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Archaeological Damage Assessment in Conflict Zones: Integrating Satellite Imagery and Ground Surveys in Daraa, Syria

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ABSTRACT

Satellite remote sensing is among the most significant modern methodologies supporting field archaeology. In addition to its efficiency in identifying archaeological sites, remote sensing offers a safe and cost-effective approach in conflict zones. However, supplementing it with field investigations enhances accuracy by confirming or correcting results. For Daraa, southern Syria, freely available high-resolution satellite imagery has been used effectively in documenting 196 archaeological sites. However, during ground-truthing of 28 sites, significant discrepancies were observed, reinforcing the notion that remote sensing and fieldwork are complementary methods, giving best results when used jointly. This integration enables precise damage assessment and helps prioritize sites for urgent protection or excavation. Our field visits identified several sites requiring urgent excavation, particularly where looting pits have exposed stratigraphy—evidence that remote sensing alone cannot verify. Finally, engaging local communities and understanding both environmental and social conditions are essential for maximizing the effectiveness of integrating remote sensing with field investigations.

1 | Introduction

In recent decades, the evaluation of the condition of archaeological sites has increasingly relied on remote sensing of satellite imagery (Izzo et al. 2021; Philip et al. 2002; Rayne et al. 2017; Rouhani and Huet 2024; Tapete and Cigna 2019; Wilkinson et al. 2006). It has emerged as a critical tool for archaeologists working in Syria since the 2011 Arab Spring and has been integrated into strategies to effectively protect cultural heritage and mitigate risks. Here, heritage sites faced widespread threats, including destruction, looting, illicit trafficking, neglect and

occupation by militias, as a result of armed conflict and the absence of state authorities. In this context, looting in particular escalated into a large-scale, systematic activity, driven both by impoverished local populations seeking survival under siege by the Assad regime and by organized criminal networks and extremist groups such as ISIS, who exploited the illicit trade to fund terrorism. Because of security concerns, which can impede on-the-ground access to sites, satellite remote sensing is particularly useful in conflict zones. Custodians of heritage may face direct threats, displacement or even death, as in the case of Khaled al-Asaad, head of antiquities in Palmyra, who was

Abbreviations: CNES, Centre National d'Études Spatiales; DGAM, Directorate-General of Antiquities and Museums; EAMENA, Endangered Archaeology of the Middle East and North Africa; GE, Google Earth.

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publicly beheaded by the Islamic State on 18 August 2015 at the age of 83. For Syria, satellite remote sensing was practically the only secure method of monitoring sites in this critical period.

Further bolstering the use of satellite remote sensing are limited funding opportunities, economic sanctions and the time commitment required to conduct field surveys across large areas. Efforts to assess the condition of Syria's cultural heritage sites continue to face these obstacles, leaving many universities and international organizations with few viable options for contributing to site protection and preservation beyond remote monitoring. Remote sensing contributes directly to the development of targeted heritage protection strategies, such as implementing regular monitoring systems, establishing buffer zones to limit human activity near vulnerable sites and prioritizing sites at the highest risk of damage (Smith et al. 2020; Jones and Brown 2019).

Since 2011, archaeological sites across Syria—both those officially registered by the Directorate-General of Antiquities and Museums (DGAM) and unregistered ones—have suffered severe damage. Satellite image assessments, in particular, have exposed looting as one of the most destructive and frequently observed threats to these sites (Cunliffe 2014; Danti et al. 2014; Danti et al. 2017; Casana 2015; Parcak et al. 2016; Tapete and Cigna 2018; Tapete and Cigna 2020; Zerbini 2018; Khalaf and Insoll 2019; Rayne et al. 2020; El-Hajj 2021; Mamo et al. 2022; Al Kassem et al. 2024). The widespread looting can be attributed to several key factors: The severe economic hardship faced by local populations, the exploitation by organized criminal networks and extremist groups and the easy accessibility of archaeological sites. These factors are all exacerbated by the absence of effective state authority and a general lack of awareness among local communities regarding the value and significance of cultural heritage.

Satellite imagery has proven to be highly effective in monitoring the condition of archaeological sites over time; however, it still encounters numerous limitations in providing a comprehensive and accurate evaluation. It often relies on freely available satellite imagery from platforms like Google Earth (GE) and other services. These platforms, however, provide infrequent updates, limiting their effectiveness for monitoring cultural heritage in contemporary conflict zones (Casana and Panahipour 2014). As Tapete and Cigna (2019) noted, while multiple images are usually available for a given site, the number and frequency of these images are highly variable from site to site. While commercial imagery can help address these gaps by offering high-resolution, frequently updated data that enables more accurate and timely monitoring of changes, its high cost can be limiting for many academic or community-based projects (Stone 2015). Despite these challenges, our choice to use freely available imagery in our study is intentional. By using free data sources, we aim to develop a monitoring approach that is accessible, affordable, easy to use and capable of being embedded within local communities for sustainable heritage protection.

Some researchers have sought to assess the severity of damage. This is particularly true for looting and has been done by measuring the looted area (e.g., Stone 2008a; Stone 2008b), or counting individual looting holes (e.g., Casana and Laugier 2017;

Parcak 2015). Despite these efforts, determining the extent of damage in satellite imagery remains a challenging task (Al Kassem et al. 2024). Other challenges are related to the terrain of the study area; for example, distinguishing looting pits in regions covered by basalt, such as southern Syria, is difficult due to the similar dark colour reflected by both the looting pits and the surrounding terrain (Al Kassem et al. 2024). Additionally, cloud cover, vegetation and human-made structures like trees or buildings can obscure important ground features. Certain types of damage may also go undetected due to their location (e.g., within modern settlements) or small size (e.g., bullet holes). Alternative data sources such as Synthetic Aperture Radar (SAR) or medium-resolution satellite imagery can help supplement these observations, as suggested by Tapete et al. (2016) and Rayne et al. (2020), but still cannot account for all damage types. Accordingly, while satellite imagery has limitations that can undermine research accuracy, its benefits remain undeniable.

Daraa province (Figure 1), in southern Syria, has been the focus of several projects documenting damage to archaeological sites during the Syrian conflict (e.g., Tapete and Cigna 2020; Casana and Panahipour 2014; Al Kassem 2016; Nasrullah and Al Doss 2016; Cunliffe et al. 2014). The most comprehensive study to date on damaged archaeological sites in Daraa province was conducted by Al Kassem et al. (2024). This study analysed available imagery on GE and covered both well-known and previously unrecorded sites, identifying 196 damaged archaeological sites on images captured between 2004 and 2022. Additionally, the study correlates political and military activities on the ground with the temporal and spatial distribution of damage. The certainty of these assessments was recorded on a scale from negligible to high, with higher quality imagery and multiple images of the damage reflecting higher certainty. An instance of damage can only be deemed 'definite' if it has been observed on the ground. This study also presented a chronological and geographical analysis of the damage and reported that looting was the most frequent type of damage associated with the Syrian conflict during the study period.

The goal of the current paper is to compare the assessments derived from satellite imagery with those recorded during on-the-ground site visits. Our study followed a phased approach shaped by the evolving security context. The first field visit took place in 2015 (Al Kassem 2016), during the height of the conflict, limiting documentation to accessible sites. In 2022, for the first time, we conducted a comprehensive study relying exclusively on satellite imagery to monitor and assess site conditions across the Daraa governorate (Al Kassem et al. 2024). These constraints included armed conflicts peaking in 2014, 2016 and 2018, as well as widespread kidnappings by armed groups. There was no clear correlation between military activity and the availability of satellite imagery: Despite major battles in 2014 and 2016, the frequency of imagery did not increase (see Figure 10). A further field visit in 2023 enabled us to document additional sites that became accessible with improving security conditions, improved local cooperation and safer access routes.

Comparable assessments from satellite imagery and ground-based survey therefore exist for 28 sites in the region. The ground-based assessments were undertaken during two visits in 2015 and 2023. This is important to note, as both

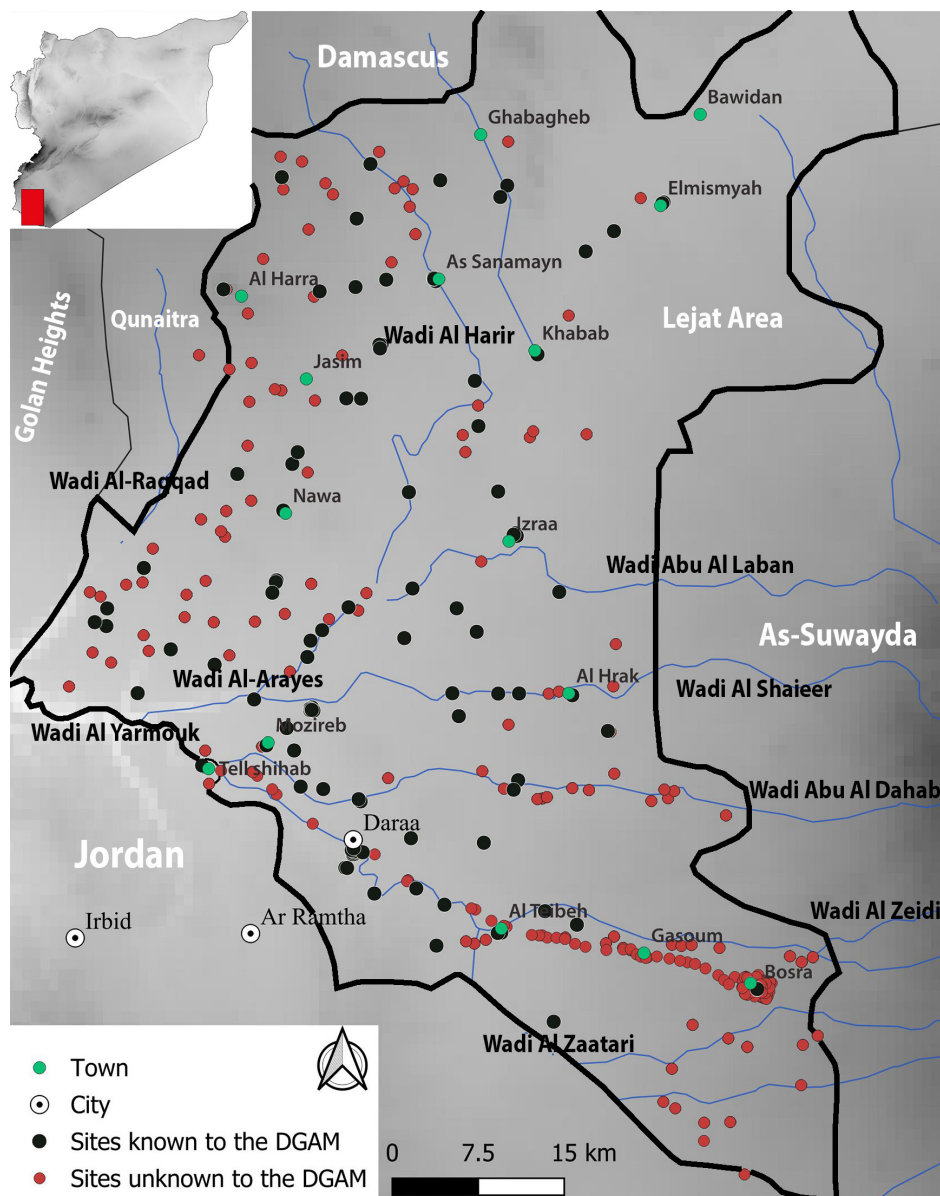


FIGURE 1 | A map depicting the locations of the damaged archaeological sites in the Daraa region of southern Syria, including both previously documented sites known to DGAM and newly identified, unrecorded sites. Daraa is situated along the Syrian–Jordanian border and shares administrative boundaries with As-Suwayda to the east, Damascus to the north and Quneitra and the Golan Heights to the west (adapted from Al Kassem et al. 2024). The sites are often clustered near rivers and seasonal water sources, highlighting the historical reliance on water for the establishment and sustainability of past settlements (GADM database of Global Administrative Areas, 2012), Mediterranean shapefile (www.marinerregions.org), Generated by QGIS Desktop 3.34.1, Coordinate system used: WGS 84/EPSSG 4326.

datasets must be from a comparable time frame. The results highlight the damage types that may be underrepresented, misinterpreted or underestimated from studies employing remote sensing alone, especially in similar environments. We then consider these results in light of the pros and cons of each approach, including cost-effectiveness, inclusivity and sustainability.

