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Review

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

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Abstract: The Dead Sea region, characterized by its hypersaline conditions, significant base-level fluctuations, and active tectonic processes, presents a uniquely challenging environment for geological and geophysical studies. Recent advancements in remote sensing techniques have opened new avenues for exploring and understanding the complex subsurface dynamics. This review synthesizes findings from recent studies that employed diverse remote sensing methods to investigate the geomorphological, tectonic, and hydrological processes shaping the Dead Sea region. The studies underscore the effective use of drone-based photogrammetry, frequency domain electromagnetic methods, and integrated geophysical techniques, providing comprehensive insights into the subsurface geology and the mechanisms driving environmental changes. Additionally, the review discusses the challenges posed by sinkhole formation to major industrial operations in the region and how remote sensing has been pivotal in monitoring and mitigating these hazards. The successful integration of these methods demonstrates their potential in overcoming the limitations imposed by the extreme conditions of the Dead Sea, delivering valuable data for both scientific inquiry and environmental management.

Keywords: dead sea; remote sensing; geophysics; sinkholes; subsidence; landslides

1. Introduction

The Dead Sea, Earth's lowest point on continents, offers a unique setting for studying geological, hydrological, geomorphological and climatic processes. Dynamic tectonics, rapid base-level changes, and hypersaline conditions challenge conventional geophysical approaches. Advanced remote sensing technologies now allow more detailed insights into this complex region. This review highlights recent research using innovative remote sensing methods to better understand the Dead Sea's subsurface dynamics and surface changes [1,2].

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, provides 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].

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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 [17,18].

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, particularly in regions like the Dead Sea [16–20].

2. Methods and Tools

Understanding the dynamic and complex environment of the Dead Sea requires a robust set of tools capable of monitoring surface and subsurface processes. Here we introduce the key remote sensing and geophysical methods that have been employed. It focuses on the technological advancements and methodological approaches of these tools, including satellite imagery, drone-based photogrammetry, InSAR, LiDAR, and ground-based geophysics. This section lays the foundation for comprehending how these techniques enable accurate mapping, detection, and monitoring of geological and hydrological phenomena such as subsidence, sinkholes, and shoreline retreat.

2.1. Satellite Images Time Series Analysis

The Dead Sea region, characterized by rapid environmental changes, has benefited significantly from time series analysis of imagery derived from various sources. Satellite missions such as Corona, Landsat, and Sentinel-2 provide multispectral and panchromatic data, while web platforms like Google Earth and Bing Maps offer continuously updated mosaics of Very High-Resolution (VHR) images. Together, these resources enable detailed monitoring of geological, geomorphological and hydrological transformations.

Corona imagery, collected in the 1960s and early 1970s, offers historical benchmarks with resolutions ranging from 1.8 to 7.5 meters. These declassified images have been used to analyze past stream channels and their correlation with current sinkhole locations [21–23]. This historical perspective has been instrumental in linking changes in hydrology to the region’s geological instabilities.

The Landsat program has provided multispectral data since 1972, with resolutions from 15 to 60 meters and a 16-day revisit cycle. Landsat imagery has been widely used to document the retreat of the Dead Sea shoreline and monitor industrial activities such as the expansion of evaporation ponds. For example, [24] used Landsat data to quantify annual water level declines and track shoreline shifts, providing critical insights into the environmental impacts of water diversion.

Since 2015, Sentinel-2 has enhanced time series analyses with its higher spatial (10–60 meters) and temporal (five-day) resolutions. [21] utilized Sentinel-2 data to map sinkholes and landslides prone areas, identifying key drivers such as groundwater salinity gradients and declining water levels. Sentinel-2 spectral capabilities have also been employed to monitor vegetation changes and land degradation in the surrounding regions.

