
Research article

Post-emergence deformation of the Dead Sea margin from shoreline palaeo-contours and Sentinel-1 InSAR

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Abstract: Rapid anthropogenic decline of the Dead Sea has exposed extensive marginal flats that are increasingly affected by subsidence, sinkholes, collapse, and slope instability. In this study, we investigated whether these newly emerged surfaces have preserved their original emergence geometry or have undergone subsequent topographic modification. Historical shorelines extracted from Landsat-5 and Sentinel-2 imagery were used as dated palaeo-contours for selected Dead Sea level thresholds between 1984 and 2018 and were compared with homologous contours derived from the Airbus WorldDEM surface acquired in November 2019. For the analysis, we focused on the Ghor Al-Haditha–Lisan sector, Jordan, where low-gradient terrain provides high sensitivity to vertical change through amplified horizontal displacement. To test whether the observed mismatches reflect ongoing deformation, the geomorphic comparison was complemented by Sentinel-1 DInSAR analysis using short-baseline interferometric pairs and sibling-coherence filtering. In all benchmark cases, the WorldDEM contour of the same nominal elevation as the palaeo-shoreline failed to reproduce shoreline geometry, whereas lower present-day contours consistently provided a closer fit. The strongest and most persistent discrepancies occurred across the Wadi Kerak delta plain, where planimetric separations reached about 450 m, while Ghor Al-Haditha showed a more segmented response, with different shoreline reaches matching different present-day contour levels. These patterns indicated that post-emergence deformation is spatially heterogeneous and cannot be explained by vertical-datum differences alone. The interferometric results independently revealed recent localized ground motion in the same sectors, confirming that deformation remains active. Together, the results showed that the exposed Dead Sea margins have undergone substantial post-emergence lowering and geomorphic reorganization, controlled by interacting subsidence, dissolution, collapse, compaction, and incision processes.

Keywords: Dead Sea; land subsidence; InSAR; Palaeo-shorelines; WorldDEM; salt karst; sinkholes; Lisan Peninsula; Ghor Al-Haditha; post-emergence deformation

1. Introduction

The Dead Sea is undergoing one of the fastest anthropogenic lake-level declines documented for a large terminal basin, with a recent mean lowering rate of about 1.1 m yr^{-1} in the monthly series of the Government Water and Sewerage Authority, Israel [1]. This sustained fall has exposed extensive tracts of former lake floor and generated a broad spectrum of geomorphic and geotechnical hazards around the lake (Figure 1 and supplementary). Along the Dead Sea shore, several thousand sinkholes have developed since the 1980s [2–4]. In Jordan, probably 2,500–3,000 sinkholes have appeared in the Lisan Peninsula/Ghor Al-Haditha [Long. $35^{\circ}31'$ –Lat. $31^{\circ}19'$], accompanied by subsidence and slope instabilities, with recurrent impacts on infrastructure and agricultural land [5–8].



Figure 1. Eastward-looking aerial view of the Lisan Peninsula and Ghor Al-Haditha, Jordan, acquired in 2011. From the 1960s to 2026, the Dead Sea water level has declined by 46 m (from -395 m to -441 m). As a result, a wave-cut platform, approximately 1.6 to 5 km in width, has developed around the former Point Costigan. The failure of Arab Potash Company's Dike 19 on 22 March 2000 exemplifies the geotechnical instability of this recently exposed terrain.

The Lisan Peninsula has relief of no more than $\sim 50 \text{ m}$ over large sectors, with the pre-1960s peninsula (Figure 1: Point Costigan) occupying approximately -395 m to -352 m and the younger wave-cut platform approximately -395 to -441 m (Figure 1: Wadi Kerak; Dike 19 collapse). Earlier geomorphological work likewise describes a landscape dominated by sub-horizontal strata and a wave-cut platform fringing the peninsula to the north, east, and west [9,10]. By contrast, the margins of the

peninsula are structurally controlled [11,12]. They are defined by a fault escarpment subsequently modified by wave erosion, while the peripheral zone is marked by badland topography incised by Wadis and bordered locally by cliffs exceeding 10 m in height. The Lisan Peninsula overlies an actively rising salt diapir at a depth of ~120–400 m below the ground surface [13,14].

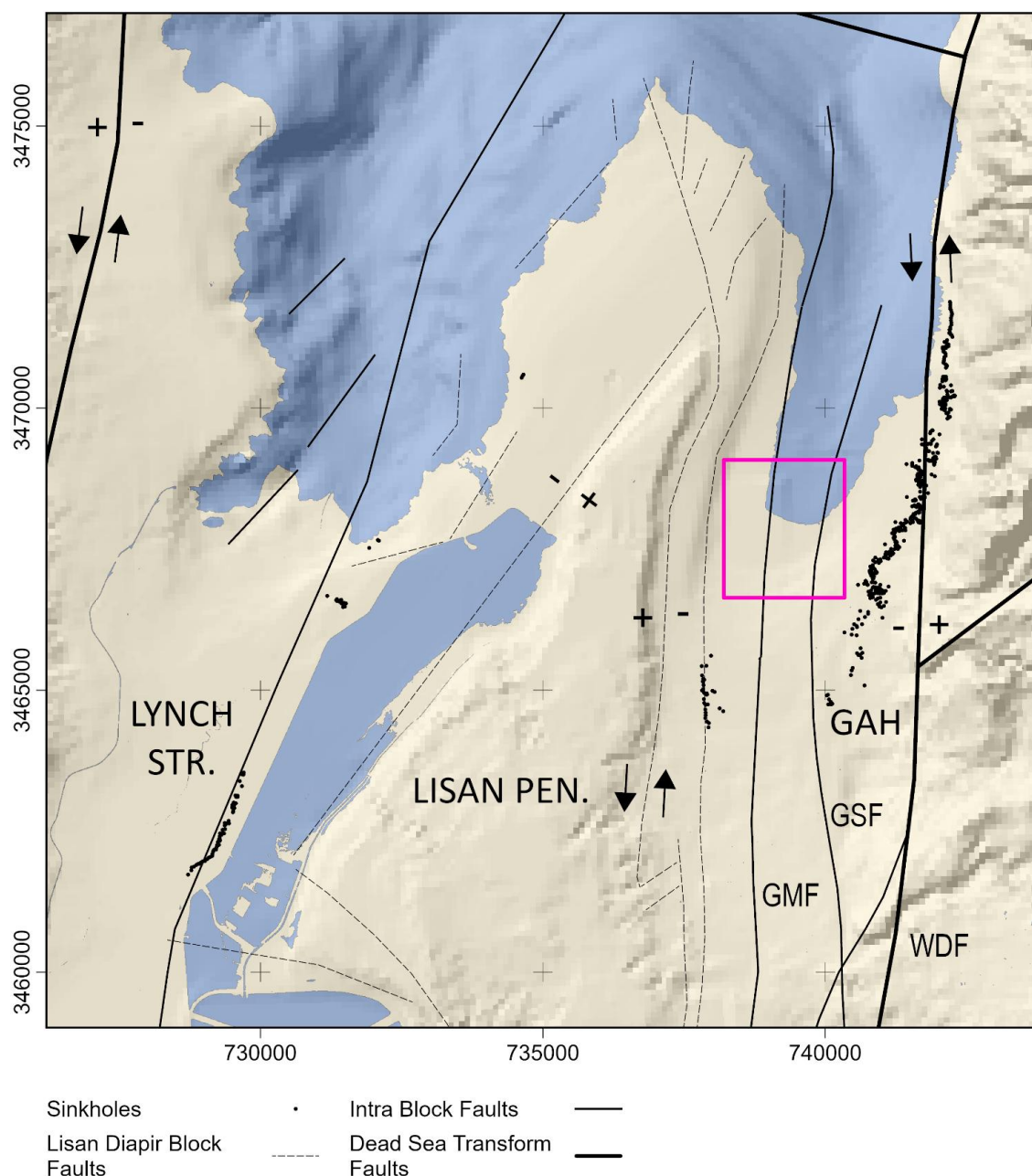


Figure 2. Tectonic setting of the Lisan Peninsula and Ghor Al Haditha (GAH), central Dead Sea basin. GMF = Ghor Mazra'a Fault; GSF = Ghor Safi Fault; WDF = West Dhira Fault. The purple square corresponds to the delta of Wadi Kerak–Wadi Ibn Hammad. Dead Sea shoreline from Sentinel-2 image acquired in 2024 (−439 m).

Ghor Al-Haditha, situated east of the Lisan, is a gently sloping, wave-eroded platform approximately 3 km wide (Figure 2). Accordingly, the study area is dominated by a low-relief coastal platform and adjacent plain. Ghor Al Haditha is bounded by the most active segment of the Jordan–

Dead Sea Transform (DST), a ~1,000 km-long sinistral strike-slip system linking the Red Sea spreading center to the Taurus continental collision zone and separating the Arabian Plate from the Sinai sub-plate [15]. The Dead Sea occupies the largest pull-apart basin along this transform, approximately 80 km long and 5–17 km wide, formed by two major sub-parallel fault segments: The Araba Fault to the south and the Jordan Valley Fault to the north, connected by ESE–WNW transfer faults (Khunezira, Boqeq, Gedi) spaced 20 to 30 km apart [16,17]. Since the late Pleistocene, the basin's tectonic subsidence rate has been approximately 4 mm yr^{-1} , underscoring its ongoing tectonic activity. The basin is divided into three major compartments, where the Lisan Peninsula and Ghor Al Haditha (Figure 2) belong to the “middle” morpho tectonic unit, characterized by the greatest salt diapir in the system and the highest concentration of sinkholes/subsidence along the Dead Sea shore [18].

Figure 2 shows three N–S elongated fault-bounded tectonic blocks: The lowered Mazra'a–Ghor Al-Haditha graben to the east, the uplifted Lisan block in the center, and the Lynch Strait graben to the west.

The northern part of the Mazra'a–Ghor Al-Haditha graben, which is our focus of this study, is structurally defined by a set of N–S left-lateral strike-slip faults, the Ghor Mazra'a, Ghor Safi, and West Dhira faults, bounding and crossing the gravelly platform on its western, central, and eastern sides, respectively. Seismic reflection profiling indicates that this graben hosts a stack of lacustrine and alluvial deposits approximately 200 m thick [19].

The Lisan Peninsula is underlain by an actively rising salt diapir (Sedom Formation, top at ~100–400 m depth), whose doming generates a radial and concentric fracture network superimposed on the DST-inherited N–S to NNE fault fabric [9].

Superimposed on the N–S structural grain of the graben is a NNE-trending element evidenced by an alignment of more than 2,000 sinkholes [5], approximately 6 km long and 600 m wide, oriented $\text{N}24^\circ\text{E}$, and interpreted as a hidden fault connecting the Ghor Safi and West Dhira faulted zones. This direction is consistent with the focal mechanism of the $m_b = 5.1$ earthquake of 23 April 1979 ($\text{N}20^\circ\text{E} \pm 5^\circ$), and paleo-stress analysis in the adjacent bedrock, which confirms dominant N–S and ENE–WSW trends coinciding with crack orientations measured in the sinkhole sediments [20].

These inherited structural discontinuities exert a primary control on hydrogeological pathways. The subsurface of the Ghor Al-Haditha graben hosts a stack of lacustrine and alluvial deposits approximately 200 m thick [8], very likely correlating to the Ze'elim Formation documented on the western shore [21], though direct borehole confirmation is lacking on the eastern shore.

Evaporite-rich deposits, including rock salt, are progressively exposed at the surface in the northern part of the study area as the shoreline retreats, providing direct evidence of the dissolution-prone substrate. Faults and fractures act as preferential conduits for unsaturated groundwater descending from the Moab Plateau through three distinct substrate types: alluvium, lacustrine mud, and evaporites [22]. The Dead Sea level has fallen from approximately -395 m in the 1970s, at rates accelerating from $\sim 0.5 \text{ m yr}^{-1}$ in the 1980s to $\sim 1.1 \text{ m yr}^{-1}$ in the 2010s [1]. This base-level fall has displaced the freshwater–brine interface seaward [23,24], reactivated sealed karst conduits, and focused dissolution at the intersection of the DST fault network and the diapiric fracture system [25]. This tectonic and structural inheritance constitutes the first-order control on the spatial organization of post-emergence deformation across the Ghor Al-Haditha–Lisan sector, and its explicit framing is necessary to interpret the segmented, non-uniform shoreline–contour mismatches documented in the following sections.

GNSS and InSAR observations have linked the present lake-level fall to shoreline subsidence that may locally reach about 15 cm yr^{-1} , with a measurable lag relative to hydrological forcing [26–30].

InSAR studies around the Dead Sea have mapped wide shallow subsidence, documented sinkhole-related deformation, reconstructed long-term displacement histories, and supported hazard assessment in collapse-prone sectors [31]. These works collectively show that the emerging margins of the Dead Sea do not respond as passive surfaces, but as mechanically evolving terrains shaped by dewatering, dissolution, compaction, and mass movement. Moreover, researchers studying the Dead Sea coastal zone have examined sinkhole evolution, subsurface salt dissolution, subsidence, flood recharge, and drainage reorganization at specific sinkhole clusters, streambeds, or alluvial fans [26–30]. They address active geomorphic change, but do not directly test whether newly exposed former lake-floor surfaces preserve their original emergence geometry after exposure, or whether they have since been modified by subsidence, incision, warping, or fault-related displacement. That question therefore remains distinct from the sinkhole-focused literature and motivates this analysis.

Here, we combine multi-temporal optical imagery, a radar-derived elevation model, and Copernicus Sentinel-1 radar interferometric observations to examine whether the newly exposed margins of the Dead Sea have remained geometrically consistent with the former lake floor or have undergone subsequent topographic modification after emergence. Historical shoreline positions extracted from Landsat-5 and Sentinel-2 scenes acquired near selected Dead Sea level thresholds are used as dated proxies for former waterline positions, that is, approximate emergence contours.

