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Using web GIS to promote stakeholder understanding of scientific results in sustainable urban development: A case study in Bergen, Norway

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Abstract

This paper highlights the importance of improving stakeholder understanding of environmental factors such as air quality and the urban heat island effect to achieve sustainable development goals. While accurate spatial and temporal environmental data are critical for sustainable solutions, the challenge lies in translating complex environmental information for non-specialists. To solve this problem, we propose using web GIS storytelling as a powerful tool for communicating and disseminating information about the environment. This paper aims to show example of implementation of a web-based geographic information system (GIS) on our case study in Bergen, Norway. This platform "Web GIS Bergen, air quality and thermal comfort" was created as an open portal. This document explains the components of the platform, their rationale, and implementation, which includes important steps. They involve the collection of relevant environmental data, including modeling results and remote sensing data. Futhermore, the design and interface of the platform has been carefully considered to provide a user-friendly experience based on interactive maps and storytelling. Combining data visualization and storytelling, the platform promotes a comprehensive understanding of complex environmental data, including "invisible killers" such as air pollution and the urban heat island effect, which significantly affect sustainable development. The strategic integration of this web-based GIS platform in Bergen can serve as an attractive model for other urban areas looking for practical tools for sustainable development, engaging stakeholders for a healthier and more sustainable urban future.

KEYWORDS
air quality, stakeholders, sustainable solutions, urban climate, web-GIS

1 | INTRODUCTION

Supporting sustainable solutions involves increasing people's understanding and knowledge of environmental issues (Holden et al., 2017). Central to achieving this is providing new communication tools and the desire to convey potentially invaluable ecological information to stakeholders and society. The primary purpose of this paper is to demonstrate a straightforward method for efficiently organizing and sharing diverse urban environmental data through a web-based mapping tool. To illustrate this approach, we will use a case study in Bergen, Norway, to provide a clear and practical example.

FIGURE 1 Cruise ships in Bergen harbor, as featured in Bergens Tidene, Published on July 23, 2018.

The main challenge is to effectively communicate complex environmental data to stakeholders, including, for example, simulation results (Rössler et al., 2019). However, presenting complex urban environmental studies can create significant communication barriers (Oltra & Sala, 2015). Here, we conclude that the paramount importance of effective communication of scientific results is based on the fact that research results must not only be accurately disseminated but also be understood by relevant stakeholders (Dahlstrom, 2014; Hutchins, 2020). Visualization techniques have become a critical channel for transforming complex data into a human-readable format for seamlessly communicating these research results, especially in spatial complexity (Caquard & Cartwright, 2014). Here, we borrow the term "smart maps" (ESRI) to emphasize that web maps can be complex but effectively make complex data accessible and functional, especially for non-technical audiences. Visual tools such as interactive maps embellished with color cues and simple data markers (Andrienko et al., 1999), combined with explanatory videos and visual effects, become tools to help communicate data related to air quality, pollutant concentrations, emission sources, and key variables, to a wide range of stakeholders.

The paper demonstrates a user-friendly geographic information system (GIS) web-based platform for reporting urban climate and air quality in Bergen, Norway. The means to achieve this goal materialized through the ArcGIS cloud software, a channel for creating interactive web maps that seamlessly integrate survey data, simulated scenarios, remote sensing data, and in situ measurements. The case study in Bergen was chosen strategically due to the complex ecological landscape and abundance of scientific evidence, making it the perfect model to showcase the full potential of this platform. Bergen serves as a shining example of the environmental issues that plague many cities worldwide. Particularly during winter, the city grapples with poor air quality, largely driven by elevated levels of nitrogen dioxide (NO_2) stemming from road traffic and wood-fired heating systems (Wolf-Grosse et al., 2017). These unfavorable air conditions, combined with occasional heatwaves (Rousi et al., 2023), highlight the urgent need to address the urban environmental quality problem. It is worth noting that air pollution and urban heat have often earned the nickname "invisible killers" due to their subtle but highly detrimental effects on public health (Manisalidis et al., 2020; Massay-Kosubek, 2018; Masselot et al., 2023). Unfortunately, these problems often go unnoticed by both the general public and the authorities, which highlights the importance of innovative communication methods to effectively address these problems.

In July 2019, a severe summer heat wave hit Bergen, exacerbating air pollution problems. The combination of calm winds, stable air, cloudless skies and high temperatures created a scenario in which air pollution was particularly severe (Wolf-Grosse et al., 2017). Layers of haze became visible, drawing the attention of the public. For example, Figure 1 clearly shows haze coming from the exhaust gases of cruise ships in Bergen harbor. This situation has caused tension among social activists, local stakeholders and Bergen port authorities. Although visible haze was conspicuous, true pollutants such as aerosols or particulate matter (PM) and nitrogen oxides (NOx) remained invisible. This invisibility was exacerbated by the limited number of air quality measurement stations in this area of the city —- only two (Høiskar et al., 2017).

Scientists have solved this problem using advances in remote sensing and local climate modeling (Piracha & Chaudhary, 2022; Schaefer et al., 2021; Wolf-Grosse et al., 2017). Using remote sensing data and high-resolution urban models, areas prone to heatwaves and air pollution can be pinpointed, allowing targeted action (Lappalainen et al., 2022; Schaefer et al., 2021). In Bergen, this information can help prioritize mitigation measures such as green infrastructure development (Venter et al., 2020) and implementation of heat warning systems (Tilley Tajet et al., 2022; Toloo et al., 2013).

The integration of high-resolution satellite remote sensing and city modeling data into GIS tools represents a progressive step in supporting urban resilience and planning (Sidiqui et al., 2022). GIS tools have historically played a key role in the visualization of scientific data (Ferda, 1993; Goodchild, 2005). However, conventional GIS software often has limitations: it can be expensive, complex, and require specialized knowledge. The advent of the World Wide Web (www) has revolutionized many areas, including GIS. The advent of web GIS, an extension of traditional GIS to web platforms, makes it easier to interactively visualize and interact with geospatial data through common web browsers on a variety of devices. Consequently, these platforms offer greater access by eliminating geo-restrictions and device dependencies without requiring special skills or licenses. However, web GIS and storytelling have their limitations. Web GIS can inadvertently exclude specific stakeholders due to connectivity issues and data quality concerns. The complexity of web GIS interfaces can make it difficult for users with limited technical knowledge. At the same time, storytelling is challenged to strike a balance between technical accuracy and interesting storytelling, thereby convincingly conveying complex scientific details. The effectiveness of storytelling depends largely on the skill of the communicator, making it a time-consuming task. Recognizing these limitations and developing strategies to address these issues can greatly enhance the effectiveness of these tools for more efficient communication of scientific information.