This study not only highlights the importance of integrating remote sensing and ground verification for damage assessment but also underscores its critical role in cultural heritage preservation. The findings contribute to prioritizing sites for emergency interventions, guiding restoration efforts and informing policymakers about necessary conservation strategies. By

integrating scientific analysis with heritage management, this approach ensures a more effective response to the ongoing threats faced by archaeological sites in conflict zones. It also offers a pragmatic and replicable model for strategic heritage management in conflict-affected and resource-constrained regions. By integrating open-access satellite imagery with ground-truthing supported by local communities, the approach enables the creation of reliable, cost-effective damage inventories under difficult conditions. In doing so, it provides a scalable methodology for prioritizing interventions, allocating limited conservation resources more effectively and supporting the development of context-specific protection strategies. Crucially, it empowers both national institutions and local stakeholders to engage in heritage documentation,

even in the absence of advanced technological infrastructure or extensive funding. Ultimately, while the methodological approach is not innovative from a technical remote sensing standpoint, this study makes a significant practice-oriented contribution to cultural heritage conservation.

2 | Materials and Methods

This study employed a combined approach of remote sensing and field assessment to document and verify damage to archaeological sites in Daraa (Figure 2).

2.1 | Satellite Imagery

The remotely sensed assessments of sites in the Daraa area employed visual inspection of high-resolution satellite imagery from Google Earth Pro captured between 2004 and 2022 (Al Kassem et al. 2024). The imagery was acquired from high-resolution satellites operated by Airbus (@2024 Airbus), CNES/Airbus (@2024 CNES/Airbus) and Maxar Technologies (@2023, 2024 and 2025 Maxar Technologies). Images attributed to Airbus and CNES/Airbus were taken by Pléiades and SPOT satellites, with CNES (Centre National d'Études Spatiales) collaborating on the latter. Meanwhile, imagery from Maxar Technologies originated from WorldView and GeoEye satellites. These satellites provide imagery with a spatial resolution ranging between 0.5 and 30 m (Parcak 2009). For the observations we discuss in this analysis, however, we

relied only on the highest resolution images available (e.g., 0.5 m). We selected GE for this analysis due to our team's prior experience with the platform from the project's initial phase, its efficient workflow compatible with our timeline and its accessible historical imagery, maintaining methodological consistency while optimizing researcher productivity. While GE imagery has undergone postprocessing by Google, the details of which are not fully available, this does not impact the usefulness of these images for the purposes of this study. In fact, this adds to its ease of use, combined with its cost-effectiveness (it is a free dataset), wide availability and coverage of the geographic area of interest (Mamo et al. 2022; Al Kassem et al. 2024). We would stress that the ease of use of this dataset is particularly important if we hope to see our methodologies integrated into community-based projects. In addition to the general limitations associated with the use of satellite imagery (see Cunliffe 2014; Vella et al. 2015), the Daraa region presents several unique limitations. For instance, within the basalt plateaus of northeastern Daraa, near the Jebel Al Arab volcano in As-Swuyda, the dark stone made it difficult to confidently attribute some disturbances to looting. To avoid redundancy, we will not reiterate these issues here, but they are thoroughly discussed in our previous study (see Al Kassem et al. 2024). In total, 1632 instances of damage were recorded across 196 archaeological sites following the methodology developed by the Endangered Archaeology of the Middle East and North Africa (EAMENA) project (Bewley et al. 2016) (Figure 1). Each instance of damage was assigned a time frame of occurrence (e.g., a specific date, before or after a certain date or between two specific dates).

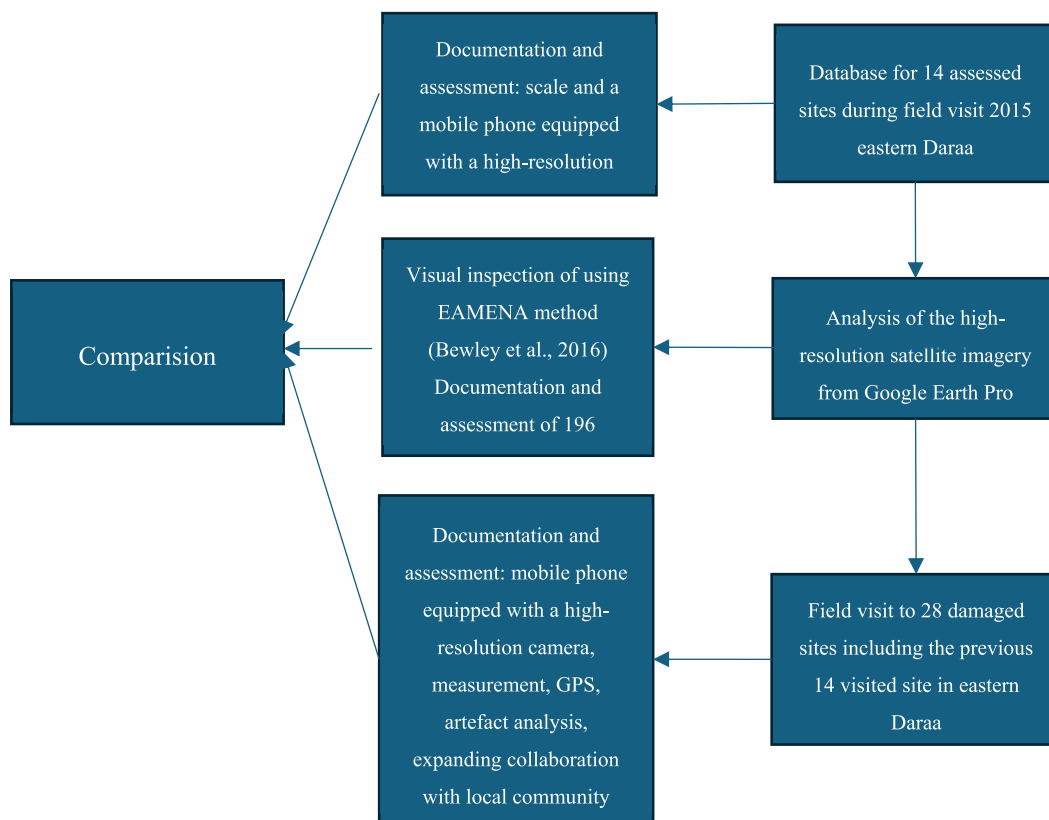


FIGURE 2 | Typo for comparison in the workflow illustrating the integration of satellite imagery analysis with on-the-ground-truthing for documentation and assessment of damaged archaeological sites in eastern Daraa.

2.2 | Field Assessment (Ground-Truthing)

We concentrated our field assessments in the eastern sector of Daraa due to security reasons and time limitations; a formal sampling strategy was not feasible. This area was previously documented and assessed in 2015, which allowed us to build upon existing data. We documented the type and severity of damage in recorded and unrecorded sites. The 2023 season systematically expanded on the 2015 findings by reassessing the same sites, applying improved tools and protocols and integrating community insights and satellite data for a more comprehensive evaluation.

Additionally, we are significantly more familiar with the eastern sector than with the western part of Daraa, which helped facilitate efficient and safe work in the limited time frame. During the 15-day field assessments, we evaluated 28 damaged sites in this region, of which 14 sites had been visited in 2015, including the types and extent of visible damage, and these sites were prioritized for reassessment to assess the evolution of damage over time. Additionally, when selecting other sites for the 2023 assessments, we prioritized those that appeared to have suffered severe or recent damage according to satellite imagery, as well as sites of known archaeological significance based on DGAM records. This ensured that both heavily impacted and culturally important sites were included despite the constraints of access and safety. The sites were visited based on a combination of local community recommendations, preliminary assessments using satellite imagery and the DGAM's official site records. We aimed to include a diverse range of archaeological sites affected by various types of damage; however, the decisive criterion for site selection was ensuring safe access to each location. The sites represent a diverse range of damage types (even within the same site) and chronological periods. While these 28 sites do not purport to be statistically comprehensive, they offer clear insight into the main types of damage in the region. However, we acknowledge that this approach may introduce certain selection biases. We have thus treated the field results as a qualitative ground-truthing complement to the broader satellite-based assessment, rather than as a statistically representative sample.

The field assessments were conducted on specific days and recorded visible damages that occurred either prior to or at the times of the visit, either in 2015 or 2023. The results of the 2015 field assessments were published in Al Kassem 2016. The results of the 2023 field assessments are presented here in summary form (Appendix 1) for the first time.

The 2023 assessments were undertaken with the permission of the DGAM in Daraa. The goal was to evaluate as many archaeological sites, which appeared to show damage, as possible based on the results of the satellite imagery assessments (Al Kassem et al. 2024). The field assessment was supported by the local community, who played a key role in identifying new sites not detectable via satellite imagery. Their support and knowledge substantially strengthened our understanding of site locations and potential new threats. Planned cultural dialogues and heritage awareness activities—aimed at engaging local communities in preservation efforts—could not be carried out due to time limitations, security risks and widespread

social fatigue from prolonged conflict. However, we hope to use the results of the project to engage in community outreach moving forward. It resulted in the evaluation of the condition of 28 archaeological sites (Figure 3 and Appendix 1), including sites that were evaluated on the ground in May 2015, which was, at that time, still an active conflict zone. For both visits, basic tools like a scale and a mobile phone equipped with a high-resolution camera were used. In 2023, the Gaia application (Gaia GPS 2023) was used to trace the surveyed areas and record the coordinates of sites, which was not possible during the field visit in 2015. Also, the 2023 field visit employed controlled vocabulary (developed by the EAMENA project) to describe the damages recorded and to ensure the comparability and reliability of our observations across both field seasons. To optimize the quantity of recorded observations, we adhered to the following protocols:

1. We involved the local community during our field assessments to ensure safe navigation and access to archaeological sites in a region affected by security risks. Specifically, a trusted local community member with a strong social network accompanied us to each site. His deep familiarity with the area and connections ensured that we received local support in every location we visited. This collaboration was crucial not only for security and logistical guidance but also for identifying areas where looting activities and potential sites were concentrated. The community's intimate knowledge of the landscape and recent disturbances allowed us to efficiently locate sites that required urgent assessment, including those not visible in satellite imagery.
2. Motorcycles were used to enhance our mobility during the survey. This facilitated the potential of uncovering additional archaeological sites because of better ground visibility. Additionally, it served to minimize costs associated with transportation and decreased risk by following existing tracks.
3. The visible damage was photographed and, in some cases, videoed. Additionally, each site was described and the mechanism of damage recorded. At some sites, looting pits were measured (e.g., the largest and smallest pits).
4. All the evaluated sites were located using the free Gaia GPS application, which was activated while moving between the sites. Thus, the entire route (not just each site) was recorded.
5. If any artefacts were scattered in or around the looting pits, they were photographed. This record can help to estimate the chronology of the site for future research.
6. Samples of stone tools scattered on sediments in the vicinity of the looting pits were specifically documented. Prehistoric sites are underrecorded in the region, and this information will be useful in identifying sites for further investigation in future projects.

Permission to collect artefacts or samples from the sites was not granted. Therefore, all artefacts were documented in situ through photography and description.

