Routledge Taylor & Francis Group

Journal of Field Archaeology

ISSN: 0093-4690 (Print) 2042-4582 (Online) Journal homepage: https://www.tandfonline.com/loi/yjfa20

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To cite this article: Achim Lichtenberger, Rubina Raja, Eivind Heldaas Seland, Tim Kinnaird & Ian A. Simpson (2019) Urban-Riverine Hinterland Synergies in Semi-Arid Environments: Millennial-Scale Change, Adaptations, and Environmental Responses at Gerasa/Jerash, Journal of Field Archaeology, 44:5, 333-351, DOI: 10.1080/00934690.2019.1625619

To link to this article: https://doi.org/10.1080/00934690.2019.1625619

Published online: 25 Jun 2019.

JOURNAL OF FIELD ARCHAEOLOGY
2019, VOL. 44, NO. 5, 333–351
https://doi.org/10.1080/00934690.2019.1625619

Urban-Riverine Hinterland Synergies in Semi-Arid Environments: Millennial-Scale Change, Adaptations, and Environmental Responses at Gerasa/Jerash

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ABSTRACT
This interdisciplinary study addresses issues of urban-riverine hinterland relationships in semi-arid environments over millennia at Gerasa/Jerash in Jordan, presenting research that stimulates new lines of enquiry with much broader implications than those relating to this single site. Through the presentation of new data on wadi-sediment responses to social and environmental change, we assess ways in which urban settlements, their hinterlands, and rivers interact over long time periods and how such changes may be read together with historical sources and shed new light on urban-hinterland dynamics. We explore the hypothesis that synergistic relationships between an urban core and its hinterland are essential to the long-term sustainability of both. Our integrated approach gives new insight into settlement dynamics and resource use and carries implications for our understanding of the present through the past.

KEYWORDS
riverine landscapes; urban hinterlands; semi-arid regions; environmental change

Introduction

Across the world, rivers are complex and dynamic systems that constitute essential resources for viable urban settlements. They shape the natural-environment setting of cities and are important for water supply and associated food security as well as movement, communication, and perception of space, while at the same time their course and nature are changed and modified by human intervention (Cordova, Foley, Nowell, et al. 2005; Edgeworth 2011; Franconi 2017; Levis, Costa, Bongers, et al. 2017; Soroush and Mordechai 2018). Understanding the long-term evolution of urban systems with riverine hinterlands is paramount to tackling a number of major challenges facing today's world. Rivers are and have always been a magnet for human settlement, providing resources, communication, and travel routes. However, climate- and human-made changes to the environment can easily affect the fragile balance between the "natural" and the "urban," causing droughts, floods, and other changes in riverine systems, which challenge social, economic, and environmental resilience. Given the current pace of climate change and human-driven deterioration of environments, what is urgently needed is a better understanding of the evolution of the urban-riverine hinterland relationship within long-term and historical frameworks spanning centuries or even millennia.

This is especially the case in semi-arid environments where seasonal and long-term fluctuations in water availability together with competing demands for a limited resource between urban and hinterland requirements have made decision-making and management, from the individual to the collective, vital for the long-term resilience and sustainability of communities within catchments (Issar and Zohar 2007; Rosen 2007; Wilkinson 2003). While there have been important studies undertaken on urban and rural water management systems over extended periods of time within antiquity that highlight storage and flow regime systems (Beckers, Berking, and Schütt 2013; Gilliland, Simpson, Adderley, et al. 2013a; 2013b; Kourampas, Simpson, Nashli, et al. 2013; Mays, Koutsoyiannis, and Angelakis 2007; Miller 1980; Mithen 2010), synergistic multi-period urban-riverine hinterland relationships in semi-arid environments over extended periods of time are poorly understood (but now see Parayre [2016] and Wilson [2017]). This is a significant omission given the mutual dependencies embedded within these relationships, their sensitivities to internal and external forces of change and the evidence for human adaptations in challenging environments.

A long-term aim of our work at the multi-period archaeological site and landscape of Gerasa/Jerash, developed by the recent Danish-German Jerash Northwest Quarter Project (Danish-German Jerash Northwest Quarter Project n.d., "International Jerash"; Danish-German Jerash Northwest Quarter Project n.d., "Ceramics in Context"; Lichtenberger and Raja 2017), is to give new understanding of the complex relationships between this urban space and its hinterland with a focus on the primary resources of water and river over long periods of time (Holdridge, Kristiansen, Lichtenberger, et al. 2017; Stott, Kristiansen, Lichtenberger, et al. 2018). Our starting hypothesis is that synergistic relationships between the urban area and its hinterland are essential to the long-term sustainability and resilience of both. Assessing this hypothesis requires new syntheses conceptualizing human-environment relationships, review of archaeological evidence from different scales of hinterland, geosciences identification of environmental responses to hinterland change, and integration of climate data. We set out these themes in this paper from which to answer the questions of what makes urban-hinterland relationships in semi-arid environments resilient and

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sustainable in the long term, and what factors may contribute to the breakdown of these relationships. Focusing on data from the hinterland, from the river, we will discuss its relevance for a better understanding of intra-urban processes.

Urban Spaces and Riverine Hinterland Synergies: New Conceptualizations

The "spatial turn" is an important point of departure and influence when considering urban-riverine relationships. This has increased interest in geographic entities and units, with area studies conceptualizing relationships between humans/communities and geography and posing new research questions regarding the constitution of space, whether it is a natural given or a cultural construction (Bernhardt, Koller, and Lichtenberger in press; Dipper and Raphael 2011; Döring and Thielemann 2008; Horden and Purcell 2000; Kneer 2010; McNeill and Mauldin 2012; Middell 2006; Osterhammel 1998). It is in this context that rivers and the dynamic resources they provide come into focus.

While we recognize that the identification of a water resource has to be based upon the DPSIR (Driving force, Pressure, State, Impact, and Response) assessment framework (European Environmental Agency 2009), the term resource is used here in its broadest sense (Bartelheim, Hardenberg, Knopf, et al. 2015), since resource management has natural as well as anthropogenic driving forces. In our view, water and rivers are best studied as dynamic resources, a term by which we understand the varying cultural manifestations of nature in space and time, defined in relation to human demands, innovations, and inheritance. In the first place, "resource" covers the material and economic resources that are taken from the river, thus transforming from common property—common-pool—to private and contested resources (Campbell 2012; Miller and Spoolman 2011; Ostrom 2009; Schlüter and Pahl-Wostl 2007; Wutich 2009), but also ideological and spiritual resources are taken into account, since rivers were venerated as deities (Klementa 1993; Lichtenberger and Raja 2016a) and defined space and power relationships (Purcell 2012). Understanding the resources of the river as dynamic, accounts for the fact that these were in constant change, responding to human interaction or initiating them (Edgeworth 2011).

In recent years, investigation of the relationship between humans and river environments has developed into an innovative approach to study civilizations (Ackroyd 2008; Alley 2012; Barca 2010; Bernhardt, Koller, and Lichtenberger in press; Campbell 2012; Castaneda and Simpson 2013; Dan and Lebreton 2018; Kibel 2007; Mauch and Zeller 2008; Possehl 2010; Rau 2010; Rossiaud 2007; Schmid 2009; Thonemann 2011; Tvedt 2004; Wright 2010). For example, recent interdisciplinary research in the Amazon Basin has challenged previous beliefs of an evolutionary cradle undisturbed by humans and climate change (Levis, Costa, Bongers, et al. 2017; Wang, Lawrence Edwards, Auler, et al. 2017). In the Mediterranean world, contributions such as Thonemann's (2011) book on the Maeander valley, Campbell's (2012) study on Rome and rivers, or Rossiaud's (2007) on the Rhône also considered human relations with rivers; however, most of these studies, focusing on antiquity, did not interrelate their findings with results from the natural sciences (however, see Brückner [2003], Drew [2012], Edgeworth [2011], and Roe [2012]) and were, for the most part, based only on archaeological and written sources. Other studies, such as Edgeworth's (2011) *Fluid Pasts*, looked more at the environmental aspect and less at cultural history.

Early calls for greater synergy between archaeology and the natural sciences to offer a better understanding of human-river environments (Macklin 1999; Passmore, Waddington, and Houghton 2002) have stimulated new approaches to these complex relationships. Academic discourse in this arena has focused on identifying buried palaeo-landscapes and site visibility within flood-plains (Clevis, Tucker, Lock, et al. 2006; Woodward and Huckleberry 2011) and on river environment contextualization of archaeological sites (Cremonini, Labate, and Curina 2013; Issmer, Krupa, and Kalicki 2015; Kluiving 2015; Morozova 2005; Ravesloot and Waters 2004). Additionally, understanding of early management of changing riverine and fluvial environments has emphasized particular social groups within narrowly defined timescales (Kidder and Saucier 1991; Lucero, Gunn, and Scarborough 2011; Zhuang, Ding, and French 2014). It is these conceptual integrations of material and economic, ideological and spiritual, humanities and sciences over extended periods that form the foundation of our consideration of urban-riverine hinterland relationships.

Gerasa/Jerash in its Semi-Arid Environmental Setting

The multi-period urban site of Gerasa/Jerash in northern Jordan is one of the great cities of the classical Near East, forming part of the so-called "Decapolis" (Kennedy 2007; Kraeling 1938; Lichtenberger and Raja 2015, 2016a, 2017; Raja 2012) (FIGURES 1–3). The ancient city was called Gerasa, while Jerash is the name used later in history. For the sake of consistency, the city will be referred to as Jerash in this article, no matter the time period. Jerash is situated on the river Chrysorrhoas, the Golden River, and this had considerable impact on the urban development of the city. Due to its good state of preservation, the site has been the subject of ongoing archaeological investigations since the early 20th century, which have endeavored to understand its evolution from ancient times through to the early modern period. Jerash's origin can be traced to prehistoric periods when the earliest settlement was established at nearby Tell es-Suwwan (al-Nahar 2018). In the 2nd century B.C., Jerash was founded by the Seleucids, and since then, the city gradually grew to become an important urban center during the Roman period, home to monumental public architecture, as well as a commercial and political focal point of the region. The city also prospered during the Byzantine and Early Islamic periods. The importance of Jerash abruptly ended after a devastating earthquake hit the city in A.D. 749 as a result of major seismic activity along the Jordan Valley strike-slip fault (Lichtenberger and Raja 2016b; Marco, Hartal, Hazan, et al. 2003; Russell 1985, 47–49; Sbeinati, Darawcheh, and Mouty 2005, 362–365; Tsafrir and Foerster 1992). Only a small urban core survived the earthquake and continued its subsistence until modern times, but the city never regained its central position within the region. In the Middle Islamic period, a resettlement of the site took place but this was small-scale and short-lived (Lichtenberger and Raja 2018a).

