

CHANGING CITIES

AI That Anticipates Decay

Predictive Satellite Intelligence for Climate-Resilient Heritage Cities

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[1]*CERN, Experimental Physics*

Introduction - What is Predictive Heritage Monitoring?

Definition: A proactive AI-driven framework that transforms multi-sensor satellite time series into probabilistic deterioration forecasts for cultural heritage sites.

The three “Pillars”:

- **Earth Observation (EO):** Integration of Copernicus Sentinel missions (Sentinel-1, 2 and 5P).
- **Multimodal AI:** Deep learning architecture combining Convolutional Neural Networks (CNNs) for image analysis and Long Short-Term Memory (LSTMs) for temporal modeling.
- **Decision Intelligence:** Actionable risk scores that allow for intervention before visible damage occurs.

Purpose: To shift from reactive "damage mapping" to proactive risk governance and urban resilience.

The Importance of AI in Heritage Conservation

- Cultural heritage is exposed to complex risks (Climate Change, Pollution, Ground Deformation) that are often invisible until it is too late.
- Manual inspections are labor-intensive, fragmented and detection occurs only after damage is visible.
- This AI framework allows managers to:
    a. Monitor large-scale urban areas continuously.
    b. Forecast structural risk acceleration up to 12 months in advance.
    c. Prioritize preventive conservation without physical intervention in sensitive sites.



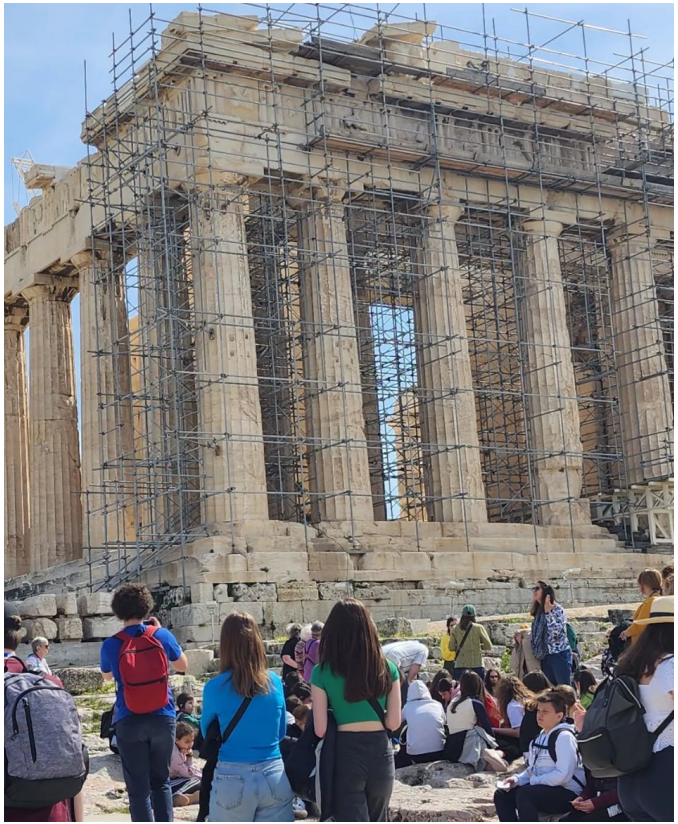
Case Study Presentation (Athens, Greece) (1/3)

Theme: Modeling 30+ sites across different urban typologies (Flood corridors, Heat Islands, Wildfire Edges, Industrial zones).

Multi-factor stressors (e.g., millimetric ground deformation + NO2 pollution) interact to accelerate decay, leading to:

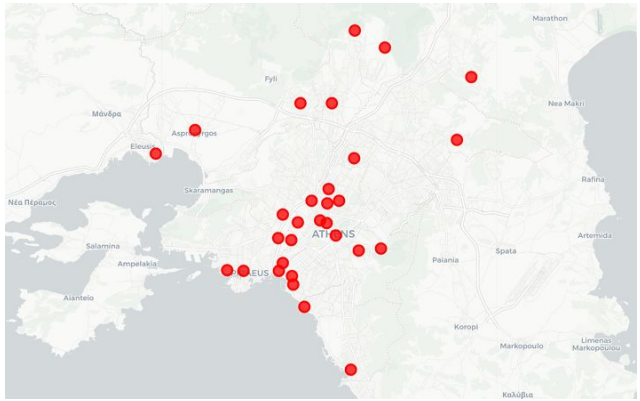
- Irreversible loss of cultural identity.
- Economic impact on tourism and urban social cohesion.

Athens serves as the perfect "urban laboratory" due to its high density, aging building stock and diverse environmental stressors.



