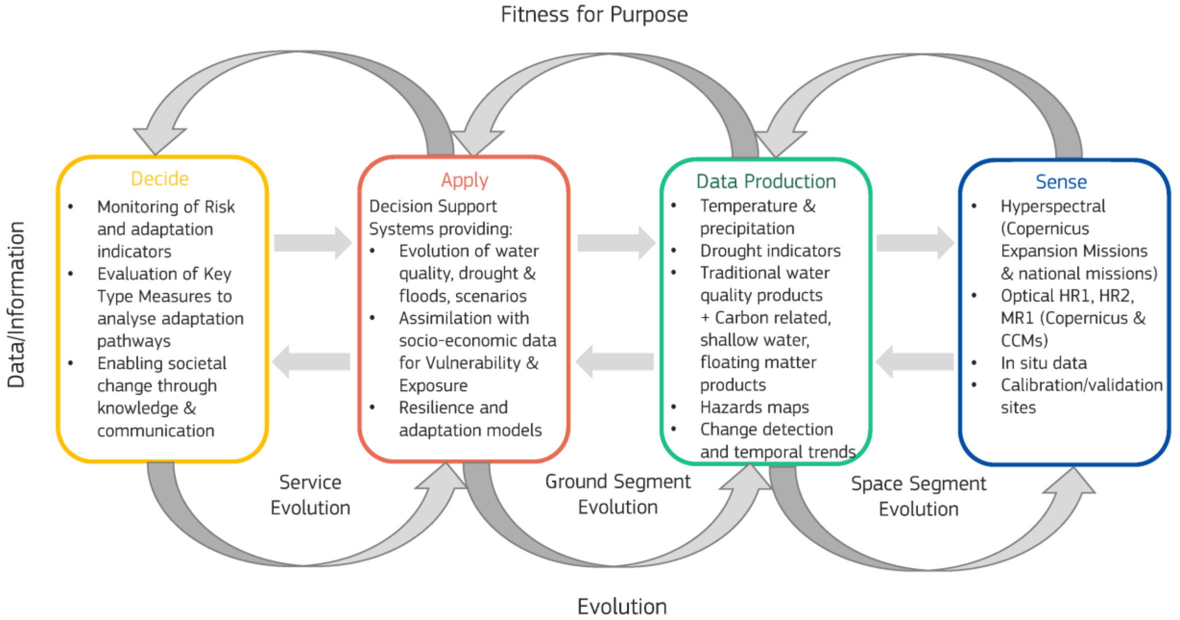
Hazard related impacts can be quantified, both for adaptation scenarios and extreme events, as:

- Impacts of climate change
    - Economic losses attributable to floodings and droughts (percentage of the city's gross domestic product, damages on infrastructures and properties, or any other meaningful parameter);
    - Number of flood-related mortality;
    - Number of people permanently displaced from homes as a result of flood or drought;
    - Agricultural production loss;
- Impacts of climate change adaptation
    - Percentage of brownfield/greyfield redevelopment.

With many other indirect impacts available through a combination of EO and socio-economic data (Kilsedar et al., 2024).

Figure 15 shows the Earth Observation value chain.

Figure 15. Earth Observation value chain for Drought and Floods. (SAR=Synthetic Aperture Radar; CCMs= Copernicus Contributing Missions)



Source: Internal EC KCEO.

6.5.6 Fitness for purpose of existing products and services

The fitness for purpose discussed below is based on the technical assessment (spatial resolution, temporal resolution, time series length), the products/services' thematic content, and fitness to application needs. The critical aspects of uncertainty and accuracy, as well as ratings of the overall quality of EO products/services, were not considered since they would require extensive analysis beyond the scope of the deep dive.

Table 17 shows a summary of the results, and Source: Internal EC KCEO.

Table 18 summarises the fit to application needs of all technical requirements.

Table 17. Examples of EO-derived products and services that could contribute to the assessment and their technical specifications. (n/a = not applicable, n/d = not defined)

Parameter	Service(s)/Product(s)	Spatial resolution	Temporal resolution	Temporal extent
Main physical parameter				
Precipitation	ERA-5	0.1° (about 10 km)	1 hour, 1 month	1979-present
	E-OBS	0.1° (about 10 km). 0.25° (about 25 km)	1 day	1950-present
	CORDEX	0.11° (about 10 km)	From 3 hours to seasonal	1948-2100
Temperature	CLMS Temperature and Reflectance (Land Surface Temperature)	5 km	1 hour	2010-present

	Urban Heat Island Intensity for European Cities	100 m (downscaled)	1 hour	2008-2017
	CURE LST	100 m (downscaled)	~3 days	2018-2019
Environmental dimension				
Risk-prone areas	European Drought Observatory	Between 5 km and 100 km	1 month	n/a
	JRC River flood hazard maps for Europe and the Mediterranean Basin region	100 m	n/a	>100 years return period
	Copernicus Emergency Management Service (CEMS)	2500 m^2	On demand	2012-present
Land cover	CORINE Land Cover (CLC)	25 ha	6 years	1990, 2000-2018
Green cover	Urban Atlas Street Tree Layer	500 m2	6 years	2012, 2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
	High Resolution Layer Tree Cover Density	10 m, 20 m, 100 m	3 years	2012, 2015, 2018
	Riparian Zones	0.5 ha	6 years	2012, 2018
	Coastal Zones	0.5 ha	6 years	2012, 2018
Impervious surface	High Resolution Layer Imperviousness	10 m, 20 m, 100 m	3 years	2006-2018
	High Resolution Layer Impervious Built-up	10 m, 100 m	3 years	2018
	Urban Atlas Land Cover/Land Use	0.25 ha	6 years	2006-2018
Topography	EEA-10	10 m	Continual	Continuous
	GLO-30	30 m	Continual	Continuous
	SRTM	30 m	Continual	2000
Natural areas	Natura 2000	0.5 ha	6 years	2006, 2012 and 2018
Infrastructures	Urban Atlas Building Height	10 m	n/d	2012
	OpenStreetMap	n/d	Continual	n/a
Climate dimension				
Climate variables	Water vapour (C3S Agrometeorological indicators)	0.1° (about 10 km)	1 day	1979-present
	Wind speed and direction (C3S	0.1° (about 10 km)	1 day	1979-present

	Agrometeorological indicators)			
Socio-economic dimension				
Population/population density	Eurostat data	DEGURBA	1 year	Different by region
Population grid	Global Human Settlement Layer (GHSL)	100 m, 1 km, 3 arcsec, and 30 arcsec	5-year intervals	1975-2020 (and projections to 2025 and 2030)
Demographic statistics	Eurostat data	NUTS3	1 year	Different by region
Poverty and social exclusion statistics	Eurostat data	NUTS2	1 year	Different by region
Tourism statistics	Eurostat data	NUTS3	1 year	Different by region
Population living in floodplain areas	European Environment Agency	WS04 subcatchment	n/d	n/a

Source: Internal EC KCEO.

Table 18. Fit for application needs. (n/a = not applicable, n/d = not defined)

Parameter	**Service(s)/Product(s)**	**Fit to application needs**
Main physical parameter		
Precipitation	ERA-5 E-OBS CORDEX	<u>Spatial resolution:</u> for all products, the spatial resolution is unsuitable for monitoring local variations at the municipality level. <u>Temporal resolution:</u> fit the application's needs for all products. <u>Temporal extent:</u> for all products, the available time series is suitable for assessing long-term trends (for the past) and projecting future trends.
Temperature	CLMS Temperature and Reflectance (Land Surface Temperature)	<u>Spatial resolution:</u> is unsuitable for monitoring local variations at the municipality level. On the other hand, it is suitable for aggregated statistics at the regional, national or European levels. <u>Temporal resolution:</u> fits the application's needs for all the spatial scales. <u>Temporal extent:</u> is suitable for assessing short/very short-term trends. However, long-term analyses and assessments of urban adaptation to policies require observations over a more extended period.
	Urban Heat Island Intensity for European Cities	<u>Spatial resolution:</u> fits the application needs. <u>Temporal resolution:</u> fits the application needs. <u>Temporal extent:</u> doesn’t fit the application needs.
	CURE LST	<u>Spatial resolution:</u> fits the application needs. <u>Temporal resolution:</u> doesn’t fit the application needs. <u>Temporal extent:</u> doesn’t fit the application needs.
Environmental dimension		

Risk-prone areas	European Drought Observatory	Spatial resolution: could be unsuitable for the application's needs at higher resolution spatial scales. Temporal resolution: fits the application's needs for all the spatial scales. Temporal extent: each indicator has a different temporal extent.
	JRC River flood hazard maps for Europe and the Mediterranean Basin region	Spatial resolution: fits the application's needs. Temporal resolution: n/a. Temporal extent (return period): fits the application's needs.
	Copernicus Emergency Management Service (CEMS)	Spatial resolution: fits the application's needs, but the spatial extent might not be sufficient for large-scale events. Temporal resolution: the temporal resolution is not pre-defined. Products are made on demand. Temporal extent: does not fit the application's needs.
Land cover	CORINE Land Cover (CLC)	Spatial resolution: fits the application's needs. Temporal resolution: is sub-optimal for the application's needs. Time series: fits the application's needs.
Green cover	Urban Atlas Street Tree Layer	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
	High Resolution Layer Tree Cover Density	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.
	Riparian Zones	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
	Coastal Zones	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
Impervious surface	High Resolution Layer Imperviousness	Spatial resolution: fits the application's needs. Temporal resolution: is sub-optimal for the application's needs.

		Temporal extent: the available time series is suitable for assessing short-term trends. However, long-term analyses and assessments of urban adaptation to policies require observations over a more extended period.
	High Resolution Layer Impervious Built-up	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs (new product). Temporal extent: does not fit the application's needs (new product).
	Urban Atlas Land Cover/Land Use	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
Topography	EEA-10 GLO-30 SRTM	Spatial resolution: all products fit the application's needs for all the spatial scales. Temporal resolution: n/a. Time series: n/a.
Natural areas	Natura 2000	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
Infrastructures	Urban Atlas Building Height	Spatial resolution: fits the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: is sub-optimal for the application's needs.
	OpenStreetMap	Spatial resolution: cannot be assessed. Temporal resolution: fits the application's needs. Temporal extent: n/a.
Climate dimension		
Climate variables	Water vapour (C3S Agrometeorological indicators) Wind speed and direction (C3S Agrometeorological indicators)	Spatial resolution: all products do not fit the application's needs. Temporal resolution: all products fit the application's needs. Time series: all products fit the application's needs.
Socio-economic dimension		
Population/population density	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable

		for assessing medium-term trends. In some other cases, a more extended period is required.
Population grid	Global Human Settlement Layer (GHSL)	Spatial resolution: data have different spatial scales. Overall, they do not fit (or are sub-optimal for) the application's needs. Temporal resolution: is sub-optimal for the application's needs. Temporal extent: fits the application's needs.
Demographic statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Poverty and social exclusion statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Tourism statistics	Eurostat data	Spatial resolution: data have different spatial scales. Overall, they are sub-optimal for the application's needs. Temporal resolution: data have different temporal scales. Overall, they are sub-optimal for the application's needs. Temporal extent: the available time series are different by region. In some cases, they are suitable for assessing medium-term trends. In some other cases, a more extended period is required.
Population living in floodplain areas	European Environment Agency	Spatial resolution: is sub-optimal for the application's needs. Temporal resolution: does not fit the application's needs. Temporal extent: does not fit the application's needs.

Source: Internal EC KCEO.

6.5.7 Gap analysis

Today, there are already available EO products/services and additional socio-economic statistical data that are useful for the assessment. Moreover, some new experimental products that extend the analytical capabilities are being proposed or demonstrated. Nevertheless, to date, there are still some significant gaps.

It is to be mentioned that the uncertainty and accuracy of EO products could not be considered and are beyond the scope of this deep dive. Thus, no recommendations can be made in this respect.

Spatial resolution

- There are many products for temperature (main physical parameter); nevertheless, none provide information at a suitable spatial resolution for monitoring variations at the municipality level. That is a severe limitation. On the other hand, new services that use downscaled temperature data to 100 m have already been demonstrated (e.g. UrbClim model or CURE portal), but they are not operational;
- The drought-related indicators provided by the Global Drought Observatory (main physical indicators) have a coarse spatial resolution that is not suitable for the municipality level;
- Increasing the spatial resolution of climate variables, including both ECVs and derived datasets, will bring overall benefits in modelling the temperature and water-related risks;
- A closer match between Eurostat's spatial extent and the spatial resolution of EO-derived products will significantly improve the resilience analysis at the municipality scale.

Temporal resolution

- CORINE Land Cover's frequency update is lower than the use case requires, and a more frequent update is desirable. However, since CORINE is not the main land cover product for urban areas, a sub-optimal temporal resolution seems to be acceptable;
- Regarding the land cover products, the use case would benefit from a more frequent update of the key indicators derived from the high-resolution data (Urban Atlas, High Resolution Layer Imperviousness, High Resolution Layer Impervious Built-up, Riparian Zones, Coastal Zones, High Resolution Layer Tree Cover Density, and Natura 2000). Ideally, an annual update is desirable.

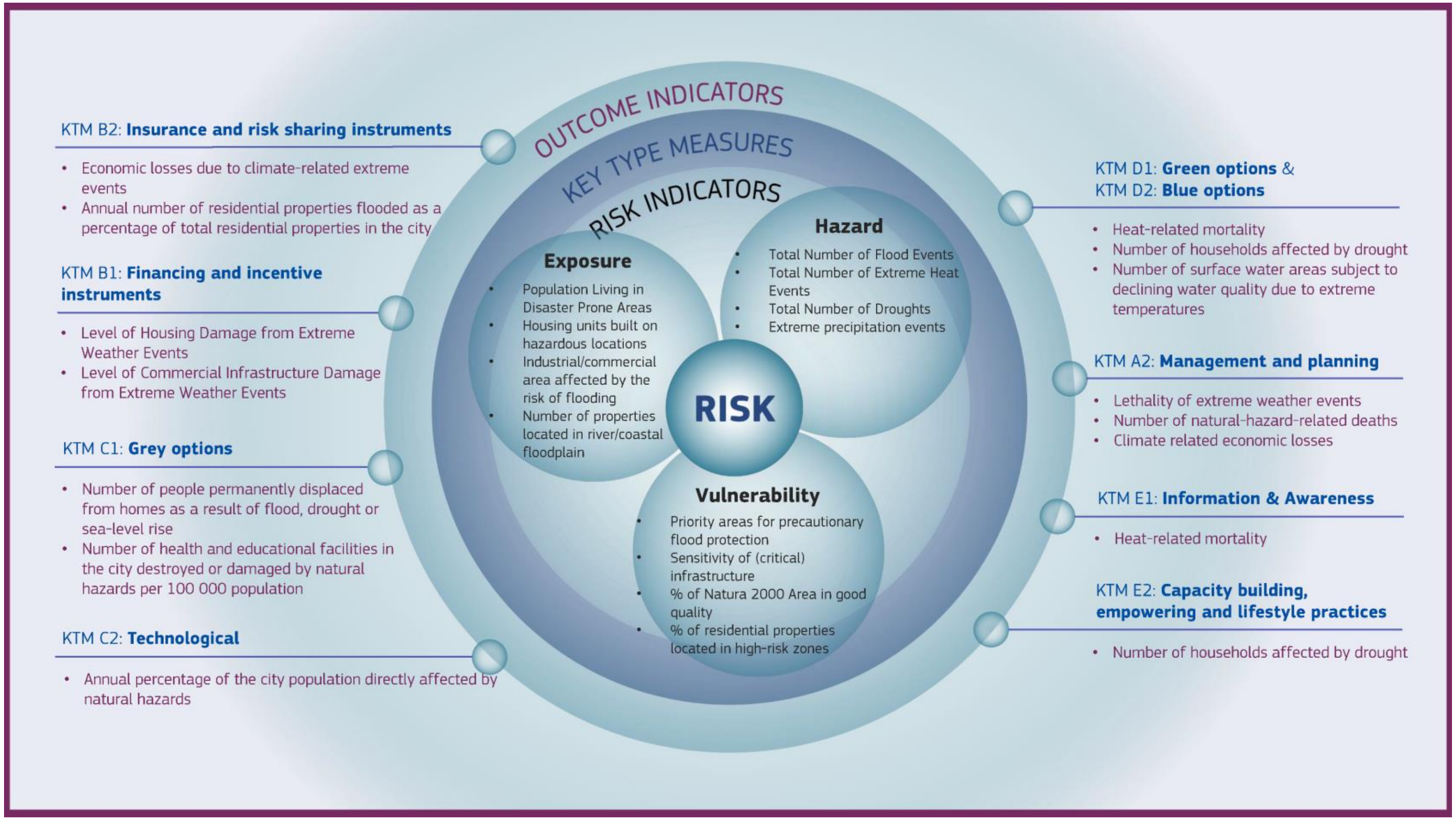
Temporal extent

- The temporal resolution of coarse temperature and precipitation data is very high. Nevertheless, their spatial resolution is low. Processing data from Landsat Complementary Data could increase the temporal resolution of finer EO-derived parameters, thus increasing the overall reliability of downscaled models. Moreover, the assimilation and expansion of E-OBS in situ meteorological data will enhance the spatial density of measures;
- The temporal extent of all land cover products is minimal, with the exclusion of the CORINE land cover going back to 1990. That severely limits trend analyses (in the past) and thus the ability to observe the impacts of policies. An increase in the temporal extent of land cover, green cover and impervious surfaces with data from Complementary Data , even if at a lower resolution than the available Copernicus products, will partially fill this gap;
- The available temporal extent for the Copernicus Temperature product is suitable only for assessing short/very short-term trends. Long-term analyses require observations over a more extended period;
- Each indicator of the drought-related indicators provided by the Global Drought Observatory has a different temporal extent. A harmonisation of the data is desirable;
- Copernicus Urban Atlas, Riparian Zones, Coastal Zones, High Resolution Layer Imperviousness, High Resolution Layer Impervious Built-up, and Natura 2000 have a sub-optimal temporal extent. A more extended period is desirable.

6.5.8 Monitoring risk, adaptation and outcome

Figure 16 shows an illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators. The schematic aims to bring out the applicability of Earth Observation in the Climate Adaptation aspects of Risk Assessment (comprising the components of Hazard, Exposure and Vulnerability); of the climate action reporting framework of Key Type Measures; and the outcome of this action through pertinent indicators (all indicators within are EO-addressed). Moreover, it aims to encapsulate the discussion in the Indicators chapter and link it with each Use Case through an illustrative example of a particular hazard, a traditional starting point for Risk Assessments and identification of adaptation measures, in essence presenting the Earth Observation 'value proposition' to the adaptation cycle (e.g. contributing to steps 2 till 6 in Climate-ADAPT's Adaptation Support Tool). The schematic does not aim to paint Earth Observation as a cure-all. Dozens of indicators and KTMs are solely dependent on socio-economic data and many will remain unapproachable by EO alone. Nevertheless, the schematic, as the Deep Dive as a whole, advocates for the Earth Observation potential in direct monitoring (the bane of most adaptation frameworks) of the above but also in overall support through contributing in e.g. monitoring the presence of KTMs, designing KTMs and allowing for more harmonized and more frequent risk assessments.

Figure 16. DG REGIO – Drought and floods in European cities. Illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators.



Source: Internal EC KCEO.

This illustrative example focuses on drought and floods in European cities, featured in the DG REGIO Use Case on Water management in urban areas.

When it comes to the risk factors, Earth Observation offers a straightforward approach: satellite observations supplemented by *in situ* measures, climate projections, and modelling, delivering time series of risk indicators at different spatial and temporal scales. Estimation of vulnerability and exposure require integrating socio-economic datasets with hazard maps and landscape attributes. The former, among other things, are mainly provided by Eurostat, while the latter, among other things, are provided primarily by the Copernicus products and services reviewed in the previous sections. Again, Earth Observation plays an essential role in supporting their quantification.

Turning to sub-KTMs and their outcome, only those in which Earth Observation has a potential role are here represented:

- Grey options (C1): are among the most relevant measures for this use case. Earth Observation can help evaluate *ex ante* risks and exposures and *ex post* interventions, for instance providing valuable estimations on the number of people permanently displaced from homes as a result of flood, drought, or sea-level rise or the number of health and educational facilities in the city destroyed or damaged by natural hazards.
- Green options (D1) & Blue options (D2): together with grey options, these are valuable measures where Earth Observation provides information on estimating heat-related mortality, the number of households affected by drought, or the number of surface water areas subject to declining water quality due to extreme temperatures.
- Management and planning (A2): incorporating Earth Observation can add value, for instance, in estimating the lethality of extreme weather events, the number of natural-hazard-related deaths, or climate-related economic losses.1
- Financing and incentive instruments (B1) & Insurance and risk sharing instruments (B2): in incentives/insurance domains, Earth Observation can help estimating damages, such as the level of housing/commercial infrastructure damage from extreme weather events, or the annual number of residential properties flooded as a percentage of total residential properties in the city, or economic losses due to climate-related extreme events.
- Information & Awareness (E1) & Capacity building, empowering and lifestyle practices (E2): in this case, Earth Observation can significantly contribute to the assessment of the number of households affected by drought and evaluating heat-related mortality.

6.5.9 Recommendations

One critical goal of the Urban Climate Adaptation assessment is to support DG CLIMA and DG REGIO in evaluating the outcomes of the current policy and targeting better interventions for future Cohesion Policies. Specifically, intervention areas for investments in climate change adaptation include climate-related risks such as floods, drought, and other relevant risks.

In this context, Earth Observation is essential for comprehending environmental systems and evaluating feedback loops and impacts in urban and peri-urban areas.

Usable intelligence derived from Earth Observation data has advanced significantly. However, gaps still exist, and the analysis has identified the following areas where improvements might facilitate the uptake of EO products and services for urban climate adaptation at the European, national and local scales.

On the evolution of Copernicus, recommendations include the promotion of:

- Further development and integration of temperature modelling, such as the UrbClim or CURE models, bringing them to operational products and services into the Copernicus ecosystem. This is crucial for building better interpretative and predictive models.
- Further increase of spatial resolution for drought-related indicators and climate variables. This is crucial for building better interpretative and predictive models.
- Further processing/re-processing of data collected before Copernicus from the Member States' national and international programs to build a more extended time series. This is crucial for creating more reliable analyses.
- Further development of high-resolution land cover products (e.g. Urban Atlas, High Resolution Layer Imperviousness, High Resolution Layer Impervious Built-up, Riparian Zones, Coastal Zones, High Resolution Layer Tree Cover Density, and Natura 2000), with the ideal goal of annual update cycles (plus one-year latency). This is crucial for enhancing the description of the land cover dynamics and, thus, improving the estimation of the Vulnerability and Exposure components.
- Further development of all relevant change detection products (e.g. Urban Atlas Land Cover/Land Use Change, Imperviousness Change, Imperviousness Classified Change), with the ideal goal of annual update cycles (plus one-year latency). This is crucial for highlighting hot spots and fast land changes, thus focusing and prioritizing high/very-high resolution data collection.
- Further integration with Eurostat statistical data, asking the statistical institute to produce data with a finer granularity. This is crucial for bringing the socio-economic dimension into the models and better evaluating the Vulnerability and Exposure components.
- Further integration into the Copernicus products and services of higher spatiotemporal data from the Landsat programme and (future) Contributing Missions. This is crucial for improving the main physical variables observed.
- Integration of future Copernicus Expansion Missions (e.g. Land Surface Temperature Monitoring, Copernicus Anthropogenic Carbon Dioxide Monitoring). This is crucial for improving the main physical variables observed.

