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Earth observation: An integral part of a smart and sustainable city

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A R T I C L E I N F O

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A B S T R A C T

Over the course of the 21st century, a century in which the urbanization process of the previous one is ever on the rise, the novel smart city concept has rapidly evolved and now encompasses the broader aspect of sustainability. Concurrently, there has been a sea change in the domain of Earth observation (EO) where scientific and technological breakthroughs are accompanied by a paradigm shift in the provision of open and free data. While the urban and EO communities share the end goal of achieving sustainability, cities still lack an understanding of the value EO can bring in this direction, an next a consolidated framework for tapping the full potential of EO and integrating it in their operational modus operandi. The "SMart URBan Solutions for air quality, disasters and city growth" H2020 project (SMURBS/ERA-PLANET) sits at this scientific and policy crossroad, and, by creating bottom-up EO-driven solutions against an array of environmental urban pressures, and by expanding the network of engaged and exemplary smart cities that push the state-of-the-art in EO uptake, brings the international ongoing discussion of EO for sustainable cities closer to home and contributes in this discussion. This paper advocates for EO as an integral part of a smart and sustainable city and aspires to lead by example. To this end, it documents the project's impacts, ranging from the grander policy fields to an evolving portfolio of smart urban solutions and everyday city operations, as well as the cornerstones for successful EO integration. Drawing a parallel with the utilization of EO in supporting several aspects of the 2030 Agenda for Sustainable Development, it aspires to be a point of reference for upcoming endeavors of city stakeholders and the EO community alike, to tread together, beyond traditional monitoring or urban planning, and to lay the foundations for urban sustainability.

1. A convergence in scope

The term "smart city" emerged in the late 20th century (Bastelaer, 1998; International Mahizhnan, 1999), a century characterized by population growth and ever rising urbanization in megacities (United Nations - UN, 2019) or even at the gigacity scale (Kulmala et al., 2021), and has since been studied with multidisciplinary approaches (e.g. Li et al., 2019; Baklanov et al., 2020; Kanakidou et al., 2011). There exist various definitions reflecting the width of the stakeholders' perspectives of the domain, ranging from city administrations, to the Information and

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Communications Technology (ICT) industry and academia (Bolívar, 2015). In the European Union (EU), although the term is firmly affixed to its ICT origins, its scope encompasses grander aspects of urban sustainability and quality of life and its potential for ensuring the needs of present and future generations with respect to economic, social and environmental challenges is acknowledged (Eurostat, 2018) and is underpinned in several policies.

In the EU 2014–2020 Programming Period, smart cities was one of the key components of the Shaping Europe's digital future Policy (European Commission - EC, 2013) where the focus was on the rising urban demand for energy, water, waste, mobility and any other services that would be essential to a city's prosperity and sustainability. The European Innovation Partnership on smart cities and communities (EIP-SCC) was one the EU initiatives to realise this dimension bringing together cities, industry, small business (SMEs), banks and research working for integrated solutions on different policy areas such as energy, mobility and transport, and ICT. The Smart Cities Marketplace is a new platform spawned from the merging of the EIP-SCC and the Smart Cities Information System working to bring communities together in a market-changing manner. The smart city concept thus permeates into other policies of the EU and especially the Regional policy's Urban Development (EC, 2020a), where two of the five policy objectives referred to a Smarter and Greener Europe and priority themes for EU cities included digital transition, energy transition, urban mobility, air quality, climate adaptation and sustainable use of land and nature-based solutions in cities, pursued by explicit partnerships within the Urban Agenda for the EU initiative (EC, 2016). Launched in 2016 with the Pact of Amsterdam it represents a multi-level working, collaborative method to "stimulate growth, liveability and innovation in the cities of Europe and to identify and successfully tackle social challenges" (EC, 2021a). A 2014 study of the Directorate General for Internal Policies consolidated this overlap of objectives between smart cities and sustainable urban development as it identified Smart Environment as one of six smart city characteristics (European Union - EU, 2014), while the Horizon Europe's mission on 'Climate neutral and smart cities' EC (2020b) encapsulates the shift in focus.

Globally, the convergence between smart city and sustainable urban development solidified towards the International Telecommunications University Recommendation (ITU-T Y.4900, ITU, 2015). According to this, a smart sustainable city is *an innovative city that uses ICTs and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects*. In the same period, the 2030 Agenda for Sustainable Development was adopted by UN-Habitat III as was the New Urban Agenda that localized actions through, inter alia, calls for improved access to science, technology and innovation (EC, 2021b). The encompassing policy framework was thus set and several initiatives set out to delineate or codify this universal need for convergence into indicators. Such examples include the JRC's Handbook of Sustainable Urban Development (Fioretti et al., 2020), also aiming at the new Programming Period of 2021–2027 and the "United for Smart Sustainable Cities" (U4SSC) UN initiative's Key Performance Indicators (KPIs) for Smart Sustainable Cities (SSC), i.e. ITU-T Y.4903/L.1603 "KPIs for smart sustainable cities to assess the achievement of sustainable development goals" (ITU, 2015). The latter explicitly aims at achieving Sustainable Development Goal 11: "Make cities and human settlements inclusive, safe, resilient and sustainable" and defines relevant KPIs for capturing sustainability and smartness such as air pollution, greenhouse gas (GHG) emissions and green areas (ITU, 2017).

Currently, Europe's new growth strategy, the "European Green Deal", will be the driving force in the continent to transform into a fair and prosperous society where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use, at the same time conserving and enhancing the EU's natural capital, and promoting citizen's well-being. While at the global level, the digital Earth concept points to "an interactive digital replica of the entire planet that can facilitate a shared understanding of the multiple relationships between the physical and natural environments and society", its European twin, known as the "Digital Twins", is placed in action to formulate the appropriate methodological framework in achieving the above and in parallel drive the desired "green transition" (Bauer et al., 2021). In such initiatives, Earth observation (EO) proves to be a valuable and necessary means to "oversee" the planet, and it is safely assumed that sustainable development can serve as the cornerstone linkage between the EO and smart city domains.