To circumvent these complexities, Bergen's web GIS platform adopted a user-centric approach. "User-centered approach" means a design philosophy that prioritizes the needs, preferences, and experience of the user throughout the development process (Morgan, 2016; Norman, 2002). This approach, adapted to the design of a web-based GIS platform, entails ease of use, increased accessibility, and optimization of user understanding. Achieving these goals involves incorporating interactive elements, intuitive navigation, clear explanations, and user-friendly interfaces, all of which enhance overall user experience and engagement

The implementation of the web GIS platform in Bergen entailed several pivotal steps. The process commenced with the comprehensive compilation of pertinent environmental data, encompassing modeling results, remote sensing information, and more. Subsequently, meticulous attention was directed towards designing a user-friendly interface and platform layout, ensuring a seamless and uncomplicated user experience. Interactive visualizations, intuitive navigation features, and descriptive explanations were thoughtfully integrated to foster greater understanding of the presented data.

Our web GIS platform wasn't simply created to raise awareness about the issue. It was also crafted to assist stakeholders in evaluating impacts, gauging vulnerability, identifying risks, exploring adaptive solutions, setting priorities, planning actions, and monitoring the sustainability of implemented measures. To this end, the "Steps to Resilience" concept was applied in the platform's development, aligning with its guiding principles (Gardiner et al., 2019, 2022).

The strategic implementation of the web GIS platform in Bergen effectively showcases its potential as a robust tool for communicating intricate scientific information. The use of web GIS technologies facilitates the integration of diverse environmental information into a single data ecosystem that is easily accessible for use. By rendering environmental data more accessible and visually engaging, stakeholders are better equipped to comprehend the implications of their choices on the environment (Caquard & Cartwright, 2014; Sundin et al., 2018). This subsequently cultivates a culture of informed decision-making, fostering a shift towards more sustainable practices and policies. This endeavor marks a significant step towards ensuring that urban areas are better equipped to address and overcome complex environmental challenges.

2 | DATA AND METHOD

2.1 | Geography and population

Bergen is a city located on the west coast of Norway at 60° N latitude and 5° E longitude. The town is surrounded by seven mountains and is known for its rainy weather and beautiful fjords. The central part of the city (Figure 2) lies in a narrow, curved valley with the valley floor at least 1 km wide and the surrounding mountain peaks ranging from 344 to 642 m high. The municipality of Bergen has 282,000 inhabitants, of which 84,000 live in these central areas. Currently, the population density of the whole city of Bergen is 630 inhabitants per km^2, whilst the main areas have a population density of 2111 inhabitants per km^2. The central area makes up 12% of the total built-up areas in the Bergen municipality. The municipality of Bergen aims to densify 50 percent of new housing within the city's central parts and add 10,000 new dwellings by 2030 (Koning et al., 2020; Koning et al., 2022). As a city experiencing densification over the years, Bergen has seen the development of more tall buildings and narrow streets, which can create an urban canyon effect in certain areas. An urban canyon is a term used to describe a narrow, street-like space flanked on either side by tall buildings. This can create a canyon-like effect, where sunlight is blocked out, and shadows are cast over the area, giving it a unique character. While the urban canyon effect can contribute to a city's visual interest and character, it can also negatively impact air quality, thermal comfort, and the urban environment more broadly.

The recent shift in policy reflects a global trend of moving towards low-carbon, low-emission cities in the battle against climate change, global warming, and dwindling resources. Following national and local objectives, the municipality aims to reduce urban sprawl into the countryside and transport energy usage by investing in public transport and increasing the building intensity and land-use mix around these public transport lines.

2.2 | Framework "Web GIS Bergen, air quality and thermal comfort"

The integrated framework (Figure 3) "Web GIS Bergen: Air Quality and Thermal Comfort" consists of two essential components. The first

FIGURE 2 Map of Bergen. Sources: Esri, DigitalGlobe, GeoEye, i cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

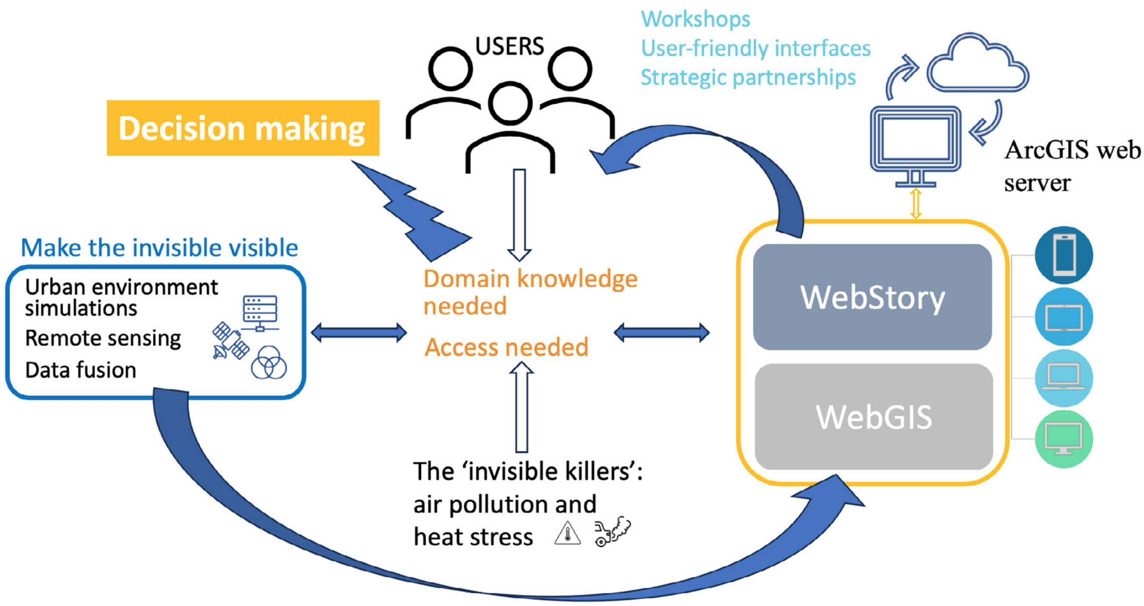

FIGURE 3 Integrated framework “Web GIS Bergen: Air quality and thermal comfort”.

component is an immersive web-based narrative that delves into the intricacies of Bergen's air quality and local climate zones. This interactive storytelling experience combines a variety of multimedia elements, including interactive maps, captivating images, enlightening videos, and compelling narratives. Within this narrative, users can explore and understand the multifaceted aspects of Bergen's urban environment. The seamless integration of simulation outcomes and remote sensing data in these maps provides users with a comprehensive view of various attributes of the city. This unique blend of information sources facilitates a deeper understanding of the interplay between air quality and thermal comfort in Bergen, ultimately empowering users with valuable insights into their local environment.

