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Smart heritage preservation: Digital transdisciplinary framework for sustainable urban planning in sensitive natural areas

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Abstract: Urban development often conflicts with natural heritage preservation, threatening ecological integrity and community well-being. This study introduces a Digital Transdisciplinary Place-Based Sustainability Assessment (D-TPSA) methodology to evaluate urban development scenarios before implementation. Focusing on the Bousselam Valley in Setif – a natural heritage area under environmental pressure – the research aims to balance development with ecological and social sustainability. Using the updated Boussole21 evaluation tool aligned with Agenda 2030, the study assesses projects across four dimensions: environmental impact, economic viability, social inclusion, and governance. Data were collected through document analysis, interviews, and GIS-based cartography. The research team received training in Boussole21 to ensure precise assessments. Three development scenarios were compared, with expert input refining recommendations to align with community goals and heritage preservation. Results demonstrate that the D-TPSA approach effectively combines technological innovation with real-world challenges, offering a replicable framework for sustainable urban planning. By integrating local knowledge with global principles, this methodology redefines strategies to protect natural heritage while improving residents' quality of life. The study highlights the potential of transdisciplinary, place-based approaches to promote sustainable development in the digital era.

1. Introduction

A recent UN report predicts 2.5 billion more urban residents by 2050, raising global urbanization to nearly 66%, with peak population at 10.3 billion by the mid-2080s (United Nations, Department of Economic and Social Affairs, 2024). This rapid urbanization, driven by human activities and environmental crises (Sabri, 2020), exacerbates climate change, sprawl, and land degradation (Youssef, 2019). Land-use changes (Roy et al., 2022) disrupt ecosystems, threatening biodiversity and ecological integrity, particularly in natural heritage areas (UNESCO, 1972a). Protecting cultural and natural heritage is increasingly framed as being within the umbrella of sustainable development. UNESCO emphasizes balancing Outstanding Universal Value (OUV) protection with equitable sustainable development across environmental, social, economic, peace, and security dimensions (UNESCO, 2015). The Kunming-Montreal Global Biodiversity Framework (2022) urgently calls for integrating biodiversity conservation into planning, protecting 30% of ecosystems by 2030 (CBD, 2022).

Aligned with this, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services IPBES's 2025 Methodological Assessment focuses on integrating biodiversity into land/sea-use decisions via participatory, regionally-adapted approaches in urbanizing contexts (IPBES, 2024). Sustainable urban planning balancing development, ecology, and community well-being is essential (Thiele, 2024).

Multi-Criteria Assessment (MCA) and spatial analysis provide planners with structured decision-making tools to evaluate urban sustainability trade-offs (Malczewski, 2006; Munda, 2008; Malczewski, J., & Rinner, 2015). The Analytic Hierarchy Process (AHP) (Saaty, 2008) is a widely adopted multi-criteria decision-making (MCDM) method designed to address complex decision problems through a structured hierarchical framework. AHP is extensively applied across diverse disciplines including engineering, social sciences, and urban planning, often in combination with other methodologies to increase analytical depth and reliability (Khan & Topi, 2019). In spatial planning contexts, AHP and Geographic Information System GIS-based modelling (Geneletti, 2013) have been used to quantify environmental, economic and social impacts, while participatory approaches (Thoneick, 2021) integrate community perspectives. This integrated framework, combining technical rigor with stakeholder engagement (Kahila-Tani et al., 2016), enables balanced urban development that protects ecosystems while meeting societal needs, demonstrating how digital tools and transdisciplinary methods can reconcile competing planning priorities.

The Transdisciplinary Place-Based Sustainability Assessment weighting in the decision matrix used a hybrid approach: (1) expert panels assigned baseline weights (ecological: 40%, social: 30%, economic: 30%); and (2) participatory workshops refined weights via AHP, increasing flood resilience emphasis (↑15%) by consensus. This dual method balances technical rigor with local relevance, addressing critiques of purely top-down weighting (Roy et al., 2023). While tools like LEED-ND standardize urban sustainability metrics (Pedro et al., 2018), they often neglect localized socio-ecological trade-offs. Boussole21 addresses this gap by combining Agenda 2030-aligned indicators (DFAE, 2025) with place-based adaptability – enabling dynamic weighting (e.g., biodiversity weight: 0.4 in Bousselam Valley versus generic 'green infrastructure' scores), similar to the SDG Index's national focus. Unlike SAFA's agro-centric framework, Boussole21's transdisciplinary design integrates GIS-driven spatial analysis with stakeholder narratives, bridging

technical and community knowledge gaps. Sustainability assessment (SA) is a cross-cutting analysis used to evaluate the environmental, social, and economic impacts of a project. It applies to strategies, legislation, and specific projects at all levels of government (RCDD, 2020). Rather than delivering a final verdict, SA identifies both positive and negative effects, potential conflicts of interest, and opportunities for improvement. Conducted before, during, or after implementation, it supports informed decision-making and encourages dialogue among stakeholders. A range of tools tailored to different contexts guide the assessment process (RCDD, 2023).

Digital tools like modeling and simulations are increasingly integrated into planning for optimized decisions and smart forms (Spiridonov & Shabiev, 2020; Sabri & Witte, 2023). Tools like the Bernese Compass as reported by OCEE (Canton of Bern, 2008), and Boussole21 (Viviane et al., 2010; Marthaler, 2010), updated in 2023 for Agenda 2030 (Canton of Fribourg, 2023), enable multi-dimensional SA. Several studies have explored this methodology to inform urban planning and environmental decision-making. Ghennaï et al. (2023), for instance, applied an early version of Boussole21 in Skikda Algeria, emphasizing the value of planning tools in balancing development and sustainability. However, limitations such as the omission of governance and vague criteria highlighted the need for refinement. The updated 2023 version addresses these gaps, and the present study builds on this by integrating digital tools and a place-based approach to enhance both the contextual relevance and practical usability of SA. To this end, the study introduces the "Digital Transdisciplinary Place-Based Sustainability Assessment (D-TPSA)" methodology, leveraging GIS (Pandolfi & Campi, 2018) and Boussole21 (using 20 Agenda 2030-aligned criteria (Walsh et al., 2022)). It is applied to evaluate development scenarios in the Bousselam Valley (Sersoub & Djirar, 2012), a natural heritage area in Setif-Algeria (Madani, 2012) under pressure. D-TPSA integrates digital tools, local knowledge, and stakeholder engagement for context-specific, adaptive, and scalable planning (Grifoni et al., 2014). It combines spatial analysis, MCA, and participation to reconcile urban growth with natural heritage (Noss et al., 2024) preservation. D-TPSA integrates Boussole21, localized GIS (Prodanova et al., 2024), and participation (Grifoni et al., 2014) to address heritage area challenges (UNESCO, 1972b), using a place-based framework (Chand, 2018) for dynamic, scalable assessments.

The primary objective is to assess urban development scenarios using digital tools to preserve natural heritage, facilitate stakeholder engagement aligning local and global priorities, and equip decision-makers with data-driven tools for adaptive strategies. The central question is: "How can D-TPSA effectively integrate digital tools, spatial analysis, and participatory approaches to evaluate and optimize urban development scenarios while preserving natural heritage in rapidly urbanizing areas?" D-TPSA combines digital intelligence with human expertise, using spatial analysis, MCA, and engagement to enhance data-driven decision-making in urban planning (Champlin & Brömmelstroet, 2019). By leveraging Boussole21, GIS, and quantitative frameworks, it systematically evaluates scenarios, aligning local priorities with international standards (Elidrisy, 2024). It fosters collaborative planning for socio-environmental challenges, enhancing heritage site resilience, supporting evidence-based policy, and promoting socio-ecological sustainability.

Findings demonstrate D-TPSA's effectiveness. Applying updated Boussole21 to Bousselam Valley shows the efficacy of integrated spatial analysis, expert consultation, and participatory evaluation in comparing scenarios, identifying Scenario 1 as the most balanced option. The article follows IMRAD structure (Introduction, Methods, Results, and Discussion). The introduction outlines the background, objectives, research question, and relevance. Section 2 presents methodology, data collection,

conceptual framework, and tools (e.g., Boussole21, GIS). Section 3 describes the case study area (geographic, social, environmental characteristics) and analyses three scenarios. Section 4 combines results and discussion. The conclusion reflects on implications and outlines future research and planning recommendations.

2. Methodology and data

This research introduces a D-TPSA, an innovative methodology for evaluating natural heritage project scenarios in sensitive areas. D-TPSA rethinks sustainability planning by integrating local knowledge with digital global frameworks, emphasizing scenario-based decision-making to ensure well-being and ecological preservation. It combines expert insights, citizen perspectives, and human effort, empowering decision-makers with smart analytical tools such as GIS and Boussole21 (Ghennaï et al., 2023) to preserve natural heritage. The following section outlines the key components and contributions of this novel approach (Figure 1).