On the risk side, recommendations include the promotion of:

- Advanced adaptation scenario modelling capacity for all European cities, under a range of KTM-classified adaptation and hazard scenarios.
- Advanced early warning modelling capacity for all European cities.
- Indicators that could be used across different use cases (e.g. greening, drought and floods in European cities).
- Combined risk indicators for key user archetypes (e.g. potential or realised economic damage, population affected, public health risks).

On the policy-making side, recommendations include the promotion of:

- User-friendly web-based dashboards that integrate available information into specific, quantitative, measurable, and standardized indicators. This would provide give policymakers and local authorities, non-EO experts, simple effective tools to make better decisions and evaluate *ex post* impacts of their policies. In this regard, Destination Earth could be an appropriate platform to provide a common framework for the provision of such indicators and services. The Destination Earth digital twins, specifically the climate adaptation digital twin and weather-induced extremes digital twin, in conjunction with information from the European Data Spaces ecosystem provide significant potential to realise the necessary extension of the EO value chain. The identification of user needs – most specifically around key type measure focused decision making - is an important first step in supporting the co-design of tailored services for EC policymakers.
- Increased use of EO-derived indicators within Member States' national legislation. This is crucial to accelerating Copernicus information, products, and services uptake.
- Further use, in future policy documents, of specific and quantitative indicators that can be measured with Earth Observation or are EO-based, as evaluation metrics. This is crucial to have *ex ante* measurable parameters.
- Dissemination to politicians, national authorities and local administrators of the potential of Earth Observation and geodata. This is crucial as a whole.
- It is also worth noting that to help assess the effects of climate change adaptation policies, continuity of the products and services reviewed is necessary for at least the policies' time horizon. In the present use case, since DG REGIO is preparing the 2028-2034 Cohesion Policy, data continuity should be provided until 2034.

Short Use Case 2: Monitoring Water Quality/Quantity

The objective of this short use case is to describe how Copernicus data, services and derived products can be used to monitor water quality and quantity.

Abstract
Impact Pathways: reduced drinking & food security; reduced wellbeing; public health risks; economic losses. **Key Adaptation Activities**: Hard (water supplies, water treatments), soft (incentives, planning, awareness), accommodation (technical, social, knowledge), ecosystem based (urban green, natural and protected areas). **Potential EO Value:** Physical hazard drivers of water quality & pollution (hyperspectral, optical, SAR, TIR, models). Hazard products (magnitude and frequency), both predictive, near real time and historical. Vulnerability products including water quality, water quantity, risk-prone areas, potential pollution sources (optical, SAR, models). Exposure products and inventories (optical, SAR, models). **Key Risk/Adaptation Indicators:** Variation rate of natural hazards-prone areas, protected natural areas, achieve no net loss of wetlands, streams, and shoreline buffers, Number of different sources providing at least 5 percent of total water supply capacity, green and blue area which is essential to combat the heat island effect in urban areas.

The scarce availability of good-quality water is a severe concern threatening human health. Water pollution has been becoming a complex problem in urban areas, and the increasing frequency of climate-related hazards, such as floods, storms, droughts, or heat waves is exacerbating this issue.

Earth Observation has long been used in research to retrieve water quantity and quality. Multispectral and hyperspectral sensors can estimate the presence of optically significant components like suspended matter, chlorophyll-a, dissolved organic matter, and can be used to indirectly estimate nutrient driven potential for eutrophication. Infra-red sensors can be used to measure surface water temperatures. Microwave remote sensing could complement estimating sea surface salinity. However, the transition from research to operational services and market products is still ongoing and needs to be further developed. This partial maturity is also reflected in the Copernicus services; although some products are dedicated to water management, currently, there is no dedicated service.

The EU strategy on adaptation to climate change highlights the focus on developing solutions to help reduce climate risk, increase climate protection, and safeguard freshwater access. In this context, EO can provide objective and helpful tools to policymakers for increasing resilience to freshwater access. Recently (2024), the Water scenarios For Copernicus Exploitation (Water-ForCE) consortium has developed a roadmap for Copernicus water [R1]. This roadmap has identified the main bottlenecks which limit the use of Copernicus services for water management:

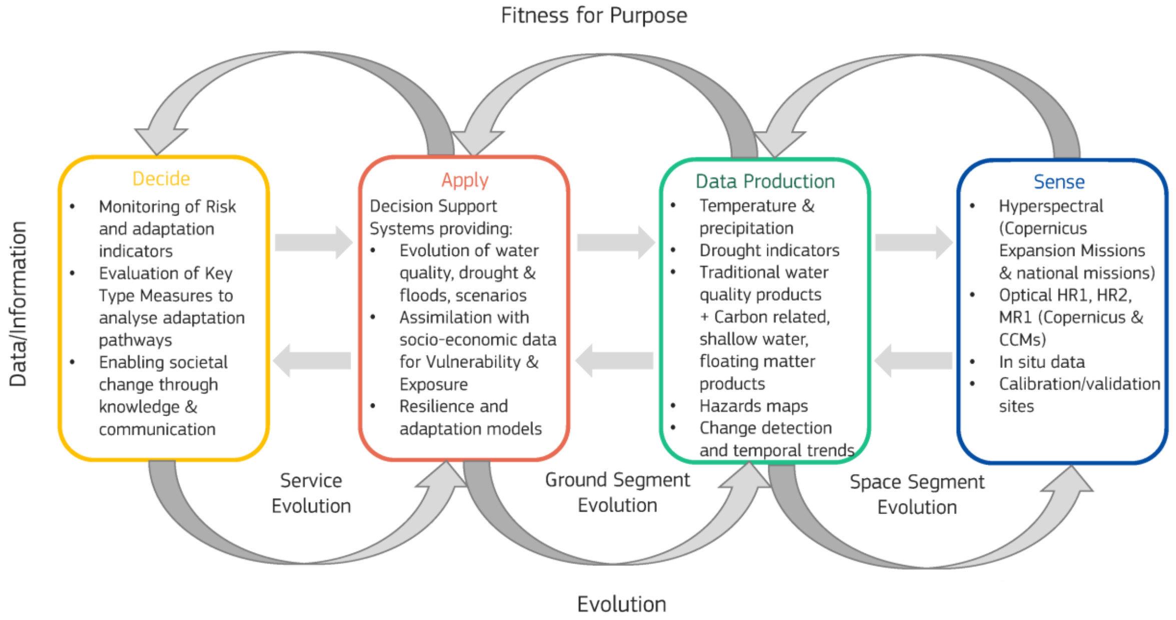
- Lack of a dedicated *in situ* water component;
- Limited trust in Copernicus water products;
- Lack of compatibility between EO and EU directives and international monitoring initiatives;
- Fragmentation of existing Copernicus services;
- Sentinel sensors suboptimal for inland waters;
- Lack of funding mechanisms in supporting of Copernicus services inland water portfolio;
- Lack of awareness with key user communities;
- Water domain insufficiently recognized within Copernicus programme.

While water quantity management is more developed in the Copernicus services and is already monitored in all its components (precipitation, snowmelt, runoff, humidity, evapotranspiration, storage), often also in close relation to natural hazards (please refer to the use case on urban droughts and floods for further details), water quality management has several specific needs that are not yet fully met. With reference to freshwaters, the use case has the following main application needs:

- Sufficient *in situ* data collection activities for calibration and validation;
- Inclusion of trophic state products, inclusion of Carbon related products (e.g. coloured dissolved organic matter, dissolved organic carbon, total organic carbon, dissolved inorganic carbon, total inorganic, CO2), shallow water products (e.g. bathymetry, benthic habitat cover and type, benthic primary production, benthic carbon), and floating matter products (e.g. plastics and other litter, cyanobacterial surface scum, macroalgae, floating plants, pollen);
- Easy access to data, information and models at the regional and municipality levels needs to be made available to help identify effective long-term solutions to different climate risks;
- Higher level biogeochemical indicators like eutrophication and primary production.

With respect to the EO component, water quality products related to gross trophic state and turbidity can be derived with good confidence at a 20m – 300m spatial resolution from Sentinel 2 and Sentinel 3 at a sub-weekly temporal resolution. A hyperspectral capability in the UV-VNIS-SWIR domains would be advantageous; thus, data should be collected with continuous narrow-bands (typically less than 10 nm). The spatial resolution of available data is often suitable for the application's needs when dealing with sea, lakes and major reservoirs; however, it is insufficient for most rivers and streams of the European Union. Also, the temporal resolution should be suitable for certain water bodies and indicators, e.g. near daily for major inland water bodies > ±600m in size, but sub-optimal for others, such as small, rapidly changing water bodies.

Figure 17. Earth Observation value chain for Water Quality.



Source: Internal EC KCEO.

Some of existing Copernicus products and services, project-derived demonstrators or community contributions are helpful for this use case. It should be mentioned that critical aspects of uncertainty and accuracy, as well as ratings of the overall quality of EO products/services, were not considered since they would require extensive analysis beyond the scope of this assessment.

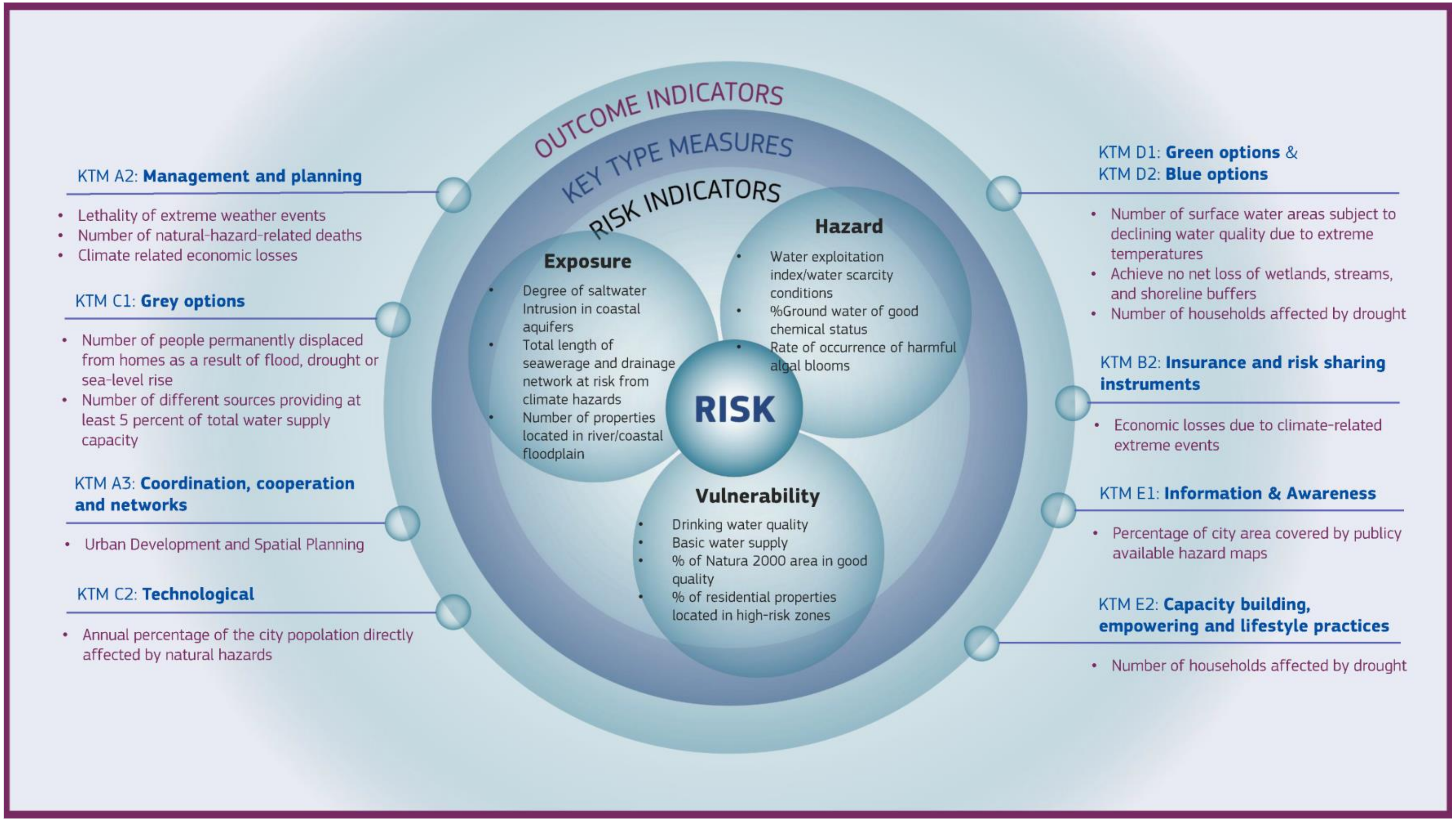
A non-exhaustive list includes (please refer to the Appendix 2 for the products description):

- Water Bodies;
- River and Lake Water Level;
- Lake Water Quality;
- River and Lake Ice Extent;
- Hydrology-related climate impact indicators;
- Lake Surface Water Temperature;
- Global Surface Water Explorer;
- Mediterranean Sea Physics Analysis and Forecast;
- Mediterranean Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis;
- Lakes Climate Change Initiative;
- Hydroweb Project;
- Community scripts for water quality mapping, like:
    - Ulyssys Water Quality Viewer;
    - MAGO Water Quality Monitoring Tool;
    - Sentinel-2 Water Quality Script;
    - Water Surface Visualizer.

Most of the products mentioned above have a spatio-temporal resolution and extent which are unsuitable or suboptimal for the application's needs. This is all the truer when the targets are rivers.

Figure 18 shows an illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators. The schematic aims to bring out the applicability of Earth Observation in the Climate Adaptation aspects of Risk Assessment (comprising the components of Hazard, Exposure and Vulnerability); of the climate action reporting framework of Key Type Measures; and the outcome of this action through pertinent indicators (all indicators within are EO-addressed). Moreover, it aims to encapsulate the discussion in the Indicators chapter and link it with each Use Case through an illustrative example of a particular hazard, a traditional starting point for Risk Assessments and identification of adaptation measures, in essence presenting the Earth Observation 'value proposition' to the adaptation cycle (e.g. contributing to steps 2 till 6 in Climate-ADAPT's Adaptation Support Tool). The schematic does not aim to paint Earth Observation as a cure-all. Dozens of indicators and KTMs are solely dependent on socio-economic data and many will remain unapproachable by EO alone. Nevertheless, the schematic, as the Deep Dive as a whole, advocates for the Earth Observation potential in direct monitoring (the bane of most adaptation frameworks) of the above but also in overall support through contributing in e.g. monitoring the presence of KTMs, designing KTMs and allowing for more harmonized and more frequent risk assessments.

Figure 18. DG CLIMA – Water quality. Illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators.



Source: Internal EC KCEO.

Earth Observation capabilities for water management have advanced significantly in the last decade, however gaps still exist.

This short use case has identified the following areas where improvements might facilitate the uptake of EO for increasing freshwater security in European cities:

- Further increase of the spatial and spectral resolution of data. This is crucial for detecting specific water pollutants and their impacts, for building better interpretative and predictive models, and for supporting water management of rivers;
- Further integration of water products with socio-economic data. Today, this integration seems to be underdeveloped and is needed for a better evaluating the Vulnerability and Exposure components;
- Further development of *in situ* component for cal/val activities. This is crucial for increasing reliability and trust in Copernicus water products;
- Further integration of the water domain within Copernicus services. A dedicated entry point would be helpful for the uptake within key end users.

6.6 Sustainable Expansion and Development of Cities and Preventing Urban Sprawl (DG INTPA)

Earth Observation Use Case: Promoting the Sustainable Expansion & Development of Cities; Preventing Urban Sprawl Through Monitoring, Analysis, Projections & Interventions

The European Green Deal is an integral part of the EU's response to the 2030 Agenda and the Paris Agreement, and is a key driver of the promotion of sustainable urban development and urban prosperity in EU Partner countries. Under the Green Deal Knowledge Hub and the Global Gateway strategy, Earth Observation intelligence can play a critical role in monitoring and analysing urban development and provide critical knowledge for climate adaptation in partner countries. Africa as a continent has particularly high vulnerability to climate-related hazards – often experiencing rapid urbanisation, land use change, and loss of biodiversity, often with insufficient planning.

The first Use Case focuses on compact urban development, desirable in the context of urban functionality and resilience, but often compromised in African strategic corridors by large scale unplanned development - leading to greater exposure to hazards such as floods and heat, and greater vulnerability associated with informal settlements. Earth Observation can provide valuable intelligence using the concept of urban typologies, integrating urban function (such as transport and economic activity) and development dynamics with quantitative geospatial hazard and exposure risks. The second Use Case, driven by the same spread of developmental issues, focuses on the need for urban resilience intelligence systems that can be used to implement local and project-based green and blue infrastructural adaptation.

Broader policy-related needs include balanced urban development, safeguarding key ecosystem services, better knowledge of key land use/cover changes, and tools for hazard screening. These drive a range of Earth Observation application needs including: dynamic hazard and exposure indicators in strategic corridors; hazard screening to support nature-based solutions; high-resolution vulnerability and deprivation products and predictive models; urban and land use trend analyses and predictive models.

A significant gap across the use cases is a lack of the higher resolution Earth Observation and socio-economic products needed to address dynamics at the intra-urban scale in the available global product sets. Key recommendations include the need for higher granularity urban form products at the intra-urban scale; higher resolution global environmental and climate products; more time-extensive and frequently updated EO services; greater access to policy-enabling intelligence and indicators; and accessible dashboards offering easily-used products, actionable intelligence and aggregated compound indicators at a range of scales.

The majority of the countries where INTPA is active are experiencing rapid urban growth, often without or insufficient planning control. Earth Observation can play a critical role in monitoring and analysing urban development and provide critical data for climate adaptation.

6.6.1 Policy context

The current urban growth dynamics present in the majority of cities in INTPA's partner countries are characterised by deregulated, unsustainable patterns of urban sprawl and unlimited encroachment of natural areas, leading to irreversible biodiversity loss that poses threats to natural habitats and communities' ability to cope with the compound effects of climate change.

Under DG INTPA Green Deal Knowledge Hub, DG INTPA F4 has launched an Urban Development Technical Facility ([98]). Among other Technical Support Facilities ([99]) this is the first one focusing on sustainable urban development and associated with urban sectors. It is instrumental in shaping INTPA's strategy towards sustainable and prosperous cities and concretely supporting EU Delegations' activities on the ground, simultaneously delivering on the Global Gateway ([100]) strategic priorities (Figure 19). This service is designed to support actors managing or implementing EU cooperation programmes at global, regional, and country levels in assessing, designing, monitoring, implementing, and evaluating sustainable urban development and planning interventions and in supporting policy work on this matter. The technical assistance work is demand-driven and covers all the countries where INTPA is active, and the requests come from both EU Delegations and INTPA HQ. As such, the service is expected to deliver high-level technical assistance and policy advice at country, regional and global levels through expert advice and field missions to support committed countries and partners in reaching the Sustainable Cities and Communities SDG11 ([101]) objectives ([102]). Climate change poses a significant threat to sustainable urban development (Bolan et al., 2024). For example, the economic loss of climate-related damages can divert resources away from long-term sustainability urban development plans, hindering progress toward a more equitable and environmentally responsible urban future.

Figure 19. Strategic Corridors with links to the Global Gateway Africa.

Source: JRC Digital Media Hub ([103]).

([98]) Urban Development Technical Facility

([99]) Technical support facilities

([100]) JOIN(2021) 30 final (the EU's Global Gateway strategy connects countries and regions around the world, by encouraging public and private investment in a global network of transportation and supply chains, green energy, modern telecommunications, education and research. And all with an emphasis on sustainable development and on European values, such as good governance, transparency, and equal partnership.)

([101]) https://sdgs.un.org/goals/goal11

([102]) Tender reference number INTPA/2021/EA-RP/0096

([103]) JRC Digital Media Hub

Climate change-related hazards seriously affect all countries where INTPA is active, with a particularly severe impact on Africa. The adverse impacts are stressed by the Europe Initiative on Climate Change Adaptation and Resilience in Africa, which is part of the Global Gateway in Sub-Saharan Africa ([104]). Therefore, this assessment is focusing on Africa. As part of the Gateway, the Great Green Wall Initiative focuses on 18 countries in the Sahel and the Horn to foster resilience, stability, and sustainable development throughout the focal region.

Africa is projected to have the fastest urbanisation rates by 2050 (OECD/SWAC, 2020). Presently, most of this urban growth is happening without (or limited) planning control. Consequently, urban growth is often in the form of sprawl, contributing to the loss of biodiversity and massive land consumption, e.g. arable land and forest areas. Many African urban areas are already experiencing frequent climate hazards such as heat waves or flash floods. Understanding climate exposure and vulnerability at an urban scale requires an approach that looks at both the physical dimensions, e.g. urban morphology, infrastructure and material resources, and social dimensions, e.g. internal susceptibility and coping capacity of different groups (De Sherbinin et al., 2019). Vulnerability is best understood as an aggregation of three components: exposure, sensitivity, and adaptive capacity (Figure 1). High levels of exposure and sensitivity equate to higher levels of vulnerability, with adaptive capacity counteracting the former attributes.

6.6.2 Description of the use cases

For DG INTPA, two related use cases are presented; the first use case explores the role of EO in monitoring the compactness of urban development, and the second use case explores the potential of EO to support local and project-based adaptation measures to make urban areas more resilient. Geospatial data, particularly EO data, are essential for monitoring climate change impacts and developing location-specific adaptations. However, Africa has limited data coverage, e.g. low density of metrological stations. These coverage disparities introduce knowledge gaps and uncertainties to data on urban development and climate models. For example, many global models record cities with 'no hazard exposure' while hazards frequently occur. For example, the city of Nairobi is recorded with no flood exposure in global models (Figure 20), while many parts of the city experience frequent flooding ([105]). Furthermore, the continuous growth of cities, i.e., the change from green to grey areas (impervious surfaces), increases the hazard risk (Dinku, 2019; Pérez-Molina et al., 2017). Built-up areas in Africa are rapidly growing into natural or agricultural areas; besides adverse impacts on food security and biodiversity, the reduction of green spaces increases the hazard risks, e.g. increase in urban heat events. The continuous sprawl is both planned and unplanned (Kolowa et al., 2024). It is estimated that most of the urban population in Africa lives in unplanned areas, commonly referred to as informal settlements (UN, 2022). In unplanned areas, climate impacts are specifically high. For example, frequent flash floods occur because of the complex urban morphology, e.g. high-density unplanned areas and lack of waste management, i.e., waste causing drainage blockages. Such areas, in general, lack green and blue infrastructure planning for effective climate adaptation. However, data to support adaptation plans are often insufficient. Earth Observation (EO) can fill critical gaps in such data-scarce areas, as well as provide city-to-global scale data.

([104]) Global Gateway in Sub-Saharan Africa

([105]) The difference between flood models and frequently occurring flash floods in African cities is that global flood models often only capture river floods. However, local floods are caused by heavy rainfall events (in particular during El Niño and the Southern Oscillation years), where many parts of the city get flooded because of insufficient or blocked drainages (e.g., blocked by waste).

Figure 20. Urban Centre Database of the EC (Florczyk et al., 2019) and recent Flood Event in Nairobi.

Source: CommunityMappers, January 2024.