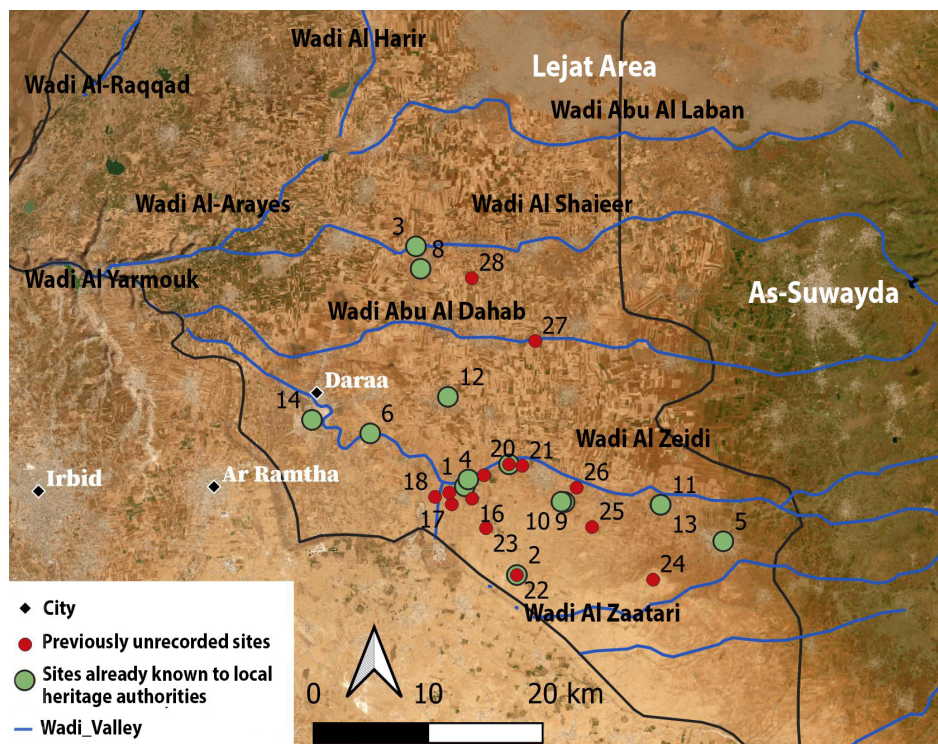


FIGURE 3 | Overview of previously recorded and newly documented archaeological sites evaluated during the field visits in 2015 and 2023, with site names and corresponding numbers provided in Appendix 1. Employed in compliance with the terms of service of Google Maps/Earth for research purposes. The cities of Irbid and Ar Ramtha are located in Jordan, which shares its northern border with Syria (specifically Daraa and As-Suwayda). As previously mentioned, As-Suwayda forms the eastern administrative boundary of Daraa Governorate.

To make these two datasets comparable, we had to limit the data derived from satellite imagery to include only damage that occurred at the time or prior to the dates of the field visit. However, no imagery was available on the GE Platform for the exact dates of our assessments. Therefore, we compared the observations of damage made in the field visits with the imagery from the closest available dates (e.g., images from 2014 and 2017 for the 2015 field visits) and images from 2020–2022 for the 2023 field visits.

3 | Role of the Local Community

The role of local communities in the assessment and documentation of damaged archaeological sites in conflict-affected regions extends beyond individual case studies or specific areas of Syria. Each region possesses distinct cultural norms and traditions that often exert greater influence over societal behaviour than formal state legislation. In this context, we present key observations from our fieldwork in the tribal communities of Daraa, where local governance is deeply rooted in customary practices and traditional authority structures.

During our field assessments in 2015 and 2023, the local communities played an essential role in identifying previously undocumented damaged archaeological sites. For example, Khirbet Hamas was not identifiable through satellite imagery; however, local people guided us to this significant site, which required urgent intervention due to its deteriorated condition. Indigenous communities possess an unparalleled understanding of their surrounding landscape. We emphasize that collaboration with

the local community is essential for ensuring the safety of field assessments. Local knowledge is invaluable for identifying the safest and most efficient routes, and the most appropriate means of transportation. For instance, following the tracks of previously used vehicles across agricultural land using motorcycles enabled us to avoid potential hazards while also reducing travel time. Without such local guidance, the risk to field teams would be considerably heightened.

Security was another unique aspect of our experience in Daraa. Personal connections within the community were vital—not only did they ensure a warm reception and widespread support but they also facilitated access to sites located in neighbouring villages. These relationships have proven to be long-lasting, as community members continue to inform us of newly observed damage, often through digital platforms such as WhatsApp. This ongoing communication is crucial for the development of sustainable conservation strategies.

Furthermore, local communities contribute valuable contextual knowledge that enhances our understanding of site vulnerability. They can provide insights into ongoing environmental changes, such as erosion, flooding, agricultural expansion and grazing activity, as well as information about planned development projects. In Daraa, for instance, damage attributed to looting was frequently observed in conjunction with grazing activities. These findings, initially noted through satellite imagery and field observation, were later confirmed through discussions with the local community, thereby reinforcing the importance of community engagement in heritage monitoring and risk assessment.

In line with our experience, we propose a structured model that integrates local communities into fieldwork in collaboration with heritage authorities. This approach can be operationalized by engaging the local community through workshops focused on mapping the distribution of damaged sites, providing training in damage assessment methodologies and establishing direct communication protocols—such as dedicated mobile applications—for real-time reporting. By combining community-based knowledge with satellite imagery analysis, this model enhances both the accuracy and efficiency of detecting changes at archaeological sites, while also significantly improving field safety. Such collaboration fosters sustainable heritage management and strengthens local communities' sense of ownership and responsibility toward their cultural heritage.

4 | Results

Fourteen of the 28 sites visited had been previously recorded by local heritage authorities (Figure 3 and Appendix 1). These tended to be within villages distinguished by the presence of an old, abandoned town (e.g., Tell Al Teibeh (Al Kown), the ancient towns of Al Jeezah, Gasoum, Al-Ghariya Al-Gharbiyah and Al-Ghariya Al-Sharqiyah). A notable and common feature among most of these historic towns is the practice of using uncut basalt stones in construction, mainly built and fixed without mortar. These ancient towns often rest upon the remnants of earlier settlements, presumed to be of Roman or Byzantine origin. In some cases, this is evidenced by the presence of churches (e.g., Al Teibeh), where mosaic remnants are distributed within the site. However, it also includes Ottoman train stations, which are located along the Al Hijaz Railway. This railway connected Bosra in the east with Acre (Akko), Haifa and Nablus on the Mediterranean coast in the west. It intersected with the line running from Damascus to Al Madina al Munawara in Saudi

Arabia, further enhancing the historical and cultural significance of the region (Al Kassem et al. 2024).

We evaluated an additional group of 14 sites, which had, before our remote sensing study, not been recorded by local heritage authorities (Figure 3 and Appendix 1). A common feature of these sites is that they are all located on the basalt plateaus, either directly on or near water resources (i.e., Wadi Al Zeidi, Wadi Abu Al Dahab and Wadi Al Zaatar).

4.1 | Comparison of Damage to Previously Known Archaeological Sites in the Field and on Imagery

All the previously recorded historical sites (i.e., the ancient towns, the railway and the train stations) showed evidence of severe damage in the ground-based assessments. However, only 24% of the instances of damage documented in the field assessment were visible on satellite imagery (i.e., 31 of 127 instances) (Figure 4). Again, it is worth noting that imagery was not always available for the exact same dates as the field assessments. We used whatever images were closest in date (either before or after) to make our comparison.

Despite this, it is clear that a significant percentage of damage types observed at these sites would not have been recorded on satellite imagery alone. While looting (primarily by hand) is the most common damage (see below) and is often clearly visible on the satellite assessments, many of the pits also show traces of explosives, something visible on field visits. This is evidenced by the presence of very fine sediments accumulated around the pits (Figure 5A). Looting operations have also increased the fragility of existing walls, which in many cases led to partial and sometimes complete demolition of buildings, as is the case in the church in the ancient town of Al Moutayah (Figure 6). Damage to stations and infrastructure on the historical Al Hijaz railway

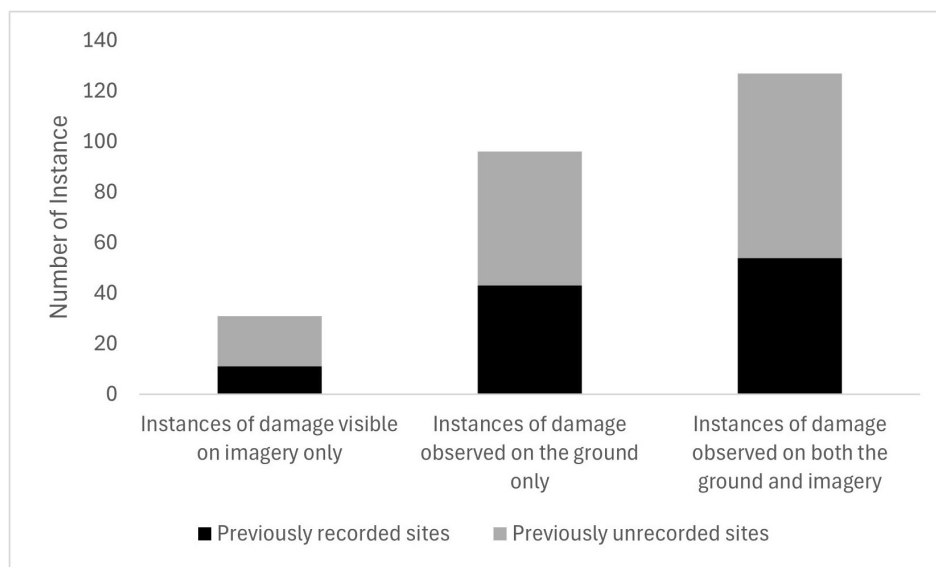


FIGURE 4 | Comparison of damage types recorded in satellite imagery (left), confirmed via field visits (middle) and observed on both of them (right). The results show that greater percentage of damage types—such as wall collapses, looting using explosives and structural instability—were only detected through ground verification, demonstrating the limitations of satellite-based assessments. The available imagery dates back to 2014–2017 and 2020–2022, while the ground assessments are from 2015 and 2023.



FIGURE 5 | (A) Evidence of explosive use in looting at the ancient town of Saida Village, documented during a 2015 field visit (Al Kassem 2016). This mechanism of looting was not detected using satellite imagery, and only visible in field visits. (B) Cracks in the walls, looting of the doors and ceilings, and felling of the trees in the periphery of the Al Teibeh station. Again, none of these damages were clearly visible in satellite imagery, as can be seen in the train station of Al Teibeh in (C) (Image 2025 Maxar Technologies. Used in accordance with the Google Maps/Earth terms of service for research purposes).

also included the looting of wooden materials from station ceilings, doors and windows (e.g., at the stations of Al Teibeh, Bosra, Garz and Daraa). Additionally, we observed cracks in the walls of the stations (Figure 5B), though the cause remains unknown, as none of these stations had been subjected to severe military attacks except for Garz train station.

Looting pits, referred to above, which were documented in limited quantities during field visits in 2015, were a frequent category of damage by the time the 2023 assessments took place. Often this type of damage was clearly visible on the imagery and, in fact, was one of the most recorded types across the wider survey area. While identifying this damage category on imagery has not proved challenging, interpreting the mechanism by which it has been carried out can be. By this, we mean being able to distinguish between looting by hand and looting carried out using machines.

The Hijaz Railway was severely damaged, making it difficult to differentiate between looting-related cuts and those made to construct roads over the railway. Damage often appeared worse on the ground than in satellite imagery. For example, south-east of Al Jeezah (Figure 7A,C), the railway was dismantled in two abandoned places presumably to facilitate military vehicle movement. Dozens of looting pits were recorded in the same area, causing cavities and structural imbalances in the railway (Figure 7B). Looting pits were often concentrated directly on

the railway or along its edges. Additionally, parts of the railway were lost due to destruction and buried under asphalt in areas like Al Teibeh to allow vehicle movement during the conflict.

While the Ottoman rail network was easily visible on imagery, the well-known Roman Road network, expanding from the ancient city of Bosra and extending throughout Daraa province, was not. However, on the ground, the road linking Bosra and Daraa (Bauzou 1985), referred to as Trajan's Road, is paved with small basalt stones of different shapes and sizes and is recorded in places as more than 2 m in width. In the field, we documented several looting pits along the course of the road, located south-east of the town of Al-Jeezah (Figure 8A–C). Looting using both hand and bulldozer was documented, which has led to the destruction of large segments of the road.

4.2 | Comparison of Damage in the Field and on Imagery to Previously Unrecorded Archaeological Sites

Many of the sites that were previously unrecorded by local heritage authorities are located on small basalt plateaus or consist of tells, situated near wadis. Daraa has historically lacked systematic archaeological investigations of any kind. There was also a clear bias in earlier DGAM surveys, which focused predominantly on the north, northeast, and central regions of



FIGURE 6 | (A and B) Looting pits documented in the church of Al Moutayah, extending beyond 2 m in depth, increase the likelihood of the wall collapsing in the future. The severity of this damage cannot be accurately assessed using satellite imagery alone, highlighting a key limitation of this method. (C) The church of Al Moutayah on satellite imagery in 07.2017 (Image 2025 Maxar Technologies. Used in accordance with the Google Maps/Earth terms of service for research purposes).