The importance of the Chrysorrhoas, the river running through the center of Jerash, is conveyed strongly in the Hellenistic city's toponym "Antiocheia-on-the-Chrysorrhoas".

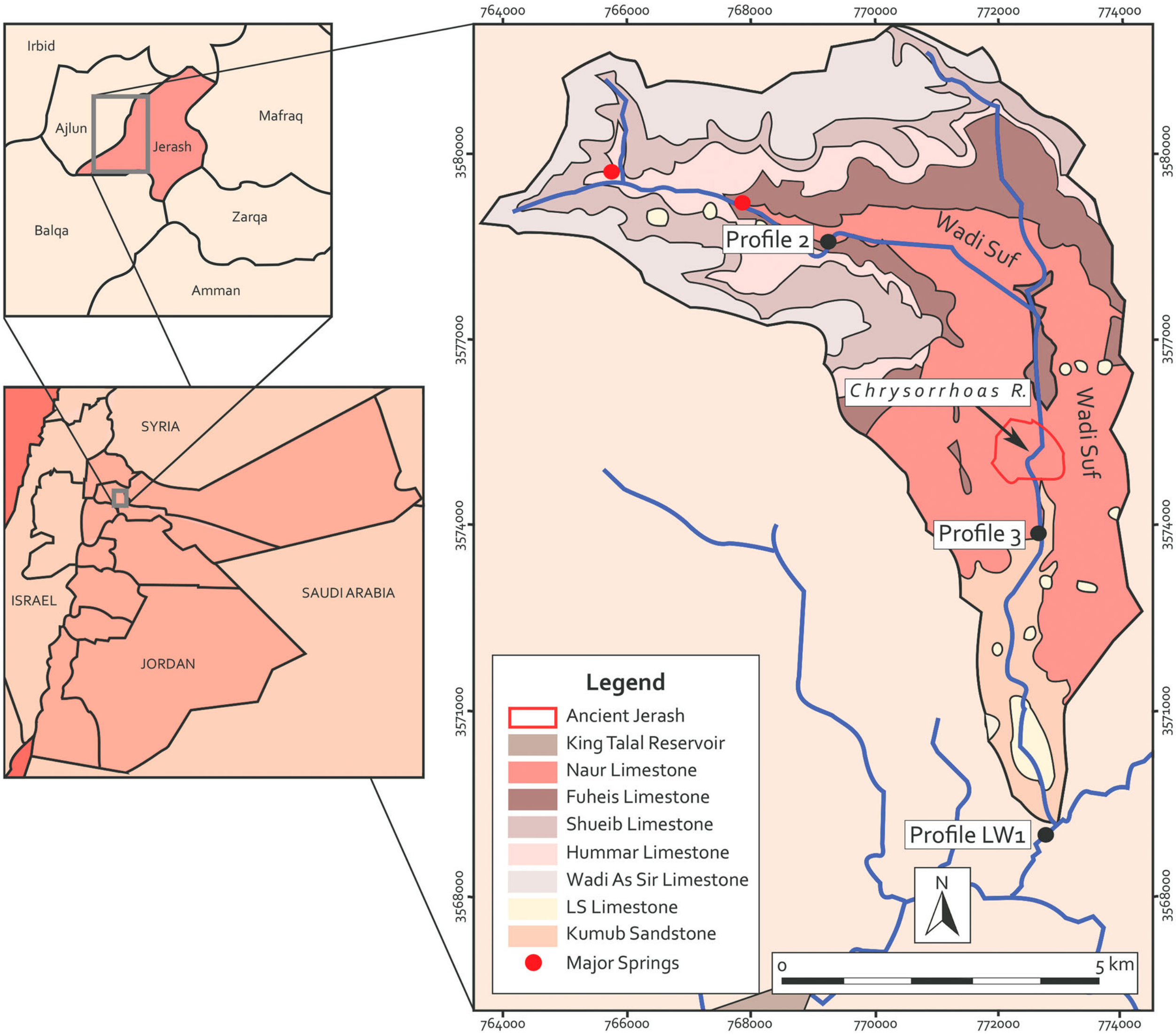

Figure 1. Wadi Suf location and region with indication of the three sampled profiles. Modified from Hammouri and El-Naqa (2008).

While "Antiocheia" identified the city and rebranded the territory as part of the Hellenistic and Seleucid worlds, the name of the river was used to distinguish this Antiocheia from the many other cities bearing the same name. An attractive epithet—"of the Golden River"—shared with no fewer than 12 other known waterways in the ancient world (Wissowa 1899, 2519–2520), also situated the city and helped it stand out in the intense regional competition for prestige and privilege among other cities of the Hellenistic and Early Roman worlds (Andrade 2013; Butcher 2003, 99–106, 227–234).

Historical sources as well as archaeological evidence reveal that the area of the Decapolis was a fertile and highly urbanized region (Bietenhard 1977; El-Khouri 2009; Hoffmann and Kerner 2002; Kennedy 2007; Lichtenberger 2003, 6–20; Raja 2012, 137–190). The Decapolis was connected to neighboring regions through innumerable everyday interactions. While its long-term development can be approached in terms of its position as a micro-region on the edge of the Mediterranean world (Braudel 1966; Horden and Purcell 2000; Kennedy 2007), it was also influenced by the proximity of the Syrian and Arabian deserts, which in some respects resemble the sea as a contact zone and determine environmental and cultural factors in the region (Lichtenberger 2016; Seland 2015, 2018). Jerash and the Decapolis were part of the wider zone famously labelled as "[between] The Desert and the Sown" by traveler, archaeologist, diplomat, and spy Gertrude Bell (1907). In this frontier landscape, stretching through the Levant approximately between the 200 mm and 400 mm isohyets, patterns of settlement and subsistence have fluctuated between nomadic pastoralists and settled farmers since the Late Neolithic. As dry periods in the eastern Mediterranean are manifested by a higher frequency of low winter rainfall, changes of precipitation between seasons and frequency of major historical events are also important for understanding causal mechanisms between environmental and anthropogenic systems (Brooks, Barnard, Coulombe, et al. 2010; Orland, Bar-Matthews, Kita, et al. 2009; Schmidt, Lucke, Bäumler, et al. 2006). In periods with favorable climate, strong centralized polities, and/or working re-distributional economies, such as the Roman, Byzantine, and Early Islamic periods, urban life flourished, and agricultural settlement extended towards the 200 mm isohyet, the theoretical limit for dry-agriculture. In dry periods and/or times of weak states, agricultural settlement withdrew towards the 400 mm isohyet, where good harvest can be expected even in drought years (Issar and Zohar 2007; Lewis 1987; Rosen 2007).

These changing dynamics between agriculture and pastoralism were a constant geopolitical fault-line in many semi-arid environments from the Late Neolithic until the

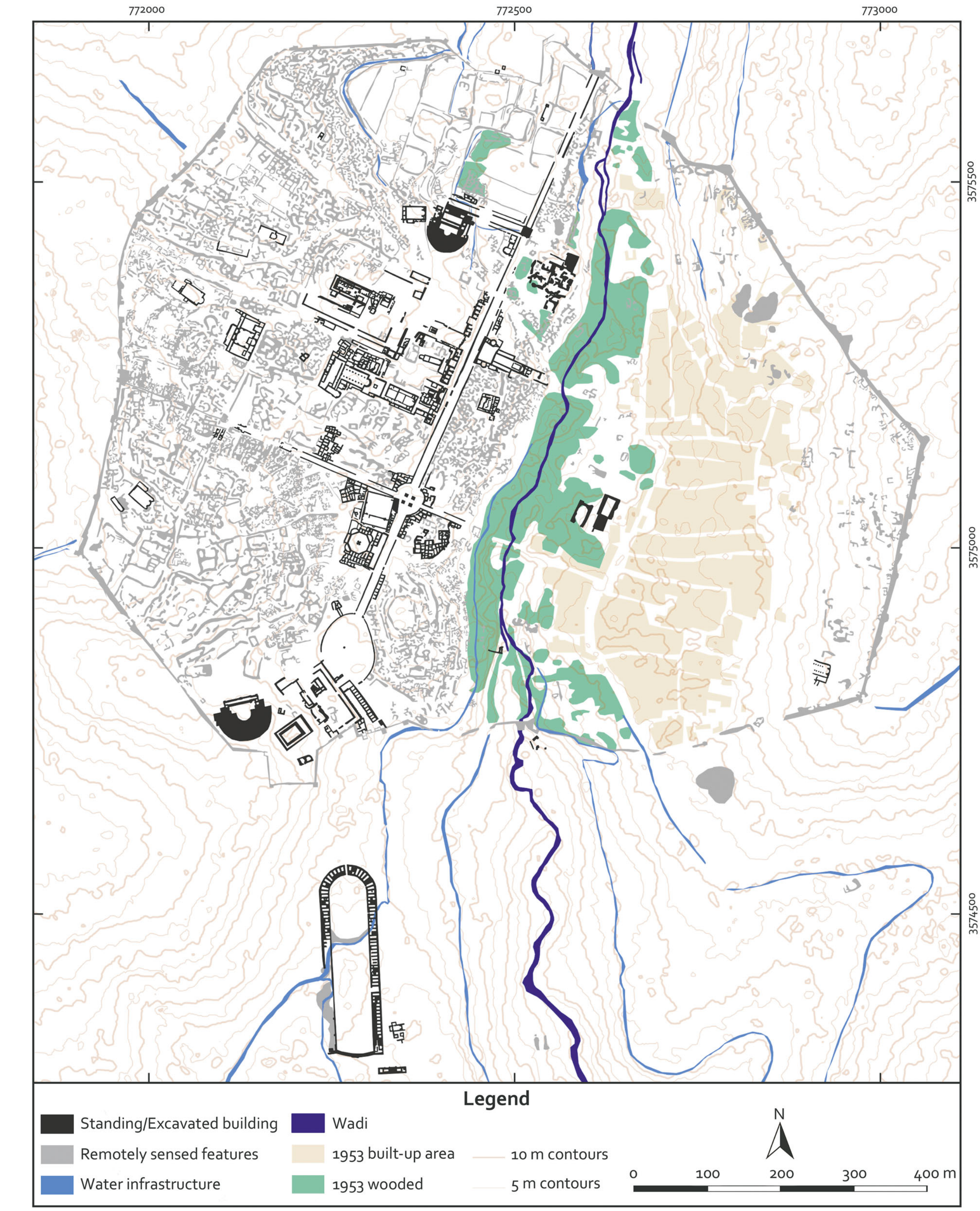

Figure 2. Map of Jerash. © Danish-German Jerash Northwest Quarter Project.

early 20th century and continue to influence conflicts between and within states today in the form of renewed significance of traditional land claims and identity markers such as tribal affiliation (Barker 2002; Dukhan 2014, 2019; Lancaster and Lancaster 1999; Lewis 1987, 1–2; Rosen 2000; Rosen 2007, 150–171; Wilkinson 2003, 168–169; Wirth 1969).