Use Case 1: Compact Urban Development and Climate Adaptation in Africa

The common absence of land use planning control and weak governance results in large-scale unplanned development (Boanada-Fuchs et al., 2024). The pressure on land is driven by the growing population of Africa, with more than half of the expected population growth (Figure 21) until 2050 (UN DESA, 2022), and the massive displacement of populations caused by conflicts and climate impacts ([106]). Generally, both unplanned and planned urban growth contribute to sprawl, with low land use efficiency (Kolowa et al., 2024; Koroso et al., 2021). These developments escalate climate change impacts, such as increasing the frequency and severity of heat events (Bedair et al., 2023) or floods with increasingly adverse health outcomes (Suhr & Steinert, 2022), as well as hindering the “progress of achieving the goal of sustainable cities” (UN-Habitat, 2022). Therefore, adaptation measures need to tackle these core problems and support sustainable urbanisation.

USE CASE 1: In the context of climate adaptation, compact urban development is essential. However, in many African regions, urban development is uncontrolled, leading to unsustainable land consumption that is undermining the essential functions of cities. Therefore, along the strategic corridors, this assessment focuses on the potential of EO products and data for developing an urban typology that relates the urban functions, e.g. transport and economic hubs, the development dynamics, e.g. land consumption and resource optimisation to climate hazards, e.g. floods, heat, and vulnerabilities, e.g. informal areas.

Thus the objective of this use case 1 is to describe how Copernicus data, services and derived products can be used to monitor the compactness of cities. Compact, sustainable and inclusive

([106]) https://africacenter.org/spotlight/african-conflicts-displace-over-40-million-people/

urban development is essential to ensure the capacity of cities to adapt to climate impacts and maintain their critical socio-economic functions.

Abstract
Impact Pathways: Land consumption; unplanned urban growth; informal settlements; sprawl; low land use efficiency; loss of green open spaces; inefficient transportation systems; insufficient infrastructure (WASH ([107]), electricity) and service provision (health, education); loss of biodiversity; environmental degradation; development in hazard zones (e.g., flood and landslide); impact on food security; increase of air temperature; increase in flood risks; reduced economic competitiveness; increase in spatial inequalities (poverty, health outcomes etc.).   **Key Adaptation Activities**: Hard (key infrastructure layout such as public transport, affordable housing, blue and green infrastructure, open spaces), soft (land use policy, planning standards, enforcement of protected areas), accommodation (technical, social, knowledge), ecosystem-based (urban agriculture, revitalisation of urban water systems, conservation of natural and protected areas).   **Potential EO Value:** Physical monitoring of the built-up cover and land use/cover dynamics, including the morphology of informal areas (optical, SAR, models). Urban growth maps and models are historical, near real-time and predictive. Hazard products include urban heat, floods, landslides and storms (optical, SAR, models). Vulnerability products include land cover/use, urban deprivation (informality/slums), green and natural areas, arable land, impervious surfaces, building footprints and heights (urban morphology), topography, and flood hazard (optical, SAR, models). Exposure products and inventories (optical, SAR, models).   **Key Risk/Adaptation Indicators:** City scale metrics on urban compactness (built-up density, Floor Area Ratio (FAR)), measure of urban morphology (e.g., irregularity, compactness), land consumption rates (related to population growth), percentage of open (green) spaces and dynamics, accessibility to public recreation sites, percentage of built-up areas in high hazard zones, Percentage of informal/slum areas, percentage of areas with access to public transportation, percentage of areas with access to WASH and (stable) electricity, percentage of areas with functioning stormwater drainage.

Measuring and characterising urban growth in Africa is complex, given the differences in definitions of “city” and “urban” on national and regional scales. The GHSL supports the harmonisation of city typologies across INTPA’s cooperation activities. The degree of urbanization can also show the location of urban agglomerations and economic centres and support projections for less dense areas that offer opportunities for managed housing and services development. However, the availability of data needs to be combined with capacity building of users, which is presently a major bottleneck. Although the availability of higher-resolution imagery has made it easier to measure changes in urban extent, the data generally only show outward growth, unable to track changes in built form within cities through inner-city redevelopment and densification. Studying urban growth must involve understanding how cities are growing three-dimensionally (He et al., 2023). However, recent EO products (e.g., GHS Settlement Characteristics, WSF 3D) provide an estimation of building heights that can be expanded in future to model (vertical) densification. Generally, EO cannot directly indicate the quality of urban infrastructure and services (only limited capacity via EO proxies ([108])). Therefore, INTPA identified two main information needs: (a) Urbanization and demographics analysis tools are required to analyse the cities and strategic corridor (expansion and land use consumption), and (b) DG INTPA requires comparable urban typologies and profiles for consistent urban data along corridors in different countries and regions that can be used to set up and maintain Urban Observatories. These have been expanded into three policy needs.

([107]) Water, sanitation and hygiene (WASH)

([108]) A proxy of insufficient WASH is often the presence of high built-up density combined with irregular building layouts. Such urban spaces in MICs often have insufficient provision of WASH.

Policy need 1: Mainstreaming Compact Urban Development, a policy associated with the provision of integrated urban development plans, the introduction of land-use mix, improved accessibility, access to infrastructure, planned and well-protected green spaces and connectivity to reduce the demand for land and negative impacts on biodiversity. Compact urban development can lower travel demand and costs and associated energy consumption (GHG emissions reduction for climate-change mitigation), reduce infrastructure provision costs, improve air quality, and promote public transportation. This includes the optimisation of efficient infrastructure layout and maintenance. The timeframe expected is 2024-2027.

Policy need 2: Analysis of the evolution and trends of urbanization in relation to cropland and areas suitable for agriculture to inform urban planning and urban development. Urbanisation and demographics analysis tools are instrumental in understanding the linkages between population growth and urbanisation, expansion, and densification trends and where they occur. Such tools can support INTPA F4 (Sustainable Transport and Urban Development) and European Union Delegations (EUDs) work to promote an integrative urban development approach and link EU actions with the overarching objectives for sustainable growth and jobs, improved connectivity, human development, and the horizontal objective of migration management, set as criteria against which to measure the successful implementation of the Global Gateway Agenda. The timeframe expected is 2024-2027.

Policy need 3: Understanding the role of Cities along Strategic Corridors ([109]) to harness the economic and human development potential of the Global Gateway Strategy. Cities along the Strategic Corridors are essential economic hubs, linking economic actors into a defined geography. However, climate change and conflicts are causing considerable threats. EO and spatial analysis offer insights into the distribution of urban agglomerations through land use and densities and contribute to enhancing economic opportunities in cities along strategic corridors. Cities in Africa are increasingly becoming regional to global economic hubs. Generally, globalisation is presenting new economic markets for Low- and Middle-Income Countries (LMICs) to promote themselves as locations for investment and development, and growing urban centres have a major role in economic integration and innovation. These policy needs are linked to SDGs 8, 9 and 11. There are considerable economic benefits of locations in close proximity to cities along international transport connections, but also negative impacts (e.g., traffic congestion, air pollution). The focus on cities along strategic corridors links to INTPA's objectives of improving the Digital, Connectivity, and Jobs and Growth objectives, and to the European Fund for Sustainable Development Plus (EFSD+) investment window, and has an important role in tackling migration and (climate) displacement. The timeframe foreseen is 2024-2027.

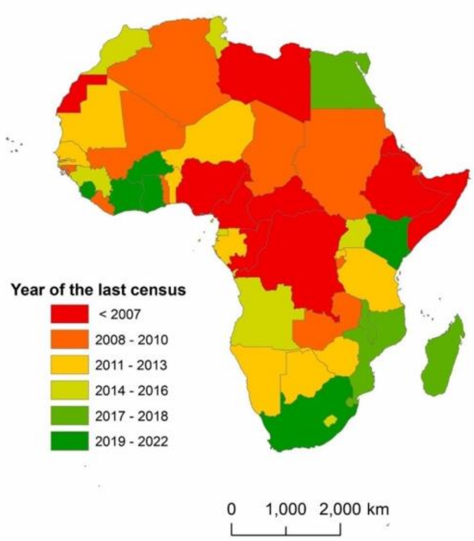
Use Case 2: Measuring and Mapping Urban Vulnerability to Make Cities Resilient in EU Partner Countries

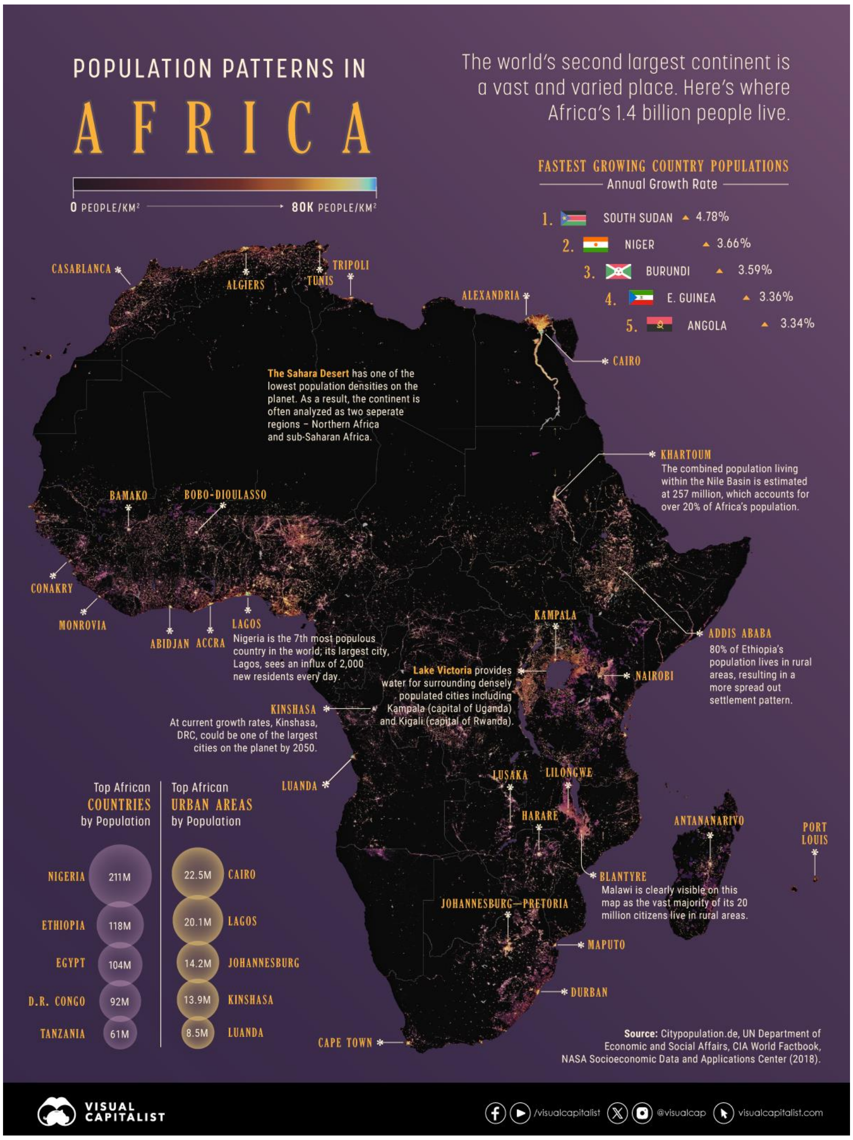
The vast majority of the urbanisation in Africa is unplanned (UN-Habitat, 2016). Consequently, around 60% of the urban population lives in areas without basic services and safe infrastructure (e.g., water, sanitation and hygiene (WASH)). A large part of such highly vulnerable areas are located in climate risk hotspots. Therefore, bottom-up and project-level plans are required to improve urban resilience. However, data that support local information on hazard exposure and vulnerability combined with urban development dynamics are mainly absent. For example, census data are often very dated, population estimates are highly uncertain (Carr-Hill, 2013; Thomson et al., 2021), but many regions have very high population growth rates (Figure 21). Hazard models usually fail to model the complexity of built-up areas in African cities. Thus, the data landscape is very restricted, e.g. limited weather and flood records. Therefore, local models are required that combine Earth

([109]) Strategic corridors to improve Europe – Africa Connectivity

Observation with local data, e.g. Citizen Contributed Data. Generally, Copernicus products and services offer continental information on climate and land. However, the spatial resolution is often too coarse to fill in data gaps at the city scale. Alternative data are of high demand that combines EO-based observation of hazards, e.g. floods, citizen science methods, and VGI (Volunteered Geographic Information such as OpenStreetMap and Humanitarian OpenStreetMap). For local adaptations, detailed data on the urban land cover/use (present and change) are required, to be combined with hazard assessments.

Figure 21. Number of years since the last census in African countries using 2022 as the reference date.





Source: Georganos et al., 2022 (top) and Population patterns in Africa, Routley, (2024) (bottom).

<u>USE CASE 2</u>: In the context of climate adaptation, hazard information systems combined with an assessment of vulnerabilities are required to develop urban resilience strategies within bottom-up planning approaches. Such strategies are commonly implemented in the form of local projects that improve infrastructure (green and blue), building on visions of green cities and nature-based solutions.

Thus the objective of this use case is to describe how Copernicus data, services and derived products can be used to support and monitor bottom-up and project-level plans. Such plans are required in many LMICs in the context of the high level of unplanned urban development and the lack of actionable data. This calls for broad access to Earth Observation data, products and services. For example, JRC tools can strengthen INTPA's actions in urban development and their alignment with the delivery of the external dimension of the European Green Deal, INTPA's Strategic Climate Change adaptation and mitigation objectives, Environment and Energy objectives, and specifically the Global Gateway "Green and smart cities" policy objective.

Abstract
Impact Pathways: Increased exposure and vulnerabilities; low resilience; unplanned urban growth; informal settlements; loss of (green) open spaces; insufficient infrastructure (WASH, electricity) and service provision (health, education); loss of biodiversity; development in hazard zones (e.g., flood and landslide); increase of air temperature; increase in flood and storm risks; increase in spatial inequalities (poverty, health outcomes etc.). **Key Adaptation Activities**: Hard (upgrading of settlements and infrastructure, low-cost housing, blue and green infrastructure, provision of open (green) spaces), soft (participatory planning, bottom-up projects), accommodation (technical, social, knowledge), ecosystem-based (urban gardens, revitalisation of urban water systems, natural and protected areas). **Potential EO Value:** Monitoring of planned and unplanned urban growth and transformations (horizontal and vertical); detailed land use/cover dynamics (optical, SAR, models); building and street-level information. City (street) block ([110]) information that allows intersecting urban land use/cover maps with hazard products, including urban heat, flood, landslide and storms (optical, SAR, models). Vulnerability products at the lowest administrative unit or city blocks that combine EO data (optical, SAR, models) with socio-economic data. Exposure products and inventories (optical, SAR, models). **Key Risk/Adaptation Indicators:** City (street) block scale metrics on urban form (built-up density, Floor Area Ratio (FAR)), classification of informal/formal areas; housing conditions; demographic information (population growth), location of open (green) spaces and dynamics; location of protected and environmental sensitive areas; accessibility to public recreation sites, percentage of built-up areas in high hazard zones, percentage of areas with access to public transportation, percentage of areas with access to WASH and stable electricity, percentage of areas with functioning stormwater drainage.

<u>Policy need 1:</u> Balanced Urban Development. The land cover, land use tools, and the basic hazard and risk products need to support INTPA F4 and EUDs to support bottom-up urban development in balance with key assets for urban resilience and preservation of urban ecosystems such as water, forests and cultivated land. This includes mapping urban vulnerabilities to strengthen urban-rural linkages, as well as urban linkages with key peripheric ecosystems such as forestry and wetlands that absorb and can buffer climate change-induced disasters. Hydrological and hydraulic analysis can support the resilience/vulnerability profiling of urban areas. (e.g., as a pre-feasibility study).

<u>Policy need 2:</u> Safeguarding key ecosystem services such as water supply and soil, water regulation to manage flooding and persistent drought can support climate change adaptation efforts (in

([110]) A city block is the smallest cluster of buildings surrounded by streets.

combination with the basic hazards filter tool), thermic regulation contributing to adaption to heat waves and (wild)fires, and carbon sinks, can contribute to the overall climate change mitigation across sector interventions. EO tool can support continuous monitoring and prioritisation activities whereby INTPA F4 and EUDs could further contribute to achieving the goal of supporting climate objectives in at least 25% of EU spending under the Neighbourhood, Development, and International Cooperation Instrument (NDICI).

Policy need 3: Analysis of the evolution and understanding of intra-city urbanisation dynamics about key land uses for (i) the water system: rivers, groundwaters, lakes, wetlands; (ii) strategic ecosystems and protected areas; and (iii) key landscape features: coastline, waterfronts, ridges to inform urban planning for greening cities. In combination with built-up (planned and unplanned), population and densification data (e.g., from the GHSL), land cover can provide information on the impact of densification, sprawling cities and new settlements (with estimates on land consumption and the associated risks for the environment, including estimates on respective measures to offset these), including the inclusiveness and sustainability of the cities and its climate proofing, stress tests for urban disaster management.

Policy need 4: A robust analytical tool for natural hazards screening would also be fundamental for the development of urban Nature-based Solutions (NbS) programmes on urban resilience, for deforestation and desertification prevention, and planning projects for the conservation, restoration and sustainable management of natural resources and ecosystems, in alignment with the EU Biodiversity Strategy 2030, EU Forest partnership and SDGs, and INTPA's global commitments.

6.6.3 Application needs

The promotion of sustainable cities aimed at addressing the negative consequences of rapid urbanization (e.g., poverty, environmental degradation, and rapid population growth) is an important component of the Global Gateway strategy. There is a clear need for a dynamic-urban growth-related intelligence provided to users in simple and understandable formats. This requires a clear understanding of the needs of various user archetypes, both providing spatial and non-spatial products (e.g., indicator summaries). Therefore, the following section summarizes the application needs for the two INTPA use cases.

Use Case 1: Compact Urban Development and Climate Adaptation in Africa

Rapid land cover and use dynamics in Africa are often paired with data scarcity. Copernicus data have a massive potential to fill data gaps for the identified policy needs (Table 19). Data allow the monitoring of the interaction between urban growth (including displacement), loss of arable land, and forest hazards. For example, cities experiencing rapid land consumption and a reduction in green spaces will face an increased risk of future floods and heat waves. A city that serves as a major economic and transport hub will not only influence its own economic stability but also affect the cities connected to it that depend on its supply chains. Available Copernicus Global Land Service products are readily available for several policy needs, however, some DG INTPA policy needs might require additional data from available sensors or the expansion of existing services. The above-specified policy needs (1-3) are linked to application needs:

Application Need 1.1: [Hazard] Access to indicators on urban growth dynamics (e.g., land consumption) and urban form (e.g., assessment of compactness of urban development) in relation to hazard maps (e.g., floods, heat) is essential for policymakers (e.g., producing statistics and useful indicators), particularly within strategic corridors.

Application Need 1.2: [Vulnerability] An application that provides access to high-resolution maps of the location and dynamics of informal settlements, socio-economic conditions, as well as city-wide deprivation (poverty) models. Furthermore, models that predict the growth of informal settlements (to understand where future settlements are likely to develop).

Application Need 1.3: [Exposure] An application that provides information on elements of risk (e.g., buildings, infrastructure, services and population). Such an application might also require additional data (not directly observed by active sensors), such as in situ or volunteer geographic information campaigns.

Application Need 1.4: [Exposure-Vulnerability] The capacity to extensively use Copernicus data to enable urban growth trend prediction (e.g., development and strategic planning to predict how cities evolve) for forecasting the loss of arable and forest lands.

Application Need 1.5: [Exposure-Vulnerability] Access to indicators and trends on the urban growth types, population data, and main urban functions (related to transport and economic functions) for policymakers (e.g., produce statistics and useful indicators).

Table 19. Objectives, spatiotemporal resolution, and user archetype intelligence dimensions.

Objectives	**Spatial dimension**	**Temporal dimension**	**User archetype**
Compact, sustainable and inclusive urban development (past-present-future) Encouraging urban development strategies that protect arable and forest areas. Support planning visions of economic hubs along strategic corridors	Neighbourhoods/ wards (main) Municipality level (main) FUA (main) Urban centres (main) Regional level (secondary) National level (main)	Short-term (secondary) ➔ Monthly updates on indicators of services and infra-structure Medium-term (main) ➔ Annual updates of indicators to show urbanisation trends Long-term (main) ➔ Growth models typically 5-year intervals – opti-mally until 2050.	Strategic: interannual policy-focused (primary) Tactical: intra-annual (secondary) Logistical: event to seasonal (secondary)

Source: Internal EC KCEO.

Challenges/limitations observed: A thorough profile mapping of the climate change exposure and vulnerability of a city would not be possible by only using GHSL layers, given the need to understand flood-prone and drought-prone areas.

Use Case 2: Measuring and Mapping Urban Vulnerability to Make Cities Resilient in EU Partner Countries

African cities have the fastest growth rates worldwide (UN-Habitat, 2022). Most cities are characterised by rapid unplanned urban developments and sprawl that lack infrastructure and services and limited access to data to monitor these dynamics. However, routine and updated spatial data on the interaction between urbanisation and climate impacts are essential for developing local resilience strategies. However, Copernicus products are often only available for EU member states and do not cover the regions that relate to the policy needs of DG INTPA. The above-specified policy needs (1-4) are linked to application needs:

Application Need 2.1: [Hazard] An application built on Copernicus data that provides urbanisation trends (dynamics) at the city scale, linked to climate hazards (e.g., heat, flood) and their relation to key ecosystem services. Urbanisation trends include mapping of the urban morphology (e.g., densities, regularity, height of the built-up areas).

Application Need 2.2: [Hazard] Availability of a robust analytical tool for natural hazards screening to support the development of urban Nature-based Solutions (NbS) programmes of combined (spatial) data on urban functions and hazard models (e.g., heat, floods, storms).

Application Need 2.3: [Vulnerability] An application that provides high-resolution maps of past and predicted future dynamics of informal settlements, including their demographic, socio-economic characteristics, and service and infrastructure provision (e.g., WASH, electricity). This requires a combination of EO products with demographic and socio-economic data.

Application Need 2.4: [Exposure-Vulnerability] Access to spatial information on economic and urban functions and the location of key city infrastructures, combined with hazard severity in relation to urban function.

Application Need 2.5: [Exposure] An application that provides spatial information on elements of risk (e.g., infrastructure, services and population).

Table 20. Objectives, spatiotemporal resolution, and user archetype intelligence dimensions.

Objectives	**Spatial dimension**	**Temporal dimension**	**User archetype**
Urban resilience via a balanced urban regional development Safeguarding key ecosystem services to support climate change adaptation efforts at the local scale to inform urban planning: (i) the urban water system (ii) ecosystems and protected areas (iii) key landscape features Understanding of intra-city urbanisation dynamics and infrastructure provision Development of urban Nature-based Solutions (NbS) programmes	City (street) blocks (main) Neighbourhoods/ wards (main) Municipality level (main) FUA and urban centres (main) Regional level (secondary) National level (secondary)	Short-term (secondary) ➔ Monthly updates on indicators on services and infra-structure Medium-term (main) ➔ Annual updates of indicators to show urbanisation trends Long-term (main) ➔ Growth models typically 5-year intervals – opti-mally until 2050.	Strategic: interannual policy-focused (primary) Tactical: intra-annual (primary) Logistical: event to seasonal (secondary)

Source: Internal EC KCEO.

