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Urbanization and Riverine Hinterlands

A Proposal for an Integrative High-Definition and Multi-Scalar Approach to Understanding Ancient Cities and their Dynamic Natural Resources

ABSTRACT Rivers have always been a magnet for human settlement, providing resources, such as water, food, and energy, and communication and travel routes. 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 that challenge economic, environmental, and social sustainability. This is especially true in semi-arid regions and in times of rapid climate change and human-driven deterioration of the environment. Therefore a deeper understanding is needed of the evolution of urban–riverine relationships within long-term historical frameworks. This article presents an integrative and interdisciplinary programme for research, which although exemplified by one case study — the city of Gerasa/Jerash and its hinterland in modern Jordan — can be applied to other locations and regions with benefits.

KEYWORDS Urban–riverine interdependencies; urban landscapes; hinterlands; Gerasa/Jerash

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Introduction

Across the world, rivers and their ecosystems are complex and dynamic systems that constitute essential resources for many settlements. The river understood as a dynamic resource is key. It serves firstly, on a landscape level, as the stage at which the settlement history of the city and its hinterland developed. Secondly, the fluvial sediments serve as an archive of its own, preserving longue-durée data of the environmental history of the region. Rivers shape the natural environmental setting of many urban settlements and are essential for the organization of water supply and associated food security as well as mobility, communication, and perception of space, while their course and nature are changed and modified by human intervention (e.g. Bernhardt, Koller, and Lichtenberger 2019; Cordova 2005; Edgeworth 2011; Franconi 2017; Levis and others 2017; Sorousch and Mordechai 2018; Tvedt and Coopey 2010). 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 that challenge social, economic, and environmental sustainability (e.g. Beckers, Berking, and Schütt 2013; Gilliland and others 2013a; 2013b; Mays, Koutsoyiannis, and Angelakis 2007; Miller 1980; Mithen 2010). However, multi-period urban–riverine hinterland relationships and trajectories in semi-arid environments over extended periods are poorly understood (cf. Döring 2016; Ohlig 2008; Parayre 2016; 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.

Since the 'Spatial Turn' in historical sciences — which increased interest in geographic entities by conceptualizing relationships between individuals/communities and their geography and by posing new research questions regarding the constitution of natural and culturally constructed space — rivers have come into focus (cf. e.g. Dipper and Raphael 2011; Döring and Thielemann 2008; Horden and Purcell 2000; Kneer 2010; McNeill and Mauldin 2012; Middell 2006; Osterhammel 1998). Water and rivers are best studied as dynamic resources, a term by which we understand the varying manifestations of nature in space and time, defined in relation to human demands, interventions, and legacy (Bartelheim and others 2015). '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 (cf. Campbell 2012; Miller and Spoolman 2011; Ostrom 2009; Schlüter and Pahl-Wostl 2007; Wutich 2009). Rivers also need to be considered as ideological and spiritual resources, since they were often venerated as deities (Klementa 1993; Lichtenberger 2019a; Lichtenberger and Raja 2016a) and as defining in space and power relationships between humans (Purcell 2012). The term 'dynamic' recognizes that these socio-natural systems were in constant flux, responding to and triggering human–nature interactions (Edgeworth 2011).