Case Study Presentation (Athens, Greece) (2/3)

Site Categorization	Meaning?	Places in Athens
Flood Corridors (F.1-F.4)	Hydrological instability	Kifisos and Ilisos Rivers
Heat Islands (H.1-H.5)	Thermal stress on building materials	Omonia, Kypseli and Patissia
Wildfire Edges (W.1-W.6)	Peri-urban interface risks	Penteli and Dionysos peri-urban interfaces
Industrial/Coastal (I.1-I.5 / C.1-C.4)	High pollution accumulation	Piraeus Port, Aspropyrgos and Glyfada
Green Buffers (G.1-G.2)	Low-risk control environments	National Garden and Stavros Niarchos Park as control environments.



Case Study Presentation (Athens, Greece) (3/3)

Sentinel	GEE Data Product ID	Band ID	Physical Role in Decay Detection
Sentinel-1	S1_GRD	VV (Vertical Transmit/Vertical Receive)	Structural: Radar backscatter reflecting building geometry and surface roughness.
Sentinel-1	S1_GRD	VH (Vertical Transmit/Horizontal Receive)	Moisture: Cross-polarization sensitive to volume scattering (detecting dampness).
Sentinel-2	S2_SR_HARMONIZED	B4 (Red)	Visual: Detects material fading and changes in surface reflectance.
Sentinel-2	S2_SR_HARMONIZED	B3 (Green)	Biological: Used to monitor moisture and biological growth.
Sentinel-2	S2_SR_HARMONIZED	B2 (Blue)	Texture: High-frequency data used to map urban fabric and surface cracks.
Sentinel-2	S2_SR_HARMONIZED	B8 (Near-Infrared / NIR)	Vegetation: Primary band for NDVI calculation to find invasive weeds/moss.
Sentinel-5P	S5P/OFFL/L3_NO2	NO2_column_number_density (Nitrogen Dioxide)	Chemical: The corrosive gas responsible for "Black Crust" on marble and stone.
Sentinel-5P	S5P/OFFL/L3_NO2	absorbing_aerosol_index (UV Aerosols)	Particulate: Tracks soot, dust, and smoke that accelerate physical erosion.

Problem Analysis & Strategic Goals

- **The Problem:** (a) Managing massive volumes of heterogeneous data (radar, optical, atmospheric) and (b) the reactive nature of current heritage management (Reactive Maintenance).
- **Strategic Goals:**
  i. **Predictive Maintenance:** Forecasting risk evolution before physical symptoms appear.
  ii. **Multimodal Data Fusion:** Breaking "Data Silos" by merging structural, environmental and atmospheric datasets into one unified model.
  iii. **ESG Integration:** Aligning heritage preservation with Environmental, Social, and Governance goals for smart cities.

The need for this system is driven by the fact that environmental stressors interact; monitoring them in isolation is no longer sufficient.

Model Training (1/2)

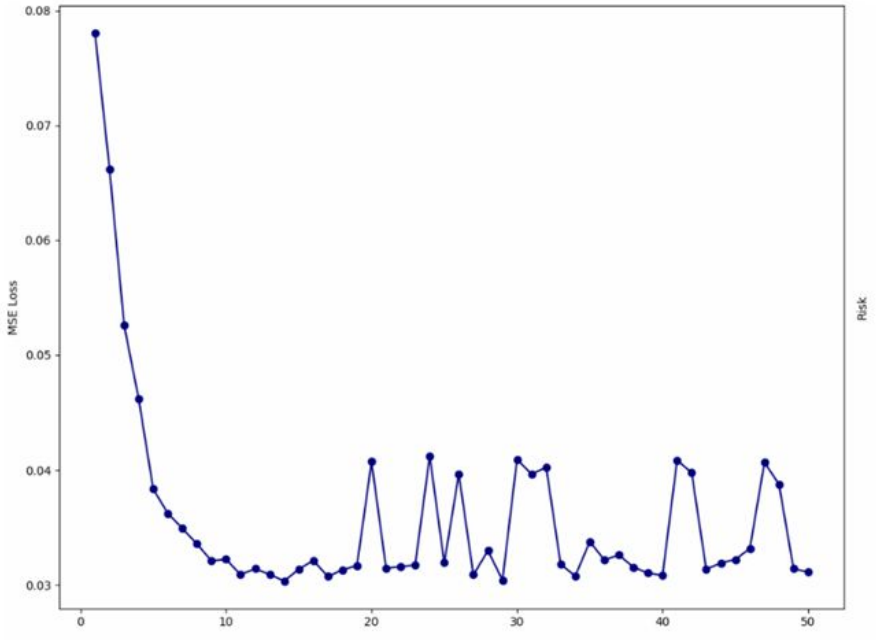
Implemented in PyTorch utilizing DataLoaders for batch-based training and improved computational efficiency.

i. Optimizer: Learning rate of 0.001.

ii. Mean Squared Error (MSE) used to formulate the framework as a probabilistic regression problem.

iii. Rapid initial learning observed, with loss stabilization achieved after approximately 10 epochs.

iv. Probabilistic Risk Scores: Normalized values ranging from 0 to 1.