These dated shoreline markers, spanning the interval from 1984 to 2018, are compared with contours derived from Airbus WorldDEM, a TanDEM-X-based edited digital surface model referenced in WGS84-G1150 horizontally and EGM2008 vertically. Comparison with Sentinel-2 acquisitions indicates that the WorldDEM surface used here corresponds to a November 2019 acquisition window, with 2 November 2019 taken as the shoreline reference date for that DEM epoch. The analysis therefore links shoreline positions formed over roughly 35 years of Dead Sea level fall to a common late-2019 topographic surface. Areas where historical shorelines diverge markedly from the corresponding WorldDEM contour, or align more closely with lower present-day contours, are treated as candidate zones of cumulative post-emergence lowering, incision, warping, or displacement, and provide the spatial framework for the subsequent interferometric analysis.

2. Materials and methods

2.1. Dead Sea level elevation

Dead Sea level data are retrieved from the national open-data portal of the State of Israel, using the dataset entitled “Dead Sea level since 1976” (accessed 4 July 2026) [1]. The file contains 690 records between 1 October 1976 and 1 July 2026, arranged as an approximately monthly series. The table includes measurement date and elevation. Reported values range from $-398,95$ m to $-441,00$ m (Figure 3).

Ein Gedi (Dead Sea’s western shore) is one of the seven stations in Survey of Israel’s national water-level network. It functions as a dedicated Dead Sea gauge, with a backup unit maintained given how fast the shoreline there is changing. At each of these stations, a level gauge is tied to a fixed tide-gauge benchmark whose own elevation is established by precise leveling, so that the raw water readings can be converted into an actual elevation rather than just a local reading. The elevation is expressed relative to Israel’s national vertical datum, which is not a Dead Sea-specific zero but the country’s Mediterranean-based mean-sea-level datum. A Dead Sea reading such as “ -441 m” means

441 m below this same national Mediterranean datum, not below the Dead Sea's own local surface. Because the Ein Gedi shoreline is subsiding rapidly as the lake retreats, its benchmark is far more likely to have shifted vertically than the coastal ones, so the Survey of Israel periodically re-surveys it with GPS, tying it back into the national network of permanent GNSS stations. This lets them separate genuine changes in the Dead Sea's water level from apparent changes that are really just the ground under the gauge sinking, keeping the readings correctly anchored to the national datum over time.

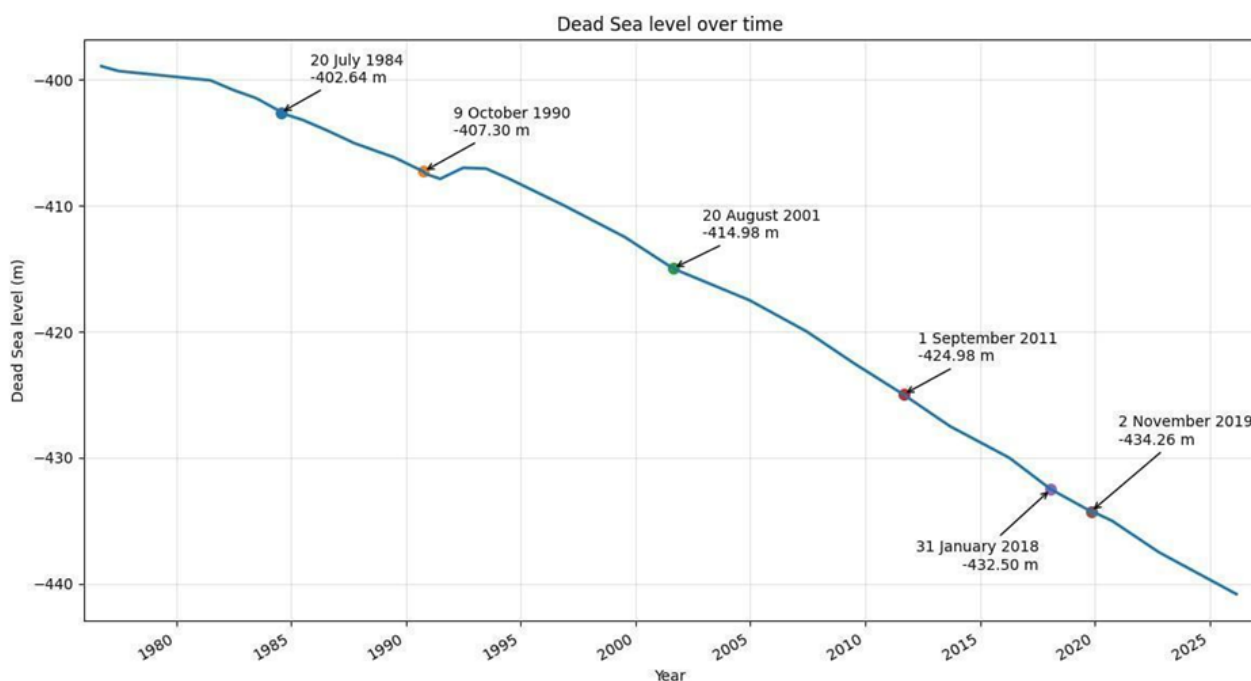


Figure 3. Dead Sea water level curve with the temporal sampling from Landsat-5 and Sentinel-2—see Results section. Source: Elevation data collected by the Government Water and Sewerage Authority, Israel, from 1976 onward.

2.2. Vertical reference framework and local working hypothesis

2.2.1. Vertical reference framework

Israel Land Survey Datum (ILSD) is the national vertical datum of Israel, realized through Israel Undulation Model (ILUM), a geometric geoid model constructed by Kriging interpolation of GPS/leveling benchmarks, with no gravity observations [32–34]. ILUM 1.2, the version operative during the study period, is based on 849 anchor benchmarks distributed over Israel's approximately 22,000 km², with a 0,5 × 0,5 km interpolated output grid [32,34].

WorldDEM is referenced horizontally to WGS84 and vertically to EGM2008. EGM2008 is a global gravimetric model computed from spherical harmonics to degree and order 2190, derived from satellite gravity missions (CHAMP, GRACE) and a worldwide gravity anomaly database [35], with an effective spatial resolution of approximately 9 km. Its geoid surface is registered as EPSG:3855. Validation of the global TanDEM-X DEM demonstrated an absolute vertical accuracy better than 2 m at the 90% confidence level (LE90) and an RMSE below 1,4 m when compared with extensive GPS measurements [36].

The vertical reference problem follows directly from the definition of heights: $H = h - N$.

Here, H is the orthometric height (height above mean sea level), h is the ellipsoidal height (as measured by GNSS), and N is the geoid undulation (the separation from the ellipsoid to mean sea level); consequently, for two vertical reference systems, ILSD and EGM2008, the height discrepancy at any point is given by: $H(\text{EGM2008}) - H(\text{ILSD}) = N(\text{ILSD}) - N(\text{EGM2008})$. The discrepancy is controlled by the difference between the two geoid models.

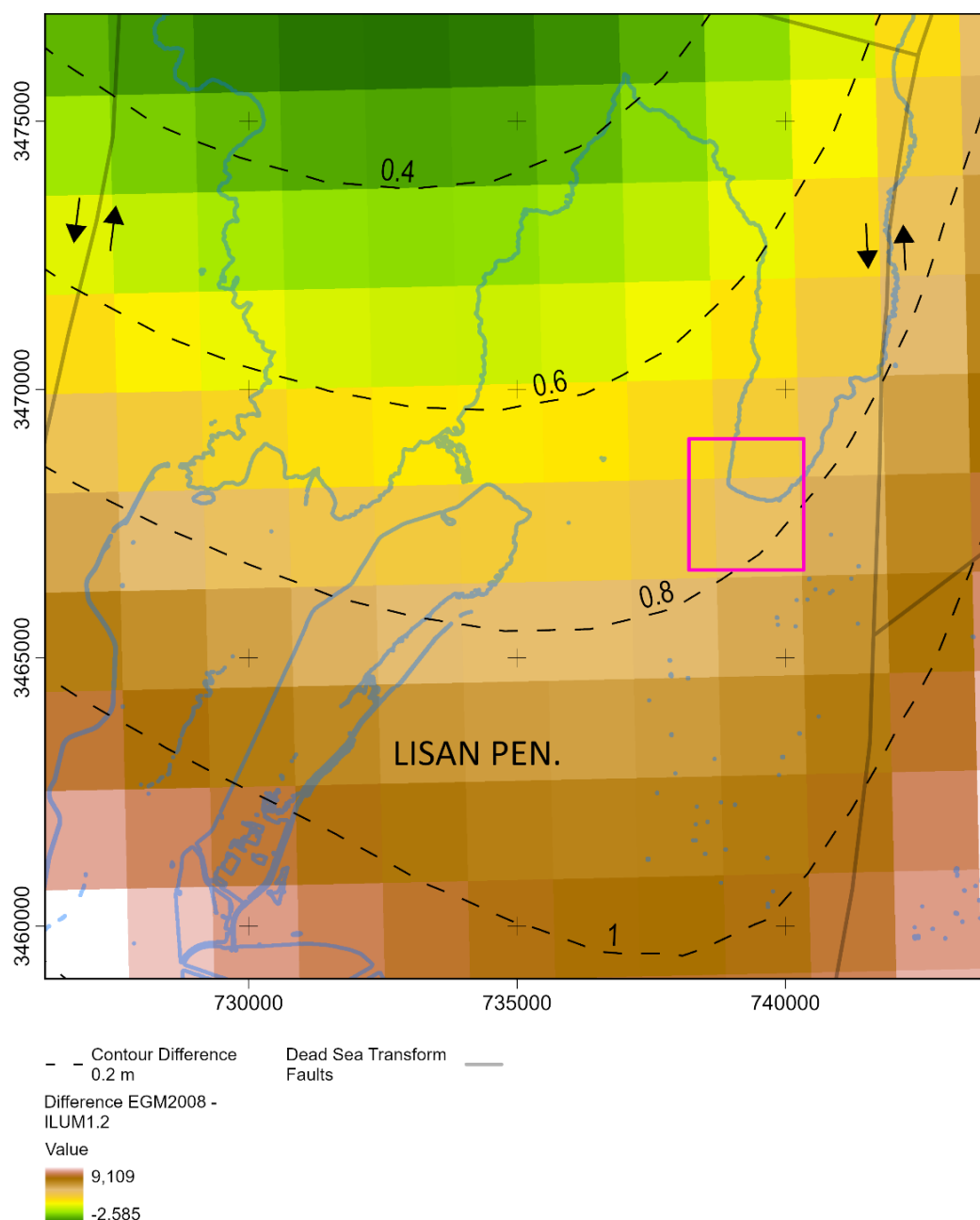


Figure 4. Pixel-by-pixel difference between EGM2008 and ILUM 1.2. Contours interval at 0,2 m. The delta of Wadi Kerak–Wadi Ibn Hammad (Ghor Al Haditha) falls on the 0,8 m contour. Source data: ILUM12.byn and Israel/EGM08.byn [37].

Datum separation is measured directly at the Ghor Al-Haditha area of interest. The official ILUM 1.2 and EGM2008 geoid grids for Israel are downloaded in the Natural Resources Canada binary

format [37], co-registered, and the pixel-by-pixel difference EGM2008–ILUM 1.2 is computed (Figure 4). Contours are generated at 0,2 m intervals. The study area Ghor Al Haditha falls on the 0,8 m contour: $\Delta H_{\text{datum}} = +0,8$ and then: $H(\text{ILSD}) \approx H(\text{EGM2008}) + 0,8$ m.

Example: The raw elevation difference between the 1984 palaeo-shoreline (−402,64 m ILSD) and the nearest WorldDEM contour (−407,64 m EGM2008) is:

$\Delta H(\text{observed}) = 5,00$ m;

Residual after applying the site-specific datum correction:

$\Delta H(\text{residual}) = \Delta H(\text{observed}) - \Delta H(\text{datum}) = 5,00 - 0,80 = 4,20$ m;

$\Delta H(\text{observed}) = \Delta H(\text{datum}) + \Delta H(\text{real})$;

Then, $\Delta H(\text{real}) \geq 4,20$ m;

If the mismatches are purely due to datum inconsistency:

$|\Delta H(\text{datum})| \geq \Delta H(\text{observed}) = 5,00$ m, but the physical constraint from Figure 4 is:

$|\Delta H(\text{datum})| = 0,8$ m at Ghor al Haditha.

Therefore: $5,00 \gg 0,8$ and $\Delta H(\text{datum})$ is bounded by direct measurement and cannot explain $\Delta H(\text{observed})$. Most of the mismatch ($\geq 4,20$ m) cannot be explained by datum inconsistency alone and is therefore interpreted as reflecting genuine post-emergence topographic modification.

2.2.2. Local working hypothesis

For the comparison, we focus on shoreline sectors and topographic contours developed across very low-gradient surfaces, because these are the locations at which real vertical change produces the largest and most readily detectable planimetric displacement. In such terrain, even a modest vertical offset generates a measurable horizontal mismatch; therefore, almost flat areas provide the highest sensitivity to post-emergence deformation. The working hypothesis is that any residual incompatibility between Israeli lake-level elevations and EGM2008-referenced WorldDEM terrain behaves primarily as a common-mode local offset rather than as a rapidly varying deformation field. If this holds, shoreline-derived and DEM-derived contours should remain broadly parallel, even where slightly displaced. By contrast, marked non-parallelism, local divergence, bending, segmentation, or contour reorganization is difficult to reconcile with datum mismatch alone and more plausibly reflects genuine topographic modification after shoreline emergence.

A datum offset, regardless of sign or magnitude, shifts all contours uniformly, preserving their geometric form and mutual parallelism. The observed patterns at Ghor Al-Haditha include cases where a single 1990 palaeo-shoreline is best reproduced by two WorldDEM contours 3 m apart within 500 m, and sectors where different shoreline segments correspond to different contour elevation levels. Spatial variations of this amplitude and geometry over distances of a few hundred meters are not produced by any geoid model.

A 2026 Sentinel-1 interferometric pair ($B\perp = 15,9$ m, height of ambiguity = 967 m) independently yields 10–12 cm Line-of-Sight (LOS) displacement over 48 days at the same location, corresponding to a vertical rate of $0,94\text{--}1,13$ m yr^{-1} , with a measurement uncertainty of $\pm 3\text{--}5$ mm. This measurement has no dependence on any vertical datum and is spatially coincident with the palaeo-shoreline anomaly, providing fully independent confirmation that the observed signal reflects real ground motion.

At Ghor Al-Haditha–Lisan sector, observed mismatches may include subsidence, uplift, erosion, channel incision, collapse, or local aggradation [38]. The flat marginal surfaces are not merely convenient comparison zones; they are the most diagnostic settings for testing whether shoreline–

contour mismatch can still be attributed to datum uncertainty, or whether it records genuine post-emergence deformation.

