geosciences

MDPI

Review

Remote Sensing and Geophysical Applications in the Dead Sea Region: Insights, Trends, and Advances

Damien Closson [1,*] and Al-Halbouni Djamil [2]

[1] Ministry of Defens, Quartier Reine Elisabeth, Everestraat 1, B-1140 Evere, Belgium
[2] Institute for Earth System Science and Remote Sensing, University of Leipzig, Talstr. 35, Room 0-11, 04103 Leipzig, Germany; dhalbouni@uni-leipzig.de
* Correspondence: damien.closson@yahoo.fr

Abstract: The Dead Sea ecosystem, with its hypersaline conditions, base-level fluctuations, and active tectonics, presents a unique challenge for geological studies. Its equilibrium is increasingly unbalanced due to overexploitation of water and mineral resources. Remote sensing, including drone-based photogrammetry and satellite imaging, monitors large-scale surface changes, while geophysical methods like electromagnetic and seismic surveys reveal subsurface structures. The integration of these methods has transformed our understanding. Combined studies now monitor hazards such as sinkholes, subsidence, and landslides with greater precision. Advances in artificial intelligence further enhance analysis by processing vast datasets to uncover previously undetectable trends. This synergy between remote sensing, geophysics, and AI offers efficient solutions for studying the disrupted ecosystem. Critical challenges include environmental degradation, rapid water loss, and sinkhole formation, threatening infrastructure, industries, and habitats. Remote sensing has been pivotal in monitoring and mitigating these hazards. Together with geophysics, it provides a robust framework for addressing these extreme conditions. By combining these methods, researchers gain valuable insights into the unique dynamics of the Dead Sea ecosystem, advancing scientific knowledge and supporting sustainable management strategies.

Keywords: Dead Sea; ecosystem; remote sensing; geophysics; AI; sinkholes; subsidence; landslides; flash floods

check for updates

Academic Editor: Yi Wang

Received: 18 December 2024
Revised: 20 January 2025
Accepted: 26 January 2025
Published: 2 February 2025

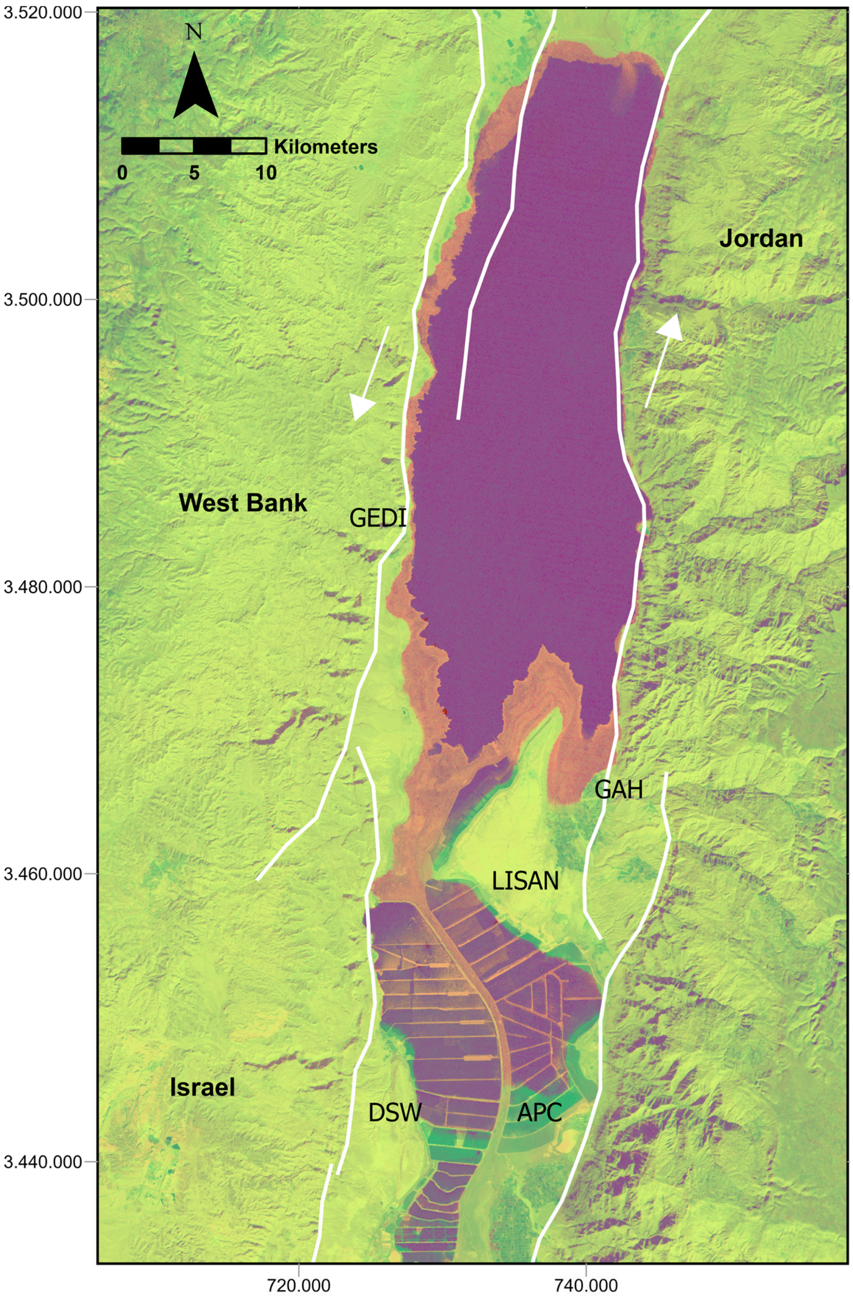
Citation: Closson, D.; Djamil, A.-H. Remote Sensing and Geophysical Applications in the Dead Sea Region: Insights, Trends, and Advances. *Geosciences* **2025**, *15*, 50. https://doi.org/10.3390/geosciences15020050

1. Introduction

The Dead Sea, Earth's lowest continental point, stood at −439.7 m below sea level on 30 December 2024 (data.gov.il). This endorheic basin, bordered by Israel, Jordan, and the West Bank, exhibits unique hydrological and geological dynamics, primarily due to its lack of a natural outlet and persistent water-level regression since the 1960s (Figure 1a,b). Currently, its water level declines at a rate exceeding one meter per year, driven by a combination of high evaporation rates in a hyper-arid environment and the diversion of nearly all inflows, including those from the Jordan River.

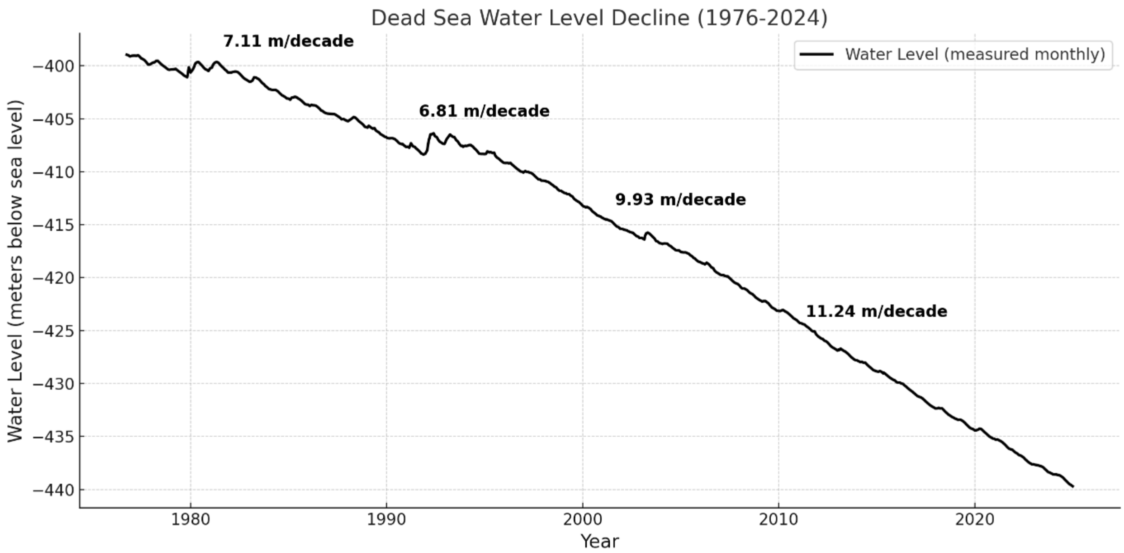
The progressive decline in base level induces profound impacts on the basin's geomorphology and subsurface stability. Lowering water levels alter regional hydrogeological gradients, intensify salinity differentials, and exacerbate evaporite dissolution, notably in halite-rich strata. These processes promote extensive karstification and subsurface void development, leading to differential subsidence and the catastrophic formation of sinkholes. Concurrently, regressive erosion along tributary channels destabilizes slopes, increasing susceptibility to mass-wasting phenomena such as rotational slides, translational slides, and debris flows, particularly in proximity to anthropogenic infrastructure [1,2].

In addition to sinkhole collapse, differential settlement, and slope failures, flash floods constitute an escalating geomorphic and geotechnical hazard in the basin. The pronounced lowering of the base level has induced longitudinal profile entrenchment in fluvial systems, enhancing hydraulic gradients and incision rates. This process generates over-steepened channel walls and promotes slope undercutting, which, in turn, compromises slope stability. The resulting retrogressive erosion and slope failures undermine structural foundations, particularly those of bridges and retaining structures, leading to severe geotechnical instability. Furthermore, short-duration, high-intensity pluvial events characteristic of the hyper-arid climate exacerbate peak discharge magnitudes, transforming ephemeral channels into destructive torrents. These events accelerate bedrock incision, sediment transport, and infrastructure degradation, further amplifying the geomorphic response to base-level changes.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. (**a**) Evolution of the Dead Sea Landscape (from 15 September 1972 to 10 January 2025). Over 53 years, the Dead Sea's base level dropped ~45 m (15-story building), exposing coastal zones, particularly around the Lisan Peninsula. The orange areas, including Ghor Al Haditha (GAH) and Ein Gedi, are impacted by thousands of sinkholes, widespread subsidence, and landslides. The basin, controlled by N24E left-lateral strike-slip faults, experiences rapid geomorphic changes. The southern lake now hosts salt evaporation ponds operated by the Dead Sea Works (DSW) and the Arab Potash Company (APC). Projection UTM 36/WGS84. Source: USGS, Landsat Imagery. (**b**) Dead Sea Water Level Decline (1976–2024), with Average Decadal Decrease. The steady acceleration of the water level decline is evident, with an expected average decrease for 2020–2030 projected at 12.45 m/decade. The temporary slowing observed in the 1990s resulted from increased flooding triggered by the climatic impacts of the 1991 Mount Pinatubo eruption. It injected massive amounts of sulfur dioxide into the stratosphere, forming aerosols that temporarily cooled the Earth's surface. This cooling disrupted global weather patterns, including an increase in precipitation in the Near East over several years. These anomalous rainfall events contributed to significant flooding, temporarily mitigating the rate of decline in the Dead Sea's water level. Source: data.gov.il.