Model Training (2/2)

The AI doesn't look at these signs in isolation (and combines them with buffers [640m x 640m] - Reminder: S1 and S5P see differently!).

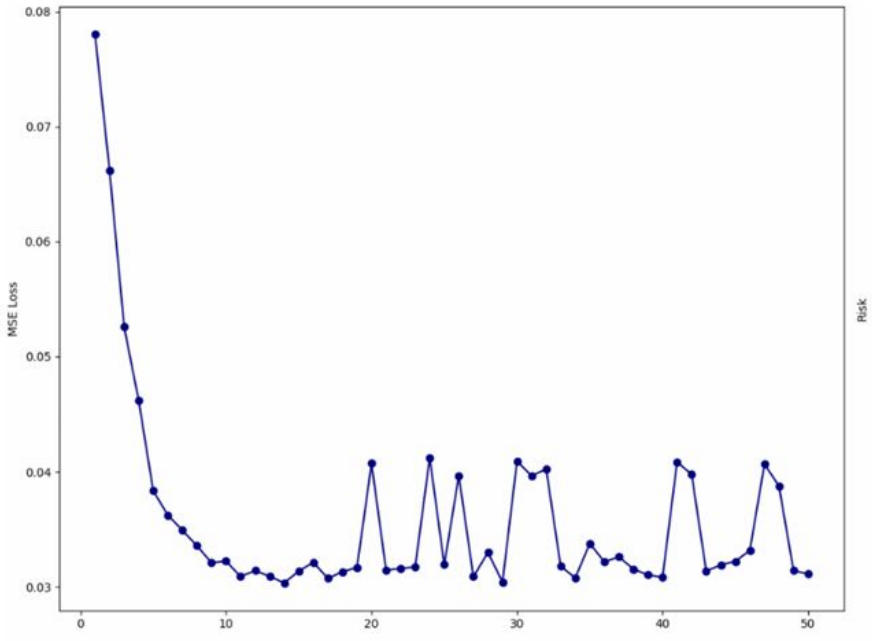
We concatenate:

- CNN features from S1, S2,
- aggregated vectors from S5P,
- the 32-dimensional Site Embedding

into a single 88-feature vector

(S1 (16) + S2 (32) + S5P (8) + Site ID Card (32) = 88)

This unified vector is what the LSTM processes to learn how these different "signs" interact over a 12-month period to cause decay ***(But how are key numbers chosen…?)***



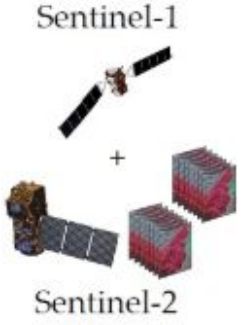
Operation & Interaction

Data Ingestion:

i. Source: Streams from Google Earth Engine (Sentinel-1 SAR, Sentinel-2 Multispectral, Sentinel-5P Air Quality).

ii. Infrastructure: Python-based automation pipelines using PyTorch for tensor generation.

iii. Normalization (Pre-processing): Logarithmic scaling (log1p) and temporal synchronization (1e5) of 12-month observation sequences.



The Simulation/Prediction Loop:

i. CNN Encoders: Extract spatial patterns of decay and urban texture.

ii. LSTM Layer: Processes temporal dependencies to learn how risks evolve over time.

iii. Predictive Output: The model compares current conditions to learned "deterioration patterns" and generates a probabilistic risk score (0 to 1).

