SPARC: SPACE-BASED PRECURSORS OF CASCADING MULTI-HAZARD EVENTS IN BULGARIA – CONCEPT AND EXPECTED RESULTS

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Keywords: *Cascading multi-hazard events, space-based precursors, GNSS, InSAR, terrestrial water storage, early warning*

Abstract: *The concept and expected results of SPARC, a 24-month Bulgarian national project linked to COST Action CA24144 ANTICIPATE, are presented. SPARC integrates GNSS/InSAR-derived ground deformation, GNSS-derived terrestrial water storage, and satellite ecological stress indicators to develop prototype early-warning indicators and a FAIR database of cascading events for Bulgaria. The concept is set against policy documents and scientific literature and compared with European, South-East European and national initiatives.*

SPARC: КОСМИЧЕСКИ-БАЗИРАНИ ПРЕДВЕСТНИЦИ НА КАСКАДНИ МУЛТИ-ХАЗАРДНИ СЪБИТИЯ В БЪЛГАРИЯ – КОНЦЕПЦИЯ И ОЧАКВАНИ РЕЗУЛТАТИ

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Ключови думи: *Каскадни мултихазартни събития, космически предвестници, GNSS, InSAR, общо водно съдържание в сушата, ранно предупреждение*

Резюме: *Представени са концепцията и очакваните резултати от SPARC – национален проект с продължителност 24 месеца, свързан с COST Action CA24144 ANTICIPATE. Проектът интегрира деформации, определени чрез GNSS и InSAR, GNSS-базирани оценки на общо водно съдържание в сушата и екологични индикатори от спътникови данни, за да се изведат прототипни индикатори за ранно предупреждение и създаде база данни с каскадни събития за България. Концепцията е съпоставена с политики, научна литература и европейски, регионални и национални инициативи.*

Introduction

Natural hazards rarely occur in isolation; more often, they manifest simultaneously or sequentially with subsequent effects. Compound and cascading events, in which one hazard triggers or preconditions another, are a main driver of systemic risk [1–4]. The 2025 UNDRR Global Assessment Report puts direct disaster losses at about USD 202 billion per year. However, when accounting for cascading impacts and macroeconomic ecosystem externalities, the aggregate systemic toll escalates significantly to exceed USD 2.3 trillion.[5]. The European Climate Risk Assessment identifies 36 major climate-induced risks that can cascade across systems and regions [6]. Current predictive modeling frameworks exhibit critical temporal and operational limitations. Forecasting lags behind: short-term forecasts (7–10 days) address single hazards, while experimental extended-range forecasts reach 46 days – the gap that COST Action CA24144 ANTICIPATE (2025–2029) was created to close [7].

This operational agenda is underscored by major international and regional policy frameworks that prioritize systemic risk governance. . Globally, the Sendai Framework 2015–2030 calls for wider availability of multi-hazard early warning systems and comprehensive disaster risk assessment by 2030 [8]. This objective is further amplified by the UN Early Warnings for All (EW4All) initiative, which extends this aim to everyone [9], and by WMO guidelines, which define multi-hazard impact-based forecast and warning services [10]. The Union Disaster Resilience Goals (Recommendation 2023/C 56/01) set five non-binding goals – anticipate, prepare, alert, respond, secure – with a 2027–2030 horizon [11]. At the national level within Bulgaria, these overarching global and European mandates are translated into domestic legislative and strategic instruments. The National Disaster Risk Reduction Strategy 2018–2030 (Council of Ministers Decision No. 505/2018) and Programme 2021–2025 (Decision No. 865/2020), implemented through annual plans under the Disaster Protection Act [12], and the National Climate Change Adaptation Strategy and Action Plan to 2030 (Decision No. 621/2019) [13] carry this agenda. All these national policy documents collectively form a cohesive legal and regulatory framework for multi-hazard risk management.

Recent Bulgarian events show why. In 2024, the European Forest Fire Information System (EFFIS) mapped 45,435 ha burnt across 256 fires – the largest area in over a decade and more than the previous four years combined; two-thirds (29,976 ha) lay in Natura 2000 sites and 48% was agricultural land [14]. In September 2023, Storm Daniel brought 311 mm of rain in about 14 hours at Kosti, roughly four times the normal September total; the Tsarevo flood killed four people and destroyed two bridges [15]. The Mw 5.6 Pernik earthquake of May 22nd 2012, 25 km south-west of Sofia, led to a state of emergency [16]. Such events are typically preceded by slowly evolving states – dry soils and fuels, accumulated crustal strain – that Earth observation (EO) and geodesy can observe.