In addition to satellite-based data, platforms such as Google Earth and Bing Maps have played a transformative role in providing the research community with free access to high-resolution image mosaics [25]. These web applications, developed by Google and Microsoft, respectively, compile imagery from various commercial satellites and aerial surveys, offering sub-meter resolution and frequent updates since the mid-2000s. Their temporal series have been invaluable for tracking fine-scale changes in shoreline positions, sinkhole development, and urban expansion. [22,25]

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demonstrated the utility of Google Earth imagery in detecting small-scale environmental changes over time, complementing lower-resolution satellite datasets.

The integration of these datasets enables a comprehensive understanding of the Dead Sea's evolving landscape. By combining the historical context provided by Corona, the long-term monitoring capability of Landsat, the high temporal resolution of Sentinel-2, and the detailed spatial resolution offered by Google Earth and Bing Maps, researchers can effectively bridge gaps in time and scale. These tools have proven essential for documenting the interplay of natural and anthropogenic forces shaping the Dead Sea, supporting efforts to mitigate hazards and promote sustainable management.

2.2. Very High-Resolution Imagery

Since the early 2000s, VHR satellite imagery has revolutionized Earth observation, providing an unprecedented level of detail for monitoring fine-scale surface changes. Spatial resolutions have improved dramatically over the past two decades, advancing from approximately 2 meters, available with early systems such as IKONOS (1999) and QuickBird (2001), to as fine as 30 centimeters, achieved by modern satellites like WorldView-3 (2014) and WorldView-4 (2016). This progression has significantly enhanced our ability to study dynamic and small-scale geological phenomena, particularly in tectonically active regions such as the Dead Sea [24,25].

Radiometric advancements have paralleled improvements in spatial resolution. Early satellites typically captured imagery in four bands: red, green, blue (RGB), and near-infrared (NIR). However, modern VHR satellites, such as Pleiades-1A/1B (2011, 2012) and GeoEye-1 (2008), now offer up to eight spectral bands, including additional bands in the shortwave infrared (SWIR) spectrum. These additional bands enable researchers to detect subtle differences in surface materials, vegetation, and water content, providing a more comprehensive understanding of environmental and geological changes [26].

This technological evolution has proven especially valuable for accurately mapping small-scale features like cracks, sinkholes, and surface deformations. In the Dead Sea region, where active tectonic and hydrological processes are ongoing, the ability to monitor such features is critical. For instance, [1,26–28] demonstrated how high-resolution imagery from satellites such as WorldView-2 (2009) and Pleiades or from drone/kite could identify sinkholes and their spatial patterns, linking them to groundwater salinity gradients and subsurface dissolution processes [1]. Similarly, [21] used temporal series from these satellites to track shoreline retreat and its relationship with industrial activities.

The accessibility of VHR imagery has facilitated detailed geomorphological studies and near real-time environmental monitoring. Platforms like Google Earth and Bing Maps have further amplified the utility of VHR data by providing researchers with mosaics of VHR imagery at no cost, often updated regularly since the mid-2000s. These resources have enabled the tracking of sinkhole formation, shoreline changes, and land use dynamics, complementing data from commercial satellites [21,26].

The integration of data from IKONOS, QuickBird, WorldView, Pleiades, and GeoEye satellites has transformed the study of the Dead Sea's dynamic landscape. By achieving unprecedented levels of detail and accuracy, VHR imagery has become indispensable for identifying subtle surface changes, assessing environmental impacts, and supporting hazard mitigation strategies in one of the world's most geologically active regions [26]. The continued advancements in satellite technology and increased accessibility promise to further enhance these capabilities, aiding researchers and policymakers in managing the challenges posed by this rapidly evolving environment.

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 region. 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

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improving from approximately 30 meters in the 1990s, as seen with the European Remote Sensing satellites ERS-1 and ERS-2, to about 25 centimeters in current commercial satellites 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 pivotal application of SAR data is Interferometric Synthetic Aperture Radar (InSAR), which detects ground deformation with millimeter-level precision by comparing radar signals acquired 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 regions [32–34].

