

Long-Term Desiccation Dynamics: AI-Driven Projections of the Dead Sea's Fate Through 2345

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Abstract

The Dead Sea, located within the Dead Sea Transform Fault System (DSTFS), is experiencing a severe hydrological decline marked by rapid decreases in both water level and surface area. This study analyzed long-term changes using a 1970 baseline map and multi-temporal satellite datasets from the USGS archive, integrating high-resolution Sentinel imagery with Landsat (1–9) data covering 1975–2025. Historical results reveal a pronounced multi-phase recession, with the most rapid contraction occurring between 1970 and 1985, when the sea lost approximately 28.49% of its surface area at a peak rate of 34.21 km² per year, leading to the complete desiccation of the southern basin. Future projections were generated using a Multivariate Long Short-Term Memory (LSTM) model combined with bathymetric analysis to forecast conditions until 2345. The results indicate a continued and irreversible decline, with a total surface area reduction of 55.31%, shrinking the Dead Sea to about 317.1 km² and lowering the water level to approximately –637.4 m, ultimately transforming it into a hypersaline remnant basin.

Key words; Hypersaline terminal lake, Shoreline retreat, Bathymetric, Long Short-Term Memory (LSTM),

2. Literature Review

The DS represents the deepest hypersaline basin over the global land, and it is the most rapidly shrinking, DS currently lying at approximately –439 m below mean sea level (2025). Historically composed of a deep northern basin and a shallow southern basin separated by the Lisan Peninsula, the DS experienced complete desiccation of the southern basin by the end of 1980s as a result of sustained regression (Alhusban Y., and Almanasyeh N, 2017; Weinberger and Ben-Zvi, 2008). Over recent decades, the water level has declined from about –400 m in the 1970s to nearly –437 m by the end of 2025,() while in the current study we found that the water level –439m, with surface area about 587.2 km². Previous studies emphasize that the lake's regression reflects a complex interaction between hydrological imbalance, climatic variability, and anthropogenic intervention (Oroud, I. M. 2023; Lensky, et al, 2005). Reduced inflow from the Jordan River due to upstream diversion, coupled with industrial evaporation pond operations, has created a strongly negative water balance (Gertman and Hecht, 2002). Reports by the World Bank (2013) and the United Nations Environment Programme (2019) confirm that anthropogenic water abstraction is the dominant driver of decline, exceeding the influence of natural climatic variability. Water, salt, and energy balance analyses (Lensky et al., 2005) demonstrate that evaporation substantially surpasses inflow under current hydrological conditions, indicating continued regression unless large-scale restoration measures are implemented. Rapid shoreline withdrawal has triggered widespread sinkhole formation along the eastern and western margins, primarily due to dissolution of subsurface salt layers

following groundwater intrusion (Abou Karaki, N., et al. 2017; Al-Halbouni et al., 2017). These processes threaten infrastructure, tourism facilities, and agricultural zones, particularly in shallow-gradient areas where horizontal retreat is most pronounced. The transformation of the southern basin into artificial evaporation ponds further illustrates the irreversible spatial restructuring of the lake system (Alhusban Y., and Almanasyeh N ,2017).

Remote sensing has been central to quantifying these spatial and temporal dynamics in this study. Multi-temporal Landsat imagery provided by the USGS has enabled consistent monitoring since the 1970s, while higher-resolution Sentinel-2 data from the European Space Agency has significantly improved shoreline delineation in recent years, besides a Multivariate Long Short-Term Memory (LSTM) model integrated with Bathymetric analysis to project conditions up to the year 2345, in many studies. Spectral indices such as the Normalized Difference Water Index (NDWI) were applied (McFeeters, 1996) and the Modified NDWI (MNDWI) (Xu, 2006) have been widely applied to extract water bodies and map exposed lakebed areas (Hereher, 2015; Al-Mashagbah, and et al, 2021; Abu Samour, and Al-Bilbisi, 2014). GIS integration further supports basin-scale morphometric analysis and exposure mapping (Ghumaid, 2021; Schneider & Lazar, 2009), the forecasting water level and surface area, constrained by bathymetric (Gertman and Hecht, 2002).

Recently research employs machine learning and deep learning techniques to forecast hydrological change. Random Forest regression has been applied to identify nonlinear relationships between climatic variables, inflow reduction, and surface-area loss (Breiman, 2001; Rodriguez-Galiano et al., 2015; Shen, 2018; Reichstein, et al. 2019). Long Short-Term Memory (LSTM) networks, introduced by (Hochreiter and Schmidhuber (1997), have demonstrated strong performance in modeling temporal dependencies in environmental time series (Ma et al., 2019). Reviews (Maier et al, 2010; Shen, 2018) highlight the suitability of AI-based approaches for complex hydrological systems, particularly where traditional linear models underperform. These methods are especially valuable for long-range forecasting under interacting climatic and anthropogenic pressures.

Using Multivariate LSTM with bathymetric data, a technique that has been utilized by numerous studies to capture nonlinear temporal patterns and improve long-term forecasting of water level and surface dynamics (Hall, 1993; Hall, 1996; Hochreiter, and Schmidhuber, 1997; Kratzert et al. 2019).