The dramatic hydrological and geomorphological transformations in the Dead Sea basin, driven by anthropogenic and climatic factors, underscore the urgency of addressing the region's complex interplay of environmental, geotechnical, and socio-economic challenges.

This evolving landscape offers an unparalleled natural laboratory for the investigation of coupled geological, hydrological, geomorphological, and climatic processes. The convergence of active tectonics, rapid base-level regression, and hypersaline conditions necessitate innovative geophysical and geotechnical approaches. Recent advancements in remote sensing, including Interferometric Synthetic Aperture Radar (InSAR) and multispectral imaging, provide unprecedented spatial and temporal resolution for analyzing subsurface dynamics, geomorphic evolution, and hazard interactions. This review synthesizes current research employing advanced methodologies to elucidate the complex interdependencies among sinkhole formation, subsidence, slope instability, and fluvial hazards, including flash floods [1,2].

The research history of the Dead Sea region dates to early geological explorations in the XIX century, but systematic analyses only began in the 1960s. Landsat images acquired from 1972 onwards enabled the identification of the first correlations between shoreline retreat and sinkhole development (Figure 1). Since the 2000s, advances in remote sensing, particularly Very High-Resolution (VHR) imaging and InSAR, have revolutionized the understanding of geodynamic and hydrological processes. These studies highlighted the impact of anthropogenic factors, such as the diversion of Jordan River waters, on the natural equilibrium of the Dead Sea. Concurrently, research into sinkhole-related risks, especially their effects on industrial and tourism infrastructures, has intensified, with mitigation measures such as advanced geophysical monitoring and early warning strategies being implemented.

The environmental and geological hazards faced by the Dead Sea coastal areas since the early 1990s are linked to several controlling factors. Among these, groundwater salinity gradients, tectonic activity, and anthropogenic changes play fundamental roles in the development and intensification of risks. Groundwater salinity gradients, for instance, are a primary driver of sinkhole formation. The dissolution of salt layers and other evaporites, triggered by the infiltration of freshwater through hypersaline aquifers, creates underground voids prone to collapse. This process is accelerated by local variations in salinity, which alter the solubility of geological formations. Recent studies [2], supported by geophysical and remote sensing techniques, have demonstrated that areas where freshwater meets saline water exhibit heightened vulnerability to sinkhole formation. Continuous monitoring of these gradients is, therefore, essential for predicting high-risk zones.

Tectonic activity also contributes significantly to hazards in the region. The Dead Sea lies along the Levant Transform Fault, a major tectonic structure separating the Arabian and African plates. This ongoing tectonic activity generates geological stresses that fragment subsurface formations and exacerbate evaporite dissolution. Tectonic movements, including fault slips and localized earthquakes, can initiate or accelerate the collapse of existing cavities. Additionally, ground deformations provide valuable indicators for identifying areas under active tectonic stress. The interaction between these tectonic processes and hydrological gradients further complicates the hazard dynamics.

Human activities have amplified these risks. Since the 1930s, the extensive diversion of Jordan River water and the industrial exploitation of the Dead Sea have caused a dramatic decline in water levels, disrupting the regional hydrological balance. This decline accelerates dissolution processes and sinkhole formation. Furthermore, infrastructures such as evaporation ponds and dikes increase pressure on local hydrogeological systems. Research indicates that anthropogenic impacts are most pronounced in areas where industrial activities intersect with natural systems.

To mitigate these complex hazards, an integrated understanding of the factors driving them is essential. Multidisciplinary approaches combining remote sensing, geophysical studies, and hydrological modeling enable the identification of interactions among these factors. For example, mapping vulnerable areas using models based on salinity gradients and tectonic data provides practical tools for industrial planning and land management. The combination of groundwater salinity gradients, tectonic activity, and anthropogenic changes creates a complex backdrop for hazards. Continuous monitoring and analysis of these controlling factors are necessary to minimize environmental and socio-economic impacts.

Technological advancements in geophysics and remote sensing have played a crucial role in addressing these challenges. Geophysics integrates physical principles to investigate Earth's interior and surface processes [3]. Techniques like seismic, electric, magnetic, gravitational, and electromagnetic methods reveal geological structures and dynamic processes [4]. Seismic methods use elastic waves to image subsurface structures, aiding in earthquake studies and resource exploration [5]. Magnetic and gravitational methods detect variations in Earth's magnetic field and gravitational pull, identifying geological features [6]. Electromagnetic and electric methods assess subsurface conductivity, helping to locate groundwater and minerals [7]. These techniques collectively enhance our understanding of Earth's composition, tectonic activity, and resources [3].

Remote sensing captures data on Earth's surface without direct contact, using satellite or airborne sensors to measure electromagnetic radiation. It supports diverse fields like geology, ecology, agriculture, and urban planning [8]. The data, processed into images or maps, provide insights into surface features and environmental changes [9]. Sensors operate across wavelengths, including visible, infrared, and radar, with advanced algorithms extracting actionable information [9,10]. In geophysics, remote sensing complements subsurface methods by offering large-scale, high-resolution datasets on surface conditions, such as topography and vegetation [11,12]. While remote sensing detects surface changes, geophysical techniques probe subsurface dynamics [13]. This synergy enables holistic analyses of geological structures and natural hazards, including earthquakes and landslides [14,15]. In dynamic environments like the Dead Sea, satellite-based systems provide critical data for monitoring geological and environmental changes [16,17].

Geophysics addresses challenges in natural hazard prediction, resource exploration, environmental monitoring, and land use [5]. It locates earthquakes, identifies resources, and monitors pollution [6,7]. Technological advances in sensors, algorithms, and machine learning improve imaging and data interpretation, expanding interdisciplinary research opportunities [3]. Combining geophysics and remote sensing strengthens our ability to understand and manage Earth's dynamic systems [16–20].

2. Methods and Tools

Understanding the Dead Sea environmental dynamics requires a comprehensive variety of tools capable of monitoring both surface and subsurface processes. Remote sensing and geophysical methods are pivotal in capturing the intricate interactions between tectonic, hydrological, and geomorphological forces. Table 1 provides a critical assessment of the principal methodologies employed: satellite imagery, drone-based photogrammetry, InSAR, LiDAR, and ground-based geophysics. This table evaluates these tools in terms of their technological advancements, operational capabilities, and limitations, providing a quantitative and qualitative foundation for understanding their applicability in detecting and monitoring, e.g., subsidence, sinkholes, and shoreline retreat. The insights offered in Table 1 aim to facilitate informed decision-making for future research and hazard mitigation strategies.

Table 1. Critically assesses the strengths, challenges, quantitative limitations, and opportunities associated with key remote sensing and geophysical methods applied in the Dead Sea area [1,2,11,14]. The evaluation encompasses parameters such as spatial and temporal resolution, accuracy, operational constraints, and potential for technological integration, offering a comprehensive perspective on the capabilities and trade-offs of each methodology.

Method/Tool	Critical Assessment
Satellite Time Series Analysis	- Strengths: Offers long-term monitoring (e.g., Corona: 1960s, Sentinel-2: 2015–present) with temporal resolution of 5–16 days; spatial resolution: Sentinel-2 (10–60 m), Landsat (15–60 m). - Challenges: Insufficient spatial resolution (<10 m) for small-scale deformation or microfeatures like sinkholes; atmospheric effects reduce data quality for optical sensors. - Quantitative Limitations: Cloud cover impacts ~30% of scenes in arid regions; moderate revisit frequency delays rapid event detection. - Opportunities: Fusing Sentinel-2 with VHR imagery (<1 m) or SAR datasets could achieve resolutions ~1–5 m while preserving temporal continuity.

Table 1. *Cont.*

Method/Tool	Critical Assessment
Very High-Resolution Imagery	- Strengths: Exceptional spatial resolution (WorldView-3: 30 cm; Pleiades Neo: 30 cm) enables precise microfeature analysis (e.g., sinkholes > 50 cm). - Challenges: Temporal resolution is limited to revisit times of ~1–5 days; high cost (USD 15–25 per km^2) restricts accessibility for regional studies. - Quantitative Limitations: Radiometric precision (11 bits) may not capture subtle changes in low-contrast environments; scene size ~10–25 km^2 limits broad spatial coverage. - Opportunities: Expansion of nanosatellite constellations (PlanetScope: daily revisits at 3 m resolution) offers cost-effective, near-VHR capabilities.
Radar imagery	- Strengths: High vertical accuracy (~1 mm using Persistent Scatterer; ~5 mm with SBAS); coverage of ~100 × 100 km per scene (Sentinel-1). - Challenges: Temporal decorrelation (>50% coherence loss in vegetated areas); high computational load for phase unwrapping and time series analysis. - Quantitative Limitations: Requires > 20 Persistent Scatterers/km^2 for high accuracy; baseline constraints (150–300 m) affect spatial resolution. - Opportunities: Advanced algorithms (e.g., machine learning for coherence enhancement) could improve accuracy in decorrelated regions, extending usability in dynamic environments.
Drone-Based Photogrammetry	- Strengths: Achieves DEM resolution of 1–5 cm and orthomosaic resolution ~1 cm/pixel; rapid deployment in inaccessible areas for localized studies. - Challenges: Limited spatial coverage (~1 km^2 per flight); operational constraints include wind thresholds (<10 m/s) and flight endurance (~20–40 min). - Quantitative Limitations: Post-processing requires ~4–8 h per flight dataset; multi-drone operations needed for areas > 10 km^2 increase logistical complexity. - Opportunities: Integration with GNSS for georeferencing could reduce DEM vertical errors (~2–3 cm). Hybrid workflows with satellite data may scale up coverage effectively.
LiDAR Surveys	- Strengths: Vertical accuracy ~10 cm; point density > 20 points/m^2 for airborne systems allows detailed morphometric analyses of features like sinkholes. - Challenges: High cost (USD 500–USD 2000 per km^2); limited effectiveness in water-saturated areas due to absorption at 1064 nm wavelength. - Quantitative Limitations: Processing requires > 50 GB/km^2 of storage; data acquisition limited to ~100 km^2/day for airborne systems. - Opportunities: Miniaturization of LiDAR sensors for drones offers potential for sub-meter resolution on-demand, addressing small-scale dynamic changes.
Ground-Based Geophysical Methods	- Strengths: High-resolution subsurface imaging: seismic refraction resolves features to ~1 m vertically; ERT penetration up to ~100 m with resolution ~2–5 m; microgravity sensitivity ~10 μGal identifies voids. - Challenges: Labor-intensive; limited coverage (~few hundred meters per survey line); inversion heavily depends on starting models. - Quantitative Limitations: Data collection rates: 1–2 km/day for seismic methods; ERT data acquisition ~2–4 h per line. - Opportunities: AI-based inversion algorithms could improve resolution and reduce dependency on initial models, optimizing data collection efforts.