6.6.4 Technical assessment

Definitions
For these use cases, we will refer to the following definitions: **Temporal resolution** Very High Resolution (VHR): <= monthly High Resolution (HR): > monthly and < =1 year Medium Resolution (MR): > 1 year and <= 5 years Low Resolution (LR): > 5 years **Temporal extent** Short Extent (SE): < 1 years Medium Extent (ME): >= 1 years and < 5 years Long Extent: >= 5 years

Use Case 1: Compact Urban Development and Climate Adaptation in Africa

The application should support the evaluation of progress towards compact, sustainable and inclusive urban development to protect natural resources, reduce climate hazard risks and protect the vital function of urban centres. For this purpose, past-present-future analysis of built-up and land cover/use is essential. Archives and ongoing observation (e.g., GHSL) offer the possibility for trend analysis, and future data through modelling are useful to prepare scenarios/future projections. Global/continental scales at the extent of FUAs are relevant to relate urban growth/form to climate impacts (e.g., flood, temperature) and adaptation (e.g., vegetation classes, high-resolution surface model). Such data also needs to provide details relevant to the intra-urban scale. However, presently, the granularity (Table 20) of most global layers does not provide sufficient information at the urban district level (ward or neighbourhood) on urban land use and form (including informality/deprivation). For example, with existing Copernicus products, it is not possible to identify different urban forms, e.g. central vs peripheral areas or informal areas. Only physical proxies are available for different urban typologies (Abascal et al., 2022). For instance, high built-up density commonly indicates informal areas. However, deduction analysis and this type of data are not enough to provide policy advice. Generally, for policymakers, city-level statistics need to be provided that support the development of urban resilience strategies and provide guidance for the development and monitoring of urban plans (e.g., strategic plans). The necessary parameters and minimum requirements are shown in Table 21.

Use Case 2: Measuring and Mapping Urban Vulnerability to Make Cities Resilient in EU Partner Countries

The application should support the evaluation of progress towards making cities resilient in EU partner countries. This builds on an ongoing collaboration with the GHSL. The GHSL architecture past-present-future analysis offers the possibility for trend analysis, and future data through modelling are useful to prepare scenarios/future projections. Furthermore, Copernicus data enable trend analysis and observation over time for actual monitoring (e.g., SDGs indicators monitoring, development planning to observe how cities evolve). However, available data are often not ready to use for policy-making consumption. JRC Disaster Risk Management (E.1) and DG INTPA are working together to process data and make them available to policymakers: translate data production to data use (e.g., produce statistics and useful indicators). Despite the availability of Sentinel data, DG INTPA would need more detailed information for intra-city analysis (e.g., unplanned developments). The current level of information suggests where potential risk ‘hotspots’ are located and where interventions could be focused. Necessary parameters and minimum requirements are shown in Table 21. General obstacles and limitations:

- Despite the advantages that sensors provide, EO data are insufficient to answer all the project policy needs of DG INTPA. For example, global climate/environmental layers are often coarse (spatial resolution), which does not provide enough detailed data at the urban regional scale. Furthermore, some variables that need to be observed require additional data (not directly observed by operating sensors). In these cases, additional data, such as in situ or volunteer geographic information campaigns, are necessary.
- Urban resilience: Insufficient data exists at the city level for hydrological analysis and to inform urban resilience plans related to urban planning.
- The granularity of data does not provide information at the city district and city block level; thus, it is impossible to identify deprived areas (e.g., slums) with available apart from general proxy indicators. For instance, the high density of households often relates to deprived areas. However, deduction analysis and this type of data are not enough to provide policy advice (where ground validation would be necessary).

Table 21. Parameters and minimum technical requirements for the INTPA use cases. (n/a = not applicable)

Parameter	**Spatial resolution**	**Temporal resolution**	**Temporal extent**
Main physical parameter			
Built-up area extent and expansion	High Resolution 1	Medium-Low Resolution	Long Extent
Land cover/use	High Resolution 1	High Resolution	Long Extent
Urban morphology	Very High Resolution 1	High Resolution	Long Extent
Urban infrastructure (streets / electricity etc)	Very High Resolution 2	High Resolution	Long Extent
Informal settlements	High Resolution 1	High Resolution	Long Extent
Environmental dimension			
Arable land	High Resolution 2	High Resolution	Long Extent
Forest and protected areas	High Resolution 2	High Resolution	Long Extent
Topography	High Resolution 2	n/a	n/a
Soil quality and land contamination	High Resolution 2	High Resolution	Long Extent
Green open spaces (ridges)	Very High Resolution 2	High Resolution	Medium Extent
Waterbodies	Very High Resolution 2	High Resolution	Medium Extent
Climate dimension			
Air quality	Medium Resolution	Medium Resolution	Long Extent
Temperature	High Resolution 2	High Resolution	Long Extent
Flood hazard	High Resolution 2	High Resolution	Long Extent
Droughts/Fires	High Resolution 2	High Resolution	Long Extent
Socio-economic dimension			
Demographic statistics	High resolution grids or wards	Medium Resolution	Long Extent

Poverty and social exclusion statistics	High resolution grids or wards	Medium Resolution	Long Extent
Health statistics	High resolution grids or wards	Medium Resolution	Long Extent
Population living in hazard zones	High resolution grids or wards	Medium Resolution	Long Extent
Economic data	High resolution grids or wards	Medium Resolution	Long Extent

Source: Internal EC KCEO.

6.6.5 Value chain analysis

The INTPA use case 1&2 focuses both on urban policies and international cooperation between the EC and partner countries of DG INTPA, supporting sustainable urban development and mapping urban vulnerability to make cities resilient in EU partner countries. Therefore, the spatial scales include the sub-municipal level (e.g., urban districts), city and regional scale up to trends at continental/global scale. The deep dive considers the minimum technical requirements to achieve these goals. Many products and services described in the next section provide parameters at a sufficient spatial resolution that allow for aggregated indicators at the municipal, national, or regional level. However, many products and services do not fully support the sub-municipality scale, as they are produced at too coarse spatial resolution or do not have the required semantic content.

For the evaluation of climate impacts and adaptation, risk components are split into hazards, exposure, and vulnerability. The main hazards that relate to the lack of compact urban development (e.g., urban sprawl) (INTPA use case 1) and the need to develop urban resilience strategies (INTPA use case 2) are:

- Urban heat (extreme temperatures) and consequences such as droughts (e.g., with relation to land subsidence or fires).
- Occurrence and magnitude of floods (pluvial, fluvial, and coastal) and consequences such as landslides.
- Increase in the frequency and severity of storms.

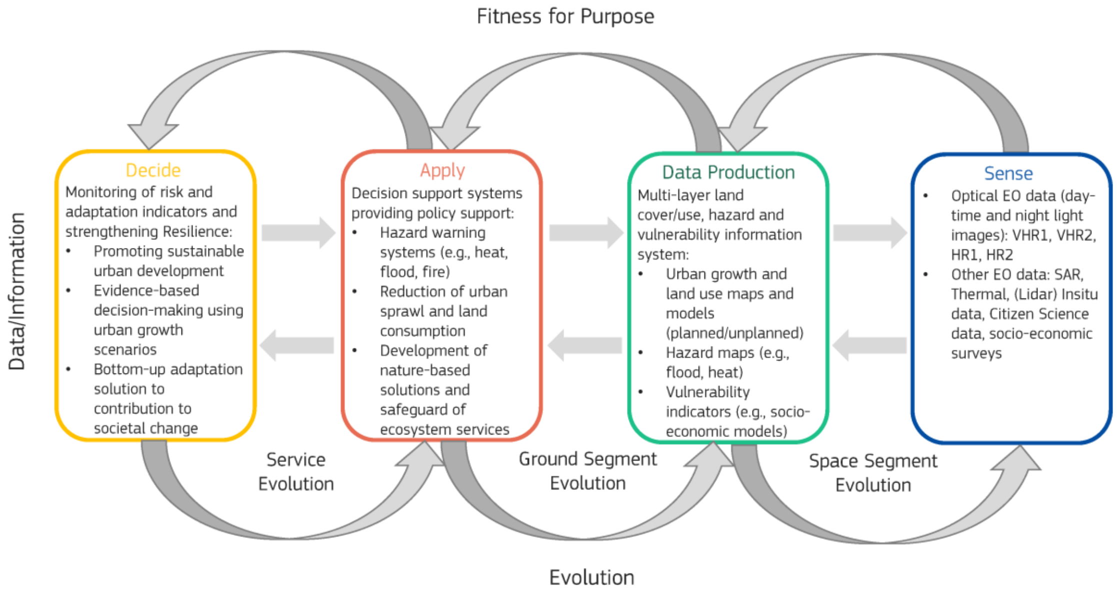
These climate impacts and disputes over access to resources (e.g., land, water) are often root causes of local and regional conflicts that have the potential to destabilise entire regions, such as leading to mass displacements (Flahaux & De Haas, 2016). Consequences are the rapid growth of cities in many regions driven by displacement (often unplanned with insufficient infrastructure provision). Exposure and vulnerability components can be evaluated and monitored using EO data or proxies built upon Geospatial models. On the exposure and vulnerability side, the required data products are:

- Urban growth maps and models
- Population density
- Housing conditions
- Basic urban infrastructure
- Socio-economic characteristics
- Informal settlements
- Green and blue infrastructure

Thus, EO data are critical to support the value chain of the use case (Figure 22). For example, global built-up time series as part of the Copernicus Emergency Management Service (CEMS) are optimal products for continental monitoring. The GHSL data packages (Corbane et al., 2018) can be used to provide information on residential and non-residential areas as well as land cover information about crops, forestry, urban green spaces, and wetlands (Sense). This information allows for monitoring compactness vs sprawl of urban growth and the loss of arable and forest land (Monitor). Such data can be applied for forest protection and future simulations, e.g. expansion of built-up areas into forest reserves. Such models also allow policymakers to work with different scenarios and policy options toward the development of nature-based solutions (Apply). Ultimately, this information can inform the development of sustainable urban planning strategies and bottom-up adaption solutions that develop, for example, nature-based solutions (Decide).

As part of data products, both short- and long-term projections alongside expansion layers can be integrated to provide information for policy analysis in identifying long-term priority investments. Supplementary survey data can be visualised and georeferenced, combined with field studies, if available. For instance, identifying water access points is important for sector development and improving access to services. However, it is not possible only via global EO data; it requires missions to study areas and local knowledge, e.g. crowd sourcing data. Data taken on the ground would be necessary to validate assumptions, e.g., through urban observatories, as in the case of Ghana ([111]). Impacts can be assessed and monitored through EO data. The optimal application for local to national authorities would be straightforward access to data and the ability to evaluate and monitor the long-term effectiveness of adaptation measures against various climate risks.

Figure 22. Value chain assessment of the compact urban development INTPA use case 1&2 combined.



Source: Internal EC KCEO.

([111]) EU-Ghana partnership for sustainable Cities. Within this Joint Programming (2021-2027), the EU supports the development of more sustainable and inclusive cities, with a specific focus on unplanned spatial expansion of urban and metropolitan areas that causes challenges to economic efficiency. https://d-portal.org/ctrack.html?publisher=XI-IATI-EC_INTPA#view=act&aid=XI-IATI-EC_INTPA-2024-PC-26030

6.6.6 Fitness for purpose of existing products and services

The fitness for the purpose outlined below is derived from a technical assessment encompassing spatial and temporal resolution and the length of the time series. It also considers the thematic content of the products/services and their suitability for specific application needs. Critical factors such as uncertainty and accuracy, along with evaluations of the overall quality of EO products/services, were not included. This is because their assessment would necessitate a comprehensive analysis that extends beyond the scope of this detailed examination. Table 22 shows a summary of the results. However, it should be noted that many global data layers have low accuracies in complex built-up areas in LMICs, e.g., the exceptionally high built-up densities cannot be sufficiently captured in built-up layers, building footprints or population datasets (Kuffer et al., 2022; Thomson et al., 2021; Wang et al., 2023). The "Fit application needs" column summarises the fit to application needs of all technical requirements considered and can take the following values:

- Match: The thematic content of products/services, their temporal and spatial resolutions, and the availability of time series match the application needs;
- Partial match: The thematic content of products/services, their temporal and spatial resolutions, or the availability of time series are sub-optimal for the application needs;
- No match: Neither the temporal nor the spatial resolution of the products/services match the application needs.

Table 22. Examples of EO-derived products and services that could contribute to the assessment for INTPA use cases 1&2. (n/d = not defined)

Parameter	Service(s)/Product(s)	Spatial resolution	Temporal resolution	Temporal extent	Fit to application needs
Main physical parameter					
Extent of built-up area	FUA	Vector	-	2015	Partial Match
	Urban Centres (+50,000 population)	Vector	-	2015	Partial Match
	Degree of Urbanization	1km	5 years	1975-2030	Match
Expansion of built-up area	GHS-BUILT-S	100m	5 years	1975 - 2030	Match
	GHS-BUILT-S and -C	10m	-	2018	Match
	GHS-BUILT-V and -H	100m	-	2020	Partial match
	WSF-Evo	30m	1 year	1985-2015	Match
	WSF	10m	-	2019	Match
	WSF – 3D	90 m	-	Approx. 2012	Partial match
Urban morphology/form	Google and Microsoft building footprints	Polygons	-	Around 2020	Partial match
	Building heights, e.g., WSF, GHS-Built-V	90/100 m	-	Around 2012	Partial match
	Local climate zone classification (WUDAPT)	100 m	-	-	Partial match
	GHS-BUILT-C	10m	-	2018	Match

Land use/cover proportions	ESA landcover	10m	-	2020	Match
	Dynamic Land Cover	100 m	1 year	2015-2019	Partial match
	UN-FAO's Land Cover Classification	100m	1 year	2016-2019	Partial match
Size and population of informal settlements	Proxy indicators via urban morphology	10 m	-	2020-present	No (present) match
	Existing maps of informal settlements - available for some cities, e.g., EO4SD ([112]), WRI ([113]) and development of scalable methods using Copernicus data (IDEAtlas Example ([114]))	10 m	-	2020-present	Partial match
Urban infrastructure (streets / electricity etc)	Streets: OSM, Microsoft ([115])	Vector	-		Partial match
	Electricity: Night Light Images	40 – 500 m	Continuous	since 2012	Partial match
	WASH: OSM POI of services	Vector	Continuous	since 2006	Partial match
	Road accessibility (e.g., Million Neighborhoods)	Vector	-	2020	Partial match
Environmental dimension					
Topography (link to land slide susceptibility)	ALOS PALSAR	12.5 m	-	2006	Match
	SRTM	30 m	-	2000	Patial Match
Surface Temperature	CLMS Land Surface Temperature Daily Cycle	5 km	1 day	2021-present	Partial match
	HR: Ecostress, SDGSat etc.	30+m	2018/ 2021	Continuous	Partial match
Arable land Forest and protected areas	Global Forest products, e.g., GLAD ([116])	30m	Decadal	2002-2022	Partial Match
	World Database on Protected Areas (WDPA)	Vector	(Annual)	1981-2019	Match
Water bodies & Flood	JRC Global Flood Map ([117]) (River Flood)	1km	-	10 -100 y return periods	Partial Match

([112]) https://eo4sd.esa.int/
([113]) https://wri-datalab.earthengine.app/view/urbanlanduse
([114]) https://ideatlas.eu/
([115]) MS Street Network - Global Street Layer
([116]) Global Land Analysis & Discovery
([117]) River Flood Hazard Maps at European and Global Scale

	Water Bodies	60m	Monthly	2020-present	Partial Match
	Global Flood Monitoring (GFM)	90m	10-day forecasts	10/20 year return periods	Partial Match
	Commercial products, e.g., Global Fathom	30m	-	10 -100 y return periods	Partial Match
Air quality	AIR-Portal	Downscaled to 100 m	n/d	n/d	Partial match
Soil and other contaminations	Surface Soil Moisture	12.5km	2 days	2015-present	Partial match
Droughts/Fires	Global fire monitoring	11km	Near-real-time observations	Continuous	Partial match
	EFFIS - European Forest Fire Information System Active Fire Detection (fire global but not burned areas)	300 m	Near-real-time observations	Continuous	Partial match
Climate dimension					
Air pollution	CAMS forecasts of aerosols, atmospheric pollutants, greenhouse gases, stratospheric ozone and the UV-Index	40 km	5 days	Continuous	Partial match
	CAMS global greenhouse gas reanalysis	0.75°x0.75°	3 hours and monthly averages	Continuous	Partial match
Socio-economic/demographic dimension					
Demographic data	GHS-Pop	100 m	5 years	1975-2030	Match
	WorldPop	100 m	Annual	2000-2020	Partial match
	HRSL Facebook [118] (30m)	30 m	-	2020	Partial match
Poverty and social exclusion statistics & Health statistics	Demographic and Health Survey (DHS)	Vector	5 years	Since 1984	Partial match
Population exposed to hazards	Urban centre database (GHS)	Urban centres	5 years	1975-2015	Partial match
Economic data	Gini index (e.g., Earth System Science Data)	Countries	1 year	1958–2015	Partial match

[118] Data for Good at Meta

	World Bank, Poverty and Inequality Platform	Countries	1 year	1984- 2021	Partial match
	Relative Wealth Index	2.4 km	-	2021	Partial match

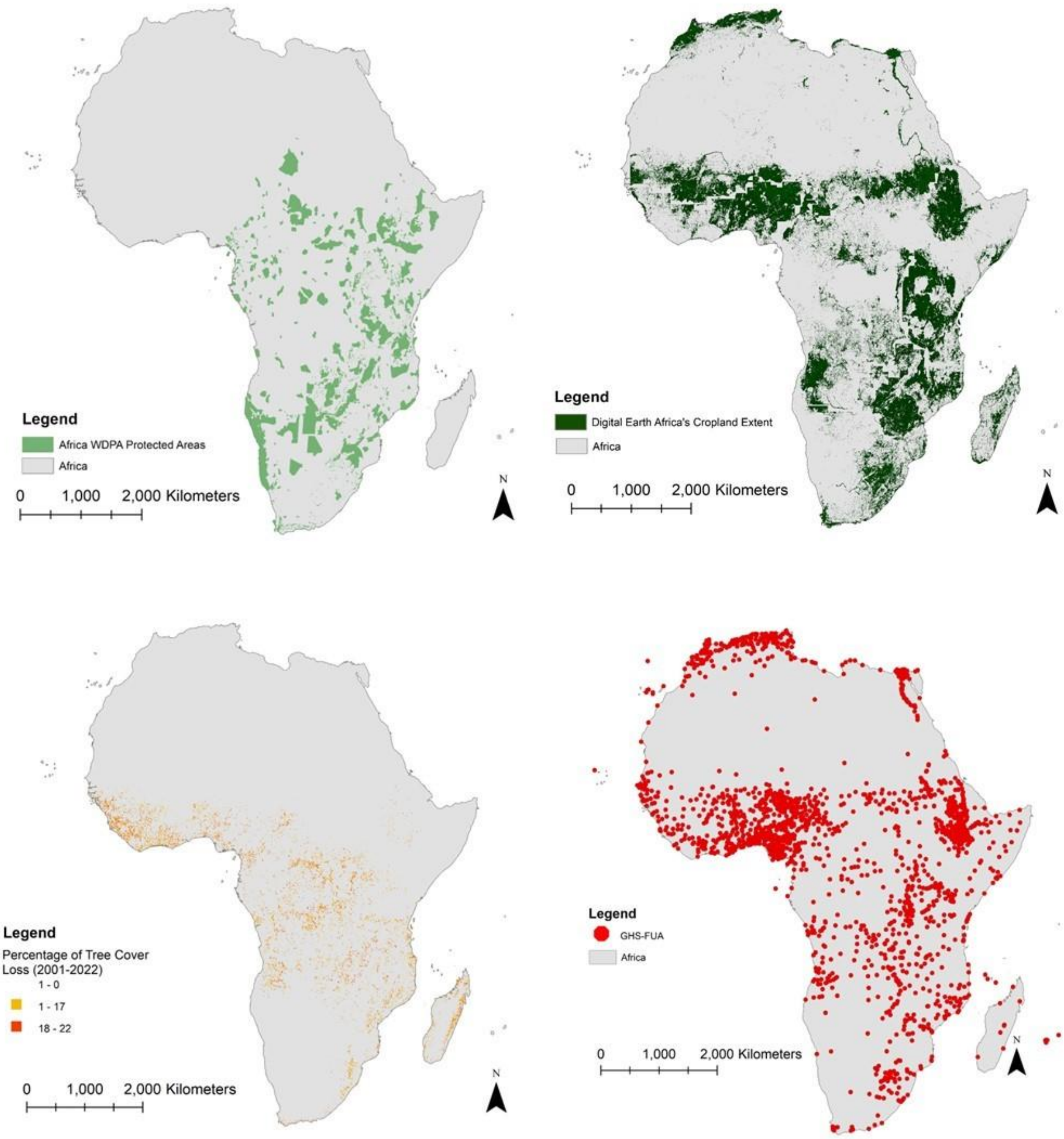
Source: Internal EC KCEO.

Main Physical Parameters with link to Climate and Environmental Dimension

Global land cover/use (including built-up) time series are optimal EO products for continental monitoring. For example, the GHSL (Corbane et al., 2018) can be used for multi-temporal analysis of land cover/use dynamics and the quantification of the loss of areas with vegetation cover (in particular forest areas, arable land) (Figure 23). Specifically, this includes the outputs:

- Global harmonised urban typology definition to classify human settlements (cities, towns, suburbs, rural) by population size and density using the GHSL tools, based on a population grid to reduce distortions created by different sizes of statistical and administrative units, including to offset the model's overreliance on official census data.
- Global land cover maps can be linked to maps of infrastructures in cities (e.g., street networks, accessibility in relation to flood risk areas). Street information is available from open data sets (e.g., OSM). Access to water and electricity infrastructure could be partially modelled with available open data (e.g., OSM) and EO (e.g., high-resolution night-time light images) and geospatial data, but no readily available products are accessible.
- Temporal dynamics modelling, which is useful for predicting urban growth (including slum and informal settlements). This allows to make projections of where future slums are likely to occur to support planning and decision-making.
- Empirical Land Sustainability (ELS) layer can be derived from a combination of Copernicus products and used to identify suitable land for urban expansion. However, such a layer is presently not available, but under development by JRC.
- Urban growth forecasts by JRC (GHSL) can inform the identification of challenges for inter-city mobility to improve regional networks and steer growth, but also to enhance links to intra-city mobility and explore how improved regional connectivity will affect urban mobility in cities.
- Data on densities, built-up heights, and volumes can inform transport and infrastructure planning, combined with land cover layer to harmonise urban and strategic corridor development with key sustainability assets.
- Recent ESA data showing more precise land cover (10m x 10m) used in the land cover tool can inform how to harmonize urban and strategic corridor development on key sustainability assets, in combination with the urbanisation and population tool using urban growth forecasts by JRC (GHSL) can inform the potential impacts of cities on the corridor's development.
- Scenario-building (short-, mid-, and long-term projections for 2030, 2050 and 2100, respectively) on urban expansion and population growth are needed to inform long-term urban policy and provide the basis for estimating future services and housing demand, including investment needs for critical infrastructure. The analysis could contribute to identifying existing and/ or project future conflicts between urbanisation along corridors development and biodiversity and key ecosystems to inform policy and planning and reduce human-wildlife conflict.

Figure 23. Land use/cover pressures – comparing the location of protected areas (UNEP-WCMC & IUCN, 2024), arable land (Digital Earth Africa, 2019) and forest loss (Hansen et al., 2013) with the location of urban areas as recorded by the Functional Urban Areas (Schiavina et al., 2019).