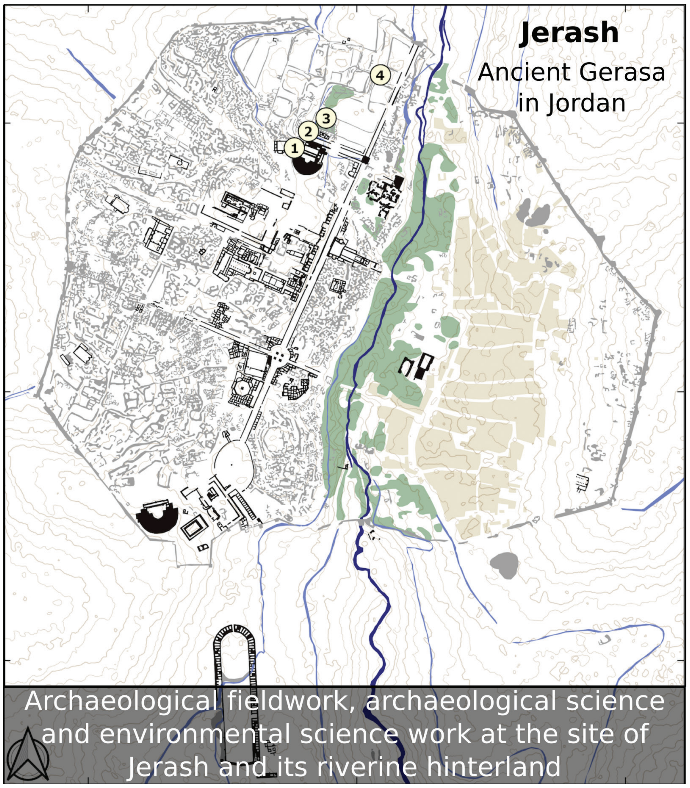
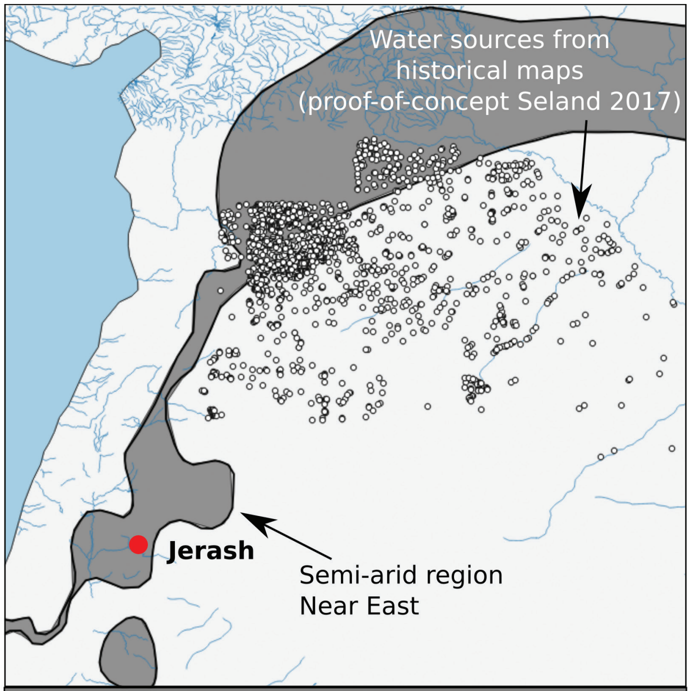
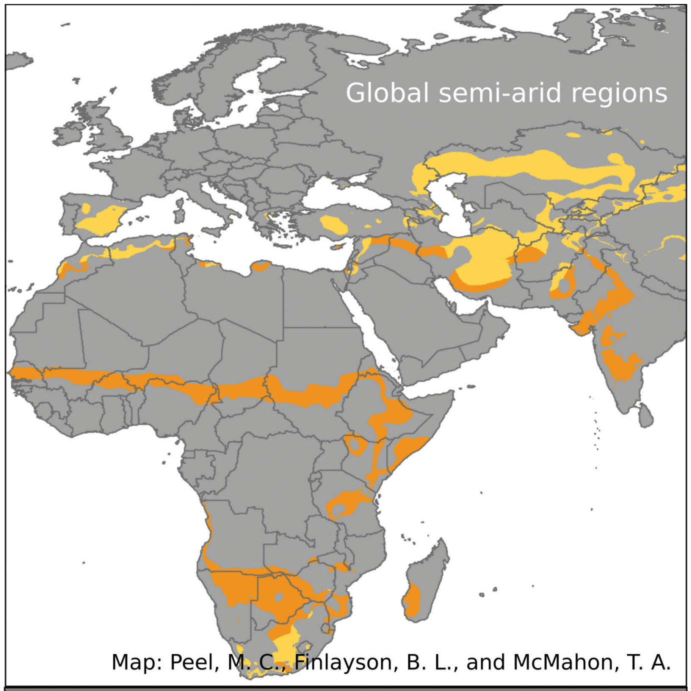


Figure 3.1. Innovative multi-scalar approach combining archaeology, environmental sciences, and global history. Figure by authors.

In recent years, investigation of the relationship between humans and river environments from spatial and resource-based perspectives has developed into an innovative approach to study civilizations (Ackroyd 2008; Alley 2012; Altaweel and others 2019; Barca 2010; Castaneda and Simpson 2013; Dan and Lebreton 2018; Kibel 2007; Mauch and Zeller 2008; Possehl 2010; Rau 2010; Schmid 2009; Tvedt 2004; Wilkinson 2003; Wilkinson, Gibson, and Widell 2013; Wright 2010). In the Mediterranean world, contributions such as *The Maeander Valley: A Historical Geography from Antiquity to Byzantium* (Thonemann 2011), *Rivers and the Power of Ancient Rome* (Campbell 2012), and *Le Rhône au Moyen Age* (Rossiaud 2007) considered human relations with rivers; however, most of these studies did not interrelate their findings with results from the natural



Climate change history of the semi-arid Near Eastern region around Jerash



Regional computational climate modelling. Implications for semi-arid regions globally.

sciences (but cf. Brückner 2003; Drew 2012; Roe 2012). Other studies (e.g. Edgeworth 2011) looked more at the environmental aspect and less at cultural history. None of these studies provided a formal framework for studying the interrelationships between rivers and human communities.