Table 1. *Cont.*

Method/Tool	Critical Assessment
Integrated Geophysical Methods	- Strengths: Integrated geophysical methods combine remote sensing tools like InSAR and LiDAR with ground-based techniques such as seismic refraction, ERT, and drone photography, effectively monitoring karst systems, sinkholes, and subsidence. LiDAR delivers high-resolution DSMs (10 cm accuracy), InSAR detects ground deformation with sub-millimeter precision, and ground-based methods provide detailed subsurface insights. - Challenges: Integrating diverse datasets is complex due to resolution differences and requires high computational power. Ground-based campaigns are labor-intensive, and hazardous areas may restrict access. Aligning InSAR and LiDAR data demands advanced expertise. - Limitations: InSAR struggles in vegetated or water-affected zones. LiDAR's high cost limits scalability and ground-based surveys are time-consuming, taking hours to complete. - Opportunities: Machine learning and cloud computing simplify data integration and interpretation. Drone-based photogrammetry and time-lapse cameras enable real-time hazard monitoring, enhancing early warning systems and accelerating research.
AI and Deep Learning	- Strengths: U-Net models achieve recall > 92% and F1 scores ~91% for sinkhole detection; efficient large-scale dataset processing (~10 GB/hour with modern GPUs). - Challenges: Model training requires extensive labeled datasets (~1000+ images); overfitting risks with limited data diversity. - Quantitative Limitations: Training times ~20–50 h on RTX 3090 GPUs; inference performance varies with input resolution (e.g., ~10 ms/image for 256 $\times$ 256 pixels). - Opportunities: Transfer learning across geologically similar areas could generalize model capabilities, reducing data requirements and training costs.

All these methodologies include strategies to manage data noise, decorrelation, and instabilities. In InSAR, techniques like adaptive spatial-temporal filtering and phase unwrapping mitigate atmospheric delays and scattering. InSAR phase decorrelation uses coherence enhancement algorithms and integrates high-resolution datasets to mitigate effects in rapidly changing or vegetated areas. In electro-optical satellite imagery, radiometric calibration, and atmospheric correction, such as the Dark Object Subtraction method, are used to enhance data quality, while cloud masking algorithms address visibility issues.

Drone-based photogrammetry and LiDAR minimize temporal decorrelation through localized studies, though hybrid workflows combining satellite data are often necessary for broader context.

Environmental instabilities, such as fluctuating water levels, are addressed through regular recalibration in ground-based methods like ERT and seismic surveys and by integrating real-time observations with LiDAR-derived DEMs to dynamically adjust models. Cloud-based processing and real-time data fusion can further enhance responsiveness, ensuring accurate and timely analysis for hazard mitigation and environmental monitoring.

2.1. Satellite Images Time Series Analysis

Monitoring the Dead Sea's environmental dynamics relies on employing diverse methodologies and tools, with Geographic Information Systems (GIS) serving as a cornerstone for diachronic analysis. GIS integrates multi-temporal data, enabling researchers to track surface changes over decades and analyze complex interactions between natural and anthropogenic processes.

Historical imagery from the Corona program (1960s–1970s), with resolutions of 1.8–7.5 m, offers critical benchmarks for assessing early hydrological and geological changes. GIS facilitates the alignment of these datasets with more recent sources, such as

Landsat (15–60 m resolution, operational since 1972) and Sentinel-2 (10–60 m resolution, operational since 2015). This temporal continuity allows researchers to identify trends in shoreline retreat, subsidence, and industrial impacts [21–24].

The advanced capabilities of Sentinel-2, particularly its five-day revisit cycle, enhance diachronic mapping in GIS, providing granular detail on sinkhole formation, land degradation, and landslides. Modern platforms like Google Earth and Bing Maps further complement this approach with their VHR mosaics, enabling precise tracking of urban and environmental changes [22,25].

GIS tools integrate these diverse datasets, supporting spatial analyses and visualizations that reveal long-term patterns. For example, combining Corona's historical benchmarks with Sentinel-2's frequent updates in GIS provides a comprehensive view of shoreline evolution. Such diachronic analyses are essential for understanding the drivers of environmental change, mitigating hazards, and promoting sustainable management of the Dead Sea region [25].

2.2. Very High-Resolution Imagery

VHR imagery has significantly advanced Earth observation since the early 2000s, providing unparalleled detail for monitoring small-scale surface changes. Spatial resolution has progressed from approximately 2 m with IKONOS (1999) and QuickBird (2001) to as fine as 30 centimetres with modern satellites like WorldView-3 (2014) and WorldView-4 (2016). These improvements have enhanced the ability to study dynamic geological phenomena, particularly in regions experiencing active tectonic and hydrological processes, such as the Dead Sea [24,25].

Radiometric capabilities have evolved alongside spatial resolution. Earlier systems captured imagery in four spectral bands (RGB and NIR), while modern satellites, including Pleiades-1A/1B and GeoEye-1, now offer up to eight spectral bands, incorporating additional shortwave infrared (SWIR) bands. This enables researchers to detect subtle differences in surface materials, vegetation, and water content, providing a more comprehensive understanding of environmental and geological changes [26].

These advancements are critical in the Dead Sea, where sinkholes, shoreline retreat, and surface deformations pose significant risks. VHR imagery allows precise mapping of small-scale features such as cracks and sinkholes, linking their formation to subsurface dissolution and groundwater salinity gradients. Studies using WorldView-2, Pleiades, and drone-based imagery have demonstrated the capability to identify sinkholes, analyze their spatial patterns, and assess their relationship with anthropogenic and natural processes [1,26–28].

Historical data available in Google Earth and Bing have amplified the utility of VHR imagery. These tools complement commercial satellite data by enabling near-real-time monitoring of shoreline changes, sinkhole development, and land use dynamics [21,26]. Researchers have integrated these resources to track shoreline retreat, understand industrial impacts, and support hazard mitigation efforts [21].

The combined use of data from IKONOS, QuickBird, WorldView, Pleiades, and GeoEye satellites has transformed the understanding of the Dead Sea's dynamic landscape. The high spatial and temporal resolutions achieved by these tools enable the detection of subtle surface changes, providing critical insights into environmental impacts and supporting the development of risk reduction strategies [26].

Looking forward, continued advancements in satellite technology and improved accessibility to high-resolution datasets hold promise for further enhancing these capabilities. The integration of VHR imagery with other remote sensing and geophysical methods will continue to support researchers and policymakers in addressing the environmental and geotechnical challenges of rapidly evolving regions like the Dead Sea.

2.3. Radar Interferometry

Synthetic Aperture Radar (SAR) technology has become indispensable for monitoring ground deformation and surface changes in the tectonically active Dead Sea basin. Operating independently of weather and lighting conditions, SAR provides high-resolution, all-weather imaging capabilities. Over recent decades, SAR satellite technology has advanced significantly, with spatial resolutions improving from approximately 30 m in the 1990s, as seen with the European Remote Sensing satellites ERS-1 and ERS-2, to about 25 cm in current commercial satellites constellations such as Umbra, Capella Space, and Iceye [29]. These enhancements have enabled near real-time monitoring of geological phenomena, including subsidence and sinkhole formation [30].

A key application of SAR data is InSAR, which identifies ground deformation with millimeter-level precision by analyzing radar signals captured at different times over the same area [30–34]. Advanced InSAR methodologies, including Persistent Scatterer (PS) and Small Baseline Subset (SBAS) techniques, have further enhanced the utility of SAR data. PS InSAR focuses on identifying and analyzing coherent targets, known as persistent scatterers, which remain stable over time. This method is highly effective in areas with abundant man-made structures or natural reflectors, allowing for the detection of very small deformations over long periods. SBAS InSAR involves generating interferograms from pairs of SAR images with small temporal and spatial baselines. This technique is particularly suited to areas with distributed scatterers and can effectively monitor gradual ground deformations over large zones [32–34].

In the coastal zones, retreating shoreline has led to widespread land subsidence and sinkholes. InSAR techniques provided invaluable observations [2,12,22,23]. They have been instrumental in identifying precursory subsidence preceding sinkhole collapse, contributing to early warning systems and hazard mitigation strategies [12].

2.4. Drone-Based Photogrammetry

Drone-based photogrammetry has proven to be a powerful tool for monitoring geomorphological changes, particularly in response to flood events and base-level lowering [9,26–28,35,36]. Researchers conducted photogrammetric surveys using drones, kites, and balloons to monitor the geomorphological responses of alluvial streams to flood events over several years. These surveys facilitated the generation of high-resolution Digital Elevation Models (DEMs) and orthophoto maps, enabling accurate quantification of elevation changes and detailed analysis of subsidence, sinkholes, and ground failures within stream channels [36]. These studies highlighted the critical role of peak discharge and flood timing in influencing sediment removal and channel incision in the Dead Sea's alluvial streams.

The application of drone-based photogrammetry provided detailed spatial and temporal data, which would have been challenging to obtain using traditional methods, showcasing the potential of drones in geomorphological research within extreme environments.

2.5. Lidar Surveys

Light Detection and Ranging (LiDAR) technology has been extensively utilized in studies of sinkholes for its capability to generate high-resolution three-dimensional representations of surface morphology. The pioneering airborne laser scanning survey conducted by [37] marked a significant advancement in sinkhole research, enabling precise 3D characterization of such features [38]. This technology provided a detailed understanding of the spatial distribution and morphometric attributes of sinkholes, which are critical for assessing their evolution and associated risks.

Subsequent research leveraged LiDAR data to develop high-resolution digital surface models (DSMs) of the Ze'elim alluvial fan, elucidating the relationship between sinkhole development and the drainage network. These models revealed how sinkhole clusters and alignments interact with fluvial processes [2,9].

LiDAR-derived DSMs were further utilized to analyze the temporal evolution of sinkholes. Multi-temporal datasets validated geomechanical models of sinkhole formation within karstic depressions, offering a dynamic perspective on their growth mechanisms [12].

InSAR combined with LiDAR provided complementary insights into ground deformation preceding sinkhole collapses. Integrated methods enhanced temporal resolution and spatial accuracy of subsidence monitoring [12,34].

2.6. Overview of the Ground-Based Geophysical Methods

Geophysical methods have been instrumental in understanding and mitigating sinkhole hazards. Seismic refraction, a widely used method, measures the velocity of longitudinal waves (Vp) to delineate salt layers. The distinct velocity of salt (2900–4500 m/s) compared to surrounding sediments allows accurate mapping of dissolution fronts and sinkhole-prone zones. This method has been extensively applied along the Dead Sea shores to identify salt boundaries and assess their role in sinkhole formation [39,40].

Seismic reflection provides detailed imaging of subsurface structures and faults. Studies employing both 2D and 3D seismic reflection have revealed critical insights into the interactions between faults, salt layers, and sinkholes [41]. More recently, S-wave seismic reflection has been introduced to enhance the resolution of shallow subsurface investigations, particularly in areas with complex geology [42].

Multichannel analysis of surface waves (MASW) evaluates shear wave velocities (Vs) to estimate the porosity and karstification of salt layers. This method has been effectively used to map underground voids and assess salt layer conditions at depths between 30 and 70 m [43]. Frequency-domain electromagnetic (FDEM) techniques have been used to assess subsurface conductivity and delineate variations in salinity. FDEM is particularly valuable in identifying zones of brackish and saline water, contributing to understanding aquifer aggressiveness and the processes driving sinkhole formation [44]. Transient electromagnetic (TEM) methods complement FDEM by providing resistivity contrasts to map groundwater salinity and delineate salt layer geometry. TEM has proven essential in defining brine interfaces and evaluating subsurface characteristics that influence sinkhole development [45].