Building upon this body of research, the present study integrates multi-decadal satellite-derived surface-area, surface level records, and Multivariate LSTM with Bathymetric Constraints networks to generate predictive scenarios up to the year 2345. Importantly, this research is distinguished by the use of a highly accurate 1 m resolution base map derived from Sentinel imagery, providing unprecedented spatial precision in shoreline delineation and exposure mapping. The integration of high-resolution remote sensing, GIS-based spatial analysis, and AI-driven modeling strengthens predictive reliability and supports scenario-based environmental planning.

Current hydrological simulations indicate that the Dead Sea will converge toward a terminal equilibrium rather than total desiccation. This stabilization is governed by the Evaporation Retardation Mechanism, where increasing magnesium chloride concentrations significantly diminish vapor pressure (Asmar & Ergenzinger, 2002). As hypersalinity intensifies, evaporation rates decline until they balance residual inflows (Yechieli et al., 1998; Lensky et al., 2005). These findings align with (Oroud ,2023), confirming that the sea will persist as a highly saline, geographically confined body. Crucially, numerous studies emphasize that the Dead Sea will not disappear entirely in the long term, a consensus that strongly validates the findings of the present research.

Overall, previous studies establish a robust empirical foundation demonstrating sustained hydrological decline, geomorphologic instability, and accelerating shoreline retreat. By combining precise satellite-based monitoring with advanced AI forecasting, and assuming constant hydrological variables, this study advances existing methodologies to provide long-term projections essential for sustainable water management and regional environmental planning.

2. Description of the study area

The DS is a Holocene hyper-saline terminal lake (Enzel et al,2003), and the base level of the Jordan River (Holy River).The DS is the lowest point on land, it occupies the central part of the DS Transform Fault extends between $31^{\circ}5' - 31^{\circ}45'N$ latitude and $35^{\circ}20' - 35^{\circ}35' E$ longitude. Historically, Until 1953, the DS level fluctuated around a historical elevation of about -392 m (b.m.s.l), with an area of 1050 km² (Topographic map,1949), and the DS was composed of two basins: the northern deep one and the shallow southern one; the Lisan Peninsula divide the two basins; however, the southern basin completely dried up by the end of the 1980s, representing the largest retreat in the surface area of the DS covered by salt evaporation ponds (Alhusban Y., and Almanasyeh N ,2017 AI-Mashagbah,et al,2021).

The DS has suffered a historic decline in its water level accompanied by a significant shrinkage in its surface area. The results of this study clearly demonstrate a continuous regression trend, as the water level

decreased from approximately -397 m in the 1970s to about -439 m in 2025. Concurrently, the surface area contracted from 952.1 km² to 587.2 km². These findings confirm a substantial hydrological imbalance and highlight the accelerating nature of lake recession over the past five decades. Nevertheless, the Dead Sea will not disappear in the long term, as demonstrated by the projected results of Dead Sea surface area and water level forecasting through the year 2345. Figure (1): the location of the study area