Similarly, archaeological research in Mediterranean archaeology has not considered millennial-scale urban–hinterland water-resource management nor the decisions and associated consequences related to these dynamic resources in a systematic manner (LaBianca, Hubbard, and Running 1990; Macklin 1999; Meyer 2017; Meyer and Seland 2016; Morandi Bonacossi and Iamoni 2012; Passmore, Waddington, and Houghton 2002). Thus, a comprehensive study of an ancient classical city and its hinterland in the Near East is still lacking. Academic discourse in this arena has focused on identifying buried palaeo-landscapes and site visibility within floodplains (Clevis and others 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), while studies of early management of fluvial environments have emphasized particular social groups within narrowly defined timescales (Kidder and Saucier 1991; Lucero, Gunn, and Scarborough 2011; Zhuang, Ding, and French 2014).

So far there has been no comprehensive study of the longue-durée dynamics of urban–riverine hinterland relationships through integration into a formal framework of the historic, economic, and environmental perspectives. However, such an approach would enable us to scale up from a unique case-study approach to its global-history implications by means of computational-assisted historical modelling, thus offering a testable, long-term high-definition perspective on the constantly shifting balance between environment and human agency (Raja and Sindbæk 2020a; 2020b). Our aim here is to use a case study to highlight the integrative and interdisciplinary possibilities that may form a best-practice approach in the future.

Gerasa/Jerash as an Example of a High-Definition and Multi-Scalar Approach to Explore Riverine Urban–Hinterland Resource Dynamics

It is possible to study human–riverine interaction at scales moving from local to global perspectives (Fig. 3.1). However, to comprehend the full complexity of such a socio-natural system, it is necessary to have precise and detailed knowledge of its functioning. Due to the lack of relevant data spanning across sites and centuries-long periods, it is neces-