Magnetic resonance sounding (MRS), also known as surface nuclear magnetic resonance (SNMR), is designed to detect water-filled voids and estimate subsurface water content and hydraulic conductivity. It has been a valuable tool for characterizing karstic cavities and assessing their role in sinkhole development [46]. Microgravity surveys detect density anomalies to identify underground voids and estimate the size of caverns, which are often precursors to sinkholes. These methods have been successfully applied in areas such as Nahal Hever South and Ghor Al-Haditha to predict sinkhole formation [47,48]. Additionally, a combination of microgravity with InSAR was employed at the Lisan Peninsula to monitor ground subsidence and identify hazardous zones linked to underground cavity formation [49].

Ground-penetrating radar (GPR) focuses on shallow subsurface investigations, detecting density deficits caused by voids or karstification and providing early warnings for potential sinkhole formation [50]. Electric resistivity tomography (ERT) maps resistivity profiles to identify anomalous zones associated with sinkholes. This method has been applied in alluvial fans and other sedimentary formations to detect structural inconsistencies contributing to sinkhole hazards [51].

2.7. Combined Geophysical Methods

Integrated approaches combining different geophysical methods have proven highly effective for understanding and mitigating sinkhole hazards. For example, the combination of TEM methods with magnetic resonance sounding (MRS) resolves interpretational ambiguities, while integrating MASW with MRS enables the assessment of in situ salt karstification by correlating shear wave velocities with hydraulic conductivity [52]. Similarly, coupling FDEM with TEM enhances the interpretation of resistivity variations, thereby improving the delineation of hazardous zones [53]. These comprehensive geophysical applications have significantly advanced insights into sinkhole mechanisms and facilitated improved hazard assessments.

Given the complexity of the Dead Sea's geological setting, the integration of multiple geophysical techniques is often indispensable for a thorough understanding of subsurface processes [23,54]. Ground-based LiDAR surveys, continuous water level monitoring, and geophysical logging have been successfully combined to investigate the formation and drainage mechanisms of submerged sinkholes along the western Dead Sea shores [13,14]. This multidisciplinary approach has elucidated the intricate links between sinkhole formation, subsurface cavity development, and the mechanical failure of overlying impermeable layers [2,16].

The integration of geophysical data with LiDAR-derived surface models and water level monitoring has provided a robust framework for understanding the dynamic processes driving sinkhole evolution [15,55]. Such studies underscore the importance of employing diverse geophysical methodologies to address the unique challenges posed by the extreme environmental and geological conditions of the Dead Sea [16,17,23]. These integrated approaches not only enhance the accuracy of subsurface interpretations but also contribute to more effective risk mitigation strategies.

2.8. Deep Learning for Sinkhole Detection

Recent advancements in Artificial Intelligence (AI) and Deep Learning (DL) have provided a new frontier for remote sensing applications, particularly in the detection of sinkholes. A study by [27] introduced a deep-learning-based automatic sinkhole recognition system, which was successfully applied to the eastern Dead Sea (Ghor Al-Haditha). Utilizing a U-Net architecture, the system was trained on high-resolution drone data and fine-tuned with satellite imagery to detect sinkholes with remarkable accuracy. This method demonstrated the ability to significantly enhance sinkhole mapping through the integration of DL [27]. The ability of AI models to process large-scale satellite data efficiently offers a promising tool for continuous monitoring and mitigation of sinkhole hazards, complementing more traditional geophysical methods such as InSAR and photogrammetry.

Technological innovation in remote sensing and geophysical tools is essential to address the complex challenges. Integrated approaches combining advancements in AI, VHR imaging, and geophysical techniques offer unprecedented insights into surface and subsurface dynamics. These efforts also provide a robust framework for developing risk mitigation strategies and sustainable management approaches.

2.9. Comparative Analysis of Geohazard Monitoring Methods

Table 2 provides a comprehensive overview to streamline the discussion strategy for each geohazard monitoring method. It systematically evaluates satellite, ground-based, and integrated techniques across five key parameters: (1) Introduction to the Method, (2) Spatial and Temporal Resolution, (3) Data Acquisition, (4) Processing Framework, and (5) Integration Opportunities. The table enhances clarity and consistency by presenting detailed quantitative insights into the strengths, limitations, and synergies of each approach.

By highlighting how these methods complement one another, Table 2 serves as a concise and informative guide for understanding their collective potential in advancing geohazard monitoring and analysis.

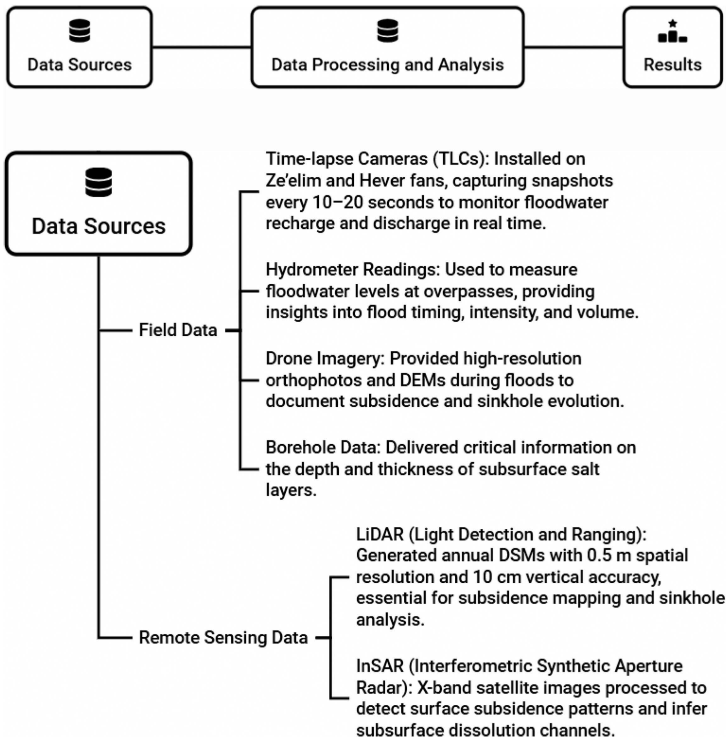
Table 2. Systematic evaluation of satellite, ground-based, and integrated geohazard monitoring techniques, providing insights into their method, spatial and temporal resolution, data acquisition, processing frameworks, integration opportunities, and specific applications. It highlights the complementary strengths of satellite-based remote sensing (e.g., SAR and VHR imaging) for large-scale monitoring, ground-based techniques (e.g., ERT and LiDAR) for detailed localized studies, and integrated approaches that combine these tools for a holistic analysis of geohazards. The methods discussed align with established research, such as studies on sinkhole formation, subsidence, and slope instability [2,12,26,27,34,38].

Parameters	Satellite	Ground-Based	Integrated Techniques
1. Introduction to the Method	Uses remote sensing technologies like SAR (sub-mm accuracy), optical imagery, and VHR imaging (30 cm resolution) for monitoring large-scale geological changes.	Employs localized techniques like ERT (depth: 100 m), seismic surveys (resolution: ~1 m), LiDAR (vertical accuracy: 10 cm), and microgravity.	Combines satellite SAR (~100 × 100 km coverage) with ground-based LiDAR (~10 cm vertical accuracy) for comprehensive geohazard monitoring.
2. Spatial and Temporal Resolution	High spatial resolution (Sentinel-2: 10–60 m; WorldView-3: 30 cm). Temporal resolution: revisit times of 5–16 days.	Centimeter-level spatial resolution but limited temporal resolution due to labor-intensive data collection.	Adaptable resolutions: satellite data for large-scale changes, ground-based methods for localized precision.
3. Data Acquisition	Freely available datasets (e.g., Sentinel, Landsat) and commercial VHR datasets (e.g., WorldView) offer global coverage with up to 30 cm spatial resolution.	Requires on-site equipment like LiDAR (point density > 20 points/m^2) and ERT (2–4 h per line), conducted by skilled operators.	Fuses datasets from SAR, LiDAR, and seismic methods, enabling multi-source geohazard analysis.
4. Processing Framework	Processes include radiometric corrections, atmospheric corrections, and SAR phase unwrapping (e.g., Sentinel-2).	Includes subsurface imaging, inversion modeling, and integration of LiDAR DEMs with geophysical survey data.	Cloud-based data fusion and real-time recalibration improve workflow efficiency and monitoring accuracy.
5. Integration Opportunities	Validates ground-based observations, integrates SAR data with LiDAR DEMs, and enhances precision in subsidence mapping.	Provides detailed subsurface data (e.g., voids detected at depths of 30–70 m) to validate satellite findings.	AI-enhanced integration of SAR and ground-based data achieves > 92% sinkhole detection accuracy.
6. Applications and Case Studies	Monitoring shoreline retreat (~1 m/year), sinkhole formation, and subsidence using SAR (15.5 mm deformation cycles) and Landsat data.	Mapping sinkholes (>30 cm diameter), assessing dike stability, and analyzing subsurface voids with ERT and seismic refraction.	Dynamic hazard monitoring: sinkhole volumes (300–4500 m^3) and subsidence rates (~45 cm/year) in the Dead Sea basin.

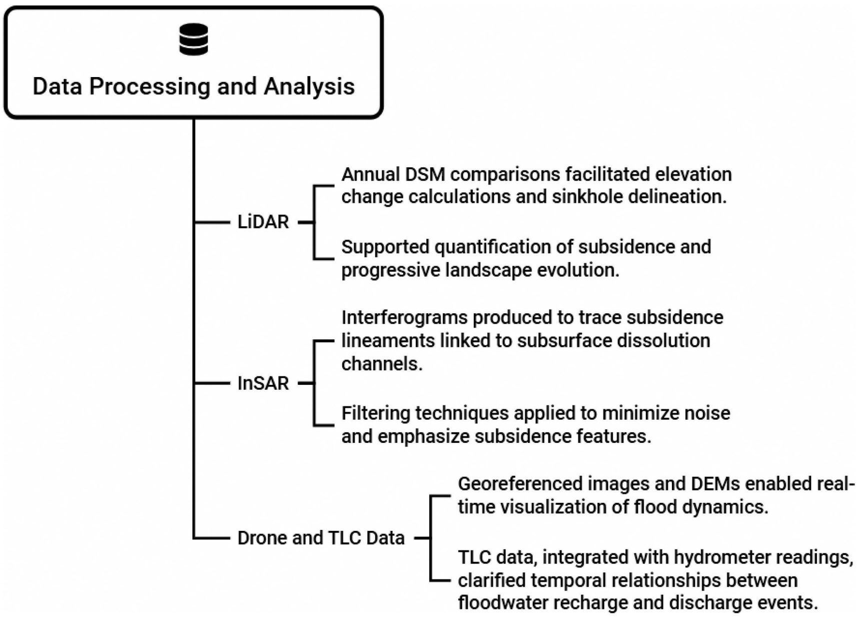
3. Applied Research

Here, we shift the focus to the practical applications and ongoing research leveraging remote sensing in the Dead Sea region. We explore how these tools are actively being used to address critical scientific, environmental, and industrial challenges, such as monitoring the Dead Sea Transform fault, detecting sinkholes, assessing shoreline changes, and mitigating risks to infrastructure and tourism. This section also highlights recent innovations, including the integration of AI and Machine Learning (ML), which enhance the efficiency and accuracy of hazard detection.