The second component is an embedded web GIS, which organizes the image of the urban environment through complex thematic layers. This field uses various tools for multi-faceted classification, rigorous evaluation, and deep metric analysis. This bifurcated architecture of Bergen's web GIS reflects the goal of accommodating diverse groups of users, each of which desires certain granularities of information and tools (Österbring et al., 2018). In addition, this separation helps simplify the system's management, maintenance, and development, allowing for autonomous action, thorough testing, and isolated deployment of each module.

Both aspects of this web GIS architecture serve different levels of information and functionality while contributing to the whole. The most crucial section, the web story, has been carefully designed to be interactive and engaging (Roth, 2021). It immerses users in a compelling narrative that reveals the historical trajectory of air pollution and local climate zones in Bergen. The accessible discourse in this section uses intuitive maps, engaging graphics, and a variety of visual aids to keep the storytelling simple.

In contrast, the web GIS extends advanced functionality for users interested in conducting more in-depth analyses of the urban environment. This module grants access to both quantitative and qualitative information concerning urban parameters. Specifically, it equips users with tools to elucidate data classifications, conduct rigorous evaluations, and perform detailed analyses tailored to thematic levels and individual interests. Consequently, this dichotomous composition allows users to interact with the web GIS based on their specific needs, whether they want to explore the engaging web narrative or delve into the complex analyses facilitated by the web GIS.

2.3 | Geospatial input data

The geospatial input data used in the web GIS tool consists of various types of spatial objects (points, lines, and polygons) with x-y coordinates, along with an attached attribute table containing relevant information about the objects. This information includes details about the shape, size, ownership, network values, dimensions, age, function, and other characteristics of the spatial objects.

The main input parameters we used in the tool describe various aspects of urban structure, urban form, building density, road centerlines, and transport use. The urban structure is represented as line segments from axial drawing, including attribute data such as network values of closeness and betweenness. Urban form is represented as polygons with building attribute data such as dimensions, age, and functions. Building density is calculated via the dimensions and spatial location of the land use plots. Road centerlines contain dimensions and spatial locations of the network of roads, streets, paths, and alleyways. Finally, transport use includes the amounts of traffic and maximum speeds on the roads and streets to calculate transport energy usage.

Some of the spatial data files we used in the tool are georeferenced axial maps hand-drawn by researchers and validated with local experts. Other data were obtained from open-source online resources via ArcGIS Editor for OpenStreetMap (OSM). Finally, information on transport capacity and building use were proprietary data provided on request by local and national authorities.

In tandem with geospatial input data, the web GIS tool necessitates various additional inputs. The initial input is a land cover layer, often in ESRI Shapefile format. Currently accessible solely for cities encompassed by the Copernicus Urban Atlas geodatabase (UA2018), this data intersects with an OSM layer housing building footprints to ascertain terrain types within shapefile polygons (pavement, vegetation, water, building). The second input is a digital elevation model (DEM) in GeoTiff format, with a recommended resolution of 25 m from the Copernicus EU-DEM. The third input encompasses building heights, also in GeoTiff format, with a recommended resolution of 10 m from the Copernicus Building Height layer.

2.4 | Leveraging remote sensing data

Integrating Land Surface Temperature (LST) is crucial for studying urban heat islands (UHI) and monitoring temperature variations across diverse environments (Miles et al., 2023; Yang et al., 2020). Satellite remote sensing is the optimal method for measuring LST and generating related data at regional to local scales. Remote sensing data from the Landsat satellite, known for its high resolution, is particularly well-suited. LST data is derived from thermal infrared (TIR) measurements captured by Landsat satellites, explicitly focusing on bands 10 and 11 (10.8–11.3 μm) from Landsat 8. This spectral band excels at capturing thermal data, providing valuable insights into temperature patterns across land surfaces.

Urban Local Heat Zones (ULHZ) are areas within urban environments characterized by elevated temperatures. By combining LST maps with GIS data, we can precisely identify areas with heightened temperature levels. Land use, urban design, and surface materials often influence these elevated temperatures. This integration of LST and GIS data allows for a comprehensive analysis of ULHZ, contributing to a better understanding of urban heat patterns.

In the context of the “Web GIS Bergen, Air Quality, and Thermal Comfort” framework, the utilization of LST data contributes to a comprehensive understanding of urban heat dynamics. By integrating LST data into the web GIS platform, stakeholders and researchers gain insights into the spatial distribution of heat zones within Bergen. This information is pivotal for informed decision-making aimed at mitigating the adverse effects of urban heat islands, enhancing thermal comfort, and promoting sustainable urban development (Gago et al., 2013).

Assessing urban vegetation distribution and type entails utilizing the Normalized Difference Vegetation Index (NDVI) (Huang et al., 2021). This index reflects vegetation vitality and productivity. Computation of NDVI relies on distinguishing between red and near-infrared (NIR) reflectance values derived from remote sensing data. This index serves as a pivotal indicator of vegetative health and density across various landscapes, enabling insightful assessments of vegetation cover and vitality. In this process, the NDVI is calculated using a formula that subtracts the NIR reflectance value from the red reflectance value and then divides the result by their sum.

The spatial information pertaining to vegetation distribution and density is gleaned by disseminating NDVI values across urban areas. Leveraging these remote sensing techniques augments the comprehensiveness of the web GIS framework, enabling a holistic depiction of the urban environment.

2.5 | Empowering data accessibility through ArcGIS server and web services

ArcGIS Server plays a key role in providing access to a wealth of data, including features, tables, maps, tools, images, and locators, to clients and possibly the wider online community through web services. These services, as defined in the ArcGIS online (ArcGIS online manual) guide, effectively act as conduits for our data, providing access to stored information without the need for direct access to the underlying storage locations.