Jerash is situated in a region in which dry-agriculture is practiced today and was practiced in recent historical times, but where mandate period authorities anticipated crop failure in as many as two out of seven years (Ionides 1939, 230–234), underlining the liminal ecological setting. Historical data from the closest weather-stations, Amman Airport (271 mm, 30 km) and Deir Alla (281 mm, 28 km), indicate that conditions at Jerash are less favorable in this respect than Jerusalem (590 mm) and even Aleppo (329 mm) (World Meteorological Organization 1996). Jerusalem and Aleppo have been home to permanent urban settlement at least since the Middle Bronze Age, making them among the most resilient human settlements worldwide. The urban

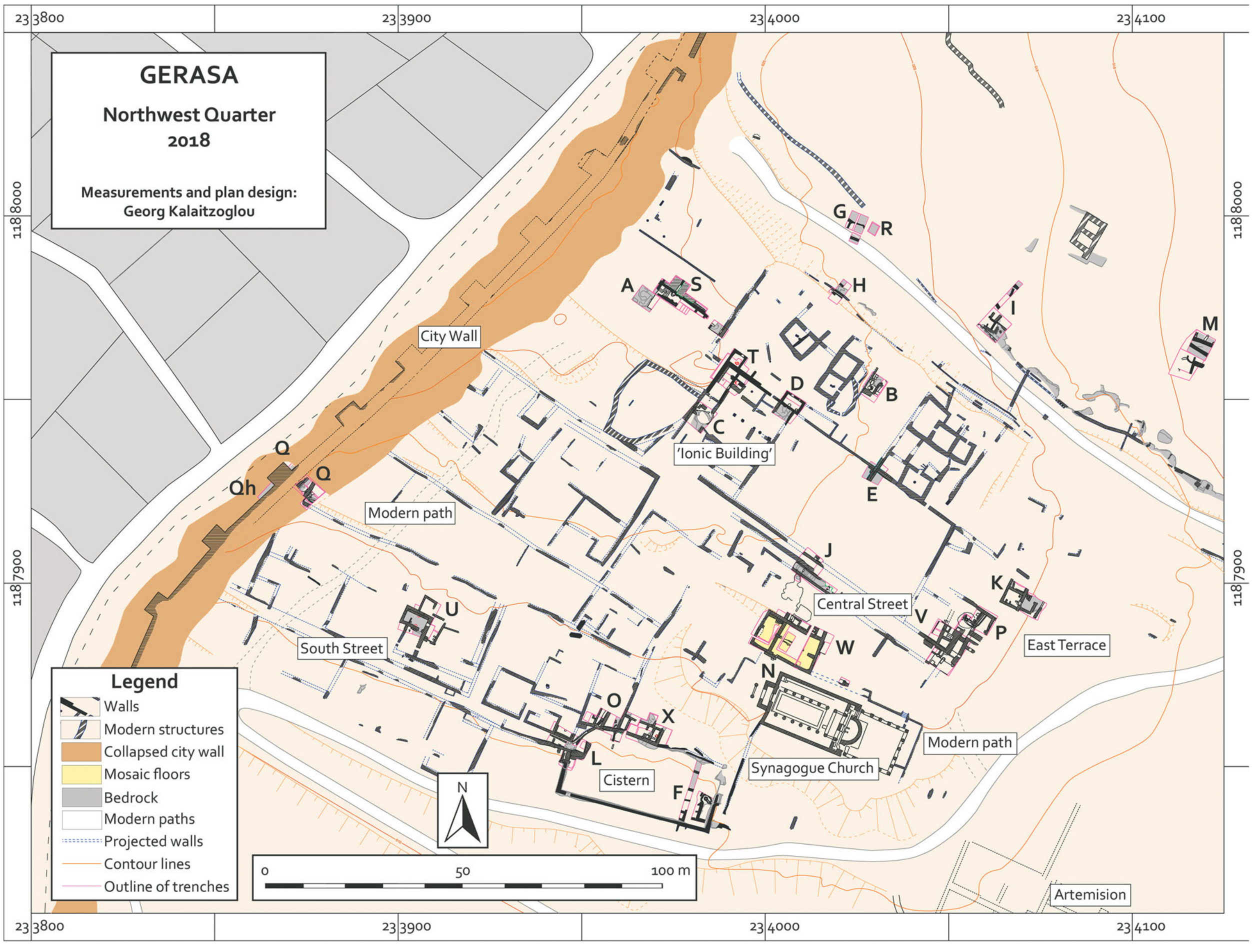

Figure 3. The Northwest Quarter in Jerash with indications of excavated trenches A–X. © Danish-German Jerash Northwest Quarter Project.

history of Jerash, in contrast, spans a millennium from the Hellenistic period until the mid-8th century A.D., and from the Middle Islamic period (Ayyubid-Mamluk period) onwards (Lichtenberger and Raja 2018a). In other periods, the region of Jerash—analogous with other parts of the Near East—was presumably used as pastureland by sheep- and goat-herding semi-nomads (Pappi 2005; Prag 1985), and from the 1st millennium B.C. also by camel-pastoralists (Retsö 1991; Rosen and Saidel 2010). The shift between settled, semi-nomadic, and nomadic modes of subsistence is actually typical for much of the region "between the desert and the sown" and highlights that subsistence patterns were influenced, rather than determined by climatic conditions (Issar and Zohar 2007; Lawrence, Philip, Hunt, et al. 2016; Rosen 2007).

One way of approaching this is the study of local and regional hydrological infrastructures. Much hydrological infrastructure, in particular wells, cisterns, and dams, represents efforts and investments made in order to adapt to climatic conditions, underlining that water is a dynamic resource (Braemer, Genequand, Dumond Maridat, et al. 2009; Kamash 2012). Maps and satellite images allow the plotting of such infrastructure on a regional scale in relation to modern and historical settlements as well as archaeological sites and known borders and routes of communication (Meyer and Seland 2016) (FIGURE 4). Data gathered from such sources have gained prominence in recent archaeological scholarship (Kennedy and Bishop 2011; Schou 2015), but are rarely followed up by work on the ground. Jerash and its environs—both immediate and regional—make it an ideal example through which dynamic resources related to urban spaces and riverine hinterlands can be studied, both in an ancient and a modern perspective.

Related to this is the question of the role of climate change in the history of Near Eastern urbanism. The geographical and chronological resolution of palaeo-climatological series have improved vastly in recent years (Finné, Holmgren, Sundqvist, et al. 2011; Issar and Zohar 2007; Lawrence, Philip, Hunt, et al. 2016; Manning, Ludlow, Stine, et al. 2017; McCormick, Harper, More, et al. 2013; Orland, Bar-Matthews, Kita, et al. 2009; Xoplaki, Luterbacher, Wagner, et al. 2018) and might be juxtaposed with the archaeological records of sites like Jerash in order to better understand human response and adaptation to climate change. This, however, is only a first step, and most studies struggle to move beyond correlation as evidence of causation. The balance between human agency and environmental determinism has been the cause of heated controversies since Huntington's (1915) seminal *Civilization and Climate* and continues to be at the forefront of the scholarly debate (Issar and Zohar 2007; Kaufman, Kelly, and Vachula 2018; Kerner, Dann, and Bangsgaard 2015; Van de Noort 2013; Vogelaar, Hale, and Peat 2018). Over time scholarly interest has shifted from emphasis on climate change as a cause of population growth to climate change as a cause of societal collapse. Climate deterioration is therefore used to explain demographic crises as well as innovation and expansion. More recently, scholarship has again shifted to address resilience over