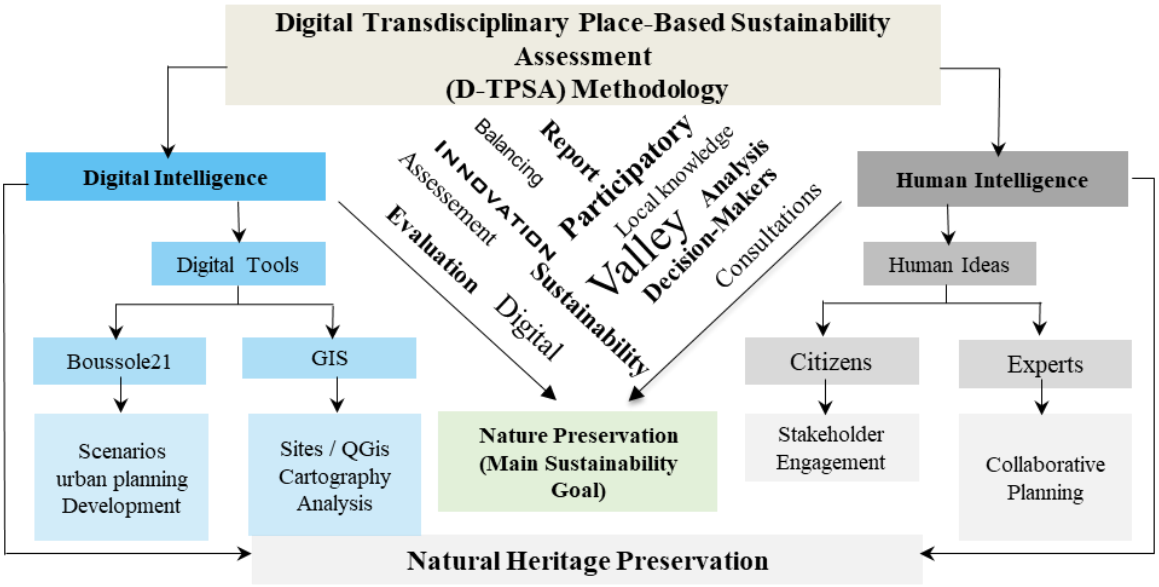


Figure 1 | D-TPSA Framework

2.1. Data collection

A comprehensive database was developed to support the research, incorporating the case study and the related urban development projects. A qualitative methodology was employed to enable an in-depth understanding of the project, which was essential to the evaluation process.

2.1.1. Document analysis

Document analysis was undertaken to gain a comprehensive understanding of the subject matter. This involved an in-depth review of existing literature, including relevant academic studies, scholarly

journals, and legal frameworks governing urban development and environmental protection. To ensure alignment with local regulations and to identify potential knowledge gaps, key planning documents, such as the Land Use Plan (POS) and the Master Plan for Development and Urban Planning (PDAU) of Setif city were thoroughly examined.

2.1.2. Semi-structured interviews

Seven interviews were conducted between March and May 2024 with key stakeholders involved in the development project. Participants included two architects with experience in previous valley projects, a hydraulic engineer responsible for the technical study, a department head from the water management authority closely monitoring the project progress, three academics from UFAS1 (PUViT Lab), a professor and two Associate Professors who contributed to the proposed planning scenarios. The interviews (Ghorab et al., 2023) aimed to trace the project's evolution from conception to its current status, identify causes of implementation delays, and gather perspectives on the valley's future. The semi-structured format facilitated the collection of detailed information while allowing flexibility to explore key themes: Project programming, objectives and governance challenges, stakeholder coordination, public participation, and recommendations for a sustainable project relaunch. Each interview lasted between 60 and 75 minutes. Notes were taken and analysed and the findings were cross-referenced with expert consultations to enrich the overall analysis and inform the formulation of recommendations.

2.1.3. Cartographic analysis

In response to the lack of updated cartographic resources, a comprehensive analysis of historical maps and satellite imagery was conducted. The objective was to produce revised cartographic representations of the valley, focusing on land use, vegetation types, and ecological characteristics.

2.2. Digital tools and materials integration

2.2.1. *Cartographic mapping using QGIS software*

Open-source QGIS 3.28.10 software was used to produce updated cartographic representations through a GIS-based approach. A land use map and the geographic locations of project scenarios within the valley were mapped in order to analyse spatial relationships and potential environmental impacts. Overlay analysis, proximity analysis, and spatial queries were conducted in QGIS. Project locations were overlaid on land use layers to identify intersecting areas, buffer zones (e.g. 500m or 1km radius) were created to evaluate proximity to sensitive areas such as water bodies, forests, or residential zones, and spatial joins were used to extract attribute data. This analysis provides critical spatial insights into land use conflict and environmental sensitivities, informing planning decisions and scenario evaluations. Table 1 summarizes the key geospatial datasets used.

Table 1 | GIS Dataset Metadata Summary for Land Use

Dataset	*Source / Provider*	*Spatial Resolution / Scale*	*Coordinate Reference System (CRS)*	*Format*	*Temporal Coverage*	*Processing Notes*
Land Use Map	Historical topographic maps, Google Earth	~10–30 m (visual interpretation)	EPSG: 32632 (UTM Zone 32N)	Vector (Shapefile)	2000–2024	Digitized manually in QGIS 3.28.10 using heads-up digitizing and visual interpretation techniques.
Vegetation Cover (NDVI)	Sentinel-2 (Copernicus Open Access Hub)	10 m	EPSG: 32632 (UTM Zone 32N)	Raster (GeoTIFF)	2015–2024	NDVI calculated in QGIS using Red (Band 4) and NIR (Band 8) for June 2024 imagery.
Project Scenario Locations	Field surveys, planning documents (authors)	Point data (field accuracy ±5 m)	EPSG: 32632 (UTM Zone 32N)	Vector (Shapefile)	2025 (planned)	Digitized in QGIS from planning blueprints and GPS coordinates collected during fieldwork.
Administrative Boundaries	GADM v4, OpenStreetMap	1:100,000 scale	EPSG: 4326 (WGS 84)	Vector (Shapefile)	2023 (latest available)	Used for contextual mapping; reprojected into EPSG: 32632 to match other datasets.

2.2.2. Participatory tools: survey and analysis

An online survey was distributed via social media and institutional mailing lists, yielding 72 responses. Thematic coding of open-ended answers identified three main citizen priorities.

1. Preservation and enhancement of natural heritage.
2. Rational development of tourism.
3. Inclusive recreational spaces as a key aspect of urban planning.

Results were visualized through charts to ensure public priorities informed the evaluation of planning scenarios.

2.2.3. *Boussole21 tool*

After collecting the information on the case study and urban development projects, the evaluation was carried out using the Boussole21 tool (Thomas, 2023) (Table 2) on its digital platform (Canton of Fribourg, 2023). Three scenarios were assessed in alignment with the Agenda 2030 SDGs (DFAE, 2022), through the Open-Source Boussole21 platform GPL license (Boussole21, n.d.)**.** Each project

was evaluated based on its type and location within the valley. Flowcharts were then created to visualise the degree of sustainability according to Boussole21's 20 criteria. A summary report of the findings was generated.

Table 2 | Overview of the Updated Boussole21 SA Tool

Brief Description (Form, Evaluation, Application, Interpretation, Documents, Languages)	*Purpose* *Project Type (Scope)*	*Current/Planned Development* *Contact/Link*
Instrument (Name): Boussole21 **Form:** Online tool with user login. **Analysis:** Evaluates 20 sustainability criteria across four dimensions: economy, environment, society, and governance. Provides an overview of project impacts, identifies conflicts of interest, and suggests improvements. Each criterion includes: Evaluation justification Risk of negative impacts Improvement potential **Evaluation Options:** Simplified Evaluation: Quick assessment using 20 criteria. Complete Evaluation: In-depth analysis with structured inputs, improvement recommendations, and observation. **Interpretation:** Results visualized via spider diagrams, dynamic dashboards, and downloadable reports. **Documents:** Online training courses **Languages:** French, German, and Italian. **Updated Features:** 2023	**Preliminary Evaluation**: -Supports optimization, -Informs decision-making, -Identifies conflicts of interest. **Post-Evaluation:** Enables verification of project effects. **Application:** Applicable to all project types with defined time and spatial boundaries. Supports evaluations at different stages: Conception: Strategic orientation Implementation: Optimization Post-completion: Verification of effects Decision-making: Justification of choices Offers both quick (simplified) and in-depth evaluation options.	Under the Intercantonal Convention for the Development and Management of Boussole21, the tool is being enhanced to: Establish a direct link with the 2030 Agenda Sustainable Development Goals (SDGs) Enable documentation of project-related climate impacts. **Contact/Link** Canton: Vaud, Fribourg, Valais. **Website:** www.boussole21.ch

2.2.4. Boussole2120 criteria

After downloading the list of 20 criteria (Table 3) and their descriptions, each is evaluated using a five-level colour scale, from very unfavourable to very favourable (Figure 2), based on the project's anticipated impacts. If a criterion is inapplicable, a grey dot is used. The "Comments" field allows

users to explain their evaluations. Scored criteria are automatically highlighted in the menu to help users track progress. Once all criteria are assessed, a textual and graphical summary is generated, providing a clear overview of the project's impacts across the four pillars of sustainability.

Table 3 | Twenty Criteria of Boussole21 Grouped into categories

Environmental Criteria	Social Criteria	Economic Criteria	Governance Criteria
2. Land use	14. Training and education	9. Wealth creation	1. Mobility
3. Outdoor and indoor air quality	15. Equal opportunities	10. Framework conditions for the economy	19. Public management
4. Living environment and public space	16. Social cohesion	11. Economic resilience	20. Governance and partnership
5. Energy	17. Health and prevention	12. Economic competitiveness and innovation	
6. Climate change and risks	18. Culture, sports, and recreation		
7. Biodiversity and natural spaces			
8. Soil and water quality			
13. Resource consumption			

Source: Boussole21
(https://www.boussole21.ch/fr/page/evaluer-les-criteres)

Figure 2 | Instructions for Downloading and Evaluating Criteria on Boussole21
(Source: www.boussole21.ch)

2.2.5. *Boussole21 training program*

To ensure consistency and reliability in data interpretation using the Boussole21 evaluation tool, the research team completed an in-depth online training program (Keller et al., 2024). This training was a prerequisite for effectively engaging with the tool's indicators and decision-making processes (Keller et al., 2023). It formed a foundational element of the study's methodological rigor, directly informing how data was collected, categorised, and evaluated within the sustainability framework (Figure 3).

