



Mapping an ancient city with a century of remotely sensed data

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The rapidly growing global population places cultural heritage at great risk, and the encroachment of modern settlement on archaeological sites means that valuable information about how past societies worked and interacted with the environment is lost. To manage and mitigate these risks, we require knowledge about what has been lost and what remains, so we can actively decide what should be investigated and what should be preserved for the future. Remote sensing provides archaeologists with some of the tools we need to do this. In this paper we explore the application of multitemporal, multisensor data to map features and chart the impacts of urban encroachment on the ancient city of Jerash (in modern Jordan) by combining archives of aerial photography dating back to 1917 with state-of-the-art airborne laser scanning. The combined results revealed details of the water distribution system and the ancient city plan. This demonstrates that by combining historical images with modern aerial and ground-based data we can successfully detect and contextualize these features and thus achieve a better understanding of life in a city in the past. These methods are essential, given that much of the ancient city has been lost to modern development and the historical imagery is often our only source of information.

archaeology | remote sensing | urban | multitemporal | heritage management

Airborne and satellite remote-sensing techniques provide archaeologists with the tools to do nonintrusive studies across whole landscapes far more expediently and cheaply than ground-based surveys. In recent years much emphasis has been placed on using these tools for recording damage caused by conflict and looting (1–4) to sites in the Middle East and beyond. While damage caused by encroachment of modern settlements is more gradual, it is nonetheless serious (5–7). The rapid pace of this development in the region (Fig. 1) means that there is a real need to undertake work of this nature now, so that features containing significant societal and environmental information can be identified, analyzed, contextualized, and preserved for the future.

In this paper, we demonstrate the utility of using multitemporal, multisensor mapping of complex urban sites, using the city of Jerash in Jordan as an example. By combining state-of-the-art airborne laser scanning (ALS) or light detection and ranging (LIDAR) and 100 y of archival aerial photography, we can obtain detailed mapping of extant archaeological features and record further archaeological remains lost due to changes in land use and encroaching urbanization. Recording and preserving these features is of vital importance in attaining a holistic understanding of the ebb and flow of urban societies in the past, and this understanding, in turn, is fundamental for managing urban development and change in the present.

Ancient Gerasa, modern Jerash, is one of the key archaeological sites in the Middle East due to its state of preservation. It is the second most visited tourist site in Jordan after Petra. Beginning in the Neolithic period the location yields a so-called

“megasite” with numerous structures (8, 9). In the Hellenistic period, Jerash developed as a noteworthy settlement, and in the Roman, Byzantine, and Early Islamic periods the site underwent intense urban development (10), which was interrupted by the earthquake that hit the region on 18 January 749 CE (11). Located on two sides of the steep wadi of Jerash, known in antiquity as the river Chrysorrhoeas (the Golden River), the city prospered during these periods (12). Limestone was the main resource for building material in Jerash. It was extensively quarried both within the city and in its surroundings. Walls enclosed the city, measuring more than 4 km, in the second century CE (13, 14). Gerasa was equipped with public monuments and colonnaded streets, largely situated on the western bank of the river (Fig. 2). In the Byzantine and Early Islamic periods numerous churches and a mosque (15) were erected in the city, and the population peaked. The urban expansion and intensification of land use within the Roman-period city walls lasted until the earthquake in 749 CE (16). This earthquake, documented in historical sources, had a devastating impact not only on Gerasa but also on other cities in the wider region. After the earthquake, city life declined heavily, and only small parts of the city were rebuilt. Medieval (Ayyubid-Mamluk period) settlement has been detected (17), but when Ulrich Jasper Seetzen visited the city in 1806 the city was largely abandoned, and mainly nomadic Bedouin were

Significance

Understanding how people in the past adapted to environmental and economic challenges can help us anticipate and meet these challenges in the present. However, these very processes threaten the physical remains embodying this information worldwide: Urban expansion and resource exploitation mean that the quantity and quality of archaeological information are diminishing daily. In this work, we demonstrate how multitemporal aerial photography and modern airborne laser scanning are invaluable tools for mapping the remaining archaeological features extant in the present and for adding context to them from what has been lost. This knowledge enables cultural heritage administrators and archaeologists to actively monitor, understand, and manage the existing remains to make sure important information is not lost to posterity.