Web services work as a means to seamlessly access and share data without the need for data duplication. In particular, for static data, caching methods are used, in which the data is stored separately from the original source. This strategic approach improves drawing performance by providing a smoother experience with data.

The choice of the appropriate type of web service is determined by the nature of the data provided and the intended user interaction. In the context of the "Web GIS of Bergen, air quality and thermal comfort", the selected web services allow visualization and querying of urban spatial data presented in a map format. This technique is particularly suited to two main types of spatial data: spatial data and image data. The map format, enriched with functional information, serves as a gateway for users to obtain detailed information about specific objects of interest.

One of the most important results of using ArcGIS Server and web services is to provide map services that allow other users to seamlessly view and interact with GIS content on the web (ArcGIS web server). These map services support rendering and querying and are flexible enough to be configured to dynamically retrieve data or use existing cached tiles. This adaptability empowers users by allowing them to seamlessly interact with content.

In the context of "Web GIS Bergen, air quality and thermal comfort", this ArcGIS option effectively transforms thematic layers into interactive elements for users. This feature makes it easy to seamlessly switch between layers, zoom in and out for closer inspection, and easily access attribute information through visual pop-ups. This integration not only enhances user engagement, but also empowers stakeholders and researchers to delve deeper into complex spatial data, contributing to a better understanding of the urban environment.

3 | RESULTS: NAVIGATING URBAN CHALLENGES WITH WEB GIS IN BERGEN

"The Urban Air Pollution and Thermal Comfort" web GIS story was created to present the model results and remote sensing studies focused on understanding the impact of these challenges and assessing the risks and vulnerabilities of the city. The story highlights the difficulties faced by Bergen, such as air pollution and extreme weather events, and the measures being taken to address them, such as reducing emissions from wood-burning stoves, promoting sustainable transportation, and supporting and developing green and blue urban infrastructure.

The Bergen web GIS story is structured around a three-step process towards building resilience: understanding the impact, assessing vulnerability and risk, and exploring options. By following this process, the city can identify the most effective ways to address its environmental challenges and build a more sustainable and resilient urban environment for its inhabitants.

3.1 | Understanding exposure: Air pollution, cruise ships, and extreme heat events in Bergen

Bergen, a picturesque coastal city in Norway, confronts a spectrum of environmental issues that impact its inhabitants' well-being. These challenges, including air pollution, cruise ship emissions, and extreme heat events, have garnered increased attention due to their potential health and environmental consequences.

Air pollution and winter Inversion: Bergen's unique topography, nestled among mountains and hills, contributes to the phenomenon of "winter inversion". During this atmospheric condition, a layer of cold air becomes trapped beneath a layer of warmer air, leading to the accumulation of pollutants at ground level (Figure 4). This is exacerbated by emissions from residential wood-burning stoves and traffic. Notably, the city's limited dispersion capacity due to its surroundings exacerbates the situation. The air pollution problem was highlighted by a significant event in January 2010 and continues to be a concern, particularly as the city aims to improve air quality by reducing emissions and promoting sustainable transportation alternatives.

Cruise ship emissions: As a gateway to the fjords, Bergen is a sought-after destination for cruise ships, welcoming hundreds of vessels and passengers annually. However, the environmental impact of cruise ship emissions cannot be ignored. These emissions, which encompass sulfur dioxide, nitrogen oxides, particulate matter, and carbon dioxide, raise concerns about air quality and public health. When cruise ships dock, they often continue running engines for onboard systems, contributing to localized pollution. The areas near the port and along the shipping route bear the brunt of these emissions, necessitating measures to mitigate their effects.

Rising heat waves: Contrary to its reputation for mild and rainy weather, Bergen has experienced an increase in extreme heat events. The number of days with temperatures exceeding 25°C has tripled since 1960. The summer of 2018 and following summer of 2019 marked a milestone with temperatures soaring to 33.4°C, surpassing previous records. These heat waves, while unusual for Bergen, pose health risks, especially for vulnerable populations. As climate change intensifies, the city's residents and infrastructure face challenges in adapting to these increasingly frequent and severe heat events (Liu et al., 2023; Tilley Tajet et al., 2022).

In the face of these interconnected environmental challenges, Bergen is taking strides to enhance its resilience and safeguard the well-being of its residents. By addressing air pollution, cruise ship emissions, and heat waves through comprehensive policies and initiatives, the city aims to ensure a healthier and more sustainable urban future.

FIGURE 4 Accumulation of pollutants at ground level due to "winter inversion." Courtesy, T. Wolf.

3.2 | Assessing vulnerability and risk in Bergen: Modeling and remote sensing

To understand the vulnerability and risk posed by urban pollution sources and extreme heat in Bergen, a comprehensive approach combining modeling and remote sensing was employed.

3.2.1 | Modeling approach

The Parallelized Large-Eddy Simulation Model (PALM) was utilized for its turbulence-resolving capabilities (Maronga et al., 2015; Wolf et al., 2020; Wolf et al., 2021). This model simulated urban air motion and pollution transport with high geographical resolution. By focusing on influential meteorological scenarios, especially calm weather conditions conducive to pollutant accumulation, the impact of sources like road traffic, harbor ships, and wood-burning fireplaces on air quality and pollution pathways were assessed. Street-level winds, temperature, moisture, and air quality were characterized. Simulation outcomes illustrated pollutant distribution and concentration around urban areas. The study (Wolf et al., 2020) produced vulnerability maps (Figure 5), highlighting the most impacted districts for each weather and emission scenario. Overall, the largest contribution to air pollution over inhabited areas in Bergen was caused by road traffic emissions for NO_2 and wood-burning fireplaces for $PM_{2.5}$ pollution (Wolf et al., 2020; Wolf et al., 2021).

3.2.2 | Remote sensing insights

Distinctive urban climates stem from diverse factors, including urban forms, land covers, and surface-atmosphere interactions. Urban environments exhibit spatial heterogeneity, creating varied microclimatic conditions. Urban conditions within a city generate distinct microclimatic conditions, primarily influenced by the presence or absence of vegetation, bodies of water, and the types of urban structures and surface materials in use. These factors collectively contribute to the formation of unique microclimates in specific areas of the urban environment, which can be categorized into four main types in Bergen (Figure 6). The uneven distribution of heat in the city results in localized areas of high thermal stress, with temperatures significantly surpassing surrounding regions. Satellite remote sensing, notably Landsat, offers critical insights into urban thermal environments. The Land Surface Temperature map derived from Landsat data enables detailed identification of the hottest urban neighborhoods, aiding efforts to mitigate the urban heat island effect (Figure 7).

