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Research paper

Assessing Soil Erosion Susceptibility in Bayelsa State Nigeria, Using Sentinel-1 in SAR Data

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Abstract

Soil erosion is a critical environmental challenge in the Niger Delta region of Nigeria, driven by a combination of fluvial processes, coastal dynamics, and anthropogenic activities. Traditional monitoring methods are often labor-intensive, spatially limited, and struggle to capture the dynamic nature of land surface changes. This study presents a novel framework for assessing soil erosion susceptibility in Bayelsa State, a predominantly low-lying, riverine state within the Niger Delta, by integrating Interferometric Synthetic Aperture Radar (InSAR) data with key environmental parameters within the Google Earth Engine (GEE) cloud-computing platform. Using the Sentinel-1 SAR data from 2019 to 2022, we employed the Small Baseline Subset (SBAS) technique to generate time-series ground deformation maps. Areas of significant subsidence were identified as potential zones of ground instability, which are intrinsically linked to soil erosion susceptibility, particularly in waterlogged and deltaic environments. These deformation signals were then integrated into a Modified Universal Soil Loss Equation (MUSLE) framework, combined with ancillary datasets such as Digital Elevation Models (DEM), rainfall data (CHIRPS), and land cover information. The results reveal that deformation rates of 0.2cm/year correspond to uplift. High Susceptibility zones account for roughly 79.3% of soil erosion, while Moderate Susceptibility zones cover 17.8%, and Low Susceptibility zones are present in 2.9% of the area. This research demonstrates the efficacy of GEE as a powerful tool for large-scale, multi-temporal geospatial analysis and highlights the significant potential of Sentinel-1 InSAR to provide actionable intelligence for land management, infrastructure planning, and mitigation strategies in vulnerable deltaic ecosystems.

***Keywords**: Soil Erosion; Sentinel-1; InSAR; Google Earth Engine; Bayelsa State; Niger Delta; Land Subsidence; MUSLE.*

1. Introduction

Soil erosion is a globally pervasive environmental issue, leading to land degradation, loss of agricultural productivity, and increased risk of natural disasters such as landslides and floods (Borrelli et al., 2017). In deltaic regions, the problem is exacerbated by low-lying topography, soft alluvial soils, rising sea levels, and intense anthropogenic pressure. The Niger Delta in Nigeria, one of the world's largest wetlands, is particularly vulnerable. Bayelsa State, located in the heart of this delta, is characterized by a complex network of rivers, creeks, and extensive mangrove forests. Its economy and livelihoods are deeply intertwined with its aquatic and terrestrial ecosystems. However, the state faces severe environmental degradation driven by soil erosion, a phenomenon compounded by oil and gas exploration, deforestation, and climate change-induced sea-level rise (Nwankwo, 2018).

Traditional methods for monitoring soil erosion, such as field surveys, erosion pins, and sediment yield measurements, provide accurate point-based data but are laborious, costly, and difficult to scale up for regional assessments. Remote sensing has offered significant advancements, with optical imagery (Landsat, Sentinel-2) being widely used for mapping land cover change and identifying erosion features (Roglassova et al., 2022). However, optical sensors are limited by cloud cover, which is frequent in tropical regions like the Niger Delta, and they primarily capture the effects of erosion rather than the precursors or underlying instability.

Recent advancements in Synthetic Aperture Radar (SAR) technology have opened new frontiers for geohazard monitoring. SAR systems provide their own illumination and can penetrate clouds, making them ideal for consistent, all-weather monitoring. Interferometric SAR (InSAR) techniques, particularly Persistent Scatterer InSAR (PS-InSAR) and the Small Baseline Subset (SBAS), can detect millimeter-scale ground surface deformations over time (Berardino et al., 2002). While traditionally used for monitoring subsidence due to groundwater extraction or mining, InSAR-derived deformation signals can be critical indicators of soil instability. In deltaic environments, ground subsidence can increase inundation risk, alter drainage patterns, and weaken soil structure, thereby accelerating erosion processes (Dixon et al., 2019).

The analysis of such multi-temporal SAR data, however, requires significant computational resources and expertise. The Google Earth Engine (GEE) platform addresses this barrier by providing a cloud-based archive of petabytes of geospatial data and a powerful computational environment (Gorelick et al., 2017). GEE enables the processing of large datasets, like the entire Sentinel-1 archive, without the need for local high-performance computing infrastructure.