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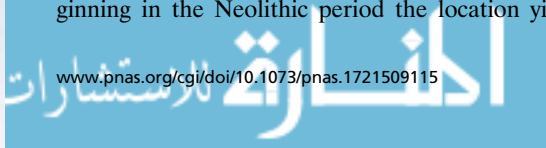
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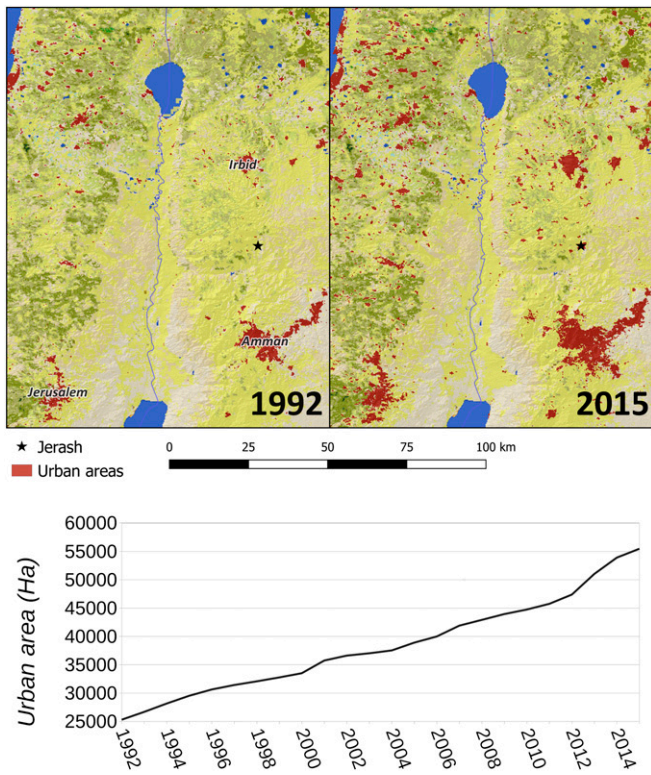


Fig. 1. (Upper) Urban areas across the region from the European Space Agency Climate Change Initiative (ESA CCI) global landcover dataset from 1992 and 2015. (Lower) The nearly exponential growth of urban areas in Jordan in the same period. ©ESA Climate Change Initiative - Land Cover project 2017.

present (18). Other travelers mention sparse settlement at Jerash in the early 19th century (19). The site was extensively resettled in the late 19th century when Circassians were moved there by the Ottoman authorities (20). This settlement was located mainly on the eastern bank of the Chrysorrhoeas. The resettlement of Jerash subsequently covered numerous ancient features, and little is known about the archaeology of the eastern part of Gerasa (14). Since 1948, the population has increased immensely, because since 1967 the environs of Jerash have come to house several tens of thousands of Palestinian refugees divided between the so-called “Souf Camp” and “Jerash/Gaza Camp,” which have developed into small towns in their own right. In 2015 the modern city of Jerash had 50,745 inhabitants with another additional 29,000 in Gaza Camp and more than 19,000 registered refugees in Souf Camp (21). Both camps are close to the city. Therefore, in the last 100 y, Jerash has continuously experienced an explosive population growth (Fig. 3), and many documented and undocumented archaeological features have been destroyed (22–24).

While the remains within the ancient city have been subject to intensive archaeological investigation for more than 100 y (25, 26), there has been little attempt to systematically map archaeological features across the city. Early surveys in the 19th century, such as those by Bankes, Buckingham (27), Burckhardt (28), Rey (29), and Kiepert (30), are at best figurative, with the exception being Barry’s 1820 plan (27). Later plans, namely those by Schumacher (31) and Fisher and Hucklesby (25), are more meticulous but tend to focus on standing monumental architectural remains and excavated buildings, excluding less obvious surficial features and neglecting those pertaining to more mundane aspects of urban infrastructure. Lepaon’s 2011 plan (32) is currently the most widely used, as it incorpo-

rates results from modern excavations. However, its use is problematic due to many discrepancies in the scale and spatial location of the features (Fig. 4), even compared with the cadastral mapping used as the backdrop for the same plan.

In recent years both ALS and archival aerial imagery have become fundamental to archaeological practice around the world. The ability of the former to penetrate vegetation, enabling the mapping of archaeological remains in densely forested regions where remote-sensing approaches historically could not be applied, has been transformative (33, 34). The declassification of historic aerial and satellite imagery has also led to their widespread use. In particular, the application of 3D reconstruction and photogrammetric techniques has enabled the creation of historic digital elevation models (DEMs), facilitating both the quantitative measurement of topographic change and the accurate rectification of these data (35, 36).

Remote-sensing techniques have previously been applied on landscape scales in the region using lower-spatial-resolution satellite imagery (37–42). The increasing availability of high-resolution data has made possible the mapping of damage to sites by conflict and looting (1, 3, 43). Additionally, extensive aerial photographic campaigns have been conducted in many places around the world. In Jordan an aerial archaeological survey has been undertaken by Kennedy et al. (44, 45). However, there has been comparatively little application of these high-resolution data for the systematic mapping of individual urban sites. This is partly due to their challenging complexity but also because many features and areas have already been obscured or destroyed in recently acquired data.

This work aims to address these issues by producing an accurate, multitemporal systematic map of archaeological remains within the city walls of Jerash and, in particular, to record features related to water management in its wider environs. Doing this is of prime importance, not only to gain a more complete understanding of this city but also to elucidate the possibilities of multitemporal, multisensor methods with worldwide applicability for managing and preserving valuable urban evidence for the future.



Fig. 2. Views over the Oval Piazza at Jerash from 1898 (Image courtesy of Library of Congress, Prints & Photographs Division, LC-DIG-matpc-04523) (A) and 2015 (Danish-German Jerash Northwest Quarter Excavation Project) (B). Note the extensive clearance of rubble, construction of tracks, and reconstruction of ruins in foreground and expansive urbanization in background in B.