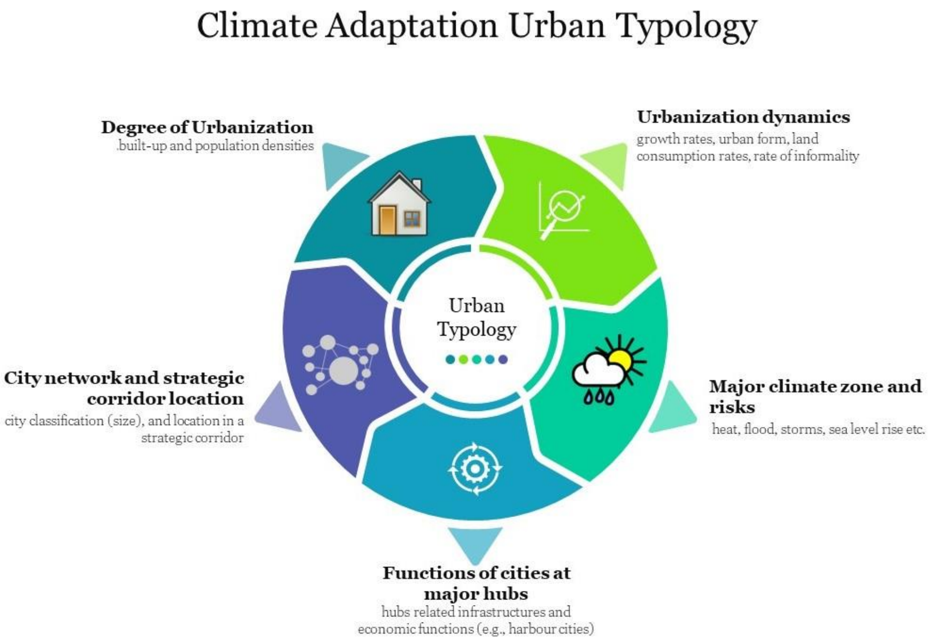
Source: UNEP-WCMC & IUCN, 2024; Digital Earth Africa, 2019; Hansen et al., 2013; Schiavina et al., 2019.

Different contextual domains (i.e., urbanisation dynamics, urban form, economic functions and climate risks) can be combined to develop an urban typology (city (class) types) that supports the design and implementation of climate adaption measurements (Figure 24). Different aspects that are contributing to the role and risks of cities and human settlements in developing an urban typology:

- Degree of urbanisation (built-up and population densities): Various databases on built-up areas (multi-temporal) (e.g., GHSL, WSF).

- Urbanization dynamics (e.g., growth rates, urban form): Urban growth models (e.g., GHSL) - buildings and street and transportation networks (combined with economic city models, topography, location and demographic data (e.g., Google, Microsoft, WorldPop).
- City network in the region and corridor location, including land cover (e.g., ESA landcover)
- Functions of cities at major hubs and infrastructures (e.g., POI ([119]) of OSM).
- Major climate zone and risks (i.e., heat, flood, storms): Location and hazard layer (multi-hazard risk assessment) captured from global hazard layers (e.g., flood risk maps).

Figure 24. Urban Typology that relates to climate change impacts.



Source: Internal EC KCEO

The increasing availability of very high-resolution (VHR) imagery is providing more detailed information about urban areas. For example, building footprints, combined with building heights allow mapping of the urban morphology (e.g., densities, irregularities, building sizes) (Porta et al., 2022; J. Wang et al., 2022). Google and Microsoft have been producing large datasets with a focus on LMICs. However, present building footprint data for Africa have consistency issues and show massive gaps in high-density areas (Chamberlain et al., 2024; Herfort et al., 2023).

Environmental & climate dimension

There is increasing availability of global environmental products that provide information about surface temperature, droughts and fires, arable and forest land, water and floods, air quality, soil and topography. Generally, the main urbanization dynamics and urban typologies can be intersected with hazard layers. However, global hazard layers, e.g. flood, heat, air quality, have commonly low spatial resolutions. For example, the CLMS land surface temperature has a spatial resolution of 5

([119]) POI: Points of Interest of main economic uses/assts.

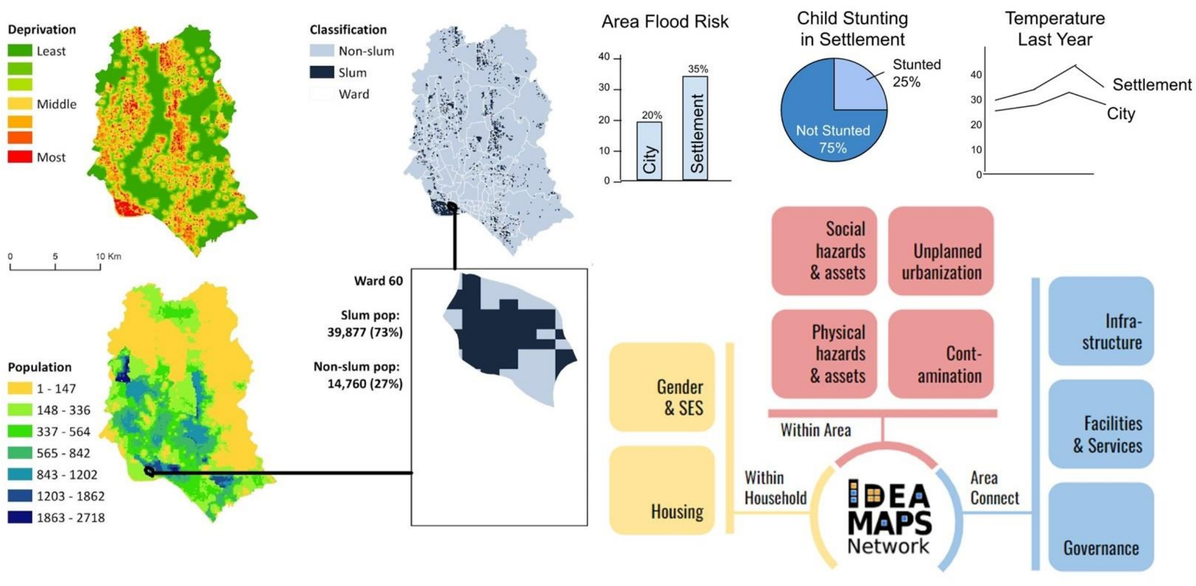
km, which does not allow the monitoring of the impact of urban climate adaption, e.g. the investment in improving green and blue infrastructure, at the neighborhood level. Most higher resolution Copernicus data and services are only available in Europe. Global urban land use/cover datasets do not cover the differences between formal and informal areas, which would be essential for climate vulnerability analysis.

EO data on the environmental & climate dimensions would be available to provide more high-resolution global products or continental products for Africa, but only project-based mapping is presently done to produce environmental indicators and maps for specific cities. The problem of low spatial resolution is particularly observed for the climate dimension; products that allow the monitoring of Greenhouse gas (GHS) emissions are of very low spatial resolution. However, one of the planned expansion missions of Copernicus will address this gap. The Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M) mission, with a suit of two satellites, is expected to be launched in 2026. This will improve the monitoring of the climate dimension.

Socio-economic/demographic dimension

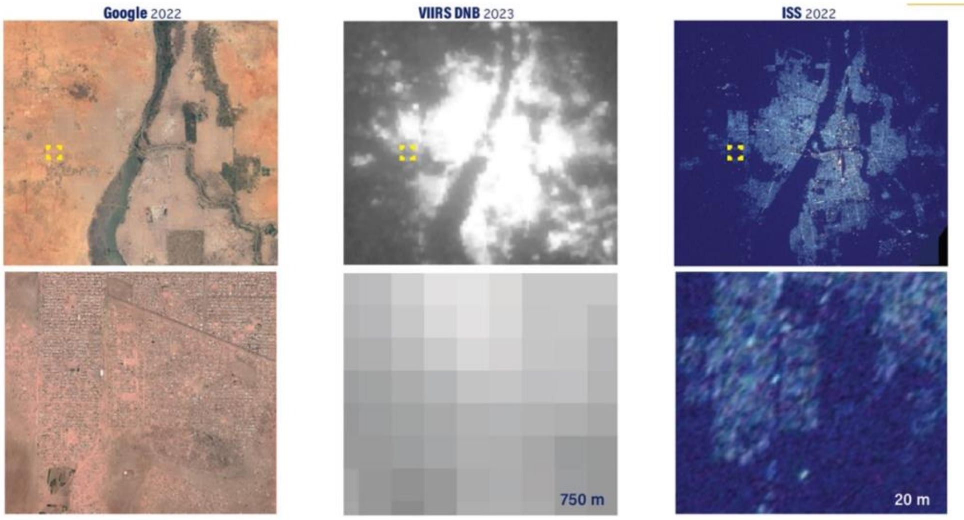
At a local level, cities face various degrees of spatial inequalities, impacting the vulnerability of the population. The term ‘spatial inequality’ refers to the unequal distribution of living conditions, resources and services across different areas or locations, such as healthcare, welfare, public services, household income and infrastructures (SDG 10). The spatial distribution of such characteristics can be described in terms of proximity, distance, clustering, and concentration. Spatial inequalities are visible in the urban/rural divide, between countries, or between more and less deprived areas within the same geographical/administrative unit or city blocks (the lowest level). However, no Copernicus product is available to provide such information. Beyond Copernicus, existing datasets are of coarse spatial resolution (e.g., Chi et al. (2022)). However, it is possible to combine EO and other geospatial, socio-economic and demographic data to model spatial inequality or employ EO proxies (Figure 25 and Figure 26). As seen during the COVID-19 pandemic, spatial inequalities are also associated with health and social inequalities and can lead to a chain effect in densely populated areas. Understanding the nature, extent, and evolution of differences between places can support the development of policies, strategies and interventions that impact the morbidity and mortality of different diseases (SDG 3).

Figure 25. Combining Earth Observation and socio-economic/geospatial data to model deprivation/informality.



Source: Abascal et al., 2022.

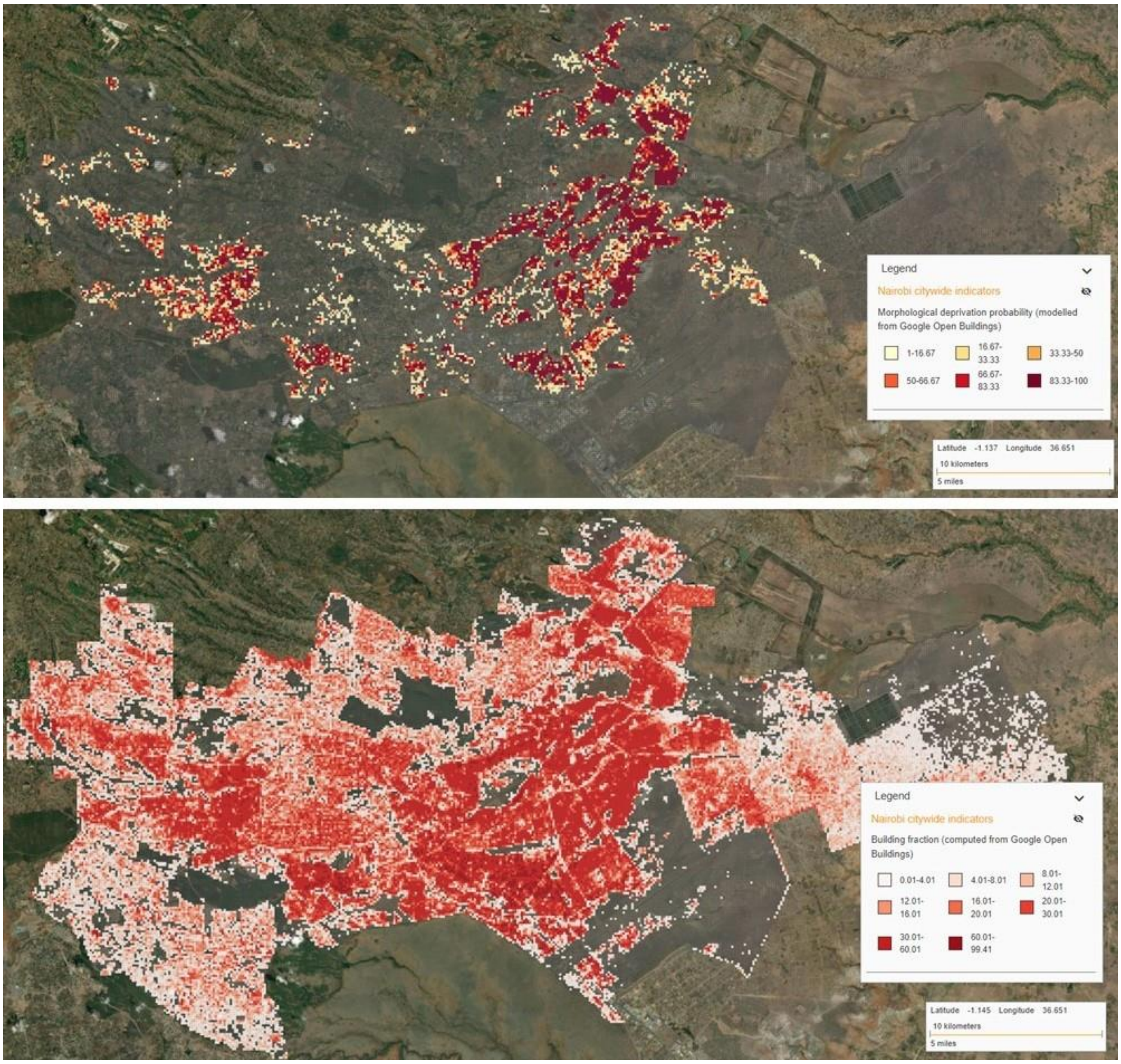
Figure 26. Khartoum, Sudan – Access to electricity with high-resolution night light images (comparing VIIRS and ISS images).



Source: Abascal et al., 2023.

Urban population growth and increasing scarcity of affordable housing push large and ever-increasing numbers of people to live and work in high-risk, low-potential, marginal urban environments. Such areas, e.g. informal settlements, are often characterised by low-quality dwellings, either in densely built-up central areas or set up around the edge of the city, where there is less land development and pressure on land. Climate change rapidly poses additional risks to these communities, making them among the most vulnerable to natural hazards. Informal settlements are often built in flood-and /or erosion-prone areas. Deforestation, pollution, lack of sanitation, waste collection, waste disposal, lack of landfill sites, and no stable electricity are amongst the most common features of informal settlements. According to the UN, the absolute number of people living in slums or informal settlements is 1.1 billion, with 80 per cent attributed to three regions: Eastern and South-Eastern Asia (370 million), sub-Saharan Africa (238 million) and Central and Southern Asia (227 million) (UN-Habitat, 2023). Informal settlement identification and tackling (spatial) inequalities may include Temporal Dynamics Modelling to map and identify informal settlements (Figure 27) and project where future slums are likely to be located in future. To avoid the growth of precarious settlements, low-cost housing is essential. For identifying suitable land for future urban expansion, applications of Empirical Land Sustainability (ELS) layers, can guide planning and decision-making. The ELS is also being developed by the team leading the GHSL.

Figure 27. Relation between the location of informal settlements (morphological deprivation: upper) and built-up density (often a relatively robust proxy: lower), for example, Nairobi, Kenya.



Source: SLUMAP, 2020 ([120]).

6.6.7 Gap analysis

Table 22 shows that EO products and services are available to guide compact urban development and the development of urban resilience strategies. However, often high-resolution intra-urban data are missing that provide information about the intersection of built-up forms, e.g. central vs peripheral areas or formal vs informal areas, infrastructure/services, climate hazards and vulnerabilities. Furthermore, main data repositories have data gaps in high-density, typically informal areas, e.g. Figure 28, and high uncertainties (both about horizontal and vertical information). High-resolution data are urgently required to allow for a profound analysis of

([120]) https://pere.gis-ninja.eu/slumaps/

elements at risk and local vulnerabilities. Overall, the main gaps in presently available data to respond to the policy needs of INTPA can be concluded as follows:

Spatial resolution

- High-resolution data for built-up and land cover/use maps are provided by the GHSL, with the exception of building height (only 100 m spatial resolution). However, very high-resolution land use, e.g. informal areas, and urban form characterisation that capture the building level are lacking. Such very high-resolution data aggregation at the lowest spatial units (city districts or city blocks) would be beneficial for policymaking.
- Data on infrastructure/services (e.g., access to WASH, electricity) and socio-economic conditions are not readily available within Copernicus and or of too coarse resolution, e.g. roads as part of the GHS-BUILT-C. Demographic data, e.g. population data, are available but have high uncertainties in high-density urban areas, e.g. not capturing extremely high population densities. The increasingly available open datasets, such as OSM and Google, provide alternatives to fill data gaps but also often come with high uncertainties in complex urban areas
- Available environmental and climate products and services do not sufficiently meet spatial requirements. Global products are of very low spatial resolution, making intra-city and neighbourhood scale analysis impossible. Many relevant higher-resolution Copernicus products and services are only available for Europe and do not cover Africa or the Global scale.
- For environmental products often higher spatial resolution EO data are available (e.g., for surface temperature Ecostress with a spatial resolution of 70 m). However, the data collected by this instrument on board the ISS would require a global data processing pipeline.
- Commercial products could fill in data gaps, e.g., higher spatial resolution flood models (e.g., Fathom) but come with considerable financial costs.

Temporal resolution

- Most available land cover/use and urban form products and services do not sufficiently meet temporal resolution requirements. For example, more frequent updates are required. Many regions in Africa have very high urbanization dynamics, where annual updates are required, while present products are available for 5-year intervals, and future GHSL products are planned for 2-year intervals. In particular, multi-temporal data on building heights are lacking, which would provide information on vertical dynamics.
- For most environmental products the temporal resolution is excellent to meet the policy needs, e.g. almost real-time fire monitoring or daily surface temperature information. However, the price of the high temporal resolution is paid by the low spatial resolution.

Temporal extent

- For the land cover and built-up products, the major bottleneck is that the Landsat-based time-series stopped in 2015. New products are available using Sentinel data of higher spatial resolution. However, the two products (Landsat and Sentinel-based) have consistency issues, which causes limitations to trend analysis and growth models (predictions).

- The available temporal extent for most Copernicus environmental products is only suitable for assessing short/very short-term trends. Long-term analyses require observations over a more extended period;

Other gaps:

- There is an essential lack of access and documentation of data for policymaking. Capacity challenges in accessing data are often preventing the use of available and very relevant data. Initiatives such as the EO Toolkit for Sustainable Cities and Human Settlements (UN-Habitat, 2021) are beneficial in providing easy access to data for urban climate adaptation. Such initiatives should be extended and combined with capacity development initiatives.
- Interactive data portals that combine relevant data layers for urban climate adaptation are lacking. Such data portals need to fit the needs of different user categories, particularly non-EO experts. To mainstream the use of EO data for climate adaptation in LMICs interactive data portals that allow summary statistics on user-defined aggregation levels and area coverage would be a breakthrough.

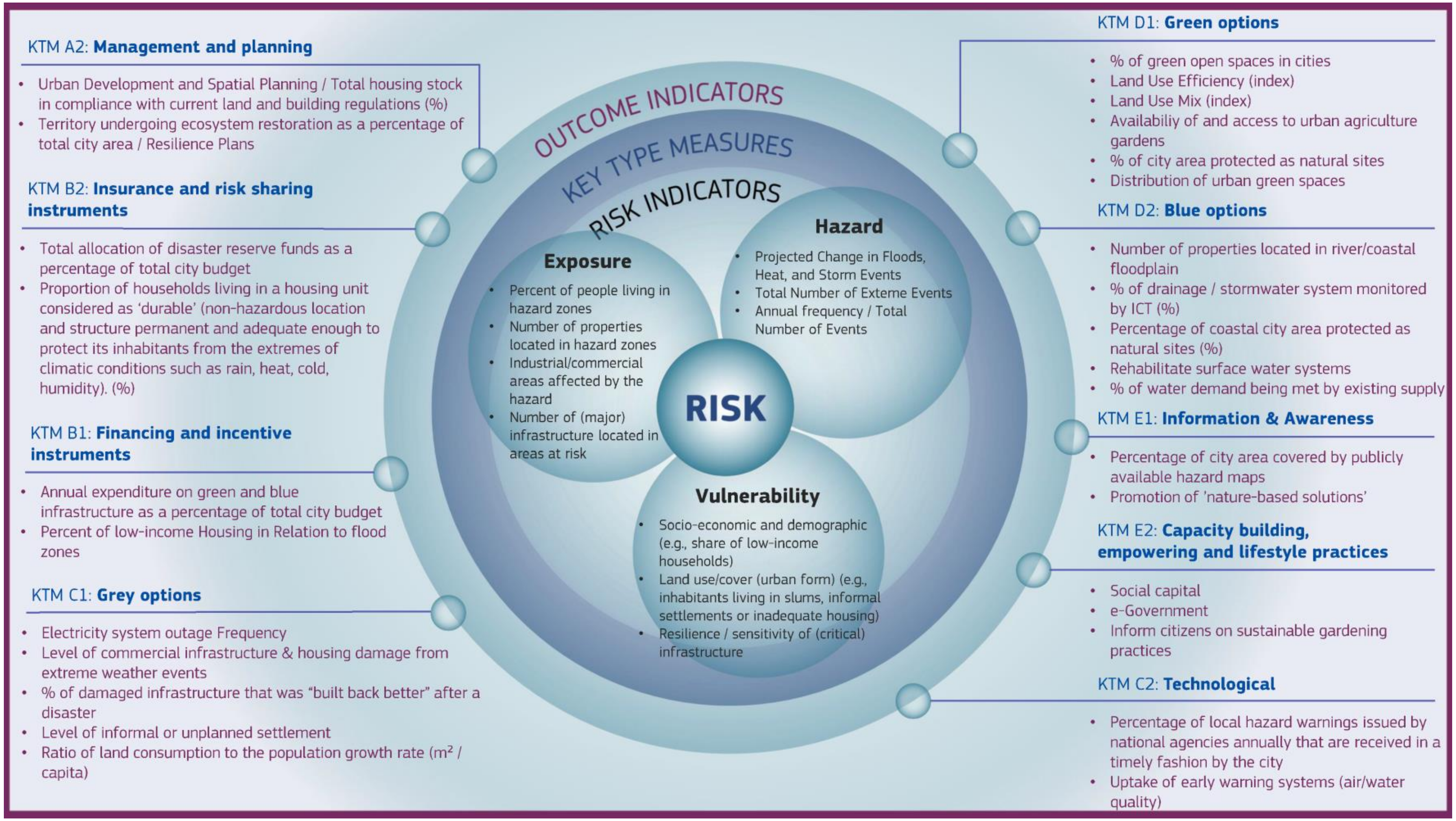
Figure 28. Nairobi – Coverage of Street Network of Microsoft, missing access roads are often a good proxy of informality/deprivation.

Source: Google and Microsoft

6.6.8 Monitoring risk, adaptation and outcome

The schematic shown in Figure 29 highlights the role of Earth Observation (EO) in Climate Adaptation, particularly in Risk Assessment (covering Hazard, Exposure, and Vulnerability), climate action reporting through Key Type Measures (KTMs), and outcome monitoring via relevant EO indicators. It connects the Indicators chapter with Use Cases, illustrating EO's contribution to the adaptation cycle. Many indicators rely on socio-economic data. However, the schematic advocates for EO's potential in direct monitoring and enhancing the design and assessment of KTMs, also areas where socio-economic data are lacking or are dated.

Figure 29. DG INTPA Use Case 1&2 – Compact Urban Development. Illustrative example of Earth Observation mapping against Risk and Vulnerability Assessment, Key Type Measures reporting, and pertaining indicators.



Source: Internal EC KCEO.