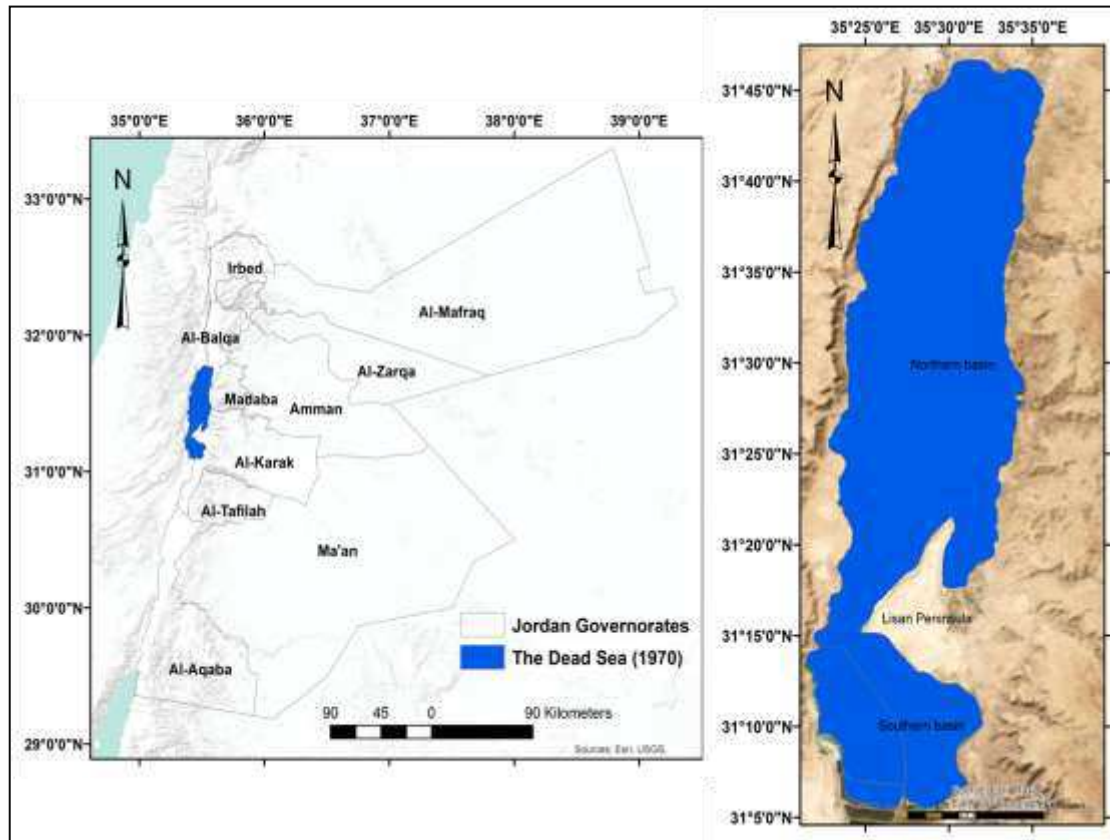


Figure (1): the location of the study area and DS 1970 as a base map

3. Data sources and Methodology

3.1 Data sources

This study monitors the historical contraction of the Dead Sea (DS) from 1970 to 2025, establishing a rigorous empirical foundation for projecting its spatial evolution through up to the year 2345. By synthesizing historical cartographic data with longitudinal field measurements, the research identifies a catastrophic baseline decline: elevation plummeted from -403 m in the 1970s to -439 m by 2025, while the total surface area constricted from 952.1 km² to 587.2 km². To quantify these morphological shifts, a high-resolution, multi-temporal inventory was processed, integrating 1m Sentinel imagery (1970) with a comprehensive Landsat (1–9) series (1975–2025) featuring spatial resolutions of 30m to 60m.

The study integrates advanced bathymetric analysis constructing a digital bathymetric model from depth measurements through geospatial interpolation to quantitatively derive basin morphology, slope gradients, and area elevation volume relationships. These parameters were incorporated into a

multivariate Long Short-Term Memory (LSTM) neural network to forecast Dead Sea dynamics under constant hydrological variables.

The modeling indicates a terminal recession phase; by 2345 the Dead Sea is projected to experience a 55.31% cumulative surface-area loss (shrinking to 317.1 km²) and a net elevation decline of 234.4 m, reaching −637.4 m. Table (1) presents the data sources.

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Source Type	Satellite / Method	Year(s)	Spatial Resolution	Data source	Purpose
Remote sensing	Sentinel imagery	1970	1 m	USGS	Extraction base map for the DS surface area
Remote sensing	Landsat 1	1975, 1980	1 m	USGS	Extraction of DS surface area
Remote sensing	Landsat 5	1985, 1990, 2010	30 m	USGS	Extraction of DS surface area
Remote sensing	Landsat 4	2000	30 m	USGS	Extraction of DS surface area
Remote sensing	Landsat 9	2025	30 m	USGS	Extraction of DS surface area
Field work	Field survey (ground verification)	Various	—	Authors	Validation and accuracy assessment
Deep learning forecasting	LSTM (Long Short-Term Memory)	2025–2100	—	Time-Series Neural Networks	Forecasting the future changes in DS surface area and water level until the end of the 2345st century

3.2 Research methodology

3.2.1. Digital image processing

This study employs an integrated, model-oriented framework to project the long-term desiccation dynamics of the Dead Sea up to the year 2345, synthesizing satellite-based monitoring with AI-driven forecasting. The methodology utilizes a multi-temporal dataset spanning 1970 to 2025, integrating high-resolution 1m Sentinel imagery with the Landsat series (1, 4, 5, 9) to quantify decadal surface area variations. Following systematic preprocessing in ArcPro—including band stacking, geometric correction, and terrain-corrected radar calibration—these data were integrated with historical water level records (1928–2025) to construct a multivariate time series.

A high-resolution bathymetric was used to derive hypsometric relationships ($\text{Area/Volume} = f(\text{Level})$), establishing the bathymetric constraints necessary for geomorphological realism. The predictive framework utilizes a Multivariate Long Short-Term Memory (LSTM) neural network architecture, implemented in TensorFlow with stacked layers and dropout regularization. By applying a sliding

window technique and Min-Max scaling, the model simultaneously predicts future water level and surface area.

3.2.3 Scenario-based Forecasting

Scenario-based forecasting was implemented to evaluate potential long-term trajectories of the Dead Sea under alternative continuation patterns derived from historical trends in water level and surface area. The forecasting framework is based on the multivariate relationship between water level and surface area, constrained by bathymetric controls and basin geometry. This approach ensures that all simulated projections remain geomorphologically consistent with the basin morphology and its underlying topographic–bathymetric structure.

Three principal scenarios were defined based on observed historical dynamics (1980–2025): (1) continuation of the current decline rate, (2) accelerated decline reflecting intensified hydrological stress, and (3) moderated decline assuming partial stabilization. In each scenario, projected water levels were generated using the trained multivariate LSTM model. These predicted levels were then converted into corresponding surface areas using the derived bathymetric function $\text{Area} = f(\text{Level})$, ensuring physically realistic shoreline evolution.

Because bathymetry governs the non-linear response between elevation loss and areal shrinkage, the scenario simulations capture threshold behaviors, particularly in shallow marginal zones where minor vertical declines produce substantial horizontal retreat. This approach allows assessment of future tipping points, basin segmentation risks, and potential exposure of previously submerged land.

Uncertainty ranges were quantified using Monte Carlo dropout simulations, producing confidence intervals for both level and area projections. The scenario-based framework thus provides a structured and physically constrained mechanism for evaluating long-term desiccation pathways and their spatial implications.

3.2.4 Model Evaluation

The multivariate LSTM model with bathymetric constraints was evaluated using standard statistical metrics to ensure predictive accuracy and physical consistency. Performance was quantified through Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and coefficient of determination (R^2) by comparing predicted water levels and surface areas against observed historical data (1980–2025). The model's ability to reproduce non-linear relationships between level and area, as dictated by bathymetry, was specifically assessed. Additionally, Monte Carlo dropout simulations were applied to estimate uncertainty ranges, providing confidence intervals for long-term projections. The evaluation confirmed the model's reliability for scenario-based forecasting and geomorphologically consistent predictions.