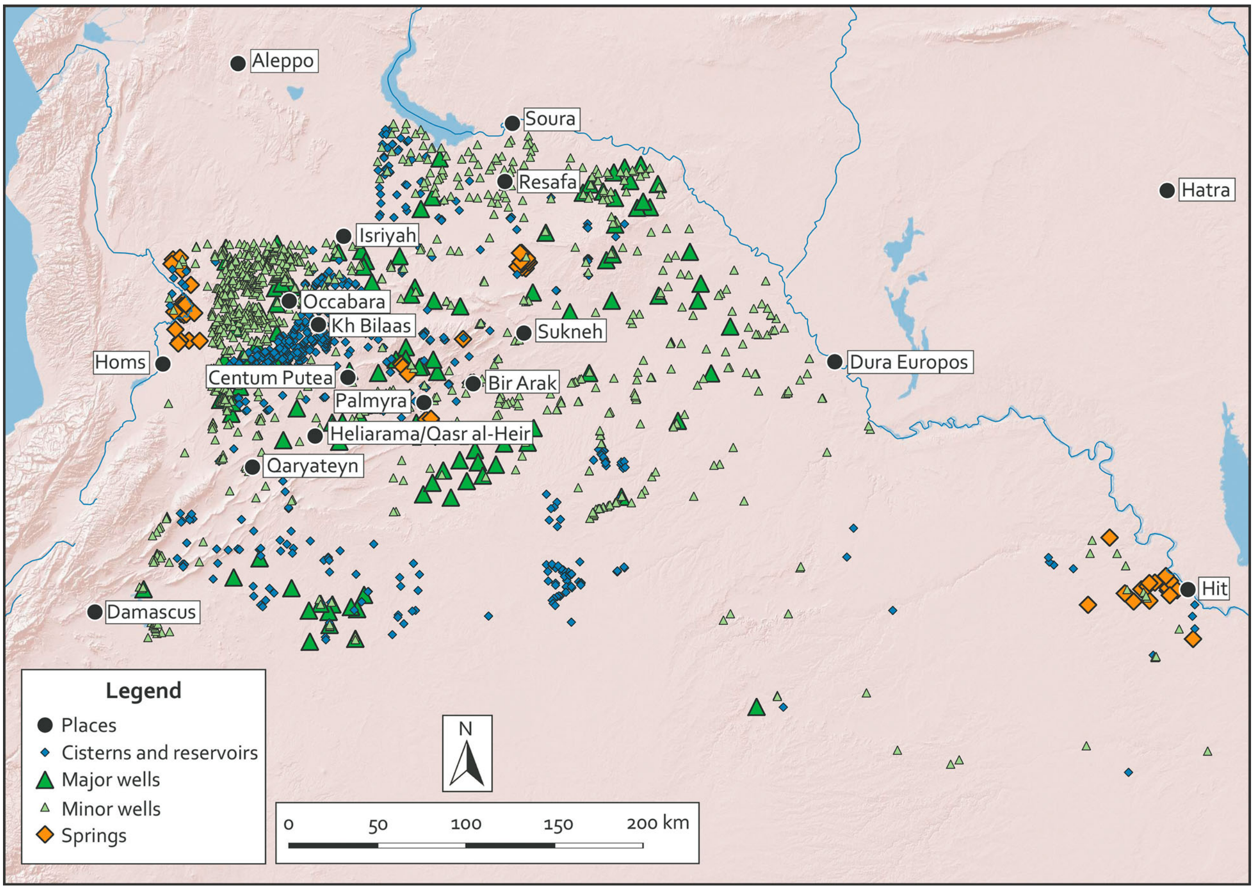

Figure 4. 1678 water sources in the Syrian desert. © E. H. Seland; basemap © ESRI 2014.

collapse, although this trend seems to be reversing (Haldon and Rosen 2018; E. H. Seland personal communication, 2019). Past scholarship might provide models for climate-society interaction that can be usefully applied to better understand the development of Jerash and other cities in marginal regions, providing basis for discussions of mechanisms of causation missing from many archaeological studies. If sufficient definition can be achieved, it allows us to approach the relative importance of climate change, geopolitical changes, economic development, and even natural disasters such as earthquakes and droughts for the fluctuating frontier between nomads, cities, and empires.

The Jerash Riverine Hinterland

Although survey archaeology has been an integral part of Mediterranean archaeology for several decades, a systematic study of an ancient city and its hinterland in the Near East is still lacking. The hinterlands of important cities such as Antiocheia (on the Orontes), Baghdad, Jerusalem, and Petra, for example, remain largely unexplored in their relation to the city cores. Notable exceptions are the site of Hesbon in Jordan (LaBianca, Hubbard, and Running 1990), which is, however, a much smaller settlement and therefore not directly comparable, and the Syrian city of Palmyra, which constitutes valuable comparative material but from a less intensively populated and slightly more arid neighboring region, where dry-agriculture would not be possible except in particularly wet years (Meyer 2013, 2017; Meyer and Seland 2016; Morandi Bonacossi and Iamoni 2012). Despite the long-recognized potential, no comprehensive study of the Jerash hinterland and its relation to the urban core has been conducted so far (however, see Kennedy [1998, 2004]) other than an assessment of the risk to the heritage posed by the development of modern Jerash (Baker and Kennedy 2011; Connolly 2008; Kennedy and Baker Firat 2009; Struckmeier and Connolly 2009) and in establishing the borders of the Roman city's territory (Kennedy 2004; Lichtenberger and Raja in press; Seigne 1997). There are, however, a considerable number of ancient sites in the hinterland of Jerash (Glueck 1945–1949, 57–89, 231–235; Mittmann 1970, 73–119, nos. 176–310) that never were documented in a systematic way or entered into a GIS. The dynamics of resource management in Jerash and the resilience strategies of the inhabitants of this micro-region or hinterland need to be investigated by considering the river as a key factor of urban development and as an archive of history. Jerash is a model for considering the resilience of past societies in general, but also at the time of its collapse with the earthquake of A.D. 749 and a later revitalization and transformation of the landscape (i.e., in the medieval period) (see Faulseit [2015]). From an interdisciplinary point of view, the interplay between intra-urban and extra-urban relations and its environmental consequences—as reflected in resource management, material culture and soils/sedimentary evidence—is a hugely understudied theme, and it holds the potential to unlock many unanswered, central historical questions relating to the rise and fall of urban societies, their resilience towards changes in political/civic structure, warfare and diseases, as well as natural catastrophes and climate change.

The extreme topography of Jerash provides a special case. The steep Wadi Jerash, which is the modern name of the river-valley, literally cuts the city into two parts, an eastern

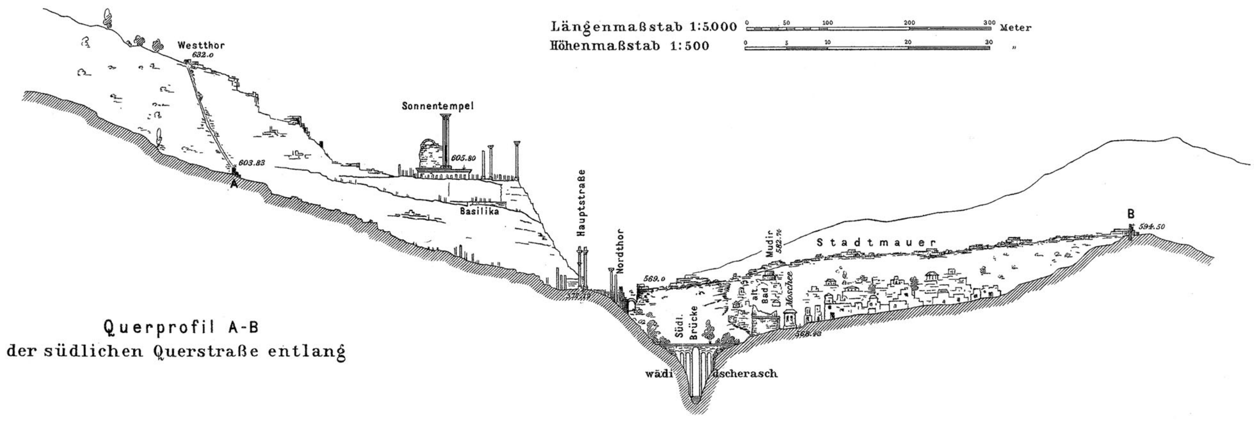

Figure 5. Profile of the city and the steep wadi published by Gottlieb Schumacher. From Schumacher (1902, taf. 7).

and a western part; physical communication between the parts was only possible by bridges (FIGURE 5). The springs of the Chrysorrhoas lie in the region of Suf, about 6 km northwest of the city center of Jerash. The Chrysorrhoas flows into Wadi Zarqa (ancient Jabbok), approximately another 6 km southeast of the city center. Wadi Zarqa finally flows into the river Jordan. The riverine environment of Jerash thus forms a well-defined Mediterranean micro-region, the resources of which are related to the river (Horden and Purcell 2000; Kennedy 2007). The catchment area of the Chrysorrhoas covers 57.1 km^2 (FIGURE 1).

The area between the springs of Suf and modern Jerash is a region with moderate topography that was and is suitable for agricultural production (FIGURE 6). The wadi—which here refers to an entire hydrological system and not only an intermittent stream as the term is sometimes used, with its immediate surroundings in Suf and until what is today Muheyyem Suf—shows strong traces of landscape management in various historical periods. This area most likely relates to an association of “gardeners of the upper valley” known through a Roman-period inscription. The inscription’s content underlines the importance of agricultural cultivation in the riverine hinterland and the impact it had on the social organization of the city (Gatier 1985, 310–312; Lichtenberger and Raja 2016a, 110–111; Seigne 2004, 176). Today, the area of the upper wadi is intensively managed with agricultural terraces on the slopes (on agricultural terraces in the Mediterranean see, for example, Countryman, Carrier, and Kane [2012], Foxhall [1996], Langdon [2013], Lohmann [1993, 196–219], Price and Nixon [2005], Rackham and Moody [1992], and Şanlı-Erler [2006, 127], on agricultural terraces in the Near East, see Beckers and Schütt [2013], Edelstein and Kislev [1981], and Ron [1966]; on problems related to recent terraces in relation to the archaeological record, see Frederick and Krathopoulou [2000]). These terraces prevent erosion, give greater crop-rooting depths, and provide a way of managing soil water and nutrients, but need steady maintenance to prevent them from eroding. Several oil presses that were found in the area of Jerash suggest that olives were cultivated on such terraces in antiquity (Kalaitzoglou, Lichtenberger, and Raja 2013, 63–68). Usually terraces cannot be dated exactly without excavation, and even when closed contexts of terraces are excavated, they are difficult to date by traditional methods because they yield only little diagnostic material such as pottery or coins. Increasingly, however, Optically Stimulated Luminescence (OSL) analysis is offering new and viable geo-chronological control on agricultural terrace formation in Mediterranean and Near Eastern environments (Davidovich, Porat, Gadot, et al. 2012; Kinnaird, Bolòs, Turner, et al. 2017a, Kinnaird, Dawson, Sanderson, et al. 2017b; Porat, Davidovich, Avni, et al. 2017). The investigation of the terrace system in a riverine hinterland such as the one in Jerash is of utmost importance for the reconstruction of the economic structure of the city and its agriculture, which is the backbone of a city’s resilience. Terraces need to be mapped in their chronological development, and the intensity of terrace management over time needs to be reconstructed; the soil archives from the wadi of Jerash offer a clue to this (see below). We are currently working on a program to map the present state of terraces within the landscape by LIDAR.