Figure 29 shows the DG INTPA use cases. Earth Observation is a straightforward approach to monitoring climate risks, e.g., using satellite observations supplemented by in situ measures. Results are able to deliver time-series of risk indicators at different spatial and temporal scales. Estimation of vulnerability and exposure requires integrating socio-economic datasets with hazard maps. Copernicus products and services play an essential role in supporting the quantification of indicators. For KTMs and their outcome, only those with EO potential roles are here represented:

- Green options (D1) & Blue options (D2): Green and blue options are essential to adapt to climate change impacts, such as extreme temperatures, droughts and floods. Earth Observation allow monitoring planning interventions. For example, an increase in green open spaces in cities, or improved distribution of urban green spaces (improved physical accessibility). For blue options, EO can support the monitoring of drainage/stormwater systems or the rehabilitation of surface water systems.
- Grey options (C1): Earth Observation can provide valuable insight into estimating electricity system outages (using night-light observations), support rapid damage assessment after a disaster (infrastructure & housing damage) and provide insights into both vulnerable and damaged areas typologies, e.g. informal vs formal areas.
- Management and planning (A2): Earth Observation can support urban development and spatial planning by providing valuable insights, such as a rapid assessment of unplanned (informal areas) that do not comply with current land and building regulations or monitor the ecosystem restoration efforts.
- Financing and incentive instruments (B1) & Insurance and risk sharing instruments (B2): Earth Observation can assist in estimating the damage from extreme weather events, or in relation to urban resilience the proportion of households living in 'durable' housing, e.g. non-hazardous location.
- Information & Awareness (E1) & Capacity building, empowering and lifestyle practices (E2): Earth Observation can play a key role in empowering local actors to get access to hazard information (disaster preparedness) as well as co-designing local adaptation solutions building on EO-data, e.g. spatial information systems of 'nature-based solutions'.

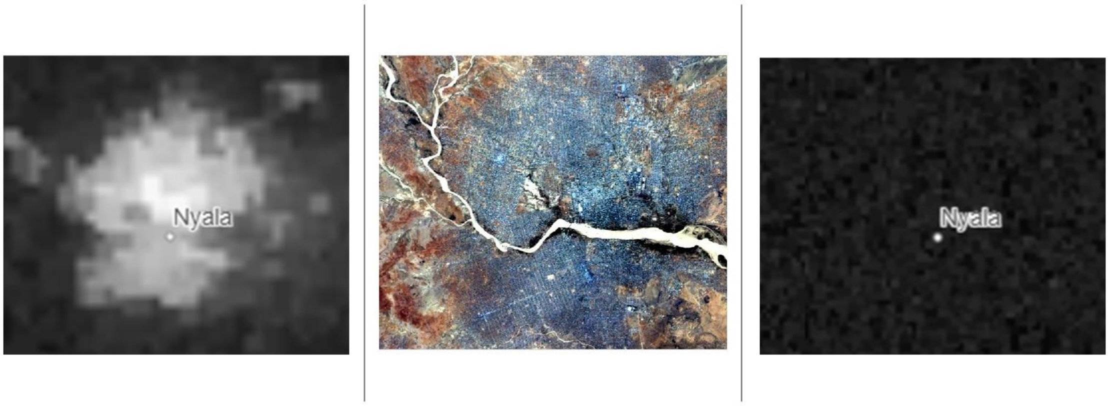
6.6.9 Recommendations

This assessment aims to support DG INTPA data and information needs in promoting compact and sustainable urbanization strategies and hazard information systems towards bottom-up urban resilience strategies in INTPA partner counties. Access to Copernicus products and services at global and continental (e.g., Africa) scale are essential to support INTPA's strategies (e.g., in the context of sustainable and prosperous cities), EU Delegations in partner counties, and provide baseline data for initiatives such as the Global Gateway. Presently, Copernicus products and services (e.g., as part of the Emergency Management Service or the Copernicus Land Monitoring Service) provide global base information on built-up, land cover and population (GHSL), and some hazard domain models. However, detailed global information at the city scale on hazards, exposure and vulnerability is insufficient. Earth Observation (EO) plays a pivotal role in understanding and monitoring urban development, population dynamics, and their effects on environmental systems, particularly concerning the loss of biodiversity and arable land. Despite the valuable insights gained from satellite data, there are significant gaps in accessing EO-derived intelligence that effectively integrates data and models across physical, socio-economic, and demographic domains. There is an urgent need to improve our ability to visualize complex interactions, such as the factors driving urban growth, and to evaluate the interplay between different domains. This involves creating and validating relevant models at the local (city) scale and developing forecasting services and scenario applications tailored to cities. The Copernicus observation and modelling capacities should be geared towards supporting ecosystem-based approaches. This includes the ability to identify problem areas (hotspots), necessary interventions, and key indicators of risk, thereby providing critical information for informed decision-making and sustainable urban planning. Building on the gap analysis and aim to boost the uptake of EO products and services for urban climate adaptation of international, national and local actors in INTPA partner counties, the following recommendations are made:

On the evolution of Copernicus, recommendations include the promotion of:

- [Space Segment] Planned upcoming Sentinel missions address some of the identified gaps, e.g., LSTM: Copernicus Land Surface Temperature Monitoring (with a spatial resolution of 50 m) will allow mapping of detailed urban heat hazards. However, for mapping detailed urban morphology and land use patterns, an increased resolution of Sentinel-2 would be beneficial. Aiming at a VHR2 (resolution of around 2-4 m for the visible (VIS) / near-infrared (NIR) bands) would be of massive benefit. Furthermore, an investment into HR1/2-night light observations (with a PAN resolution of around 10 m and RGB of 30-50 m) would boost applications on mapping settlement patterns, access to infrastructure (e.g., electricity) and emergency mapping (e.g., in case of disasters and conflicts, example Figure 30).
- [Hazard Products] Further developments should invest in the availability of global hazard models that include near real-time and forecast products (e.g., flood, heat, storm). Such products are required to cover all settlements and need to be relevant at a city/municipal scale to provide locally meaningful knowledge products. Furthermore, environmental products, e.g. high-resolution forest cover, that are presently only available in Europe should be extended to Africa (or at a Global scale).
- [Hazards] Rapid integration of future Copernicus Expansion Mission products into Copernicus services, e.g., STM: Copernicus Land Surface Temperature Monitoring at high spatial and temporal granularities is desirable.
- [Vulnerability-Exposure Products] Integration of data and models to produce information about socio-economic, infrastructure, and housing conditions. To support the analysis of vulnerability and exposure, high-resolution data on infrastructure, population, housing and socio-economic models built on EO proxies need to be targeted. This would include improvements in population estimates of high-density (informal) areas. For this, further investments in R&I are required.
- [Exposure & Vulnerability] The operational provision of automated multi-scale change detection systems built on state-of-the-art AI models would be of massive benefit considering the rapid transformation process in Africa (one of the most rapidly urbanizing regions) with limited planning control in place. This would include the detection of hotspots of land consumption in protected and environmentally sensitive areas at a global scale (moderate resolution), which would be followed by detailed mapping of land use/cover patterns at higher spatial resolution at a local scale.

Figure 30. The city of Nyala (Darfur, Sudan), with a population of around 1 M people (2022), lost most of its population, visualized by the disappearance of Night Lights: VIIRS images from March 2023 (before the conflict: left) and March 2024 (after mass-displacement: centre) and recent Planet image (March 2024).



Source: VIIRS and Planet

On addressing the value-added intelligence aspects (Research & Innovation) of integrated risks, recommendations include the promotion of:

- [Last mile problem - Vulnerability] The increasing availability of global building footprint and road layers allows the production of models that indicate the location of informal settlements. This can build on combining several morphological indicators of informality (global layer of the degree of morphological informality), e.g., the density of buildings and population, the presence of roads and the irregular layout of an area. Such a layer would provide a spatial account for the most vulnerable population.
- [Main data/method gap(s) - Hazard] High-resolution multiple-hazard models, capable of delivering neighbourhood and city-block level data (such as information on heat hazards and various types of flooding, including flash floods), must account for the intricate topography and constructed environments of cities. Such data would allow for more accurate early warnings and impact assessments, thereby enhancing the effectiveness of predictive aid strategies. In turn, this improvement in predictive capacity is instrumental for better anticipation and allocation of necessary resources for disaster relief.
- [Main data/method gap(s) - Exposure] Cities expand and densify also in the vertical direction; time series of building heights are required employing high-resolution (e.g., SAR) data. Furthermore, improvement in population estimates to model urban high-density areas is urgently needed for improved exposure models.
- [Requirements for policy uptake] To guide evidence-based policies and decision-making, adaptation scenario modelling would be of great benefit. For example, 'what-if-type scenarios' would allow simulation of adaption measure alternatives and their impacts (building on impact indicators). Such scenario outputs, if well visualized and communicated, can stimulate societal debate, and motivate behavioural changes.

- [General bottlenecks Related to Value Chain] Access to reference data (in-situ data) necessary for training data-intensive AI models presents a significant challenge, particularly in the LMICs. This is compounded by the prevalent bias in existing data repositories towards the High-Income Countries (HICs) and major cities, leaving secondary cities in the LMICs grossly underrepresented. Moreover, access to computational platforms and resources poses a major obstacle for modelers, especially in the LMICs. There is a pressing need to promote open data exchange to mitigate resource wastage and enhance data availability. For instance, public-funded projects could be encouraged to contribute to open platforms like OpenAerialMap.org. Additionally, creating stronger connections with existing open data initiatives and citizens science initiatives, such as Humanitarian OpenStreetMap Team (HOT), OpenStreetMap (OSM), IDEAMAPS, and Know Your City (KYC of SDI), could further augment the availability and diversity of data.

On addressing the enabling factors for policy uptake by Partner Countries, EU Delegations and INTPA HQ, the recommendations for improved Copernicus products and services include the promotion of:

- [Access and capacity needs] Integrating hazard, exposure, and vulnerability data within an indicator-based reporting system would enable the quantification and visualization of the economic losses, quantifying affected populations and infrastructure, health impacts, and biodiversity loss (aggregated to multiple spatial scales). Such a system would facilitate more informed adaptation planning. Incorporating scenarios for adaptation planning would foster the development of nature-based and ecosystem-based strategies (encompassing both blue and green solutions), with an emphasis on bottom-up approaches. These strategies would be tailored to leverage local capacities and conditions (avoiding 'one-size-fits-all' solutions). This approach ensures that adaptation plans are both effective and context specific.
- [Applications – use cases] To enhance the uptake of existing products tailored to Copernicus (hazard, exposure, and vulnerability), services are required to give access to hazard, exposure and vulnerability products. This should be in the form of interactive data portals that allow viewing, overlaying, analysing, and visualising products (including downloading of data layers for expert users). Such data portals need to be combined with application cases (user stories) to provide examples that relate to the application's need and show existing data products or methods. For each application case and use case example will be used to:
    - Demonstrate how EO data can be used by policymakers (indicators, dashboards).
    - Combining EO with other Geospatial data (e.g., deprivation models Figure 25).
    - Guidance on ethics and privacy concerns and biases in existing datasets, such as data gaps in most vulnerable areas (e.g., Figure 28).
    - Increased data coverage of the Copernicus services in LMICs on humanitarian data and emergency responses (e.g., as part of the Copernicus Emergency Management Service) (e.g. Figure 30).

- [Data formats] While high-resolution data is frequently unavailable LMIC cities, there is an abundance of data that could be beneficial for policymaking. However, this data is often not easily accessible for actors in INTPA's partner countries (in particular for non-EO experts). To bridge this gap, user-friendly portals and interactive web-based applications are essential. These tools should offer easily downloadable information tailored to the needs of non-EO experts, such as the ability to print maps and infographics or download statistics. Similarly, they should cater to EO experts by supporting downloads in standard data formats. Additionally, there should be an emphasis on ensuring consistency in geographic projections to maintain the usability and reliability of the data across various user groups.

7 Conclusions and recommendations

This urban climate adaptation deep dive assessment has allowed us to further refine the deep dive protocol established within the KCEO. Concerning the overall exercise and the methodology followed, the steps envisaged proved to be a good way of organising the analysis in a structured and efficient way, also maintaining a "technologically agnostic" approach in the first parts when assessing the needs and the quantitative requirements of the users.

As in the previous deep dive on biodiversity a fundamental conclusion is that for an efficient uptake of EO technology in support of EU policy, sustained assistance to cover the "last mile", so as to precisely tailor the products or applications to the specific request, is unavoidable. This is particularly true for the topic of Urban Climate Adaptation. There is a systematic need for multi-scale tools for many stakeholders and different policy use cases.

The recommendations resulting from this assessment and the gaps identified fall into two broad categories. There are recommendations that have been identified through specific use cases and that, if addressed, would incentivise the uptake of Earth Observation-based intelligence in those areas. These recommendations are included in the final section of each use case in Chapter 6. Then, there are general recommendations that are either overarching or recurrent across different use cases, address recommendations concerning the indicators, Missions or international dimensions, or have generally emerged in the context of this assessment. These recommendations are summarised below.

1. **Development of highly synthesised intelligence services providing actionable information to key user archetypes**

   The current inability of policy-relevant user archetypes to access useable and actionable EO-derived intelligence has been repeatedly identified as a primary constraint with regard to effective use of EO in the policy cycle. From a value chain perspective, this is reflected as a lack of sufficiently synthesised EO-derived intelligence, co-designed dashboard-type platforms, and pro-active community engagement and development initiatives. A range of expert Decision Support Services, developed through iterative co-design, are needed to realise the full value of currently underexploited EO capabilities to the adaptation community. These should take the form of user-friendly, web-based dashboards that integrate and assimilate all the available information into specific, quantitative, measurable, and standardized indicators. This is mandatory to give policymakers and local authorities (as non-EO experts) simple but powerful tools to make evidence-based decisions and evaluate *ex post* impacts of their policies**. It is recommended that the European Commission supports the necessary Research and Innovation activities needed to increase the effectiveness of climate-focused Decision Support Systems** - incorporating typologies of actual quantified, characterised use into emerging intelligence systems has the potential to greatly enhance the value and actionable use of climate-focused intelligence systems.

2. **Enabling policy-focused use of standardised, quantitative EO-derived adaptation indicators for legislative uptake in Member States and the European Commission**

   Current evaluation capabilities for adaptation policy implementation are immature, with a lack of standardised indicators, coupled to underdeveloped reporting implementation and documented best practices, especially regarding the outcomes of climate action. Objective, standardized, observation-based, actionable indicators should be a central tenet of adaptation monitoring and evaluation processes. These would also greatly facilitate policy-related adaptation design: defining the baseline, offering the provision of clearly quantified risk through the hazard/vulnerability/exposure nexus; and through the setting and monitoring of appropriate adaptation targets. Earth Observation is currently poorly exploited for climate adaptation due to an under-developed value chain - such EO-derived indicator frameworks have a critical role to play in the monitoring, evaluation and reporting needed for more effective adaptation design and impact. **It is recommended that the European Commission, together with the Copernicus Entrusted Entities, build on the current Core Services to derive highly synthesised EO-derived compound indicators** that represent the interface between intelligence and policy, particularly able to address the important vulnerability dimension of climate adaptation. They have considerable potential value in addressing the current lack in systematic application of formalized, consolidated EU-standard set of adaptation indicators. EO-derived indicators can offer a harmonised framework of standardised metrics, enabling optimal systems for adaptation monitoring, reporting and evaluation. They also offer capabilities for automated reporting mechanisms based on systematic assessment and standardised evaluation metrics, with potential to dramatically reduce reporting overhead for both Member States and the Commission.

3. Provision of dynamic hazard-specific combined risk products and services across a range of time scales

The need for greater availability of dynamic hazard, vulnerability, exposure and combined hazard-specific risk products across a range of time scales is repeatedly identified across the use cases. Such intelligence - ideally derived using a combination of Earth Observation and socio-economic data - should be presented in climatology, phenology and near real-time forms, with the additional provision of appropriate user-driven analytics, e.g. hazard/risk thresholding. Combined risk indicators, based on recognised and standardised approaches, need to be made available in an appropriate range of metrics for key user archetypes, e.g. potential or realised economic damage; population displacement; public health risks and other suitable key indicators. **It is important to highlight the importance of providing vulnerability and exposure metrics as dynamic continuum parameters. It is recommended that the relevant Entrusted Entities should take this into consideration. For example, the timescale continuum synergies between the C3S and the real-time elements of the CEMS and the global component of the CLMS. As well as** components of existing Copernicus Land Monitoring and other services, e.g. Urban Atlas, suites of land cover and green cover products, should be further developed with the ideal goal of annual update cycles (plus one-year latency) for greater dynamic coverage of vulnerability and exposure components.

4. Provision of automated change detection products and services to identify combined risk changes

There is substantial value in the operational provision of automated change detection for assessing changes in exposure and vulnerability in dynamic urban areas or for critical infrastructure/assets. There is also considerable semantic value to automated adaptation monitoring and reporting of key LC/LU classes, and arguably such a capability would significantly increase Copernicus' benefit to a wide range of user archetypes. **It is recommended that the Commission and Entrusted Entities consider a systematic and consistent approach to change detection across Copernicus Services and further develop existing relevant change detection products** in the Copernicus services, e.g. Tree Cover Change Mask, Urban Atlas Land Cover/Land Use Change, Imperviousness Change, Imperviousness Classified Change, should focus on an ideal goal of annual update cycles. This is crucial for highlighting urban hot spots and sub-annual land use changes, thus focusing and prioritizing additional high/very-high resolution data collection, e.g. through "tip and cue" acquisition of Copernicus Contributing Missions.

5. Facilitate and implement capabilities for city-based adaptation scenario modelling

The value and need for advanced adaptation scenario modelling capacity for European cities is repeatedly identified across the use cases. Policy-driven adaptation measures require significant investment, and scenario models - coupled to key indicators - provide a critically needed ability to evaluate the potential effectiveness of available adaptation measures from a cost/benefit perspective. Such models also provide the ability to assess the combined risk and benefits of improved resilience across a likely range of future climate-driven hazards, coupled to adaptation scenarios. **It is recommended that the relevant Commission DGs (DEFIS, CNECT) should consider how the combined contributions from Copernicus and Destination Earth programmes can help to support this effort.** The more widespread use of such models, with city-level scaling, is now considered technically feasible and (beyond EO-derived vulnerability and exposure parameters) requires the use of emerging urban land surface temperature models and flood adaptation models, such as UrbClim and FloodAdapt. The uses cases demonstrate that evidence-based and coherent networks of connected nature-based solutions are most effective in mitigating urban floods and heat island effects and thus enhancing urban adaptation to climate change. Enabling a network of cities to utilise Decision Support Systems, scaling as needed to address the bane of resource-poor municipalities while allowing for local particularities and with a strong focus on the collaborative use of standardised adaptation scenario tools, would greatly facilitate policy-driven adaptation.

6. Optimised integration of EO-derived intelligence with Eurostat and socio-economic data

Optimised vulnerability and exposure parameters rely on the integration of EO-derived Land Cover/Land Use information with socioeconomic data, typically from Eurostat. Expanding the process already initiated through the recent Implementing Act of the High-Value Dataset ([121]) and the dissemination in gridded form of the 2021 census would have significant value. A closer match between Eurostat's granularity and extent and the spatial resolution of EO-derived products will significantly improve risk and resilience analysis at the municipality scale, thanks to the ability to systematically integrate EO products with Eurostat statistical data. Global and European definitions on administrative units and urban areas/extent are designed for statistical purposes. Accordingly, territorial units (e.g. NUTs or LAUs) have different sizes and include different numbers of inhabitants. Thus, they have a variable scale. When assimilating Copernicus products and services with other socio-economic data, if the latter information were available as grids with a higher spatial resolution (and also higher than actual Eurostat grids, when available) would significantly improve dynamic vulnerability and exposure parameters, bringing the socio-economic dimension into routine risk models.

7. Developing & supporting an adaptation intelligence community

The effective development, implementation and uptake of EO-derived adaptation intelligence systems is strongly dependent on the creation of an active, coherent, adaptation planning community - driven by strong user co-design principles and including a range of user archetypes, scientists and service providers. The Missions have an important role to play here: through the Adaptation Mission and optimisation of the Adaptation Dashboard; facilitating monitoring and reporting co-benefits of the Cities Mission; and contributing to

([121]) https://eur-lex.europa.eu/eli/reg_impl/2023/138/oj convergence of the Missions knowledge bases. **It is recommended that the relevant Commission DGs take action to enable the best EO-derived Intelligence through the Mission processes**. Realising full value of the currently underexploited EO-derived intelligence offering requires community-driven, aspirational, co-designed Decision Support systems, with a strong focus on the collaborative use of adaptation analysis tools and establishing best practice.

8. Systematic acquisition and integration of very high-resolution optical imagery for urban area intelligence

Several use cases highlight the need for intelligence based on a higher spatial resolution than that offered by the Sentinel 2 missions (<10 m spatial resolution), with significant value for mapping detailed urban morphology, infrastructure, urban greening and land use patterns. Systematic, targeted access to data of VHR2 (Very High Resolution 2) spatial resolution of < 5m for the VIS/NIR bands would be of substantial benefit. Further integration of such data from Copernicus Contributing Missions into Copernicus products and services would be highly beneficial and could be accommodated at a relatively low cost using the "tip and cue" approach discussed in Recommendation 4 above. **It is recommended that the European Commission (DG DEFIS) and the European Space Agency take this into consideration in future planning for the Copernicus Contributing Missions programme element, and that the Commission and Member States consider this for future space segment evolution planning.**

9. Establishment of a Thematic Hub for Urban Climate Adaptation

The need for adaptation solutions for less-specialized stakeholders are commonplace throughout this assessment. There are a range of emerging platforms addressing components of this democratization process including the Climate Data Explorer, the European Climate and Health Observatory, ClimateAdapt and the Urban Adaptation Map Viewer. There would be significant benefit to the formation of a coherent Copernicus Thematic Hub on Urban Climate Adaptation, or on Urban aspects more generally, supporting the aforementioned adaptation intelligence community and leading to a more coherent and effective exploitation of EO as outlined in the above recommendations, with the inherent EU-wide harmonization it brings. This would include the promotion of systematic production and uptake of flagship climate adaptation indicators for urban areas using the KTM framework and in collaboration with the EEA. It would also greatly facilitate the standardisation and internal consistency required to address indicator and stakeholder needs across the municipal – member state – EU – global scales required. **It is recommended that the European Commission and Entrusted Entities include a Thematic Hub on Urban issues on the roadmap for future consideration.**

10. Facilitate the use of Destination Earth to develop more actionable intelligence and cater for policy-relevant audiences with "last-mile" applications

Destination Earth is an appropriate platform to provide a common framework for the provision of the policy-relevant indicators and actionable intelligence services described above. The Destination Earth digital twins, specifically the climate adaptation digital twin and weather-induced extremes digital twin, in conjunction with information from the European Data Spaces ecosystem provide significant potential to realise the necessary extension of the EO value chain (see Recommendations 1 to 7). Coupled to the predictive and early warning capabilities of the Destination Earth platform, this would provide policymakers and local authorities, as non-EO experts, simple effective tools to make better decisions and evaluate ex post impacts of their policies. The identification of user needs – most specifically around key type measure focused decision making - is an important first step in supporting the co-design of tailored services for EC policymakers. In this regard, Destination Earth could also identify and synthesise the range of end user needs for the adaptation community, and translate them into implementable requirements.