This study aims to assess soil erosion susceptibility in Bayelsa State. The central ground deformation patterns derived from Sentinel-1 SBAS-InSAR can serve as a crucial proxy for identifying areas of heightened soil instability, thereby improving the accuracy of conventional soil erosion susceptibility models. The specific objectives are:

1) To process the Sentinel-1 SAR archive for Bayelsa State using GEE to generate a time-series ground deformation map from 2019 to 2022;
2) To integrate the InSAR-derived subsidence layer with key environmental factors (topography, rainfall, land cover) within a Modified Universal Soil Loss Equation (MUSLE) framework; and
3) To map and analyze the spatial patterns of soil erosion susceptibility, highlighting the contribution of the InSAR data in identifying critical risk zones.

2. Study Area

Bayelsa State (latitude 4°15′N to 5°25′N and longitude 6°00′E to 6°55′E) is situated in the central part of the Niger Delta (Figure 1). It covers an area of approximately 10,524 km², with over 80% of its terrain being less than 5 meters above mean sea level (Amangabara, 2014).

Fig. 1: Map of Africa and Location Nigeria.

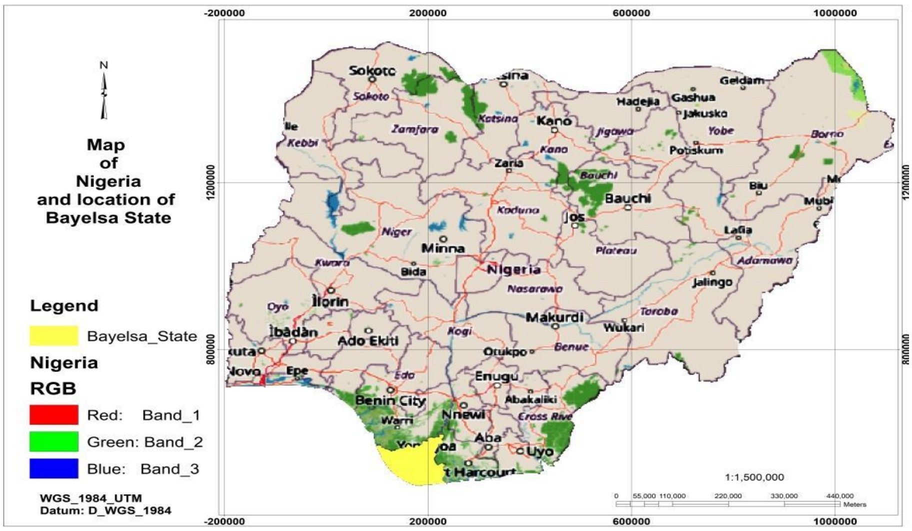

Fig. 2: Map of Nigeria and Location Bayelsa State within the Niger Delta.

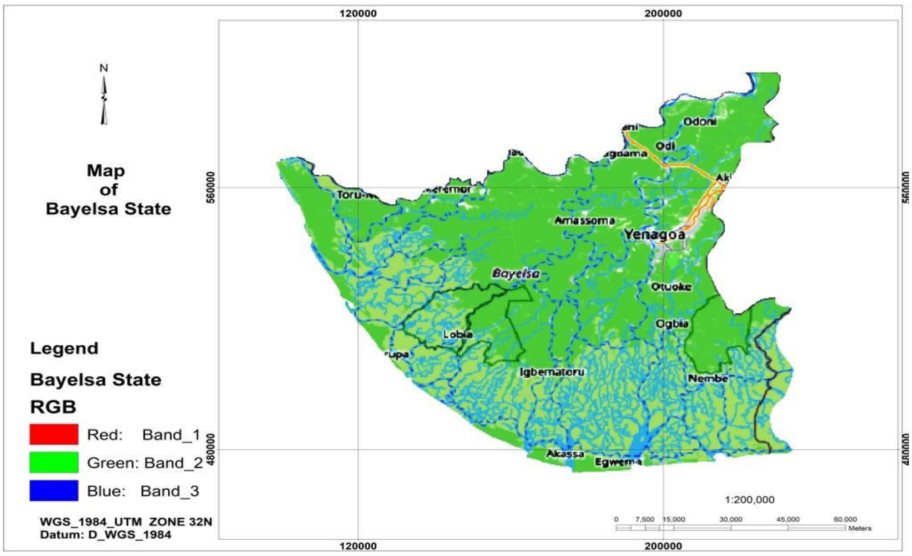

Fig. 3: Map of Bayelsa State.