Figure 2a–c illustrates the workflow employed to study subsidence and sinkhole evolution [2]. It integrates field and remote sensing data with advanced processing techniques. Field data were collected using time-lapse cameras (TLCs) installed on alluvial fans to monitor floodwater dynamics, hydrometer readings at overpasses to track flood timing and intensity, and drone imagery to capture high-resolution orthophotos and digital elevation models (DEMs). Borehole data provided critical insights into the subsurface salt layers.

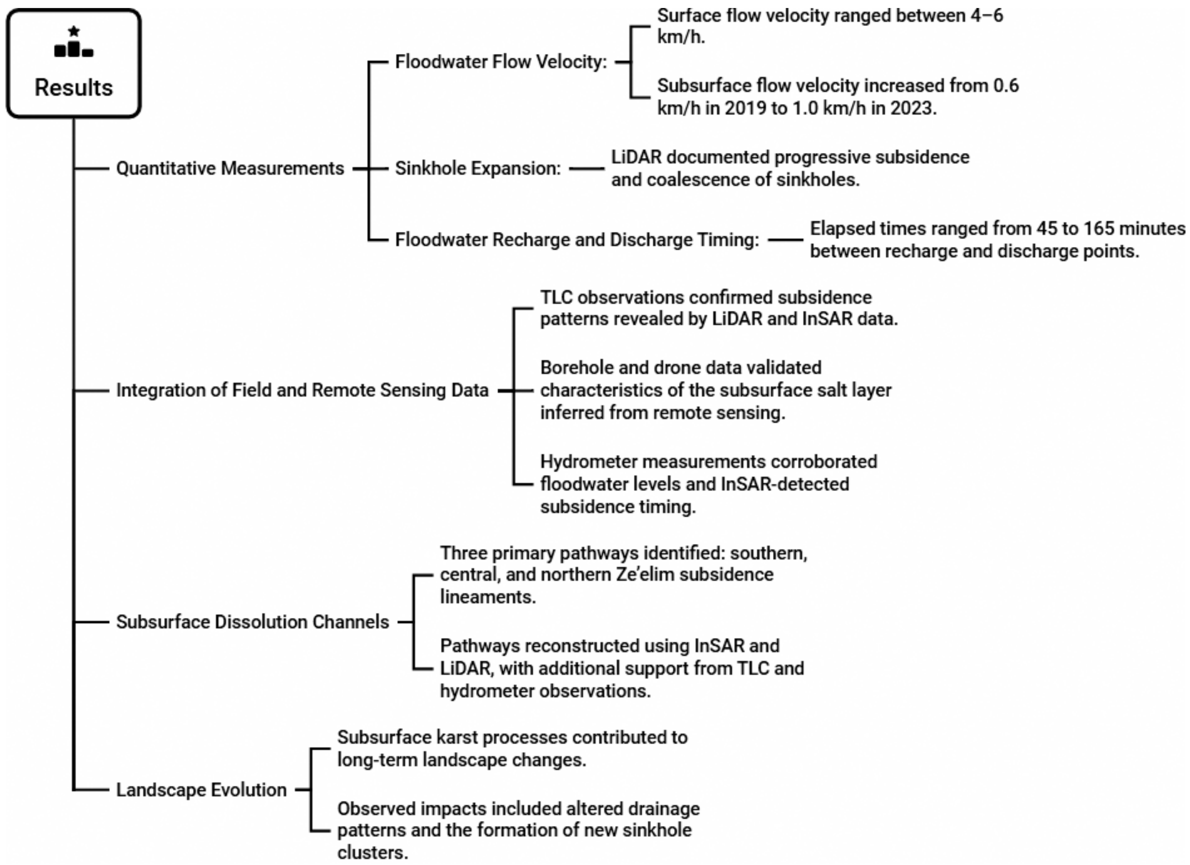


(**a**)



(**b**)

Figure 2. *Cont.*



(**c**)

Figure 2. (**a**) Workflow illustrating the integration of field data, remote sensing data, and data processing to produce actionable insights into subsidence and sinkhole evolution in the Dead Sea region. Key components include data collection from time-lapse cameras, hydrometer readings, drone imagery, and borehole studies, complemented by LiDAR and InSAR analysis. (**b**) Data processing and analysis workflow integrating LiDAR, InSAR, and drone/TLC data. LiDAR facilitated elevation change calculations and sinkhole delineation, while InSAR generated interferograms to trace subsidence lineaments associated with subsurface dissolution channels. Drone and TLC data enabled real-time visualization of flood dynamics and clarified temporal relationships between recharge and discharge events. (**c**) Results derived from the comprehensive workflow showing quantitative measurements such as floodwater flow velocities, sinkhole expansion rates, and floodwater recharge and discharge timings. The integration of field and remote sensing data reveals subsurface dissolution channels and landscape evolution patterns.

Remote sensing methods, including LiDAR and InSAR, complemented field observations. LiDAR data facilitated high-resolution subsidence mapping through annual DSM comparisons, while InSAR provided detailed interferograms to detect surface subsidence patterns and infer subsurface dissolution channels.

The integration of these datasets enabled a robust analysis of floodwater recharge and discharge dynamics, sinkhole expansion, and the progressive evolution of the landscape. This comprehensive approach underscores the interplay between subsurface processes and surface geomorphological changes, offering valuable insights into the complex karst dynamics of the region.

The Dead Sea presents significant challenges for remote sensing due to its extreme environmental conditions, including high salinity, fluctuating water levels, and active tectonics [9,19]. Despite these obstacles, advanced remote sensing technologies have offered critical insights into the geological, hydrological, and ecological processes [10,16] (Table 3).

Table 3. Summary of the methodologies, specific applications, and quantitative results from [16]. It highlights tools such as UAV photogrammetry, GIS-based analysis, and morphometric assessments, providing insights into sinkhole distribution, dynamics, and hazard implications.

Specific Examples	Method/Tool	Quantitative Results
Mapping sinkholes on the western shore of the Dead Sea from 2005–2021 using aerial photographs, satellite imagery, and high-resolution UAV photogrammetry (SfM models for 2018, 2021).	Multi-temporal cartographic sinkhole mapping using aerial/satellite images and UAV photogrammetry	702 new sinkholes identified (2005–2021). An average subsidence rate of 45 cm/year over the total area was calculated.
Measuring the 3D morphometry of sinkholes (depth, volume, and surface area).	High-resolution Digital Surface Models (DSM) derived from drone images	Median sinkhole depth: 1.5 m (2021); Maximum depth: 21.2 m; Maximum volume: 228,343 m^3. Total volume of sinkholes in 2021: 329,148 m^3.
Identifying clusters of sinkholes and their spatial distribution in the study area.	Kernel density analysis using GIS tools	Density of 191 sinkholes/km^2 for the entire area, rising to 488 sinkholes/km^2 within a smaller, denser zone.
Identifying densely packed sinkhole clusters and marking outliers.	DBSCAN clustering algorithm	Sinkholes are highly clustered along a narrow N-S-oriented strip; clusters are enclosed within a 1.13 km^2 area with exceptionally high densities compared to global standards.
Assessing the evolution of sinkholes, such as lateral expansion and coalescence.	Morphometric analysis (area, perimeter, circularity ratio)	Median areal growth: 1 m^2/year for single sinkholes. Areal increase of 5362 m^2/year (total area). Median deepening rate: 5.9 cm/year; fastest deepening rate: 2 m/year.
Assessing the degree of clustering and spatial randomness of sinkholes.	Nearest Neighbor Index (NNI)	Indicates clustering with values close to 0; sinkholes display highly aggregated spatial patterns.

Among the most impactful applications is the monitoring of sinkholes and surface deformations, which pose considerable risks to infrastructure, industrial activities, and human safety [21,22,26,56]. Using VHR imagery and InSAR, researchers have achieved precise detection and mapping of sinkholes. InSAR's ability to monitor ground subsidence with millimeter-level precision provides early warning data for sinkhole development (Table 4), while VHR imagery offers detailed spatial information on sinkhole locations, sizes, and growth rates, enabling effective hazard assessment and mitigation [15,55]. The integration of these techniques has significantly improved the timeliness and accuracy of sinkhole monitoring efforts [11,14].

Remote sensing has been pivotal in studying the tectonic dynamics of the Dead Sea Transform (DST) fault system, a major geological feature. InSAR has been widely applied to detect subtle ground movements over time, offering invaluable data for understanding fault slip behavior and assessing seismic hazards [16]. These insights have enhanced the understanding of active faulting and its role in triggering sinkholes and ground subsidence [13,14]. Remote sensing technologies have also documented water level and shoreline changes as the Dead Sea has experienced significant declines in water levels due to human activities and natural evaporation processes [23,57]. Multispectral and hyperspectral sensors, alongside VHR imagery, have enabled precise mapping of shoreline retreats, analyses of water composition, and assessments of the ecological impacts of these changes [26,54]. Satellite missions like Landsat and Sentinel-2 provide invaluable long-term data, aiding the understanding of these transformations and their implications for regional sustainability [10,14].

Table 4. Summary of the methodologies, specific applications, and findings from [34]. The study uses advanced geodetic techniques, including InSAR, airborne Lidar, and stress field modeling, to analyze the evolution of sinkholes and their precursors along the Dead Sea shorelines. It provides insights into subsidence patterns, cavity deflation volumes, and stress-induced sinkhole formation, contributing to hazard assessment and prevention.

Specific Example(s)	Method/Tool	Quantitative Results
Monitoring ground subsidence in Hever, Ze'elim, and En Gedi sites using COSMO-SkyMed satellites (2011–2014).	Interferometric Synthetic Aperture Radar	Ground subsidence measured at 15.5 mm per phase cycle; volumes of subsiding cavities: Hever: 300 m^3, Ze'elim: 460 m^3, En Gedi: 870 m^3.
Producing high-resolution Digital Elevation Models (DEMs) for Dead Sea sinkhole areas using laser-based terrain mapping.	Airborne Lidar	Elevation change maps revealed subsidence at 10–20 cm vertical precision and spatial resolution of 0.5 m/pixel.
Analyzing subsurface cavity roof deflation using mathematical models of sinkhole-induced surface displacement.	Elastic inverse modeling	Tensile dislocation volumes: Hever: 1580 m^3, Ze'elim: 1200 m^3 (estimated), En Gedi: 4500 m^3.
Calculating stress distributions above deflating cavities using Coulomb Failure Stress (CFF) models.	Stress field analysis	Sinkholes found to form at perimeters of subsiding areas, correlating with peak stress areas.

Remote sensing applications extend to environmental and climate studies, including the monitoring of vegetation cover, soil moisture, and land use patterns [58]. By using multispectral sensors and LiDAR, researchers have gathered critical data to address land degradation and guide sustainable resource management [2]. These efforts provide valuable insights into the region's response to climatic variability and inform long-term strategies for managing the Dead Sea basin [13,14].