Model performance was rigorously evaluated using standard statistical metrics, including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2). To ensure the reliability of long-term forecasts, sensitivity analyses were performed to quantify the relative contribution of individual predictors, while uncertainty ranges were established to account for stochastic variables. The model's predictive accuracy was validated against the historical DS levels recorded from 1970 to 2025. The resulting projections demonstrated strong congruency with observed measurements, confirming the model's robustness in capturing the complex hydrological dynamics of the basin, as presented in Table (2).

Table (2) summarizes the research methodology.

Phase	Key Actions & Technologies
I. Data Acquisition	Integration of multi-temporal satellite imagery (Sentinel-1, Landsat 1, 4, 5, 9) spanning 1970–2025, alongside Ground Verification for accuracy.
2. Pre-processing	Optical: Layer stacking (Visible/NIR) and geometric correction in ArcPro. Radar (Sentinel-1): Radiometric calibration, speckle noise reduction, and terrain correction.
3. Spatial Analysis	Mosaicking and clipping to the study area. Extraction of shoreline positions and calculation of historical surface area variations.
4. AI Forecasting	Deployment of LSTM (Long Short-Term Memory) networks to simulate future trends (2025–2345) based on historical data and bathymetric model.
5. Validation	Evaluation of model reliability using statistical metrics: R2, RMSE, and MAE.

4. Results and discussions

4.1. Results

Until the late 1970s, the DS consisted of two basins: northern and southern, with the northern basin representing the natural DS and the southern basin still part of the sea; but by the end 1980s, the southern basin had completely dried up due to multiple factors, including the continuous diversion of water to artificial evaporation pools for mineral extraction, which began in the late 1960s along the western and eastern margins of the Dead Sea, the construction of dams on the outlets of tributaries that historically replenished the sea, and Water scarcity. The results will be presented as follows;

4.1.1. Temporal Changes in the DS Surface Area during (1970–2025)

Based on the results shown in Tables (3–5), the Dead Sea surface area changes (1970–2025) can be divided into two main periods as follows:

First Period (1970–1985):

During this period, the DS experienced a rapid and severe decline in surface area and shrank from 952.1 km² in 1970 to 680.861100 km² in 1985, resulting in a total shrinkage of 271.2 km², equivalent to 28.49% of the initial area. The average annual decline was approximately 18.08 km² per year, with the most dramatic shrinkage occurring between 1975 and 1980, when the DS lost 171.057967 km² (–19.41%), representing the peak acceleration in the entire record. This rapid decline is primarily attributed to the large-scale diversion of the Jordan River and the expansion of industrial potash extraction, particularly by the Arab Potash Company, whose evaporation ponds significantly increased artificial water withdrawal. Subsequent intervals within this period

show smaller losses of 71.000563 km² (1970–1975) and 29.142227 km² (1980–1985), indicating that while the rate of shrinkage varied, the overall decline remained pronounced. Notably, by the end of the 1980s, the southern basin of the DS had completely dried out and converted in to evaporation ponds.

Second Period (1990–2025):

In this period, the DS continued to shrink, but at a slower and more stable pace, with its surface area decreased from 661.996150 km² in 1990 to 587.176407 km² in 2025, resulting in a total shrinkage of 74.819743 km², or 11.30% relative to 1990. The average annual decline was approximately 2.14 km² per year, with interval losses ranging from 16.271855 km² to 38.646678 km² and percentage reductions between 2.46% and 6.17%. Compared to the first period, the rate of shrinkage was considerably lower, reflecting a more stabilized but persistent long-term decline, with the extreme losses of the 1970s and early 1980s had slowed, ongoing water abstraction, high regional evaporation, and industrial activities continued to drive the DS’s gradual shrinkage, table(3) summarizes these characteristics.

Table (3): Temporal variation in the DS surface area and percentage change during the period (1970–2025).

Period	Area Start (km ²)	Area End (km ²)	Change (km ²)	Percentage Change (%)
1970–1975	952.061857	881.061294	–71.000563	–7.46
1975–1980	881.061294	710.003327	–171.057967	–19.41
1980–1985	710.003327	680.861100	–29.142227	–4.10
1985–1990	680.861100	661.996150	–18.864950	–2.77
1990–2000	661.996150	645.724295	–16.271855	–2.46
2000–2010	645.724295	625.823085	–19.901210	–3.08
2010–2025	625.823085	587.176407	–38.646678	–6.17

Table (4) illustrates the comparative results between the two periods.

Table (4): Comparative Analysis between the Two Periods

Indicator	1970–1985	1990–2025
Total Loss	271.20 km ²	74.82 km ²
Percentage Decline	28.49%	11.30%
Avg. Annual Loss	18.08 km ² /year	2.14 km ² /year

Peak Annual Rate	34.21 km ² /year	2.58 km ² /year
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Furthermore, Table (5) illustrates the integrated shrinkage statistics of the Dead Sea.