In the wadi, parts of rock-cut channels and cisterns for ancient water management systems remain visible. Most noticeable is a large bipartite cistern complex about 1.2 km to the north of Jerash, the so-called Birketein complex, which fed parts of the lower city of Jerash. Birketein lies in a small plain from which the Chrysorrhoas flows into the city. In the city, the terrain slopes steeply from both sides down to the riverbed (Lichtenberger and Raja 2016a). Extensive intra-urban water management systems were in place at least as early as the 1st century A.D. and most likely earlier. In antiquity, the river was controlled by a water gate as it reached the city, situated at the height of the ancient North Gate (FIGURES 2, 5). Within Jerash there is a strong spring called Ain Karawan (Kraeling 1938, 11; Lichtenberger and Raja 2016a; Seigne 2004, 2008). This spring lies on a low elevation and therefore did not supply the higher areas of the city. Extensive foundations dating to the Roman period can still be seen inside the modern water station of Ain Karawan, which delivers fresh water to modern Jerash. Further down its course through the city, the river was once again managed by a water gate at an approximate height of the area below the ancient so-called Eastern Baths (FIGURES 2, 5) (Lepaon, Turshan, and Weber-Karyotakis 2016, 2018), and on leaving the city the wadi broadens and the hills around the wadi become steeper.

The river was the basis for urban settlement at Jerash, and the remains of extensive hydrological and agricultural infrastructure show that it required investment, surveillance, and maintenance in order to serve the community in a safe, predictable, and effective manner. The river basin can shed light on what happened with this infrastructure in times of political

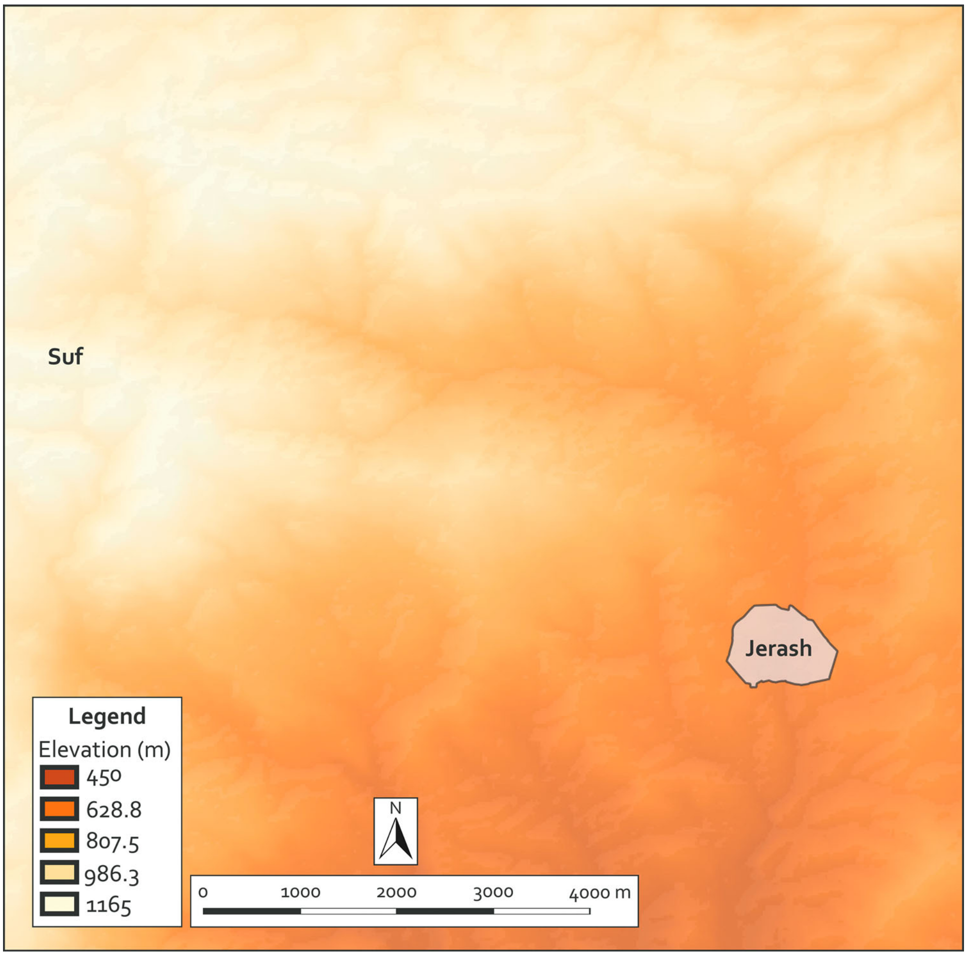

Figure 6. Topography, between Suf and Jerash. © Danish-German Jerash Northwest Quarter Project.

turmoil and climate change, as well as during natural disasters, thus establishing tipping points and causal mechanisms in the development of the urban settlement. Jerash thus also serves as a point of comparison for other Near Eastern settlements, including cities situated on rivers such as Damascus (Chryorrhoas [Barada]) and Aleppo (Belos [Queiq]).

The Wadi Suf Sediment Record

An extensive record of scholarship notwithstanding, systematic understanding of the evolution of river and water management systems over extended periods is only beginning to emerge through a deeper integration of the humanities and the natural sciences (Hassan 2010). One way of studying the relationship between settlements and rivers is by considering sediment deposits and soil formation in river catchments and early water management infrastructures, which offer chronological and spatially based archives of the intimate association between human activity and natural processes in riverine environments. New readings of sediment-movement archives in catchments is being made possible by advances in novel geoscience approaches including OSL dating and profiling, thin-section micromorphology with scanning electron microscopy of sediment architectures, and traditional assessment of particle-size distributions and mineralogy. Such chronology-based analyses offer new insight into catchment slope processes, flooding deposition patterns and intensities, periods of catchment stability, and changing sediment patterns associated with water management. Careful embedding of such findings within political, economic, and palaeo-climatic contexts offers new explanations of emergence, development, and abandonment of water management systems (Gilliland, Simpson, Adderley, et al. 2013a, 2013b). These advances, resulting from interrelating analytical methods from the natural sciences with conceptual methods from the humanities, enable researchers to take a longue durée perspective on the dynamic relationship between a city and its riverine resources.

Sediments are a defining characteristic of riverine systems and are sensitive indicators of environmental change; within the Wadi Suf catchment, they hold potential for new understanding of how the city interacted with and changed its hinterland over extended periods of time. To realize this potential, new geoscience approaches are needed that can interface with and complement the high-definition archaeology approach pioneered by the Danish-German Jerash Northwest Quarter Project (Lichtenberger and Raja 2018b; Raja and Sindbæk 2018). Here we present results from the application of a novel sampling and analytical approach based on OSL of the sediments giving absolute and relative chronologies of sediment-formation processes that can be directly related to the archaeological evidence base. This approach is necessary as, although most of the sediments stem from historical periods and are assumed to be related to human activities, hardly any datable material such as pottery is found with the sediments. Even if datable material is found, the complex post-depositional processes related to erosion do not allow for accurate attribution and dating. Therefore, traditional archaeological dating methods such as pottery typology cannot be applied to dating the sediment movements.

Recent engineering works together with river channel cutting have exposed and given access to soils and sediment stratigraphies infilling the length of Wadi Suf. Geomorphological survey and assessment of these sediments, which overlie the Na'ur limestone formation, confirm the presence of fluvial sediments with a range of particle sizes from cobbles to silty loams, indicating variances in deposition energy environments; substantial thicknesses of colluvial deposits; and, in places, underlying and intact Red Mediterranean soils. Samples for OSL measurement—for both dating and profiling—have been collected at three exposed locations within the Wadi Suf catchment. Sampling for OSL dating focused on measurement from the top and base of the stratigraphies; for OSL profiling, the whole stratigraphy was sampled. Field-based OSL profiling methods (see Kinnaird, Bolòs, Turner, et al. 2017a, Kinnaird, Dawson, Sanderson, et al. 2017b) permits rapid appraisal of the luminescence behavior of all sediment, and assesses lateral and vertical variations in OSL (blue light stimulation of quartz) and Infra-red Stimulated Luminescence (IRSL, infra-red light stimulation of potassium feldspars) intensities with respect to the stratigraphies. Interpretation of OSL and IRSL signal intensities and depletion indices have been discussed in a number of recent publications (Kinnaird, Dawson, Sanderson, et al. 2017b; Sanderson and Murphy 2010; Turner, Bolòs, and Kinnaird 2017). The locations were chosen in order to achieve a representative profiling within the catchment areas of the Chrysorrhoas (FIGURE 1). Profile 2 is upstream from the ancient city (upper wadi; 32.310550° 35.860350°) and located in an area considered to be the agricultural hinterland of the city. Profile 3 is immediately downstream from the ancient city (mid wadi; 32.269683° 35.894550°). Finally, Profile LW1 is located further downstream just beyond the junction of Wadi Suf and Wadi Dayr (lower wadi; 32.228739° 35.899516°).

The regional limestone geology (Abu-Jaber, al-Saad, and Smadi 2009; Bender 1974) is deficient in the quartz or feldspar mineralogy that is essential for luminescence dating. Our application of the technique is therefore dependent on aeolian-deposited quartz grains, as evident in thin-section micromorphology, which typically measure less than 50 μm in diameter. These grains are considered to be a component of Saharan dust deposited during the Pleistocene, which ceased with the onset of the Holocene (Issar and Bruins 1983; Issar, Tsoar, Gilead, et al. 1987; Lucke, Kemnitz, Bäumler, et al. 2014). The lower wadi also has local quartzose sandstone outcrops (Kumub) contributing to the quartz-based OSL signal (Abu-Jaber, al-Saad, and Smadi 2009; Amireh 1997; Bender 1974). OSL is dependent on naturally occurring radionuclides within the soils and sediment, which provide the dominant contribution to the environmental dose rate received at the position of the dating sample. The concentration of these will vary within a sediment stratigraphy (FIGURES 7–9), leading to local variations in dosimetry (ionizing radiation absorbed by an object). In situ gamma dose rate was quantified in the field using an Ortec Digibase connected to a 2 × 2" NaI detector (referred to hereafter as a "dosimeter"). The methodologies used in determining the environmental dose rate received at the position of the dating sample and in determining equivalent doses leading to the calculation of the burial dose are given in Cresswell, Sanderson, Kinnaird, et al. (2018).

Optically Stimulated Luminescence Sediment Profiling

With cross-referral to parallel field textures and particle-size distribution data, our analysis models recognize several luminescence patterns within and between field-observed stratigraphic units. Stable soil surfaces are identified by linear vertical luminescence signal intensities indicating little disturbance or addition of new materials over extended periods of time. Conversely, fluvial (carried by rivers and streams) and colluvial (downslope movement) sediment depositions are identified by positive or negative signal progression through the stratigraphy, indicating accumulation or redeposition over time; accumulation rates are slower where signal intensities are more widely distributed and conversely more rapid where signal intensities are less widely distributed. Colluvial deposition is evident where signal intensities are more scattered within the profile.