In the Dead Sea region, where rapid water level decline has led to widespread land subsidence and sinkhole development, these InSAR techniques are invaluable [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 in the Dead Sea region, 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 along the Dead Sea region 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].

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2.6. Overview of the Ground-Based Geophysical Methods

Geophysical methods have been instrumental in understanding and mitigating sinkhole hazards in the Dead Sea region, providing critical insights into the complex interactions between geology, hydrology, and human activities. Seismic refraction, a widely used method, measures the velocity of longitudinal waves (Vp) to delineate salt layers. The distinct velocity of salt (2,900–4,500 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, another vital technique, 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 meters [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]. This integrated approach enhanced spatial resolution and temporal monitoring, providing critical insights into sinkhole development mechanisms.

Ground-penetrating radar (GPR) focuses on shallow subsurface investigations, detecting density deficits caused by voids or karstification, 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 in the Dead Sea region. 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

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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 [2,17].

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 [17,18,23]. These integrated approaches not only enhance the accuracy of subsurface interpretations but also contribute to more effective risk mitigation strategies in this highly vulnerable region.

2.8. Deep Learning for Sinkhole Detection

Recent advancements in AI and deep learning have provided a new frontier for remote sensing applications in the Dead Sea region, 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) region. 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 deep learning, with a recall rate of 92.06% and an F1 score of 91.23% in its satellite image-based phase [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 in the Dead Sea region, 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 of the Dead Sea region. 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 in a region subject to rapid environmental changes and dynamic geological processes.

3. Applied Research

Here we shift the focus to the practical applications and ongoing research leveraging remote sensing in the Dead Sea region. We explores 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 artificial intelligence and machine learning, which enhance the efficiency and accuracy of hazard detection.

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 region's complex geological, hydrological, and ecological processes [10,17]. 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 millimetre-level precision provides early warning data for sinkhole development, 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 across the Dead Sea region [11,14].

Remote sensing has also 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 behaviour

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and assessing seismic hazards [17]. These insights have enhanced the understanding of active faulting and its role in triggering sinkholes and ground subsidence [13,14]. Additionally, remote sensing technologies have played a crucial role in documenting water level and shoreline changes, as the Dead Sea has experienced significant water level declines in recent decades due to human activities and natural evaporation processes [23,57]. Multispectral and hyperspectral sensors, alongside VHR imagery, have enabled researchers to map shoreline retreats with precision, study water composition, and assess the ecological impacts of declining water levels [26,54]. Time-series analyses from satellite missions like Landsat and Sentinel-2 have further provided invaluable long-term data for understanding these changes and their implications for regional sustainability [10,14].

Remote sensing applications extend to environmental and climate studies, where they have been instrumental in monitoring vegetation cover, soil moisture, and land use patterns [58]. Using multispectral sensors and LiDAR, researchers have gathered critical data for addressing land degradation and guiding sustainable resource management practices [2]. These studies offer valuable insights into the region's responses to climatic variability and support the development of long-term management strategies for the Dead Sea basin [13,14].

The formation of sinkholes in the Dead Sea region also presents serious challenges to industrial operations, particularly for the Dead Sea Works and the Arab Potash Company. These companies, which extract minerals from the Dead Sea, have incurred significant financial losses due to sinkhole-induced damage to infrastructure, such as earthen dikes used to contain evaporation ponds [21,59]. The collapse of these dikes often results in flooding of industrial areas, disrupting operations and necessitating substantial repair and prevention measures [16,17]. In response to these challenges, both companies have adopted extensive monitoring and mitigation strategies. InSAR technology has been central to these efforts, providing continuous monitoring of ground subsidence over large areas and delivering critical data for the maintenance and repair of dikes and other industrial infrastructure [15]. By detecting early signs of sinkhole formation, this technology has enabled timely interventions to prevent catastrophic failures [21,22,33,34].