The formation of sinkholes presents significant challenges to industrial operations, particularly for the Dead Sea Works (DSW, Israel) and the Arab Potash Company (APC, Jordan). These companies, which extract minerals from the Dead Sea, have faced substantial financial losses due to sinkhole-induced damage to infrastructure, such as earthen dikes containing evaporation ponds [21,59]. Dike collapses often result in flooding, disrupting operations and requiring extensive repairs [16,18]. InSAR technology plays a central role in addressing these challenges by providing continuous monitoring of ground subsidence over large areas, enabling timely interventions to prevent catastrophic failures [15,21,22,33,34]. Early detection of sinkhole precursors has minimized economic losses and ensured operational continuity [26].

Beyond industrial concerns, sinkholes also pose threats to tourism. Their sudden appearance has forced the closure of beaches and tourist sites, reducing visitor numbers and causing economic losses for local communities [22,33]. Remote sensing offers a proactive approach to mitigating these risks by delivering accurate and timely data that enhance safety measures and support local businesses. Preserving the tourism sector is vital for the economy, and these technologies play a key role in its resilience [15,16].

Integrating remote sensing and geophysical methods has transformed hazard mitigation in the region. Ground-based LiDAR surveys, combined with InSAR, provide high-resolution data for predicting sinkholes and monitoring subsidence. Drone-based photogrammetry enables detailed mapping of geomorphological changes [30,38]. The application of AI and deep learning to remote sensing data has further improved sinkhole detection and monitoring, complementing traditional methods [27]. These innovations underscore the critical role of remote sensing in mitigating hazards, supporting industrial resilience, and promoting sustainable development.

Coastal zones face escalating threats from flash floods, driven by the regression of the base level and the entrenchment of longitudinal profiles [22,33], which intensify hydraulic gradients, accelerate channel incision, and destabilize adjacent slopes. These processes intensify mass-wasting phenomena, such as landslides and retrogressive erosion, which endanger natural landscapes and vital infrastructures like bridges, hotel foundations, and road networks [13,14].

Mitigating these hazards requires advanced engineering and geotechnical solutions. Key strategies include reinforcing dikes with geotextiles, employing soil consolidation through cement or bentonite injections, and utilizing embedded sensors for real-time structural monitoring. Drainage systems reduce freshwater infiltration, mitigating evaporite dissolution and void formation [21,23]. Remote sensing tools like InSAR enable early detection of subsidence, guiding interventions to prevent structural failures and economic losses [15]. Subsurface stabilization, including cement/clay injections and dynamic compaction, addresses sinkhole risks, while underground barriers maintain hydrogeological balance [16,26].

Modern monitoring systems, combining deformation sensors, real-time data platforms, and remote sensing technologies, provide predictive capabilities for adaptive risk management. Numerical models incorporating geophysical and structural data enhance the planning and effectiveness of mitigation efforts [15,27]. Despite their complexity and cost, these solutions are essential for preserving infrastructure and minimizing geotechnical risks. Continuous integration of remote sensing technologies and digital modeling will further improve regional resilience.

A case study exemplifies these approaches. The APC operates salt ponds surrounded by dikes in a sinkhole-prone area. In one instance, an unnoticed sinkhole caused a dike breach, draining an entire basin and resulting in USD 38 million in damages. To address such risks, APC partnered with SkyGeo, Oude Delft - Dutch company, to implement InSAR monitoring, providing high-density measurements that detected displacement patterns and enabled timely interventions. These measures prevented significant damage and underscored the effectiveness of modern engineering solutions in mitigating geohazards [21,34].

By integrating remote sensing technologies with advanced geotechnical practices, the Dead Sea region has taken significant steps toward addressing its unique environmental challenges. These efforts ensure the safety and sustainability of industrial and tourism operations, preserving critical infrastructure in the face of dynamic tectonic and geomorphic pressures.

4. Challenges and Future Directions

Sinkholes, caused by natural or anthropogenic processes, require high-resolution monitoring for accurate characterization and risk assessment. Techniques like TLS and ground-based radar enable 3D mapping of sinkhole-prone areas with sub-centimeter precision, while 4D monitoring tracks temporal changes through repeated scans. Integrating subsurface imaging methods, such as GPR and ERT, creates comprehensive 3D models.

Data processing involves noise reduction, reconstruction of digital elevation models, and time series analysis to identify precursors to sinkhole formation.

Challenges include high data volumes, environmental factors, and integrating datasets from diverse sources. Future advancements in AI, sensor fusion, and edge computing will streamline data processing, improve resolution, and enable real-time hazard detection. Emerging techniques like distributed acoustic sensing and probabilistic models will further enhance capabilities.

Subsidence and landslides related to continuous base-level drop and ongoing adaptation of underground water flows pose additional challenges. These phenomena are exacerbated by fluctuating water tables, sediment redistribution, and karstification, leading to surface instability. Continuous monitoring using InSAR, combined with hydrological modeling, is essential to understand these processes and their interactions with geological and human-induced activities. By identifying regions experiencing rapid changes, mitigation strategies can be designed to reduce risks.

Economic and logistical challenges, particularly in hazardous or remote areas, underscore the importance of collaborative data-sharing platforms and open-access satellite data. Policy-level engagement and international partnerships will promote the widespread adoption and integration of these advanced technologies, fostering resilience to geological and environmental changes.

Future directions involve leveraging new satellite missions, such as Sentinel-3, Sentinel-4, Landsat 9, WorldView, and Pléiades Neo, which provide higher spatial and temporal resolutions, improved data coverage, and enhanced spectral imaging. Additionally, constellations of small satellites from private companies like PlanetScope (US), Umbra (US), Capella (US), and Iceye (Finland) significantly shorten revisit periods while enabling the use of a wide range of electromagnetic waves to image the ground. These advancements are crucial for 4D monitoring, as they allow detailed tracking of surface deformation and environmental anomalies over time. Combining these datasets with methodologies like InSAR and ML facilitates a more precise analysis of geological processes, including ground subsidence and tectonic shifts. Ground-based techniques, such as LiDAR, GPR, and TLS, can complement satellite data for increased accuracy and reliability.

Advancements in remote sensing, particularly InSAR and machine learning, offer promising solutions for sinkhole detection and hazard assessment. Among these, the Sinkhole Scanner [60] stands out for its ability to identify sinkhole-related spatiotemporal deformation patterns in InSAR time series data. Using a mathematical framework such as an inverted Gaussian function applied within a moving window, it calculates posterior variances to pinpoint subsiding zones indicative of sinkhole activity. The Scanner has proven effective across varying spatial scales, including Sentinel-1 imagery over Ireland, detecting precursory deformation zones with precision and enabling early hazard warnings.

Challenges remain, including noise introduced by hyper-salinity, fluctuating water levels, and active tectonics. The Scanner's effectiveness relies on high CCS density, which may be limited in rural or unstable areas. Additionally, the temporal resolution of available satellite datasets can constrain the capture of rapid deformation processes. Addressing these limitations, integrating the Scanner with advanced ML frameworks like LSTMs and CNNs [27] enhances its scalability and precision. Complementary approaches, such as Multiple Hypothesis Testing (MHT), can further refine anomaly detection in deformation time series.

AI, encompassing ML, enables systems to autonomously analyze data and identify patterns. ML models excel in classifying images, detecting anomalies, and predicting events. For example, U-Net-based DL systems [27] have demonstrated high accuracy in sinkhole detection using high-resolution drone and satellite imagery, showcasing adaptability to varying resolutions and scalability for broader geohazard applications.

Integrating these methodologies with remote sensing advances provides a robust framework for addressing geological and environmental challenges. Combining AI, 3D/4D ground-based techniques, and new satellite missions enhances our ability to monitor, predict, and mitigate hazards, improving public safety and infrastructure resilience.

5. Conclusions

Since the 1960s, the progressive retreat of the Dead Sea has induced significant disruptions in the hydrodynamic equilibrium and geomorphology of the basin. The continuous decline in the Dead Sea's water level has resulted in a landward migration of the freshwater/saline water interface, necessitating hydrodynamic readjustment. This process drives hundreds of millions of cubic meters (Mm^3) of freshwater per meter of sea level decline to discharge from adjacent aquifers, compensating for evaporative losses and interface migration [60–66].

This intensified influx of groundwater into salt-saturated coastal deposits has triggered the dissolution of soluble evaporites and the erosion of the unconsolidated, fine-grained material. The entrenchment of wadi profiles has led to increased landslide activity, posing severe risks to infrastructure in the region. Exacerbated flash floods are causing rapid erosion and structural destabilization in areas already weakened by subsidence and slope failures.

These interrelated hydrological, geomorphological, and geotechnical processes have profound implications for environmental stability and infrastructure resilience. These dynamics serve as the foundational context for modern research integrating advanced geophysical methods and remote sensing technologies. These studies aim to predict and mitigate geohazards associated with the Dead Sea's retreat, providing critical insights into subsurface instability, structural deformation, and the broader impacts on civil and environmental engineering challenges.

The evolution of remote sensing and geophysical methodologies reflects significant advances in understanding the geological and hydrological dynamics of the Dead Sea basin. Corona satellite imagery, acquired in the 1960s but made accessible only after declassification in the 2000s, played a pioneering role in tracing early morphological changes, such as shoreline retreat and alterations in river channels, providing essential historical benchmarks. The integration of these data with more recent satellite missions, including Landsat, Sentinel-2, and VHR imagery, has expanded the temporal and spatial scope of analyses.

Simultaneously, geophysical techniques have undergone a remarkable evolution. Initially focused on seismic refraction and electrical resistivity surveys, these methods enabled the mapping of evaporitic layers and the identification of subsurface weaknesses. The development of advanced tools, such as seismic tomography, electromagnetic surveys, and magnetotelluric analyses, now facilitates the detection of forming cavities, the assessment of sinkhole risks, and the modeling of underlying processes with unprecedented precision.

The advances in remote sensing, particularly the advent of SAR and InSAR, have revolutionized ground deformation monitoring. InSAR provides millimeter-level precision, allowing the detection of sinkhole precursors, subsidence, and tectonic movements with exceptional granularity. Techniques like Persistent Scatterer and Small Baseline Subset, which leverage temporal series of SAR data, have further enhanced this capability by identifying subtle surface deformations.

These remote sensing tools are now systematically coupled with geophysical approaches to validate and refine observations. For instance, InSAR data on subsidence are cross-referenced with geophysical surveys to quantify dissolution processes and better understand the interactions between groundwater flow, evaporitic deposits, and active fault systems.

Recent research has led to the development of integrated tools such as the Sinkhole Scanner, which combines remote sensing data with advanced mathematical models. This tool identifies spatiotemporal deformation patterns indicative of sinkhole formation, setting a benchmark for early warning systems. Supported by geophysical surveys, the Sinkhole Scanner offers promising prospects for mitigating risks related to industrial operations, tourism infrastructure, and environmental management.

The integration of artificial intelligence (AI) and machine learning (ML) into remote sensing and geophysical workflows marks a promising next step. Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) models could enhance the precision and efficiency of analyses. Additionally, the development of drone-based geophysical technologies, such as 3D tomography and airborne electromagnetic surveys, will enable finer-scale monitoring of high-risk zones.