The Group on Earth Observations (GEO), a high-level organization representing worldwide EO players and activities under an intergovernmental partnership began in 2005 working to improve the availability, access and use of EO for a sustainable planet (Group on Earth Observations, GEO, 2020a) and its scope entails explicitly addressing sustainable urban development by assisting in the development of resilient cities and assessment of urban footprints as well as providing objective information to stakeholders (GEO, 2015). Underlining this commitment, GEO has set the UN 2030 Agenda for Sustainable Development as one of its three Engagement Priorities (along with the Paris Agreement and the Sendai Framework for Disaster Risk Reduction) while, only recently, "resilient cities and human settlements" has been endorsed as a fourth one, partly due to the work described here, officially acknowledging the convergence of scopes under urban resilience as also reinforced by UN-Habitat's recognition of the value of Earth Observations (GEO, 2020b). A secondary linkage exists because of the geospatial nature of the urban issues and the targets or indicators set to address these. The 2030 Agenda explicitly calls for disaggregation by geographic location in accordance with the Fundamental Principles of Official Statistics (UN, 2017). Lastly, the two domains converge in the use of methodologies for data gathering and the engagement of citizens, the latter being a substantial objective of the EU's Green Deal strategy. Smart sensors, powered by ICT, have continuously gained ground as a substantial means to gather environmental data (e.g. Motlagh et al., 2020; Zaidan et al., 2020; Su et al., 2021; EEA, 2019), to boost interaction between citizens and the scientific community serving Citizen Science (Fritz et al., 2019) and engaging urbanites, a prerequisite for a smart city [EU, 2014].

Despite the growing overlap in scope and goals between the EO and city communities in terms of policy frameworks and top-down initiatives, a well identified lack of engagement exists between the urban planners and the EO community (UN Habitat, 2019). Projects and initiatives within both domains have attempted to bridge this divide and match city stakeholder needs with EO capabilities, and, alternatively, steer EO expertise towards applications and improvements within the urban context such as Smart Cities Marketplace (EC, 2020c) and Eurisy, which continuously catalogue applications and success stories where EO solutions have improved resiliency in cities throughout Europe (Eurisy, 2020). The recently launched Earth Observations Toolkit for Sustainable Cities and Human Settlements also aims to facilitate engagement among cities, national agencies, and EO experts under the frame of SDG indicators' monitoring (Kavvada, 2020). From such efforts, it has become clear that city stakeholders want, need and seek solutions and innovative tools to streamline their workflows, transcending beyond simply providing EO resources. Connecting these two domains is the foundational step to facilitating engagement, gathering user needs, and transferring technology, knowledge and tools to exploit EO capabilities and to ultimately enhance the "smartness" and resilience of cities.

The "SMart URBan Solutions for air quality, disasters and city growth" (SMURBS/ERA-PLANET) H2020 project (GA: 689443), exploiting the nature of the ERA-PLANET programme (Tsinganos et al., 2017) which gathered a considerable number of EO experts in Europe to address four selected strands, during its implementation between 2017 and 2021 garnered significant lessons that can further the discussion outlined above. Following a mostly bottom-up approach in several European cities, SMURBS revisited the smart city concept via leveraging state-of-the-art EO provided by its wide consortium, which in turn was enriched by assimilating smart-city methods to ultimately enhance environmental and societal resilience to collectively selected, specific urban pressures. The chapters below describe the steps undertaken, from identifying what already exists in the field, engaging city stakeholders and comprehending their needs and requirements, refining, or creating EO solutions to address the latter and delivering a fully furnished, tested and fine-tuned portfolio of Smart Urban Solutions that reflects experiences and good practices gained. Through its tangible solutions, the project manages to serve as an ambassador for the use of EO from city stakeholders. Critical points such as implementation barriers and sustainability are also documented under foundational aspects, and, along with the impacts of EO-driven solutions on real world urban issues, provide a handbook to communicate to city stakeholders and the EO community who aspire to exploit the benefits of bringing the two domains closer.

2. Mapping the state of play of EO against urban environmental pressures

Identifying the issues that cities face, and assembling the varying perspectives of stakeholders on what is needed and how to address these stressors lays the basis to begin building a common roadmap for the future of sustainable cities. From the descriptive point of view, ambient stressors are defined as environmental factors that are perceptible (although they may go unnoticed), chronically present, negatively valued, non-urgent and intractable, meaning an individual cannot alter these stressors structurally (Campbell, 1983). Rapid and uncontrolled urban growth during the last decades has amplified or accelerated pressures on the urban ecosystem. These pressures may morph or new ones may be formed due in part to technological advancement, social/behavioral changes and other local factors and currently include traffic and/or industrial noise, ambient (outdoor) and indoor air pollution, deterioration and/or lack of public green and blue spaces, high population density, unpleasant odor burdens, over-accumulation of waste and/or inadequate waste management, heat waves, pollution of water bodies, natural hazards, resource degradation (soil erosion, deforestation, acid precipitation, loss of biodiversity), pre-emption or loss of resources, urban climate change and biological pathogens (Satterthwaite, 2003; Rishi and Khuntia, 2012; Kabisch and Haase, 2014; Park and Evans, 2016; Sabel et al., 2016 and references therein). The implications of these pressures can be as serious as the pressures themselves and include significant challenges to urban physical and mental health, well-being and socio-environmental justice (Rishi and Khuntia, 2012; Kabisch and Haase, 2014; Sabel et al., 2016; Krefis et al., 2018).

With the aim of ameliorating environmental pressures in the urban fabric there is an acknowledged need to bring together space and technology with cities, emphasizing and capitalizing on cities as incubators for innovation and citizen ingenuity, in order to make urban governance more effective (Alberti et al., 2019). Notably, there is a duality in urban regions where cities are especially exposed to climate change and other stressors, with a concentrated, and in some cases, growing population at risk, while also serving as economic cores, driving trends and innovation, and holding arguably the greatest impact capacity in terms of mitigation, adaptation, and investment (Rosenzweig et al., 2010; Alberti et al., 2019) or, conversely, where the impacts of economic crises are more directly felt (e.g. Vrekoussis et al., 2013; Gratsea et al., 2017) and require targeted policy responses (e.g. Bailey et al., 2019). While monitoring environmental pressures is a prerequisite, it should be complemented by the provision of targeted, useful, digestible information to decision makers. Moreover, cities particularly need geographically disaggregated information for incorporation into decision making and smart solutions, to assess the current state, trends and projections, but also require this in a sustainable fashion, possibly integrating it with existing data streams in a way that will not entirely interrupt existing and entrenched workflows (Caribou Space, 2020). EO largely fulfils these requirements and global implementations are already supporting short and long-term evidence-based policy making such as designing interventions, allocating resources, and aligning cities with national and global policy frames as regards monitoring, tracking and reporting requirements (examples of such initiatives provided in supplementary information (S1)).

The SMURBS project found itself situated within this turning point, i.e. a maturing smart city concept and an exponential growth of EO availability with a demand to serve international policy making. In this context, the project implementation mirrors the larger frame discussed above, and had a unique opportunity to fully exploit its rich EO consortium (consisting of 19 European research Institutes or Universities) and the weathered relationships built with city stakeholders, to explore pathways and identify inhibitors in achieving the wanted convergence. From its initial conception, SMURBS acknowledged the fact that in order for EO data and tools to actually be effective and fit-for-purpose for city use, the users themselves should be involved from the early stages. Interaction with more than 250 stakeholders (more information can be found in S2) led to the identification of the “Urban State of Play” (SMURBS, 2020), which in turn culminated in the identification of different types of gaps related to air pollution (including health-related problems), (peri-)urban disasters and urban growth (including migration aspects) (Georgiadis et al., 2021, this issue).