Syria, leaving southern areas like Daraa underrepresented in the national records. Looting activities occur extensively across all landscapes, including the plateaus. Based on our field observations, we also assume that some of them are organized groups who are familiar with the distribution of archaeological sites along the wadis, as they graze livestock in these areas throughout the year. Of the 14 previously unrecorded sites, six showed clear evidence of looting both on the satellite imagery and during ground-truthing. However, at the Al Mintar site, for

instance, (imagery captured in 2017, Figure 8D), the satellite imagery failed to detect the type of looting (explosives and bulldozing) and clearance (bulldozing/leveling) activities, which were recorded in the 2023 field visit. Rather, inspection of images from 2017 classified this particular incidence of damage as having been made by excavation by hand (Figure 9A).

The large number, extensive distribution and significant depth of looting pits visible at these sites would require considerable

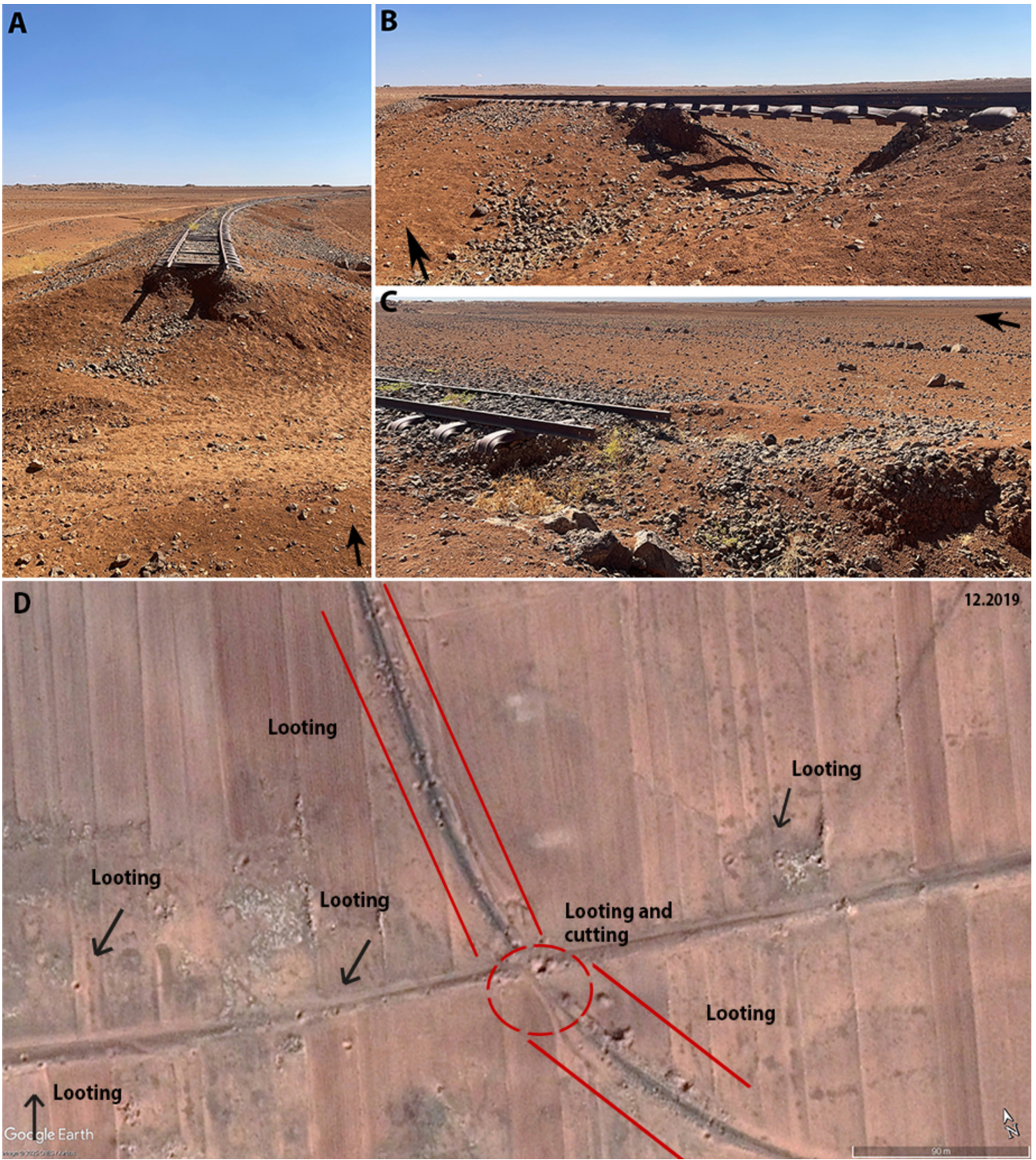


FIGURE 7 | (A and C) Railway cuts near the southeast of the town of Al Jeezah, where sections were dismantled, possibly to facilitate military vehicle movement. (B) An example of hundreds of looting pits documented between Daraa and Bosra. (D) The cutting and looting pits along the Al Hijaz Railway were clearly visible on satellite imagery (Image 2025 Maxar Technologies. Used in accordance with the Google Maps/Earth terms of service for research purposes).

time and other technologies, such as drones, for thorough aerial documentation. However, a sample of looting pits at the sites of Al Mintar, Om Sanam and Al-Salytee (We hoped to record the size and shape of looting pits at several other sites, but ongoing digging by armed looters made it unsafe to do so) was recorded in more detail in 2023. Here some of the pits reached depths of

3 m, as depicted in Figure 9B. Interestingly, a prominent and recurrent feature observed on all these sites is the distribution of pastoral activities, where vehicles, tents and animal corrals are dispersed throughout these basalt plateaus (refer to Al Kassem et al. 2024). In other areas (e.g., in western Al Jeezah), some pits stretched up to 6 m in length and exceeded depths of 10 m.

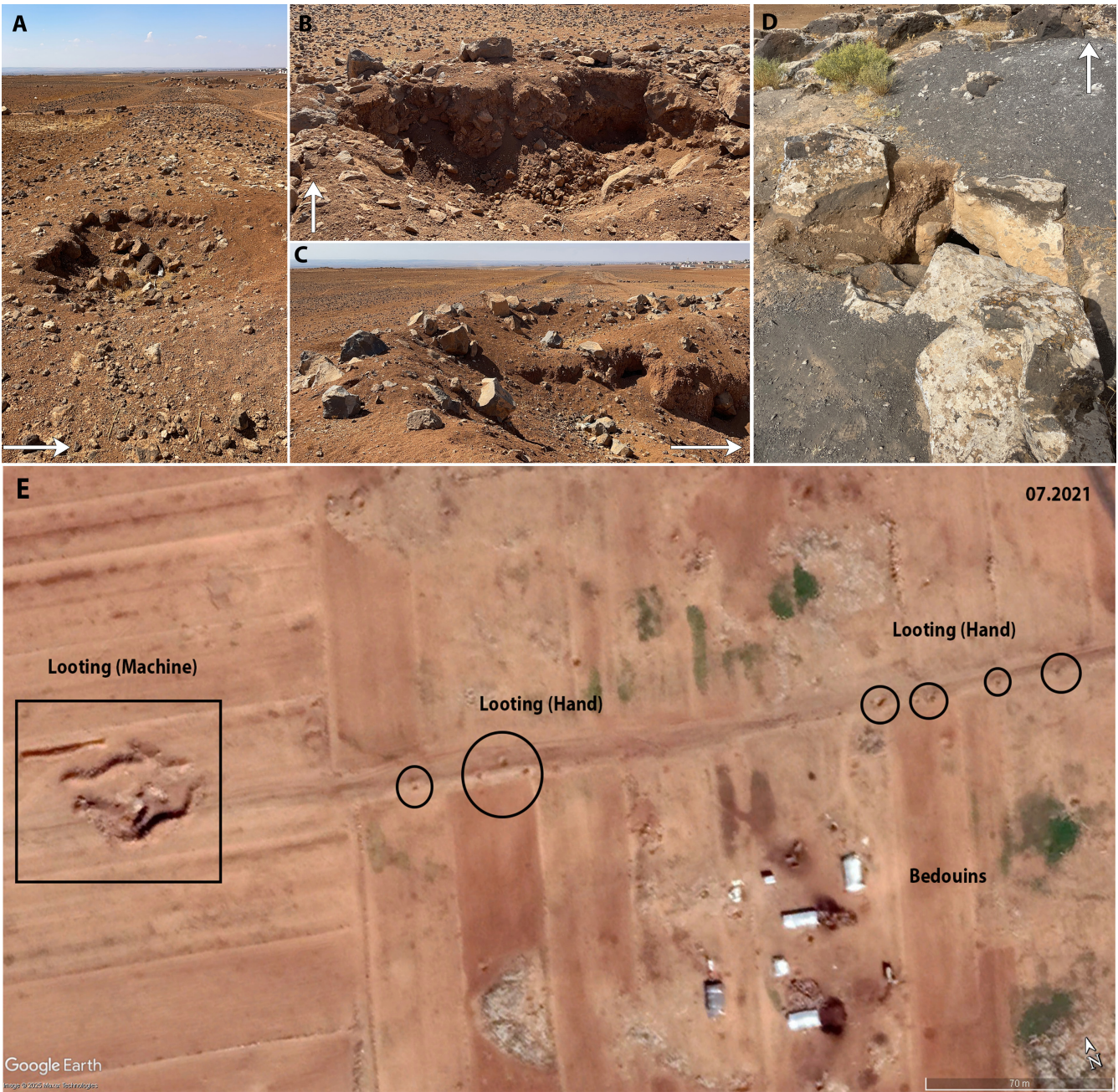


FIGURE 8 | This photo demonstrates different looting mechanisms, each causing varying degrees of damage to the site. This includes looting pits (A–B) created using hand tools and bulldozing (C). We also observed pits, such as here at the site of Al Mintar site (D) and Figure 9, where explosives were used during looting activities. The site is a basalt plateau, making looting using hand tools difficult. The looting pits along the Roman Road (Trajan’s Road) were clearly visible on satellite imagery after their confirmation during the site inspection (E) (Image 2025 Maxar Technologies. Used in accordance with the Google Maps/Earth terms of service for research purposes).

Overall, the field assessment suggests not only that the quantity of looting pits is greater than the number located through the satellite assessment but also that it much more accurately provides us with the mechanism of damage. The field survey also evidenced what is likely repeated looting through time, evidenced by faint depressions, which are not clear on satellite images. These depressions are sometimes pits that have naturally filled in over time, while looting (by hand) and bulldozing are common. Some sites, such as Al-Salytee, Al Mintar, Khirbet Al Jeezah, Khirbet Hamas, Khirbet Souhoob, Khirbet Gasoum, Khirbet Al Qnaia and Khirbet Tabeel, also show evidence of looting with explosives (Figures 5A and 8D).

The destruction of these sites presents a significant challenge for heritage management, as they have not yet been officially registered. Without systematic documentation, critical archaeological information may be permanently lost, underscoring the urgent need for proactive site monitoring and conservation efforts.