To further advance this field, we recommend the following actionable steps:

- Advancing Remote Sensing Integration: Future research should focus on combining AI algorithms with SAR data from emerging satellite missions like Sentinel-3 to enhance monitoring capabilities.
- Establishing Data-Sharing Platforms: We advocate for the development of international data-sharing platforms to facilitate real-time hazard monitoring and collaborative research efforts, improving regional preparedness and response strategies.
- Enhancing Policy Engagement: Policymakers should integrate these technological advancements into hazard mitigation strategies, prioritizing investment in remote sensing infrastructure and training programs. By fostering collaboration between scientists and decision-makers, the resilience of communities can be significantly strengthened.
- Promoting Sustainable Management Practices: It is essential to align research findings with sustainable management policies, emphasizing the mitigation of industrial and environmental impacts while preserving the natural heritage. Recent developments highlight a shift in regional water management strategies following the discontinuation of the Red Sea–Dead Sea Water Conveyance Project in June 2021. The project's abandonment underscored the complex geopolitical and logistical challenges in addressing the Dead Sea's retreat. In its place, alternative initiatives like Jordan's Aqaba-Amman Water Desalination and Conveyance Project have gained prominence. This project aims to produce 250 million cubic meters of potable water annually through desalination and distribute it via a 450-km pipeline to Amman and surrounding areas, addressing a significant portion of Jordan's water needs by 2027. Similarly, Israel has prioritized expanding its desalination infrastructure and fostering collaborative efforts to manage shared water resources. These localized and technologically advanced approaches underscore the necessity of adaptive and cooperative solutions to address the region's water scarcity and environmental challenges while ensuring the sustainable management of the Dead Sea's unique ecosystem.
- Incorporating Regional Geological Insights: Leverage the findings from detailed stratigraphic and geophysical studies [67,68] to refine hazard models and resource management strategies. Understanding tectonic subsidence rates and sedimentary cycles can greatly enhance predictive capabilities.

The historical progression from Corona imagery to state-of-the-art machine learning applications underscores the transformative impact of remote sensing on Dead Sea research. By building on this legacy and implementing these recommendations, future efforts can address emerging challenges, improve hazard resilience, and contribute to the sustainable management of this uniquely dynamic environment.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Al-Halbouni, D.; Watson, R.A.; Holohan, E.P.; Meyer, R.; Polom, U.; Santos, F.M.; Comas, X.; Alrshdan, H.; Krawczyk, C.M.; Dahm, T. Dynamics of Hydrological and Geomorphological Processes in Evaporite Karst at the Eastern Dead Sea—A Multidisciplinary Study. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 3351–3395. [CrossRef]
2. Baer, G.; Gavrieli, I.; Swaed, I.; Nof, R.N. Remote Sensing of Floodwater-Induced Subsurface Halite Dissolution in a Salt Karst System. *Remote Sens.* **2024**, *16*, 3294. [CrossRef]
3. Lowrie, W.; Fichtner, A. *Fundamentals of Geophysics*, 3rd ed.; Cambridge University Press: Cambridge, UK, 2020.
4. Telford, W.M.; Geldart, L.P.; Sheriff, R.E. *Applied Geophysics*; Cambridge University Press: Cambridge, UK, 1990.
5. Reynolds, J.M. *An Introduction to Applied and Environmental Geophysics*; Wiley-Blackwell: Hoboken, NJ, USA, 2011.
6. Sharma, P.V. *Environmental and Engineering Geophysics*; Cambridge University Press: Cambridge, UK, 1997.
7. Kearey, P.; Brooks, M.; Hill, I. *An Introduction to Geophysical Exploration*; Wiley-Blackwell: Hoboken, NJ, USA, 2002.
8. Lillesand, T.M.; Kiefer, R.W.; Chipman, J.W. *Remote Sensing and Image Interpretation*, 7th ed.; Wiley: Hoboken, NJ, USA, 2015.
9. Al-Halbouni, D.; Holohan, E.P.; Taheri, A.; Watson, R.A.; Polom, U.; Schöpfer, M.P.J.; Emam, S.; Dahm, T. Distinct Element Geomechanical Modelling of the Formation of Sinkhole Clusters within Large-Scale Karstic Depressions. *Solid Earth* **2019**, *10*, 1219–1241. [CrossRef]
10. Mallast, U.; Siebert, C. Combining Continuous Spatial and Temporal Scales for SGD Investigations Using UAV-Based Thermal Infrared Measurements. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 1375–1392. [CrossRef]
11. Polom, U.; Alrshdan, H.; Al-Halbouni, D.; Dahm, T.; Sawarieh, A.; Atallah, M.Y.; Krawczyk, C.M. Shear Wave Reflection Seismics Yields Subsurface Dissolution and Subrosion Patterns: Application to the Ghor Al-Haditha Sinkhole Site, Dead Sea, Jordan. *Solid Earth* **2018**, *9*, 1079–1098. [CrossRef]
12. Nof, R.N.; Abelson, M.; Raz, E.; Magen, Y.; Atzori, S.; Salvi, S.; Baer, G. SAR Interferometry for Sinkhole Early Warning and Susceptibility Assessment along the Dead Sea, Israel. *Remote Sens.* **2019**, *11*, 89. [CrossRef]
13. Lazar, M.; Siebert, C. Out of Sight, Out of Mind. Submarine Springs in the Dead Sea—An Underappreciated Phenomenon. *Geomorphology* **2023**, *436*, 108777. [CrossRef]
14. Shalev, E.; Wetzler, N.; Shatanawi, A.; Rödiger, T.; Kurzon, I.; Lyakhovsky, V.; Salameh, E.; Siebert, C. Induced Seismicity by Groundwater Extraction at the Dead Sea Fault, Jordan. *J. Geophys. Res. Solid Earth* **2023**, *128*, e2022JB025044. [CrossRef]
15. Munwes, Y.Y.; Geyer, S.; Katoshevski, D.; Ionescu, D.; Licha, T.; Lott, C.; Laronne, J.B.; Siebert, C. Discharge Estimation of Submarine Springs in the Dead Sea Based on Velocity or Density Measurements in Proximity to the Water Surface. *Hydrol. Process.* **2020**, *34*, 455–472. [CrossRef]
16. Sevil, J.; Gutiérrez, F. Temporal Variability of Sinkhole Hazard Illustrated in the Western Shore of the Dead Sea. *Nat. Hazards* **2024**, *120*, 12663–12677. [CrossRef]
17. Mallast, U.; Gloaguen, R.; Geyer, S.; Rödiger, T.; Siebert, C. Airborne Thermal Data Identifies Groundwater Discharge at the North-Western Coast of the Dead Sea. *Remote Sens.* **2013**, *5*, 6361–6381. [CrossRef]
18. Schulz, S.; Siebert, C.; Rödiger, T.; Al-Raggad, M.; Merz, R. Application of the Water Balance Model J2000 to Estimate Groundwater Recharge in a Semi-Arid Environment—A Case Study in the Zarqa River Catchment, NW-Jordan. *Environ. Earth Sci.* **2013**, *69*, 605–615. [CrossRef]
19. Vey, S.; Al-Halbouni, D.; Haghshenas, M.; Alshawaf, F.; Vüllers, J.; Güntner, A.; Dick, G.; Ramatschi, M.; Teatini, P.; Wickert, J.; et al. Delayed Subsidence of the Dead Sea Shore Due to Hydro-Meteorological Changes. *Sci. Rep.* **2021**, *11*, 13518. [CrossRef] [PubMed]
20. Romanov, D.; Kaufmann, G.; Al-Halbouni, D. Basic Processes and Factors Determining the Evolution of Collapse Sinkholes—A Sensitivity Study. *Eng. Geol.* **2020**, *270*, 105589. [CrossRef]
21. Abou Karaki, N.; Fiaschi, S.; Closson, D. Sustainable Development and Anthropogenic Induced Geomorphic Hazards in Subsiding Areas. *Earth Surf. Process. Landf.* **2016**, *41*, 1191–1208. [CrossRef]
22. Abou Karaki, N.; Fiaschi, S.; Paenen, K.; Al-Awabdeh, M.; Closson, D. Exposure of Tourism Development to Salt Karst Hazards along the Jordanian Dead Sea Shore. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 2111–2127. [CrossRef]
23. Closson, D.; Patil, A.; Musthafa, M.; Das, N. Impact of Dead Sea Halo-Karst Development on an Earthen Dike Rehabilitation Project. *Geosciences* **2023**, *13*, 42. [CrossRef]

