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From Fault Fabric to Early Warning: High-Resolution Geomorphology and Enhanced DInSAR Over the SP-0B Saltworks (Dead Sea, Jordan) - Mini Review

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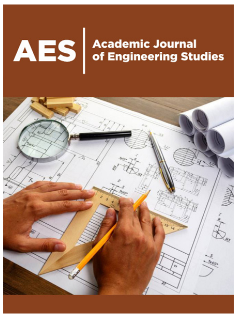

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Context and Problem

The Dead Sea has dropped ~40m since 1980, removing ~0.48-0.49MPa of hydrostatic buttress from the basin walls. This rapid base-level fall steepens hydraulic gradients, depressurizes adjacent aquifers, and accelerates dissolution of evaporites in the Lisan Peninsula. The emergent wave-cut platform around Cape Costigan was converted to industrial salt-evaporation ponds by the Arab Potash Company (APC). SP-0B, bordered on the west by earthen Dike 19, catastrophically failed on 22 March 2000, releasing ~56Mm^3 of brine and revealing solution voids beneath the platform. Although Dike 19 has since been rebuilt and densely instrumented, the substrate remains karst-prone and structurally complex, necessitating a quantitative, operations-ready early-warning approach.

Objectives

This work asks two questions: (i) Can we map, at basin scale, the structural corridors (faults, diapiric joints, sinkhole belts) that localize karst beneath SP-0B; and (ii) Can space-borne deformation be converted quickly into an early-warning stream that informs day-to-day dike management?

Data and Methods

Two complementary streams are fused (1) A six-decade morpho-tectonic reconstruction uses aerial photographs (1953, 1992, 1999), CORONA (1971-1974), Landsat/ASTER/Sentinel-2 (1973-2025), Space-Shuttle photography and sub-meter VHR satellites (2000-2012) to delineate transform splays, diapiric joints, teepee ridges, sag ponds and shoreline retreat. (2) ERS-1/2 (1992-1999) and Sentinel-1 (2015-2025) Differential InSAR (DInSAR) time series are processed within SBAS. A "sibling-coherence" filter clusters only neighbors with matching multi-date amplitude statistics, preserving sharp deformation gradients and increasing the density of reliable pixels by ~20-30% relative to boxcar averaging, yielding 6- to 12-day LOS-displacement cubes at centimetric precision. All layers are integrated in UTM-36N and tied to the continuous Dead Sea gauge.

Geologic-Hydrologic Setting

The Lisan Peninsula overlies an actively rising salt diapir cross-cut by Dead Sea Transform (DST) splays. Two stacked fluids govern near-surface hydrology: (i) A dense, hypersaline brine wedge (~1.24g cm^{-3}) extending inland; (ii) a 2-6m perched lens of fresh to brackish water (~1.00-1.02g cm^{-3}) above it. The DST's N-S sinistral faults and a NE-SW normal-fault array create a high-permeability lattice that funnels recharge toward the retreating shoreline, where freshwater-brine mixing drives evaporite dissolution and sinkhole development. As lake level fell from ~-395m in the 1950s to ~-440m by 2025, the operative halokarst column thickened and the wave-planed platform widened, exposing structurally guided lineaments, teepee structures and sag ponds.

Evolution 1971-1999 from Imagery

Annualized shorelines and lineaments reconstructed from CORONA and Landsat show a west-widening platform sloping 1-2° lakeward. Lineaments align with the DST strike-slip corridor (N-S) and the western normal-fault array (NE-SW), confirming tectonic control on groundwater flow. A longitudinal discharge corridor developed along the N-S strike-slip zone, marked by aligned teepees and a cluster of sag ponds; this corridor later overlapped the western margin of SP-0B.