The state is characterized by a dense network of rivers and creeks, with the Nun, Ekeremor, and Orashi rivers being the most prominent. The climate is tropical wet and dry, with an annual rainfall exceeding 2,500 mm, concentrated between April and October. The intense rainfall, coupled with the low-lying topography and permeable sandy-loam soils, makes the region naturally susceptible to fluvial erosion. The geological foundation consists of unconsolidated Quaternary alluvial and deltaic deposits, which are inherently unstable. Bayelsa is a major hub for Nigeria's oil and gas industry, leading to the presence of extensive pipeline networks, flow stations, and other infrastructure. The associated activities, such as land clearing, pipeline laying, and occasional oil spills, have significantly altered the landscape and contributed to land degradation and increased erosion susceptibility (Omeje, 2018). The dominant land cover types are mangrove forests, freshwater swamp forests, and water bodies, with increasing areas of urban/built-up land and agricultural land.

3. Methodology

3.1. Data acquisition

All datasets were sourced from publicly available archives accessible through GEE (Table 1).

- SAR Data: The Sentinel-1 Ground Range Detected (GRD) VV and VH polarization C-band SAR data, acquired from 2019-01-01 to 2022-12-31, were used. Only data from ascending orbit (relative orbit 68) with a 12-day revisit period were selected to ensure consistent viewing geometry and reduce geometric distortions. The study period was chosen to capture recent changes and provide a sufficient temporal baseline for InSAR processing.
- Topographic Data: The Copernicus DEM 30 m (GLO-30) was used to derive slope, aspect, and topographic wetness index (TWI).
- Climate Data: The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) daily rainfall product (0.05° resolution) was used to calculate the rainfall erosivity factor.
- Land Use/Land Cover (LULC): The Dynamic World V1 product, derived from Sentinel-2 imagery, was used to classify land cover and derive the cover and management factor

This study employs a multi-stage workflow entirely within the Google Earth Engine platform. The methodology involves data acquisition, pre-processing, InSAR analysis, creation of a susceptibility model, and final validation and mapping.

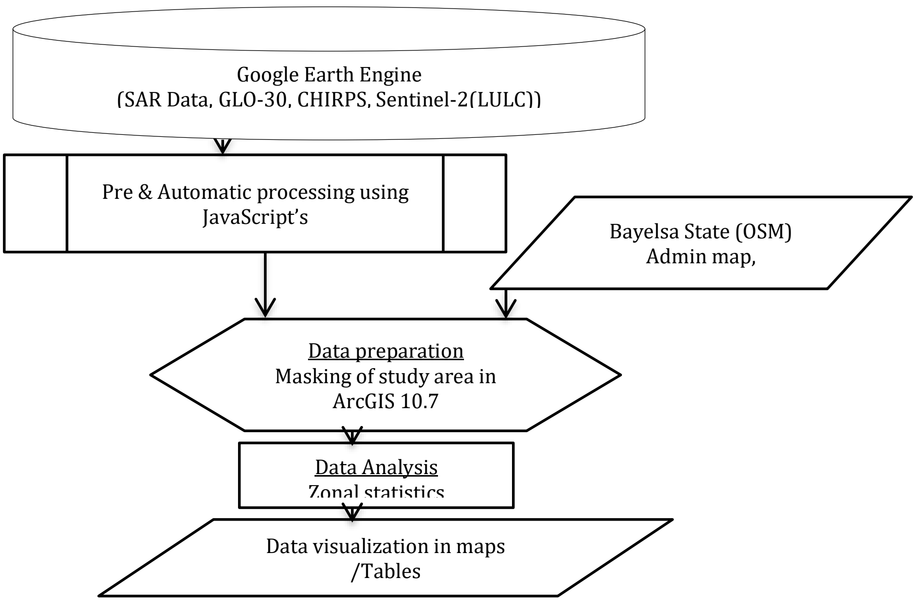

Fig. 4: Method of Soil Erosion Susceptibility Estimation in Bayelsa State with Sentinel-1 InSAR Data.