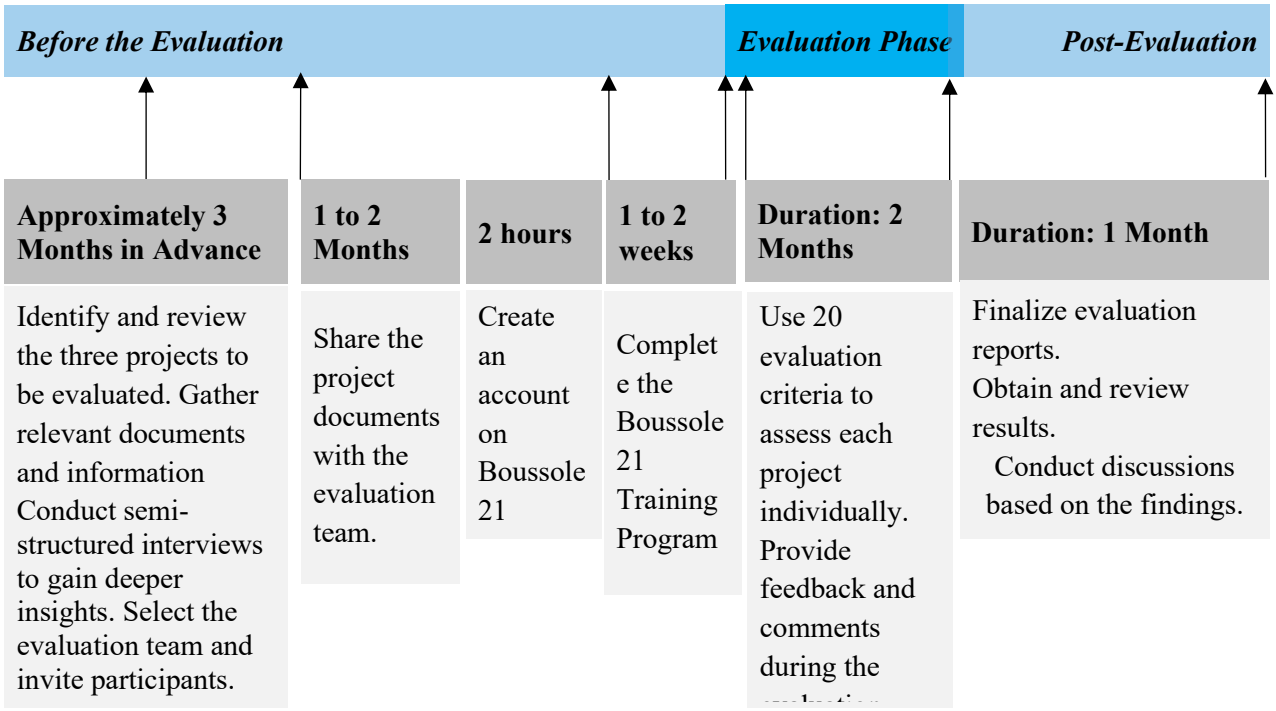


Figure 3 | Evaluation Process Timeline with Boussole2: Phases and Key Steps

2.2.6. *Comparative analysis*

Following cartographic mapping and evaluation with the Boussole21 tool, a comparative analysis was conducted to determine which projects were most sustainable and best aligned with the initial objectives. This step offered key insights into the effectiveness of the proposed urban development initiatives.

2.2.7. *Expert consultations*

To ensure a robust and transdisciplinary evaluation, structured consultations were conducted with 12 experts in relevant fields: urban planning (3), environmental management (3), hydraulic engineering (2), biodiversity conservation (2), and agricultural development (2). The consultation process included:

- Five half-day in-person workshops, held at experts' workplaces to foster contextual engagement and align with local planning dynamics.
- Follow-up questionnaires and feedback exchanges to refine assessments and incorporate additional insights.
- One synthesis meeting aimed at cross-validating results and co-formulating final recommendations.

Experts were selected based on their experience in scenario-based territorial planning and prior involvement in SA projects. Most participants were university faculty, several affiliated with PUVIT research laboratory, and practitioners active in local and regional planning. Discussions focused on key methodological steps:

- Validation and weighting of the 20 sustainability criteria from the updated Boussole21 framework.
- Evaluation of three land-use planning scenarios for the study area.
- Identification of trade-offs, synergies, and priority actions to enhance scenario sustainability

Guiding questions included:

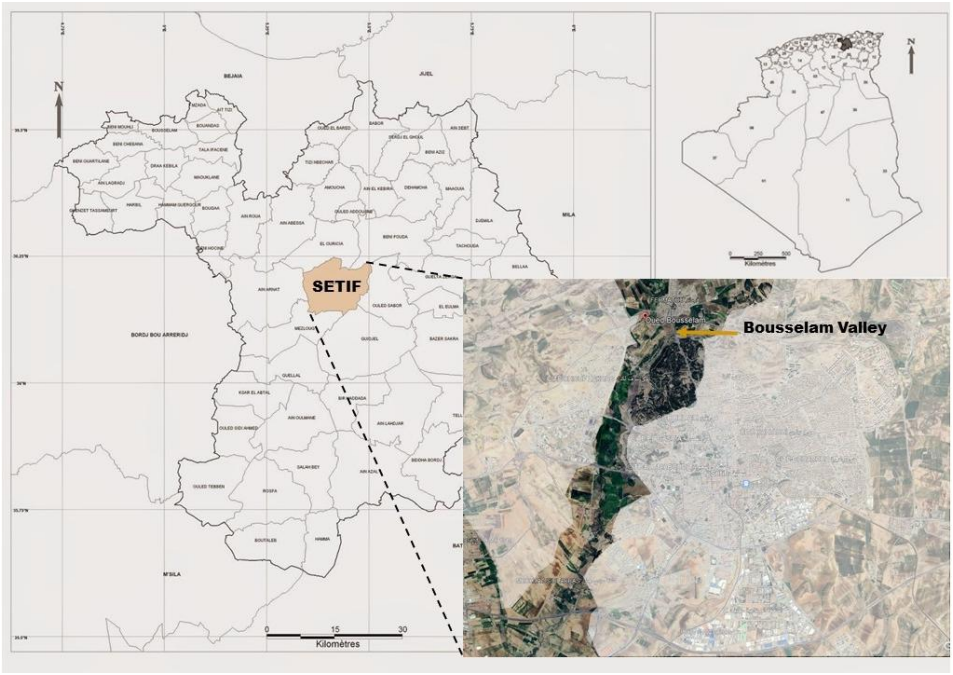
- Which scenario best supports long-term ecological resilience?
- How can governance, stakeholder participation, and social equity be better integrated?
- What are the main strengths, weaknesses, and risks of each scenario?

Expert input was analysed through thematic coding and synthesized into summary tables. This approach ensured that the consultations enriched the scenario evaluation and reinforced the relevance and rigor of the final recommendations.

3. Case study

3.1. Context

The Bousselam Valley, often referred to as the green lung of Setif, spans 150 kilometres as the main tributary of the Soummam River and serves as a critical ecological asset for the city. Designated as a natural park in Setif's 2010 Urban Development Master Plan (PDAU) (Centre d'études et de réalisations en urbanisme URBA.SETIF, 2010), it is one of Algeria's few permanent watercourses. Despite urban expansion, the valley retains rich biodiversity, featuring a gallery forest of alder, willow, and poplar trees that provide habitats for species like the cattle egret and white stork. It also supports peri-urban agriculture, including cereal crops, dairy farming, and market gardening, while offering recreational spaces that enhance the mental and physical well-being of residents (Figure 4).



(a) (b)

Figure 4 | (a) Geographical location map of Setif city (Source: Arour, 2024)
(b) Bousselam Valley location and urban sprawl (Source: Authors)

3.2. Challenges

The valley faces significant threats to its ecological integrity. Urban sprawl, industrial pollution, wastewater discharge, and conflicting land-use practices have degraded the landscape and reduced biodiversity. Pollution and erosion have left the area in a fragile state, undermining both ecological functions and public health. These impacts have prompted urgent calls for coordinated management to restore and protect this vital natural heritage.