3.3 | Exploring mitigation strategies in Bergen: Addressing air pollution and local urban heat islands

In the face of mounting challenges posed by air pollution and the urban heat island effect, Bergen is taking proactive steps to mitigate their impacts and enhance the urban environment's quality and resilience.

3.3.1 | Maritime emission reduction

Bergen's role as a prominent maritime hub necessitates a focus on reducing emissions from ships. The implementation of a shore power system at the port exemplifies a pioneering move to cut down emissions by allowing ships to connect to the grid while docked. Collaborative efforts with cruise ship operators and stakeholders further emphasize the commitment to curbing emissions within the port area. By introducing economic incentives and collaborative measures, the

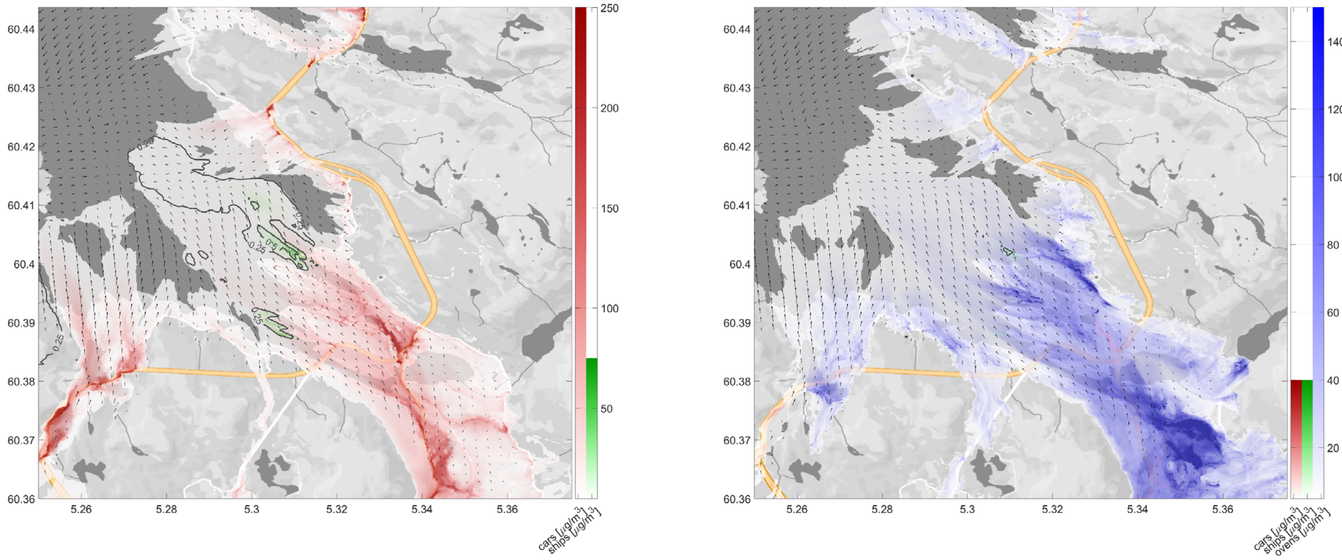

FIGURE 5 Dispersion and concentration of NO_2 (left panel) and $PM_{2.5}$ (right panel) in central Bergen.

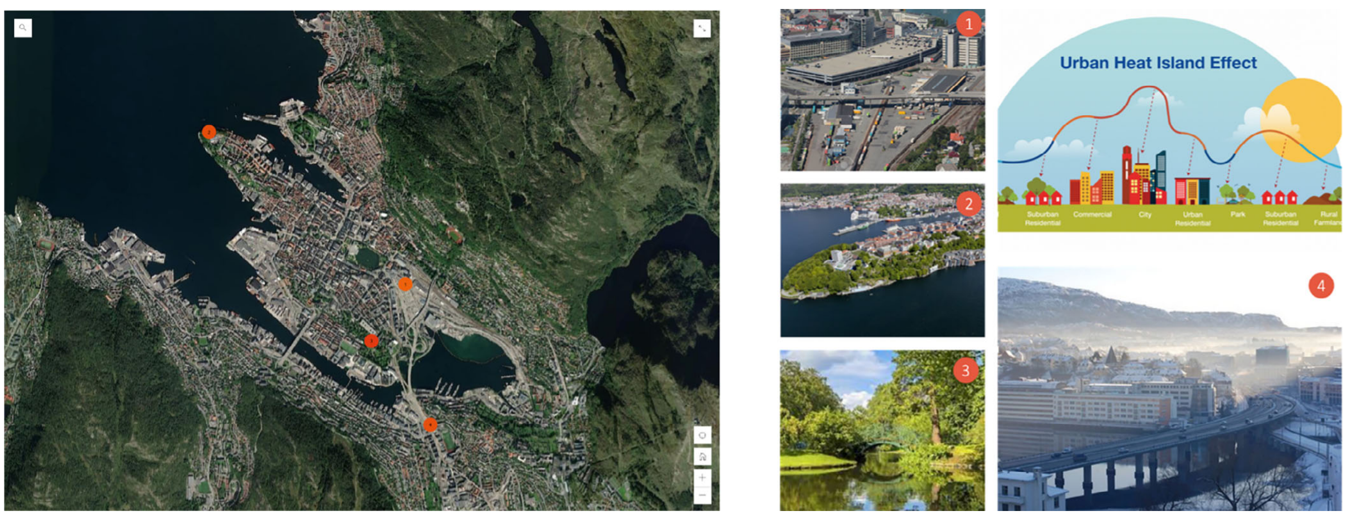

FIGURE 6 Various urban environments of Bergen, ArcGIS base map. (1) No vegetation, dense paved area. (2) Urban areas surrounded by water and vegetation. (3) Urban Park. (4) No vegetation but waterfront.

city aims to create a cleaner and healthier environment around the port and adjacent regions (Wolf et al., 2021).