Some findings from this inventorying exercise denote, for example, air quality (AQ) as an already favorable domain for smart city approaches to flourish, especially regarding smart sensors technology, reconfirming that in-situ measurements are traditionally the prevailing type of observational platforms in this domain, but also recognizing the reluctant but nevertheless steadily growing trend of stationary and portable low-cost sensors, as well as smartphone solutions used in supplement to regulatory networks. Remote sensing and modelling tools are integrated to a larger extent into smart-city concepts, to cover various spatio-temporal scales and different types of applications, while feeding decision support tools in support of environmental governance i.e. early warning systems, evaluation of policies and measures, and health impact assessments. Still, those applications are mostly fragmentary and prolonged sustainability of the products and services is rarely achieved. Concepts of public involvement (e.g. participatory environmental health monitoring) are evidently becoming an important element of smart-city projects, while the tailoring of the processes to improve public awareness is a universal, theme-independent request.

The end goal of these mapping activities, and the project itself, was the building of a portfolio of smart city solutions based on EO data. The potential of synergies between different EO platforms and their added value compared to the individual use of those data was among the challenges faced. It is notable that although satellites represent the most commonly perceived definition of EO data resources according to stakeholders, specifically elevating the Copernicus Sentinel family of satellites, it turns out that especially in the urban context, in situ platforms with state-of-the-art instrumentation for ground-based monitoring of environmental stressors are essential for a wide array of information, services and applications. This proves how timely and to the point the efforts of the global EO community are, with respect to more efficiently standardizing and collecting in situ data and incorporating them into the EO resources ecosystem. A widening of the EO definition is probably needed to more clearly include modeling (e.g. Karl et al., 2019, Ramacher et al., 2021) as an integral part of this ecosystem of EO platforms, along with other innovative approaches of observation, which SMURBS attempted to incorporate, such as citizen observatories (e.g. Robinson et al., 2021) and smart sensors (e.g. Grivas et al., 2019; Stavroulas et al., 2020), the latter within the frame of the Internet of Things (IoT).

The online and openly available Portfolio of SMart URBan Solutions (SMURBS, 2021), despite its variety of more than 40 solutions implemented in approximately 30 cities and almost 15 countries ((Fig. 1).),

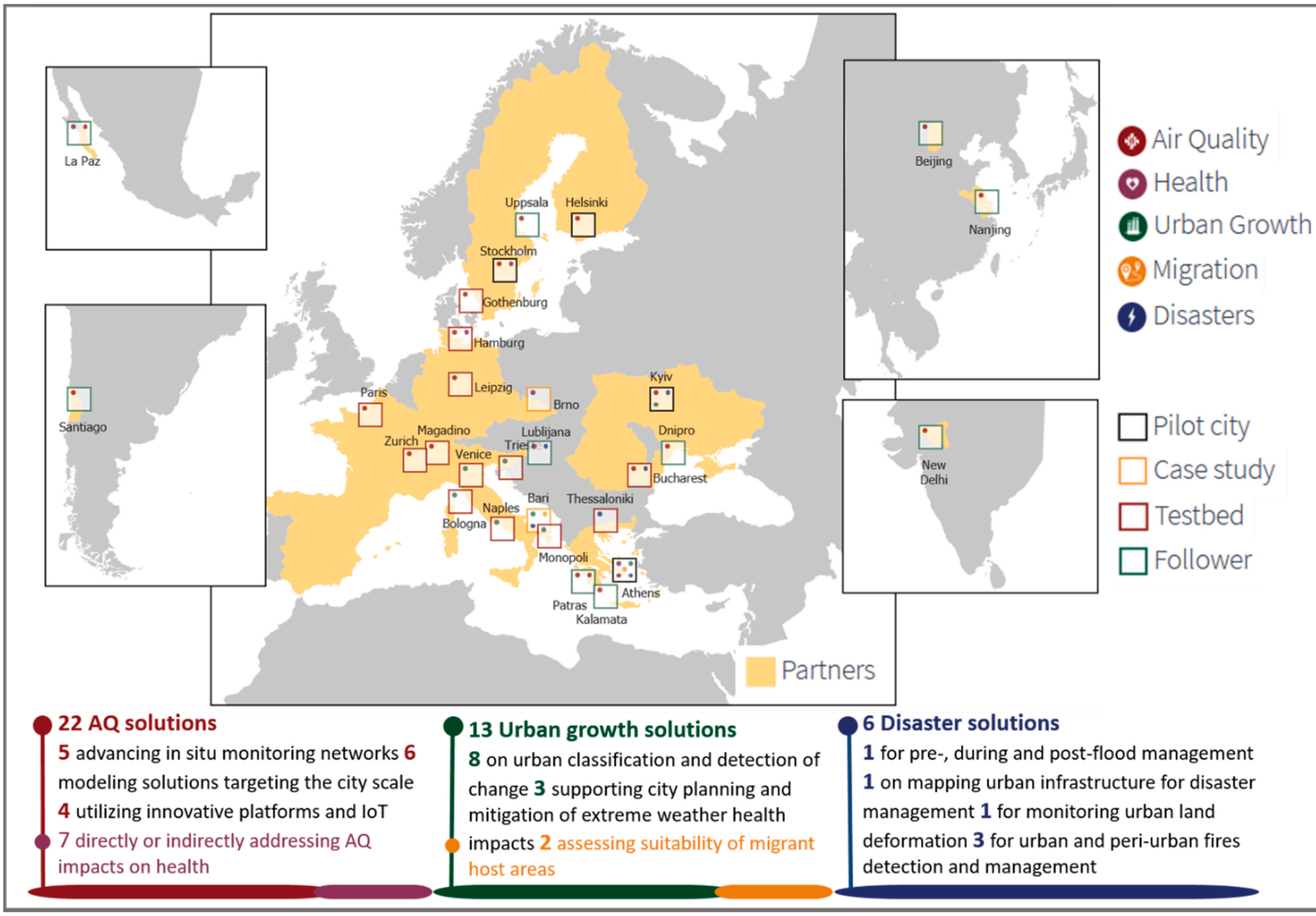

Fig. 1. The map of SMURBS network of cities along with the type of stressor(s) addressed by the SMart URBan Solutions (color-coded circles embedded in the squares). The color of city squares shows the different degree of solution implementation (pilot-cities, case-studies, test-beds and followers). A summary of the 41 solutions of the SMURBS portfolio is also presented, organized by theme and following the same color-code. The online, interactive version can be found here: https://smurbs.eu/interactive_map/.

presents just a part of the real breadth and depth of EO platform exploitation via tools, products and services to support urban planners, decision-makers, and other stakeholders, adding tools to a smart city's arsenal to address environmental pressures. Important elements for the creation of this portfolio include the fact that most solutions were not built from scratch or in vacuum, but upon existing methodologies; they were based off of sustainable and robust science (pursuing wider awareness of the limitation brought in, e.g. from low cost sensors non-authoritative use); and that a distinct and major effort was put forth to transfer existing EO advancements from their global to a local, urban context, which inherently introduces different requirements.