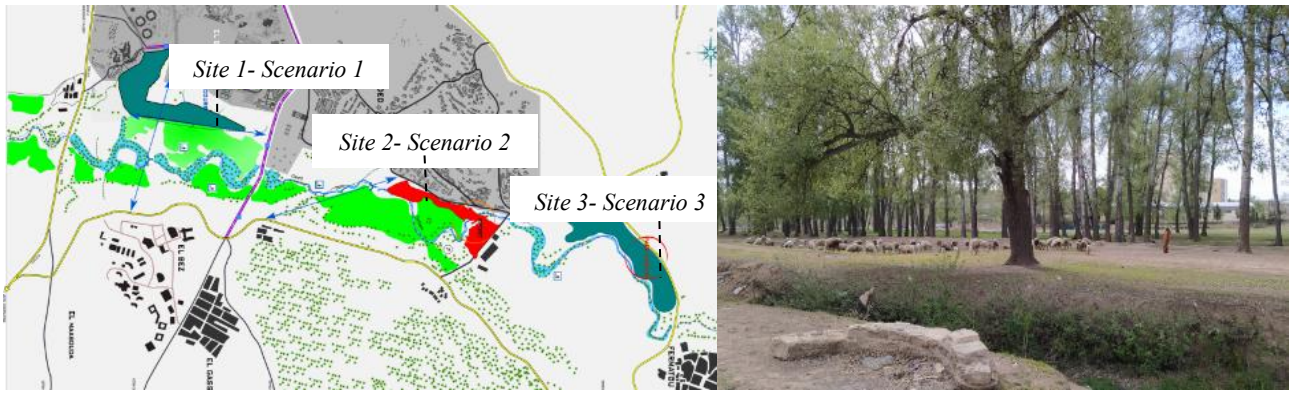
3.3. Urban development projects' scenarios

In response, stakeholders from the hydraulic sector, urban planners, architects, and researchers from the University of Setif proposed three development scenarios in 2015 to address environmental pressures and guide sustainable management, under the initiative titled "*Study of the Development of Oued Boussellam Crossing the City of Setif*". (Taibi, 2015). See Table 4 and Figure 5.

Table 4 | Description of the Three Intervention Sites

Site	*Location and context*	*Main features*	*Opportunities and challenges*
Site 1: Valley–Village Relationship (El Bez)	Lower Bousselam Valley, El Bez	• Harmonious mix of urban, rural, and natural elements; • Biodiversity-friendly zoning; • Adjacent agricultural zones; • Urban recreational projects (e.g., Corniche, hotel Bayazid) (Ghorab & Chaib, 2016); • Major infrastructure: ENSO, El Bez Olympic pool, university campus	Opportunities • Sustainable tourism • Ecological and educational integration Challenges • Balancing development with ecological integrity
Site 2: Valley–Chouf Lekdad–Znadia Forest	Northwestern edge of Setif Along Bousselam and Lekbir rivers	• Forested area created by CPR (1965–1970) • Ecological and recreational roles • Mixed-use land (natural, agricultural, urban) • Vulnerable to industrial/urban pollution	Opportunities • Ecosystem restoration; • Green recreation Challenges • Flooding; • Water pollution; • Waste management
Site 3: Valley–Fermatou–City of Setif	Between Fermatou village (regularized in 1856) and Chouf Lekdad Near Djbel Znadia Forest	• Natural, vegetated land with no agriculture; • Scenic views over the valley; • Accessible via RN75; • Close to industrial zone	Opportunities • Strategic site for eco-sensitive development • Natural flood resilience Challenges • Managing proximity to industrial activity • Preserving landscape integrity

However, budget constraints and the COVID-19 pandemic stalled the project, limiting progress to the installation of a canal system. Despite these setbacks, the valley remains a compelling case study in sustainable urban planning, emphasizing the need for integrated solutions that balance ecological preservation with development.



(a) (b)

Figure 5 | (a) Geographical location map of intervention sites (Source: Taibi, 2015);
(b) Bousselam valley, April 2024 (Source: Authors)

3.3.1. Project description

The Bousselam Valley Urban Development Project follows an integrated approach with three scenarios (Figure 5, a) aimed at combining environmental protection, improving local quality of life, and enhancing the valley's natural heritage. Each scenario incorporates innovative ecological solutions for wastewater treatment, flood risk management, and sustainable materials. These interventions strive to balance urbanization with ecosystem preservation, while strengthening the area's ecological resilience. Key stakeholders consider these conditions essential for the project's success (Table 5).

Table 5 | Key conditions for successful park development and stakeholder perspectives

Key condition	*Description*	*Stakeholder perspective*
Creation of a Strong Brand Identity	The park will have a distinctive visual identity, showcasing the valley's natural and cultural assets through cohesive signage.	Stakeholders see this identity as essential to promote visitor awareness and appreciation of the valley's heritage
Collaborative Governance	A participatory approach with ongoing consultation of residents, associations, and authorities will ensure transparent governance.	Collaboration is critical to building trust and enhancing community engagement.
Diversity of Funding Sources	A mixed funding model combining public funds, private investment, and grants will ensure financial viability.	Funding diversity is essential for long-term sustainability and conservation.

Based on Taibi (2015)

3.3.2. Key objectives

Ecological wastewater treatment. The project uses sustainable systems that purify water and restore ecosystems by enhancing aquatic biodiversity. Techniques include soil infiltration-percolation, planted filters with aquatic vegetation, and natural or aerated ponds where plants and microorganisms work symbiotically and purify water.

Flood risk management. To tackle recurring flooding, the project proposes nature-based solutions such as wooden structures to slow water flow and stone dams to stabilize the riverbed and create flood buffer zones, boosting resilience to climate events.
Ecological urban furniture and sustainable materials. The park will feature eco-designed infrastructure using natural materials (mainly wood) for benches, pergolas, and shading, reducing carbon footprint and enhancing natural ambiance.
Signage and heritage enhancement. Directional and interpretive signage will guide visitors and highlight the valley's biodiversity, history, and agriculture, promoting environmental awareness and respect for local heritage.
Participatory approach and innovation. The project fosters collaborations with research institutions to innovate in eco-friendly wastewater treatment and sustainable landscape design, encouraging continuous improvement in natural resource management.

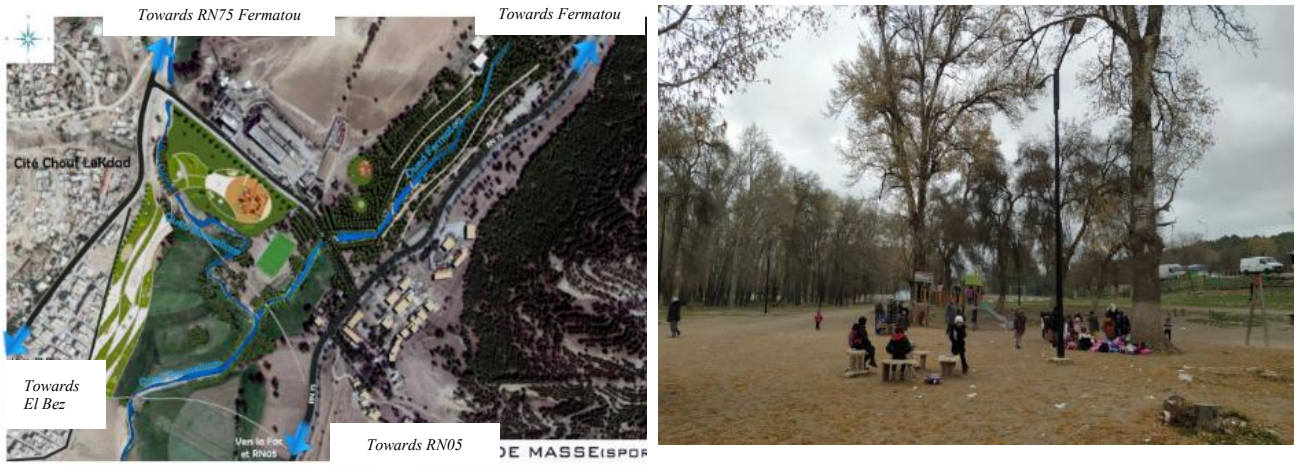
3.3.3. The three scenarios of the development project

Scenario 1. This scenario envisions development that connects residents with the valley's natural and agricultural heritage through harmonious landscaping. Pathways will be safe, accessible, and follow durable, nature-integrated designs to offer an immersive experience. Vegetation will include shaded areas with deciduous and fruit trees, applying a zero-waste approach to removal of non-preserved trees. Rest and picnic areas will be located near the valley and gallery forest, allowing visitors to experience tranquillity and a deeper connection with nature (Figure 6, a). Social spaces beneath tree canopies will be equipped with sustainable, colourful furniture to encourage interaction. Participatory features like temporary seating and a pergola aim to foster community use and gathering. The recreational path will support walking and sport activities, with a design that ensures universal accessibility.

(a) (b)

Figure 6 | (a) Scenario 1 Development (Source: Taibi, 2015);
(b) Bousselam valley urban sprawl, January 2024 (Source: Authors)

Scenario2. This plan envisions a multifunctional park offering Setif residents accessible spaces for recreation and community life, strengthening their connection to the Valley (Figure 7) The park will host a variety of sporting, cultural, social, and festive activities, supporting local community development. Accessible via RN75, it includes multiple entry points for cars, public transport, and pedestrians. Facilities include playgrounds, picnic areas, sports courts (football, handball, tennis), a cycling track, and walking trails through wooded areas.



(a) (b)

Figure 7 | (a) Scenario 2 Development (Source: Taibi, 2015);
(b) Bousselam Valley Urban Park, May 2024 (Source: Authors)

Outdoor performance spaces and nature education zones will promote biodiversity awareness. A central landscape maze will offer panoramic views and interactive experiences, creating a rich visitor experience. The design was shaped by informal citizen consultations, ensuring it reflects community needs and fosters ownership and long-term engagement.

Scenario 3. Eco-Urban Park for Wellbeing and Conservation. This municipal park proposal balances ecological preservation with recreation and community needs. Located near RN75, between Farmatou and Chouf Lekdad, and adjacent to the river, it offers easy access from Setif's neighbourhoods. The park includes wooded areas, sports zones, playgrounds, picnic spots, walking trails, an outdoor theatre, and spaces for biodiversity education. Developed through informal community consultations, it integrates ecological principles with urban planning to support relaxation, physical activity, and community events. Its dual goals are to protect the Valley's natural heritage and improve residents' quality of life. (Figure 8).