3.3.2 | Wood-burning emission mitigation

Addressing localized sources of air pollution, particularly residential wood-burning, requires tailored strategies. Concentrated efforts in specific areas have been identified as an effective way to combat particulate matter and air pollution. This targeted approach demonstrates the potential to significantly reduce pollutants by addressing pollution at its origin. By pinpointing areas with higher emission levels, Bergen can enact policies that address sources of pollution directly, thereby contributing to improved air quality across the city (Wolf et al., 2021).

3.3.3 | Urban greenery for temperature regulation

To counteract the urban heat island effect, the importance of urban green spaces emerges as a vital mitigation strategy (Pereira et al., 2023). In Figure 8, left panel, featuring the vegetation-temperature map, prominently illustrates that areas surrounded by vegetation and located in close proximity to water bodies experience more comfortable temperatures. On the right panel of Figure 8, a detailed analysis reveals a clear correlation between elevated temperatures and areas lacking vegetation. Incorporating trees and water bodies in urban planning significantly mitigates temperature stress, creating cooler microclimates. This approach exemplifies how strategic urban design can not only lower temperatures but also enhance residents' quality of life and well-being.

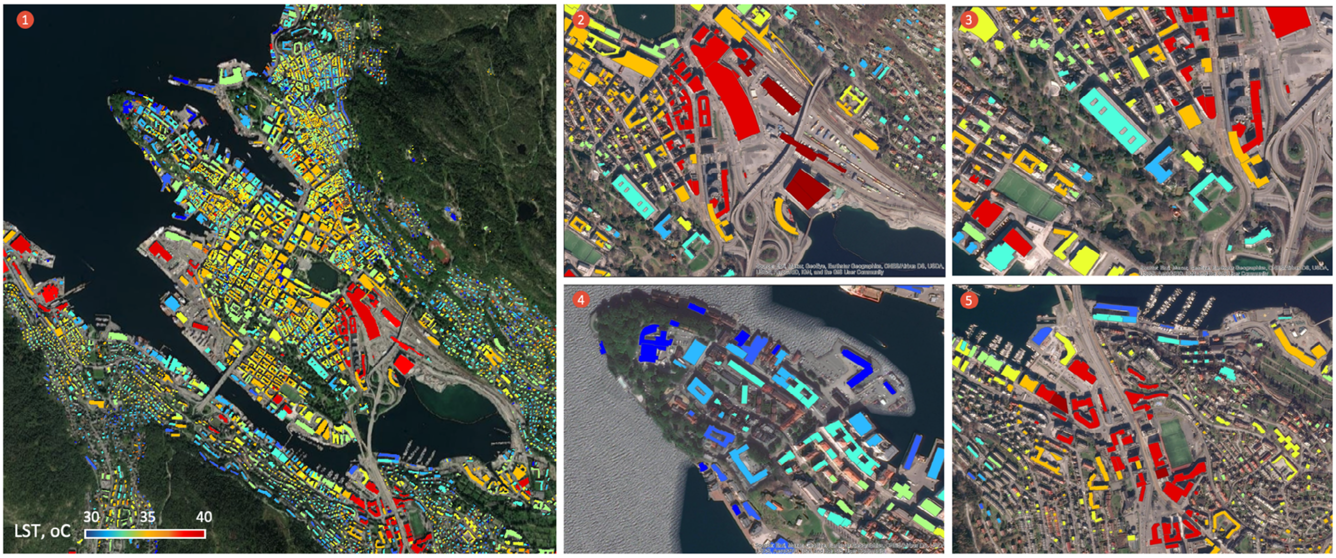

FIGURE 7 (1) Localized areas of increased thermal stress. Landsat LST map, July 2019, overlaid on ArcGIS base map. (2) In areas characterized by a lack of vegetation and extensive pavement, such as urban downtowns or industrial zones, microclimatic conditions often include elevated temperatures due to the heat-absorbing properties of pavement. These areas may experience urban heat islands, with increased heat retention. (3) Urban locations surrounded by bodies of water and lush vegetation typically exhibit more temperate microclimates. The presence of water bodies and vegetation can mitigate temperature extremes, providing a cooling effect and contributing to improved air quality. (4) Urban parks are characterized by an abundance of vegetation and green spaces. They create microclimatic conditions conducive to lower temperatures and improved air quality. The vegetation in parks provides shade and helps reduce heat, making them cooler and more comfortable areas within the city. (5) Areas along waterfronts that lack substantial vegetation can have distinct microclimates. The proximity to water bodies can moderate temperatures, leading to milder conditions compared to inland areas without vegetation.

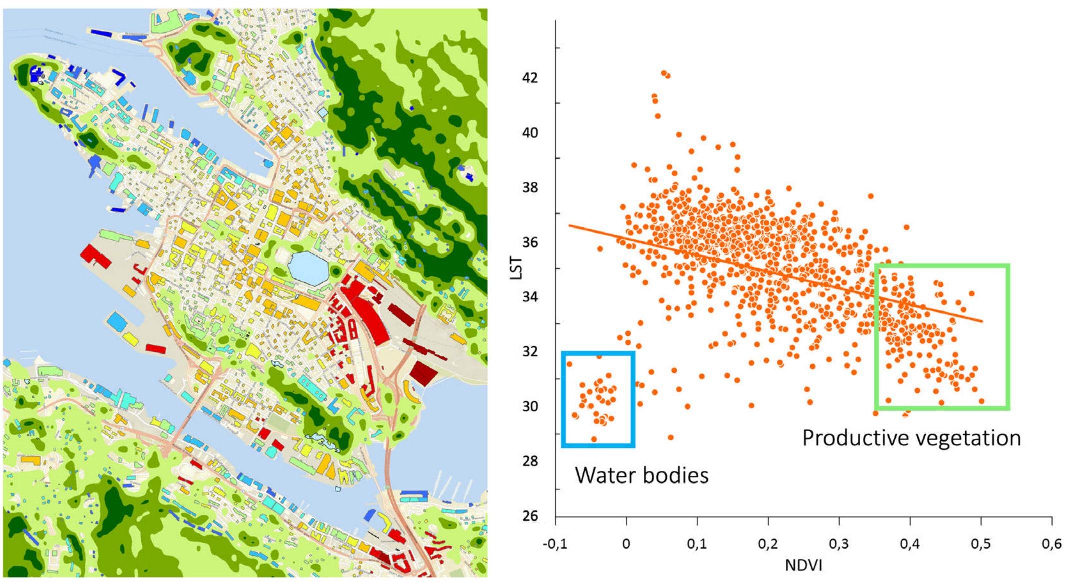

FIGURE 8 Left Panel: The vegetation and temperature map uses green areas to represent urban vegetation, with the darkest green indicating the highest vegetation productivity, typically urban trees. Right Panel: This panel shows the correlation between remotely sensed land surface temperatures and the quantity of vegetation.