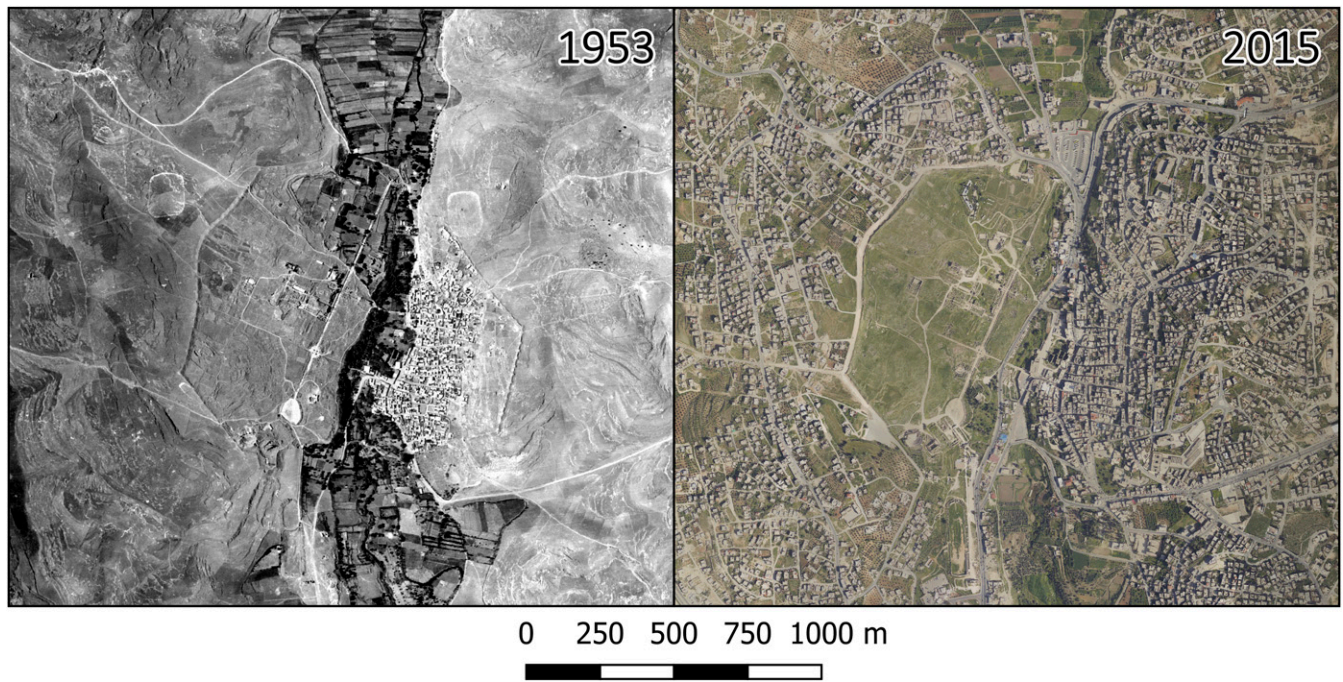


Fig. 3. Urban expansion in and around Jerash is dramatic. Since 1953 much of the area around the city has been developed. Within the city walls, the eastern half of the city is nearly totally overbuilt.

Approach

Modern color orthophotographic and ALS data were purchased from the Jordanian government. These were cocollected using a real-time kinematic GPS and inertial measurement, meaning that the data were accurately georeferenced to local and global spatial reference systems. This was verified using features recorded by total station survey in the northwest quarter of Jerash, and the spatial error was found to be within two pixels in the orthophotograph (0.2 m). As such, these data provide an accurate backdrop for the geo-referencing of archival photographic datasets and the evaluation of prior surveys.

These data were used to perform initial mapping of extant archaeological features. Visualization techniques appropriate to enhancing local topographic contrast for archaeological interpretation, including residual relief modeling (46, 47), skyview factor (48–50), and local dominance (51, 52) were applied to the ALS data.

Scans of the archival photographs were acquired (*SI Appendix, Table S1*). Individual photographs were rectified and georeferenced using AirPhotoSE. Sequences of images from 1939 and 1953 were processed using Agisoft PhotoScan to derive georeferenced orthoimagery. Creation of a digital terrain model (DTM) from these sequences was also attempted; however, the poor condition and limited geometric control of the scanning process meant that the attainable accuracy was low. Only the 1953 sequence produced a usable model, with a spatial resolution of 2 m and 1-m vertical accuracy. While this is coarse for prospecting archaeological features, it is useful for examining topographic features relating to cultivation terraces and water management both within and outside the city walls.

The georeferenced data were interpreted in GIS software. Possible archaeological features were vectorized as polygons. The mapping process was performed in several passes. First, features in the 2015 ALS residual relief and sky-view factor data were digitized, using the 2015 aerial photography as a check to make sure erroneous features such as recent spoil heaps and stone dumps were not recorded as features. Then, the 2015 im-

agery was compared with the older images so that areas obscured by recent activity on the site could be identified. Features discernible in these images were then recorded. The attribute data for the digitized polygons record a classification for the type of feature, the dates the feature was first and last observed, and a confidence level indicating the degree of confidence in the interpretation of the features. (Vectorized interpretation data are available at <https://figshare.com/s/80dc8add945d65bc8238>.)