Table (5) Integrated Shrinkage Statistics of the DS

Indicator / Period	1970 – 1975	1975 – 1980	1980– 1985	1985– 1990	1990– 2000	2000– 2010	2010– 2025	1970– 1985 (Over all)	1990– 2025 (Over all)	1970– 2025 (Long-term)
Time span (years)	5	5	5	5	10	10	15	15	35	55
Total loss (km ²)	71.00 0563	171.0 5796 7	29.142 227	18.864 950	16.271 855	19.901 210	38.646 678	271.2 0	74.82	365.932 555
Avg. annual loss (km ² /yr)	14.20	34.21	5.83	3.77	1.63	1.99	2.58	18.08	2.14	6.65
Percentage decline (%)	7.45	19.41	3.31	2.14	1.63	1.99	2.58	28.49	11.30	—
Peak annual rate (km ² /yr)	—	34.21	—	—	—	—	2.58	34.21	2.58	34.21

As shown in tables 3-5 the Dead Sea's surface area declined most sharply between 1975 and 1980, losing 171.06 km² at 34.21 km²/year, while over the entire period 1970–2025, the average annual shrinkage slowed to 6.65 km²/year; clearly, the early period (1970–1985) experienced a much faster contraction than the later period (1990–2025), reflecting the strong impact of water diversion and industrial activities which began in 1968 in the 1970s and early 1980s, as illustrated in figures (2-3).

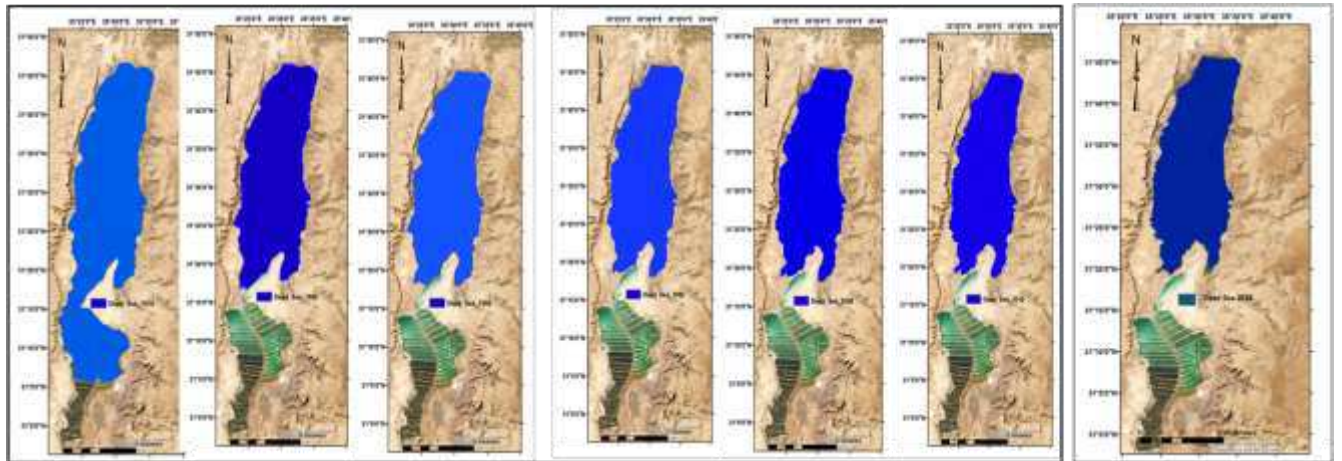


Figure (2) The Dead Sea during the period (1975-2025)

4.1.2. The spatial distribution of the newly exposed areas during (1970–2025)

Satellite image analysis of the DS surface area during the study period (1970–2025), as illustrated in the figure (4), reveals a substantial spatial contraction of the DS. The 2025 shoreline belt representing newly exposed land that was previously submerged. The total area that has retreated and become terrestrial surface reaches approximately 365.9 km², indicating a pronounced and continuous decline over 55 years.

The retreat pattern shows clear differentiation between the two basins. The southern basin completely desiccated between 1970 and 1980 and was subsequently converted into artificial evaporation ponds; this transformation was primarily driven by intensive industrial water extraction for mineral production, which diverted significant water volumes and accelerated the

The spatial distribution of exposed land highlights the long-term negative water balance caused by reduced inflow and industrial exploitation. Consequently, as a result of this hydrological imbalance, the shallow southern basin has transformed into dry land, reflecting the severe and ongoing decline in water levels. Meanwhile, the northern basin remains the only natural water body but has experienced persistent shoreline regression. The newly exposed areas appear as elongated and irregular belts along the eastern and western margins, reflecting gradual lateral retreat controlled by basin morphology and bathymetry.

Tables (5-6) indicates that the DS surface area declined continuously from 952.06 km² in 1970 to 587.2 km² in 2025, representing a total loss of approximately 364.89 km² over 55 years (about 38% of its area in 1970).

The most dramatic contraction occurred during 1975–1980, when the lake lost 171.06 km², equivalent to a 19.41% decrease, marking the most severe five-year decline in the record. The period 1970–1975 also showed substantial shrinkage (–71.00 km²; –7.46%) سبب.

After 1980, the rate of decline slowed considerably; between 1980 and 1990, losses became more moderate (–29.14 km² and –18.86 km², respectively). During 1990–2010, the retreat continued at a relatively gradual pace, with percentage declines ranging between 2.46% and 3.08% per period.

However, 2010–2025 shows a renewed acceleration, with a loss of 38.65 km² (–6.17%), indicating that although the extreme collapse of the late 1970s was not repeated, significant shrinkage persists. Overall, the data demonstrate a sharp initial contraction followed by sustained but variable long-term decline.