The scientific basis exists but is fragmented [17, 18]. Frameworks for hazard interactions and compound events are well developed [1, 2, 4]. A pan-European analysis of compound and cascading heatwave–drought–fire hazards covers summers 1990–2018 [19], and fire trends, drivers and warming-driven exacerbation in Mediterranean Europe are documented [18,19]. GNSS vertical displacements respond elastically to hydrological loading and yield regional terrestrial water storage (TWS) [22]; for the severe 2012–2015 Californian drought, GPS indicated a water loss of 57 ± 30 km^3 in the southern Sierra Nevada and San Joaquin mountains against 12 km^3 in hydrological models [23] – a persistent storage deficit that models underestimate, i.e., a physical preconditioning signal. For Bulgaria, the only peer-reviewed GNSS-TWS study known to us used 32 stations (2004–2025) and found an annual amplitude of 10–30 mm (locally above 40 mm) with minimum storage in August–October [24], which coincides with the usual late-summer fire season. Sentinel-1 persistent-scatterer InSAR is now available Europe-wide through the Copernicus European Ground Motion Service (EGMS) [25].

Three critical knowledge and operational deficits persist in current risk assessment frameworks. First, geodetic, hydrological and ecological indicators are analysed separately; to our knowledge, to date, a unified, national-scale preconditioning index that synthesizes these distinct lithospheric, hydrospheric, and biospheric variables remains non-existent for Bulgaria. Second, there is an absence of a curated, empirically verified repository archiving cascading multi-hazard events within the region. The lack of a historical dataset structured in accordance with FAIR (Findable, Accessible, Interoperable, and Reusable) data principles fundamentally restricts the empirical validation and calibration of predictive preconditioning indicators [26]. Third, existing European Union and regional diagnostic services remain limited by their architecture which is specific to particular hazards or based exclusively on atmospheric factors thereby failing to capture the complex interactions between hazardous hydrometeorological and geodynamic processes. The SPARC initiative directly addresses these systemic vulnerabilities at a national level by deploying open-access datasets and open-source computational tools.

SPARC concept and approach

SPARC is a 24-month Bulgarian national project led by the Space Research and Technology Institute of the Bulgarian Academy of Sciences (SRTI-BAS) and linked to COST Action ANTICIPATE. Its premise is that slow geophysical and ecological processes observable from space precondition hazards and can extend the lead time of early warning beyond what atmospheric forecasts alone provide. SPARC does not aim at operational forecasting; it tests whether space-based precursors add information in three cascade scenarios (Fig. 1): drought → wildfire → ecosystem degradation; prolonged rainfall → landslides → infrastructure damage; and geophysical deformation → activation of natural or technogenic processes.