2.3. Selection of Landsat/Sentinel-2 scenes and threshold levels

Dead Sea level thresholds (Table 1) are derived from the monthly lake-level series [1] to compare dated shoreline positions with remote-sensing images. When the exact threshold value is not present in the series, the crossing date is estimated by linear interpolation between the two consecutive monthly observations bracketing that level.

An initial reference framework based on regular elevation thresholds is used to structure the comparison, but only a limited number of levels are retained for detailed analysis. The final selection is controlled not only by chronological distribution along the lake-level curve, but also by the availability of satellite scenes in which the shoreline could be delineated reliably. In practice, image selection depended fundamentally on cloud conditions, haze, and overall radiometric legibility over the land–water boundary. Because shoreline extraction requires a clear and continuous coastal trace, a scene slightly farther from the interpolated threshold date is preferred whenever the nearest image is affected by cloud cover or poor visibility. Table 1 therefore lists selected benchmark levels and their most suitable corresponding satellite scenes, rather than a complete regularly spaced threshold series. The selected threshold dates are compared with the archive of available Landsat scenes for WRS path/row 174/038 and Sentinel-2 scenes for tile T36RYV.

Table 1. Estimated dates of selected Dead Sea level thresholds and corresponding satellite scenes.

Dead Sea level (m)	Threshold date	Selected Satellite scene	Dead Sea level (m)	Δt (days)
–402,50	1984–07–04	1984–07–20 (Landsat-5)	–402,64	+16
–407,53	1990–11–19	1990–10–09 (Landsat-5)	–407,39	–41
–415,00	2001–08–25	2001–08–20 (Landsat-5)	–414,98	–5
–425,00	2011–09–06	2011–09–01 (Landsat-5)	–424,98	–5
–432,50	2018–01–31	2018–01–31 (Sentinel-2)	–432,50	0

Table 1 displays the target water level and the estimated date it is reached alongside the specific satellite scene selected for analysis. It then quantified the “mismatch” by showing the actual lake level on the day the image was taken, the time gap in days, and the vertical height difference in centimeters. As an example, the first row shows a target Dead Sea level of –402,50 meters, which the lake reached on July 4, 1984. However, the best available clear image from the Landsat-5 satellite was captured on July 20, 1984, representing a 16-day gap. By the time the satellite took the image, the water level had dropped to –402,64 meters, resulting in a vertical difference of 14 centimeters from the original target. Documenting these precise offsets enables a distinction between minor shoreline shifts caused by water level fluctuations and significant horizontal displacements indicating actual geological changes, such as subsidence or erosion.

The shoreline is extracted based on the following workflow:

1. Water detection (NDWI): Water bodies are first identified using the Normalized Difference Water Index (NDWI): $NDWI = (Green - NIR) / (Green + NIR)$. For Landsat 5: Green (Band 2), NIR (Band 4); and for Sentinel 2: Green (Band 3), NIR (Band 8). Water surfaces yield positive NDWI values, while land surfaces are near zero or negative.

2. Binary reclassification (land vs water): The NDWI raster is reclassified in ArcGIS Pro into a binary mask: If $NDWI > T$, then Water, and if $NDWI \leq T$, then Land. The threshold T is determined empirically for each scene (typically close to 0), based on histogram inspection and visual agreement with imagery. This step isolates a clean land–water boundary.

3. Raster to Vector conversion: The binary raster is then converted into polygon features: Raster to Polygon produces water body polygons; and then Polygon to Line gives the shoreline.

4. Quality control: The extracted shoreline is systematically validated by overlay on original multispectral imagery; visual inspection of misclassified shallow water/wet sediment, small, disconnected polygons, and manual cleaning where necessary (removal of noise, simplification).

5. Shoreline uncertainty estimation arises from three major sources:

a) Spatial resolution: i.e., for Landsat 5 at 30 m per pixel and for Sentinel 2 at 10 m per pixel; shoreline position uncertainty is defined as $\sigma(\text{pixel}) \approx \pm 0,5 \text{ pixel}$, then $\pm 15 \text{ m}$ for Landsat, and $\pm 5 \text{ m}$ for Sentinel-2.

b) Threshold selection (NDWI): Variations in threshold T shift the shoreline by 1–2 pixels depending on turbidity, shoreline slope, and mixed pixels; then $NDWI \approx \pm (1-2) \text{ pixels}$.

c) Mixed pixels and shoreline gradient. On low slope surfaces (as in this study), a small vertical or spectral variation translates into a larger horizontal shift: $\sigma(\text{planimetric}) = \sigma(\text{vertical})/\tan(\theta)$, where θ = ground slope (very small); this amplifies horizontal uncertainty locally.

6. Total uncertainty (planimetric)/combining sources conservatively:

Landsat 5: $\sigma(\text{total}) \approx \pm 20-40 \text{ m}$ and Sentinel 2: $\sigma(\text{total}) \approx \pm 10-20 \text{ m}$

7. Implication for interpretation: Observed shoreline – contour separations $\Delta x \approx 450 \text{ m}$.

This exceeds uncertainty by $450 / 40 > 10$ (Landsat) and $450 / 20 > 20$ (Sentinel-2). The shoreline extraction method is deterministic, reproducible, and controlled, with a maximum positional uncertainty of a few tens of meters. This is at least one order of magnitude smaller than the observed shoreline–contour offsets, which therefore cannot be attributed to extraction error.

2.4. Integrated uncertainty budget

To evaluate whether the observed shoreline–contour mismatches could be explained by measurement uncertainty alone, the principal uncertainty sources are considered jointly. Three independent contributions affect the comparison: Uncertainty of the WorldDEM elevation model; uncertainty of palaeo-shoreline extraction from optical imagery; and uncertainty associated with the vertical reference transformation between ILSD and EGM2008.

The local datum discrepancy at Ghor Al-Haditha is measured directly from the ILUM 1.2 and EGM2008 geoid models and is approximately 0,8 m (Figure 4). This value represents a deterministic correction rather than a random error source. The residual uncertainty associated with the datum transformation is therefore significantly smaller than the measured offset.

For shoreline extraction, conservative planimetric uncertainties were estimated as $\pm 20-40 \text{ m}$ for Landsat-5 and $\pm 10-20 \text{ m}$ for Sentinel-2 imagery. However, the observed shoreline–contour separations reach 150–450 m, exceeding the corresponding extraction uncertainty.

The elevation accuracy of the underlying TanDEM-X/WorldDEM product has been independently validated with millions of GPS observations and exhibits a global RMSE generally below 1,4 m and a LE90 below 2 m under most terrain conditions [36].

Accordingly, under a conservative scenario combining the TanDEM-X DEM LE90 uncertainty

of approximately 2 m, the locally measured datum difference of approximately 0,8 m, and shoreline-extraction uncertainties of $\pm 20\text{--}40$ m, the uncertainty contributions remain insufficient to explain the largest shoreline–contour mismatches observed in the study area, where vertical-equivalent differences reach approximately 4–5 m and planimetric separations reach 450 m.

More importantly, the interpretation does not rely solely on the magnitude of individual offsets. The same geometric behavior is observed repeatedly in five independent shoreline benchmarks spanning 1984–2018. The anomalies are concentrated in the same sectors, particularly the Wadi Kerak–Wadi Ibn Hammad delta, and display systematic non-parallelism, segmentation, and contour-level shifts. Random DEM errors, shoreline extraction uncertainties, or vertical datum inconsistencies would not be expected to reproduce coherent spatial patterns repeatedly through time.

The conclusion that the shoreline–contour mismatches reflect real post-emergence topographic modification therefore rests on three independent observations: Offsets substantially exceeding shoreline-extraction uncertainty; mismatch amplitudes greater than the measured local datum difference; and spatially coherent patterns reproduced across benchmark shorelines and independently supported by Sentinel-1 DInSAR deformation measurements.

2.5. Improved DInSAR analysis

Coherence in InSAR is a normalized measure of how similar the complex radar returns are between the two SAR acquisitions that make up an interferometric pair. Physically, it reflects whether the same population of scatterers within a resolution cell reflects the radar wave in the same way on both passes. It degrades through several distinct physical mechanisms: Geometric decorrelation from the change in look angle between acquisitions, temporal decorrelation from real changes in the scatterers between passes, volume decorrelation from penetration into a scattering volume, and system decorrelation from receiver noise and finite signal-to-noise ratio.

The “sibling” strategy is a way of estimating coherence that replaces the classic fixed spatial window with a statistically selected set of pixels, and it exists specifically to fix a physical flaw in the standard “boxcar” approach. To assess the performance gains afforded by the “sibling” selection approach for coherence and interferometric-phase estimation, we analyze a validation site in Inner Mongolia, China (45,52 °N, 119,77 °E), located just east of the East Ujimqin Banner. The area is characterized by semi-arid conditions, sparse vegetation ($\text{NDVI} < 0,1$), and loess-mantled terrain. Compared with the Ghor Al-Haditha–Lisan study area, which is hyperarid, vegetation-free, and exhibits minimal inter-acquisition soil-moisture variability, Inner Mongolia experiences greater temporal decorrelation and consequently lower expected coherence. This makes it a conservative test environment: A method capable of producing reliable coherence estimates under these more challenging conditions is expected to perform at least as well at the study site. The validation area lies within the stable northern sector of the Eurasian Plate, far from active plate boundaries, and is characterized by low to moderate seismicity and long recurrence intervals. This tectonically quiescent setting provides a suitable benchmark for evaluating topographic-phase contributions and coherence-estimation performance without contamination from ongoing fault-related deformation.

Surface deformation is quantified using a DInSAR workflow applied to Sentinel-1 imagery and incorporating sibling-coherence filtering. Following [39], pixels exhibiting similar amplitude statistics are grouped into sibling ensembles, within which coherence is estimated. Unlike conventional boxcar filtering [40], this approach preserves narrow, high-gradient deformation features and has been shown

to yield 20–30% more reliable pixels in sinkhole-prone environments, thereby providing denser and more robust phase information for deformation monitoring at 6–12-day revisit intervals.

DInSAR processing begins with the precise co-registration of multiple Sentinel-1 acquisitions to achieve pixel-level alignment [41]. Interferograms are then generated by computing the phase difference between corresponding pixels, typically through multiplication of the complex primary image by the conjugate of the secondary image. Under stable acquisition conditions, the resulting phase difference primarily reflects variations in the sensor-to-ground distance because the random phase contributions of distributed scatterers are largely cancelled during differencing. However, temporal or spatial decorrelation and surface disturbances between acquisitions violate this assumption and degrade phase reliability.

The reliability of the interferometric phase is assessed through coherence (γ), a measure of phase stability derived from local cross-correlation and ranging from 0 to 1. Low coherence values indicate decorrelation and unreliable phase measurements, whereas high coherence identifies stable scatterers suitable for deformation analysis. Coherence-guided filtering is subsequently applied to enhance the signal-to-noise ratio before phase unwrapping, typically performed using SNAPHU [42]. Orbital and topographic phase contributions are removed using the Copernicus GLO-30 Digital Elevation Model, and the unwrapped phase is converted into LOS displacement before geocoding into map coordinates.

To ensure that detected deformation signals are not artefacts arising from geodetic datum inconsistencies, the resulting displacement estimates are cross-referenced with independent vertical-offset measurements. This integration helps distinguish genuine topographic changes, such as localized subsidence, uplift, channel incision, or terrain collapse, from apparent displacements caused by referencing errors. For long-term monitoring, multiple interferograms are further processed using a Small Baseline Subset (SBAS) approach [43], in which displacement maps are stacked and filtered to isolate gradual deformation trends and produce high-resolution ground-motion time series.

Boxcar is the most common implementation of the coherence estimator, using the N pixels within a rectangular window around the pixel to compute the cross correlation of the two coregistered SAR images z_1 and z_2 (1):

$$\gamma = \frac{|\sum_{i=1}^N z_1(x_i, y_i) z_2^*(x_i, y_i)|}{\sqrt{\sum_{i=1}^N |z_1(x_i, y_i)|^2} \sqrt{\sum_{i=1}^N |z_2(x_i, y_i)|^2}} \quad (1)$$

This approach tends to overestimate the coherence values and does not perform well in areas that are not homogeneous. A way to improve the coherence estimation is to consider only those pixels in the neighborhood that are somehow similar to the current pixel. These pixels, termed “siblings” [39], would be the ones that satisfy a particular selection criterion. Several procedures have been proposed for sibling selection. For this work, we follow the approach proposed by [39] and references therein, where the similarity measure between two pixels, i and j , is defined as (2):

$$S = 1 - \frac{|\bar{A}(x_i, y_i) - \bar{A}(x_j, y_j)|}{\bar{A}(x_i, y_i) + \bar{A}(x_j, y_j)} \quad (2)$$

where A is the average amplitude of the M coregistered images in the stack (3):

$$\bar{A}(x, y) = \frac{1}{M} \sum_{m=1}^M |z_m(x, y)| \quad (3)$$

and the siblings for the current pixel would be those neighboring pixels for which S exceeds a given threshold. Typically, values of 0,85 to 0,95 are chosen, yielding a collection of K siblings for the current pixel. Coherence $|\hat{\gamma}| = \hat{\rho}$ and interferometric phase φ can then be estimated by computing the following quantity (4):

$$\hat{\gamma} = \hat{\rho} e^{i\varphi} = \frac{|\sum_{i=1}^K z_1(x_i, y_i) z_2^*(x_i, y_i)|}{\sqrt{\sum_{i=1}^K |z_1(x_i, y_i)|^2} \sqrt{\sum_{i=1}^K |z_2(x_i, y_i)|^2}} \quad (4)$$

These estimates are further refined by applying second kind statistics filtering. The resulting value for coherence is (5):

$$\bar{\rho} = \exp \left(\frac{1}{K} \sum_{k=1}^K \ln(\hat{\rho}_k) \right) \quad (5)$$

and the filtered interferometric phase is obtained by weighted averaging (6,7):

$$e^{i\hat{\varphi}} = \sum_{k=1}^K e^{i w_k \varphi_k} \quad (6)$$

$$w_k = \frac{\bar{\rho}_k}{\sum_{j=1}^K \bar{\rho}_j} \quad (7)$$

To take advantage of this approach, we implement this model as a plugin for the ESA SNAP software application [41].