24. El-Hallaq, M.A.; Habboub, M.O. Using GIS for Time Series Analysis of the Dead Sea from Remotely Sensing Data. *Open J. Civ. Eng.* **2014**, *4*, 386–396. [CrossRef]
25. Closson, D.; Karaki, N.A. Salt Karst and Tectonics: Sinkholes Development along Tension Cracks between Parallel Strike-Slip Faults, Dead Sea, Jordan. *Earth Surf. Process. Landf.* **2009**, *34*, 1408–1421. [CrossRef]
26. Watson, R.A.; Holohan, E.P.; Al-Halbouni, D.; Saberi, L.; Sawarieh, A.; Closson, D.; Alrshdan, H.; Abou Karaki, N.; Siebert, C.; Walter, T.R.; et al. Sinkholes and Uvalas in Evaporite Karst: Spatio-Temporal Development with Links to Base-Level Fall on the Eastern Shore of the Dead Sea. *Solid Earth* **2019**, *10*, 1451–1468. [CrossRef]
27. Alrabayah, O.; Caus, D.; Watson, R.A.; Schulten, H.Z.; Weigel, T.; Rüpke, L.; Al-Halbouni, D. Deep-Learning-Based Automatic Sinkhole Recognition: Application to the Eastern Dead Sea. *Remote Sens.* **2024**, *16*, 2264. [CrossRef]
28. Al-Halbouni, D.; Holohan, E.P.; Saberi, L.; Alrshdan, H.; Sawarieh, A.; Closson, D.; Walter, T.; Dahm, T. Sinkholes, Subrosion and Subsidence Revealed by a Close-Range Photogrammetry Survey. *Geomorphology* **2017**, *285*, 305–324. [CrossRef]
29. Parra Garcia, L.; Furano, G.; Ghiglione, M.; Zancan, V.; Imbembo, E.; Ilioudis, C.; Clemente, C.; Trucco, P. Advancements in On-Board Processing of Synthetic Aperture Radar (SAR) Data: Enhancing Efficiency and Real-Time Capabilities. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2024**, *17*, 16625–16645. [CrossRef]
30. Baer, G.; Schattner, U.; Wachs, D.; Sandwell, D.; Wdowinski, S.; Frydman, S. The Lowest Place on Earth Is Subsiding—An InSAR Perspective. *Geol. Soc. Am. Bull.* **2002**, *114*, 12–23. [CrossRef]
31. Abelson, M.; Yechieli, Y.; Crouvi, O.; Baer, G.; Wachs, D.; Bein, A.; Shtivelman, V. Evolution of the Dead Sea Sinkholes. *Geol. Soc. Am. Spec. Pap.* **2006**, *401*, 241–253. [CrossRef]
32. Fiaschi, S.; Closson, D.; Abou Karaki, N.; Pasquali, P.; Riccardi, P.; Floris, M. The Complex Karst Dynamics of the Lisan Peninsula Revealed by 25 Years of DInSAR Observations, Dead Sea, Jordan. *ISPRS J. Photogramm. Remote Sens.* **2017**, *130*, 358–369. [CrossRef]
33. Fiaschi, S.; Closson, D.; Paenen, K.; Abou Karaki, N. Mapping Vulnerable Tourism Infrastructure in Karst Environment with an Integrated Remote Sensing Approach. The Dead Sea, Jordan, Case Study. In Proceedings of the IGARSS 2018—2018 IEEE International Geoscience and Remote Sensing Symposium, Valencia, Spain, 22–27 July 2018; pp. 490–493. [CrossRef]
34. Atzori, S.; Baer, G.; Antonioli, A.; Salvi, S. InSAR-Based Modeling and Analysis of Sinkholes along the Dead Sea Coastline. *Geophys. Res. Lett.* **2015**, *42*, 8383–8390. [CrossRef]
35. Al-Halbouni, D.; Holohan, E.P.; Taheri, A.; Schöpfer, M.P.J.; Emam, S.; Dahm, T. Geomechanical Modelling of Sinkhole Development Using Distinct Elements: Model Verification for a Single Void Space and Application to the Dead Sea Area. *Solid Earth* **2018**, *9*, 1341–1373. [CrossRef]
36. Ben Moshe, L.; Lensky, N.G. Geomorphological Response of Alluvial Streams to Flood Events during Base-Level Lowering: Insights from Drone-Based Photogrammetric Surveys in Dead Sea Tributaries. *Remote Sens.* **2024**, *16*, 1346. [CrossRef]
37. Filin, S.; Avni, Y.; Marco, S.; Baruch, A. Land Degradation Monitoring Using Airborne Laser Scanning. *Int. Soc. Photogramm. Remote Sens. Arch.* **2006**, *36*, 1–6.
38. Filin, S.; Baruch, A.; Avni, Y.; Marco, S. Sinkhole Characterization in the Dead Sea Area Using Airborne Laser Scanning. *Nat. Hazards* **2011**, *58*, 1135–1154. [CrossRef]
39. Ezersky, M. The Seismic Velocities of Dead Sea Salt Applied to the Sinkhole Problem. *J. Appl. Geophys.* **2005**, *58*, 45–58. [CrossRef]
40. Ezersky, M.G.; Frumkin, A.; Al-Zoubi, A.; Abueladas, A.; Keydar, S.; Eppelbaum, L.; Akkawi, E.; Medvedev, B.; Levi, E. Geophysical Assessment of Salt Sinkhole Hazards along the Dead Sea Shore in Israel and Jordan. In Proceedings of the Near Surface 2011—17th EAGE European Meeting of Environmental and Engineering Geophysics, Leicester, UK, 12–14 September 2011; European Association of Geoscientists & Engineers: Bunnik, The Netherlands, 2011. [CrossRef]
41. Ezersky, M.G.; Keydar, S.; Al-Zoubi, A.; Medvedev, B.; Eppelbaum, L. Relations between Dead Sea Sinkholes and Faulting. In Proceedings of the Near Surface Geosciences 2012—18th European Meeting of Environmental and Engineering Geophysics, Paris, France, 3–5 September 2012. [CrossRef]
42. Ezersky, M.; Eppelbaum, L.V.; Legchenko, A. Geophysical Methods Applied to the Sinkhole Investigation at the Dead Sea Coasts. In *Applied Geophysics for Karst and Sinkhole Investigation*; IOP Publishing: Bristol, UK, 2023; pp. 4-1–4-248. [CrossRef]
43. Ezersky, M.G.; Frumkin, A. Identification of Sinkhole Origin Using Surface Geophysical Methods, Dead Sea, Israel. *Geomorphology* **2020**, *364*, 107225. [CrossRef]
44. Goldshleger, N.; Basson, U.; Fastig, S.; Azaria, I. Using Combined Close-Range Active and Passive Remote Sensing Methods to Detect Sinkholes. *J. Remote Sens. GIS* **2018**, *7*, 222. [CrossRef]
45. Ezersky, M.; Legchenko, A.; Al-Zoubi, A.; Levi, E.; Akkawi, E.; Chalikakis, K. TEM Study of the Geoelectrical Structure and Groundwater Salinity of the Nahal Hever Sinkhole Site, Dead Sea Shore, Israel. *J. Appl. Geophys.* **2011**, *75*, 99–112. [CrossRef]
46. Ezersky, M.; Legchenko, A.; Camerlynck, C.; Al-Zoubi, A.; Eppelbaum, L.; Keydar, S.; Boucher, M.; Chalikakis, K. The Dead Sea Sinkhole Hazard: New Findings Based on a Multidisciplinary Geophysical Study. *Z. Geomorphol. Suppl.* **2010**, *54*, 69–90. [CrossRef]
47. Ezersky, M.; Frumkin, A.; Yechieli, Y. Microgravity Survey and Borehole Imaging for Identifying Sinkhole Precursors in Dead Sea Area, Israel. *J. Environ. Eng. Geophys.* **2011**, *16*, 127–140. [CrossRef]

48. El-Isa, Z.; Rimawi, O.; Jarrar, G.; Abu-Karaki, N.; Taqieddin, S.; Atalah, M.; Abderahman, N.; Al-Saed, A. *Assessment of the Hazard of Subsidence and Sinkholes in Ghor Al-Haditha Area. Report Submitted to Jordan Valley Authority*; University of Jordan: Amman, Jordan, 1995; p. 141.
49. Closson, D.; Karaki, N.; Klinger, Y.; Hussein, M.; Al-Fugha, H. Subsidence and Sinkhole Hazard Assessment in the Southern Dead Sea Area, Jordan. *Pure Appl. Geophys.* **2005**, *162*, 221–248. [CrossRef]
50. Ronen, A.; Ezersky, M.; Beck, A.; Gatenio, B.; Simhayov, R.B. Use of GPR Method for Prediction of Sinkhole Formation along the Dead Sea Shores, Israel. *Geomorphology* **2019**, *328*, 28–43. [CrossRef]
51. Ezersky, M. Geoelectric Structure of the Ein Gedi Sinkhole Occurrence Site at the Dead Sea Shore in Israel. *J. Appl. Geophys.* **2008**, *64*, 56–69. [CrossRef]
52. Ezersky, M.; Legchenko, A. Quantitative Assessment of In-Situ Salt Karstification Using Shear Wave Velocity, Dead Sea. *Geomorphology* **2014**, *217*, 82–95. [CrossRef]
53. Ezersky, M. *Applied Geophysics for Karst and Sinkhole Investigation: The Dead Sea and Other Regions*, 1st ed.; IOP Publishing: Bristol, UK, 2023; pp. 1–639. [CrossRef]
54. Ionescu, D.; Siebert, C.; Polerecky, L.; Munwes, Y.Y.; Lott, C.; Häusler, S.; Bižić-Ionescu, M.; Quast, C.; Peplies, J.; Glöckner, F.O.; et al. Microbial and Chemical Characterization of Underwater Fresh Water Springs in the Dead Sea. *PLoS ONE* **2012**, *7*, e38319. [CrossRef] [PubMed]
55. Abelson, M.; Yechieli, Y.; Nof, R.; Baer, G. *Levels of Sinkhole Susceptibility Along the Western Coast of the Dead Sea*; Geological Survey of Israel: Jerusalem, Israel, 2020; Volume 37.
56. Nof, R.N.; Baer, G.; Ziv, A.; Raz, E.; Atzori, S.; Salvi, S. Sinkhole Precursors along the Dead Sea, Israel, Revealed by SAR Interferometry. *Geology* **2013**, *41*, 1019–1022. [CrossRef]
57. Baer, G.; Bernstein, M.; Yechieli, Y.; Nof, R.N.; Abelson, M.; Gavrieli, I. Elevation and Thickness of the 11–10 Kyr Old 'Sinkholes Salt' Layer in the Dead Sea: Clues to Past Limnology, Paleo-Bathymetry and Lake Levels. *J. Paleolimnol.* **2023**, *3*, 159–173. [CrossRef]
58. Oroud, I. Spatial and Temporal Surface Temperature Patterns across the Dead Sea as Investigated from Thermal Images and Thermodynamic Concepts. *Theor. Appl. Climatol.* **2020**, *142*, 747–764. [CrossRef]
59. Closson, D.; Karaki, N.A.; Hansen, H.; Derauw, D.; Barbier, C.; Ozer, A. Space-Borne Radar Interferometric Mapping of Precursory Deformations of a Dyke Collapse, Dead Sea Area, Jordan. *Int. J. Remote Sens.* **2003**, *24*, 843–849. [CrossRef]
60. Kulshrestha, A.; Chang, L.; Stein, A. Sinkhole Scanner: A New Method to Detect Sinkhole-Related Spatio-Temporal Patterns in InSAR Deformation Time Series. *Remote Sens.* **2021**, *13*, 2906. [CrossRef]
61. Salameh, E.; El-Naser, H. Does the Actual Drop in the Dead Sea Level Reflect the Development of Water Resources within Its Drainage Basin? *Acta Hydrochim. Hydrobiol.* **1999**, *27*, 5–11. [CrossRef]
62. Salameh, E.; El-Naser, H. Changes in the Dead Sea Level and Their Impact on the Surrounding Groundwater Bodies. *Acta Hydrochim. Hydrobiol.* **2000**, *28*, 24–33. [CrossRef]
63. Salameh, E.; El-Naser, H. The Interface Configuration of the Fresh-/Dead Sea Water—Theory and Measurements. *Acta Hydrochim. Hydrobiol.* **2000**, *28*, 323–328. [CrossRef]
64. Salameh, E.; El-Naser, H. Retreat of the Dead Sea and Its Effects on the Surrounding Groundwater Resources and the Stability of Its Coastal Deposits. In *Sustainable Use of Water Resources along the Lower Jordan River*; Hoetzl, H., Ed.; Springer: Berlin/Heidelberg, Germany, 2005; pp. 247–264.
65. Salameh, E.; Alraggad, M.; Amaireh, M. Degradation Processes along the New Northeastern Shores of the Dead Sea. *Environ. Earth Sci.* **2019**, *78*, 164. [CrossRef]
66. Kottmeier, C.; Agnon, A.; Al-Halbouni, D.; Alpert, P.; Corsmeier, U.; Dahm, T.; Eshel, A.; Geyer, S.; Haas, M.; Holohan, E.; et al. New Perspectives on Interdisciplinary Earth Science at the Dead Sea: The DESERVE Project. *Sci. Total Environ.* **2016**, *544*, 1045–1058. [CrossRef]
67. Charrach, J. Investigations into the Holocene Geology of the Dead Sea Basin. *Carbonates Evaporites* **2019**, *34*, 13–29. [CrossRef]
68. Charrach, J. Comments on "Internal Deformation and Uplift-Rate of Salt Walls Detected by a Displaced Dissolution Surface, Dead Sea Basin" by Zucker et al. *J. Struct. Geol.* **2020**, *140*, 104018. [CrossRef]