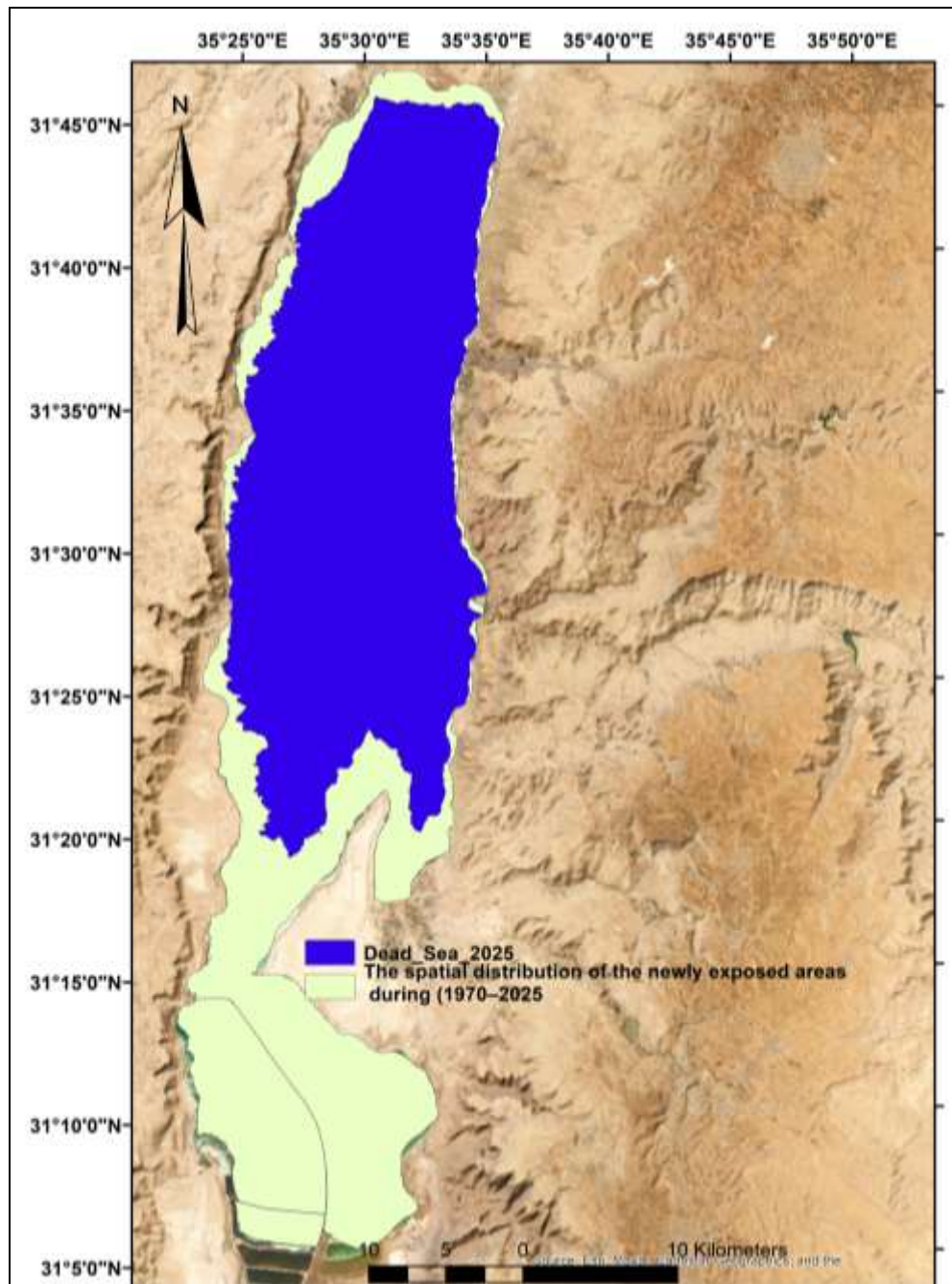


Figure (3); The spatial distribution of the newly exposed areas during (1970–2025).

The spatial analysis of the newly exposed areas along the Dead Sea shoreline during 1970–2025 indicates that approximately 365.9 km² of former lakebed has emerged as terrestrial surface due to the continuous decline in water level. These newly exposed zones have become highly susceptible to sinkhole development, which represents one of the most significant geomorphological hazards in the region. The rapid lowering of the Dead Sea level allows fresh groundwater to penetrate subsurface salt layers, accelerating their dissolution and creating underground cavities. Over time, these cavities collapse, forming sinkholes and collapse depressions that may appear suddenly and expand rapidly. Consequently,

many of the exposed coastal areas have evolved into unstable landscapes, posing increasing risks to infrastructure, agriculture, tourism, and transportation networks surrounding the Dead Sea basin.

During 1970–2025, approximately 365.9 km² of the former Dead Sea lakebed has already been exposed as the shoreline retreated. These newly emerged areas have evolved into geomorphologically unstable zones, where groundwater intrusion dissolves subsurface salt layers, creating underground cavities that may eventually collapse. One of the most dangerous consequences of the Dead Sea level decline is the development of dissolution sinkholes, which occur as salt strata are progressively dissolved. Between 1970 and 2345, the Dead Sea is projected to shrink from 952 km² to about 317.1 km², representing a total loss of 634.9 km² (66.69%) and an average decline of 1.69 km² per year. Consequently, sinkholes and collapse depressions are increasingly forming along the Dead Sea margins, transforming the exposed coastal belt into hazard-prone terrain that threatens infrastructure, tourism, agriculture, and transportation networks across the basin,((Abou Karaki, N., et al. (2017; Frumkin ,2002; Lensky et al., 2005; Gavrieli et al., 2006).