Results

Summary. The results of the mapping reveal a palimpsest of archaeological features within the city walls (Fig. 5). The majority of these had not previously been mapped. The greatest density of these features is in the western half of the city, with many fewer in the eastern half. Even in the earliest aerial imagery the modern settlement had already obscured the archaeological features in this area, and field clearance related to modern cultivation is most intense adjacent to the settlement.

The mapped features are difficult to interpret, as they indicate surficial remains related to multiple phases of occupation over a considerable span of time. This makes ascribing phasing or detailed, functional interpretation complex and requires carefully targeted ground-based work to unpick. This should include surface survey, geophysics, and trial excavation. Comparison between the results of surface survey in the northwest quarter and the features detected in the airborne survey is encouraging in this respect and indicates that there is good correlation between the surveys (*SI Appendix, Fig. S2*). While the features in the ground-based survey are better defined, most of them are visible in the airborne data. Additionally, a number of possible archaeological features not visible on the surface were detected.

It is likely that many of the surficial features relate to the latest phases of occupation, especially in the southwest quarter where many complexes of rectangular features are likely indicative of the remains of buildings. Extensive clearance of rubble from the fields within the city walls (*SI Appendix, Fig. S3*) is likely contemporaneous to these features, as such together probably

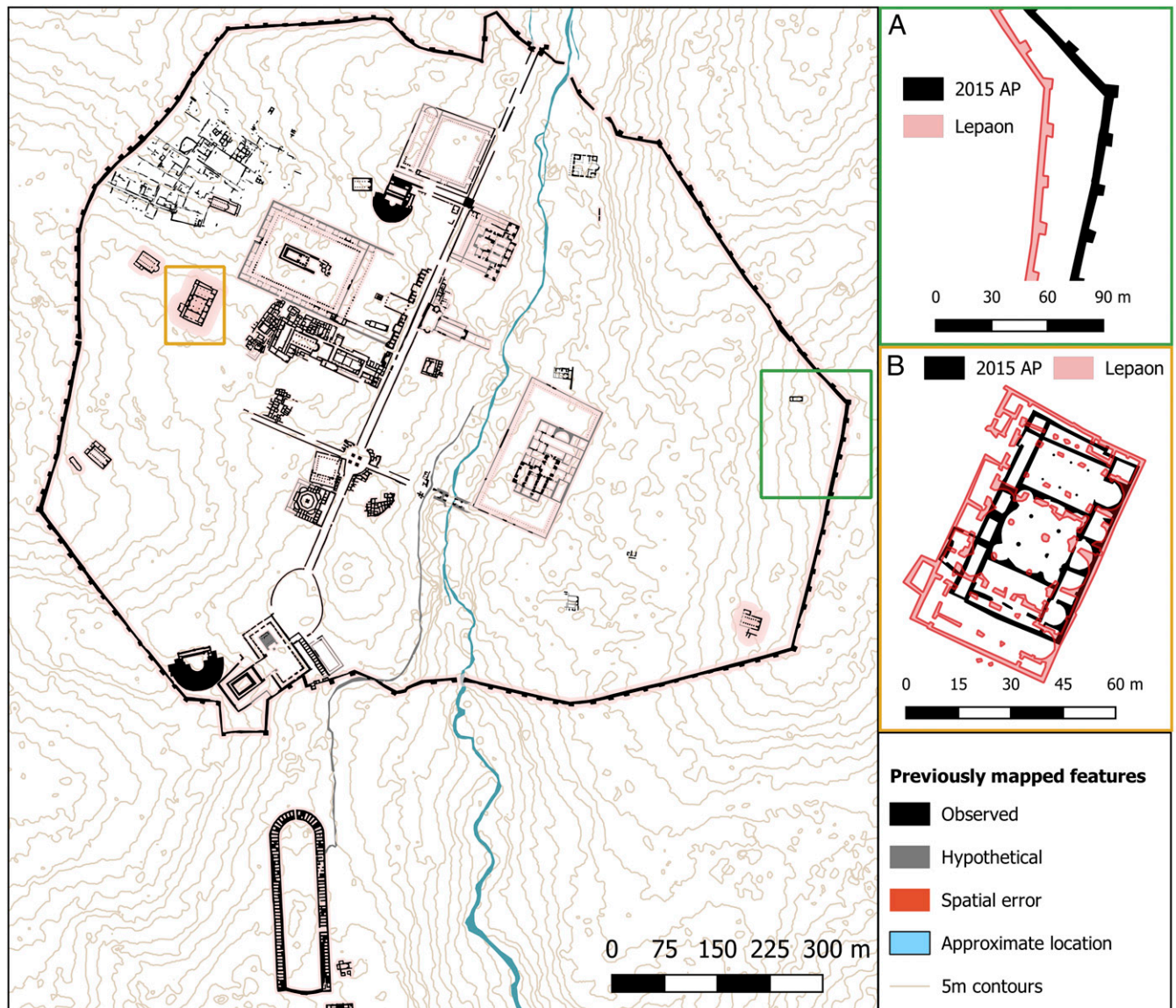


Fig. 4. Previously mapped features at Jerash after Schumacher (31), Kraeling (25), Lepaon (32), and the Danish-German Jerash Northwest Quarter Project (53), showing observed and extrapolated features and spatial uncertainties compared with airborne data. *Inset A* shows 25-m displacement of city wall in Lepaon's plan. *Inset B* shows scaling errors of 125% at the Church of the Three Saints.

indicate the low-intensity medieval and later occupation of the city observed in excavations in the northwest quarter (17, 53).