2.5.1. Accuracy assessment

To assess the performance gains afforded by the sibling-selection approach for coherence and interferometric-phase estimation, we analyze a test site in Inner Mongolia, China within the stable northern sector of the Eurasian Plate, far from active plate boundaries. Seismicity is generally low to moderate, with long recurrence intervals (especially around Ujimqin Banner) relative to tectonically active provinces such as the Dead Sea Transform. The area therefore provides a quasi-stable backdrop for investigating topographic-phase contributions without appreciable interference from contemporary fault motion.

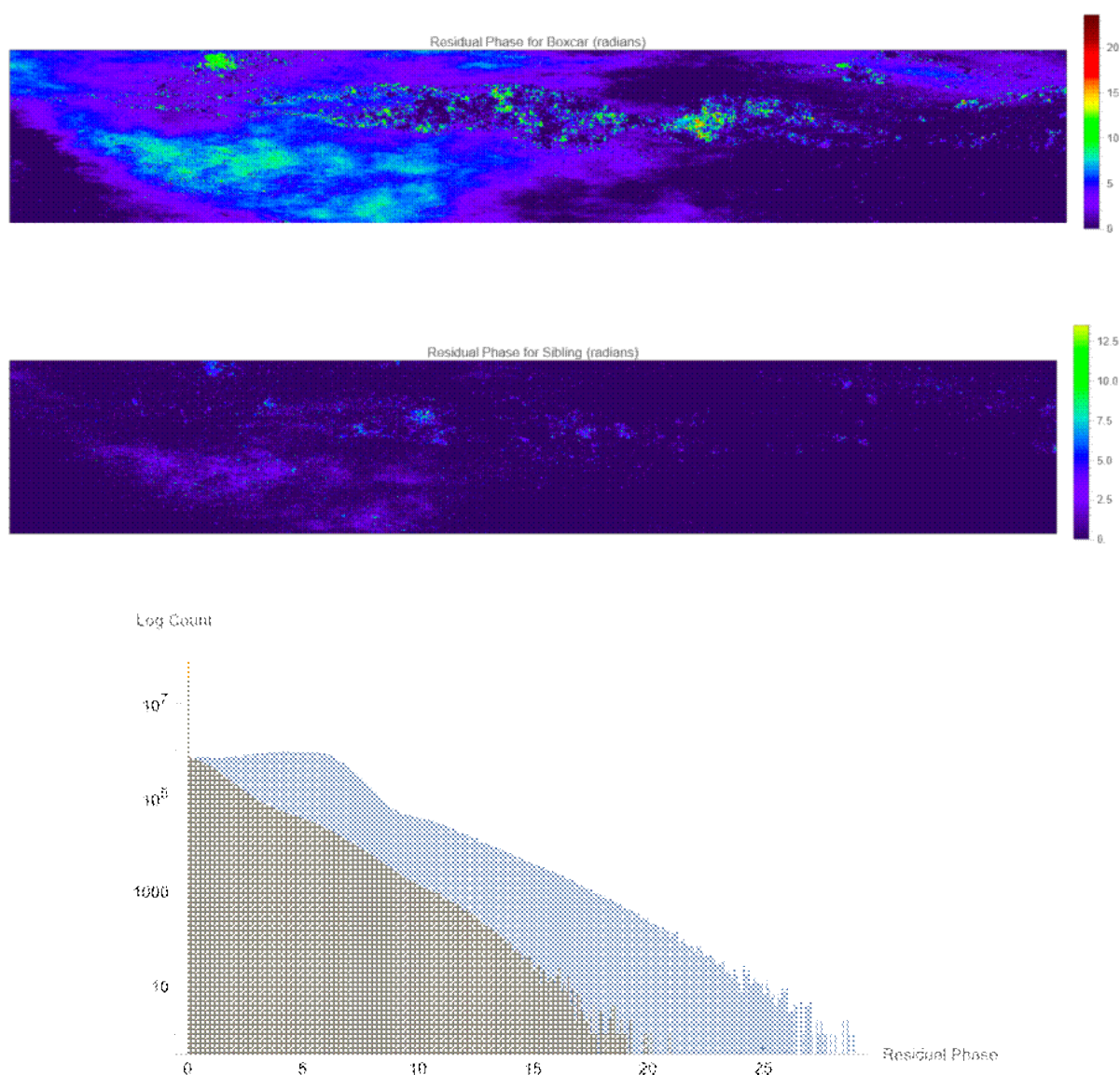


Figure 5. (top) Residual phase in radian for the Boxcar method (SNAP default method), sensor coordinates; (middle) residual phase for the Sibling method; and (bottom) the histogram of the residual phase values shows the Sibling method (brown) yields a better reconstruction (blue) after unwrapping.

The processing workflow, implemented in SNAP, comprises the following steps:

1. Data acquisition: Download an interferometric-wide-swath (IW) pair of Sentinel-1 scenes covering the study area together with the Copernicus GLO-30 DEM.
2. Coregistration: Apply the TOPS Enhanced Spectral Diversity (ESD) coregistration routine, selecting a single subswath and VV polarization.
3. Tropospheric correction: Remove stratified atmospheric delay using temperature, pressure, and humidity fields from the European Center for Medium-Range Weather Forecasts (ECMWF) [44] re-analysis data in conjunction with the incidence angles generated by SNAP's Ellipsoid Correction tool.
4. Interferogram and coherence generation: Form the interferogram and initial coherence map, subtracting the topographic phase simulated from the GLO-30 DEM.

5. Phase filtering and unwrapping: Apply coherence-guided phase filtering, then unwrap the filtered interferogram with SNAPHU in deformation mode.
6. Phase assessment: Calculate the mean value of the unwrapped phase across the scene.

Because the region is effectively tectonically quiescent, the mean unwrapped phase should approach zero throughout (Figure 5); any residual signal therefore reflects algorithmic artefacts rather than ground deformation. Comparative tests show that the sibling-selection method yields lower phase bias and variance than the conventional boxcar coherence estimator followed by Goldstein filtering, confirming its superior performance in heterogeneous terrains.

3. Results

3.1. *Palaeo-shorelines and WorldDEM contours*

Figures 6–10 compare benchmark shorelines extracted from Landsat-5 and Sentinel-2 imagery with contours derived from the 2 November 2019 WorldDEM surface in the Ghor Al-Haditha–Lisan sector. Across all five benchmarks, the same first-order pattern is observed: The homologous WorldDEM contour does not satisfactorily reproduce the historical shoreline geometry, whereas a lower contour provides the closer match. This systematic behavior indicates net post-emergence land-surface lowering between shoreline formation and the 2019 DEM epoch. In all cases, the mismatch is strongest in the low-gradient Wadi Kerak–Wadi Ibn Hammad delta plain (UTM km 739–3468), where even modest vertical lowering is amplified into large horizontal offsets, whereas the response in Ghor Al-Haditha (741–3466) is more heterogeneous and locally segmented.

For the 1984 benchmark, the shoreline mapped from the 20 July 1984 Landsat-5 image at a Dead Sea level of $-402,64$ m is compared with the $-402,64$ m and $-407,64$ m WorldDEM contours. The palaeo-shoreline is poorly reproduced by the homologous $-402,64$ m contour, with the largest divergence across the low-gradient southern deltaic arc and a clear offset along the eastern margin. By contrast, the $-407,64$ m contour follows the 1984 shoreline much more closely over substantial parts of the southern and eastern sectors, indicating that the present-day emerged surface is better represented by an elevation about 5 m lower than the 1984 shoreline datum. The maximum measured black-blue planimetric separation reaches 450 m at UTM km 738–3465. If that full 5 m offset is treated as the cumulative subsidence signal, it corresponds to an apparent average long-term rate of about $0,14$ m yr⁻¹ over the 35,3-year interval to November 2019.

For the 1990 benchmark, the shoreline extracted from the 9 October 1990 Landsat-5 image at a Dead Sea level of $-407,39$ m is compared with the homologous $-407,39$ m WorldDEM contour and a second contour 5 m lower ($-412,39$ m). As in 1984, the contour of the same nominal elevation does not satisfactorily reproduce shoreline geometry, whereas the lower contour provides the closer overall match over much of the southern and eastern margins. The discrepancy is smaller than in the 1984 benchmark, with a maximum measured planimetric separation of 210 m at (738–3466), indicating reduced cumulative displacement over the shorter time interval. If the full 5 m offset is taken as the cumulative subsidence signal, the implied apparent average long-term rate is about $0,17$ m yr⁻¹ over 29,1 years.

However, at Ghor Al-Haditha (741–3467), additional contour tests show that the 1990 paleo-shoreline cannot be explained by a single laterally uniform offset. Instead, it is reproduced by at least two distinct topographic levels in the November 2019 WorldDEM, indicating segmented and spatially heterogeneous post-1990 lowering. A first reach, extending over 300 m, coincides best with the

–417,39 m contour. Relative to the 9 October 1990 Dead Sea level of –407,39 m, this implies an apparent lowering of 10 m and an average long-term rate of about 0,34 m yr⁻¹ over 29,1 years.

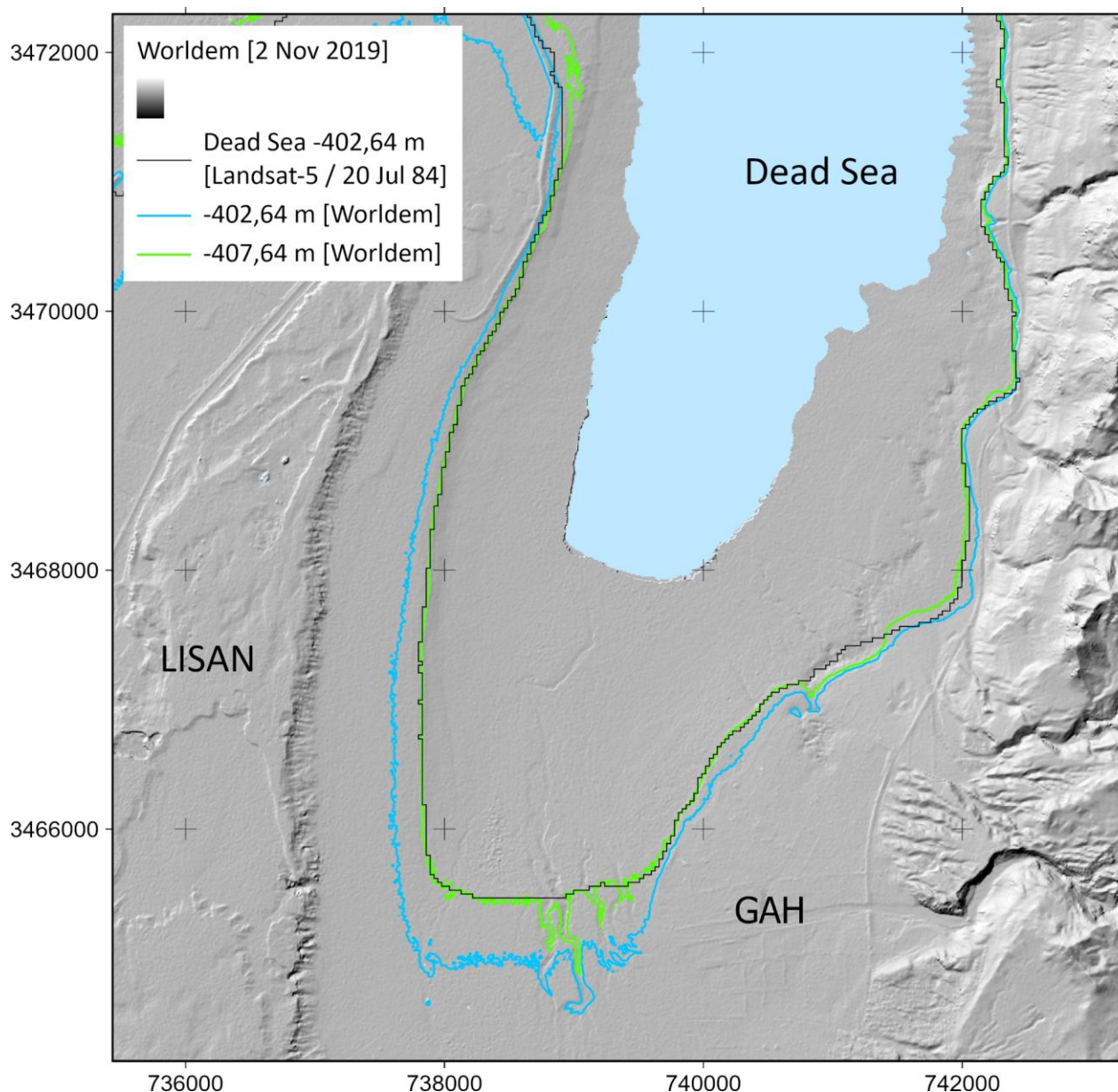


Figure 6. Overview of the comparison between the 20 July 1984 shoreline (black) and the WorldDEM –402,64 m contour (blue) on a WorldDEM hillshade/elevation background.

A second reach, extending over about 220 m, is more consistent with the ca. –414,4 m contour, implying an apparent lowering of about 7 m and an average rate of about 0,24 m yr⁻¹. These tests materially refine the earlier bulk comparison: The geomorphic signal is not one of simple rigid subsidence, but of differential lowering along the strike, with at least one sector recording stronger displacement than the adjacent one. In this sense, Ghor Al-Haditha appears to contain multiple deformation cells, or at least multiple zones of unequal response to the same regional forcing. This interpretation is explicitly linked in the present study to the landslide model of [30], which describes Ghor Al-Haditha as a sinkhole-affected, strongly subsiding sector underlain by a shallow alluvial

aquifer and an important salt layer at roughly 20–30 m depth; in that model, rapid base-level fall reorganizes groundwater circulation, promotes salt dissolution, and drives subsidence, sinkholes, and landslides.