While the portfolio was built through the efforts of SMURBS, the consortium acknowledges the current fragmentation (Tsinganos et al., 2017) between similar initiatives and thus, the need for more authoritative spaces (e.g. GEOSS portal, WRI data portal for cities, the Smart Cities Marketplace) to broker available solutions and ensure they remain openly accessible and sustainable, available to any and all, and continuously updated. Given the unprecedented speed of technological progress, building a portfolio is a dynamic and evolving process. It serves as a methodological compilation of state-of-the-art EO solutions and constitutes a jumping-off point for future EO implementations in smart cities.

3. Building EO into a smart city

The SMURBS experience in building a portfolio of smart solutions for cities in the face of a wide variety of environmental pressures, illuminated the importance of and need for initial and persistent co-design and engagement with users and stakeholders. Moreover, to truly begin building a smart city, resiliency enhancing solutions and tools must be put into practice, piloted and tested so that they can be fine-tuned to meet unique user needs, requirements, and local particularities (see the SMURBS project concept below in Fig. 2).

The concept of developing solutions to target urban environmental issues, followed by a demonstration of outcomes in selected cities is adopted by several relevant projects in the last 5 years (non-exhaustive list from the Cordis database, Table 1). The active participation of citizens is one of the common aspects in all projects. While focus to the use of and synergies between specific EO platforms is prioritized in SMURBS, the CURE project is dedicated to Copernicus uptake. All projects promote smart aspects related to ICT and ultimately contribute to improved health and wellbeing. The goal of building EO into a smart city is a unique feature brought in by SMURBS.

In an effort to assemble learnings from the SMURBS project, 6 foundational aspects were identified, and are exemplified through four indicative smart urban solutions (Table S1), aspects which are interlinked and interdependent and that are critical for any EO/smart city integration.

3.1. Co-design

The systematic and sustained collaboration with different types of stakeholders during the design of a scientific product is crucial so as to create tailored, functional and attractive solutions. Co-design can be integrated throughout the course of solution development, from the

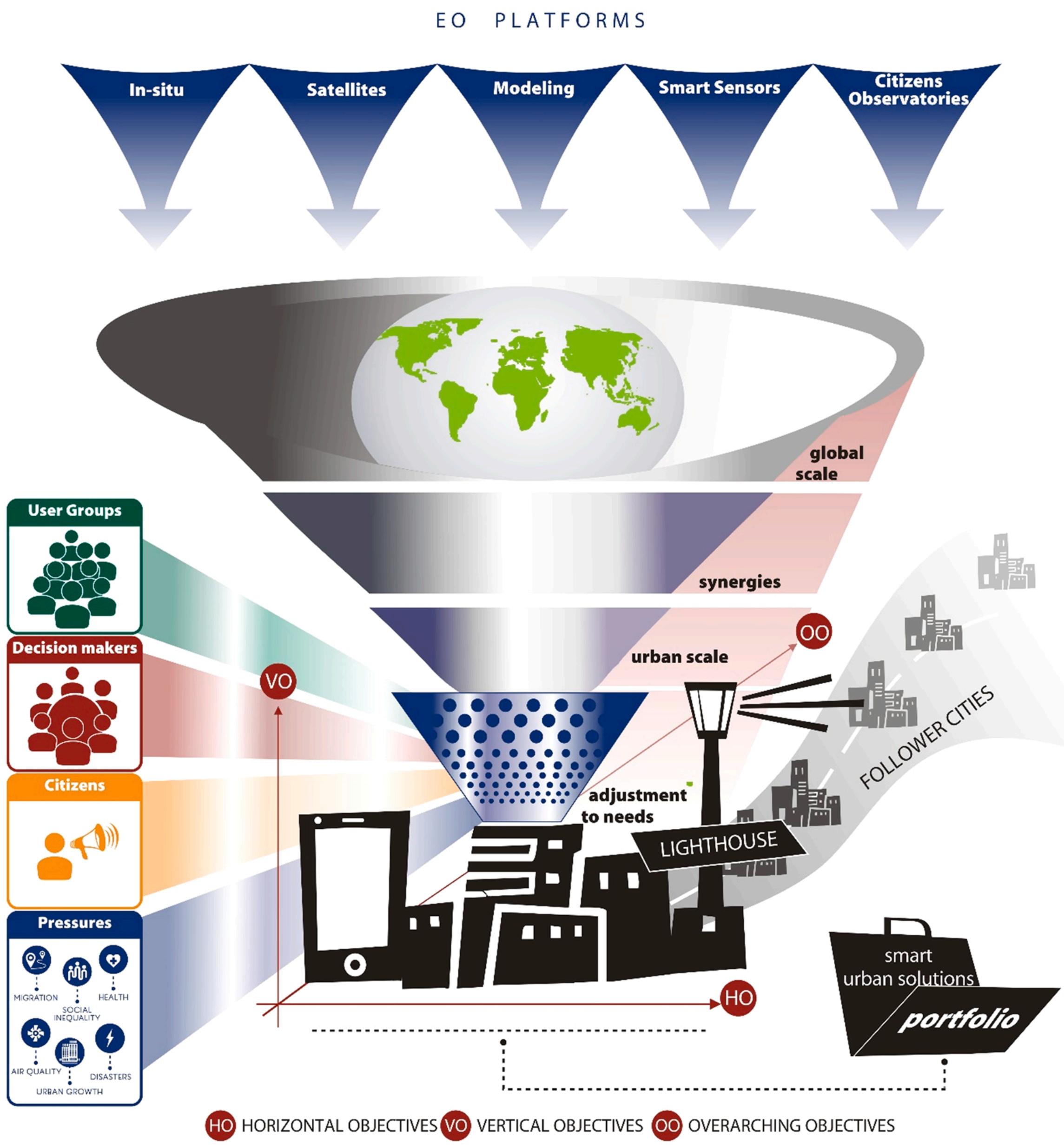

Fig. 2. Schematic depicting the overall concept of SMURBS, directly tied with and driven by the overarching goal and objectives of the "Smart Cities and Resilient Societies" strand of the ERA-PLANET Joint Call 2016. At the core of the proposed actions lies the creation and exploitation of a portfolio of Smart Urban Solutions, based on the full exploitation of EO products, towards increased societal resilience against air pollution (including health impacts and social inequalities), disasters (natural and manmade) and urban growth (including the migrant crisis). The portfolio entails tools and solutions in support of urban planners, decision-makers and urban ecologists, for a better understanding of the structure and function of smart urban ecosystems under an urban ecology concept, where cities are represented as complex adaptive systems whose boundaries are not fixed but depend on the questions and pressures to be addressed.

concept phase through the implementation and beyond. It helps to optimize the product through and by building traction with stakeholders to discover and identify gaps that may exist, as well as test and refine the end-product collectively. A currently common approach is that instead of stakeholders presenting providers with a need, it is the providers who bring a solution to the table. While the need might occasionally be apparent perhaps due to existing obligations for reporting, by definition, co-design requires two-way interaction, which can reveal an unidentified need. This further clarifies the need for the process to be dynamic, allowing for the inclusion of new and diverse perspectives or even new and diverse experts.