Google Earth Engine

Result Highlight - Multi-Hazard Sensitivity

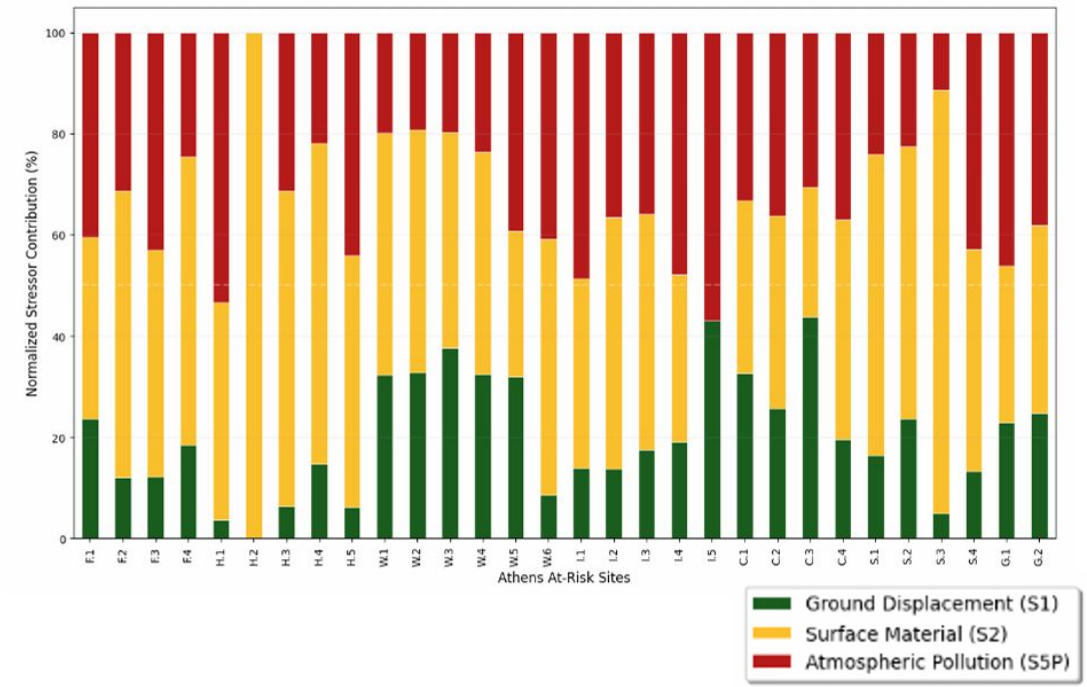
Findings: *Different urban environments are driven by different "decay accelerators."*

But what exactly?

i. Structural signals (Sentinel-1) are dominant in infrastructure-intensive and flood-prone areas.

ii. Pollution signals (Sentinel-5P) are the primary risk drivers in transportation corridors.

iii. Multispectral changes (Sentinel-2) are most relevant in residential zones with vegetation variability.



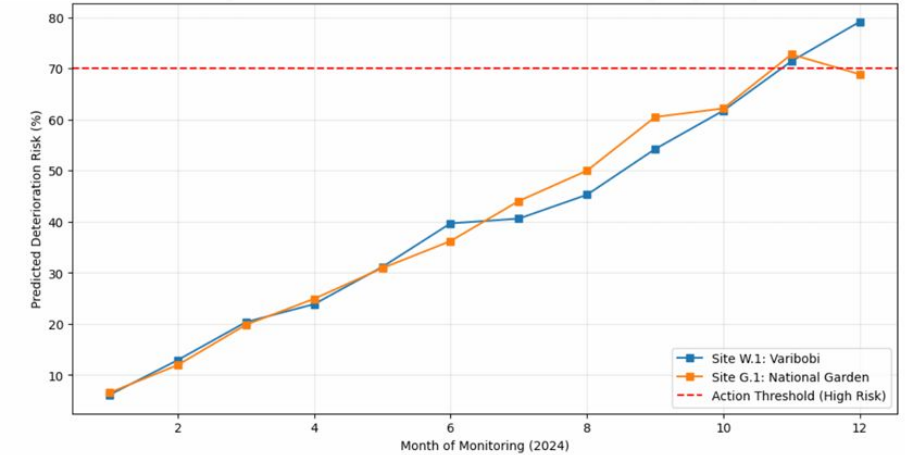
Result Highlight - Multi-Hazard Sensitivity

The 12-Month Window: *The model successfully generated rolling risk trajectories, showing when it is risky enough for a small 'change'/decay to happen.*

Case study comparing predictions of two sites...

i. Site W.1 - Varibobi: Steady, non-linear increase in risk, ending well above the threshold. Areas where stressors (like wildfires) cause compounding decay.

ii. Site G.1 - National Garden: Even "Green Buffers" can spike above high-risk thresholds (likely due to seasonal stressors like heatwaves or moisture shifts) → temporary stabilization.



Takeaway: Managers can identify *when* a site will become critical, not just *if*.

Comparison with Traditional Methods & Practical Implications

Traditional: Fragmented, labor-intensive, manual surveys. Deterioration is detected after damage is visible.

Generally, the solution should aim towards being:

- **AI-Driven:** Continuous, large-scale monitoring. Detection occurs before structural failure is visible.
- **Preventive**: Supports scheduling of inspections and conservation based on ranked risk scores.
- **Integrating GIS**: Risk maps can be integrated directly into urban "Digital Twins" for real-time decision support.
- **Adaptive to Climate**: Provides evidence-based data for long-term urban resilience planning.
- **Scalable:** The framework can monitor an entire metropolitan area simultaneously using freely available satellite data.

Limitations & Future Work

- Reliance on semi-supervised labeling due to a lack of fully annotated global heritage decay datasets.
- Future Scope:
  - Integration of Mixed Reality (HoloLens) for guided on-site maintenance.
  - ***Expanding the dataset to include longer historical archives (5+ years) to capture seasonal and decadal patterns.***



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Thank you for your attention!

Any questions?