Table 1: Data Sources Used in the Study

Dataset	Source	Resolution/Scale	Purpose
Sentinel-1 GRD	European Space Agency (via GEE)	10 m	InSAR (Ground Deformation)
Copernicus DEM	European Space Agency (via GEE)	30 m	Topographic Factors (Slope, TWI)
CHIRPS Precipitation	UCSB CHG (via GEE)	0.05°	Rainfall Erosivity (R)
Dynamic World LULC	Google/World Resources Institute(via GEE)	10 m	Cover & Management (C)

3.2. InSAR processing (SBAS technique)

The SBAS technique was implemented in GEE using a custom script adapted from open-source InSAR processing libraries. The process involved the following steps:
1) Image Collection Filtering: The Sentinel-1 collection was filtered for the study area, date range, orbit direction, and instrument pass (interferometric).
2) Interferometric Pair Generation: Pairs of SAR images with a short temporal baseline (< 30 days) and a small perpendicular baseline were generated. This minimizes decorrelation noise.
3) Interferogram Creation: For each pair, an interferogram was formed by multiplying the complex conjugate of the two SAR acquisitions. The resulting phase contains information about ground deformation, topography, and atmospheric delays.
4) Deformation Time-Series Estimation: A least-squares inversion method was applied to the stack of interferograms to solve for the cumulative ground displacement over time. This process separates the deformation signal from other phase contributions, yielding a time-series of displacement for each pixel.
5) Result Aggregation: The average annual line-of-sight (LOS) deformation velocity was calculated for the entire 2019-2022 period. Negative values in the LOS direction indicate subsidence (ground moving away from the sensor), while positive values indicate uplift.

3.3. Soil Erosion Susceptibility Modeling

We adapted the Modified Universal Soil Loss Equation (MUSLE) to model soil erosion susceptibility. The original USLE and MUSLE(via GEE) models predict average annual soil loss. For this study, we reinterpreted the model to represent susceptibility, where higher values indicate greater potential for erosion. The MUSLE format is:

$$A = (R * K * LS * C * P)$$

Where A is soil loss, and the other factors are as defined below. For this study, we focused on the environmental potential and treated the InSAR data as an additional modifier.
1) Rainfall Erosivity (R): Calculated using the Fournier index (F) based on CHIRPS data: $F = (P^2 / P)$, where P is the mean annual precipitation. The R factor was then estimated as $R = 0.43 * F$.
2) Soil Erodibility (K): Since a detailed soil map for Bayelsa is not available in GEE, a simplified map was derived from the FAO-UNESCO soil texture classification data, assuming higher erodibility for sandy soils common in the delta.
3) Topographic Factor (LS): Calculated from the Copernicus DEM using the standard formula: $LS = (As / 22.1)^m * (\sin \theta / 0.0896)^n$, where As is the specific catchment area, θ is the slope angle, and m and n are empirical exponents (0.4 and 1.3, respectively).
4) Cover and Management (C): Derived from the Dynamic World LULC classification. C-factor values were assigned based on standard literature (e.g., Water: 0, Forest: 0.001, Agriculture: 0.3, Urban: 0.1).
5) Support Practice (P): In the absence of detailed data on conservation practices, a uniform value of 1 (no support) was assumed for the entire study area, representing a worst-case scenario.

3.4. Integration of InSAR data and final susceptibility map

The core innovation of this study lies in the integration of the InSAR-derived subsidence map. A susceptibility index (S_erosion) was constructed by combining the MUSLE-derived score with the subsidence rate (via GEE):

$$S\_erosion = (R * K * LS * C) * W\_sub$$

Where W_sub is a weighting factor derived from the average annual subsidence velocity (d). We defined W_sub as follows, with negative values representing subsidence:
- If d > 0.5 cm/year (negligible deformation or uplift): W_sub = 1
- If -1.0 < d ≤ -0.5 cm/year (minor subsidence): W_sub = 1.2
- If -2.0 < d ≤ -1.0 cm/year (moderate subsidence): W_sub = 1.5
- If d ≤ -2.0 cm/year (severe subsidence): W_sub = 2.0

This weighting amplifies the susceptibility score in areas experiencing significant ground compaction or subsidence, reflecting the in-creased vulnerability of the soil structure. The final S_erosion map was reclassified into five susceptibility classes using quantile breaks: Very Low, Low, Moderate, High, and Very High.