(a) (b)

Figure 8 | (a) Scenario 3 Development (Source: Taibi, 2015);
(b) Urban park proposition (Source: Taibi, 2015)

4. Results and discussion

4.1. Boussole21 evaluations results

4.1.1. Scenario 1

Notable strengths are seen in participation/cooperation (criterion 2). For biodiversity protection (criterion 10), measures support local flora/fauna and are rated "Favourable with Reservations" however, further protection would improve sustainability. Accessibility (criterion 12) is rated "Favourablefavorable" due to universally accessible trails, including for those with reduced mobility, promoting inclusivity (Figure 9). Transparency of information (criterion 1) and economic impact (criterion 20) need improvement. Transparency is rated "acceptable" while economic impact is "Unfavourableunfavorable". The project's potential economic benefits are unclear, making it difficult to assess its ability to generate meaningful local advantages. The natural pathways and picnic areas of Scenario 1 support sustainable development. Strong results in participation and accessibility underscore the importance of community involvement. However, improving transparency is critical for long-term success. Although biodiversity efforts are commendable, ongoing monitoring is needed to ensure effectiveness. Furthermore, the lack of clarity around economic impact calls for a more thorough evaluation to enhance community benefits and project viability.

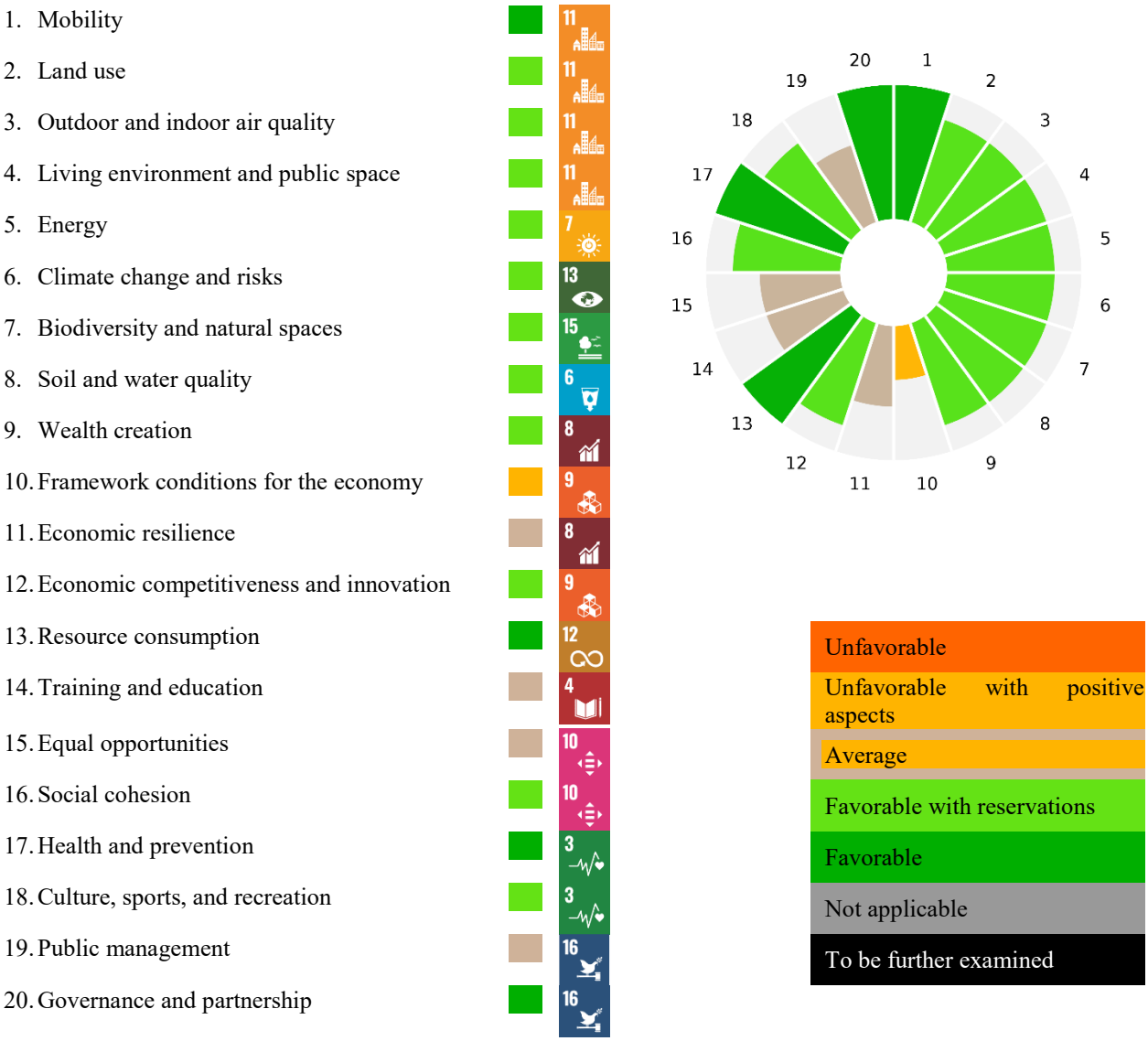


Figure 9 | Synthesis of evaluation results – Scenario 1 chart a (Source: Boussole21)

4.1.2. Scenario 2

The *Chouf Lekdad* project, assessed via Boussole21's 20 criteria, shows both strengths and weaknesses. It performs strongly in quality living environments/public spaces (criterion 4), energy efficiency (criterion 5), wealth creation (criterion 9), education/training (criterion 14), and public management (criterion 19). It also shows potential in land use (criterion 2), climate risk management (criterion 6), biodiversity/natural spaces integration (criterion 7), economic conditions (criterion 10), resilience (criterion 11), resource consumption (criterion 13), social cohesion (criterion 16), health/prevention (criterion 17), and cultural/sports facilities (criterion 18). Weaknesses are noted in equal opportunities (criterion 15) and governance/partnerships (criterion 20) (Figure 10). *Chouf Lekdad* lays a solid foundation for sustainability through strengths in public spaces, energy efficiency, and local economic growth. However, to ensure long-term resilience land use, climate risk adaptation, and biodiversity integration must be strengthened. While economic and health infrastructure show potential, expanding these efforts could enhance inclusivity and impact. Key weaknesses in governance and equal opportunities require urgent attention to prevent exclusion and ensure effective

management. Addressing these gaps is vital for community support and long-term success. A balanced focus on environmental strengths and social/governance improvements is essential for lasting, inclusive benefits.

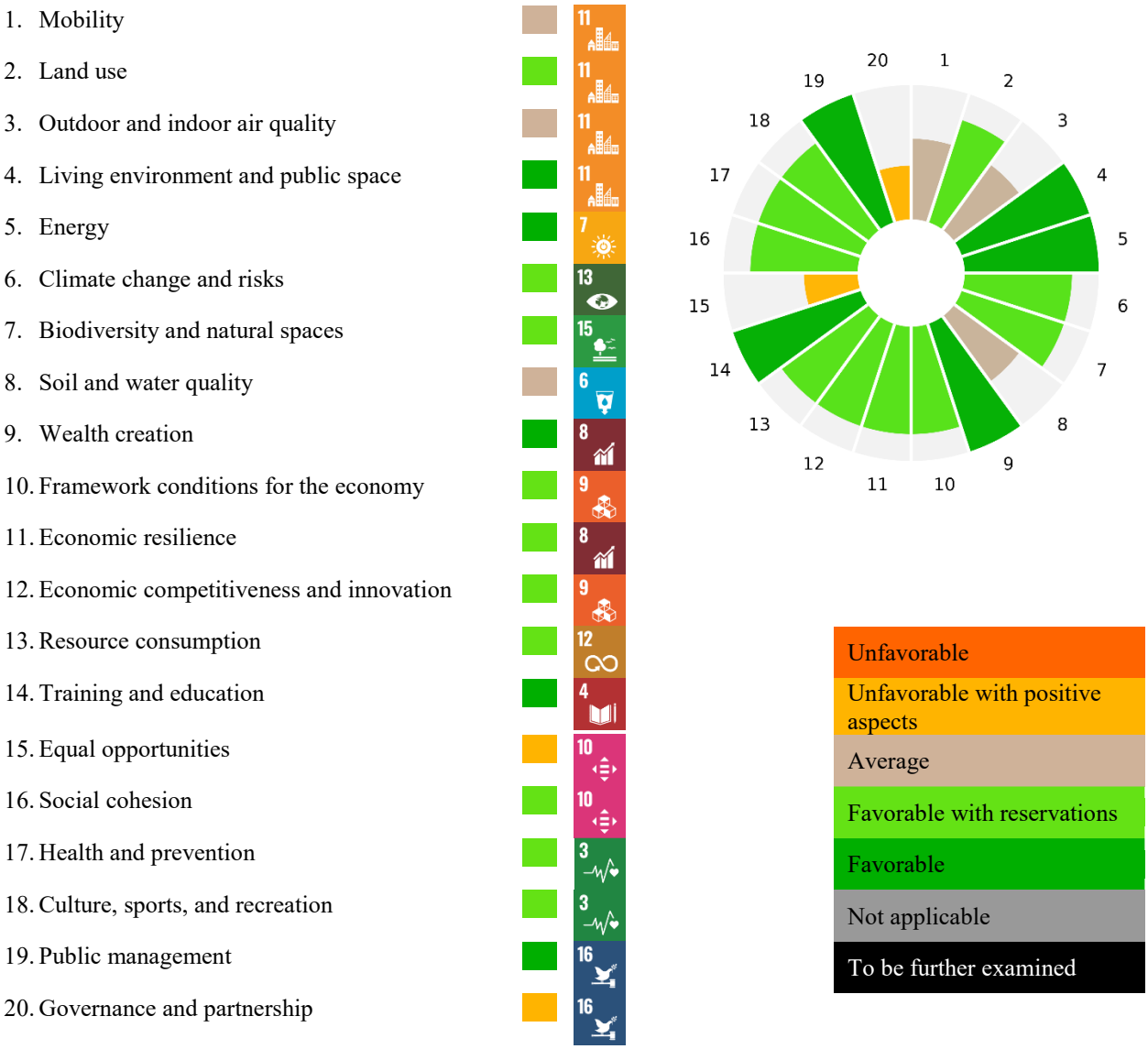


Figure 10 | Synthesis of evaluation results – Scenario 2 chart b (Source: Boussole21)