4.1.3. Forecasted Retreat and Exposure up to 2345

The analysis of historical data regarding the Dead Sea’s water levels and surface area, combined with bathymetric analysis for the period between 1980 and 2345, reveals a severe and irreversible hydrological recession (Hall, 1993; Abou Karaki et al., 2017; Talafeha, and Al-Hadidi,2008). The data indicates that the surface area is projected to shrink from 709.6 km² in the baseline year (1980) to just 317.1 km² by 2345, resulting in a 55.31% cumulative area reduction (Asmar and Ergenzinger, 2002). This contraction is accompanied by a dramatic drop in elevation, falling from -403.0 m to a catastrophic level of -637.4 m, representing a net elevation drop of 234.4 m by the end of the forecast period (Ghazawi et al., 2021). The most aggressive decline occurs in the mid-term; by 2045, the sea will have already lost nearly a quarter of its area (24.84% or 533.3 km²), a phase primarily driven by the desiccation of the shallow southern basin which transitions the lake’s morphology toward a smaller northern pool (Lensky et al., 2005). Although the rate of areal shrinkage slows after 2045, averaging approximately 0.72 km²/year, this deceleration is a function of the retreat into the steep, V-shaped northern trench rather than a reduction in volumetric loss. Consequently, as the surface footprint narrows, the remaining water body becomes increasingly deep and hypersaline, indicating persistent volumetric depletion. Bathymetric analysis highlights that while early retreat occurs in shallow zones, later centuries see the sea confined to deeper channels, exacerbating salinity and volume loss. This dual-axis decline—horizontal surface contraction combined with a vertical elevation drop reaching nearly 0.64 m per year in the final centuries—marks a profound geographic transformation. Ultimately, the 365-year projection underscores a permanent ecological crisis, as the Dead Sea transitions from a vast inland sea into a remnant hyper-saline terminal pool, severely impacting regional industrial operations, tourism, and the historical landscape, demonstrating the extreme vulnerability of terminal lake systems to sustained inflow reduction and environmental pressures. Table (6) summarizes the projected surface area and water levels of the Dead Sea during the period (1890-2345), while table (7): Projected hydrological and morphological changes of the Dead Sea during (2025–2345)

Table (6) Statistical Analysis (Values & Ratios)

Year	Surface Area (km2)	Cumulative Area Reduction (%)	Elevation (m)	Net Elevation Drop (m)
1980	709.6	<i>Baseline</i>	-403.0	0.0
1985	680.8	4.06%	-404.0	-1.0
1990	661.9	6.72%	-408.0	-5.0
2000	645.7	9.00%	-415.0	-12.0
2010	625.8	11.81%	-423.0	-20.0
2025	587.1	17.26%	-439.0	-36.0

2035	577.7	18.59%	-445.2	-42.2
2045	533.3	24.84%	-451.4	-48.4
2145	444.4	37.37%	-513.4	-110.4
2345	317.1	55.31%	-637.4	-234.4

Table (7): Projected Hydrological and Morphological Changes of the Dead Sea (2025–2345)

Feature	Short-Term (2045)		Long-Term (2345)
Primary Driver	Rapid Southern Basin Drying		Deep Northern Trench Contraction
Main threat	Sinkholes & Infrastructure Loss		Microclimate Change & Border Shift
Industrial State	High-cost Extraction		Post-Industrial Mineral Residue
Time scale / Projection period	Area change (km ²)	Water level change (m)	Hypsometric status / condition
Short-term (2025)	587.1	-439	Recession of shallow margins
Medium-term (2145)	444.4	-513.4	Shrinkage toward the deep center
Long-term (2345)	317.1	-637.4	Stabilization within the trench floor

With regards to the DS Morphological Evolution the spatial modeling for the period 1980–2345 illustrates a radical transformation in the Dead Sea basin's environment, transitioning from a "youthful" stage characterized by a broad surface area in shallow zones to a trench stabilization stage. The Hypsometric Integral (HI) indicates a shift in the basin's profile from a convex curve to a concave curve, where the remaining brine is confined within the deepest tectonic graben. By the year 2345, the sea is projected to lose approximately 46% of its 2025 surface area, with the water level dropping to an ultimate elevation of -637.4 meters, leading to a final equilibrium within the steep-walled trench floor, tables (8 -9) and figure (5).

Table (8): Projected Spatio-Temporal dynamics of Dead Sea Surface area and elevation with Associated Morphological and Hypsometric Shifts (2035–2345)

Year	Surface Area (km ²)	Elevation (m)	Hypsometric status and morphological change
2035	577.7	-445.2	Active drawdown: Continued retreat from the southern and eastern shorelines.
2045	533.3	-451.4	Transitional contraction: Accelerated loss of surface area as water moves toward steeper bathymetric walls.
2145	444.4	-513.4	Medium-term concentration: The water body shrinks toward the deep center of the northern basin.
2345	317.1	-637.4	Long-Term stabilization: The sea stabilizes within the deepest part of the trench floor.

Table (9): Multi-temporal Projections of Dead Sea surface area, Water level, and morphological Transformations during (2025–2345).