3.2. Engagement

The continuous and active involvement of stakeholders is an imperative component of any successful smart urban solution's development and application, and, while overlaps exist with co-design, it comes in many forms, beyond the stakeholder actively shaping a solution being built. In some cases, the first step of engagement may require a value proposition to be made, with tangible proof given at these initial stages (i.e. a demonstrable or ready solution), which can also stimulate interest and serve as a stepping stone for later engagement. An important facet of engagement is to build trust and relationships with stakeholders, ultimately furthering cohesion and serving as a building block for successful collaboration. In the case of SMURBS, the continuous exchange of data and information from and the participation and/or

Table 1
Comparison of SMURBS with other relevant European funded projects.

No	Name/ Duration	Topic/Theme	Indicative smart-city aspects	EO platforms	citizen involvement/ Copernicus interaction	Spatial focus	Application	Official website
1	euPOLIS 2020–2024	Nature Based Solution interventions for improved public health and Well Being	Advanced ICT (monitoring, visualization, network of sensors)		Yes/ -	city interventions	4 runner cities 5 follower cities	https://eupolis-project.eu/news/
2	goGREENroutes 2020–2024	implementing “nature-based solutions” to enhance the physical and mental health of their urban residents	data hub		Yes/ -	city interventions	Burgas (Bulgaria), Lahti (Finland), Limerick (Ireland), Tallinn (Estonia), Umeå (Sweden) and Versailles (France)	https://gogreenroutes.eu/
3	IN-HABIT 2020–2025	foster inclusive health and wellbeing (IHW) through mobilising existing undervalued resources (culture, food, human-animal bonds and environment)	mobile app, operational platform	sensor network	Yes/ -	city interventions	Cordoba (Spain), Riga (Latvia), Lucca (Italy) and Nitra (Slovakia)	https://www.inhabit-h2020.eu/
4	CURE 2020–2022	exploiting Copernicus Core Services towards urban (environmental and/or human) resilience against climate change, air pollution, floods etc		satellites, models	Yes/ Yes	city interventions	Berlin, Copenhagen, Sofia, Heraklion, Bristol, Ostrava, Basel, Munich, San Sebastian, Vitoria-Gasteiz	http://cure-copernicus.eu/
5	ICARUS 2016–2020	develop integrated tools and strategies for urban impact assessment in support of air quality and climate change governance	online DSS portal	models, in situ	Yes/ -	city interventions	Basel, Brno, Ljubljana, Roskilde, Stuttgart, Thessaloniki, Athens, Milan and Madrid	https://icarus2020.eu/
6	SMURBS (2017)- (2021)	Smart Urban Solutions for air quality, disasters and city growth	ICT, online platforms, high spatial resolution, near realtime information, crows sourcing, mobile apps, personalized information,	in situ, satellites, smart sensors, models	Yes/ Yes	city interventions	20 smart cities (Athens, Helsinki, Gothenburg, Bologna, Bari, Bucharest etc) and 8 followers	https://smurbs.eu/

uptake by both governmental and non-governmental or academic experts were shown to be a significant means for engaging stakeholders, tackle fragmentation of data and efforts as well as improve the overall efficiency of the solution at hand. It is important to note however that resource limitations, reporting and policy obligations, workflow disturbance, openness, and impact can be barriers that influence the degree of engagement and must be considered.

3.3. Capacity

From both the stakeholder (end user) and provider perspective, it is most beneficial to exploit existing investments, enhancing their value and building off of the effort already put in and allowing for improvements to be made as opposed to starting anew. This greatens the ability for users to sustain such assets and products, and allows for their improvement in the process. Identifying and registering the existing technological assets, solutions, good practices and research infrastructure of the city at hand as well will reduce duplication of efforts and it will make the proposed solution more appealing to the city stakeholders. This holds particularly true for smart cities where the IoT and cloud infrastructure can offer a huge push to all EO implementations. The level of expertise of those involved must be also taken into account, as it influences the engaging capacity and sustainability elements.

3.4. Versatility

All SMURBS solutions entailed one or more features of this foundational aspect: modular design, allowing for add-on features or data if/when developed, scalability and/or use of open data enabling replication or transferability in different locales or domains, and innovative aspects and methods, putting solutions beyond the state-of-the-art, thus enhancing attractiveness. The modular and adaptable design of the SMURBS SDG Indicator 11.6.2 EO platform, which provides the annual average population-weighted fine particulate matter concentrations for more than 800 European cities, according to two definitions of city delineation is an ideal example showcasing utility and versatility as it based exclusively on open data retrieved from the Copernicus Atmospheric Monitoring Service (CAMS), and it allows not only add-on features for inter-comparison purposes among years and cities, but also enables addition of other regions, data layers or even different city definitions in future upgrades or similar applications.

3.5. Piloting

Truly and effectively building any novel smart solution targeting urban environmental problems requires a pilot implementation period in a city or cities. Real world implementation translates into practical steps of garnering feedback, making refinements, tailoring and quality control of a solution, to ensure an optimized, solid product. The process of piloting also reveals obstacles and inhibitors to implementation or practicality, potentially illuminating how to overcome such hindrances. Returning to the foundational and ubiquitous aspect of engagement, piloting solutions facilitates active collaboration, identification of good practices and is effective at further expanding and building a network of stakeholders and partners.

3.6. Sustainability

As previously discussed, continuation of the products and services produced within projects is rarely achieved. To absolve this issue, project-based solutions for city problems should be accompanied by long-term planning from the very beginning of the process, in apparent terms for the stakeholders. Once the targeted pressure is incorporated into a city's strategic agenda, the resources for sustainability can be more readily planned. To this end, successful co-design and piloting in a city should aim at both showcasing the benefits achieved against the regular modus operandi but also eliminating avoidable and recurring costs by following the versatility paradigm. Such a cost assessment, displaying cost savings, efficiency gains, and the new ability for proactivity, can serve as both incentives to prioritize and achieve long-term sustainability and provide justification for it. Moreover, sustainability should be assessed and presented in a holistic manner by accounting for significant co-benefits of a solution such as health benefits, financial privileges, and the contribution to overall wellbeing of society. While some stakeholders may not be willing or able to sustain a service, as producers, it is important to find ways to bolster an asset until full buy-in can be achieved, avoiding collapse. Finally, ownership aspects (e.g. who is the final user/owner, what is the intervention level allowed, where is the infrastructure physically located, other branding issues) of the solution from the end users, hand in hand with capacity development, is also critical in the chain of factors that build sustainability.