While the complexity of the identified features makes interpretation of phasing difficult, it is possible to infer elements of the city's street plan during different phases using the orientation of the features with respect to excavated structures (Fig. 5, *Inset*). It is apparent that there are at least two alignments: one respecting the orthogonal alignment of the Roman buildings and a second, more organic radial alignment likely indicating activity following the earthquake.

Water Infrastructure. Some of the most apparent features are elements of urban infrastructure within the city. In particular, a complex system of channels relating to water supply and reuse was detected in the aerial imagery. While these have been previously investigated (12, 54–56), they have not been integrated with the wider mapping of the city, and this work provides additional insight into their form and function. A constant and reliable water-management system is essential to maintaining a

large urban population in a semi-arid region with little precipitation. Modern Jerash only has one perennial spring, Ain Kerawan (Fig. 6), which is located in the northern part of what was within the boundaries of the walled ancient city. Since this source is situated down in the wadi-bed, its water could not, in times before pumping systems, supply higher-lying areas of the city. Therefore, water from springs located in the higher terrain around the city had to be brought in. Intensive systems of both functioning and relict irrigation channels are apparent in the aerial photography of the city and its environs.

It is possible to investigate potential areas of supply within the city using these channels in conjunction with the terrain model derived from the 1953 images and the published locations of springs and cisterns within the city. In the western half of the city ~55% of the ancient city could be supplied by the spring and reservoir at Birketein or could be abstracted from the wadi further upstream, evidenced by a complex network of channels following the contours of the western slope of the valley and into the city. While a number of these clearly relate to medieval and