4. Results

4.1. Ground deformation (InSAR)

The average annual ground velocity map from the SBAS-InSAR analysis (2019-2022) reveals significant spatial variability in ground stability across Bayelsa State (Figure 5). Widespread stability (deformation rates between 0.8 and 0.1 cm - 0.2cm/year) is observed in most forested areas. However, several localized zones of significant subsidence are evident.

4.2. Soil erosion susceptibility map

The final integrated soil erosion susceptibility map & table (S_erosion) is shown in Figure 5, 6 & Table 2. The spatial distribution of susceptibility classes reveals clear patterns:

- High Susceptibility: These zones occupy approximately 79.3% of the study area and are almost exclusively located along the banks of the Nun, Ekeremor, and Orashi
- Rivers, and in the coastal deltaic plains. These areas coincide with the zones of highest recorded subsidence and high LS and R factors.

Moderate Susceptibility: Covering about 17.8% of the area, this class includes areas adjacent to the “High" zones, as well as some inland areas with moderate slopes and degraded land cover.

Low Susceptibility: These classes are predominantly found with 2.9%, forested regions of the state, where topography is flatter, rainfall erosivity is slightly lower, and the vegetation cover (C-factor) provides significant protection. The mangrove forests along the coast, despite being in a high-energy environment, show a lower susceptibility score primarily due to the protective effect of the dense root systems, unless they are experiencing significant subsidence.

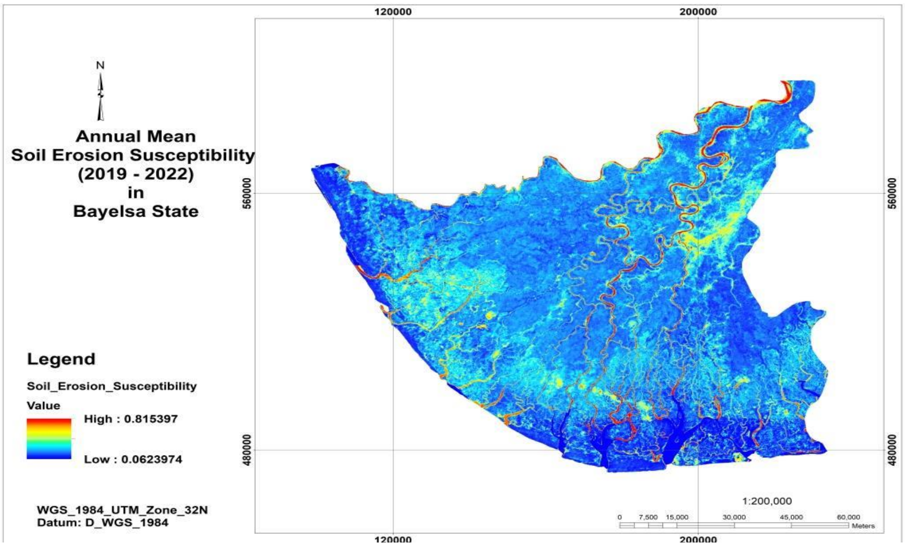

Fig. 5: Soil Erosion Susceptibility Derives from Average Annual Ground Velocity (0.8cm to 0.1 cm) from Sentinel-1 SBAS-InSAR for Bayelsa State (2019-2022).