The economic impact of sinkholes on these industries is substantial. Studies have documented several instances where sinkhole-induced dike collapses resulted in significant brine losses, disrupting mineral extraction processes and causing severe financial repercussions for the Dead Sea Works and Arab Potash Company [12,14]. These events underscore the importance of robust early warning systems informed by remote sensing data to minimise economic losses and ensure operational continuity [26]. Beyond industrial concerns, sinkholes also pose a threat to the region's tourism sector. The sudden appearance of sinkholes has forced the closure of beaches and tourist sites, leading to declines in visitor numbers and substantial economic losses for local communities [22,33]. Remote sensing technologies offer a proactive approach to mitigating these risks by providing accurate and timely data that can enhance safety measures and support local businesses. Preserving the tourism industry is vital for the region's economy, and these technologies play a key role in ensuring its resilience [15,17].

The integration of remote sensing and geophysical methods has been transformative in addressing the complex challenges posed by the Dead Sea region's dynamic environment. The combination of ground-based LiDAR surveys with InSAR has provided high-resolution data for predicting sinkholes and monitoring subsidence, while drone-based photogrammetry has enabled detailed mapping of geomorphological changes [30,38]. Moreover, the application of artificial intelligence (AI) and deep learning to remote sensing data has enhanced sinkhole detection and monitoring capabilities, demonstrating the potential for these advanced technologies to complement traditional methods [27]. These innovations highlight the critical role of remote sensing in mitigating hazards, supporting industrial resilience, and fostering sustainable development in the Dead Sea region.

4. Challenges and Future Directions

The Dead Sea region presents unique challenges for monitoring and understanding its complex geological and environmental dynamics, but advancements in remote sensing, particularly InSAR

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and machine learning, offer promising solutions. Among the methodologies addressing these challenges is the Sinkhole Scanner [60], a novel tool designed to detect sinkhole-related spatiotemporal deformation patterns in InSAR time series data. The Sinkhole Scanner models deformation patterns using a spatiotemporal mathematical framework, such as an inverted Gaussian function, applied within a moving window across a study area. By fitting this model to deformation time series from Constantly Coherent Scatterers (CCS), it calculates a posterior variance that identifies subsiding regions indicative of sinkhole activity. The Sinkhole Scanner has proven effective in detecting sinkholes at varying spatial scales, using both simulated and real datasets, such as those obtained from Sentinel-1 imagery over Ireland. It has demonstrated the ability to identify precursory deformation zones with significant precision, providing early warning for potential hazards.

Despite the promise of this methodology, several challenges remain. The region's extreme environmental conditions, including hypersalinity, fluctuating water levels, and active tectonics, introduce noise and variability that complicate data analysis. The success of the Sinkhole Scanner also depends on high CCS density, which can be limited in rural or environmentally unstable areas due to decorrelation effects. Furthermore, temporal resolution constraints in available satellite datasets pose additional barriers to accurately capturing rapid deformation processes.

Looking ahead, integrating the Sinkhole Scanner with other advanced technologies, such as machine learning frameworks like Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNNs) e.g. [61], represents a critical step forward. These models excel in classifying and detecting deformation anomalies in complex datasets, enhancing the scalability and precision of the Sinkhole Scanner. Complementary methodologies, such as Multiple Hypothesis Testing (MHT), provide additional tools for identifying temporal anomalies, such as Heaviside or Breakpoint patterns, in deformation time series. Together, these approaches offer a comprehensive strategy for sinkhole detection and hazard assessment.

To further advance these capabilities, efforts should focus on leveraging the latest advancements in remote sensing, including the launch of new satellites that provide improved data coverage, higher spatial and temporal resolutions, and enhanced spectral imaging capabilities. Sentinel-3 and Sentinel-4 missions, for instance, offer multi-spectral data and atmospheric monitoring crucial for environmental studies. Additionally, satellites like Landsat 9, with its improved radiometric resolution, and WorldView-3 and WorldView-4, renowned for their extremely high spatial resolution, provide unprecedented opportunities for detailed surface analysis. Pléiades Neo, with a resolution of 30 cm, and PlanetScope's SuperDove constellation, offering daily high-frequency revisits at up to 3-meter resolution, further push the boundaries of monitoring capabilities. These advancements enable the detection of subtle surface deformations, land cover changes, and environmental anomalies on both regional and global scales.