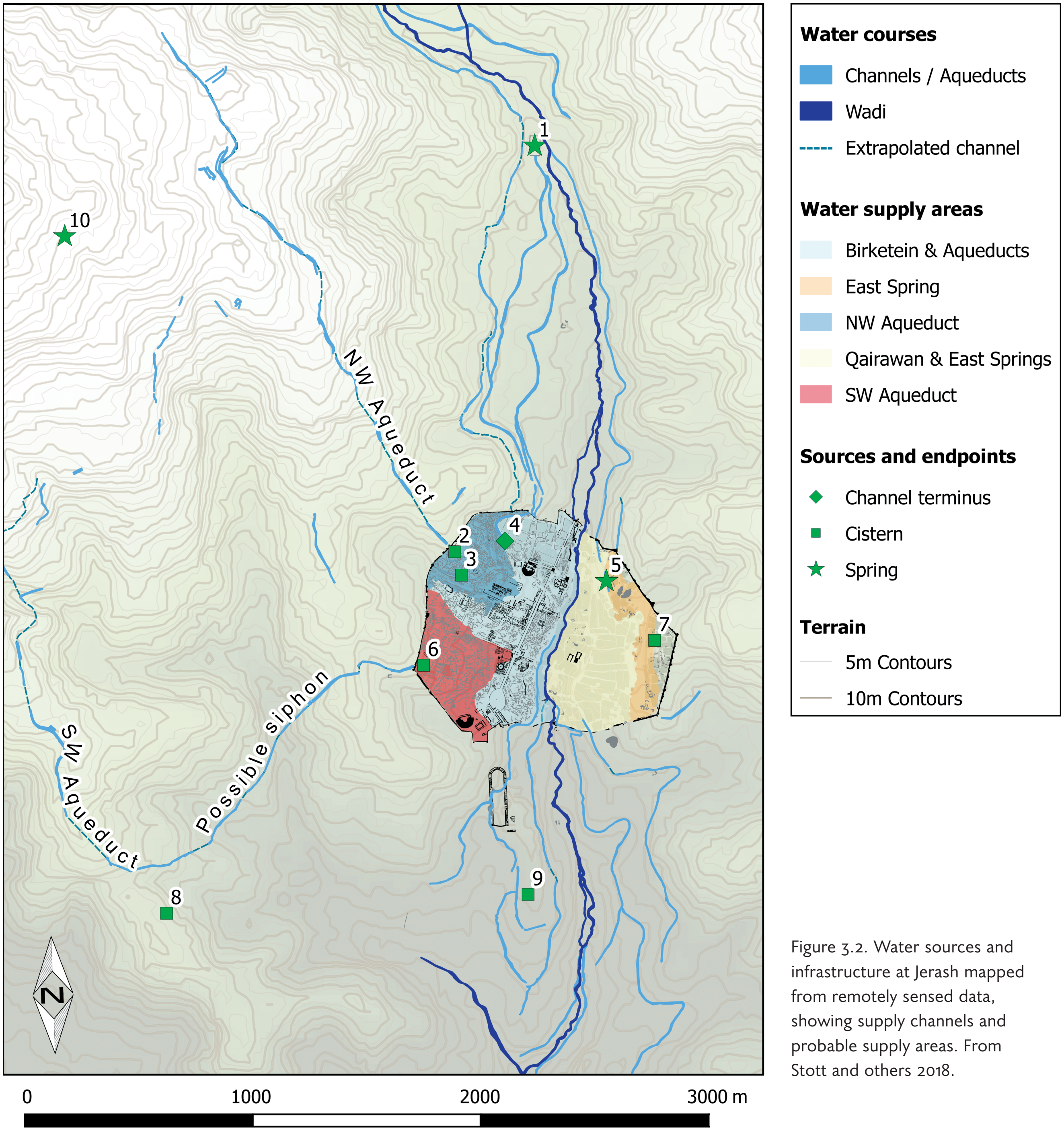


Figure 3.2. Water sources and infrastructure at Jerash mapped from remotely sensed data, showing supply channels and probable supply areas. From Stott and others 2018.

sary to zoom in on a particular case study, to investigate it in a holistic manner and scale up from such a high-definition point of departure to a broader view. Insight into the long-term processes and interdependencies is perhaps the biggest lesson that historical studies can offer at the dawn of the Anthropocene (Brooke 2014; Chakrabarty 2009; 2015; Contreras 2017; Guldi and Armitage 2014; Van de Noort 2013; Wilkinson 2003). The multi-period, mid-size urban site of Gerasa/Jerash in the semi-arid part of northern Jordan (Kraeling 1938; Lichtenberger and Raja 2015; 2016a; 2017; 2018a; 2020a; Raja 2012) is an ideal case (Fig. 3.2). It combines a long history of human habitation, subsistence patterns typical for the region, and extensive multi-period water-management features throughout the city and its hinterland, with the excellent state of preservation and systematic archaeological investigations since the early twentieth century (Kennedy 2004; Lichtenberger and Raja 2018a). Gerasa is more representative of