OSL sediment profiles for the three analyzed stratigraphies highlight the movement of fluvial and colluvial sediment into and through the wadi. Figure 7 showing sediment-luminescence profiles from Profile 2, indicates fluvial deposition from 180 cm below the surface superimposed on bedrock at 300 cm. Breaks in the linear pattern of luminescence signal, indicating change in flow regimes, together with switching of intensities between OSL and IRSL net signal, indicating change in sediment composition, suggest an episodic nature of fluvial deposition; four major phases have been identified in this stratigraphy. Above the fluvial deposits, the colluvial deposits are characterized by more scattered signal intensities and indicate that as the wadi filled, colluvial deposition became a dominant process. Four phases of fluvial deposition with superimposed colluvial deposition, with elements of soil stability, are also evident in Profile 3 (FIGURE 8), although based on the absolute-dating evidence (TABLE 1; below) these more rapid accumulations are not the same occurrences as in the upper wadi (Profile 2). Similarly, Profile LW1 (FIGURE 9) contains sequences of fluvial events of varying intensities and give evidence of short-term switches of intensity within longer-term trends. Later colluvial deposits are again superimposed on the fluvial sediments.

Moreover, the correlations drawn between the three luminescence stratigraphies have enabled us to more fully appraise wadi-formation processes at the catchment scale. First, these stratigraphies provide a landscape context to each of the sediment ages reported below. Second, they have provided the first evidence for sensitization of the quartz dosimeter down-stream, with repeated cycles of deposition, erosion, and transportation. This is illustrated in Figure 10, which shows the range in luminescence intensities within each profile and with distance down the wadi; the maxima and range in intensities increase with distance. The data are further sub-divided on the basis of the sediment ages presented below, with the division set before and after the onset of catchment-scale colluvial activity. Importantly, these stratigraphies highlight that similar depositional processes have occurred throughout the wadi's later history, although the rates of sedimentation have changed. Coupled with our sedimentological observations, these results have provided important insights into sediment processes acting at the local (within profiles) and regional (across profiles) scales.

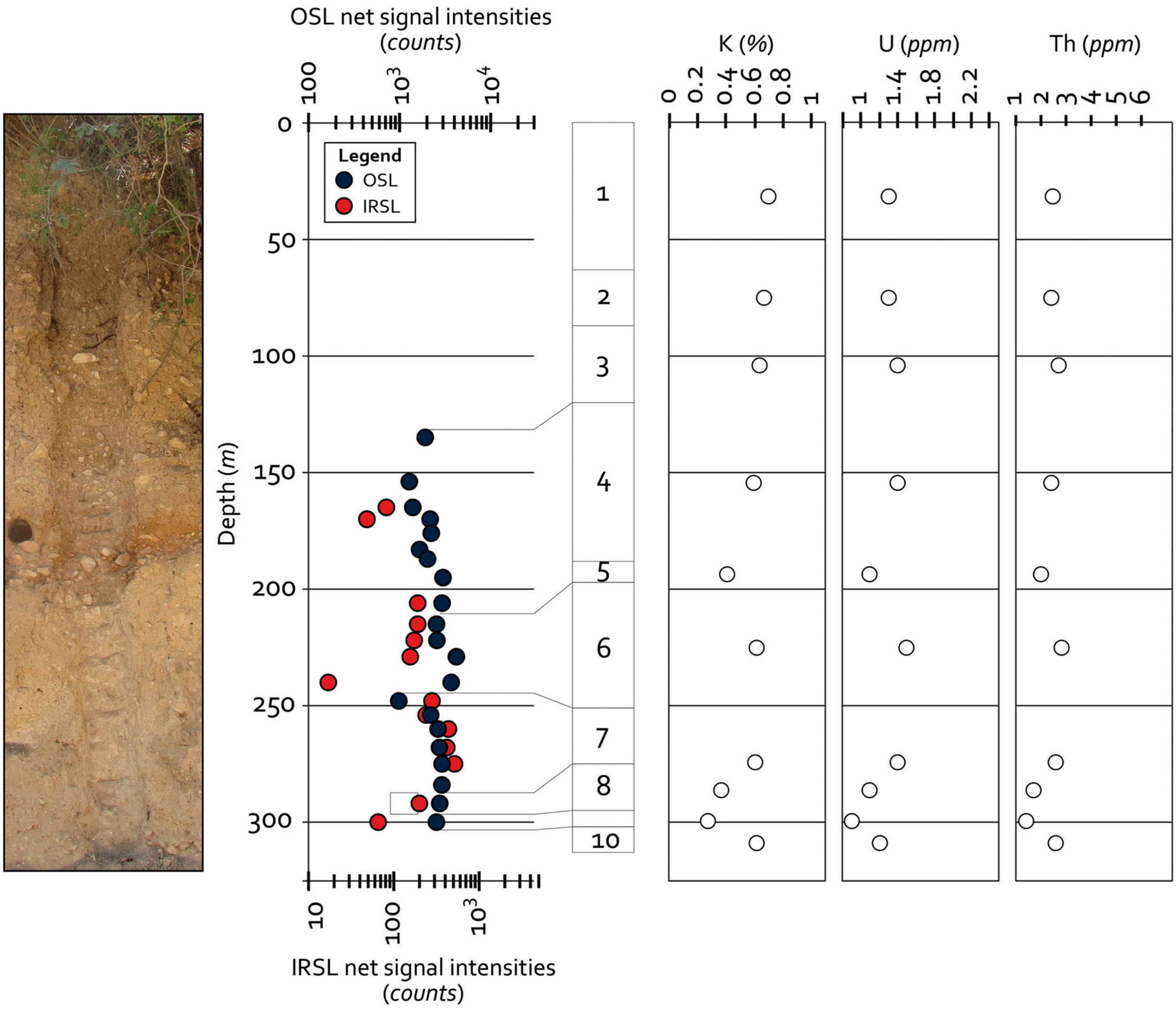

Figure 7. Field stratigraphy for Wadi Suf Profile 2, also showing infra-red stimulated luminescence (IRSL) and optically stimulated luminescence (OSL) net signal intensities expressed as photon counts and plotted against depth. Radionuclide concentrations of K (%), U (ppm), and Th (ppm) are shown as a proxy for variations in environmental dose rate within the profile.

Optically Stimulated Luminescence dating of wadi sediments

The ages of the sediments determined by the quotient of the burial dose to the dose rate are given in Table 1, representing the period when the sediment was last exposed to light. Our measurements suggest that each area of the wadi (upper, Profile 2; mid, Profile 3; and lower, Profile LW1) has contrasting and localized sediment-accumulation characteristics reflecting diversity of catchment processes. Improved resolution on these sediment chronologies will be obtained with further sampling and statistical appraisal of these sediment ages. Refining of the current data set is possible where there are closely similar ages and similar OSL-profiling attributes; this applies to the upper- and lower-wadi profiles where statistical combination of the respective A.D. 790 ± 110 and A.D. 740 ± 150 ages (FIGURE 10) suggests a date for colluvial activity at A.D. 760 ± 40.

Two samples from Wadi Suf show anomalously old ages with large uncertainties (TABLE 1, WS3 [9] and LW1 [23]); we suggest that these measurements show natural background variances in exposure of the sediment to light over extended periods of time. The very early date of 33,600 ± 5900 B.C. is of particular geomorphological interest indicating that aeolian accumulations of quartz were occurring during the later Pleistocene.

Our initial interpretation sequence for the upper-wadi profile is of a freely flowing river and an intact landscape with no sediment accumulation until A.D. 640 ± 240. After this time, fluvial sedimentation and wadi infilling commences, indicating increasing degradation of the upper catchment. Above the fluvial deposits the onset of colluvial activity at A.D. 760 ± 40 marks an acceleration of land degradation in the upper wadi. Further analyses are required to securely date the earlier fluvial history in the mid-wadi location, but this process had ceased by A.D. 1400 ± 60, after which colluvial accumulation indicates accelerated land degradation. Fluvial sediment accumulations in the lower wadi commence from 510 ± 310 B.C., paralleling OSL dates from soils underlying Jerash city (Cresswell, Sanderson, Kinnaird, et al. 2018), through to the statistically derived A.D. 760 ± 40 date (see above) when colluvial processes become more dominant.

These chronologically based analyses identify critical junctures in the formation of the wadi that require explanation. What stimulated the commencement of fluvial deposition at the 510 ± 310 B.C. OSL marker in the lower wadi, downstream from the city, and again at the A.D. 640 ± 210 OSL marker (and given its stratigraphic position, prior to A.D. 760 ± 40) in the upper wadi? Perhaps the beginnings of urbanization, at the latest in the 2nd century B.C., when the