Integrating these high-resolution datasets with advanced methodologies, such as InSAR and machine learning frameworks, allows for more precise analysis of surface processes beyond sinkholes, including ground subsidence, tectonic shifts, and environmental changes. Complementary approaches that incorporate ground-based validation and geophysical surveys, such as LiDAR, electromagnetic techniques, and terrestrial laser scanning, will further enhance the reliability of these monitoring efforts.

Economic constraints, alongside the logistical challenges and dangers of large-scale monitoring in hazardous and remote areas, underscore the importance of collaborative data-sharing platforms and policy-level engagement. Initiatives promoting open-access satellite data, improved data integration workflows, and international partnerships will ensure that these advancements are widely adopted and effectively utilized.

The Sinkhole Scanner, with its ability to detect and model spatiotemporal deformation patterns, exemplifies the potential of innovative remote sensing methodologies. When combined with cutting-edge technologies, such as new satellite missions like Sentinel, Landsat 9, WorldView, and Pléiades Neo, alongside machine learning-based anomaly detection, researchers can address a broader range of geological and environmental challenges. This integrated and collaborative approach unlocks new

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opportunities for monitoring dynamic regions like the Dead Sea, providing a robust framework for mitigating geological hazards and enhancing resilience to environmental changes.

5. Conclusions

The evolution of remote sensing methodologies in the Dead Sea region mirrors the broader advancements in geospatial technology, from historical analyses to modern machine learning applications. Beginning in the 1960s with the pioneering use of Corona satellite imagery, researchers established a foundation for understanding the region's geomorphological and hydrological processes. These declassified images provided critical historical benchmarks, enabling comparisons with modern datasets to trace shoreline retreats, stream channel changes, and early indications of geological instability. The integration of these historical insights with subsequent satellite missions, such as Landsat, Sentinel-2, and VHR imagery, expanded the temporal and spatial scope of remote sensing, facilitating detailed studies of the Dead Sea's dynamic landscape.

As technologies advanced, the focus shifted to precision and real-time monitoring. The advent of SAR and its derivative techniques, particularly InSAR, revolutionized ground deformation studies. InSAR's millimeter-level precision allowed researchers to monitor sinkhole precursors, subsidence, and tectonic activity with unparalleled accuracy. The integration of Persistent Scatterer (PS) and Small Baseline Subset (SBAS) techniques further enhanced the ability to detect subtle surface deformations over large regions. These tools have been instrumental in understanding the link between subsurface dissolution processes and sinkhole formation, a hallmark challenge of the Dead Sea region.

The development of the Sinkhole Scanner represents a culmination of decades of research and innovation. This method, which combines InSAR time series analysis with advanced mathematical modelling, exemplifies the synergy between traditional remote sensing and cutting-edge data analysis techniques. By identifying spatiotemporal deformation patterns indicative of sinkhole development, the Sinkhole Scanner has set a new standard for hazard detection and early warning systems. Its application in both real-world and simulated datasets has demonstrated its robustness, providing actionable insights for mitigating risks associated with industrial operations, tourism, and environmental management in the Dead Sea basin.

Looking forward, the incorporation of artificial intelligence and machine learning into remote sensing workflows marks the next frontier. Convolutional Neural Networks (CNNs), Long Short-Term Memory (LSTM) models, and other deep learning frameworks promise to enhance the scalability and precision of tools like the Sinkhole Scanner. Coupled with the ongoing refinement of ground-based geophysical methods, such as LiDAR and electromagnetic surveys, these advancements will enable a more holistic understanding of the region's complex processes.

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, future efforts can address emerging challenges, improve hazard resilience, and contribute to the sustainable management of this uniquely dynamic environment.

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