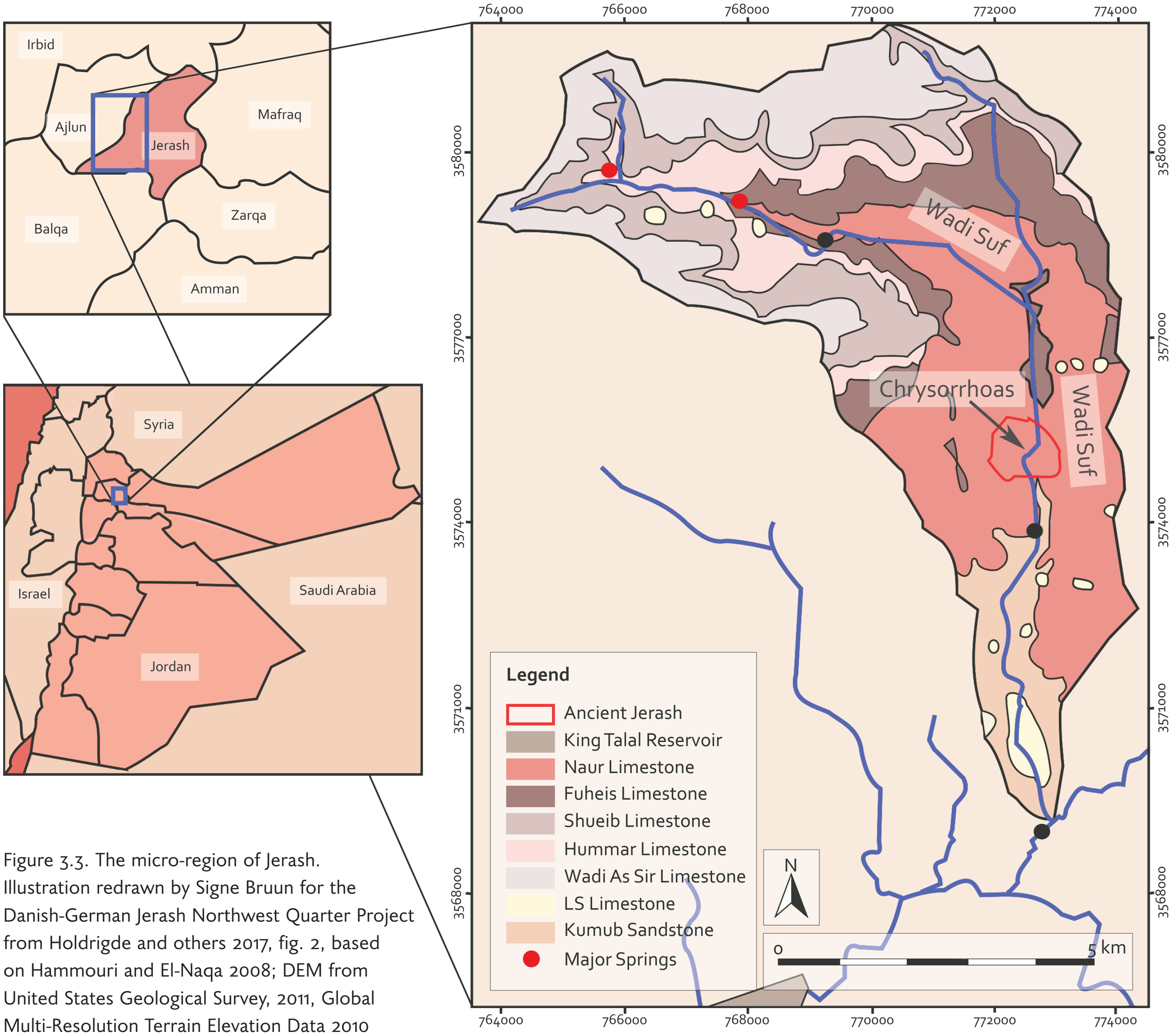


Figure 3.3. The micro-region of Jerash. Illustration redrawn by Signe Bruun for the Danish-German Jerash Northwest Quarter Project from Holdrigde and others 2017, fig. 2, based on Hammouri and El-Naqa 2008; DEM from United States Geological Survey, 2011, Global Multi-Resolution Terrain Elevation Data 2010 (GMTED2010N30E030_075). Sioux Falls (SD): United States Geological Survey Earth Resources Observation and Science (EROS) Center.

premodern cities and their historical trajectories than ancient megacities like Rome, Constantinople, Cairo, or Baghdad, making it a perfect case for investigating the critical balance between human agency and environmental change (Lichtenberger and Raja 2018b; 2019a; 2020a).

Gerasa's origin can be traced to prehistorical times (al-Nahar 2018). Since then, humans occupied the site with changing intensity. Phases of occupation followed phases of abandonment. From the Hellenistic period onward (second century BC), Gerasa grew to become an important urban centre of the region. It continued to thrive into Late Antiquity and the early Islamic period, but the importance of Jerash ended after an earthquake hit the city in AD 749 as a result of major seismic activity along the Jordan Valley strike-slip fault (Lichtenberger and Raja 2016b; Marco and others 2003; Russell 1985, 47–49; Sbeinati, Darawcheh, and Mouty 2005, 362–65; Tsafrir and Foerster 1992). A small urban core survived and continued its subsistence until modern times, but the city never regained its position within the region (Lichtenberger and Raja 2018a; 2019a).

The decline of Gerasa is a telling example: the region was often hit by earthquakes, although we do not have extensive evidence for the impact of the earthquakes on Gerasa, apart from the AD 749 earthquake. However, usually cities were swiftly rebuilt after such catastrophes. So why did this not happen in Gerasa after AD 749 despite a millennium of what comes across as thriving urban life? Such questions can only be addressed through a comprehensive investigation of the city and its riverine hinterland, including the interrelated global and meso-regional developments in climate history and geopolitics.