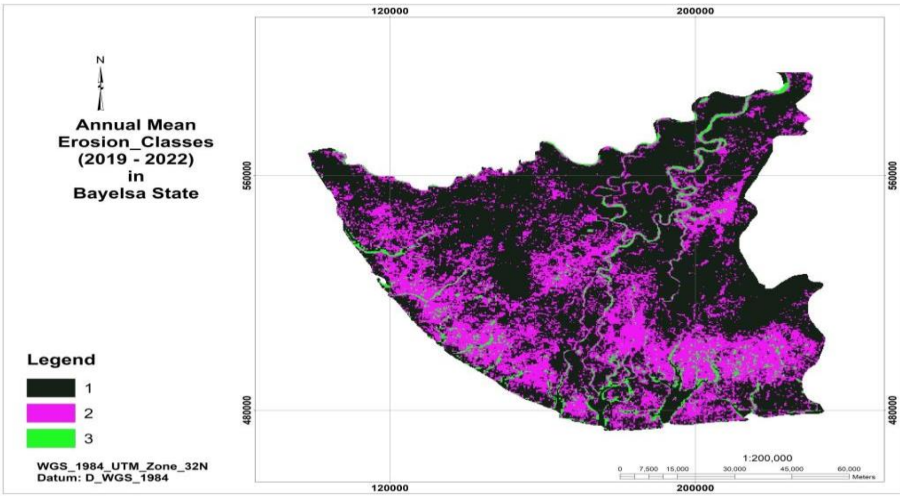

Fig. 6: Final Soil Erosion Susceptibility Map for Bayelsa State, Showing the Integration of MUSLE Factors and InSAR-Derived Subsidence.

Table 2: Soil Erosion Susceptibility Classes and Sizes

Value	Susceptibility Classes	Area (m²)	Classes %
1	High	14759687500	79.3
2	Moderate	3321062500	17.8
3	Low	532000000	2.9
TOTAL		18612750000	100.0

5. Discussion

This study successfully demonstrates the feasibility and utility of integrating Sentinel-1 InSAR data for large-scale soil erosion susceptibility assessment in a complex deltaic environment. The results strongly support our hypothesis that ground deformation is a critical, yet often overlooked, factor in soil instability.

The identified subsidence hotspots along the coastal and riverine fringes are consistent with studies on coastal vulnerability and deltaic subsidence, which agrees with the research of Anthony et al. (2020). The Niger Delta is known to be undergoing natural subsidence, but this is likely accelerated by sediment compaction due to reduced sediment inflow (from damming upstream) and the effects of climate change (sea-level rise). The amplified susceptibility in these zones is logical: subsidence lowers the land surface, increasing the frequency and duration of inundation, which in turn weakens soil cohesion and makes it more prone to being washed away by fluvial and coastal erosion.

The use of GEE was instrumental in this research. Processing a multi-year stack of Sentinel-1 data for a state-sized area would be prohibitively time-consuming and computationally expensive on a local machine. GEE's pre-processed data archives and parallel processing capabilities made this analysis possible and efficient.

5.1. Limitations and future work

- Ground Truthing: A primary limitation is the lack of extensive, quantitative ground-truth data on soil erosion rates to perform a robust statistical validation. Future work should aim to establish field measurement campaigns in high-risk zones.
- Model Simplifications: The use of a uniform P-factor and a simplified K-factor map introduces uncertainty. Higher-resolution soil maps and detailed data on conservation practices would improve the model's precision.
- InSAR Limitations: The InSAR signal in densely vegetated or water-dominated areas can be noisy (low coherence). While our analysis focused on areas with good coherence, some information may be lost in the most intensely vegetated swamps.
- Causality vs. Correlation: This study demonstrates a strong correlation between subsidence and high erosion susceptibility, but it does not definitively prove causality. Subsidence, soil compaction, and erosion are likely part of a complex, interconnected feedback loop.

6. Conclusion

This research provides a comprehensive assessment of soil erosion susceptibility in Bayelsa State, Nigeria, pioneering the integration of Sentinel-1 InSAR-derived ground deformation data. By leveraging the power of cloud computing and the unique capabilities of SAR, we have moved beyond static susceptibility models to a more dynamic, process-based assessment.

Our findings reveal that significant portions of Bayelsa State, particularly its coastal and riverine fringes, are at "High" to "low" susceptibility to soil erosion. Critically, the inclusion of the InSAR signal uncovered latent risk hotspots that would be missed by conventional methods, underscoring the vital role of ground instability as a precursor to erosion in deltaic settings.

The methodology presented here is a scalable, cost-effective, and replicable framework that can be applied to other vulnerable deltaic regions worldwide. For policymakers and environmental managers in the Niger Delta, the resulting maps provide crucial information for prioritizing intervention strategies, planning resilient infrastructure, and mitigating the impacts of land degradation. Ultimately, this study advocates for the wider adoption of advanced remote sensing techniques like InSAR in environmental monitoring and management frameworks to build resilience in the face of complex global changes.

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