Pre-Failure Deformation (ERS-1/2 SBAS, 1992-1999)

Time-series InSAR reveals a bowl-shaped subsidence field in northern SP-0B reaching -40 to -48 cm yr^{-1}, superposed with localized uplift patches up to +5cm yr^{-1}. The March 22, 2000 dike failure occurred within the maximum-subsidence zone, linking regional drawdown, dissolution along structural corridors, and engineered failure. While geotechnical analyses emphasized weak, sensitive laminated clays and load-induced pore-pressure rise, the present synthesis shows these materials concentrate within a structurally inherited accommodation space (pull-apart/mini-basin/salt-induced synform) that predisposed the site to settlement and collapse.

Near-Term Deformation (Sentinel-1 DInSAR, 2025)

Two high-quality interferograms bracket key pre-refilling intervals: (a) 23 Feb-7 Mar 2025 (descending, 12 days, coherence ~0.98; height of ambiguity ~1,899m) and (b) 10 Jan-16 Apr 2025 (ascending, 96 days). Both show widespread subsidence in the southeastern sector of SP-0B and persistent localized uplift to the northwest, consistent with ERS patterns and the interplay of dissolution, groundwater flow, anhydrite-to-gypsum hydration, and halokinetic doming. DInSAR motions are relative to a presumed stable reference; absolute magnitudes require GNSS/leveling.

Sibling-Coherence Filter and Accuracy

Conventional boxcar coherence over-smooths heterogeneous terrains and overestimates coherence in mixed pixels. The sibling-coherence approach clusters pixels by similarity in amplitude statistics, then computes coherence and phase within this adaptive ensemble, followed by second-kind statistical filtering. Implemented as a SNAP plug-in within an SBAS workflow, it retains narrow, high-gradient rupture/sinkhole zones and increases reliable-pixel density by ~20-30%. Over a tectonically quiescent Inner-Mongolia test site, sibling selection reduced phase bias/variance versus the boxcar+Goldstein chain.

Process Rates and Mechanics

The 40m drawdown since 1980 translates to ~490 kPa of lost hydrostatic buttress, steepening hydraulic gradients that drive fresh/brackish water through fractured, soluble units. A simple Darcy estimate gives $q \sim 8\times10^{-6}$ m s^{-1}--several-fold higher than pre-1980 flux--supplying chemical work for halite dissolution and gypsum hydration plus mechanical work that fractures roofs and collapses voids. ERS and Sentinel-1 time series thus capture a "leaky-capacitor" behavior: stress accumulates during dissolution until roof failure releases it as accelerated subsidence.

Early-Warning Framework

A static hazard layer (faults, diapiric joints, sinkhole belts, discharge corridors) is fused with Sentinel-1 displacement cubes to partition SP-0B into watch cells. Trial rules escalate responses when $|dLOS| > 6$mm in 12 days or when acceleration turns positive: field inspections intensify, sensor sampling densifies, and brine inflow is temporarily throttled; three simultaneous cell breaches halt impoundment. InSAR streams are cross-validated with extensometers, piezometers and GNSS to anchor relative motions to absolute frames.

Limitations and outlook. Current displacements are referenced to assumed-stable zones; Sentinel-1's ~14 m GSD misses metre-scale ruptures; thresholds are rule-based rather than fully coupled hydro-mechanical responses. Planned upgrades include tying the InSAR grid to a permanent GNSS backbone, extending coherence selection with single-date deep-learning classifiers, and coupling displacement cubes to 3-D transient hydro-mechanical models driven by the continuing Dead-Sea drawdown.

Contribution and transferability. The framework shifts SP-0B management from reactive repair to proactive mitigation by (i) establishing a structural baseline that identifies dissolution corridors; (ii) delivering near-real-time ground-motion cubes with higher fidelity in heterogeneous karst terrain; and (iii) operationalizing thresholds that link geodetic precursors to concrete dam-management actions. Because Sentinel-1 data are free and global, and processing uses open tools (ESA SNAP + SNAPHU), the workflow offers a reproducible template for other evaporite basins undergoing rapid base-level fall.

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