4.1.3. Scenario 3

The project shows strengths in Education/training (criterion 14), through biodiversity and ecological promotion. It supports Cultural, sporting, and leisure activities (criterion 18); enhancing social well-being (Figure 11). It improves Living environments/public spaces (criterion 4) with accessible areas, uses Energy-Efficient materials (criterion 5) and considers Climate Risks (criterion 6). Biodiversity Integration (criterion 7) and Soil/Water Quality monitoring (criterion 8) are commendable. The project has potential for Wealth creation, supports Health and prevention, and manages Resource consumption. Weaknesses include lack of measures for Air quality (criterion 3), unclear Public management (criterion 19), and insufficient Governance/partnerships (criterion 20). Scenario 3 significantly enhances resident quality of life and local biodiversity conservation. It effectively

addresses sustainability objectives in natural resource management, public space creation, and reducing environmental impact, benefiting social and environmental outcomes. However, deeper analysis reveals critical gaps: it lacks robust climate risk management, economic resilience strategies, and defined governance structures. While meeting immediate social and environmental needs, ensuring the park's long-term viability requires urgent attention to improving air and water quality, establishing effective governance, and fostering partnerships for local economic initiatives. Addressing these gaps is crucial to secure lasting community and environmental benefits.

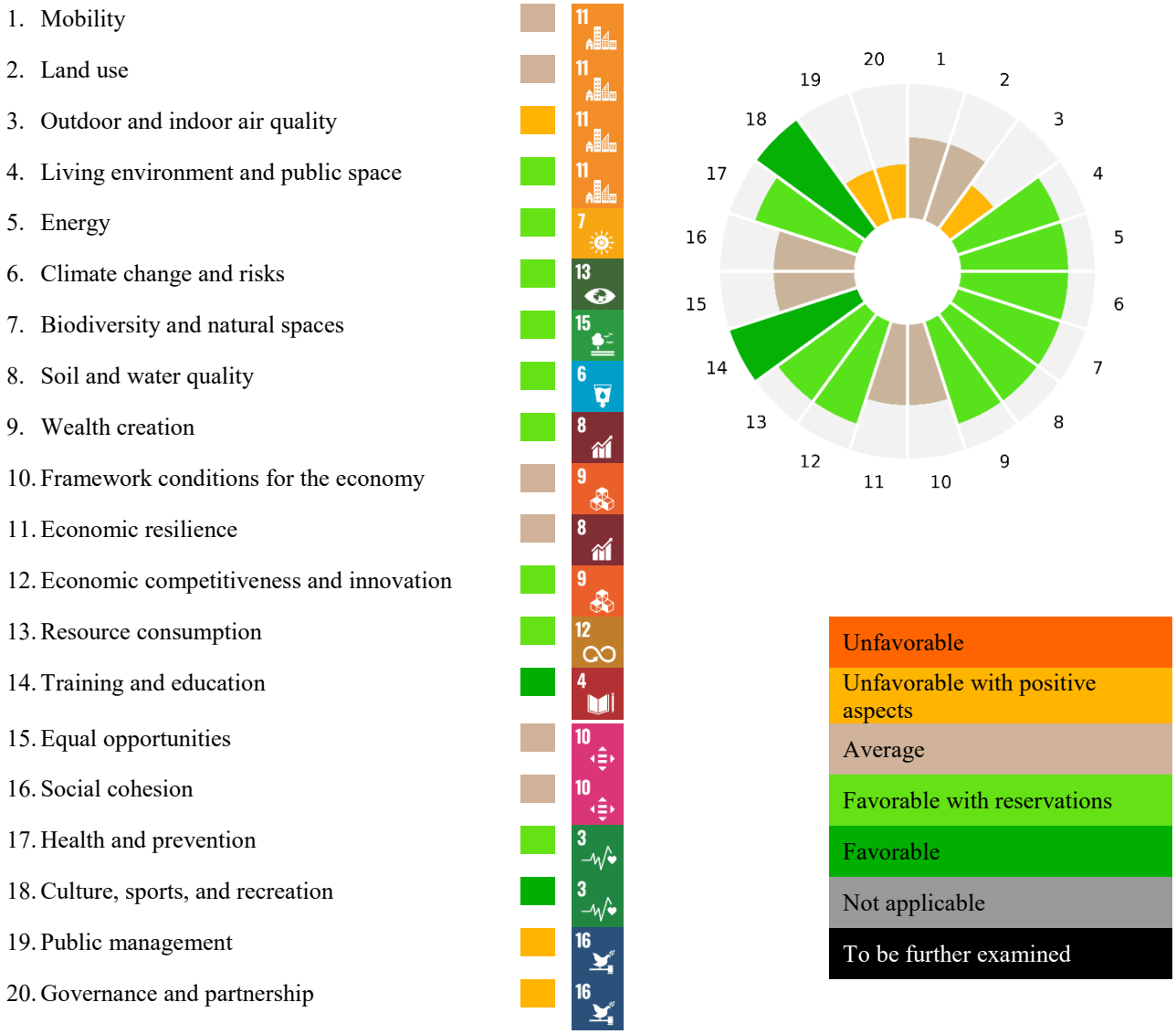


Figure 11 | Synthesis of evaluation results – Scenario 3 chart c (Source: Boussole21)

4.2. Comparison of results

The results are analysed using Boussole21's 20 criteria, categorized into four dimensions: *Environmental Impact*, *Economic Viability*, *Social Inclusion*, and *Governance Effectiveness*. Radial charts (a, b, c) (Figure 12) and the comparison table (Table 13) highlight key performance differences among the three scenarios.

4.2.1. The environmental impact

This dimension includes indicators such as climate change risk, biodiversity, soil and water quality, and energy. In the charts, the green, orange, and red segments represent favourable, moderate, and unfavourable performance, respectively.

- Scenario 1 (chart a): The predominance of green segments for indicators like Energy and Climate Change indicates strong performance. Biodiversity and Soil and Water Quality are also well-rated, reflecting sustainability alignment.
- Scenario 2 (chart b): This scenario shows moderate performance, with a mix of green and yellow segments. Energy scores well, but Climate Change and Biodiversity show more limited results (yellow and orange, respectively).
- Scenario 3 (chart c): Marked by several orange and red segments for Climate Change and Biodiversity, this scenario suggests potential ecological degradation and unsustainable practices.

Scenario 1 delivers the best environmental outcomes, while Scenario 3 raises concerns over long-term ecological risks.

4.2.2. Economic viability

This dimension includes Economic Resilience, Competitiveness, Wealth Creation and Resource Consumption.

- Scenario 1 (chart a): Green segments for Competitiveness and Resource Consumption indicate an efficient, sustainable economic approach.
- Scenario 2 (chart b): Shows moderate Economic Resilience, but orange segments for Competitiveness suggest room for improvement.
- Scenario 3 (chart c): Excels in Economic Resilience (green) but underperformance in Wealth Creation and Competitiveness (orange), highlighting a focus on short-term priorities.

Scenario 1 shows the most balanced economic growth, while Scenario 3 emphasizes resilience at the expense long-term viability.

4.2.3. Social Inclusion

This dimension focuses on Social Cohesion, Equal Opportunities, Training/Education, and Health and Prevention, as reflected in the table and chart color codes:

- Scenario 1 (chart a): Strong performance with green segments in Social Cohesion, Equal Opportunities, and Health, indicating an inclusive approach.
- Scenario 2 (chart b): Moderate results, with yellow and green segments for Education/Training, showing adequate but limited outcomes.

- Scenario 3 (chart c): Presence of orange and red segments in Social Cohesion and Equal Opportunities points to social fragmentation and inequality (Table 6).

Scenario 1 fosters inclusivity, while Scenario 3 risks deepening social disparities.