11. Expansion of Copernicus urban-relevant services to global

Whilst many of the urban facing Copernicus services have emerging relevance to European urban centres from a scale perspective, the same is not true in the developing world. The granularity and accuracy of global products need to be relevant at the city scale, e.g. to provide high-resolution global ready-to-use risk products to support evidence-based policymaking at the scale of cities. An expansion of Copernicus products and services, or a contribution of Copernicus capabilities to emerging global initiatives under WMO or GEO that provide global coverage, would have considerable value to support sustainable urban development and climate change adaptation outside European borders, but within European areas of geopolitical and socioeconomic interest. Global scaling needs to be sensitive to addressing the needs of resource- and data-poor developing world urban centres, while allowing for the fullest exploitation of local intelligence and capabilities. Urbanization dynamics are fast and complex in most Low-and-Middle-Income Countries (LMICs), while local data are often dated or patchy. To bridge the information asymmetry between Global North and South, and within the Global South context between primary and secondary cities, facilitating or contributing to a global urban data service is highly recommended, and to be considered by the European Commission and Entrusted Entities in partnership with international peers (e.g. WMO, GEO, UN Habitat).

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List of abbreviations and definitions

AN	Application Needs
C3S	Copernicus Climate Change Service
CAMS	Copernicus Atmosphere Monitoring Service
CCC	Climate City Contract
CCM	Copernicus Contributing Missions
CDR	Carbon Dioxide Removal
CEMS	Copernicus Emergency Management Service
CEOS	Committee on Earth Observation Satellites
CEP	City Energy Plan
CLMS	Copernicus Land Monitoring Service
CMEMS	Copernicus Marine Environment Monitoring Service
CoM	European Covenant of Mayors
COP	Conference of the Parties
CPR	Common Provisions Regulation
CRF	Common Reporting Framework
CSS	Copernicus Security Service
CURE	Copernicus for Urban Resilience in Europe
CWRA	City water resilience assessments
DEFIS	Defence Industry and Space
DEGURBA	Degree of urbanisation
DG	Directorate-General
DHS	Demographic and Health Surveys
EEA	European Environment Agency
EGD	European Green Deal
EGNOS	European Geostationary Navigation Overlay Service
EMODNET	European Marine Observation and Data Network
EO	Earth Observation
EUDs	European Union Delegations
EUSPA	European Union Agency for the Space Programme
GCoM	Global Covenant of Mayors
GEO	Group on Earth Observations
GGA	Global Goal on Adaptation
GHG	Greenhouse gases
GHSL	Global Human Settlement Layer
HE	Horizon Europe
ICLEI	Local Governments for Sustainability (originally International Council for Local Environmental Initiatives)
IPCC	Intergovernmental Panel on Climate Change
KCEO	European Commission Knowledge Centre on Earth Observation
KTM	Key Type Measure
LC/LU	Land Cover / Land Use
LMICs	Low- and Middle-Income Countries
MS	Member States
NAP	National Adaptation Plans
NDC	Nationally Determined Contributions
NIR	Near-infrared

RCN	Resilient Cities Network
SECAP	Sustainable Energy and Climate Action Plan
SUMP	Sustainable Urban Mobility Plan
UHI	Urban Heat Island
UNFCCC	United Nations Framework Convention on Climate Change
VIS	Visible
WMO	World Meteorological Organization

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Appendices

Appendix 1: Consolidating and categorising indicators

Appendix 1A: Methodology for consolidating frameworks

An initial inventory of more than 130 indicator frameworks from the EEA, with additional frameworks from authoritative sources to ensure appropriate thematic coverage, were filtered to yield a manageable, urban-focused indicator compilation. The initial list of top-down indicator frameworks provided by the EEA necessitated a heavy filtering process in order to create a targeted and manageable compilation of indicators for it to be exploited in this assessment especially as regards the urban focus. While the filtering perspective was infused by the objectives of this assessment, the final set of frameworks comprises a wide and encompassing corpus of city-relevant indicators that echo both the inherent complexity of the urban environment and the previous discussion on the interplay of the climate change aspects and the many dimensions of vulnerability. Apart from filtering, some additional frameworks were considered and included, coming from authoritative EU sources and enriching the thematic breadth of the list. Lastly, each of the consolidated indicators derived from this process was categorized/mapped in an analytical spreadsheet file (see Kilsedar et al. (2024)).

Regarding the filtering step, frameworks that lacked an urban focus or were too wide in scope (such as the Essential Climate Variables or quality of life-type indicators) were removed. Frameworks that were clearly targeting other sectors/domains (e.g. biodiversity, agriculture) were also removed, as were purely process-based frameworks, following the Covenant of Mayors for Climate & Energy discussion in the main text. Lastly, frameworks coming from particular cities, mostly outside Europe, were not retained - barring two, to serve as examples of a detailed (pragmatic) breakdown of a city (Boston) preparedness to climate change and of minimum Regional-level disaggregation of information (Vermont). Two frameworks hailing from the standardization community (ITU-T and ISO) were deemed critical as their integrated approach to the Smart and Sustainable City paradigm is fully aligned with the multi-dimensional nature of risk and vulnerability and of course link directly to the Smart City Mission. The last framework retained was a publication from GIZ (which provided us with the main understanding of the AR5 approach) as an early, manifestation of monitoring and evaluation systems (Hammill et al., 2014).

The addition step entailed a review of publications coming from European Topic Centres (ETCs) which are consortia of organisations in EEA member countries with expertise in specific environmental areas and contracted by the EEA to support the implementation of the EEA work programmes. The repository in the Eionet portal ([122]) was explored and two more frameworks were added (from the ETCs of on Climate Change Impacts, Vulnerability and Adaptation / on Spatial Information and Analysis and the ETC on Land and Soil Systems). ETC publications regarding justice perspectives of climate adaptation were considered but ultimately not included as the subject was not explicitly flagged in this assessment. Following the growing discussion on the health-climate nexus, receiving heightened attention among others in COP26's "WHO: Health Argument for Climate Action" (WHO, 2021) and a watershed moment in this year's COP28 ([123]), the specialized framework found in the Lancet Countdown on health and climate change (Romanello et al., 2022) was added

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([122]) Repository in the Eionet portal

([123]) https://www.who.int/teams/environment-climate-change-and-health/climate-change-and-health/advocacy-partnerships/talks/health-at-cop28 as a dedicated entry addressing this nexus. Another entry came from the DG MARE Use Case (Rouleau et al., 2022) offering unique coastal specific indicators that were otherwise missing and, lastly, the recently published by JRC technical report “Towards a European wide vulnerability framework” (Eklund et al., 2023) provided a set of 43 vulnerability indicators which belong to four dimensions (social, economic, political and environmental) at different administrative levels. It is noteworthy that this last JRC framework will be adopted by EEA regarding the vulnerability part of the Adaptation Dashboard as well as the CLIMAAX project (as presented in the Mission on Adaptation webinar in January 2023 ([124])).

Appendix 1B: Description of the indicators inventory

The output of the Indicator consolidation process yielded 8 frameworks hailing from different domains and points of view regarding Climate Change Adaptation comprising in total 511 Indicators that have been also categorized and 4 more frameworks with hundreds of indicators which have not. This Appendix gives further technical detail on the supplementary indicator material provided in (Kilsedar et al., 2024), which contains the full list of indicators in spreadsheet format.

FrameworkID is the unique identifier of the database and Framework the actual name. The next column is the Provider of the framework. The Indicator name has been left largely intact (including the numbering) for traceability back to the original source which can be found through the links in the tab of the spreadsheet file “Framework IDs and URLs”. Some indicators are relatively straightforward but a search in the original source may be necessary or even beneficial for deeper comprehension of a particular framework/indicator as its name may be misleading or not intuitive.

The frameworks in the tab “Framework IDs and URLs” in orange have not been categorised but have been retained for completeness and potential ad hoc utilization. “Evaluating the impact of nature-based solutions - A handbook for practitioners” (EC: DG RTD, 2021) was included as it epitomizes the EC perspective as formed by relevant research projects, at least regarding monitoring of outcome. It has 12 dimensions in total with recommended and additional indicators. The numerous indicators were not categorized as it was considered more meaningful to exploit particular indicators on a per project basis. The framework “VulneraCity - The urban vulnerability drivers database” was produced by the myriad_eu project ([125]) and again, an ad hoc approach regarding the uptake of the vulnerability indicators of the database (Stolte et al., 2023) is suggested.

The needs of the DGs were captured by initial and follow-up discussions that drove the categorization in the DG Relevance in the KCEO Deep Dive which should be considered the most subjective one as it does not take into account the refined needs and it was decided to err on the false positive-side, i.e. indicators are considered relevant (green) but this is not the case for the DG. This DG influence further impacts the categorization of the Risk components. As an example, while green areas reduce vulnerability of the population by decreasing sensitivity (against heat, floods etc. as described in Eklund et al. (2023) they are exposed to fire especially in peri-urban areas. This ambivalence is the trade-off of taking into account all DG needs and refraining from performing impact chain analysis (hazard specific and very detailed) while following its general methodology.

The Key Type Measure columns were added to align with this EEA-sanctioned method of reporting adaptation action and the bottom-up inventorying process discussed above (where indicators are also mapped against the KTMs). The sub-KTMs utilised were extracted from the Reportnet 3 ([126]) new e-Reporting platform (under any country's "Reference data.zip"). An indicator was deemed

([124]) https://climate-adapt.eea.europa.eu/en/mission/events/how-to-assess-climate-change-risks-and-vulnerabilities

([125]) https://www.myriadproject.eu/library/

([126]) https://reportnet.europa.eu/public/dataflow/110 pertinent to a sub-KTM when it relevant for monitoring the presence of KTMs, for designing KTMs and for monitoring the outcomes of KTMs. As is the spirit of the categorization, it was decided to err on the inclusive side and this also echoes the acknowledgement by the KTM community that several adaptation options and measures can, in principle, fall within multiple categories and be described using multiple attributes (however, unlike here, in the case of Member States the most suitable option must be selected). The last two columns are Climate Change Impact and Adaptation Action Outcome. Impact is considered as the realization of the Risk and the outcome as the results of climate action, i.e. implementation of sub-KTMs. The outcome is limited to the most attributable results. As an example, the green area indicator is suitable for describing the outcome of Green options measures (D1 sub-KTM) but the Costs of heat-related mortality (which green areas reduce) is not as it involves several other parameters and it is difficult, if not impossible, to attribute the effect of the particular adaptation measure.

In full transparency, the KCEO brief reasoning or the datasets themselves are included for each of the 217 EO indicators. The reasoning is not exhaustive as other EO resources may exist for a particular indicator. This allows traceability and it also provides the user a jumping-off point to explore further the potential EO holds for a particular line of inquiry/indicator.

Appendix 2: Data, product and service resources for urban climate adaptation

This Appendix provides supplementary information on data, products, and services identified in the use cases for this deep dive assessment.

Copernicus data, products and services

Copernicus Land Monitoring Service

Urban Atlas

Copernicus Urban Atlas ([127]) of Copernicus Land Monitoring Service (CLMS) provides information on detailed land cover/land use maps for 788 Functional Urban Areas (FUAs) across Europe, in addition to street tree maps, building block height measurements, and population estimates.

Among Copernicus Urban Atlas of CLMS, the following products are potentially interesting for this use case:

- Urban Atlas Land Cover/Land Use: provides land cover and land use for 17 urban classes with a Minimum Mapping Unit (MMU) of 0.25 ha and 10 rural classes with an MMU of 1 ha (only 2 rural classes for 2006). The dataset is available as vector data for 2018 and 2012 with the integrated population estimates in 788 FUAs with more than 50,000 inhabitants in EEA38 countries and the United Kingdom (only 785 FUAs for 2012), and for 2006 but limited to 319 FUAs with more than 100,000 inhabitants in EU member states. The product is updated every 6 years and has a higher spatial detail (granularity) than the CORINE Land Cover;
- Urban Atlas Street Tree Layer: provides a separate layer of Urban Atlas showing contiguous rows or patches of trees covering 500 m^2 or more and with a Minimum Mapping Width of 10 m over Artificial surfaces inside each Functional Urban Area. The product is updated every 6 years and has a higher spatial detail (granularity) than the CORINE Land Cover.
- Urban Atlas Building Height: provides height information at high spatial resolution (10 m) for core urban areas in 870 European cities. The dataset is available as raster data for the 2012 reference year and has no defined update frequency. This information could be used to estimate the urban canyon effect that contributes to Urban Heat Island.

High Resolution Layer Tree Cover Density

High Resolution Layer Tree Cover Density ([128]) of Copernicus Land Monitoring Service (CLMS) provides information on the percentage of tree cover at the pan-European level.

The product is available from 2012 and has a three years update cycle (at the time of writing, the latest product is 2018). The spatial resolution ranges from 10 m (for the 2018 product) to 20 m (for the 2012 and 2015 products) to an aggregate 100 m (for all the products). It is to be

([127]) https://land.copernicus.eu/en/products/urban-atlas

([128]) https://land.copernicus.eu/en/products/high-resolution-layer-tree-cover-density mentioned that the additional High Resolution Layer Dominant Leaf Type and High Resolution Layer Forest Type products are available on request.

Vegetation

Copernicus Vegetation ([129]) of Copernicus Land Monitoring Service (CLMS) provides a collection of datasets designed to provide analysis of vegetation, updated yearly.

Among Copernicus Vegetation of CLMS, the following products are potentially interesting for this use case:

- Vegetation Properties/Fraction of Green Vegetation Cover: quantifies the spatial extent of the vegetation at the global scale. It is available since 2014 as 10-daily observations at the highest spatial resolution of 300 m;
- Vegetation Indices/Fraction of Absorbed Photosynthetically Active Radiation: provides in near-real-time updates of the fraction of the solar radiation absorbed by live leaves for the photosynthesis activity at pan-European level. Since 2016, the data are available at the highest spatial resolution of 10 m. A second product is available since 2014 as 10-daily observations at the highest spatial resolution of 300 m;
- Vegetation Indices/Leaf Area Index: provides in near-real-time updates of the fraction of the leaf area index at pan-European level. Since 2016, the data are available at the highest spatial resolution of 10 m. A second product is available since 2014 as 10-daily observations at the highest spatial resolution of 300 m;
- Vegetation Indices/Normalised Difference Vegetation Index: provides daily updates of the normalised difference vegetation index at pan-European level. Since 2016, the data are available at the highest spatial resolution of 10 m. A second product is available since 2014 as 10-daily observations at the highest spatial resolution of 300 m;
- Vegetation Indices/Plant Phenology Index: provides daily updates of plant phenology Index (a vegetation index for improved monitoring of plant phenology) at pan-European level and in near-real-time. The product is available since 2016 with 10 m spatial resolution.
- Vegetation Indices/Start-of-season Date: provides the date when the vegetation growing season starts with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/End-of-season Date: provides the date when the vegetation growing season ends with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Season Amplitude: provides the difference between the maximum and minimum Plant Phenology Index values reached during the season. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Season Minimum Date: provides the date in the vegetation growing season when the maximum Plant Phenology Index value is reached. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.

([129]) https://land.copernicus.eu/en/products/vegetation

- Vegetation Indices/Season Minimum Value: provides the average Plant Phenology Index value of the minima before the growing season. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Season Maximum Date: provides the date in the vegetation growing season when the maximum Plant Phenology Index value is reached. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Season Maximum Value: provides the peak value that the Plant Phenology Index reaches during the vegetation growing season. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Slope of the Green-up Period: provides the rate of change in the values of the Plant Phenology Index at the day when the vegetation growing season starts. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Slope of the Green-down Period: provides the rate of change in the values of the Plant Phenology Index at the day when the vegetation growing season ends. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Seasonal Productivity: provides the sum of all daily Plant Phenology Index values between the dates of the season start and end, minus their base level value. The data are available at the pan-European level, with a spatial resolution of 10 m and temporal extent from 2017.
- Vegetation Indices/Dry Matter Productivity: provides the overall growth rate or dry biomass increase of the vegetation. From 2014, the data are available as 10-daily observations at the global scale, with a spatial resolution of 300 m.
- Vegetation Indices/Gross Primary Production: provides the total amount of carbon compounds produced by photosynthesis of plants in an ecosystem in a given period of time. This is a new product of 2023, available as 10-daily observations at global scale in the spatial resolution of 300 m.
- Vegetation Indices/Net Primary Production: provides the amount of carbon retained in an ecosystem (increase in biomass). This is a new product of 2023, available as 10-daily observations at global scale in the spatial resolution of 300 m.

High Resolution Layer Small Woody Features

The Small Woody Features ([130]) of Copernicus Land Monitoring Service (CLMS) are thematic layers that include herbaceous features like hedgerows, shrubs, and small clusters of trees. These green structures help regulate the water cycle, prevent soil erosion and enhance biodiversity.

Small Woody Features are produced from very high-resolution optical satellite images and describe linear structures whose width is ≤ 30 m and length is ≥ 30 m, as well as patchy structures whose area is between 200 m^2 and 5000 m^2. The data are available for 2015 and 2018 in 5 m spatial resolution and aggregated 100 m spatial resolution. The update is planned every 3 years.

([130]) https://land.copernicus.eu/en/products/high-resolution-layer-small-woody-features

Although not specifically designed for urban areas, Small Woody Features could complement Urban Atlas Land Cover/Land Use and Urban Atlas Street Tree Layer.

CORINE Land Cover

The CORINE Land Cover ([131]) is Europe's primary information source for land cover/land use.

The inventory contains 44 land cover classes with a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena. Nine urban land cover classes are pertinent to this use case. The available time series (1990, 2000, 2006, 2012, and 2018) are complemented by layers highlighting changes in land cover with an MMU of 5 ha.

This product could be used to fill any gaps of the higher resolution Copernicus Urban Atlas, High Resolution Layer Imperviousness, and High Resolution Layer Impervious Built-up products that should be used preferentially.

CORINE Land Cover+ Backbone (CLC+ Backbone)

The CORINE Land Cover+ Backbone ([132]) is part of the new products and applications, known as CLC+, which serves to complement and extend the current CORINE Land cover product.

The CLC+ Backbone provides a detailed pan-European wall to wall geometric vector reference layer with 18 basic thematic classes and 0.5 ha Minimum Mapping Unit (MMU), and an 11-class 10 m spatial resolution raster product. It is currently available only for year 2018 and has a three year update cycle.

Riparian Zones

Riparian zones ([133]) of Copernicus Land Monitoring Service (CLMS) describe the buffer regions between land and waterways that help filter pollutants from the water, regulating floods and increasing soil health. Riparian zones play a critical role in local climate regulation by providing cool, moisture-rich, shaded areas to surrounding ecosystems. This product could be used to monitor floodplain characteristics and sensitive ecosystems. It also provides information on waterways and the restoration of freshwater ecosystems.

Riparian zones are identified using very high-resolution optical satellite images and other available data. The classification, available for 2012 and 2018, provides 55 distinct classes with a Minimum Mapping Unit (MMU) of 0.5 ha and a Minimum Mapping Width (MMW) of 10 m. The update is planned every 6 years.

Although not specifically designed for urban areas, riparian zones could complement Urban Atlas Land Cover/Land Use and Urban Atlas Street Tree Layer with a dedicated mapping for urbanised areas around rivers and streams.

Coastal Zones

Coastal Zones ([134]) of Copernicus Land Monitoring Service (CLMS) provide 71 distinct thematic classes for the coastal territory to an inland depth of 10 km. This layer is helpful for coastal ecosystem management (e.g., identifying areas that require conservation), land-use planning (e.g., in

([131]) https://land.copernicus.eu/en/products/corine-land-cover

([132]) https://land.copernicus.eu/en/products/clc-backbone

([133]) https://land.copernicus.eu/en/products/riparian-zones

([134]) https://land.copernicus.eu/en/products/coastal-zones areas with competing resource demands), and disaster management (e.g., forecasting the impact of storms and flooding).

Coastal Zones are generated using very high-resolution optical satellite images and other available data. The classification is available for 2012 and 2018 with a Minimum Mapping Unit (MMU) of 0.5 ha and a Minimum Mapping Width (MMW) of 10 m. The update is planned every 6 years.

Although not specifically designed for urban areas, riparian zones could complement Urban Atlas Land Cover/Land Use and Urban Atlas Street Tree Layer with a dedicated mapping for urbanised areas close to the sea.

High Resolution Layer Imperviousness

High Resolution Imperviousness data ([135]) are available from 2006 to 2018 (update frequency 3 years) and contain the following products:

- Status layers: describes the percentage of sealed area at 10 m spatial resolution (2018), 20 m spatial resolution (2006-2015), and as aggregated 100 m datasets.
- Change layers: for each of the 3-year periods between the 5 reference years (2006-2009, 2009-2012, 2012-2015, 2015-2018) are available the following change products:
    - The percentage of sealing increase/decrease for pixels with real sealing change in the period covered. This product is available at 20 m and 100 m spatial resolution.
    - Most relevant categories of sealing change (e.g. unchanged no sealing, new cover, loss of cover, unchanged sealed, increased sealing, decreased sealing). This product is available at 20 m spatial resolution.

High Resolution Layer Impervious Built-up

The High Resolution Layer Built-Up ([136]) provides a detailed overview of built-up areas across Europe. The product shows built-up areas, the part of the sealed surfaces where buildings can be found, as a sub-group of the sealed areas. However, in contrast to the High Resolution Layer Imperviousness product which describes the continuous range of imperviousness measurements, the High Resolution Layer Built-Up is a binary map of built-up vs non-built-up.

This new product for the 2018 mapping campaign is fully harmonised with the High Resolution Imperviousness dataset and is available at 10 m and 100 m (the Share of Built-up) spatial resolutions.

Natura 2000 (N2K)

Natura 2000 ([137]) delivers an overview of grassland-rich Natura 2000 protected sites under the European Union's Habitats Directive. The layers are generated using very high-resolution optical satellite images and are available for 2006, 2012 and 2018, updated every 6 years. This product provides 55 distinct thematic classes with a Minimum Mapping Unit (MMU) of 0.5 ha and a Minimum Mapping Width (MMW) of 10 m.

([135]) https://land.copernicus.eu/en/products/high-resolution-layer-imperviousness

([136]) https://land.copernicus.eu/en/products/high-resolution-layer-impervious-built-up

([137]) https://land.copernicus.eu/en/products/n2k

Land Surface and Lake Surface Water Temperature

The Copernicus Land Monitoring Service provides the following Land Surface Temperature (LST) at 5 km spatial resolution ([138]):

- Hourly LST from geostationary sensor observations: The data are available from 2009 to the present;
- Statistical overview of LST daily cycle for each 10-day compositing period. The data are available from 2016 to the present;
- Thermal Condition Index. Provides a statistical overview of LST over each 10-day compositing period regardless of any specific hour. The data are available from 2017 to the present.

In addition, the Copernicus Land Monitoring Service provides the following Lake Surface Temperature (LST) at 1 km spatial resolution:

- Historical LST observations from 2002 to 2012;
- The near real-time observations from 2016 to the present.

Water Bodies

Copernicus Land Monitoring Service (CLMS) Water Bodies products ([139]) support applications like food security, public health safeguarding, climate studies, and responsible water management practices. The dataset includes:

- Water Bodies: shows areas covered by inland water and provides the maximum and the minimum extent of the water surface. Ten-daily data are available at the global scale with a spatial resolution of 300 m, while monthly updates are available at the global scale with a spatial resolution of 100 m and 300 m. The temporal extent ranges from 2020 to the present.
- River and Lake Water Level: provide water level (above the geoid) as observed by space radar altimeters. The data at the global scale are available in near real-time from 1992 for lakes and from 2002 for rivers.
- Lake Water Quality: provide a semi-continuous observation record for about 4,200 medium and large-sized lakes (turbidity, trophic state). Ten-daily observations are available in near real time since 2002 in the spatial resolution of 300 m, and since 2019 in the spatial resolution of 100 m.
- River and Lake Ice Extent: provide daily information on the area of snow-free or snow-covered ice. The data are available at a pan-European scale in 20 m spatial resolution from 2016 to the present. Northern Europe freshwater bodies are mapped with 250 m spatial resolution since 2017.