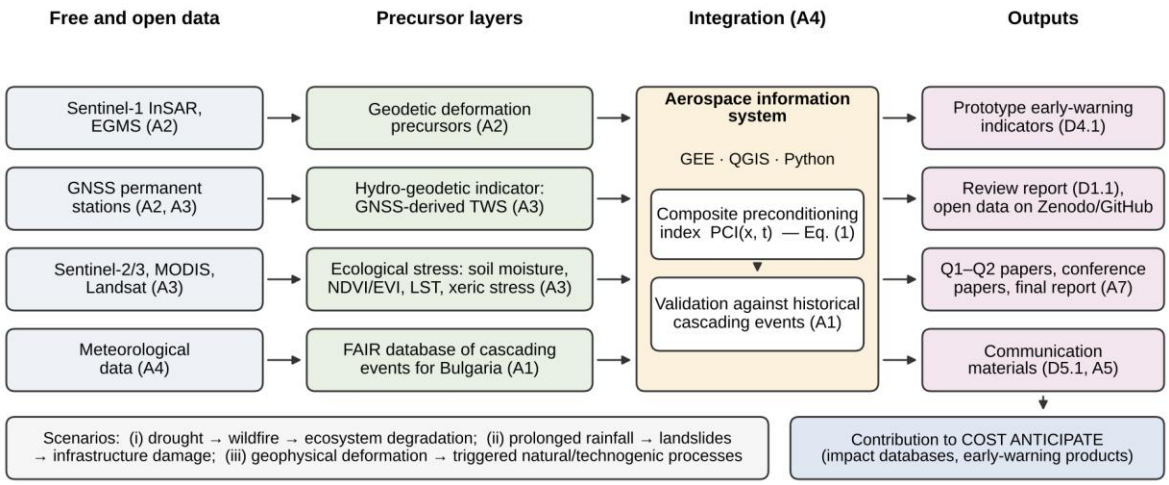


Fig. 1. SPARC concept: data, precursor layers, integration and outputs (A1–A7: activities, Table 1)

Three precursor layers are built solely from free and open data (Sentinel-1/2/3, MODIS, Landsat, EPOS Platform (https://www.ics-c.epos-eu.org/), and national and international GNSS networks). The geodetic layer (A2) processes GNSS time series and Sentinel-1 InSAR in test zones with known seismic, landslide, or deformation activity. The ecological layer (A3) uses soil moisture, vegetation indices (NDVI/EVI), land-surface-temperature anomalies, and xeric-stress indicators from long historical series, complemented by GNSS-derived TWS as a physically based drought indicator. Both are anchored in a database of historical and current cascading events for Bulgaria (A1), with spatial and temporal extents, affected areas, and available observations, and are published on Zenodo/GitHub.

Data management follows the FAIR principles [26]: ISO 19115-compliant metadata, open repositories (Zenodo, GitHub) and quarterly monitoring of data and code deliverables. Free data (Sentinel, GNSS networks) and free infrastructure keep costs low and make the workflow reproducible by other national teams.

The layers are combined in aerospace information systems built on open-source tools (Google Earth Engine, QGIS, Python) (A4). Because a small project cannot deliver a comprehensive methodology, A4 concentrates on practical approaches to co-analyse indicators of different origins and resolutions. The central concept is geophysical and ecological preconditioning: the degree to which prior states of soil, vegetation, water storage and crust raise the probability of a hazardous event. In its simplest candidate form, a composite preconditioning index (PCI) is a weighted sum of standardised anomalies:

(1) $$\mathrm{PCI}(x,t) = \Sigma_k\, w_k\, z_k(x,t), \quad z_k(x,t) = [X_k(x,t) - \mu_k(x,d)] \,/\, \sigma_k(x,d),$$

where X_k is one of K indicators (soil moisture, NDVI/EVI, land-surface temperature, TWS, deformation rate), μ_k and σ_k are its climatological mean and standard deviation for day of year d, and w_k are weights calibrated against the event database. Prototype indicators will be tested in the test zones and evaluated against historical cascading events, e.g. by hit rate and false-alarm ratio. Work is organised in seven activities (Table 1).

Table 1. SPARC activities, timing, and outputs (M – project month)

Activity	Months	Main outputs
A1 Data collection, event database	M1–M6	Event database; systematised indicators; review report D1.1
A2 Crustal movements, deformation precursors	M3–M12	Geodetic precursor set; Q2 article on cascading georisks
A3 Ecological precursors and GNSS-TWS	M4–M14	Ecological-stress indicators incl. TWS; Q1 article (EO-based drought–fire)
A4 Integration in aerospace information systems	M6–M18	Integration approaches; prototype indicators D4.1; Q1–Q2 article(s)
A5 Synthesis, visualisation, dissemination	M12–M24	≥ 2 indexed conference papers; ANTICIPATE report; materials D5.1
A6 ANTICIPATE working groups and meetings	M1–M24	Meeting reports; contributions to joint documents
A7 Q1–Q2 publications	M10–M24	Two Q1–Q2 articles (≥ 1 first-authored by Iliev); final report