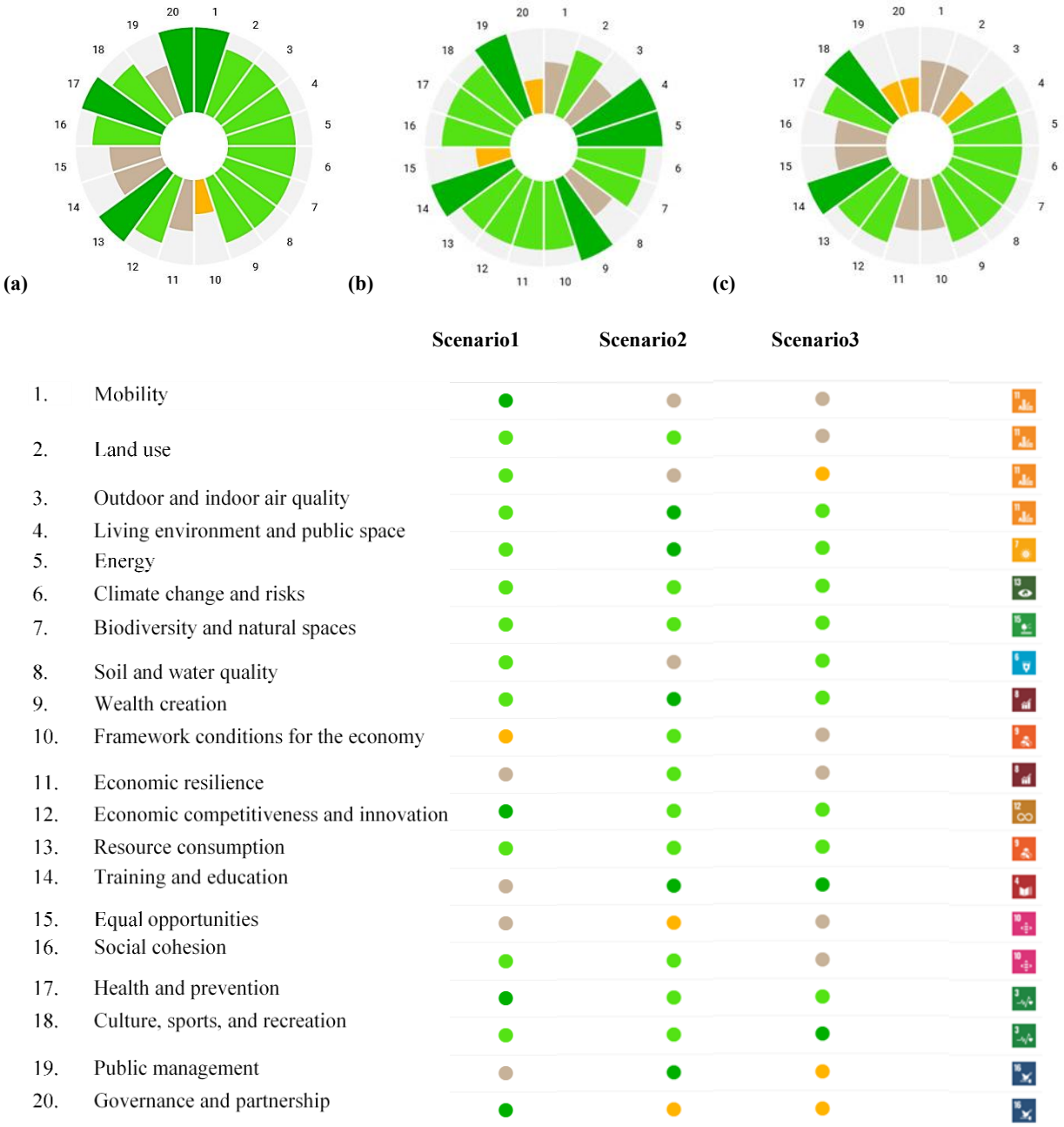


Figure 12 | Comparative Evaluation results: (a) scenario1; (b) scenario2; (c) scenario3, based on Boussole21 indicators

Table 6 | Summary table of scenarios' performance across the four dimensions of Boussole21

Dimension	*Scenario 1 (Balanced Approach)*	*Scenario 2 (Moderate Approach)*	*Scenario 3 (Economy-First Approach)*
Environmental Impact	**Strong** High performance in Energy, Climate Change, and Biodiversity	**Moderate** Mixed results, weaker in Climate Change and Biodiversity	**Weak** Poor performance in Climate Change and Biodiversity
Economic Viability	**Strong** Balanced growth, excelling in Competitiveness and Resource Use	**Moderate** Strong in Resilience, weaker in Competitiveness	**Polarized** Excels in Resilience, underperforms in Competitiveness
Social Inclusion	**Strong** Inclusive, excelling in Social Cohesion and Health	**Moderate** Adequate in Education, weaker in Social Cohesion	**Weak** Fails in Social Cohesion and Equal Opportunities
Governance Effectiveness	**Strong** Effective in Governance and Partnerships	**Moderate** Adequate in Public Management, weaker in Governance	**Weak** Poor governance and weak partnerships

4.2.4. Governance effectiveness

This dimension includes Governance and Partnerships, Public Management, and Framework Conditions for Economy, as shown in the table and charts:

- Scenario 1 (chart a): Green segments in Governance and Partnerships indicate strong collaboration and effective policies.
- Scenario 2 (chart b): A mix of green and yellow segments suggests moderate governance, with leadership inefficiencies.
- Scenario 3 (chart c): Red segments reflect governance failures and weak collaboration.

Scenario 1 sets the benchmark for governance, while Scenario 3 shows major shortcomings.

4.2.5. Discussion of the three scenarios comparison

- Scenario 1: Dominated by green segments across all dimensions in the radial charts, indicating a balanced and sustainable approach. Table 7 supports its strong alignment with environmental, social, and governance goals.
- Scenario 2: Shows moderate performance with mix of yellow and green segments. It reflects a strategy of compromise – strong in some areas but weak in Governance and Competitiveness.
- Scenario 3: Marked by orange and red segments in key dimensions, reflecting a model that prioritizes economic resilience at the expense of environmental and social outcomes.

Table 7 | Decision Matrix: Best Scenario Selection

Criteria Category	*Weight (%)*	*Scenario 1 score*	*Scenario 2 score*	*Scenario 3 score*
Environmental Impact	30%	✅ 8.5/10	🟡 7.0/10	🔴 5.5/10
Economic Viability	25%	✅ 8.0/10	🟡 7.5/10	🔴 6.0/10
Social Inclusion	25%	✅ 8.0/10	🟡 7.0/10	✅ 8.5/10
Governance Effectiveness	20%	🔴 6.0/10	🔴 6.0/10	🔴 5.0/10
Final Weighted Score	100%	7.7/10 ✅	7.0/10 🟡	6.3/10 🔴

4.2.6. Recommendations

Prioritize Scenario 1: As the strongest performer, Scenario 1 should guide decision-making. It can be strengthened further by improving governance and enhancing biodiversity conservation.
Improve Scenario 2: Address environmental and governance gaps, particularly flood risks management and biodiversity integration, to make it a viable alternative.
Reform Scenario 3: Mitigate negative impacts on biodiversity, governance, and social cohesion by improving air and water quality and fostering local partnerships.
These actions will support a balanced strategy that promotes ecological health, social equity, and economic sustainability.

4.3. Urban analysis result

The urban analysis of Bousselam Valley, based on field observations and QGIS mapping, identifies key risks and opportunities. In Scenario 1, ongoing real estate developments in El Harir pose a major risk, threatening rural habitats and agricultural land. Increased investor interest could fragment natural spaces and reduce ecological connectivity if vacant lands near the valley are urbanised. Scenario 2 shows reduced impact from urban sprawl, offering a chance to preserve the area's natural character. However, the terrain is prone to flooding, requiring effective mitigation. The mapping revealed

diverse land use patterns, environmentally sensitive zones, and key environmental threats. The creation of ecological corridors is proposed to protect rural landscapes from urban encroachment. The study's primary objective – preserving the valley's natural and agricultural heritage for sustainable development – highlights the urgent need for protective measures, particularly in Site 1. This area is especially vulnerable to urban sprawl and related threats, underscoring the need for importance of immediate, sustainable interventions. Scenario 1 emerges as the optimal choice, offering a balanced approach that aligns development with ecological conservation. This strategy is essential to safeguarding the valley's integrity while supporting responsible growth (Figure 13).