3.3.4 | Integrated visualizations for informed decision-making

Navigating complex urban challenges requires a holistic understanding facilitated by integrated visualizations. By overlaying diverse datasets, such as air quality, temperature distribution, and land use patterns, decision-makers gain insights into the intricate urban dynamics. This comprehensive perspective aids in identifying synergistic mitigation opportunities and crafting well-informed policies for sustainable urban development. Figure 9 serves as a showcase for the diverse thematic

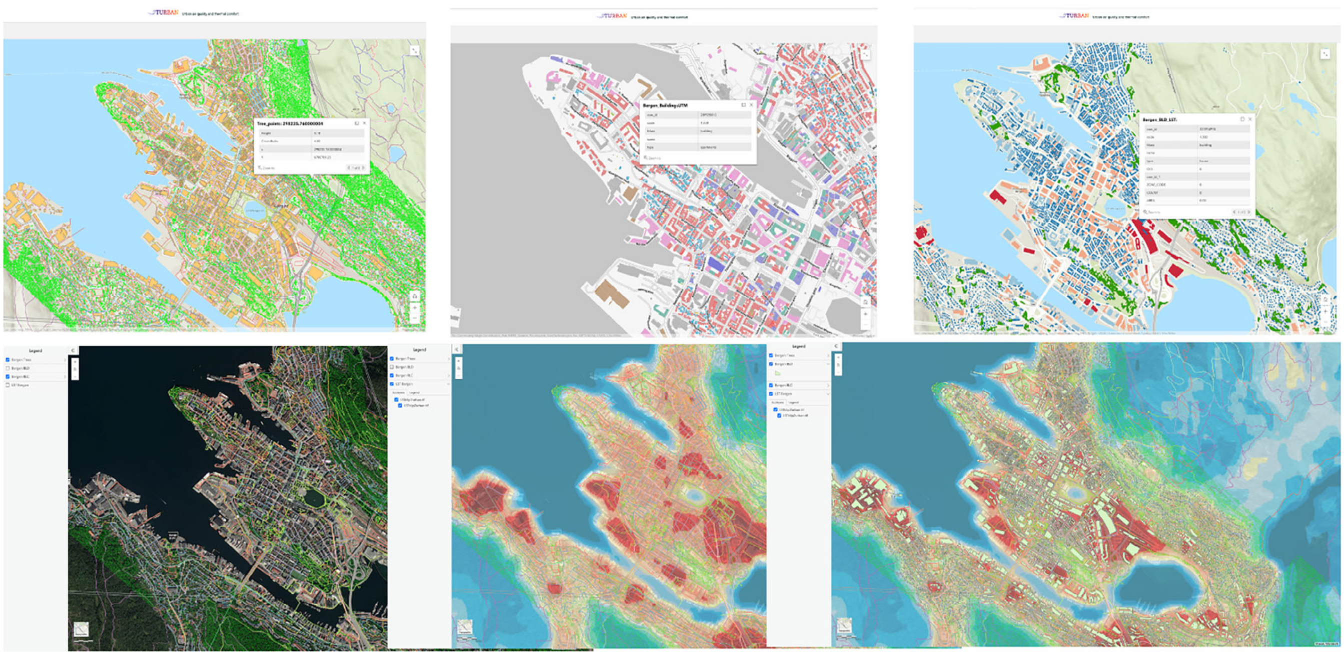

FIGURE 9 Examples of thematic layers within the Bergen eb GIS.

layers employed to represent the urban environment within the Bergen Web GIS. Such integrated visualizations align with Bergen's commitment to data-driven decision-making and fostering a resilient urban environment.

4 | DISCUSSION

Prioritizing, planning, and taking action are critical steps in addressing environmental issues in the city (Wolf et al., 2020). As with many cities, Bergen faces various environmental issues, including air pollution and heat stress. Therefore, the city needs to take a proactive approach to address these challenges, leveraging technology and data to develop effective interventions and improve the quality of life for its residents (Oltra & Sala, 2015).

Bergen web GIS appears to be a valuable tool in this process, providing updates on the impact of interventions and helping urban authorities refine their approaches. Thus, for example, storytelling about a Bergen port solution for air pollution is a story of a past event and actions taken in response. It fits the most common historical pattern in which mitigating measures are taken after the situation becomes a "hot spot" of urban public discourse. This web GIS storytelling increased awareness and explored mitigation solutions about local air quality and climate change information. This storytelling has resulted in a pilot climate service project and subsequent enhancement of the web GIS results. Once priorities are identified, policymakers can develop plans and interventions to address these issues (Trane et al., 2023). Addressing environmental issues in the city requires collaboration and partnership across diverse stakeholders (Hartman et al., 2002). Stakeholders (Bergen Port AS and the Bergen municipality) were engaged from the outset in the development of the case. The storyline captured the direct and indirect consequences of polluting emissions from the harbor areas. A co-production approach was used to design model simulation setups and to collect information about exogenous factors of potential importance for this case (Wolf-Grosse et al., 2017). The resulting storytelling was compelling for considering risks from compound air quality hazards, namely, when air pollution from the port, road traffic, and household wood combustion was considered.

The scientist's quest to improve the urban environment relies on sophisticated tools such as satellite remote sensing, GIS, and high-resolution urban modeling (Esau et al., 2021). This arsenal provides insights critical to urban resilience and planning, especially in extreme weather conditions, shedding light on thermal comfort and air quality. For example, in Bergen, these tools have identified strategies such as cleaner wood-burning stoves and green spaces to reduce air pollution and temperature stress in central areas (Wolf et al., 2021). The ability of satellite remote sensing to measure ground surface temperature (LST) helps assess thermal comfort and heat stress, thus facilitating the development of strategies to combat urban heat islands and improve citizen well-being (Han et al., 2022).