Expected results

The outputs in Table 1 fall into four groups. **Data and knowledge repository:** the Bulgarian cascading-event database, a systematised set of space-based geodetic and environmental precursor indicators and a review report (D1.1), scheduled for completion by Project Month 6. **Scientific indicators and indices:** verified geodetic precursors for the designated experimental test zones, an ecological-stress metric indicator set including a hydro-geodetic TWS anomaly index , and a composite multi-hazard preconditioning index. **Functional prototypes:** combined early-warning indicators (D4.1) tested against historical cascades. Peer-reviewed **publications and dissemination:** Research outputs are targeted for high-impact dissemination, including two to three Q1–Q2 journal articles (cascading georisks; EO-based drought–fire analysis with GNSS-TWS; data-integration approaches), at least two papers in Scopus/Web of Science-indexed forums (EGU, IGARSS, ISPRS, Living Planet Symposium), at least one publication first-authored by the early-career researcher, alongside stakeholders' communication materials (D5.1), a collaborative ANTICIPATE report, and a final scientific report.

The expected scientific gain is threefold: (i) a test of whether slow precursors add information on cascade likelihood beyond meteorological indices; (ii) an assessment of GNSS-TWS as a preconditioning indicator, building on the Bulgarian seasonal signal [24]; and (iii) Bulgarian event and indicator data for ANTICIPATE's work on multi-hazard impact databases and early-warning products [7]. In policy terms, the results address the Union Disaster Resilience Goals on anticipation and early warning [11] and can inform the next national disaster risk reduction programme cycle. Added value should be judged against operational benchmarks such as the Standardised Precipitation Index (SPI) and the Fire Weather Index (FWI). An additional value will explore the possibilities of incorporating some of the results obtained into the acting BG-Alert warning system.

Discussion

Table 2 compares SPARC with initiatives outside ANTICIPATE for which key facts could be verified in public sources; unverified initiatives are omitted.

Table 2. SPARC compared with European, South-East European and Bulgarian initiatives (project data: CORDIS [25])

Initiative	Type, period	Scope	Gap addressed by SPARC
MYRIAD-EU	H2020, 2021–2025	Multi-hazard, multi-sector risk framework	No EO/geodetic precursors; no Bulgarian pilot found
MEDiate	Horizon Europe, 2022–2025, EUR 3.55 M	Multi-hazard decision support	No satellite/GNSS precursor layer
CLIMAAX	Horizon Europe, 2023–2026, EUR 20 M	Regional climate-risk toolbox	Scenario risk, not precursors; reusable workflow
FirEURisk, FIRE-RES, SAFERS	H2020, 2020–2025, EUR 2.9–19.9 M	Wildfire risk, management, response	Single hazard; no geodetic or TWS drivers
ANYWHERE	H2020, 2016–2019, EUR 12.0 M	Impact-based warning, weather extremes	Short-range, weather-driven; no geophysical hazards
CASCADES	H2020, 2019–2023, EUR 6.9 M	Cross-border climate-risk cascades	Socio-economic, not physical cascades
Destination Earth	EU Digital Europe, live since 2024	Digital twins: weather extremes, climate	Atmosphere-centered; no solid-Earth component
EFFIS	Copernicus service, JRC	Fire danger (FWI), burnt area	Single-hazard indices; no subsurface water
EGMS	Copernicus LMS, baseline 2015–2020	Sentinel-1 ground motion, Europe-wide	Deformation only; SPARC builds on it
DMCSEE	Regional centre, bulletins since 2010	SE Europe drought (SPI, water balance)	Meteorological drought only
DriDanube	Interreg Danube, 2017–2019, EUR 1.97 M	Drought risk, Drought Watch	No Bulgarian partner; drought only
BG-ALERT	Ministry of Interior, since 2023	Public warning (cell broadcast)	Dissemination only; SPARC is upstream
DRR Programme 2021–2025	Council of Ministers	National risk-reduction activities	Policy instrument; indicators can inform next cycle

European initiatives. MYRIAD-EU and MEDiate develop multi-hazard, multi-risk frameworks and decision support; CLIMAAX offers a climate-risk toolbox; FirEUrisk, FIRE-RES and SAFERS address wildfire risk, management and response; ANYWHERE buildts impact-based warnings for weather extremes; CASCADES addresses socio-economic cascades. None of those reviewed monitors geodetic or hydro-geodetic precursors or builds on a Bulgarian cascade record. Operational services are closest in data: EFFIS provides fire danger and burnt-area maps [14], EGMS provides ground motion [25], and Destination Earth digital twins weather extremes and climate adaptation [28]. These supply hazard-specific indices, whereas SPARC examines the preconditioning states beneath them. The design is complementary: reuse EGMS and Sentinel products, add GNSS-TWS and ecological stress, and test the index against SPI and FWI.