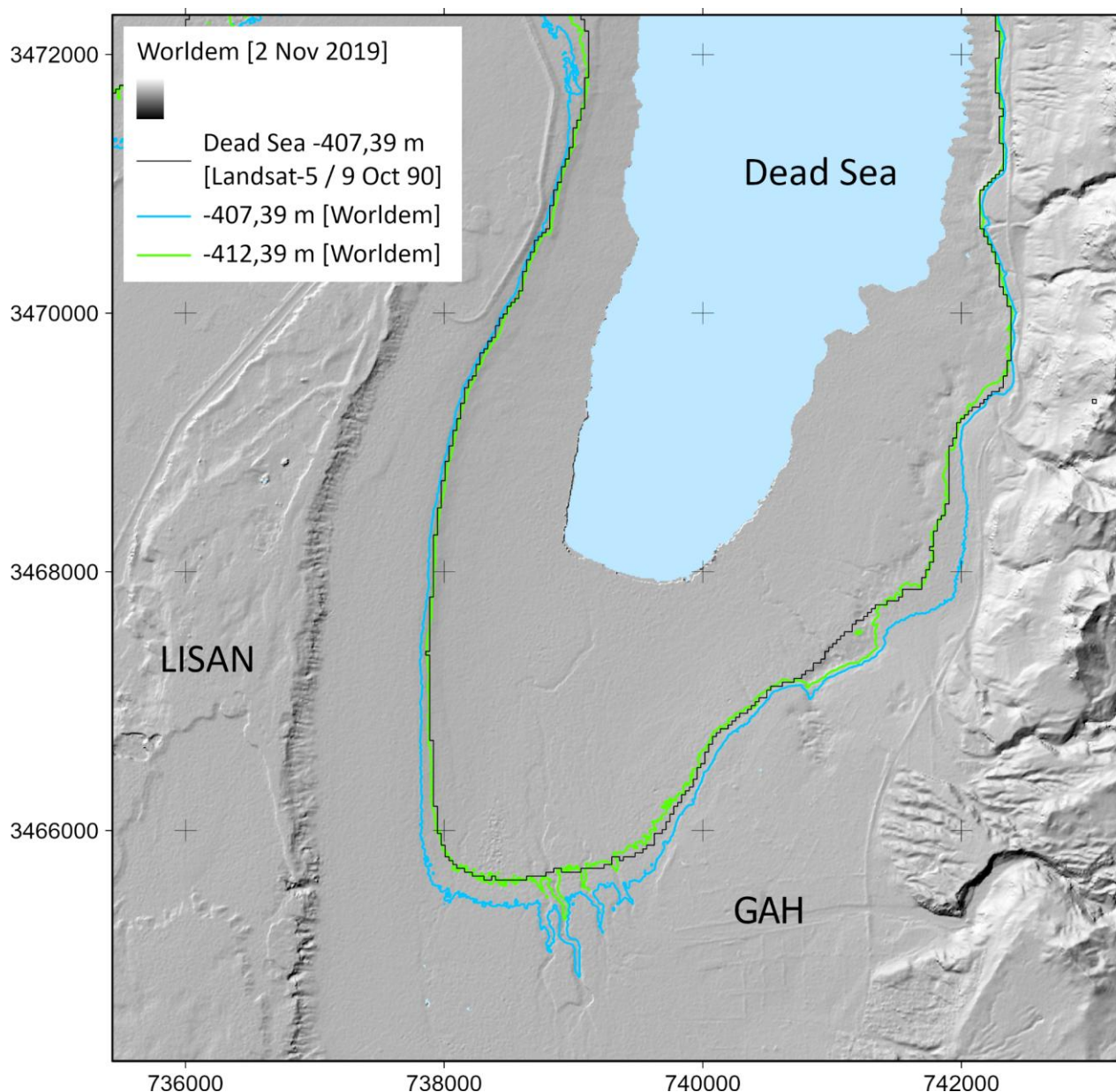


Figure 7. Overview of the comparison between the 9 October 1990 shoreline (Dead Sea level: $-407,39$ m) and the corresponding WorldDEM contours extracted from the 2 November 2019 surface in the Ghor Al-Haditha–Lisan sector. The 1990 paleo-shoreline is compared with the homologous $-407,39$ m contour and with the lower $-412,39$ m contour, shown on a WorldDEM hillshade/elevation background.

For the 2001 benchmark, the shoreline extracted from the 20 August 2001 Landsat-5 image at a Dead Sea level of $-414,98$ m is compared with the homologous $-414,98$ m contour and a contour 4 m lower ($-418,98$ m). Again, the homologous contour does not satisfactorily reproduce shoreline geometry, whereas the lower contour provides the closer overall match, particularly along the southern

shoreline and large parts of the eastern margin. The mismatch is especially pronounced across the Wadi Kerak plain and at Ghor Al-Haditha, where the maximum measured black-blue planimetric separation reaches 415 m at (738–3466). Relative to the 1990 benchmark, the larger maximum separation, despite the shorter elapsed interval, suggests that subsidence remains strongly differential and concentrated in the low-gradient southern emerged flats, where modest vertical lowering is laterally amplified. If the full 4 m offset is taken as the cumulative subsidence signal, it implies an apparent average long-term rate of about $0,22 \text{ m yr}^{-1}$ over 18,2 years.

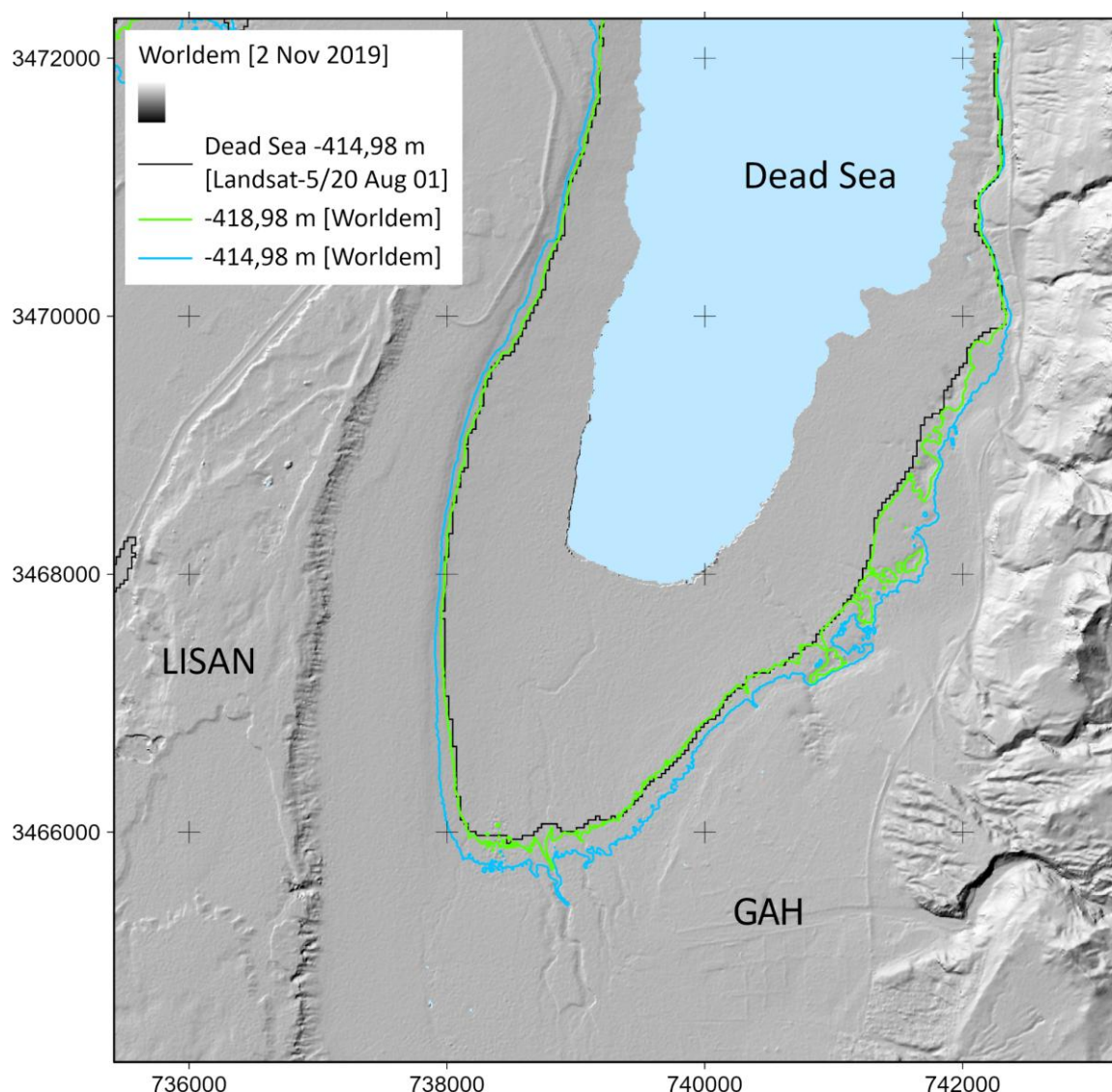


Figure 8. Overview of the comparison between the 20 August 2001 shoreline (Dead Sea level: $-414,98 \text{ m}$) and the corresponding WorldDEM contours extracted from the 2 November 2019 surface in the Ghor Al-Haditha–Lisan sector. The 2001 paleo-shoreline is compared with the homologous $-414,98 \text{ m}$ contour and with the lower $-418,98 \text{ m}$ contour, shown on a WorldDEM hillshade/elevation background.

For the 2011 benchmark, the shoreline extracted from the 1 September 2011 Landsat-5 image at a Dead Sea level of $-424,98 \text{ m}$ is compared with the homologous $-424,98 \text{ m}$ contour and a contour 4 m lower ($-428,98 \text{ m}$). As in the previous comparisons, the contour of the same nominal elevation does

not reproduce the shoreline geometry, whereas the lower contour provides the closer overall match along much of the southern and eastern margins. The discrepancy is greatest across the Wadi Kerak delta plain, where the measured black-blue planimetric separation reaches 425 m at (739–3467), indicating a strong lateral mismatch between the 2011 palaeo-shoreline and the homologous 2019 contour. By contrast, on the platform north of Ghor Al-Haditha, the black-blue separation is smaller, ranging from about 150 to 200 m (741–3469). This spatial contrast shows that the post-2011 lowering signal is not uniformly expressed but remains concentrated in the low-gradient southern emerged flats, while the northern Ghor Al-Haditha platform records a more limited planimetric response. If the full 4 m offset is taken as the cumulative subsidence signal, the implied apparent average long-term rate is about $0,49 \text{ m yr}^{-1}$ over approximately 8,2 years.

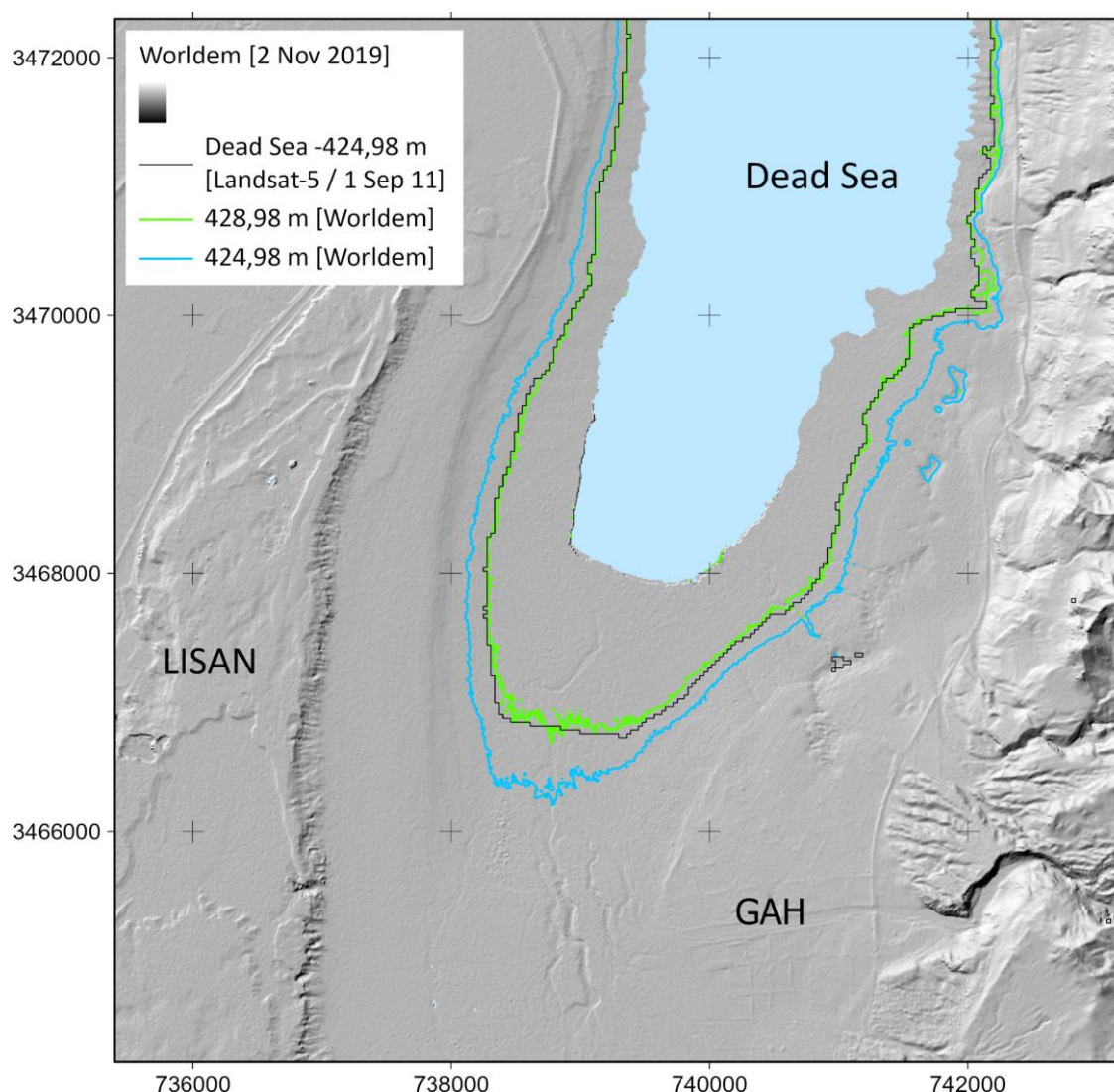


Figure 9. Overview of the comparison between the 1 September 2011 shoreline (Dead Sea level: $-424,98 \text{ m}$) and the corresponding WorldDEM contours extracted from the 2 November 2019 surface in the Ghor Al-Haditha–Lisan sector. The 2011 palaeo-shoreline is compared with the homologous $-424,98 \text{ m}$ contour and with the lower $-428,98 \text{ m}$ contour, shown on a WorldDEM hillshade/elevation background.