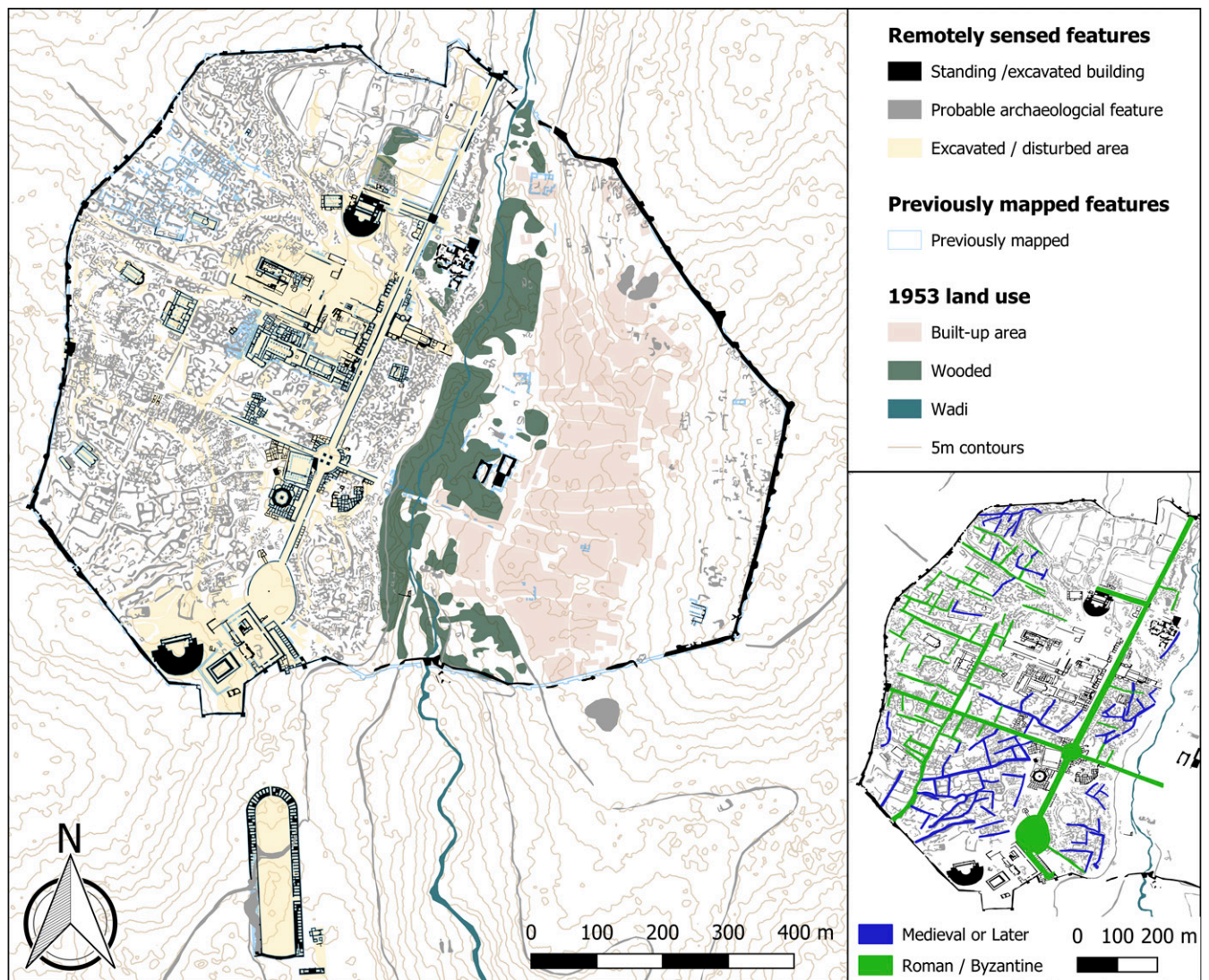


Fig. 5. Results of the mapping process, showing newly identified features and previously mapped structures. The results demonstrate that a substantial number of archaeological features can be identified. These are complex to interpret, but the outline of a probable road network (*Inset*), and urban subdivisions are visible, along with a large number of subrectangular features likely indicative of building foundations.

later irrigation, it has been postulated that highest elevation of these dates to antiquity (54, 55). The densely populated northwest and southwest quarters lie at a higher elevation than these channels can supply. In the northwest quarter two large cisterns have been identified (53) which probably were supplied by the northwest aqueduct identified by Boyer (54, 55). While the course of this aqueduct is fragmentary, it appears to run upslope of Wadi Jerash, abstracting water from springs at high elevation. The supply for the cistern identified in the southwest of the city has yet to be identified. However, a short section of a feature very similar to the double-banked sections of the northwest aqueduct (Fig. 6, *Inset a*) meets the city wall (Fig. 6, *Inset b*). The supply for the possible southwest aqueduct is as yet undetermined, but fragmentary linear features to the north and west may represent elements supplying this feature, likely from the springs at Deir el-Liyat or sources potentially more distant such as the those at Souf.

While this aqueduct could have been supplied directly by gravity-fed channels from the springs to the north, the features running west span a shallow valley for a distance of 1,700 m, suggesting the existence of an inverted siphon related to this aqueduct. Inverted siphons are well known from other cities

during the Roman period but have not yet been identified at Jerash (57, 58). While siphons of this length are unusual, far more extensive examples are known elsewhere in the Roman provinces, for example at Smyrna (59) and Pergamon (60), both in modern Turkey, and at Lyon (61) in modern France. Closer to Jerash, the bath house at the city of Gadara in Jordan was supplied by a double inverted siphon connected to a system of aqueducts over 100 km in length (62, 63). While two large cisterns are identifiable on either side of the valley close to the ends of the possible siphon in Jerash, their respective elevations mean that they could not have functioned together as header and receiver tanks to supply the city. Further work is required at Jerash to identify and investigate any surviving portions of this feature, as the evidence for its existence is inconclusive.

In the eastern part of the city, additional to the spring at Ain Kerawan, the existence of a large cistern at higher elevation has been identified (55). This is possibly fed by a spring that flowed as recently as the 1920s. Together these sources are capable of supplying over 93% of the eastern city. However, fragmentary linear features indicating parts of further aqueducts enter the city from the north and east, suggesting further supply was required