South-East Europe and the Balkans. The Drought Management Centre for South-Eastern Europe (DMCSEE), established in 2007 and hosted by the Slovenian Environment Agency, issues bulletins based on SPI, percentiles and water-balance outlooks [29]. DriDanube (Interreg Danube, 2017–2019, EUR 1.97 M) built drought-watch and user services across ten countries but had no Bulgarian partner [29]. Both are meteorological or drought-only; neither links drought to fire, landslides or deformation. We found no regional system that combines geodesy with ecological EO indicators; other regional programmes could not be verified and are not discussed. A Bulgarian cascade database and precursor set therefore fill a regional and national gaps.

Bulgaria. BG-ALERT, the cell-broadcast public warning system run by the Ministry of Interior since 2023, is a dissemination channel; it was criticised after floods in which no alerts were received, and in April 2025 the Prime Minister ordered it to be fixed [30]. It generates no hazard intelligence. The risk reduction programme and its annual plans (2024: 117 activities, indicative budget of BGN 78 million) are policy instruments, not monitoring systems [12]; no successor programme for the period after 2025 was found in public sources at the time of writing. SPARC therefore sits upstream: its indicators serve the risk-knowledge and monitoring stages on which warning dissemination depends, and its event database can inform the next programme cycle. The Bulgarian GNSS-TWS study [24] shows the approach is feasible with national stations.

Positioning. At all three levels the pattern is consistent: European services deliver hazard-specific indices and forecasts, regional centres deliver meteorological drought monitoring, and national systems deliver warning dissemination and policy frameworks. What is missing is a layer that characterises the slowly varying states that precondition several hazards simultaneously. Because TWS, soil moisture and ground-deformation anomalies evolve over weeks to months, such a layer could in principle support lead times beyond those of medium-range forecasts and thus complement the extended-range forecasts of ANTICIPATE [7]. Whether it does so for Bulgaria is the empirical question SPARC will answer.

Limitations. SPARC's budget is roughly two orders of magnitude below that of the EUR 3.5–20 M projects in Table 2, so its scope is limited to test zones, free data and prototype indicators. GNSS-TWS depends on station density and on separating non-hydrological deformation: the Bulgarian study found weaker agreement between GNSS and model products than among the models themselves, attributed to station distribution and non-hydrological deformation [24]. The EGMS baseline covers 2015–2020 with annual updates [25], and a short event record limits statistical power. Results will therefore be pilot-scale; benchmarking, open data and feedback from the ANTICIPATE network are the main safeguards.

Conclusions

The implementation of the planned research activities under the SPARK project is expected to lead to the systematisation of the multi-hazard risk profile and the identification of existing gaps at the national level, yielding measurable multi-risk indicators to improve multi-hazard risk assessment. More specifically:

- Bulgarian fires, floods and earthquakes combine slow preconditioning with fast triggers; policy calls for anticipation and multi-hazard early warning, yet no national precursor layer exists.
- SPARC integrates GNSS/InSAR deformation, GNSS-derived TWS and EO ecological indicators into a preconditioning index and a FAIR event database for Bulgaria, using free data and open-source tools.
- Expected results: the database, indicator sets, prototype early-warning indicators (D4.1), two to three Q1–Q2 articles, at least two indexed conference papers and input to ANTICIPATE.
- SPARC is complementary to European, regional and national initiatives – an upstream, low-cost layer whose added value must be demonstrated against SPI and FWI benchmarks.

Acknowledgments

This study was nationally co-funded by the project “SPace and Ground Technologies for Studying Cascading Multi-hazard Events – models, Applications, PreCursors (SPARC)”, supported under Co-funding Contract No. KP-06-COST / 23 / dated 18 August 2026, concluded between the Space Research and Technology Institute at the Bulgarian Academy of Sciences (SRTI-BAS) and the Bulgarian National Science Fund (BNSF) within the framework of BNSF-1.009 – “Procedure for Providing National Co-funding for the Participation of Bulgarian Research Teams in Established Actions in Science and Technology.

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