While each of the above foundational aspects is important in its own right, once purposely interlinked, they maximize the capacity of the solution at hand. The profiling of the engagement derived from the experience of SMURBS is described in S3.

In the initial project design stage several risks and obstacles were identified, a list further enriched during the development and testing phases of SMURBS solutions. Gathered in Table S2. are the key obstacles faced during the implementation of the project per risk type. Experience showed that once foundational aspects were taken into account to frame a solution, then risks were minimized and the ability to overcome obstacles was improved. For instance, once engagement with authorities was established and sustained, then reluctance to disturb current workflows, delays due to bureaucracy and other communication bottlenecks were strongly abated.

4. What impacts does EO have on the urban domain?

As SMURBS nears the end of its project life, and as its legacy take shape, it is beneficial to examine the project's envisioned objectives in line with actual impact. Generally, and from the SMURBS perspective, impact can be perceived at different levels. On the higher level, decision and policy making bodies have put forth frames, which can drive EO integration into the urban domain through explicitly acknowledging its usefulness and setting the requirements for the creation of tools and products for implementation in cities. In more tangible terms, impact within the cities themselves can be triggered through direct interaction with the competent authorities, which may be reflected through either modernization of operations and workflows or as improvement felt in terms of addressing the problems at hand (e.g. increased green space). Further, and somewhere in between the two, networking with a variety of key players and city constellations can allow for a snowball effect, spreading knowledge of EO usefulness along with solutions to a wider range of cities and contexts. While the higher level impacts are more traceable, as these entities maintain convening authority, bringing together the competent fora and creating working groups to produce strategies and material for policy frames, at the city level, the real impact of solutions for answering to urban pressures proves much more challenging to quantify.

From an international perspective, SMURBS has managed to solidify its position as an authoritative EO ambassador in dealing with the smart city domain and in the EO community as a reference project that created needed bridges with the growing ecosystem of smart cities. In this sense, its legacy and resources along with substantial contributions of other initiatives who have been laying the groundwork, supported the formulation of a high-level group in GEO focused solely on urban resilience, to justify and facilitate "resilient cities and human settlements" adoption by GEO as its 4th engagement priority (late 2021), bringing the topic in the GEO agenda on par with climate change, sustainable development and disaster risk reduction. Further, SMURBS has helped to materialize the EO4SDGs Initiative's vision by utilizing its network to build specific EO-based applications of SDG indicator monitoring (11.1.1, 11.3.1, 11.6.2) and provide feedback on the Initiative's compilation of use cases and good practices. Moreover, through iterations within its consortium, the project has arrived at a set of Essential Urban Variables (EUVs) that, in line with the established process, will propose to the EO community for further discussion, commencing with the GEOEssential project of ERA-PLANET. Expanding on this work within the urban domain, and in an effort to address the specific challenges (Esau et al., 2021) that Arctic cities face in relation to urban development the iCUPE project of ERA-PLANET compiled a suite of novel data sets, including "Microclimatic features and urban heat island intensity in cities of the Arctic region" data (Petäjä et al., 2020).

Even though city authorities were foreseen as key players in the portfolio building process from the start, it was soon realized that building out a diverse network, also including additional facets of the city community, was essential to drive far-reaching impacts of the project's solutions. The combination of such a network and the portfolio provided the means to solidify the SMURBS brand, which in turn elevated visibility within other networking channels, thus validating and accelerating the EO gospel for urban application.

To begin to form an understanding around how EO solutions can affect the smartness and resiliency of communities using the example of SMURBS, each impact can be categorized under the types of academic, cultural, economic, health, political, environmental, social, and/or capacity building as can be seen in Fig. 3 where indicative and high-level impacts are presented.

Most solutions provided tangible and clear-cut advancements and enhancements in the academic realm through scientific publications, innovation, new research opportunities and positions, collaborative research, courses and trainings. This also included doctoral studies in the field of citizen science as part of the EO ecosystem (Robinson et al., 2021), an emerging domain within the new EU policy (i.e. Green Deal) which includes untapped prospects for triggering facets of social reformation. An interesting feedback effect occurred as the EO experts were brought closer to the smart city paradigm. In the latter, openness and (especially) interoperability of data is a given, even by definition. While EO is at the forefront of open data among the STEM disciplines and beyond, there is still a lot to be achieved regarding interoperability. The consortium of SMURBS, in order to be aligned with ERA-PLANET but also the cities in which it operated, had to actively work towards this direction and avoid closed solutions (by e.g. contributing to the ERA-PLANET GEOSS portal catalogue or making data directly available to citizens or city stakeholders via APIs). Along the same vein, capacity building or development held important weight within this process, not only to allow for replication, but as a necessary means for cooperation between and amongst academic institutions, local authorities, the private sector and/or volunteers, which made solutions fit-for-use. As new EO tools and methodologies (i.e. smart sensors, artificial intelligence) were utilized and tested by the SMURBS community, it was imperative to provide the training and tools to help cities actually integrate these practices into their toolbox. The research investment on innovative sensors as a part of integrated AQ monitoring networks (AQMNs) in cities like Athens, Helsinki, Oslo, Gothenburg and Leipzig serve to showcase this aspect.

Many SMURBS solutions resulted in direct or indirect environmental impacts. These include helping to resolve air quality issues, enhance preparedness to natural or manmade hazards and provide real-time