Integrating physical plausibility into storytelling via web GIS plays a key role in enhancing the credibility and reliability of storytelling of various events (Sundin et al., 2018). This approach achieves this by using simulation results to describe complex process interactions, feedback loops, and observable patterns. Notably, these modeling efforts contribute to scientific understanding by delving into modeling that considers local extreme events, taking into account their relationship to broader, large-scale background patterns (Wolf et al., 2014).

For example, consider the case of air pollution dispersion in Bergen's urban environment. Using web GIS stories, simulation results can visualize the likely movement of pollutants, taking into account factors such as wind patterns, emission sources, and geographic features. This approach not only enhances the visual storytelling but also lends scientific credibility by ensuring that the scenarios depicted are based on the physical plausibility of the real world.

Moreover, the use of high resolution modeling can extend the capabilities of web GIS to include risk assessment. In the context of extreme heat, such modeling can quantify the likelihood and intensity of heatwaves based on historical climate data and predictive models. This will allow stakeholders to assess the likelihood of such events occurring, helping to formulate proactive mitigation strategies.

While this paper highlights the introductory, rationale, technical, and demonstrational aspects of urban-scale storytelling of environmental web GIS, it has the potential to be applied more widely. This technology could evolve into an integrated urban system (IUS), reminiscent of the concept of urban digital twins (Allam et al., 2022). This extension may include multifaceted solutions such as the inclusion of economic models to assess the plausibility of urban development scenarios. Through this holistic approach, stakeholders gain insight into the complex interplay between different urban elements, in line with the overarching vision of smart cities.

Integrating simulation-derived believability into storytelling via web GIS offers a solid scientific basis for urban storytelling. By linking simulation results to real events and future scenarios, this approach provides decision makers with a deeper understanding of urban dynamics and a more holistic view of potential outcomes.

Integrated storytelling with web-based platforms GIS has a remarkable ability to bridge the gap between complex urban environments and diverse audiences. The Bergen Web GIS in particular is a testament to the effectiveness of this approach in conveying important messages and raising awareness of the complex interplay between urban dynamics and environmental issues.

Using web GIS technology, the Bergen Initiative goes beyond technical experts and politicians to reach a wider range of users. This inclusiveness makes the platform an outreach tool that goes beyond the traditional dissemination of data. Web GIS is becoming a conduit for the democratization of information, allowing citizens, community members, and even students to access and understand complex environmental concepts. Affordable visualizations and interactive features transform scientific data into understandable narratives, allowing people of all skill levels to understand the nuances of air pollution, heat stress, and their potential impacts on public health and well-being.

In the context of urban environmental issues such as air pollution and heat stress, Bergen Web GIS creates a compelling story that resonates with its audience. Instead of presenting an abstract set of data, the platform creates a coherent narrative that connects the dots between environmental factors and their human impact. It explains how air pollution and rising temperatures can have a tangible impact on the health and well-being of citizens, fostering a sense of personal importance and urgency.

A remarkable aspect of the Bergen Web GIS is the collaborative approach to information dissemination. By reporting results to the Bergen Health Department, the initiative not only raises public awareness but directly informs local governments responsible for public health and well-being. This integration of scientific results into decision-making processes illustrates the practical utility of integrated storytelling. This ensures that the insights generated by web GIS are translated into real actions and policies that effectively address urban environmental issues.

In essence, the power of web GIS lies in its ability to move beyond technical jargon and create a common language through which to understand, absorb, and solve problems in the urban environment. The role of the Bergen WebGIS as an outreach initiative highlights its potential as a catalyst for positive change, raising public awareness and intensifying collaborative efforts to create a healthier and more sustainable urban environment. Engaging and involving the community in efforts to address environmental issues in the city is essential, as they are the ones most impacted by environmental stressors. According to Talley et al. (2016), community engagement is critical to developing practical solutions tailored to residents' needs. The Bergen Web GIS serves as an outreach and education initiative to raise awareness about air pollution, heat stress, and other environmental concerns and their potential impact on public health and well-being. By involving residents in planning and implementing interventions, urban authorities can develop more effective and sustainable solutions in the long term (Lafrance et al., 2019).

Addressing urban environmental challenges requires an unwavering commitment to sustainable development—a comprehensive strategy that effectively balances current needs with the long-term well-being of both present and future generations. To pave the way for sustainable progress, cities must direct resources towards ongoing research and innovative solutions, spurring the identification of practical approaches to solving environmental problems (Esau et al., 2021; Wolf et al., 2020, 2021).

Sustainability is based on a delicate balance between economic growth, social progress and environmental conservation. This balance ensures that today's aspirations do not compromise tomorrow's potential, allowing both current and future residents to access the essential resources and opportunities needed for a prosperous life (Hopwood et al., 2005; Kuhlman & Farrington, 2010).

The story of the Bergen Web GIS demonstrates a structured, three-step approach that embodies this sustainability principle. By embarking on a comprehensive understanding of the complex implications of environmental issues, this approach provides a solid foundation for future action. For example, a holistic understanding of the sources of air pollution and the complex dynamics of the urban heat island effect sheds light on the complex interplay between the multiple factors that shape the urban landscape.

However, sustainable development is not just a theoretical concept; it is a driving force that drives real change in communities (Dobson, 2007). The Bergen Web GIS platform embodies this idea by communicating complex data in the form of sequential stories, making environmental issues tangible and understandable to both experts and the general public. This story-driven approach stimulates awareness, fosters collaboration, and guides decision-making, ultimately moving beyond formality and becoming a catalyst for transformative social change. The lessons learned from Bergen's experience can be useful for other cities facing similar environmental challenges.

5 | CONCLUSIONS

In conclusion, Bergen's web GIS represents a powerful tool in the city's efforts to address environmental challenges and advance sustainable development. Its advantages in communication, data-driven decision-making, community involvement, and scientific credibility align seamlessly with Bergen's commitment to a more sustainable future.

However, it's crucial to acknowledge the challenges related to effectively communicating the capabilities and benefits of this tool to stakeholders. To fully harness the potential of the Bergen web GIS, proactive strategies like hosting workshops, implementing user-friendly interfaces, and forging strategic partnerships are imperative.

Ultimately, Bergen's web GIS's success hinges on its alignment with the city's sustainable development goals. Recognizing its strengths and challenges ensures effective implementation and a lasting impact on environmental issues while advancing sustainable urban development. In essence, the web GIS serves as a practical means to convey scientific knowledge and facilitate solutions, contributing significantly to a more resilient and sustainable future for the city.

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