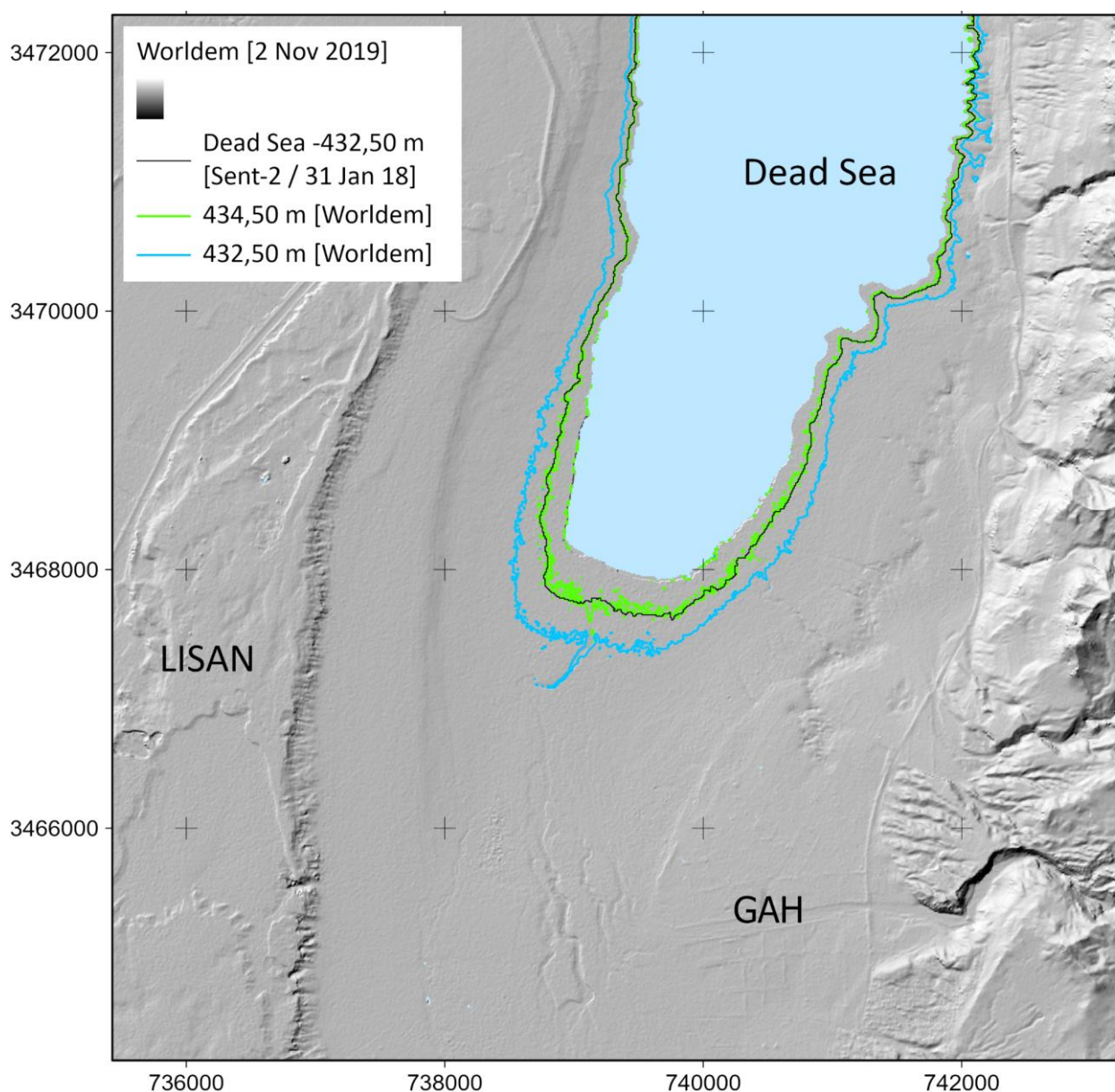


Figure 10. Overview of the comparison between the 31 January 2018 shoreline (Dead Sea level: $-432,50$ m) and the corresponding WorldDEM contours extracted from the 2 November 2019 surface in the Ghor Al-Haditha–Lisan sector. The 2018 palaeo-shoreline is compared with the homologous $-432,50$ m contour and with the lower $-434,50$ m contour, shown on a WorldDEM hillshade/elevation background.

For the 2018 benchmark, the shoreline extracted from the 31 January 2018 Sentinel-2 image at a Dead Sea level of $-432,50$ m is compared with the homologous $-432,50$ m contour and a contour 2 m lower ($-434,50$ m). The homologous contour again does not fully reproduce shoreline geometry, whereas the lower contour generally provides the closer match, particularly along the Wadi Kerak delta plain and the southern embayment. The largest mismatch is measured across the Wadi Kerak plain, where the black-blue planimetric separation reaches 320 m (739–3468), while on the platform north of Ghor Al-Haditha, the corresponding separation is reduced to about 150 m (741–3469). This contrast indicates that the residual displacement between the 2018 shoreline and the 2019 topography remains

spatially heterogeneous, with the strongest apparent lowering concentrated in the low-gradient southern flats and a more limited response on the northern Ghor Al-Haditha platform.

Relative to the 2001 and 2011 benchmarks, the 2018 comparison shows that the same geometric pattern persists until shortly before the WorldDEM acquisition, although over a shorter time span and with a smaller vertical offset. If the full 2 m offset is taken as the cumulative subsidence signal, it implies an apparent average long-term rate of about $1,14 \text{ m yr}^{-1}$ over approximately 1,75 years; the present study explicitly notes that this value should be treated cautiously, because the lowering is unlikely to have been either temporally uniform or spatially homogeneous.

Taken together, the five benchmark comparisons show persistent post-emergence lowering between 1984 and 2019, but not as a simple rigid vertical translation of the whole exposed margin. The strongest signal is repeatedly observed in the Wadi Kerak–Wadi Ibn Hammad delta, where planimetric separations reach 450 m in 1984, 210 m in 1990, 415 m in 2001, 425 m in 2011, and 320 m in 2018, whereas Ghor Al-Haditha shows a more complex internal organization, with shoreline segments matching different 2019 contour levels. The cumulative evidence therefore supports differential deformation, spatially variable subsidence, and local geomorphic adjustment rather than a single homogeneous lowering surface. Figure 11 shows a rise in the apparent benchmark-average subsidence rate from $0,14 \text{ m/yr}$ in the 1984 benchmark to $0,17 \text{ m/yr}$ in 1990, $0,22 \text{ m/yr}$ in 2001, $0,49 \text{ m/yr}$ in 2011, and $1,14 \text{ m/yr}$ in 2018 over the Wadi Kerak delta. The corresponding maximum planimetric separations reported for the Wadi Kerak sector are about 450 m in 1984 at UTM km 738–3465, 210 m in 1990 at (738–3466), 415 m in 2001 at (738–3466), 425 m in 2011 at (739–3467), and 320 m in 2018 (739–3468).

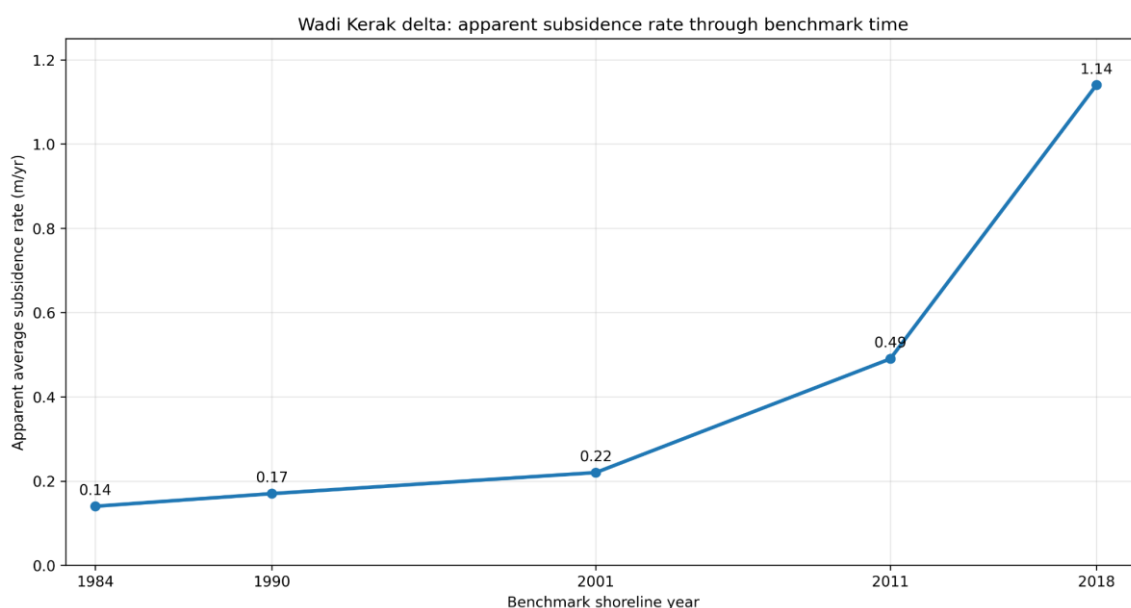


Figure 11. Rates are backward-looking averages referenced to the common 2 Nov 2019 WorldDEM epoch.

Figures 6–11 support the interpretation that the Wadi Kerak–Wadi Ibn Hammad delta remains the most deformation-sensitive part of the emerged margin, with repeated large horizontal mismatches between paleo-shorelines and homologous 2019 contours, exactly where the surface is flattest and therefore most responsive to geometric amplification of vertical change. The curve also suggests that

the apparent lowering signal becomes stronger toward the 2019 DEM epoch. The main caution is that this is not a true year-by-year kinematic time series. It is a sequence of backward-looking average rates, each computed from a benchmark shoreline to the same 2019 reference surface. That means the sharp increase toward 2018 is influenced not only by deformation magnitude, but also by the progressively shorter averaging interval. The present study explicitly warns that the 2018 value of 1,14 m/yr should be treated cautiously because the interval is only about 1,75 years, and the lowering is unlikely to have been temporally uniform or spatially homogeneous.

3.2. Improved DInSAR deformation fields

Figure 12 A-B compares two unwrapped, geocoded Sentinel-1 interferograms of Wadi Kerak–Wadi Ibn Hammad (UTM km 740–3469) delta in Jan-Feb 2024 and Jan-Feb 2026. The interferometric phase has been converted to LOS displacement in meters. Both pairs are selected based on very small perpendicular baselines (10,6 m and 15,93 m) combined with short temporal separations (48 days). In small-baseline interferometry, spatial decorrelation is minimized, and the topographic phase contribution is strongly attenuated, maximizing sensitivity to surface displacement after removal of the flat-Earth term. Sentinel-3 imagery and meteorological web services are used to minimize atmospheric and tropospheric contamination.

The residual topographic contribution is quantified by the height of ambiguity, i.e., the elevation difference required to generate one full 2π topographic phase cycle. Heights of ambiguity of 1,452 m (2024 pair) and 967 m (2026 pair) are far larger than the local paleo-shoreline relief relevant to the deforming surfaces (~ 46 m for the platform sectors north of Ghor Al-Haditha). Even a 10 m marginal scarp contributes at most 0,01 fringe. The subsidence visible in Figure 12 A-B (reddish colors) cannot be attributed to topographic artefacts. After flat-Earth correction and tropospheric mitigation, three residual error sources govern LOS displacement uncertainty (Table 2):

Table 2. Main characteristics of the two Sentinel-1 interferometric pairs used in Figure 12 A-B. The heights of ambiguity (967 m and 1,452 m) are far larger than the local relief of the study area (≤ 45 m), making the residual topographic phase contribution negligible ($< 0,047$ fringe) and rendering DEM subtraction unnecessary. The same small perpendicular baselines ensure that the wrapped phase is dominated by surface displacement rather than topography, enabling reliable detection of centimeter- to decimeter-scale ground deformation not discernible in the field.

Error source	Magnitude	Mitigation
Phase noise (coherence-dependent)	$< 0,5$ mm LOS (coh = 0,9, ~ 20 looks)	Small perp. baseline ($B_{\perp} \leq 16$ m); stable arid surface conditions
Topographic phase contribution	$< 2,5$ mm LOS (worst case: $H_a = 967$ m, relief ≤ 45 m $\rightarrow < 0,047$ fringe)	No DEM correction applied. Pair selection ensures $H_a \gg$ local relief; topographic phase negligible.
Atmospheric delay residual	$\pm 2\text{--}5$ mm LOS	Sentinel-3 / meteorological web service correction
Combined LOS uncertainty (1σ)	$\pm 3\text{--}5$ mm	Dominated by atmospheric residual

The combined LOS uncertainty of $\pm 3\text{--}5$ mm is below 13% of all measured peak values and below 7% of the 2026 peak displacement values observed in Figure 12 A-B. Phase unwrapping integrity is ensured by the high modelled coherence (0,9); unwrapping errors (integer multiples of $\lambda/2 = 27,7$ mm) are unlikely at this coherence level but cannot be excluded in isolated pixels near sharp discontinuities.