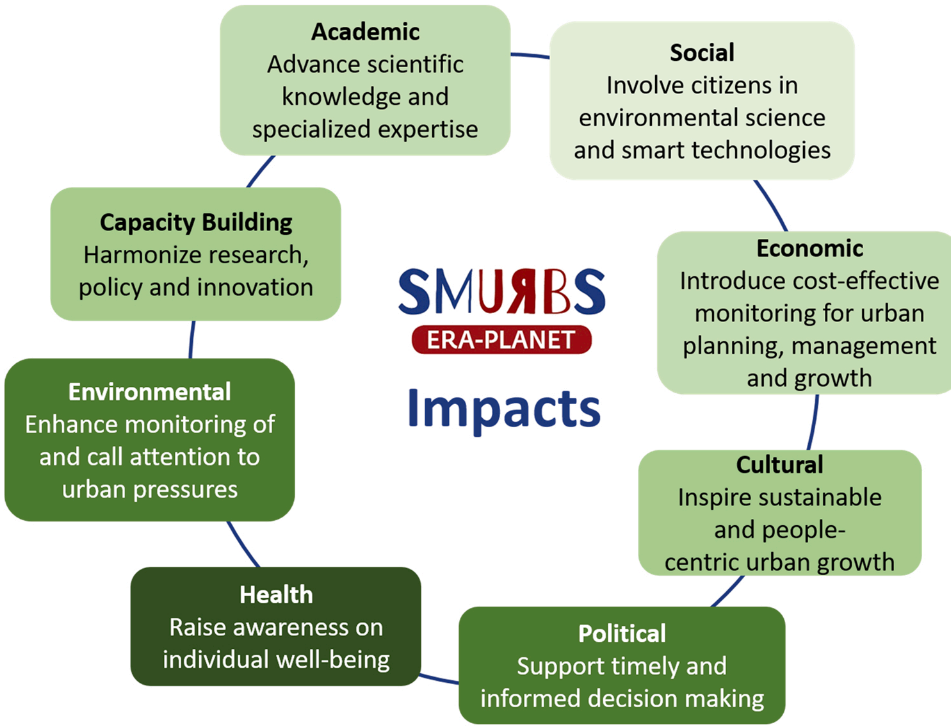

Fig. 3. Schematic showing the different impact areas of SMURBS along with indicative, high-level learnings (adapted based on type of impacts suggested by Withyman (2018).

information on environmental conditions to citizens. It has been made clear that the environmental domain can act as the forerunner and driver for utilizing EO to cope with urban issues, upon which resilience and sustainability can then be pursued. As an example, activities directly addressing the linkage between environmental degradation and health entailed providing products and information to lessen the health risk due to a host of urban stressors such as air pollution episodes, fires, and flood events. This combined knowledge empowered and triggered the interest of several stakeholders, enticed by the endpoint information (i.e. static and/or dynamic exposure; Ramacher and Karl, 2020), and not just the proxy (i.e. pollutant fields), the curation of this information via integrated indices (Olstrup, 2020; Dimitriou et al., 2020a) as well as individuals, who benefited from services transmitting localized and personalized health risk information.

As was intended from the project's scope, there were felt political impacts from solutions, especially in terms of supporting decision making. Valid and timely alerts, reports and assessments and authoritative citizen information for environmental threats, such as smog episodes due to residential wood burning, profiling air pollution to apportion it to specific sources (Stavroulas et al., 2019; Dimitriou et al., 2020b; Tobler et al., 2020; Canonaco et al., 2021; Manousakas et al., 2021), smoke plumes due to industrial accidents or peri-urban wildfires and pre-/post assessment of flood events were issued based on the project's urban solutions during the piloting phase and decisively drove administrative and political decisions (e.g. for evacuation measures, public guidance provision). Regarding the migration theme, new information was created and visualized, like distribution in a city and inadequate housing (as in the case of Bari, Italy; Aquilino et al., 2020) or vulnerability of migrant Hotspots (EC, 2015) to natural hazards (as in the case of Ritsona-Athens, Greece), providing important knowledge in this relevant and extremely sensitive policy field.

Tools (maps and metrics) for urban planning, along with specificities on topics such as illegal buildings and green space distribution, are only a few of the cultural impacts that were identified, at least to the degree that those tools have begun to be used to form future actions. Continuous and detailed monitoring of the urban landscape provides valuable data towards prospective cultural changes in urban development and the overall wellbeing of citizens, while in certain regards, it also holds several economic implications, immediately felt or projected. For instance, proposed urban monitoring solutions can deliver cost-effective alternatives to traditional methods of tracking changes in the urban fabric (e.g. periodic identification of new buildings and urban expansion instead of building censuses), but also unveil opportunities for sustainable urban development with significant future returns and co-benefits. Finally, many social impacts were also recognized, especially in terms of improving social resilience of sensitive populations in certain locales (e.g. elderly, asthmatics, migrants), bringing the end-user into the process as a key stakeholder, getting citizens involved in city planning and in some cases as data gatherers, and generally increasing citizen awareness.

5. In conclusion

The term "smart city" emerged in the late 20th century and although it has evolved from its ICT origins, its scope has grown to include the larger aspects of urban sustainability and quality of life. Global policy frameworks, but also Europe's new growth strategy, the "EU Green Deal", will push forward this effort, while other global partnerships, like the Group on Earth Observations (GEO), are working to highlight that EO is a valuable and necessary means to surveil the planet. Given the above convergence in scope and goals, shared methodologies for data gathering and the engagement of citizens and the inherent geospatial nature of urban issues, sustainable development can serve as the cornerstone linkage between the EO and smart city domains.

Despite the growing overlap in scope and goals as well as the convergence in the use of methodologies for data gathering and the engagement of citizens, a well identified gap exists between the urban planners and the EO community. Past and ongoing projects that have tried to address this find that city stakeholders want, need and seek innovative solutions to streamline their workflows, beyond simple provision of EO information. The H2020 SMURBS/ERA-PLANET project gathered a wide pool of European EO experts to further this discussion, following mostly a bottom-up approach in EU cities to arrive at a handbook for the two communities to collaboratively tackle environmental urban stressors. Identifying the latter in the perplexing urban environment is a challenge as cities where additionally many interlinkages exist (e.g. climate change implications and the synergies between them, which can amplify or accelerate risks and impacts).

The conceptual framework proposed by SMURBS for the successful implementation of smart and EO-based solutions in cities is visualized in Fig. 4. As the smart city evolves and EO availability grows exponentially, the SMURBS project found itself at a turning point where EO-driven solutions should more substantially serve international to local policy making. The launch of the New Urban Agenda (NUA) provides the global framework to foster traction between the two communities. In parallel, the increasing usage of EO for SDG indicator monitoring, the latter being coordinated, among others, by the GEO EO4SDG Initiative, have set the "resilient cities and human settlements" as the 4th Engagement Priority of GEO towards enhancing the visibility of urban activities within the GEO Work Programme, and eventually leading to more direct interaction with city level authorities.

SMURBS, mirroring the frames discussed above, and acknowledging the unambiguous necessity to involve the cities as the main end-users from the get go, set up a real-world laboratory and conducted a convergence experiment that revealed new or confirmed existing findings. The exercise to map existing EO and smart city interaction demonstrated a clear lack of consolidated up-to-date inventories of relevant data sets, applications, services, good practices, use cases and success stories, and reconfirmed the fragmentation of information between similar initiatives and projects. The end goal of these mapping activities was to construct a project portfolio of smart city solutions based on EO data. This in turn, reveals the need for federated and authoritative spaces to divulge available solutions and ensure they remain relevant, openly accessible and sustainable.