([138]) https://land.copernicus.eu/en/products/temperature-and-reflectance

([139]) https://land.copernicus.eu/en/products/water-bodies

Copernicus Marine Service

Mediterranean Sea Physics Analysis and Forecast

The Mediterranean Sea Physics Analysis and Forecast of Copernicus Marine Service ([140]) implements the coupling of the physical component of the Mediterranean Forecasting System (Med-Physics) with the hydrodynamic-wave model implemented over the Mediterranean Basin. The spatial resolution is about 4 km.

Mediterranean Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis

The Mediterranean Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis ([141]) provides daily gap-free maps of the sea surface temperature at high (0.0625°) and ultra-high (0.01°) spatial resolution by combining nighttime images collected by different thermal infrared sensors.

Copernicus Emergency Management Service

Risk and Recovery Mapping

The Copernicus Emergency Management Service (CEMS) provides information for emergency response in relation to different types of disasters, including meteorological hazards, geophysical hazards, deliberate and accidental man-made disasters and other humanitarian disasters, as well as prevention, preparedness, response and recovery activities. It covers the prevention, preparedness, disaster risk reduction, and recovery phases.

The Risk and Recovery Mapping provides locally relevant information at the city and regional levels, which helps support the cost-benefit analysis of major investment projects for disaster prevention and climate change adaptation.

Among the Risk and Recovery Mapping Portfolio of CEMS ([142]), the following products are potentially interesting for this use case:

- P04 Flood delineation: the product provides a comprehensive assessment of flood events, delivering information on flood extent and water depth for coastal and inland events. The area of interest is between 25 km^2 and 500 km^2, the minimum mapping unit is 2,500 m^2, and the scale/resolution is 1:25,000.
- P05 Modeled flood extent for major events: the product provides modelled, simulated flood extent information about the flood based on estimated discharges and water levels using statistical methods or modelling of the hydrologic cycle (runoff models). The area of interest is between 25 km^2 and 500 km^2, the minimum mapping unit is 2,500 m^2, and the scale/resolution is 1:25,000.

([140]) https://data.marine.copernicus.eu/product/MEDSEA_ANALYSISFORECAST_PHY_006_013/description

([141]) https://data.marine.copernicus.eu/product/SST_MED_SST_L4_NRT_OBSERVATIONS_010_004/description

([142]) https://emergency.copernicus.eu/mapping/ems/risk-and-recovery-mapping-portfolio

- P06 Temporal analyses of occurred flood events: the product provides temporal analyses of flood events within a defined area of interest. The Flood Temporal Evolution layer delivers the information on the flooded area for defined time intervals of the modelled flood event (e.g. extension of the flooded area every 12 hours, every day at 12:00, every two days). The service provider establishes the time intervals for the output as the most suitable based on the characteristics of the event and the results of the model or can be specified by the authorised user in the Service Request Form document. The area of interest is between 25 km^2 and 500 km^2, the minimum mapping unit is 2,500 m^2, and the scale/resolution is 1:25,000.
- P14 Impact assessment/exposure analysis on assets and population: the product delivers two types of analyses, dependent on input data. An impact assessment analysis on assets and population for events where a disaster extent is available and exposure analysis on assets and population in the case of a predicted/modelled event. The main outputs are general statistical information about assets and population exposed during or affected by an event. The area of interest is between 25 km^2 and 500 km^2.
- P15 Detailed impact assessment/exposure analysis on selected aspect: similarly to P14, the product delivers analyses on impact or exposure, but relies on provided-by-user data on selected assets (i.e., agriculture production and crop, forest stand information, economic values). The main outputs are detailed statistical information on a selected asset exposed to / affected by an event. The area of interest is between 25 km2 and 500 km2.

JRC River Flood Hazard Maps for Europe and the Mediterranean Basin Region

The JRC River flood hazard maps for Europe and the Mediterranean Basin region ([143]) provides information on flood-prone areas for six different flood frequencies (from 1-in-10-years to 1-in-500-years). The extent comprises most of geographical Europe and all the river basins entering the Mediterranean and Black Seas in the Caucasus, Middle East and Northern African countries with a spatial resolution of 100 m. The maps return the water depth and can be used to assess the exposure of population and economic assets to river floods and to perform flood risk assessments.

Global Human Settlement Layer

The Global Human Settlement Layer (GHSL) is a set of raster products available for different epochs and resolutions ([144]). Among them, the following products are potentially interesting for these use cases:

- GHSL built-up surface: European settlements that shows the distribution of the total built-up surface and the built-up surface allocated to dominant non-residential uses. Data are spatial-temporal interpolated or extrapolated from 1975 to 2030 in 5 years intervals and have 10 m, 100 m, 1 km, 3 arcsec or 30 arcsec spatial resolution.
- GHSL built-up height: spatial distribution of the building heights as extracted from the ALOS World 3D (30 m) and the Shuttle Radar Topography Mission (30 m) digital elevation models. Daya have 100 m spatial resolution and no planned update.

([143]) https://data.jrc.ec.europa.eu/dataset/1d128b6c-a4ee-4858-9e34-6210707f3c81#dataaccess

([144]) https://human-settlement.emergency.copernicus.eu/download.php

- GHSL built-up volume: spatial distribution of the total built-up volume and the built-up volume allocated to dominant non-residential uses. Data are spatial-temporal interpolated or extrapolated from 1975 to 2030 in 5 years intervals and have 100 m spatial resolution.
- GHSL Urban Centres: Consists of contiguous grid cells with a density of at least 1,500 inhabitants per km2. An urban centre has population of at least 50,000
- GHSL Degree of Urbanisation: classifies the entire territory of a country along the urban-rural continuum. It combines population size and population density thresholds to capture the full settlement hierarchy.
- GHS-BUILT-C: The spatial raster dataset delineates the boundaries of the human settlements at 10m resolution, and describe their inner characteristics in terms of the morphology of the built environment and the functional use.
- GHS-POP R2015A: GHS population grid, derived from GPW4, multitemporal (1975, 1990, 2000, 2015)

European Drought Observatory

The European and Global Drought Observatory provides drought-relevant information ([145]). The following drought indicators are produced at spatial scales between 5 km and 100 km:

- Standardised Precipitation Index (SPI): This indicator measures anomalies of accumulated precipitation during a given period (e.g. 1, 3, 12 months). It is the most commonly used indicator for detecting and characterising meteorological droughts;
- Soil Moisture Anomaly (SMA): This indicator measures daily soil moisture (water) content anomalies. It is used to estimate agricultural drought conditions;
- Anomaly of Vegetation Condition (FAPAR Anomaly): This indicator quantifies anomalies of EO-based FAPAR (Fraction of Absorbed Photosynthetically Active Radiation). It is used to highlight areas of relative vegetation stress due to drought;
- Low-Flow Index (LFI): This indicator is derived from daily river discharge outputs produced by the JRC hydrological rainfall-runoff model (LISFLOOD) within the Copernicus EMS European Flood Awareness System. It is used for near real-time monitoring of hydrological streamflow drought at the European scale;
- Combined Drought Indicator (CDI): This indicator integrates information on precipitation anomalies, soil moisture and EO-based vegetation conditions into a discrete classification index. It is used to monitor the onset of agricultural drought, its evolution in time and space, and the recovery phase;
- Risk of Drought Impact for Agriculture (RDrI-Agri): This is a categorised risk index, indicating the probability of having impacts from drought, with a particular focus on vegetation;
- Indicator for Forecasting Unusually Wet and Dry Conditions: This indicator provides an early warning of unusually wet and dry cumulative periods forecasted over the next 1, 3, and 6 months.

The tool Compare Layers displays side-by-side maps of the indicators described above.

([145]) https://drought.emergency.copernicus.eu/tumbo/edo/map/

European Forest Fire Information System (EFFIS)

The European Forest Fire Information System supports the services in charge of the protection of forests against fires in the EU and neighbor countries and provides the European Commission services and the European Parliament with updated and reliable information on wildfires in Europe.

Copernicus Climate Change Service

ERA5-Land Monthly Averaged Data From 1950 to Present

This reanalysis dataset provides a consistent view of the evolution of land variables (e.g. wind speed, air temperature, precipitation, runoff, air humidity) since 1950 at the resolution of 0.1° x 0.1° (native resolution 9 km) and monthly averaged. The same dataset is available with hourly temporal resolution.

Agrometeorological Indicators From 1979 to Present Derived From Reanalysis

The Copernicus Climate Change Service (C3S) provides agrometeorological indicators ([146]), including precipitation, water vapour, wind speed and direction. The dataset is based on ERA5 hourly data from 1950 and has a spatial resolution of 0.1° (about 10 km).

CORDEX Regional Climate Model Data on Single Levels

This dataset ([147]) consists of Regional Climate Models simulations representing different future socio-economic scenarios, different combinations of Global Climate Models and Regional Climate Models, and different ensemble members of the same Global Climate Models and Regional Climate Models combinations. This experiment design through the ensemble members allows for studies addressing questions related to the key uncertainties in future climate change.

Projections are available for many climatic variables up to 2100, with a spatial resolution of 0.11° (about 10 km) for Europe and a temporal resolution ranging from 3 h to seasonal.

Essential Climate Variables

The Climate Data Store (CDS) offers data products for a wide variety of Essential Climate Variables (ECVs) ([148]), which are derived from satellite observations. C3S maintains close links with the ESA Climate Change Initiative (CCI) to ensure that the ECV products available on the CDS represent the latest research and development. In addition, the C3S quality assurance programme is designed to continuously assess the scientific quality of the ECV products and their compliance with GCOS requirements.

E-OBS Daily Gridded Meteorological Data

C3S provides E-OBS daily gridded land-only observational measures over Europe ([149]). The dataset includes daily minimum, maximum and mean air temperature measured near the surface (usually at height of 2 m), gridded with a spatial resolution of 0.1° (about 10 km) and 0.25° (about 25 km). For many of countries, E-OBS uses the complete national station network, and their density is

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([146]) https://cds.climate.copernicus.eu/datasets/sis-agrometeorological-indicators?tab=overview

([147]) https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels?tab=overview

([148]) https://climate.copernicus.eu/observations

([149]) https://cds.climate.copernicus.eu/datasets/insitu-gridded-observations-europe?tab=overview increasing through collaborations with the European National Meteorological and Hydrological Services within European research contracts.

This dataset is available since 1950 and is a valuable complement to higher spatial resolution products.

Hydrology-Related Climate Impact Indicators

This dataset [150] provides water variables and indicators based on hydrological impact modelling, forced by bias adjusted regional climate simulations. Among the many datasets, the following are potentially interesting for this use case:

- Maximum river discharge,
- Minimum river discharge,
- Total Nitrogen concentration in catchments,
- Total Nitrogen concentration in local streams,
- Total Phosphorus concentration in catchments,
- Total Phosphorus concentration in local streams,
- Water temperature in catchments,
- Water temperature in local streams.

The data are available since 1971, at the pan-European domain, and with an irregular spatial resolution (median catchment size 215 km^2).

Urban Heat Island Intensity for European Cities

The CDS of C3S shows a demo of the seasonal Urban Heat Island effect for 100 European cities over the period 2008-2017 [151]. The input data comes from the UrbClim model, which utilises ERA5 variables (air temperature, specific humidity, relative humidity and wind speed) downscaled to 100 m spatial resolution.

If the product is extended to all urbanised areas, sustained and updated regularly [152], it will significantly improve the spatial resolution of the standard Copernicus temperature products.

CERRA-Land

Copernicus European Regional ReAnalysis Land (CERRA-Land) [153] provides spatially and temporally consistent historical reconstructions of surface and soil variables at the same horizontal resolution as the CERRA high-resolution reanalysis. The spatial resolution is 5.5 km, the temporal resolution is 1 day and the temporal extent from 1984 to 2021.

Copernicus Atmosphere Monitoring Service

The Copernicus Atmosphere Monitoring Service (CAMS) delivers data related to atmospheric monitoring through its Atmosphere Data Store. Among the many datasets, the following are potentially interesting for this use case:

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(150) https://cds.climate.copernicus.eu/datasets/sis-hydrology-variables-derived-projections?tab=overview

(151) https://cds.climate.copernicus.eu/datasets/sis-urban-climate-cities?tab=overview

(152) https://destine.ecmwf.int/use-case/urban-heat-island-effect/

(153) https://cds.climate.copernicus.eu/datasets/reanalysis-cerra-land?tab=overview

- CAMS global reanalysis (EAC4): this dataset contains the reanalysis of meteorological variables since 2003 (e.g. wind speed, air temperature, relative humidity) at a coarse spatial resolution (0.75° x 0.75°) and is updated every 3 hours.
- CAMS uses near-real-time observations of the location and intensity of active wildfires to estimate the emissions of pollutants. This is done through its Global Fire Assimilation System (GFAS);
- CAMS European air quality reanalyses: annual air quality reanalyses for the European domain at 0.1 degrees spatial scale (approx. 10 km). The reanalysis combines model data with observations provided by the European Environment Agency (EEA) using different data assimilation techniques;
- CAMS European air quality forecasts & CAMS European air quality forecasts optimised at observation sites: daily (or hourly) air quality analyses and forecasts for the European domain at 0.1 degrees spatial scale (approx. 10km). The analysis combines model data with observations provided by the European Environment Agency (EEA) using different data assimilation techniques;
- CAMS global greenhouse gas reanalysis (EGG4): emissions and natural fluxes of long-lived greenhouse gases (carbon dioxide, and methane). The product is available from 2003 onwards, with 0.75 degrees spatial resolution (approx. 75 km) and 3-hourly temporal resolution.

Copernicus Contributing Missions

<u>Copernicus DEM</u>

The Copernicus DEM ([154]) is a Digital Surface Model (DSM) that represents the surface of the Earth including buildings, infrastructure, and vegetation. EEA-10 and GLO-30 are among the instances of Copernicus DEM. EEA-10 is a 10 m resolution DEM that covers 39 European countries, including all islands of those countries plus French Overseas Departments (excluding French Overseas Territories). GLO-30 is a 30 m resolution DEM with global coverage. While EEA-10 is not, GLO-30 is available for download to the general public.

Non-Copernicus multi-source geospatial data, products and services

<u>Global Surface Water Explorer</u>

The Global Surface Water Explorer ([155]) maps the location and temporal distribution of water surfaces at the global scale over the past 4 decades. It provides statistics on water extent and change over time to support water-management decision-making.

<u>ESA WorldCover</u>

WorldCover ([156]) provides the first global land cover products for 2020 and 2021 at 10 m resolution, developed and validated in near-real time based on Sentinel-1 and Sentinel-2 data.

([154]) https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model

([155]) https://global-surface-water.appspot.com

([156]) https://esa-worldcover.org/en

ESA Climate Change Initiative

The ESA Climate Change Initiative (CCI) is a programme to provide stable, long-term, satellite-based Essential Climate Variables products. The data are derived from multiple satellite data sets and include specific information on uncertainties.

The data provided include the following products that are useful for water management:

- Lakes CCI: this dashboard ([157]) provides statistics on temperature anomaly, heat waves, and ice cover, with a global coverage. Data can be filtered for countries and for different aggregation methods;
- Lakes CCI: this WebGIS portal ([158]) is a demo for mapping for many different water indicators.

DLR World Settlement Footprint

The World Settlement Footprint (WSF) 2015 is a 10m resolution binary mask outlining the extent of human settlements globally derived by means of 2014-2015 multitemporal Landsat-8 and Sentinel-1 imagery.

Hydroweb Project

Hydroweb ([159]) provides continuous time-series of water levels for large lakes, reservoirs and the 20 biggest rivers in the world.

Community Scripts for Water Quality Mapping

The EO community has developed several scripts for the cloud processing of Sentinel data with the Sentinel-hub EO Browser. These include some scripts for water quality:

- Ulyssys Water Quality Viewer: is a custom script (https://custom-scripts.sentinel-hub.com/sentinel-2/ulyssys_water_quality_viewer) to dynamically visualize the chlorophyll and sediment conditions of water bodies on both Sentinel-2 and Sentinel-3 images;
- MAGO Water Quality Monitoring Tool: is a custom script (https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/mago_water_quality_monitoring_tool) to estimate chlorophyll-a, cyanotoxins, turbidity, coloured dissolved organic matter, and total suspended solids from Sentinel-2 images;
- Sentinel-2 Water Quality Script: is a custom script (https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/se2waq) to show the spatial distribution of chlorophyll-a, cyanobacteria, turbidity, coloured dissolved organic matter, dissolved organic carbon, and water colour using Sentinel-2 images;
- Water Surface Visualizer: is a custom script (https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/water_surface_visualizer) to emphasise areas of variance on flat water surface, such as water eddies, temperature induced vortices, suspended matter in shallow water, oil slicks or sheens.

([157]) https://lakescci.climate-indicators.brockmann-consult.de

([158]) https://lakescci.eofrom.space

([159]) https://hydroweb.next.theia-land.fr/

World Urban Database Local Climate Zones

The Local Climate Zone (LCZ) classification scheme comprises 17 zones based mainly on properties of surface structure (e.g., building and tree height & density) and surface cover (pervious vs. impervious). Each zone is local in scale, meaning it represents horizontal distances of 100s of metres to several kilometres.

OpenStreetMap

OpenStreetMap [160] is a free and editable map of the world built by volunteers and released with an open-content license. The OpenStreetMap Foundation supports the project, maintains the servers that host the OpenStreetMap project and guarantees almost free access to the map and the underlying data.

NASA Earthdata Nighttime Lights

NASA's Black Marble monthly (VNP46A3) and yearly (VNP46A4) nighttime lights (NTL) composites [161] are distributed freely and openly with 15 arcsecond spatial resolution.

NASA-USDA Global Soil Moisture Data

The NASA-USDA global soil moisture data [162] provides soil moisture information across the globe at 0.25°x0.25°spatial resolution. These data sets include: surface and subsurface soil moisture (mm), soil moisture profile (%), surface and subsurface soil moisture anomalies (-). The dataset is generated by integrating satellite-derived Soil Moisture Active Passive (SMAP) and Soil Moisture Ocean Salinity (SMOS) soil moisture observations into the modified two-layer Palmer model using Ensemble Kalman Filter (EnKF) data assimilation approach.

Global Forest Watch Deforestation Products

GFW currently offers three individual deforestation alert systems. GLAD-L is GFW's longest-standing alert product from the University of Maryland's (UMD) Global Land Analysis and Discovery (GLAD) lab and uses imagery from NASA's Landsat satellites. UMD introduced the higher resolution GLAD-S2 alerts in May 2021, which use a similar methodology to GLAD-L, but are sourced from the European Space Agency's Sentinel-2 satellites. And finally, Radar for Detecting Deforestation (RADD) alerts produced by Wageningen University use Sentinel-1 radar data.

Dynamic World

Dynamic World [163] developed jointly by Google and the World Reseources Institute is a near realtime 10 m resolution global land use land cover dataset, produced using deep learning, freely available and openly licensed.

World Database on Protected Areas

The World Database on Protected Areas (WDPA) is the most comprehensive global database of marine and terrestrial protected areas. It is a joint project between UN Environment Programme and the International Union for Conservation of Nature (IUCN), and is updated on a monthly basis.

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(160) https://www.openstreetmap.org

(161) https://blackmarble.gsfc.nasa.gov/

(162) https://earth.gsfc.nasa.gov/hydro/data/nasa-usda-global-soil-moisture-data

(163) https://dynamicworld.app/

Land Cover Classification System (LCCS)

The Land Cover Classification System (LCCS) was developed by FAO to provide a consistent framework for the classification and mapping of land cover, across eight land cover classes with further sub-class & seasonal identifiers.

Microsoft Road Detections

They have detected 48.9M km of all roads and 1165K km of roads missing from OpenStreetMap. Mining is performed with Bing Maps imagery between 2020 and 2022 including Maxar and Airbus. The data is freely available for download and use under the Open Data Commons Open Database License (ODbL).

Microsoft GlobalMLBuildingFootprints

Bing Maps derived open building footprints around the world. They have detected 1.4B buildings from Bing Maps imagery between 2014 and 2024 including Maxar, Airbus, and IGN France imagery. The data is freely available for download and use under ODbL.

Shuttle Radar Topography Mission (SRTM)

The SRTM ([164]) is a 30 m resolution digital elevation model with global coverage released as open data.

JAXA ALOS Global Digital Surface Model

This dataset ([165]) is a global DSM with horizontal resolution of approximately 30 meters (basically 1 arcsecond) by the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM), which was an optical sensor on board the Advanced Land Observing Satellite "ALOS".

EO4SD-Urban

EO4SD-Urban ([166]) is an ESA project aimed at deriving key geo-information products from EO data in support of urban development programmes.

IDEAtlas

The primary objective of IDEAtlas ([167]) is to develop, implement, validate and showcase advanced AI-based methods to automatically map and characterize the spatial extent of slums from EO data.

Socioeconomic data, products and services

Eurostat Data

Eurostat provides a wide range of socio-econimic data ([168]). For instance:

([164]) https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1?qt-science_center_objects=0#overview

([165]) https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm

([166]) https://eo4sd-urban.info/

([167]) https://www.ideamapsnetwork.org/project/ideatlas

([168]) https://ec.europa.eu/eurostat/web/regions/database

- Population and population density [169],
- Population density grid at 1 km (2006, 2011, 2018 and 2021) [170],
- Demographic statistics at the NUTS3 level (e.g. population by age and sex, population mortality),
- Health statistics at the NUTS2 level (e.g. causes of deaths and health care),
- Tourism statistics at the NUTS3 level (e.g. bed-places in tourist accommodation),
- Energy statistics at the NUTS3 level (e.g. cooling and heating degree days),
- Poverty and social exclusion statistics at the NUTS2 level.

Share of Population Living in the Floodplain Areas

The European Environment Agency published a map of population share calculated per WSO4 subcatchment living in floodplains areas (2016), based on the EU Floods Directive [171].

WorldPop Open Data Repository

WorldPop [172] maps populations across the globe with age/sex breakdowns for each 100m x 100m grid square. It provides open access data for UN agencies, governments and researchers to plan and monitor population dynamics.

High Resolution Population Density Maps

Meta and CIESIN use artificial intelligence to identify buildings from satellite imagery and estimate population at a 30 meter resolution, in combination with census data [173].

Demographic and Health Surveys (DHS) Program

The Demographic and Health Surveys (DHS) Program [174] has collected, analyzed, and disseminated accurate and representative data on population, health, HIV, and nutrition through more than 400 surveys in over 90 countries.

World Bank Group Gini Index

Data are based on primary household survey data obtained from government statistical agencies and World Bank country departments. Data for high-income economies are mostly from the Luxembourg Income Study database [175].

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(169) https://ec.europa.eu/eurostat/web/gisco/geodata/population-distribution/degree-urbanisation

(170) https://ec.europa.eu/eurostat/web/gisco/geodata/population-distribution/geostat

(171) https://www.eea.europa.eu/data-and-maps/figures/share-of-population-living-in

(172) https://www.worldpop.org/

(173) https://dataforgood.facebook.com/dfg/tools/high-resolution-population-density-maps

(174) https://dhsprogram.com/

(175) https://data.worldbank.org/indicator/SI.POV.GINI?locations=1W

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