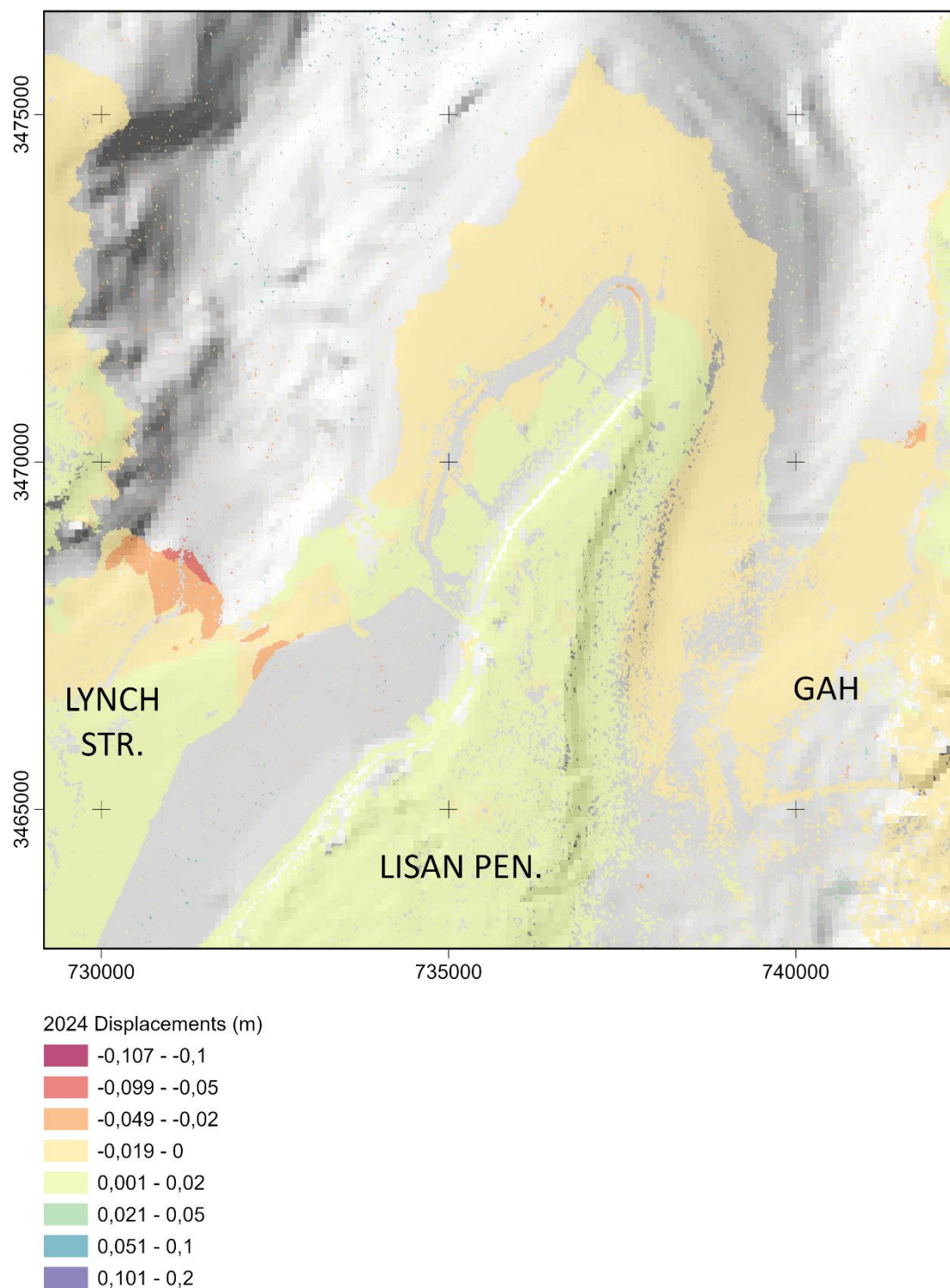


Figure 12A. Unwrapped, geocoded Sentinel-1 differential interferograms, southern Dead Sea coast, expressed as LOS displacement (meters, positive toward satellite). 04 Jan–21 Feb 2024 (48 days, $B\perp = 10,6$ m, $H_a = 1,452$ m, ascending).

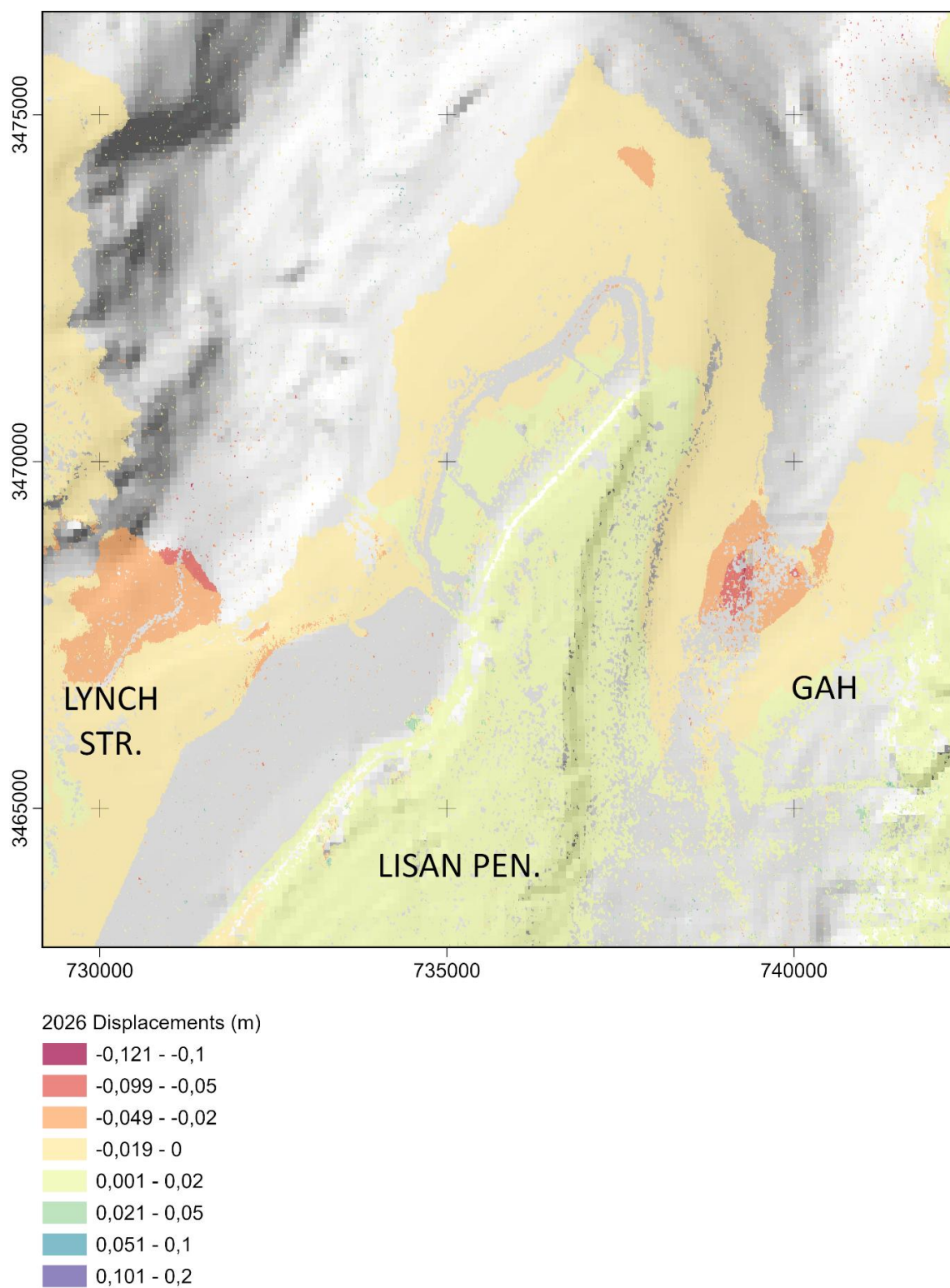


Figure 12B. Unwrapped, geocoded Sentinel-1 differential interferograms, southern Dead Sea coast, expressed as LOS displacement (meters, positive toward satellite). 11 Jan–28 Feb 2026 (48 days, $B\perp = 15,9$ m, $H_a = 967$ m, ascending).

3.2.1. Measured LOS displacements

- 04 Jan–21 Feb 2024 (48 days, $B1 = 10,6$ m, $H_a = 1,452$ m)

The unwrapped LOS displacement map (Figure 12A) shows a spatially heterogeneous deformation pattern along the southern Dead Sea shoreline. The most pronounced negative LOS displacements occur within the Wadi Araba delta sector (UTM km 731–3468), where localized areas attain values between approximately $-0,10$ and $-0,11$ m during the 48-day interval. However, these extreme values are restricted to relatively small zones at the delta front and are not representative of the delta surface. Most of the Wadi Araba delta is characterized by LOS displacements ranging from approximately $-0,05$ to 0 m, indicating more moderate surface lowering.

The maximum observed LOS displacements correspond to annualized rates approaching $-0,8$ m yr⁻¹, while the more widespread displacement range of $-0,02$ to $-0,05$ m corresponds to annualized LOS rates of approximately $-0,15$ to $-0,38$ m yr⁻¹. Using the Sentinel-1 incidence angle of approximately 36° , these values imply equivalent vertical subsidence rates of approximately $-0,2$ to $-0,5$ m yr⁻¹ over most of the delta surface, locally exceeding $-1,0$ m yr⁻¹ in the most active sectors. Such deformation is consistent with ongoing compaction of recent deltaic sediments, consolidation processes associated with rapid sediment accumulation, and possible dissolution or collapse of underlying evaporitic deposits.

The Wadi Kerak–Wadi Ibn Hammad delta on the eastern margin of the study area (UTM km 740–3468) exhibits a generally weaker and more diffuse deformation signal. Most measured LOS displacements fall within the $-0,02$ to 0 m range, although isolated sectors display values approaching $-0,05$ to $-0,10$ m. The overall pattern indicates lower displacement magnitudes and a less spatially concentrated deformation field than observed within the Wadi Araba delta.

Comparison of the two delta systems suggests that sediment loading alone is unlikely to explain the observed deformation patterns. Instead, the measured LOS displacements probably reflect the combined influence of sediment compaction, evaporite dissolution, shoreline retreat associated with the ongoing Dead Sea level decline, and local hydrogeological conditions. Although localized subsidence is observed at both deltas, the greater spatial extent and magnitude of negative LOS displacements in the Wadi Araba sector support the interpretation that its higher sediment flux contributes to enhanced surface lowering relative to the Wadi Kerak–Wadi Ibn Hammad delta.

- 11 Jan–28 Feb 2026 (48 days, $B1 = 15,9$ m, $H_a = 967$ m)

The unwrapped LOS displacement map (Figure 12B) reveals a localized zone of negative LOS displacement on the eastern side of the study area, near the GAH sector (UTM km 739–3468). This feature is expressed as a distinct deformation patch surrounded by a broader area of moderate negative displacement. The core of the anomaly exhibits LOS displacements of approximately $-0,10$ to $-0,12$ m during the 48-day observation interval, whereas the surrounding zone is characterized by values of approximately $-0,05$ to $-0,10$ m. Outside this sector, most of the exposed Lisan Peninsula and adjacent areas display considerably lower displacement magnitudes, generally ranging between $-0,02$ and $+0,02$ m.

Assuming that the measured displacement rate remains constant throughout the year, the maximum LOS displacement observed within the deformation core corresponds to an annualized LOS displacement rate of approximately $-0,76$ to $-0,91$ m yr⁻¹. Using an incidence angle of approximately 36° , the equivalent vertical displacement rate is approximately $-0,94$ to $-1,13$ m yr⁻¹. The broader surrounding zone corresponds to annualized LOS rates of approximately $-0,38$ to $-0,76$ m yr⁻¹, equivalent to vertical rates of approximately $-0,47$ to $-0,94$ m yr⁻¹.

It should be emphasized that these values represent annualized equivalents derived from a single 48-day interferometric observation and therefore assume that the observed displacement rate remains constant throughout a year. Consequently, the calculated rates should not be interpreted as directly measured annual subsidence rates without confirmation from a longer InSAR time series.

Compared with the 2024 interferogram, Figure 12B indicates a stronger concentration of deformation within the eastern sector of the study area. While localized negative LOS displacements are present in both datasets, the 2026 interferogram highlights a more spatially focused deformation anomaly near GAH, with peak LOS displacements approaching $-0,10$ to $-0,12$ m. In contrast, much of the surrounding area exhibits relatively small displacement magnitudes close to zero. This pattern suggests increased localization of ground deformation rather than widespread regional subsidence.

The observed deformation is consistent with ongoing post-emergence adjustment of the exposed Dead Sea floor and may reflect a combination of sediment compaction, evaporite dissolution, collapse of subsurface cavities, and groundwater-related processes. The elongated geometry of the anomaly and its occurrence away from this shoreline suggest that deformation mechanisms associated with the continuing base-level fall of the Dead Sea can affect extensive portions of the former lake floor and are not necessarily restricted to individual sinkhole clusters or immediate shoreline environments.

Figure 13 highlights a marked contrast between the deformation patterns observed in 2024 and 2026. The 2024 interferogram shows diffuse and spatially distributed ground motion, while the 2026 data reveal deformation concentrated within a well-defined SW–NE-trending subsidence zone approximately 2 km long. The feature forms an elongated body within the western part of the Ghor Al-Haditha graben, between the Ghor Mazra'a Fault (GMF) and the Ghor Safi Fault (GSF).

The deformation is not centered on the main sinkhole corridor but occurs approximately 1,5 km west of the dense NNE–SSW sinkhole alignment associated with the West Dhira Fault (WDF). The subsidence zone is therefore spatially separated from the principal sinkhole field and is more than 500 m inland from the contemporary shoreline.

The geometry of the subsiding area is complex and characterized by several angular boundaries rather than a simple elliptical shape. Its margins display abrupt changes in orientation defining SW–NE, NNE–SSW, and ENE–WSW segments. These directions are similar to those observed within the mapped sinkhole corridor, which shows several changes in orientation and segmentation along its length [15].

The dimensions, elongated geometry, and abrupt appearance of the 2026 feature resemble the kilometer-scale subsidence zone identified in the Lynch Strait sector from ALOS DInSAR observations, where large-scale deformation is localized along a narrow corridor extending beyond the main sinkhole field [45].