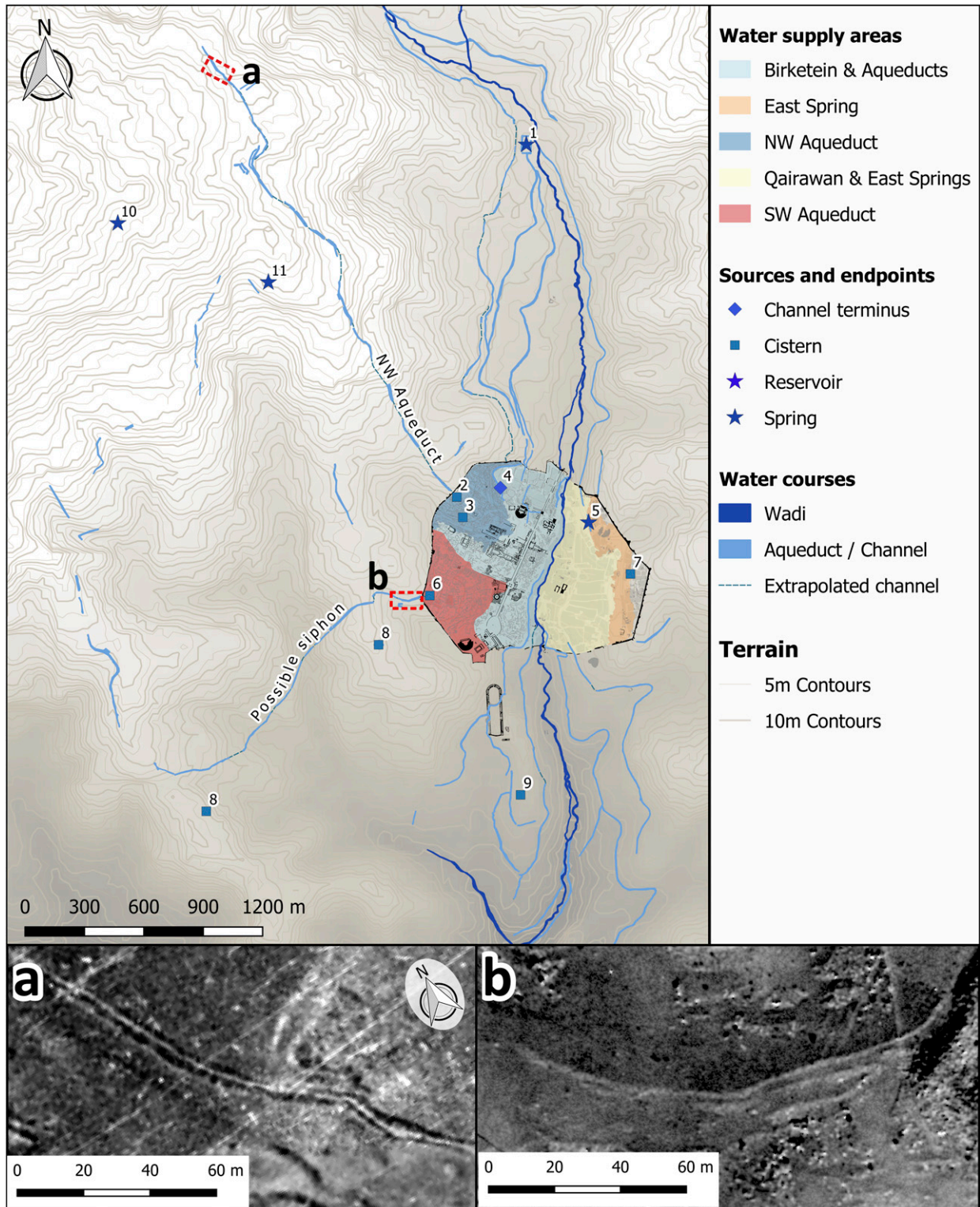


Fig. 6. Water sources and infrastructure at Jerash mapped from the remotely sensed 100-y data record, showing supply channels, probable supply areas calculated from the 1953 DTM assuming gravity-fed, open-channel distribution only and points representing sources of this supply. The major elements are as follows: (1) Spring and reservoir at Birketein. (2 and 3) Cisterns in the northwest quarter. (4) End point of channels supplied by Birketein. (5) Ain-Kerawan spring. (6) Cistern in the southwest quarter. (7) Large cistern in the east of city identified by Boyer (54). (8) Possible reservoirs associated with a possible siphon supplying the southwest of the city. (9) Cistern downstream of the city. (10 and 11) Springs in the vicinity of Deir El Liyat. (Inset A) Section of the northwest aqueduct in a 1953 photograph showing a distinctive double-banked channel. (Inset B) A portion of the possible southwest aqueduct meeting the city wall, showing construction similar to the northwest aqueduct.

to meet demand. The northern channel enters the city at ~600 m and appears to follow the contours of the eastern slope of the valley, possibly from Bisas er-Rum. At the southeastern corner a channel is visible running along the contour for a short distance.

The supplies discussed above are capable of providing water to 97% of the area within the city walls and indicate long-standing, intensive abstraction of resources from a large area around the city. Jerash also acts as a nodal point for distribution of this water further down the valley, and at least four channels run south from the city. While a number of these may relate to the supply of potable water to settlements downstream of Jerash, they may also relate to the transportation of gray and wastewater for irrigation and fertilization downstream.

Of particular interest is a channel crossing the Roman hippodrome, resulting in a semicircular subdivision in the hippodrome that was interpreted by earlier travelers as a later use of the hippodrome as an arena for naval battles (*naumachia*) (64). This was disproven by the first excavators (65), but the function and date of the semicircular wall-like structure that divides the hippodrome remained unexplained. However, from the archival imagery it is clear that it relates to a channel supplying water to fields to the southwest, as it maintains elevation over the ruins of the hippodrome. It is also apparent that this must be of a later date. The hippodrome was used in the Roman period for races, and in the Byzantine and Umayyad period it was converted into use for industrial purposes and later for burials. It is probable that the water channels postdate this use and therefore belong to the medieval period, since they are described by the earliest travelers to Jerash and therefore predate the Circassian period.

Discussion

Earlier Imagery and Newly Acquired Data. The results of this work demonstrate conclusively the ability of multitemporal, multisensor remote-sensing techniques to map urban sites. The ability of these methods to map large areas contextualizes ground-based surveys and excavations, enabling a greater understanding of the interactions between urban sites and their periphery. However, doing this without the archival aerial imagery is impossible, as a large proportion of the city and its environs has been disturbed by modern development (Fig. 7). Most of the eastern portion of the city is now lost, and a significant portion of the surrounding area has been built upon. While parts of water-management channels, roads, and field systems still exist in the curtilages of modern houses or road verges, detecting and interpreting these fragmentary features is difficult without the context provided by historical imagery. Indeed, finding these fragments in contemporary data is often dependent on identifying the feature in the earlier imagery and then attempting to discern if anything is still extant today.

While doubtless well intentioned, a large number of archaeological investigations and the clearance of rubble have also taken their toll on the archaeological features. The first duty of archaeologists is to record what they destroy during the process of excavation and to make this information available so that the extent and findings of this work are known. Approximately 29% of the western half of the city is observed in the remotely sensed data as being subject to excavation or clearance. A significant proportion of this is undocumented. This is unfortunate, as the information in these trenches is just as lost to posterity as that obliterated by development. In addition to the excavations themselves, the site is also littered with old spoil heaps and dumps of rubble. These not only obscure surficial features but also potentially confuse stratigraphic sequences by redepositing soil and cultural material. In this context the remotely sensed data are invaluable for defining the extent and impact of undocumented work.