Projection Scale	Surface Area (km ²)	Water Level (m)	Hypsometric Status & Morphological Change
Short-term (2025)	587.1	-439	Recession of shallow margins: Initial retreat from low-gradient coastal shelves.
Medium-term	444.4	-513.4	Central Shrinkage: Concentration of the water body

(2145)			toward the deep bathymetric center.
Long-term (2345)	317.1	-637.4	Trench Stabilization: Final equilibrium reached within the deepest tectonic floor.

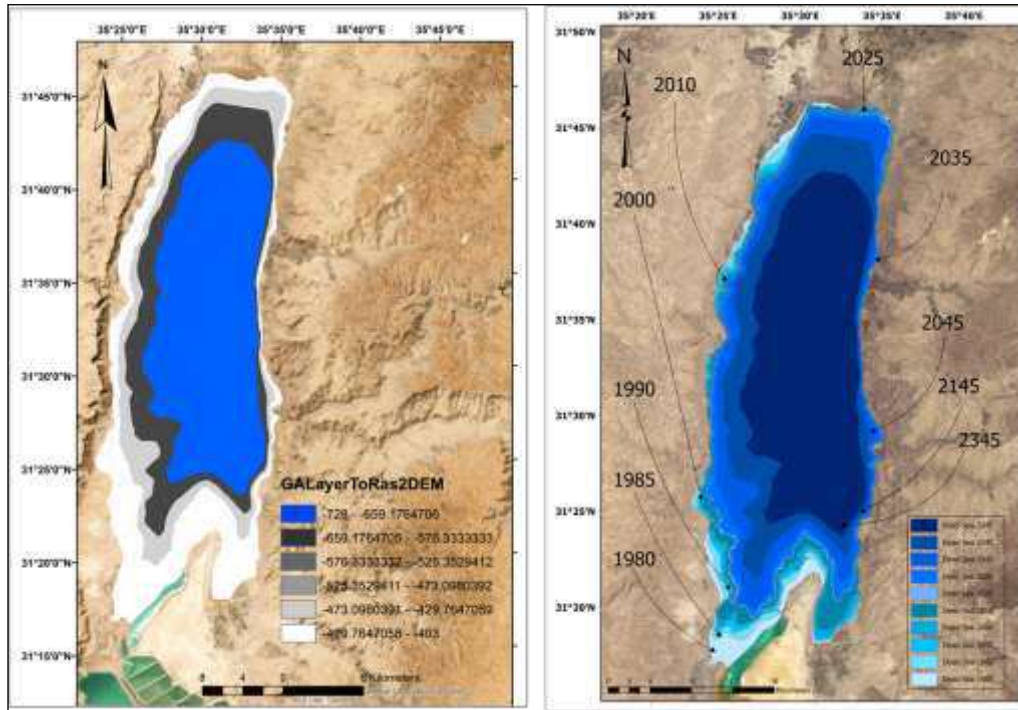


Figure (4): Spatio-Temporal Projections of Dead Sea Surface Area and Water Level with Corresponding Bathymetric Evolution (1980–2345).

4.2. Validation and evaluation model

To further verify the robustness of the model, its accuracy was assessed using field observations and ground verification surveys in addition to comparisons with historical datasets of Dead Sea water level and surface area. These field measurements, together with long-term monitoring records, provided an independent reference for evaluating the consistency and realism of the model outputs. The validation results demonstrated strong agreement between simulated and observed values. Statistical evaluation showed high predictive accuracy, with RMSE of 0.24 m, MAE of 0.18 m, and $R^2 = 0.97$ for water level estimation. For surface area simulations, the model achieved RMSE of 5.8 km², MAE of 4.1 km², and $R^2 = 0.96$, confirming its reliability for long-term forecasting.

4.3 Discussions

Satellite and historical analyses reveal a continuous decline in the Dead Sea's (DS) surface area between 1970 and 2025. The DS shrank from 952.1 km² to 587.2 km², losing about 362 km² (38%), while the water level fell from -397 m to -439 m (b.m.s.l) a drop of 42 m (0.6–0.7 m/year). Contraction accelerated after the mid-1980s, with annual losses exceeding 10–14 km² compared with <5 km²/year in

the early 1970s. Spatial analysis shows uneven shoreline retreat, strongest along the eastern and southeastern margins, where gentle slopes amplified lateral displacement. By 2025, 365.9 km² of former lakebed had been exposed, particularly in the southern basin, increasing risks to tourism infrastructure, industrial ponds, and coastal facilities.

Long-term modeling (1980–2345) projects a 55.31% reduction in surface area from 709.6 km² to 317.1 km², with water levels declining 234.4 m to –637.4 m. Rapid recession until 2045 (24.84% area loss) is followed by slower contraction (0.72 km²/year) as the lake retreats into the deep northern trench, approaching a hypersaline terminal equilibrium.

5. Conclusion

Between 1970 and 2025, the Dead Sea lost 364.9 km² (38.33%) of its surface area due to river diversion and industrial extraction. Long-term modeling (1980–2345) projects an irreversible hydrological decline, with a 55.31% total area reduction and a 234.4 m water-level drop to –637.4 m. The basin is shifting from a youthful stage of rapid shoreline retreat to a trench stabilization phase within the deep northern graben. By 2045, nearly 25% of the area will be lost; afterward, contraction slows to ≈ 0.72 km²/year due to steep bathymetry rather than hydrological recovery. Ultimately, the Dead Sea will stabilize as a hypersaline terminal pool, marking a permanent geomorphologic transformation with major environmental and infrastructure risks.

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