5 | Discussion

This study demonstrates the critical importance of an integrated approach of satellite imagery and ground verification

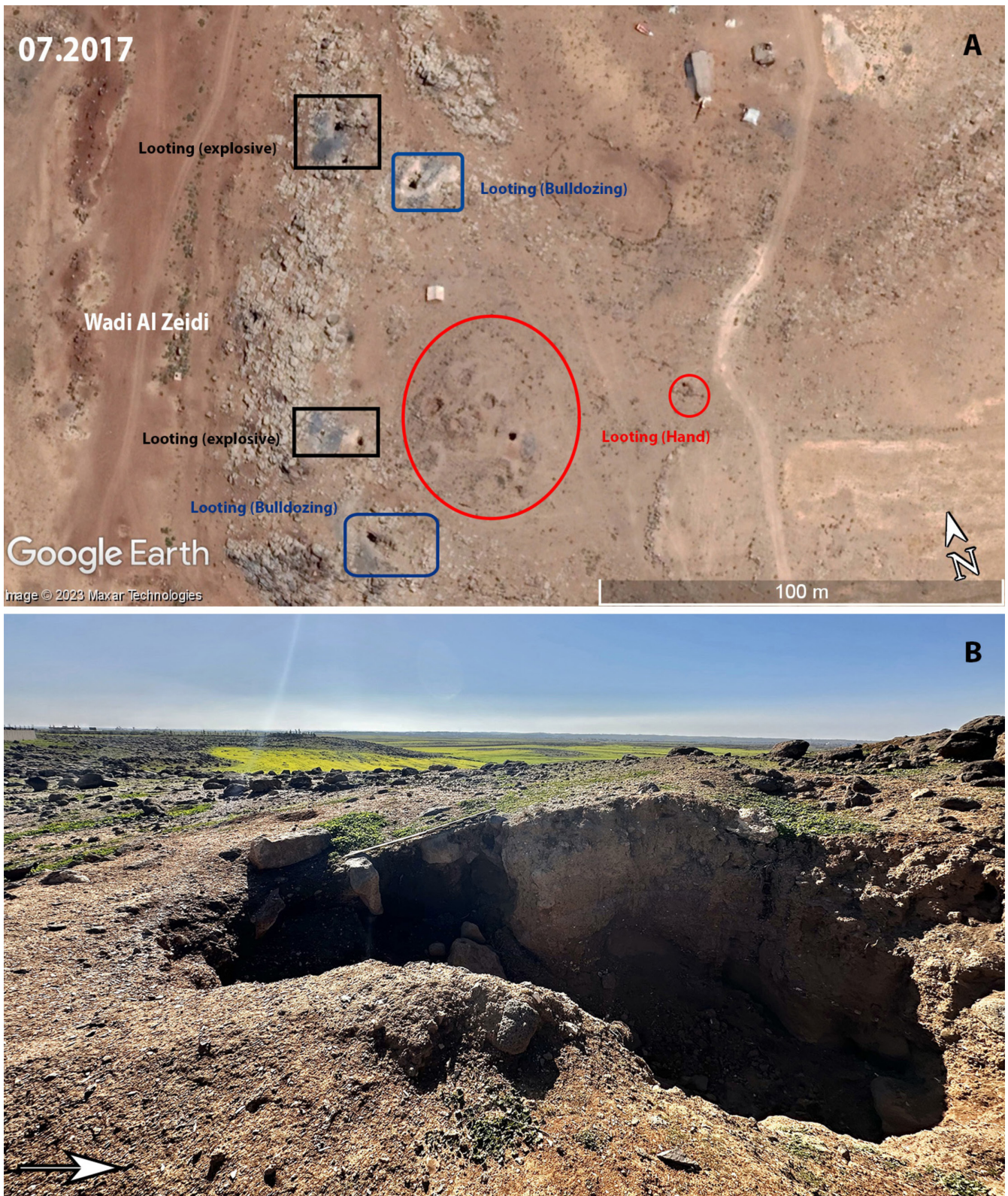


FIGURE 9 | (A) Looting pits at the Al Mintar site, initially identified as hand excavations in satellite imagery (Image 2023 Maxar Technologies. Used in accordance with the Google Maps/Earth terms of service for research purposes) but later confirmed through field visit in 2023 to have involved explosive. (B) Large looting pit (up to 3 m in depth) documented at the Al Mintar site in Al Teibeh. The pit reveals at least four layers containing bones and stone artefacts attributed to the late Epipalaeolithic period (Al Kassem et al. 2025).

for assessing damage to archaeological sites in conflict zones. The comparison between these two approaches highlights significant differences in their ability to document various types

of damage. Among the 16 damage types recorded across the 28 surveyed sites, 11 types were visible only on the ground, while only five types (Looting (hand excavation), looting (machine/

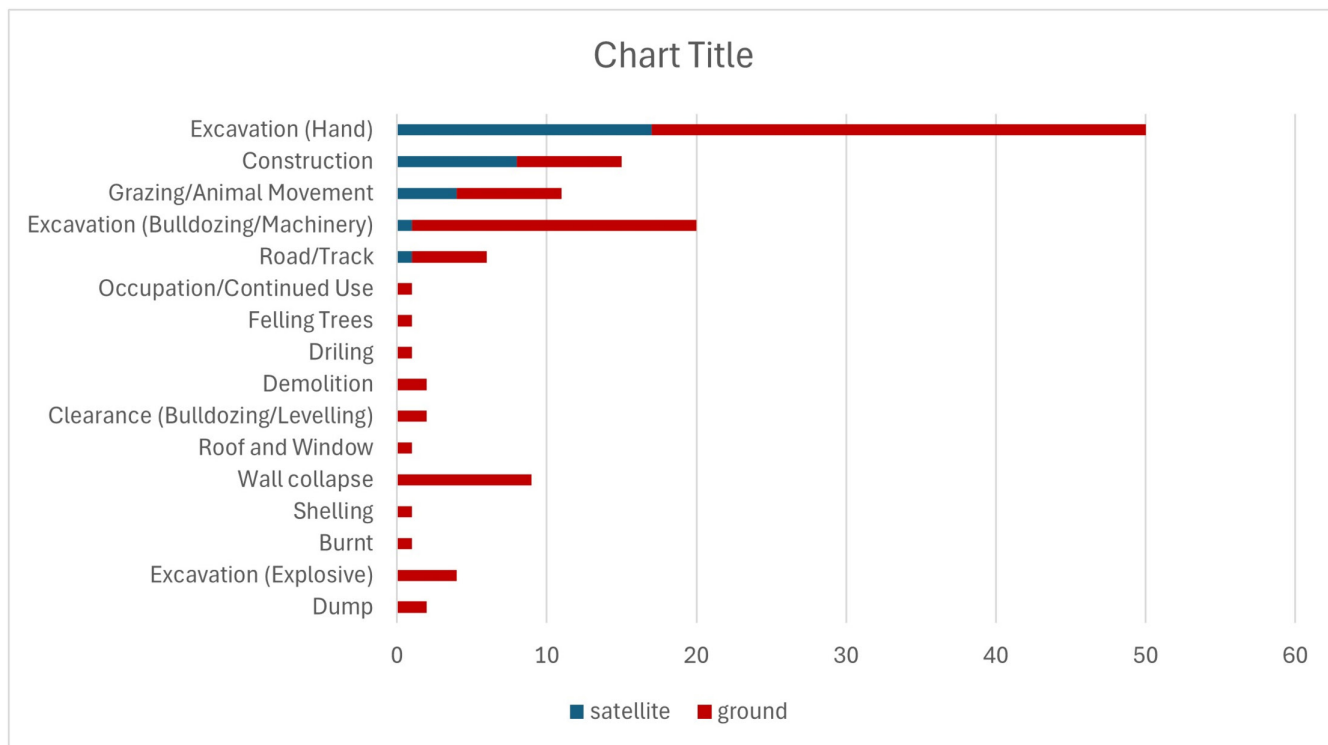


FIGURE 10 | A comparison of damage recorded in satellite imagery with those documented during field visits. No imagery was available for the surveyed sites in May 2015 or September 2023 at the time of writing. However, we compare the damages recorded in the closest available years, that is, 2014–2017 for 2015 and 2020–2022 for 2023. No damage type was detected exclusively via satellite imagery. The majority of damage types, including structural collapses, explosive-related disturbances and material theft, were only visible during on-site assessments. This emphasizes the need for combining remote sensing with ground verification for accurate damage evaluation.

bulldozing), construction, road/track construction and agricultural/pastoral use) were visible in both ground and satellite imagery (Figure 10). Notably, no damage type was exclusively identified only via satellite imagery, emphasizing the necessity of field verification for comprehensive damage assessment.

Out of the 127 recorded damage instances, 80% were observed in both field and satellite assessments. As illustrated in Figure 10 and Table 1, several damage types were only visible during the field visits. This included dumping, excavation using explosives, burning, shelling, wall collapse, roof and window damage, clearance (bulldozing/leveling), demolition, drilling, occupation/continued use and felling trees. Other damage types were identifiable through both ground and satellite imagery, including excavation using bulldozing/machinery, excavation by hand, construction, road/track damage and grazing/animal movement. However, these types of damage are much more easily recognized on the ground.

The effectiveness of satellite imagery in archaeological damage assessment is significantly influenced by multiple factors. These include spatial resolution (the level of detail captured), temporal resolution (the frequency of image acquisition), radiometric resolution (the ability to distinguish different brightness levels or colours), geometric accuracy (the precision of spatial alignment with real-world features) and atmospheric conditions (interference from haze, clouds or other environmental factors). Each of these factors plays a crucial role in determining the quality and reliability of satellite-derived data (Tapete et al. 2016; Tapete

and Cigna 2019). Additionally, the choice of data sources significantly impacts the accuracy, cost and practical utility of the imaging technology used (Fisher 2017). We must also factor in the fact that imagery captures only a limited perspective (i.e., the imagery provides only a bird's-eye view), and that the natural setting of the damage (e.g., a basaltic landscape) can make it more or less easy to identify certain damage types. We will discuss the impact of several of these factors on this study in more detail below.

5.1 | Temporal Resolution Limitations

One of the most critical limitations of satellite imagery is temporal resolution, which affects its ability to provide an accurate and continuous record of site damage. Image availability varies significantly between sites, leading to monitoring gaps that may obscure key damage events (Casana and Panahipour 2014; Stone 2008a). As noted in Appendix 1 and Figure 11, some sites have more available satellite images, allowing for more reliable tracking of changes, while others have large time gaps between images. For instance, Khirbet Gasoum had five satellite images spanning 2014–2020, whereas Khirbet Hamas had only three images in the same period. Khirbet Gasoum was captured once between January 2014 and October 2014, twice between October 2014 and February 2016, once between February 2016 and March 2017 and once between May 2020 and October 2020. In contrast, Khirbet Hamas was captured only three times, between October 2022 and January 2022.

TABLE 1 | Percentage of damage instances recorded in satellite imagery and on the ground (The total number of damage instances is 127). Possibility of detection in this study (Definite: 100%, High: 75%–99%, Medium: 50%–74%, Low: 25%–49%, Very Low: 0%–24%).

Damage type	Detected via satellite imagery		Possibility of detection at other sites in the study area	Detected via ground survey		Possibility of detection at other sites in the study area
	N	(%)		N	(%)	
Looting (hand excavation)	17	13.3	High	33	26	Definite
Looting (machine/bulldozing)	1	0.8	Medium	19	15	Definite
Construction	8	6.3	High	7	5.5	Definite
Road/track construction	1	0.8	High	5	3.9	Definite
Agricultural/pastoral use	4	3.0	High	7	5.5	Definite
Looting (explosives)	0	0	Very Low	4	3.1	Definite
Burning	0	0	Very Low	1	0.8	Definite
Shelling	0	0	Medium	1	0.8	Definite
Wall collapse	0	0	Very Low	9	7.0	Definite
Roof and window damage	0	0	Very Low	1	0.8	Definite
Dumping	0	0	Very Low	2	1.7	Definite
Clearance (bulldozing/leveling)	0	0	Very Low	2	1.7	Definite
Demolition	0	0	Very Low	2	1.67	Definite
Drilling	0	0	Very Low	1	0.8	Definite
Occupation/continued use	0	0	Very Low	1	0.8	Definite
Felling trees	0	0	Very Low	1	0.8	Definite

Additionally, no damages were documented in images from 2015 to 2023 (Appendix 1).

This uneven distribution of imagery introduces bias in damage assessments, as sites with fewer images could appear less affected than they are in reality. Figure 12 illustrates this issue, showing the number of available images per year, with peaks in 2011, 2014, 2016, 2018 and 2022. To understand the impact this could have on our interpretations, we can compare the number of images available with the number of instances of looting damage. Interestingly, more instances of looting were recorded in 2014–2016 (Al Kassem et al. 2024) than in any other years within our study. This is in spite of the fact that there are years where image availability (e.g., 2022) is higher. In addition, instances of looting in 2017 exceeded those recorded in 2018, despite fewer images being available in 2017. This suggests that the satellite assessments are broadly robust in terms of pinpointing the broad periods of increased looting activity, despite differential image availability. However, a limited number of images could still impact the observed patterns. For example, we are unsure if the fewer instances of looting recorded in 2013 and 2015 are true lulls in activity or are due to the lower number of images. This limitation is somewhat mitigated by using aoristic modeling (see Al Kassem et al. 2024) to better understand the timing of damages.