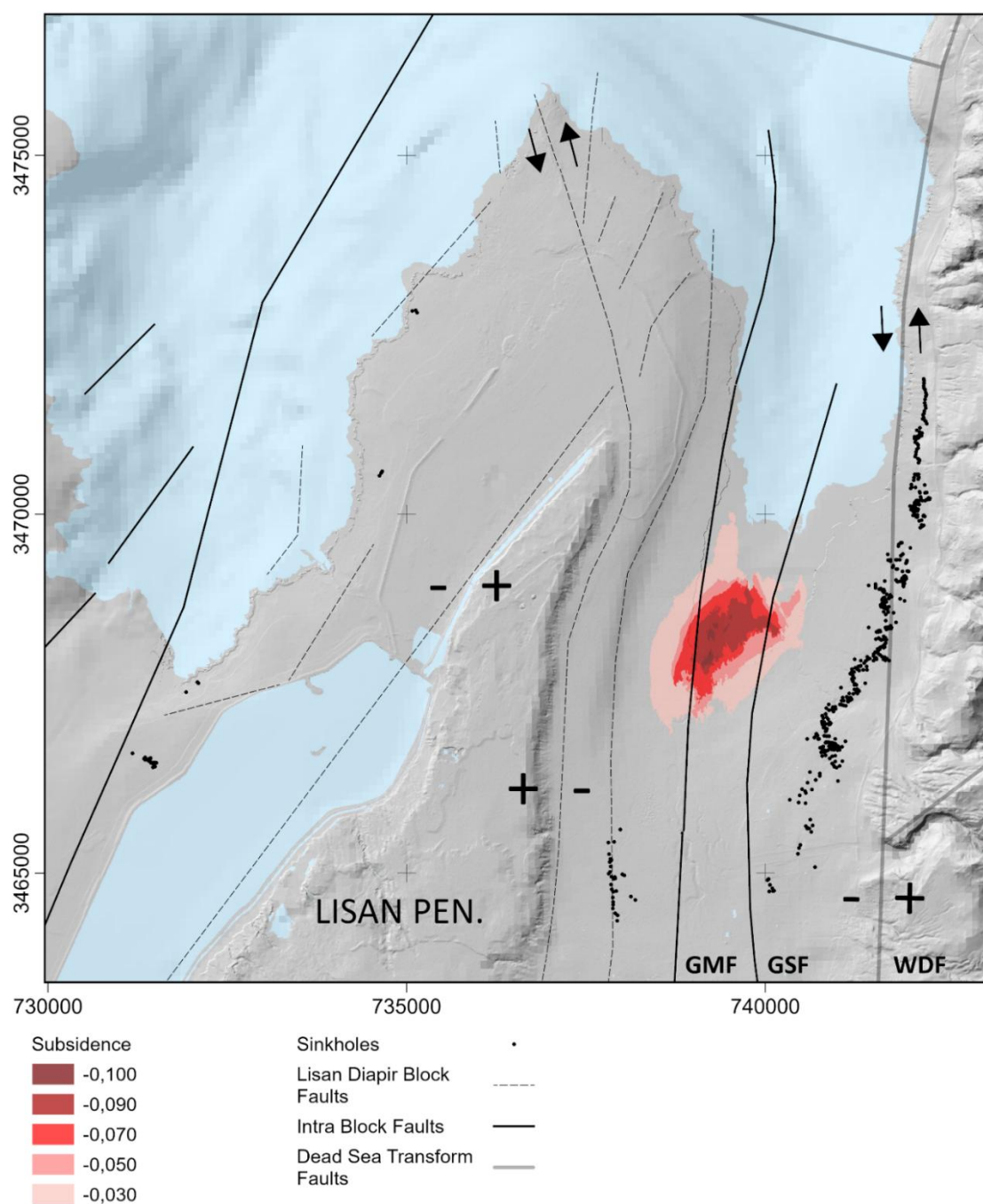


Figure 13. Subsidence pattern of Jan-Feb 2026 within the structural context of Ghor Al Haditha (GAH); GMF = Ghor Mazra'a Fault; GSF = Ghor Safi Fault; WDF = West Dhira Fault. Dead Sea shoreline extracted from contemporary Sentinel-2 image (−441 m, 2026). Subsidence is expressed in meters (see also Figure 12 A-B).

4. Discussion

4.1. Post-emergence deformation of the exposed Dead Sea floor

The comparison between paleo-shorelines and the 2019 WorldDEM surface demonstrates that the exposed Dead Sea margin has not remained topographically stable following emergence. In all

benchmark cases, the contour corresponding to the original shoreline elevation fails to reproduce the present-day geometry, whereas lower contours consistently provide a better fit. Because the local vertical datum discrepancy between ILSD and EGM2008 is approximately 0,8 m, substantially smaller than the observed elevation differences reaching 4–5 m, the mismatch cannot reasonably be explained by referencing issues alone. Instead, it indicates significant post-emergence modification of the exposed lake floor.

The deformation signal is heterogeneous. The Wadi Kerak–Wadi Ibn Hammad delta repeatedly exhibits the strongest shoreline–contour discrepancies, whereas Ghor Al-Haditha shows a more segmented response in which adjacent shoreline sectors correspond to different modern elevation levels. This spatial variability excludes a simple regional lowering of the platform and instead points to differential subsidence and geomorphic reorganization operating over the emerged margin. Such behavior is consistent with the complex geological setting of the area, where fault zones, evaporite dissolution, groundwater circulation, and sediment compaction interact over different spatial and temporal scales.

4.2. Contemporary deformation confirms that adjustment is ongoing

The Sentinel-1 interferograms provide independent evidence that the deformation inferred from the geomorphic record remains active. The observed LOS displacements, although derived from short observation intervals of 48 days, indicate rapid contemporary ground lowering affecting the same sectors highlighted by the paleo-shoreline analysis. Consequently, the shoreline–contour mismatches cannot be regarded as relic features produced during the early stages of emergence but rather as manifestations of an ongoing deformation process.

Particularly significant is the transition from the diffuse deformation pattern observed in 2024 to the localized subsidence structure detected in 2026. The latter reveals a coherent SW–NE-trending subsidence zone approximately 2 km long that developed over a relatively short time interval. Such an abrupt spatial reorganization suggests that the deformation field may evolve episodically rather than through steady, spatially uniform subsidence. The emergence of this localized feature resembles the kilometer-scale deformation corridor documented in the Lynch Strait area from ALOS DInSAR observations, where large-scale subsidence is interpreted as being localized along a pre-existing structural corridor associated with one of the earliest sinkhole alignments along the Dead Sea margin [45].

4.3. Structural inheritance appears to organize the deformation

The spatial relationship between the 2026 subsidence anomaly, the regional fault framework, and the sinkhole distribution, provides important insight into the mechanisms controlling deformation. The subsidence feature is not centered on the main Ghor Al-Haditha sinkhole corridor but occurs approximately 1,5 km to the west, between the Ghor Mazra'a and Ghor Safi fault systems. Its location, more than 500 m inland from the contemporary shoreline, is also unusual compared with the typical distribution of active sinkhole clusters.

An additional observation concerns the geometry of the subsidence polygon. Several margins display abrupt changes in orientation and locally orthogonal boundaries. These orientations correspond closely to the dominant structural directions identified by Diabat [15], namely N–S to NNE–SSW and ENE–WSW fracture sets. Diabat showed that sinkhole-related fissures, tension cracks and fault-

controlled discontinuities throughout Ghor Al-Haditha commonly form en-echelon arrays, orthogonal intersections, and angular patterns similar to those visible in the 2026 subsidence anomaly.

The similarity between the geometry of the subsidence zone and that of the regional fracture network suggests that the deformation inherits pre-existing structural discontinuities rather than developing isotropically. Hydrogeological studies further support this interpretation by demonstrating that groundwater circulation, salt dissolution, and sinkhole development are guided by concealed structural and hydrological pathways within the graben rather than strictly by the major mapped faults.

4.4. From sinkholes to kilometer-scale subsidence

Taken together, the geomorphic and interferometric evidence indicates that post-emergence deformation of the Dead Sea floor operates across several spatial scales. At the smallest scale, deformation is expressed as individual sinkholes and localized collapses. At intermediate scales, sinkholes cluster into broader subsidence areas and uvalas impacting hundreds of meters of terrain. At the largest scale, the 2026 interferometric anomaly and the cumulative paleo-shoreline mismatches indicate deformation affecting kilometer-scale sectors of the emerged platform.

This hierarchy of deformation processes is consistent with studies of the Ghor Al-Haditha area, which emphasize the progressive migration of dissolution fronts, the evolution of sinkhole fields into larger subsidence complexes, and the importance of structurally controlled groundwater pathways. Rather than representing isolated phenomena, sinkholes, uvalas, and large subsidence corridors appear to be different manifestations of the same evolving hydrogeological and tectonic system. The 2026 deformation corridor therefore provides additional evidence that large-scale ground lowering may occur independently of visible sinkhole clusters while remaining controlled by the same inherited structural framework.

5. Conclusions

In this study, we demonstrate that comparisons between dated paleo-shorelines and the 2019 WorldDEM surface provide an effective approach for detecting long-term post-emergence deformation along the eastern Dead Sea margin. In all benchmark cases examined between 1984 and 2018, the contour corresponding to the original shoreline elevation fails to reproduce the preserved shoreline geometry, whereas lower contours consistently provide a closer match. Because the observed discrepancies greatly exceed the expected offset between the Israeli water-level datum and EGM2008, they are unlikely to result from vertical referencing differences alone. Instead, they indicate significant topographic modifications of the exposed Dead Sea floor after emergence.

The spatial distribution of the shoreline–contour mismatches further shows that this deformation is heterogeneous. The Wadi Kerak–Wadi Ibn Hammad delta exhibits the largest and most persistent discrepancies, while Ghor Al-Haditha displays a more segmented response characterized by differential lowering between adjacent sectors. These observations indicate that post-emergence adjustment cannot be explained by a simple regional lowering surface but reflects localized subsidence and geomorphic reorganization.

The DInSAR results independently confirm that deformation remains active. Sentinel-1 interferograms reveal centimeter- to decimeter-scale LOS displacements over periods of only a few weeks and identify a previously unrecognized subsidence zone approximately 2 km long that

developed between 2024 and 2026. The geometry of this feature, together with its position between the Ghor Mazra'a and Ghor Safi fault systems and its structural similarity to the fracture patterns associated with the Ghor Al-Haditha sinkhole field, suggests deformation localized along inherited structural and hydrogeological pathways.

Taken together, the paleo-shoreline analysis and the interferometric observations indicate that the exposed Dead Sea floor continues to adjust decades after emergence. The results suggest that deformation operates across a range of spatial scales, from individual sinkholes and uvalas to kilometer-scale subsidence corridors, all influenced by the interaction between groundwater circulation, evaporite dissolution, and inherited structural discontinuities. Rather than representing isolated phenomena, sinkholes and broader subsidence zones appear to be different expressions of the same evolving post-emergence deformation system.

Finally, this study highlights the value of integrating geomorphological archives and satellite radar observations for investigating rapidly evolving lacustrine margins. Future work combining higher-density InSAR time series, field elevation control, and improved datum harmonization will help quantify the relative contributions of dissolution, collapse, compaction, and erosion to the ongoing evolution of the Dead Sea shoreline.

Author contributions

Damien Closson: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing (original draft, Writing) review & editing, Project administration.

Enrique Coiras: Methodology and Software (development of the sibling-coherence coherence-estimation approach, implemented as an additional module in SNAP), Writing, review & editing. All authors have read and agreed to the published version of the manuscript.

Use of Generative-AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

There is no conflict of interest.

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Supplementary



Figure S1. Aerial photograph of the Lisan Peninsula and Ghor Al-Haditha area, 25 February 1918. The Dead Sea level was approximately 395 m below mean sea level, versus about 440 m bmsl in March 2026. Consequently, Lisan Bay was far more extensive than at present. The Lisan Peninsula then appeared as a narrow tongue of salty marls extending northward into the terminal lake and ending at Cape (Point) Costigan. Ghor Al-Haditha was expressed as an inhabited fan-delta system incised by several active channels. Source: Australian War Memorial.



Figure S2. Oblique aerial view from the Moab Plateau, Jordan, looking westward over the southern Dead Sea margin, 1990s. The foreground shows the agricultural plain of Ghor Al-Haditha, followed by Lisan Bay and the Lisan Peninsula, which is surrounded by an emerged marginal platform. Cape Costigan occupies the central part of the photograph. Source: APAME.

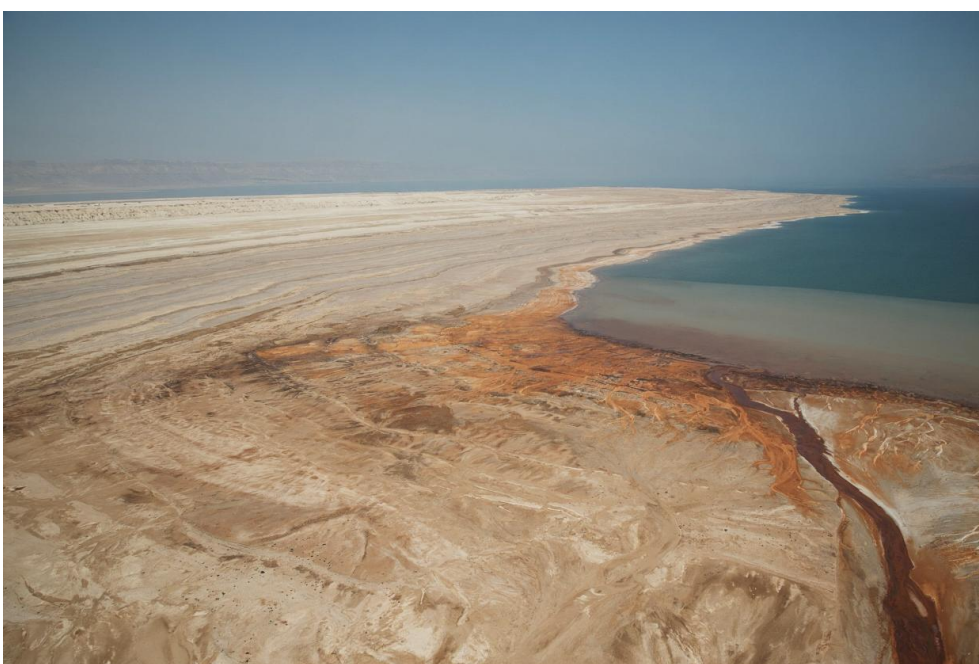


Figure S3. View of Wadi Kerak entering Lisan Bay, 2000s. The wave-cut platform fringing the Lisan Peninsula reveals sub-horizontal saline marl strata. On the horizon, in the upper left sector of the photograph, the white cliffs of the Lisan can be distinguished. Source: APAME.



Figure S4. The wave-cut platform north of Ghor Al-Haditha, severely affected by sinkholes and subsidence, 2000s. Source: APAME.



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