The real-world implementation of the portfolio showcased the potential of synergies between different EO platforms and the produced added value, especially when combined to external data, such as health and socio-economic information. It made clear the criticality of the ongoing global endeavors to incorporate in situ data more efficiently into the EO ecosystem, as well as the substantial widening of the EO definition to include modeling as the joining constituent between observational platforms. Other innovative approaches, like citizen observatories and smart sensors, are de facto entering the EO and urban landscape at such a rapid pace, in spite of the reluctance of city stakeholders, underlining the need to standardize quality assurance processes and lay the groundwork for their smooth incorporation into city workflows. An underlying denominator of the above is the openness and interoperability of data, aspects where smart city and IoT methodologies are frontrunners, followed by satellite data retrieval and ingestion, yet, in situ data still falls behind, necessitating the inception of novel frames and incentives to bring it up to speed. Transferring existing EO advancements from their global to the urban context is a challenge, almost of equal weight to familiarizing with the actual needs and workflows of urban organisms. This pushed researchers to introduce breakthroughs in their traditional approaches, revealed new aspects within each urban pressures such as the link between environmental stressors and health impacts, justified new parameter monitoring, and calls for rethinking modern monitoring infrastructure and networks.

Six foundational aspects gradually emerged for unlocking the potential and maximizing the osmosis between EO and the smart city concept. *Co-design,* to tailor solutions to the needs and existing workflows of stakeholders, at the same time revealing hidden elements that would normally delay or postpone adoption of solutions. *Engagement,* to build trust, official relationship frames and eventually sustainability options. *Capacity*, to capitalize on previous investments and make the proposed solutions more appealing to city stakeholders. *Versatility,* to allow for add-on features and scalability that in turn enable replication or transferability in different locales or domains. *Piloting,* to garner feedback about refinements, tailoring and quality control of a solution, and ensure a fit-for-purpose application, to showcase value to other parties. *Sustainability,* to avoid solution dissipation after project lifetime and call for long-term planning from the early stages of implementation.

All elements above are interlinked, and through early and sustained interaction with users and stakeholders, identification of needs and existing capacities, planning for solution versatility and sustainability, as well as testing and refining, potential risks can be minimized and EO-based services may become affixed in urban agendas. To do so, it is essential to guarantee resources for long term maintenance and upgrades. In this vein, a holistic approach should be pursued (Fig. 4). EO solutions should be supported until full buy-in can be achieved. Robust and quantified evidence of eliminating avoidable and recurring costs against the regular modus operandi, also by following the versatility aspect, should be provided. Cost savings, efficiency gains, new capabilities for acting proactively, and, finally, accounting for significant co-benefits of a solution should be documented and curated for interested stakeholders. This approach is not always straightforward because of the inherent complexity of the city system and the still immature EO permeation into it, as the capacities unleashed by revolutionary monitoring are yet to unfold.

Overall, SMURBS has gradually set itself as an authoritative EO

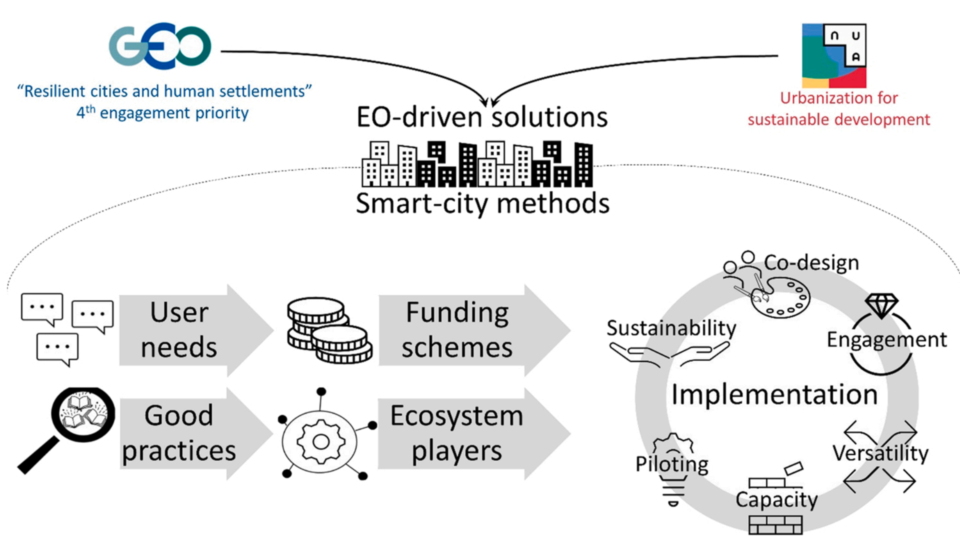

Fig. 4. SMURBS' conceptual framework for the implementation of smart and EO-based solutions in cities.

ambassador within the smart city initiative landscape and serves as a reference project linked to GEO, undertaking the role of creating bridges with the growing ecosystem of smart and sustainable cities. During this process, the lack of a common interface between the two discrete worlds was crystallized, thus, the resources and tangible outcomes of the project (i.e. portfolio, network of cities) facilitated a multifaceted interaction that soon triggered a snowball effect. In this regard, SMURBS illuminated that the way to merge EO with smart and sustainable city practices cannot only be limited to projects explicitly targeting specific urban issues, but necessitates frame programmes like ERA-PLANET, which lay the foundations and provide the authoritativeness and impetus for the desired convergence. At the city level, the full impact of EO-based solutions proves challenging, firstly to identify and subsequently to quantify, as it may have long reaching implications across types of stakeholders and timeframes. Even though mapping of environmental pressures and the monitoring of related indicators is a prerequisite, it does not guarantee the achievement of the underlying targets. The use of EO is a necessary but not sufficient condition, it needs to be expanded in the consciousness of policy makers and stakeholders, beyond monitoring into holistic planning for the sustainable future of cities. Building on the work, experience and networking of SMURBS, within the recently established policy frame of the New Urban Agenda and the anticipated momentum brought by the GEO 4th engagement priority, the relationship between EO practitioners and city level users will be cemented and more real-world solutions will emerge.

CRediT authorship contribution statement

Evangelos Gerasopoulos: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition, Supervision. **Jennifer Bailey:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Eleni Athanasopoulou:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Orestis Speyer:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **David Kocman:** Investigation, Writing – review & editing. **Astrid Raudner:** Investigation, Writing – review & editing. **Alexia Tsouni:** Investigation, Writing – review & editing. **Haris Kontoes:** Investigation, Writing – review & editing. **Christer Johansson:** Investigation, Writing – review & editing. **Charalampos Georgiadis:** Investigation, Writing – review & editing. **Volker Matthias:** Investigation, Writing – review & editing. **Nataliia Kussul:** Investigation, Writing – review & editing. **Mariella Aquilino:** Investigation, Writing – review & editing. **Pauli Paasonen:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.02.033.

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