5.2 | Spatial Resolution and Perspective Constraints

While freely available satellite imagery, such as that provided by GE, presents certain limitations, it remains a valuable tool for detecting major forms of damage. Large-scale disturbances—such as construction, destruction, looting, bulldozing and agricultural activities—can be identified with high-resolution imagery. The spatial resolution of approximately 0.5 m per pixel offered by GE makes it particularly suitable for detecting certain types of change and conducting broad site assessments (Tapete and Cigna 2020; Mamo et al. 2022). However, the spatial resolution, as we have mentioned above, is in some cases not high enough to detect some damages or to differentiate between the mechanisms of damage. The use of explosives to aid looting, the traces of which were only visible on the ground, is a clear example of this.

The natural setting of the damage also affects its visibility on satellite imagery. Looting with explosives is prevalent in the basalt plateau. Consequently, distinguishing between looting pits and natural basalt rock formations, both of which appear as dark features in satellite imagery, remains challenging when relying solely on imagery. However, with the aid of ground verification, we could sometimes see a difference between looting and the basalt rock formation when re-examining the imagery.

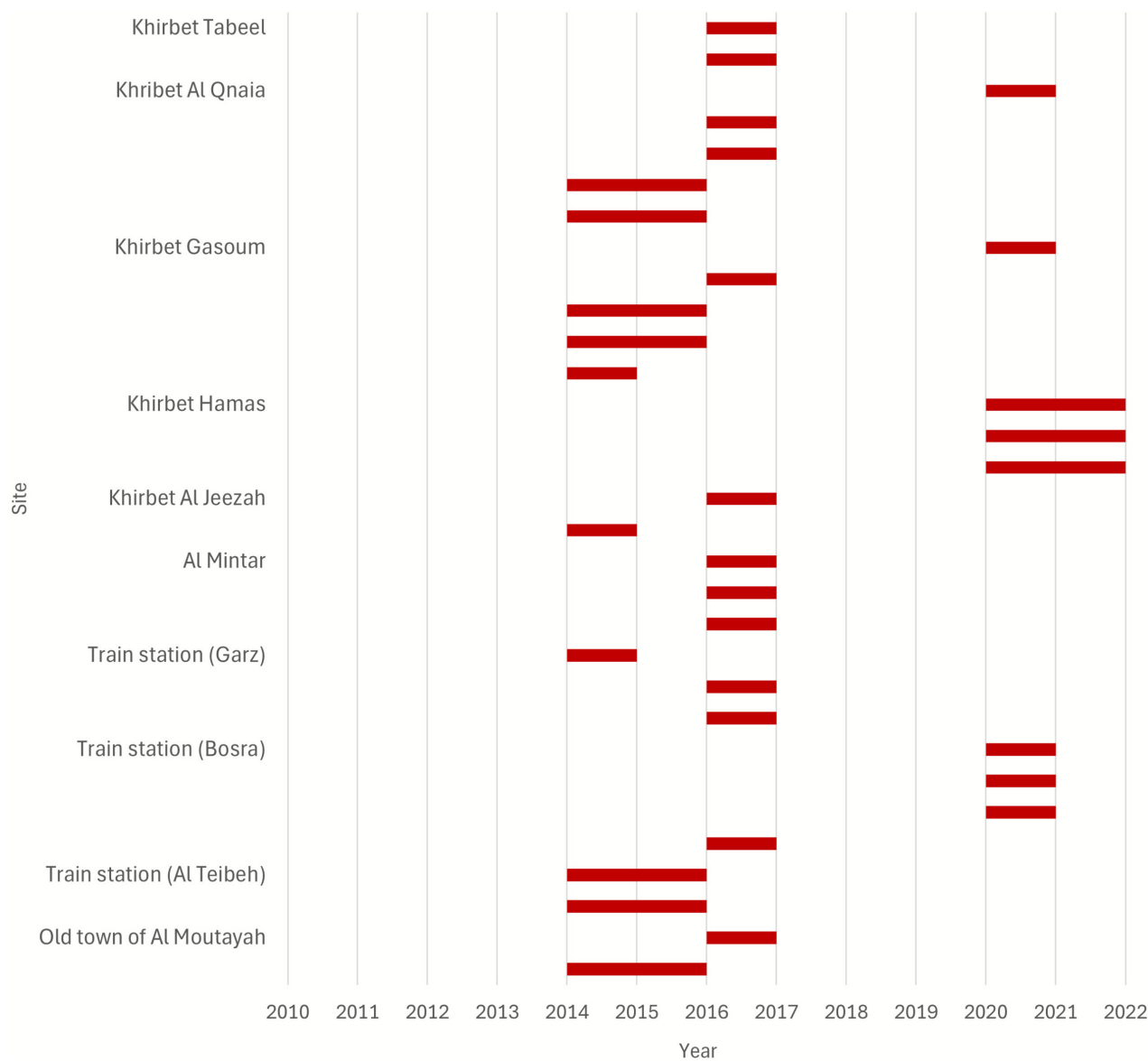


FIGURE 11 | Frequency of satellite imagery by site: It illustrates the variation in imagery availability across sites throughout the study period.

This underscores the necessity of integrating large-scale remote sensing studies and local contextual knowledge to enhance their informational value (Al Kassem et al. 2024).

Lastly, satellite imagery is limited in its perspective (i.e., vertical), which restricts the ability to identify certain structural damage such as vertical collapse, internal damage or subtle structural weaknesses such as wall deterioration at Al Omary Mosque (Figure 13).

5.3 | Advantages of a Combined Approach

Twenty-eight damaged sites were evaluated over 15 days, primarily focusing on sites identified via satellite analysis, rather than conducting random exploratory surveys. Moving between sites posed risks due to potential landmines and bandit activity. Nevertheless, with the local community's assistance, the fieldwork was safely completed. In contrast, the remote sensing assessment of 196 sites

in 30 days, including 100 previously unrecorded sites, demonstrates the efficiency of satellite-based methods. Conducting comprehensive on-the-ground monitoring of 196 archaeological sites in a conflict zone presents numerous logistical and safety challenges. Without the assistance of advanced technologies such as drones, such an undertaking would be largely impractical.

Although this study has focused on the application of freely available high-resolution optical imagery, there is substantial potential for future integration of additional remote sensing datasets to further enhance damage assessment capabilities. SAR, for example, can penetrate cloud cover and detect surface disturbances invisible to optical sensors, making it valuable for monitoring looting in areas with dense vegetation or dark basalt terrain. Hyperspectral imagery can contribute to material identification, which may help distinguish between construction phases or detect erosion of specific fabric types. Drone-based photogrammetry and LiDAR systems offer extremely high-resolution 3D mapping and can capture detailed

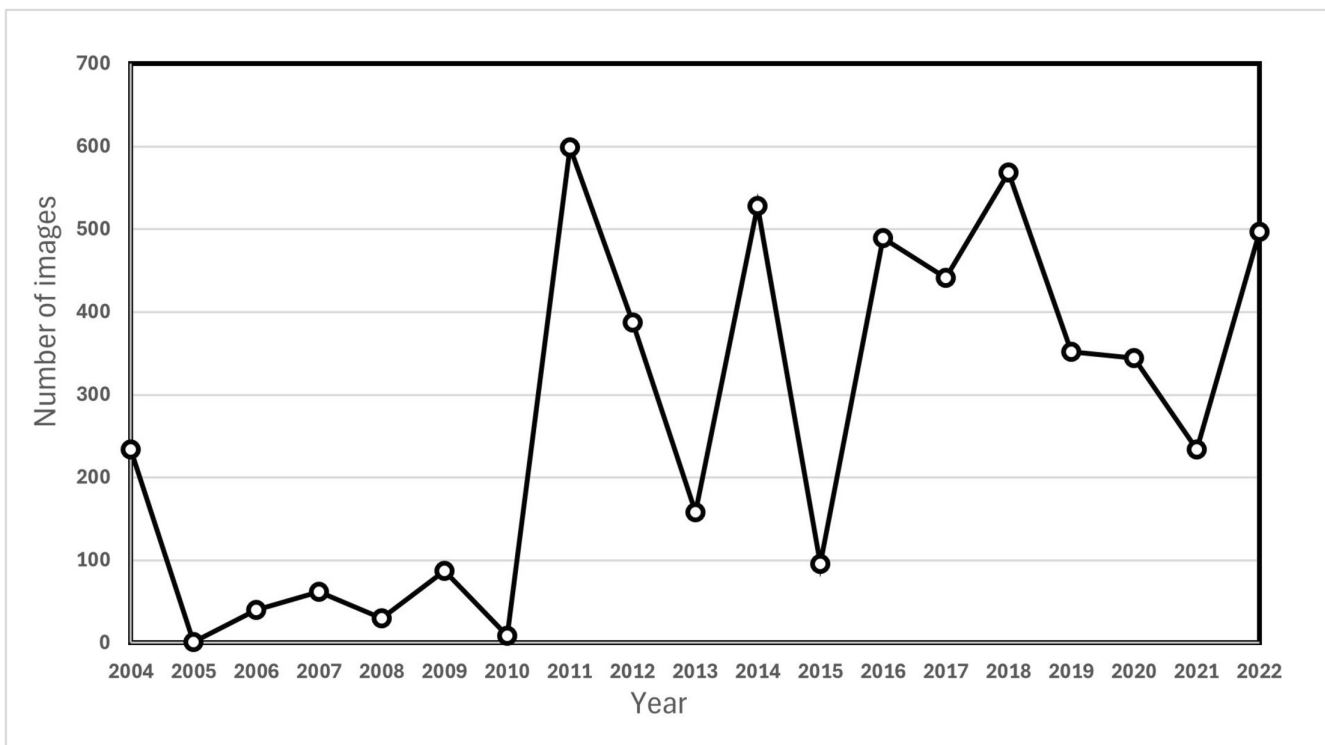


FIGURE 12 | Number of available satellite images from Google Earth Pro per year, highlighting temporal gaps in data coverage. Uneven image distribution can lead to underreporting damage and misinterpretation of its trends.



FIGURE 13 | (A) Al Omary Mosque in Ma'araba before sustaining damage, originally consisting of two floors. (B) The mosque after experiencing structural collapse during armed clashes in 2014, as documented during field visit in 2015. (C) Satellite imagery taken in 2019 shows the location of the mosque (Image 2025 Maxar Technologies. Used in accordance with the Google Maps/Earth terms of service for research purposes). This type of architectural deterioration is challenging to detect using satellite imagery alone, emphasizing the importance of ground-based assessments.

site morphology, particularly useful in urban areas or inaccessible locations. The inclusion of these technologies in a hybrid approach would enable more nuanced and continuous monitoring and further support evidence-based conservation planning in complex conflict environments.

Budgetary constraints also play a crucial role in determining the feasibility of field assessments. In conflict zones affected by war and economic sanctions, fieldwork costs are significantly higher than in stable regions. Inflation in accommodation, transportation and fuel prices—exacerbated by supply shortages—can double standard cost estimates, making satellite-based analysis the most cost-effective solution. Furthermore, field assessments involving teams traveling from abroad would incur additional expenses, further reinforcing the economic advantage of remote sensing approaches.

Despite these advantages, satellite imagery still presents significant limitations (Stone 2008a; Stone 2008b; Wolfinbarger 2015). For instance, GE imagery failed to capture the collapse of Aleppo's Citadel wall during the 2015 event. Similarly, analysis of Sentinel-2 imagery suggests that without prior knowledge, such collapses might have gone unnoticed (Tapete and Cigna 2018).

In contrast, ground observations excel at detecting structural damage to historic buildings and monuments, particularly in urban environments, where such damage is more conspicuous. However, field surveys often fail to detect large-scale looting, especially at remote archaeological sites, where field visits are not frequently undertaken (Angiuli et al. 2020). In addition, satellites equipped with multispectral imaging and SAR technologies demonstrate the capability to detect buried archaeological remains (Kainz 2016; Kaimaris 2022, 2024; Kaimaris and Tsokas 2023; Valente et al. 2024). For more accurate detection of damage, specifically looting, even when it is difficult to identify in optical imagery, SAR data can enhance results by highlighting disturbed surface textures and moisture variations—even when looting pits are not visually apparent. Future studies could benefit from such data fusion to monitor illegal activity more reliably across different seasons and environmental conditions. Nevertheless, ground verification remains essential.