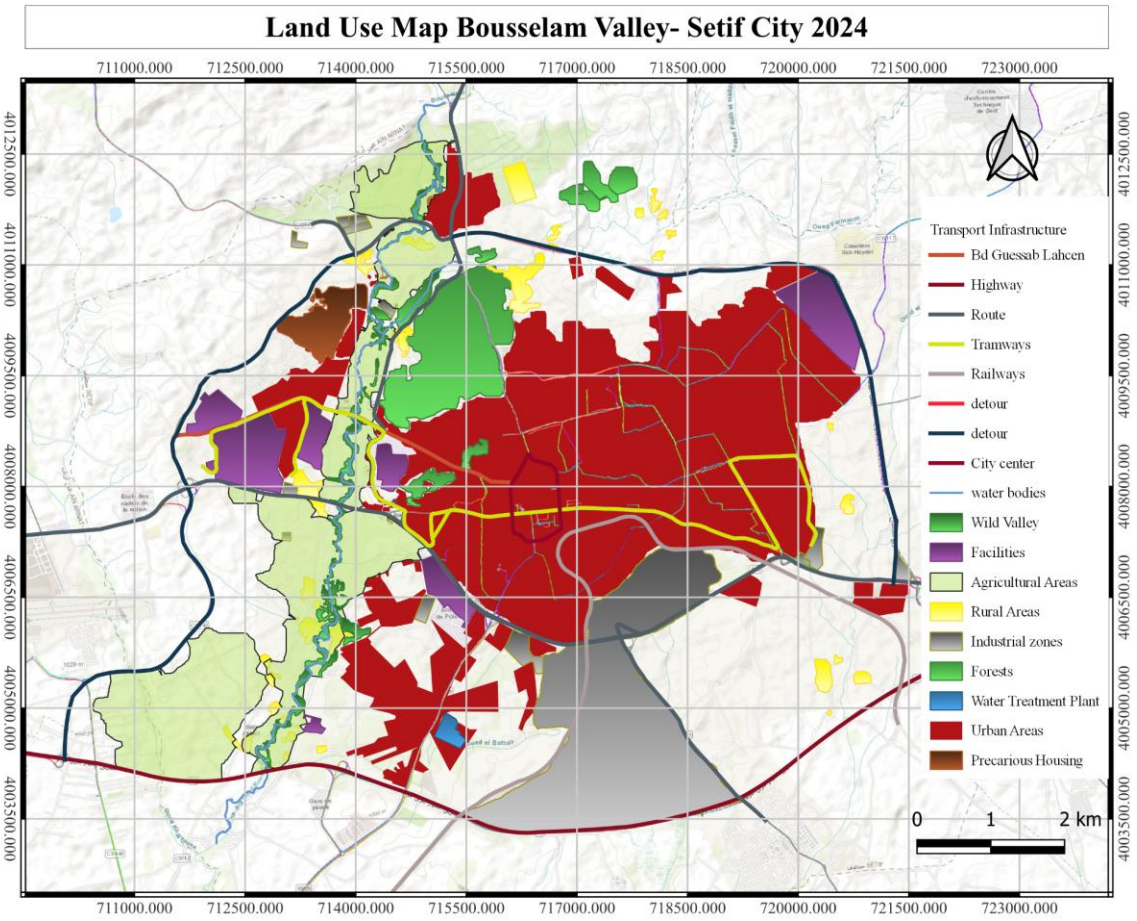


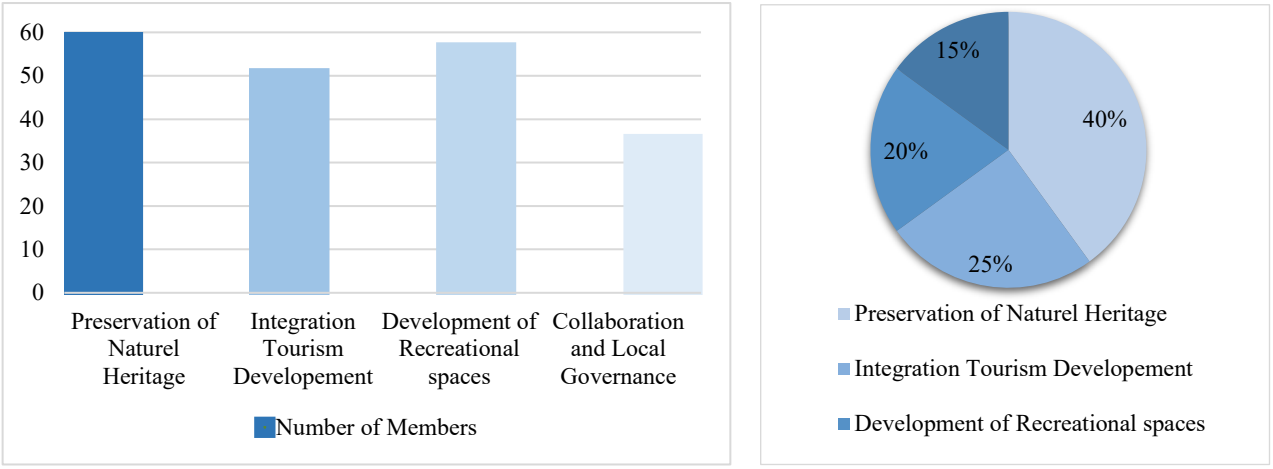
Figure 13 | Land use map (Source: Mapped with QGIS by Authors, 2024).

4.4. Participatory approach results

Data from citizens, gathered through semi-structured interviews and online surveys, revealed expectations and recommendations for Bousselam Valley development. Visualisations highlight key trends in citizen feedback. The bar chart shows that "Development of Recreational Spaces" (55 mentions) and "Preservation of Natural Heritage" (45 mentions) were the top concerns, followed by "Collaboration and Local Governance" and "Integrated Tourism Development". The Pie Chart (Figure 14) indicates that most proposed solutions focused on "Preservation of Natural

Heritage" (40%) and "Integrated Tourism Development" (25%), reflecting citizens' priorities. These insights are grouped into three themes:

1. *Preservation and enhancement of natural heritage*: Citizens emphasized ecological regeneration, cleaning the watercourse, reforesting with native trees, and launching awareness campaigns to address pollution and biodiversity loss.
2. *Rationalized tourism development*: Proposals included educational circuits highlighting local agriculture and modest development of leisure centres and tourist villages that respect agricultural and natural areas.
3. *Development of recreational spaces*: Suggestions included picnic areas, safe play zones, and amenities like waste bins, parking, and eco-friendly lighting.



(a) (a) (b)

Figure 14 | Key Issues Identified by Thematic Area*;* (b) Distribution of proposed solutions by Thematic Area

4.4.1. Discussion

- *Alignment between citizen expectations and project objectives.* Citizens' expectations align closely with the project goals, ecological preservation and recreational development.
- *Implementation challenges.* Challenges include managing land-use conflicts, zoning for tourism and agriculture, and establishing participatory governance with farmers, investors, and local authorities.
- *Perspectives for sustainable development.* Prioritising participatory governance, ecological infrastructure, and education on sustainable agriculture and biodiversity is essential for long-term sustainability.

4.5. Expert Recommendations

Based on expert consultation sessions, the following recommendations emerged:

- *Prioritise Scenario 1.* Experts agreed that Scenario 1 offers the best balance across the four dimensions of sustainability. Its focus on ecological connectivity, controlled urban expansion, and coordinated governance makes it the most viable short-term option.
- *Address weaknesses in Scenario 2.* Although environmentally ambitious, Scenario 2 lacks adequate provisions for flood risk management and biodiversity integration in urban areas. Experts proposed enhancing blue-green infrastructure and adopting adaptive landscape design.
- *Reform Scenario 3.* Experts raised concerns about governance and environmental risks in Scenario 3. They recommended strengthening institutional coordination, improving air and water quality controls, and promoting community engagement to reduce social and ecological impacts.

4.6. Limitations of the study

Despite its innovations, D-TPSA faces limitations: (1) reliance on stakeholder cooperation, which can be inconsistent in fragmented governance; (2) data gaps in informal settlements, requiring interpolation that may reduce precision; and (3) the rigidity of Boussole21's default weightings when applied to non-European heritage sites. Future versions could integrate machine learning to auto-calibrate weights based on real-time data.

4.7. Practical recommendations

To adapt D-TPSA, practitioners should: (1) conduct a scoping study to identify context-specific stressors (e.g., desertification vs. coastal erosion); (2) modularize Boussole21's indicators to allow swaps without disrupting the framework; and (3) use mobile apps for stakeholder input in low-tech settings. Pilot testing in contrasting regions (e.g., arid vs. temperate climates) is recommended to assess transferability.

5. Conclusion

This study demonstrates how digital tools like the Boussole21 platform can transform urban sustainability planning. Focusing on Setif's Bousselam Valley – a natural heritage site under environmental pressure, the research shows how data-driven evaluations can align urban development with ecological preservation and community well-being. Findings highlight Boussole21's effectiveness in assessing sustainability across environmental, economic, social, and governance dimensions. Its visualisations and stakeholder collaboration features support Agenda 2030 goals, empowering decision-makers to protect natural heritage while meeting societal needs. Boussole21's success suggests potential for broader use in diverse urban contexts. In rapidly growing cities of the Global South, such as Nairobi, the tool could assess informal settlement upgrades and green infrastructure planning for sustainable densification. Former industrial hubs like the Ruhr Valley or

Glasgow could apply it to assess brown field redevelopment, integrating ecological restoration with economic revitalization. Coastal cities vulnerable to climate change, including Cartagena or small island states, could compare adaptation strategies such as mangrove restoration versus seawall construction, while incorporating community input and cost-benefit analyses. Similarly, historic tourism-based cities like Algiers or Tunis could use Boussole21 to evaluate carrying capacity and prevent heritage degradation. The Transdisciplinary Place-Based Sustainability Assessment (TPSA) framework combines quantitative analysis, local data, participatory input, and expert insight, offering a comprehensive context-specific evaluation of project scenarios. This approach not only addresses current challenges in the Bousselam Valley but also provides a scalable model seeking to balance development with natural heritage conservation. However, challenges, such as weak governance, limited transparency, and urban overdevelopment risks, were identified. These were addressed through recommendations to strengthen infrastructure, enhance community ownership, and ensure ongoing monitoring and adaptation. In conclusion, integrating digital tools like Boussole21 into urban planning offers a transformative path for tackling today's urbanization challenges. By leveraging such technologies, planners and policymakers can build resilience in natural heritage areas while improving quality of life. This study presents a flexible, robust framework that aligns technological innovation with real-world challenges, paving the way for more inclusive and sustainable urban development.

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CRediT authorship contribution statement
Besma Ghorab: Conceptualization, Methodology, Validation, Writing, Original Draft, Investigation. Abderrahmane Diafat: Formal Analysis, Resources, Visualization, Data Curation, Supervision. Said Madani: Validation, Supervision, Project Administration. All authors participated in Writing - Review & Editing.

Use of AI tools
The authors employed Claude AI to assist with the identification and summarisation of relevant scholarly literature, and DeepL Write to enhance language and readability. All content generated or edited with the assistance of these tools underwent a rigorous review and revision process by the authors, who assume full responsibility for the final content of the publication.

Declaration of competing interest
The authors declare no conflict of interest.

Data availability
All data supporting the findings of this study are included in this published article.

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