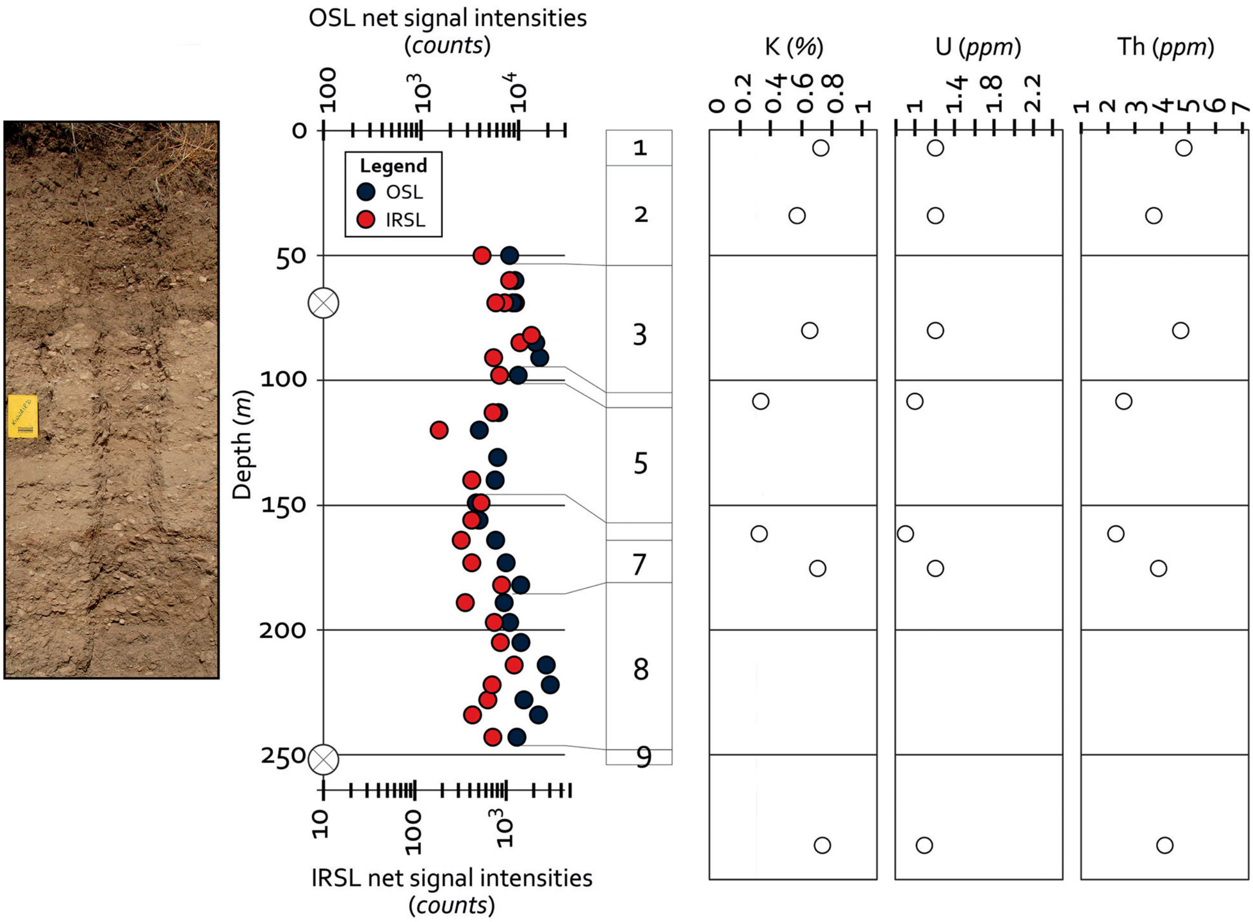

Figure 8. Field stratigraphy for Wadi Suf Profile 3, also showing infra-red stimulated luminescence (IRSL) and optically stimulated luminescence (OSL) net signal intensities expressed as photon counts and plotted against depth. Radionuclide concentrations of K (%), U (ppm), and Th (ppm) are shown as a proxy for variations in environmental dose rate within the profile. X indicates additional field dose rate measurement.

city was founded as a Seleucid settlement, explains the first. The beginnings of hinterland agricultural decline, as a herald of city decline, prior to the earthquake that destroyed the city in A.D. 749 coincides with the dry period revealed by palaeoclimatological studies, that appears to have struck the eastern Mediterranean in full force A.D. 500–750 (Büntgen, Myglan, Ljungqvist, et al. 2016; Enzel, Bookman, Sharon, et al. 2003; Finné, Holmgren, Sundqvist, et al. 2011; Harper and McCormick 2018; Issar and Zohar 2007, 215–216; Orland, Bar-Matthews, Kita, et al. 2009). This period of gradually increasing environmental stress also saw a series of known shocks to the socioeconomic system due to the dramatic climate anomaly of A.D. 536–550 (Newfield 2018), the recurring pandemic known as the Justinianic plague commencing in A.D. 540–541 (Meier 2016), and the century of Roman-Sassanian and then Roman-Arab wars unfolding in this region in the period A.D. 540–640. While current assessments reveal that urban centers of the southern Levant showed remarkable resilience in the face of this series of calamities (Haldon 2016; Walmsley 2007), it was also a period of declining long-distance trade and increased pressure of taxation (Haldon 1990). In Jerash, mass-graves with remains of victims of the Justinianic plague have been uncovered in the hippodrome (Kehrberg and Ostrasz 2017).

What stimulated the parallel onset of colluvial deposition A.D. 760 ± 40 in the upper- and lower-wadi locations and its later occurrence A.D. 1400 ± 60 in the mid-wadi location? Perhaps the best explanation for the earlier phase in upper and lower wadi is the A.D. 749 earthquake, resulting in failure of the slope-terrace system and associated irrigation due to shake and liquefaction, together with loss of hinterland land management as agricultural demand from the city declined. The earthquake came at a time when climatic conditions were more difficult than they had ever been during the urban history of Jerash with a series of misfortunes culminating in the Umayyad-Abbasid war A.D. 747–750. The post A.D. 1400 ± 60 sediments also suggest slope and terrace failure. This date might relate to the 11/12th century A.D. resettlement of Jerash during the Middle Islamic period (Lichtenberger and Raja 2018c), although currently there is no sedimentary indication of this in the wadi. After the so-called "big chill" of the late 10th through early 12th centuries, the Ayyubid and early Mamluk periods were characterized by a relatively benign climate; the latter period was also characterized by investment in hydrological infrastructure, perhaps to mitigate the intermittent draughts that continued to afflict the region (Bulliet 2009; Raphael 2013; Xoplaki, Luterbacher, Wagner, et al. 2018). Until now, we do not exactly know how long this Ayyubid-Mamluk settlement in Jerash existed, but its end or at least its decline might be related to the A.D. 1400 ± 60 date. So far, the youngest ^{14}C date related to the Middle Islamic settlement recovered from the Northwest Quarter excavations in Jerash indicates the period A.D. 1155–1271 (J16-Tb-40-3: Sample no. 25886, Institute for Physics and Astronomy, Aarhus University (Denmark), ^{14}C age 830 ± 34 B.P., d13C (AMS) -19.00 ± 1.00, calibration curve IntCal13, 1σ A.D. 1185–1254 (A.D. 1185–1254, 68.2%), 2σ A.D. 1155–1271 (A.D. 1155–1271, 95.4%)). This date is a

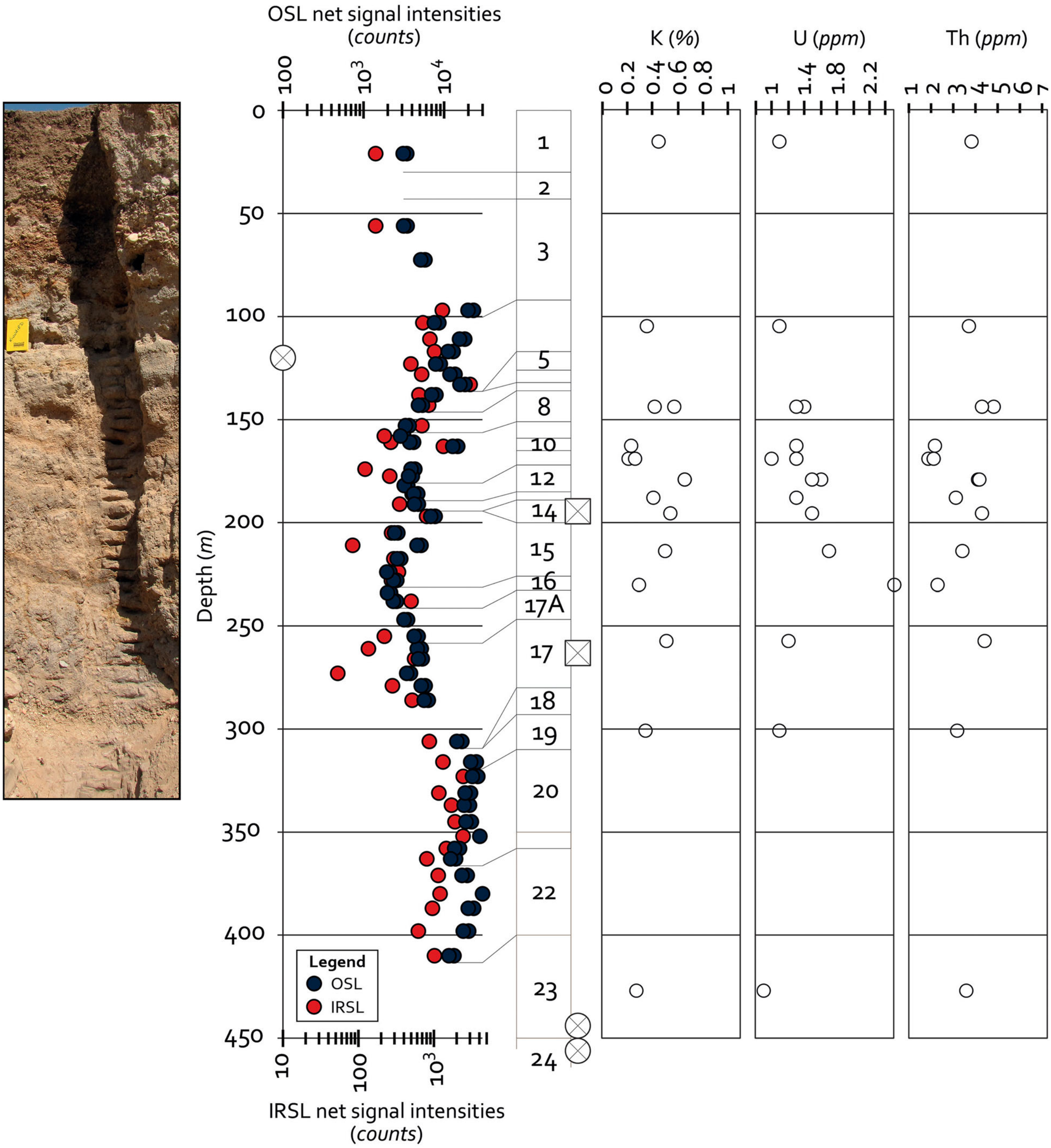

Figure 9. Field stratigraphy for Wadi Suf Profile LW1, also showing infra-red stimulated luminescence (IRSL) and optically stimulated luminescence (OSL) net signal intensities expressed as photon counts and plotted against depth. Radionuclide concentrations of K (%), U (ppm), and Th (ppm) are shown as a proxy for variations in environmental dose rate within the profile. X indicates additional field dose rate measurement.

Table 1. Wadi Suf soil and sediment ages. Based on Cresswell, Sanderson, Kinnaird, et al. (2018).