Satellite imagery has also struggled to detect small-scale changes in archaeological landscapes. For example, Sentinel-2 failed to identify small-scale damage at archaeological sites in Aswan, Egypt, and Jufra, Libya, leading to unrecognized deterioration of cultural heritage. Additional challenges including issues such as registration errors, shadows and shifting sand dunes can create false positives, reducing the reliability of remote sensing data (Rayne et al. 2020). Likewise, the spatial resolution of Sentinel-1 radar images was insufficient to detect small-scale architectural changes in Limassol City Centre and the Amathus Archaeological Site in Cyprus during the period of 2015–2020 (Agapiou 2021).

5.4 | Assessing the Severity of Damage

Various methods exist for evaluating damage severity. A common approach involves counting visible looting pits in satellite imagery (Casana and Panahipour 2014; Casana and

Laugier 2017; Parcak 2015). For example, Angiuli et al. (2020) assessed looting severity at Nineveh and Nebi Yunus sites in Iraq by analysing pits measuring 1–3 m in diameter, cross-referencing satellite images with news reports and social media data between 2014–2017 and aligning findings with NATO damage assessment standards.

However, satellite images alone cannot fully capture the complexity of looting damage. Measuring looted area necessitates an understanding of pit density, depth and spatial distribution, factors that are best evaluated through ground investigation (Casana and Laugier 2017). Findings from our field assessment of 28 sites in Daraa highlight the importance of considering archaeological context when determining damage severity. For example, Bosra City, a well-documented site, contains a rich archaeological record. While looting causes damage, the site's historical significance is well established, minimizing the loss of new information. Conversely, Al Qnaia, a previously unrecorded site, had never been surveyed or excavated before. Looting here led to the irreversible loss of stratigraphic evidence and artefacts, eliminating the potential for groundbreaking discoveries. This contrast emphasizes that not all looted sites are equally impacted—damage at previously unrecorded sites may result in the complete loss of undiscovered cultural heritage. Additionally, the method of looting significantly affects site destruction. Bulldozing and explosives cause irreversible damage, obliterating entire archaeological layers, making detection through satellite imagery nearly impossible.

5.5 | The Essential Role of Field Verification

While satellite imagery excels in mapping landscapes and identifying potential archaeological sites, it cannot replace ground verification. Valente et al. (2024) detected 131 potential archaeological sites in Iraqi Kurdistan using satellite imagery, but ground verification confirmed only 67 sites. With

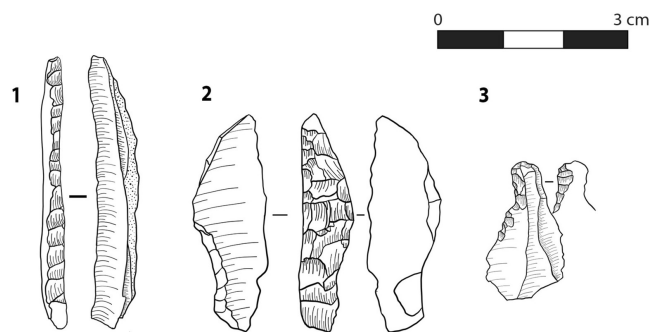


FIGURE 14 | A selection of stone artefacts recovered from the Al Mintar site, representing various Epipalaeolithic periods, primarily the Late Epipalaeolithic. Examples include (1) a backed bladelet, (2) micro-lith with abrupt bidirectional retouch and (3) a perforator (Al Kassem et al. 2025). These artefacts provide valuable insights that cannot be documented using satellite imagery, highlighting one of its key limitations. Despite visible looting damage, other parts of the site remain intact, offering good potential for future excavations that could recover faunal remains, lithic assemblages and environmental data. This site will likely contribute to understanding the Late Epipalaeolithic society in southern Syria.

nearly half of the remote identifications being false positives, this demonstrates the limitations of satellite-based archaeology and the necessity of on-the-ground assessments. Even in

very high-resolution imagery (where each pixel represents a ground area of about 50×50 cm to 70×70 cm), many small-scale features remain undetectable (Angiuli et al. 2020). Field

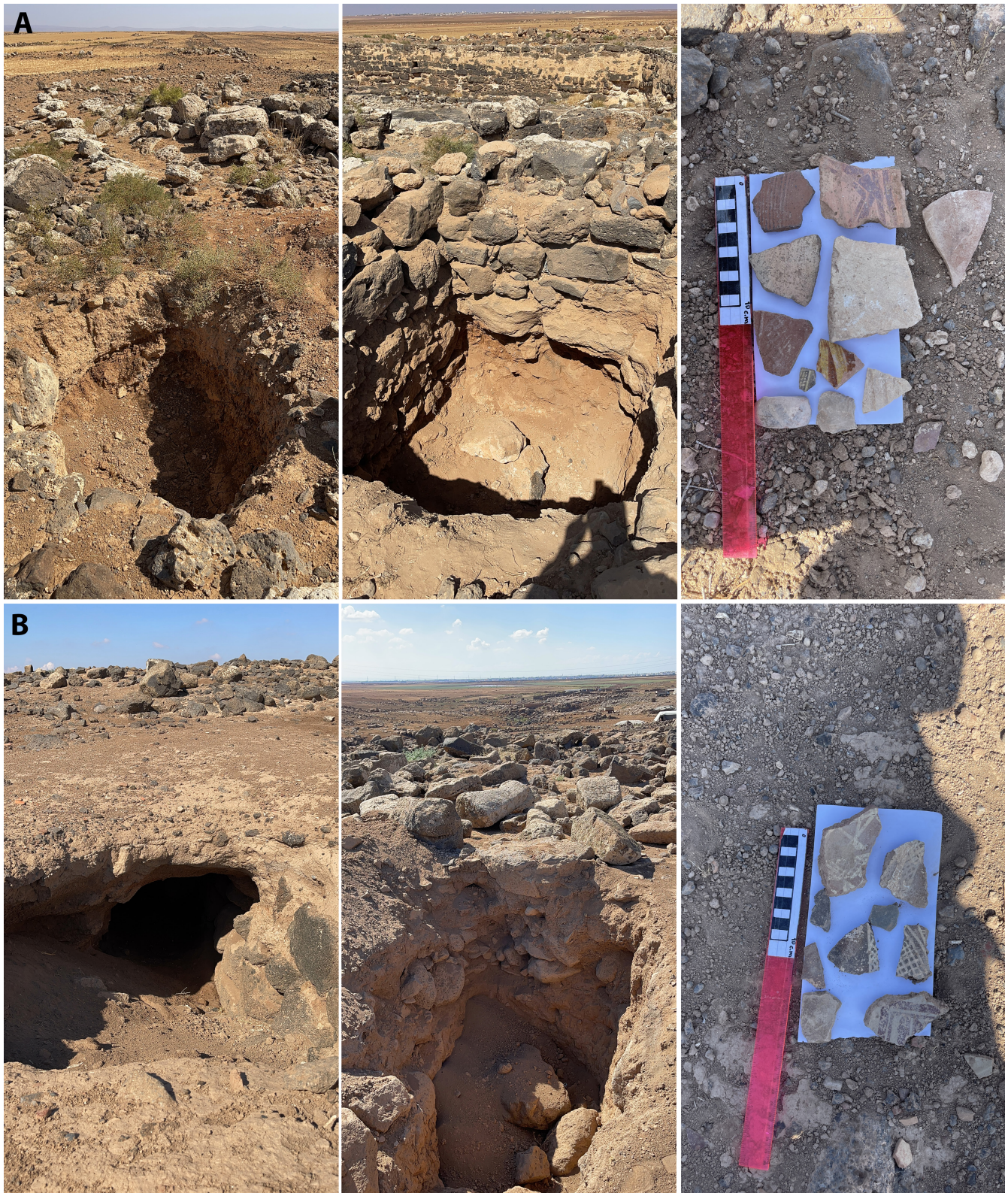


FIGURE 15 | (A) A looting pit with pottery sherds scattered on the surrounding sediment at Khirbet Hamas, located approximately 3 km south of Ma'araba and 1 km northwest of Wadi Al Zaatar. (B) A looting pit with pottery sherds at Al Qnaia site, providing evidence linking the site to the Mamluk and Ayyubid periods. These findings highlight the importance of field documentation in assessing damage to previously unrecorded archaeological sites.

visits allow for direct visual assessment of site condition, damage severity and artefact distribution, which cannot be achieved through remote sensing alone. This is evident at the Al Mintar site in Al Teibeh, a Late Epipalaeolithic (Natufian) site, where discarded stone artefacts were found within and around looting pits (Figure 14). Also, a clear stratigraphy revealed four distinct layers containing bone and lithic artefacts (Al Kassem et al. 2025).

Similarly, Al Qnaia's significance was first identified during field surveys in 2015, when visible structures were documented within looting pits (Al Kassem 2016). A follow-up visit in 2023 confirmed earlier observations, revealing numerous pottery fragments, ash layers indicative of hearths and evidence linking the site to the Mamluk and Ayyubid periods (12th–14th centuries) (per. Comm. G and Ahmad 2024) as seen in Figure 15. In contrast, satellite imagery lacks the resolution necessary for such detailed analyses. Accordingly, it is difficult to believe that satellite imagery can play a crucial role in determining the severity and accuracy of damages without field assessment.

5.6 | Importance of Remote Sensing for Cultural Heritage Preservation

Based on the above, it is clear that remote sensing imagery is not able to record all types of damage; however, it plays a fundamental role in documenting threats and damages to archaeological sites in a conflict, or in remote areas where field monitoring is difficult or costly. In this study, satellite remote sensing was excellent for revealing a significant number of sites that were subjected to certain types of looting and construction, especially those in open areas. Many of these sites, often away from large modern settlements, had been previously unrecorded. The efficiency of satellite-based methods is a critical factor in determining protection priorities and rapid intervention, especially during active conflict. It can help to draw attention to threats and be used in awareness raising in an effort to prevent further looting or further construction. As we have demonstrated in this study, it is also helpful to identify and prioritize sites for ground-based assessment, which is crucial for gathering a fuller picture of damage types and extents.

Supplementing documentation and the evaluation of satellite imagery with field verification is important when dealing with large datasets (Baratta and Magli 2025) and small detail. Remote sensing of satellite imagery from different dates provides a distinct advantage of allowing us to 'look back through time'. In the case of Daraa, it has identified a correlation between pastoral movements and the emergence of looting pits (see also Al Kassem et al. 2024, Figure 8, p. 11). This correlation could not have been made with the data from site visits alone.

Used as a near-as-possible real-time monitoring tool, it can be used by communities, local and national authorities to take timely action and prevent further looting. This is facilitated by the fact we have used freely available, ready-to-use imagery sources. More effective protection and enhanced monitoring operations could be implemented using drones equipped with advanced sensors (i.e., Blu, LiDAR, Thermal, Multispectral and

Hyperspectral sensors). By integrating these technologies, drones can provide continuous and accurate monitoring of archaeological sites, enabling the detection of suspicious activities in real time and allowing specialists to take rapid action before damage worsens. This approach enhances strategies to protect heritage sites with advanced and effective methods. Additionally, digital documentation processes, such as laser scanning (Elbshbeshi et al. 2023), can play a crucial role in the conservation and restoration of heritage sites. However, to implement this effectively, there must be more emphasis placed on heritage protection projects that involve, train and empower Syrian cultural heritage managers, archaeologists and community members.

6 | Conclusions

The Daraa region in southern Syria contains a rich archaeological landscape that has suffered extensive damage due to conflict, looting and unregulated development. This study assessed 28 sites using both satellite imagery and ground verification, comparing their effectiveness in detecting different damage types. The results revealed that 69% of damage types were only recorded through field surveys, underscoring the limitations of remote sensing alone. Additionally, the study highlighted significant temporal gaps in satellite imagery, which led to biased assessments, as well as difficulties in distinguishing looting pits from natural geological features in basalt-covered areas. Looting using explosives was also frequently misclassified, demonstrating the need for field verification to determine the true extent and severity of damage.