These problems emphasize the need to make these data available to researchers and cultural heritage managers so that they can be used to inform better research questions and man-

Category	Color	Approximate Proportion
Undisturbed	White	45%
Modern construction	Red	35%
Excavated / Cleared	Green	15%
Rubble dumps	Blue	5%

Fig. 7. Impact of recent activity on the ancient city, showing proportions of the area within the city walls affected. While the impact of modern development is most severe, the large areas subject to excavation and clearance mean that even in the protected area only a minority of the area is undisturbed. Please note that the ancient city wall (black line) is either reconstructed in modern times (western side) or is nearly lost to urban development (eastern side).

agement decisions. It is increasingly acknowledged that best practice entails making these data open, so that they are accessible across national and institutional boundaries (66, 67). In light of this, the archaeologically salient features mapped by this project are made available as open data. (Vectorized interpretation data are available at <https://figshare.com/s/80dc8add945d65bc8238>.)

While the historical imagery is indispensable for recording what is lost, modern, high-spatial-resolution, accurately georeferenced data are essential. In addition to providing a 3D baseline for accurate coregistration of the historical data, they provide the best indication of the condition of the site in the present. Only by using these data together can we hope to use them effectively.

The mapped water infrastructure represents activity over a considerable span of time, and it is thus tempting to relate these features to temporal changes in local water source availability and climate changes. However, the period(s) during which aqueducts, cisterns, rock-cut channels, and other types of water infrastructure were in use in Jerash are not yet known in detail (54), although one exception is the well-dated large rock-cut

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cistern in the northwest quarter which Lichtenberger et al. (68) showed was installed in the second century CE and was last repaired in the fifth/sixth century CE. Published paleoenvironmental records from Jerash and the near surroundings are not available, but data from the southern Levant in general suggest that the period of the Hellenistic colonization coincides with a period with more rain. The climate then gradually became drier by ca. 350 CE and again became rainier around 470 CE, and by ca. 670 CE or later the area moved into a much drier climate zone (69). Although our approach based on multitemporal data has a limited temporal depth resolution as to when a feature was constructed, the water infrastructure map presented here may facilitate targeted dating of features that collectively can form a high-definition understanding of urban water availability and its interaction with the regional climate.

Regional and Global Perspectives. The work undertaken here is extensible to the broader region beyond the city, using both airborne and satellite data. However, doing this entails a significant quantity of data, and it is not feasible at the level of detail considered here to achieve this by manual examination. Spectral and morphological classification methods can be used to identify and quantify change in the landscape automatically. There are several approaches to this. Comparing modern ALS data with elevation models photogrammetrically derived from archival aerial and satellite imagery can identify modifications to the ground surface (35, 70). Multispectral satellite imagery can identify material properties based on their reflectance in the visible and infrared regions of the electromagnetic spectrum and can distinguish road surfaces, roofing materials, and cultivation practices from unmodified ground (71, 72). In addition to using these well-established classification methods, recent developments in computer vision and machine learning have engendered the possibility of using these methods to automatically identify potential activity meriting further archaeological investigation (73–76). The multitemporal, multisensor remote approach used in our study is inherently three-dimensional. This means that it can, in theory, also be used as source data to precisely situate 3D reconstructions of lost monuments derived from historical ground-based photography. This approach has been successfully adopted using crowd-sourced images to map and document archaeology lost to the conflict in Syria at Palmyra (77–79).

Summary and Recommendations

Jerash is a well-known multiperiod historic urban site, and the results of the remote-sensing approaches considered here add to

our knowledge of it. By applying state-of-the-art ALS remote-sensing and photogrammetric techniques to archival analog images, we were able to accurately map known archaeological features and to detect a wide variety of previously unrecorded potential features. While the sheer complexity resultant from centuries of urban occupation makes these features difficult to interpret without further ground-based investigation, the broader patterns and topographical details that emerge contribute greatly to the understanding of the site and its development.

These results also highlight the extent to which a portion of the site and its landscape context have been lost to rapid urban expansion over the course of the 20th and 21st centuries. In this respect, it is far from unique. Regionally and globally, much valuable archaeological information is under threat. These threats comprise a rapidly rising population and the resulting urban and agricultural expansion and infrastructural developments, conflict, and looting. Climate change, along with the predicted rise in sea level and increased frequency of extreme weather events, results in accelerating rates of erosion. These processes are implacable and are of a scale that means we will never have the resources to totally mitigate their effects.

Remote-sensing methods allow us to monitor the progress of these threats and identify where the greatest risks are. By exploiting the vast archives of historical aerial and satellite imagery, we can qualify and quantify what has been lost and contextualize what remains. This enables better understanding of what we are losing and provides some of the evidence we need to decide what we should investigate further. In turn, applying a similar multitemporal, multisensor approach to other sites under threat may help us make persuasive arguments when we negotiate what should be preserved for the future.

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