Field ID	SUTL no.	Dose rate /mGy a^{-1}	Equivalent dose/Gy	Age/ka	Age/calendar years
WS2Profile 2 Lower	2882	0.76 ± 0.05	1.05 ± 0.16	1.38 ± 0.24	A.D. 640 ± 240
JD16 (1) WS2 [5]	2961	1.06 ± 0.09	1.30 ± 0.02	1.23 ± 0.11	A.D. 790 ± 110
JD16 (3) WS3 [4]	2963	1.00 ± 0.09	0.62 ± 0.01	0.62 ± 0.06	A.D. 1400 ± 60
JD16 (4) WS3 [9]	2964	1.00 ± 0.09	4.76 ± 1.63	4.76 ± 1.69	2740 ± 1690 B.C.
JD16 (5) LW1 [4]	2965	1.04 ± 0.09	1.33 ± 0.11	1.28 ± 0.15	A.D. 740 ± 150
JD16 (6) LW1 [23]	2966	0.71 ± 0.07	25.3 ± 3.4	35.6 ± 5.9	33,600 ± 5900 B.C.
JD16 (7) LW1 [25]	2967	0.70 ± 0.07	1.77 ± 0.12	2.53 ± 0.31	510 ± 310 B.C.

terminus post quem for the possible abandonment of the Middle Islamic settlement in Jerash, subsequent to which sediment movement in the wadi accelerated.

With detailed relative and absolute OSL dating, these analyses establish that Wadi Suf contains stratigraphic sequences from the beginnings of urbanization through to the medieval period and which indicate a sensitivity to urbanization, earthquake and slope processes, and complex series of fluvial events. This work gives new prospects for integrating high-definition archaeological records with environmental records at local and regional scales and offers deeper insight into city-hinterland relationships.

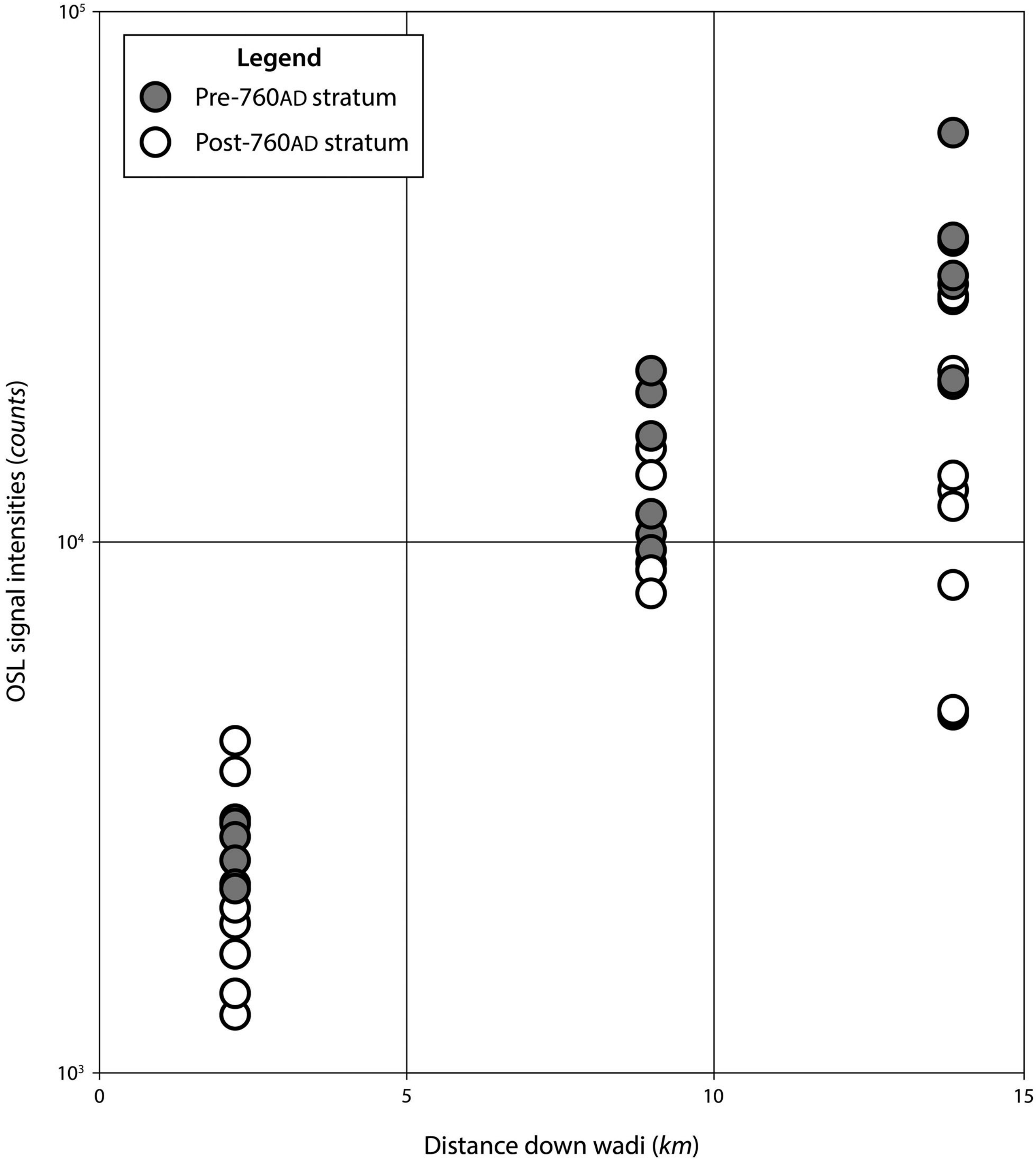

Figure 10. Optically stimulated luminescence (OSL) intensities plotted against down-stream distance in the Wadi Suf, for strata pre- and post-dating the A.D. 760 onset of accelerated land degradation. The increase in OSL intensities as a function of downstream distance implies sensitization of quartz through repeated cycles of deposition, erosion, and transportation.

While most of the data fit well into the framework of what is already known from historical and archaeological records regarding the history of the city (Hellenistic foundation and Early Islamic decline, Middle Islamic resettlement and decline), it is noteworthy that the wadi sediments suggest a more complex development. Neglect of terrace management in the upper wadi before the earthquake of A.D. 749 indicates an urban environment decline caused perhaps both by deteriorating climatic conditions, epidemics, war, failing markets, and poor governance. Jerash was hit by earthquakes throughout its history. The city after each earlier earthquake had been capable of rebuilding its environment. However, after the A.D. 749 earthquake the city was not rebuilt. The data presented here show that this earthquake acted as the final blow to an urban environment that already had lost its resilience before the catastrophe. The earthquake was then less the actual cause for the abandonment of the site, but rather the event that pushed the society beyond the capacity of upkeeping the site and its hinterland. The actual causes, which would not have been sudden impacts, are probably to be sought in wider, potentially global, developments such as slow climate change and larger political restructuring of the eastern Mediterranean region, but such conclusions need further investigation expanding on the data presented here.

Conclusion

Our analyses suggest a strong coupling of the city and its riverine hinterland through multiple factors and as evidenced in the movement of sediment in and through the wadi. When the city was growing and developing there was an enhanced sedimentation evident down-stream from the city, but the hinterland was managed in such a way that minimized the movement of sediment as evidenced in the upper-wadi location where agricultural intensification was at its greatest. The implication of these findings is that strong, and perhaps centralized, urban governance, growing markets and robust social and economic networks during wetter phases with the wider region results in an intact hinterland landscape and environmental sustainability, and which is evident in the wadi and its environs. Such social organization of a society and at the same time management of its resources, including a firm control of the hinterland's agricultural areas, can therefore be said to have added value and increased productivity. There are no signs that management of the hinterland led to overexploitation and in turn to degradation of the terrace system. Conversely, where urban organization breaks down, as after the devastating A.D. 749 earthquake during a dry phase with regional shifts to pastoralism, and after the later Ayyubid-Mamluk city abandonment, we see enhanced sedimentation in the wadi, particularly through colluvial deposition implying loss of terrace maintenance and slope failure. In long-standing cultural landscapes, active management is required to maintain landscape integrity; where management is removed, degradation sets in. Governance, regional networks, and favorable environmental conditions make urban-riverine hinterland relationships in semi-arid environments resilient and sustainable in the long term. Loss of any of these elements through internal or external system changes makes a landscape vulnerable to damaging change. The analysis of the sedimentation also helps to track long-term processes prior to events that are turning points of history. The decline of terrace systems already before the earthquake indicates a loss of urban resilience that after the earthquake of A.D. 749 became fatal.

Our work is still in an early phase, but with further refinement of chronological frameworks Jerash has the potential to integrate multiple and multi-faceted levels of analysis, from micro (e.g., house, neighborhood) through meso (e.g., city, wadi and desert frontier) to macro (e.g., climate systems, global history) with multiple variables (e.g., climate change, human exploitation of and adaptation to hinterland, geopolitics, natural disasters). The history of Jerash is in many ways representative of urban centers located in the semi-arid zone, which rose to prominence and declined as a result of a combination of geopolitical fluctuations, environmental changes, and catastrophic events. It is therefore a vital case study to investigate the balance between human agency and non-linear environmental change as a driver of historical processes. Insight into these long-term processes and interdependencies is perhaps the biggest lessons that studies of the past can offer at the dawn of the Anthropocene (Brooke 2014; Chakrabarty 2009; Contreras 2017).

Disclosure Statement

The authors declare no conflicts of interest.

Geolocation Information

WGS84: 32° 16′ 50.99″ N, 35° 53′ 30.23″ E – 32.28083°, 35.89173°
UTM: 36S 772354 3575237
Geo URI: geo:32.28083,35.89173

Acknowledgments

This work was supported by the Carlsberg Foundation; the Danish National Research Foundation under Grant DNRF119 – Centre of Excellence for Urban Network Evolutions (UrbNet); Deutsche Forschungsgemeinschaft, Deutscher Palästina-Verein; the EliteForsk initiative of the Danish Ministry of Higher Education and Science; and H. P. Hjerl Hansens Mindefondet for Dansk Palæstinaforskning. The authors would like to thank associate professors Jesper Olsen and Søren Munch Kristiansen for constructive input on the text and results offered here. There is no lead author on the article. All authors performed research, analyzed data, and wrote the article.

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