The integration of remote sensing and on-ground evaluation, combined with an understanding of local circumstances, provided an effective and comprehensive approach for assessing and documenting archaeological sites affected by armed conflict in southern Syria. This hybrid methodology enables the rapid creation of a damage database, ensuring safety, reducing costs and efficient resource allocation. Field visits provided detailed insights into the extent and severity of damage, helping to determine priority sites for urgent interventions such as first aid measures or emergency excavations. Additionally, field assessments allow for relative dating of sites, particularly through artefacts recovered from looting pits. Beyond data collection, ground surveys strengthen communication with local communities, fostering engagement and collaboration in site monitoring, thereby fostering a stronger sense of responsibility for heritage protection. This community involvement is crucial for cultural heritage protection as it cultivates a sense of ownership and responsibility, forming a strong foundation for long-term site preservation. Conversely, satellite imagery offered a broader, large-scale view of damage distribution over time, though its effectiveness depends on the availability and frequency of images. It significantly reduces effort, time and costs while minimising risk, making it a powerful tool that complements the precision of on-site evaluations.

Satellite imagery plays a critical role in cultural heritage management under restricted conditions, serving as a key tool for rapid ground-truthing and the efficient identification of high-priority sites for excavation. We therefore propose a three-tiered approach for assessing, documenting and prioritizing damaged sites: First, satellite imagery should be used to identify

damaged archaeological sites, both recorded and unrecorded, and to compile a preliminary list of sites most in need of ground verification. This prioritization will be influenced by factors such as assumed severity of damage, location, rarity of site type, accessibility and safety. Second, field assessments should be conducted to verify satellite-detected damage for selected sites. This can help to refine damage classifications across the larger sample of sites assessed on the imagery. This is not foolproof, but it can allow for reasonable assumptions to be made, which could be tested through our proposed third stage. These field visits can also help to prioritize sites requiring immediate intervention. Third, if possible, aerial photography (e.g., drones) should bridge the gap between satellite imagery and field verification, providing high-resolution documentation of damage at a site level for a much larger sample of sites. By integrating satellite-based monitoring, targeted fieldwork and advanced imaging technologies, this multilayered methodology ensures a more accurate, efficient and responsive approach to safeguarding Syria's endangered archaeological heritage.

While the methodological approach may not introduce new technical innovations in remote sensing, this study presents a replicable and practice-oriented contribution to cultural heritage conservation, particularly in conflict-affected and resource-limited areas, which could facilitate future work in other parts of Syria or other conflict areas. Importantly, this framework is not limited to the Syrian context. Its modular structure, grounded in remote identification, field verification and community participation renders it highly transferable to other endangered archaeological landscapes facing similar constraints. Whether in regions impacted by environmental degradation, rapid urbanization or political instability, the methodology is adaptable to different operational capacities. It allows practitioners to calibrate their heritage response strategies based on site accessibility, available resources and the specific types of threats encountered. Future work should aim to enhance automated satellite damage detection, strengthen community engagement and expand drone use for detailed site documentation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Appendix

Details recorded during the field visits conducted between 2015 and 2023 and available images from 2014, 2016–2017 and 2020–2022.

Nr	Site	Recorded	Method	Disturbance type	Disturbance cause	Disturbance date	Disturbance type	Date 1	Date 2
1	Tell Al Teibeh (Al Kown)	Yes	Ground	Looting	Excavation (hand)	Stone of mosaic and pottery	Occurred on	May-15	
		Yes	Ground	Looting	Excavation (Bulldozing/machinery)		Occurred on	Sep-23	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	May-15	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	Sep-23	
2	Old town of Al Moutayah	Yes	Satellite	Looting	Excavation (hand)	Pottery	Occurred between	Jan-14	Nov-16
		Yes	Satellite	Looting	Excavation (hand)		Occurred between	Nov-16	Feb-17
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	Sep-23	
		Yes	Ground	Military	Shelling		Occurred on	May-15	
		Yes	Ground	Unknown	Demolition		Occurred on	Sep-23	
3	Tell Al Koutaybah	Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		Yes	Ground	looting	Excavation (bulldozing/machinery)	Stone artefacts and pottery	Occurred on	Sep-23	
4	Train station (Al Teibeh)	Yes	Satellite	Looting	Excavation (hand)	Stone artefacts and pottery	Occurred between	Jan-14	Feb-16
		Yes	Satellite	Looting	Excavation (hand)		Occurred between	Jan-14	Feb-16
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		Yes	Ground	Looting	Wall collapse		Occurred on	Sep-23	
		Yes	Ground	Looting	Roof and window		Occurred on	Sep-23	
		Yes	Ground	Looting	Felling trees		Occurred on	May-15	

Nr	Site	Recorded	Method	Disturbance type	Disturbance cause	Disturbance date	Disturbance type	Date 1	Date 2
5	Train station (Bosra)	Yes	Satellite	Looting	Excavation (hand)		Occurred between	Mar-16	May-17
		Yes	Satellite	Looting	Excavation (hand)		Occurred between	Oct-20	Dec-21
		Yes	Satellite	Looting	Excavation (bulldozing/machinery)		Occurred between	Oct-20	Dec-21
		Yes	Satellite	Unknown	Construction		Occurred between	Oct-20	Dec-21
		Yes	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
6	Train station (Garz)	Yes	Satellite	Looting	Excavation (hand)		Occurred between	Feb-16	Apr-16
		Yes	Satellite	Looting	Excavation (hand)		Occurred between	Jul-16	Dec-16
		Yes	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	May-15	
		Yes	Ground	Military	Burnt		Occurred on	May-15	
		Yes	Ground	Military	Wall collapse/crack		Occurred on	May-15	
7	Old town of Al Jeezah	Yes	Ground	Looting	Excavation (hand)	Stone artefacts and pottery	Occurred on	Sep-23	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
8	Old town of Khirbet Gazalah	Yes	Ground	Looting	Excavation (hand)	Pottery	Occurred on	Sep-23	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
9	Railway	Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Military	Military	Cut		Occurred on	Sep-23	
10	The Roman Road	Yes	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
11	Al Omary Mosque	Yes	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		Yes	Ground	Military	Drilling		Occurred before	May-15	
		Yes	Ground	Looting	Excavation (hand)		Occurred before	May-15	

Nr	Site	Recorded	Method	Disturbance type	Disturbance cause	Disturbance date	Disturbance type	Date 1	Date 2
12	Al Omary Mosque	Yes	Ground	Military	Wall collapse/crack		Occurred before	May-15	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		Yes	Ground	Looting	Excavation (explosive)		Occurred on	May-15	
		Yes	Ground	Looting	Wall collapse/crack		Occurred on	May-15	
13	Ma'araba (Al Omary) Mousue	Yes	Ground	Military	Demolition		Occurred on	May-15	
		Yes	Ground	Domestic	Construction		Occurred between	Sep-23	
14	Roman Threatre	Yes	Satellite	Looting	Excavation (hand)		Occurred between	Sep-14	Jun-15
		Yes	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		No	Ground	Looting	Excavation (hand)	Stone artefacts and pottery	Occurred on	Sep-23	
		No	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		No	Ground	Looting	Excavation (explosive)		Occurred on	May-15	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
16	Om Sanam	No	Ground	Looting	Excavation (hand)	Stone artefacts	Occurred on	Sep-23	
		No	Ground	Domestic	Occupation/continued use		Occurred on	Sep-23	
		No	Ground	Domestic	Road/track		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (hand)		occurred on	Sep-23	
17	Umm al-Hawa	No	Ground	Looting	Excavation (hand)		occurred on	Sep-23	
18	Al-Rouysia	No	Ground	Looting	Excavation (hand)	Stone artefacts	occurred on	Sep-23	
19	Al Mintar	No	Satellite	Agricultural/pastoral	Construction		Occurred between	Feb-16	Mar-17
		No	Satellite	Agricultural/pastoral	Grazing/animal movement		Occurred between	Feb-16	Mar-17
		No	Satellite	Looting	Excavation (hand)		Occurred between	Feb-16	Mar-17
		No	Ground	Looting	Excavation (explosive)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred between	Sep-23	
		No	Ground	Agricultural/pastoral	Construction		Occurred before	Sep-23	
		No	Ground	Agricultural/pastoral	Clearance (bulldozing/leveling)		Occurred on	Sep-23	
		No	Ground	Domestic	Road/track		Occurred on	Sep-23	

Nr	Site	Recorded	Method	Disturbance type	Disturbance cause	Disturbance date	Disturbance type	Date 1	Date 2
20	Khirbet Al Jeezah	No	Satellite	Looting	Excavation (hand)	Stone artefacts, glass and pottery	Occurred between	Oct-14	Feb-16
		No	Satellite	Looting	Excavation (hand)		Occurred between	Feb-16	Mar-17
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred on	Sep-23	
		No	Ground	Looting	Clearance (bulldozing/leveling)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
21	Al Jeezah 2	No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (explosive)		Occurred on	Sep-23	
22	Khirbet Al-Moushaydah	No	Ground	Looting	Excavation (bulldozing/machinery)	Stone artefacts and pottery	Occurred on	Sep-23	
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred between	Sep-23	
		No	Ground	Agricultural/pastoral	Construction		Occurred between	Sep-23	
23	Khirbet Abu Al-Hwash	No	Ground	Looting	Excavation (hand)	Stone artefacts	Occurred between	Sep-23	
24	Khirbet Hamas	No	Satellite	Agricultural/pastoral	Grazing/animal movement	Stone artefacts and pottery	Occurred between	Oct-20	Jan-22
		No	Satellite	Agricultural/pastoral	Construction		Occurred between	Oct-20	Jan-22
		No	Satellite	Looting	Excavation (hand)		Occurred between	Oct-20	Jan-22
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
25	Khirbet Souhoob	No	Ground	Looting	Excavation (hand)	Stone artefacts and pottery	Occurred on	May-15	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred between	May-15	
		No	Ground	Looting	Excavation (hand)		Occurred between	Sep-23	
		No	Ground	Looting	Dump		Occurred between	Sep-23	
		No	Ground	Looting	Road/track		Occurred between	Sep-23	

Nr	Site	Recorded	Method	Disturbance type	Disturbance cause	Disturbance date	Disturbance type	Date 1	Date 2
26	Khirbet Gasoum	No	Satellite	Looting	Excavation (hand)	Pottery	Occurred between	Jan-14	Oct-14
		No	Satellite	Agricultural/pastoral	Grazing/animal movement		Occurred between	Oct-14	Feb-16
		No	Satellite	Agricultural/pastoral	Construction		Occurred between	Oct-14	Feb-16
		No	Satellite	Looting	Excavation (hand)		Occurred between	Feb-16	Mar-17
		No	Satellite	Agricultural/pastoral	Road/track		Occurred between	May-20	Oct-20
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Construction		Occurred between	Sep-23	
		No	Ground	Agricultural/pastoral	Road/track		Occurred between	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
27	Khribet Al Qnaia	No	Satellite	Agricultural/pastoral	Construction	Stone artefacts and pottery	Occurred between	Jan-14	Feb-16
		No	Satellite	Looting	Excavation (hand)		Occurred between	Jan-14	Feb-16
		No	Satellite	Agricultural/pastoral	Construction		Occurred between	Feb-16	Mar-17
		No	Satellite	Looting	Excavation (hand)		Occurred between	Feb-16	Mar-17
		No	Satellite	Agricultural/pastoral	Construction		Occurred between	May-20	Jul-21
		No	Ground	Agricultural/pastoral	Construction		Occurred on	May-15	
		No	Ground	Agricultural/pastoral	Construction		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (hand)		Occurred on	May-15	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred between	Sep-23	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred before	Sep-23	
		No	Ground	Agricultural/pastoral	Grazing/animal movement		Occurred before	May-15	
28	Khirbet Tabeel	No	Satellite	Agricultural/pastoral	Construction	Pottery	Occurred between	Feb-16	Mar-17
		No	Satellite	Agricultural/pastoral	Grazing/animal movement		Occurred between	Feb-16	Mar-17
		No	Ground	Looting	Excavation (hand)		Occurred on	Sep-23	
		No	Ground	Looting	Excavation (bulldozing/machinery)		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Road/track		Occurred on	Sep-23	
		No	Ground	Agricultural/pastoral	Construction		Occurred on	Sep-23	
		No	Ground	Unknown	Dump		Occurred on	Sep-23	