Water accessibility is key to understanding Gerasa and its society (Lichtenberger and Raja 2018c; 2020b). The riverine environment of Gerasa forms a well-defined micro-region, whose welfare was entirely dependent on the river Chrysorrhoas ('the Gold River' in ancient Greek) (Baker and Kennedy 2011; Kennedy 2007; Kennedy and Baker 2009; Lichtenberger 2019b), which cuts the city into two parts and is the main water source for the surrounding region (Fig. 3.2 for the city and Fig. 3.3 for the micro-region). Water accessibility was also crucial to the wider region known in Antiquity as the Decapolis — 'ten cities', but in reality more — a fertile and densely urbanized, yet ecologically vulnerable region (Bietenhard 1977; Dan and Nodet 2017; El-Khouri 2009; Hoffmann and Kerner 2002; Horden and Purcell 2000; Kennedy 2007; Lichtenberger 2003). In this frontier landscape, the long-term development of the Decapolis and neighbouring regions (Betts 1998; Lancaster and Lancaster 1999; Seland 2015; 2018; Wilkinson 2003) depended on striking a fine balance between environmental exploitation and anthropogenic interventions (Bienert and Häser 2004; Brooks and others 2010; Orland and others 2009; Schmidt and others 2006). Changes of precipitation between season and frequency of major environmental transitions had a significant impact on human settlement and mode of subsistence, which fluctuated between nomadic pastoralism and settled agriculture. In periods with favourable climate and strong centralized polities such as the Roman and early Islamic periods, Gerasa and the wider region flourished, and agricultural settlement extended towards the 200 mm isohyet, the theoretical limit for dry agriculture. In dry periods and during periods of weak governance, the limit crept back towards the 400 mm isohyet, where harvest is more dependable (Issar and Zohar 2007; Lewis 1987; Rosen 2007). In this landscape, traces of ancient water-management systems remain visible in the city: the North and South Water Gates, water infrastructure around the Ain Karawan spring (Kraeling 1938, 11; Lepaon, Turshan, and Weber-Karyotakis 2016; 2018; Lichtenberger and Raja 2016a; Seigne 2008) as well as across its hinterland, with stretches of rock-cut channels and cisterns (e.g. the Birketein bipartite cistern complex) and the irrigation features through the wadis (Boyer 2016a; 2016b; 2019; Lichtenberger and Raja 2016a; Stott and others 2018). The interplay between intra-urban and extra-urban socio-environmental relations and their consequences were negotiated through water-resource management. By unravelling these dependencies at Gerasa and its wider region, we provide a starting point for unlocking central historical questions relating to the 'rise and fall' of urban societies, their sustainability in the face of social and political transformations as well as natural pressures such as climate change.

Local, Micro-Regional, and Global Scalings: Creating Integrative Research Agendas

To unleash the synergetic potential of multi-scalar approaches, research enquiries should accordingly be designed. We here present a scaling approach going from the local to the global perspective according to the specific perspectives on the overall subject, harvesting, understanding, and using high-definition data from one case study to extrapolate and juxtapose with other settings where such data are lacking. The three scales relate to (1) the local perspective including the hinterland perspective; (2) the micro-regional perspective, and (3) the contextualization of the first two within meso-regional and global contexts of water availability and climate change as well as in narratives and causal models of historical change (micro-regional, meso-regional, and global perspective). These scaling perspectives should then be brought together in a synthetic manner through the data within theoretical frameworks in order to test theories and develop models on water sustainability in semi-arid regions and the nature of human–nature relationships giving us multi-scalar perspectives, which can provide a basis for much broader comparative studies in the future.

On the Ground: The Local Perspective

Integrated fieldwork and following analyses related to determining settlement patterns of Gerasa and its hinterland is a must in such an agenda. Such fieldwork would relate to assembling comparative data from the city centre and laboratory analyses that define the water and land uses associated with hinterland settlement patterns. Archaeological and soil-profile documentation would be an important part of such as programme. Further excavations would aim at understanding the rural settlement patterns of the area in a diachronic perspective. They should furthermore assemble soils, as already proven to yield good results in the work done within the Danish-German Jerash Northwest Quarter Project (Holdridge and others 2020) as well as zoo-archaeological and archaeo-botany samples for laboratory-based land- and water-use analyses and of which only little work has been published thus far (Bangsgaard 2020; Hald 2020). Abandonment phases are traceable through soil deposits. Dating and describing these phases through Optically Stimulated Luminescence (OSL) and radiocarbon measurement relate the inner-urban development to the use of the riverine resources in the hinterland and explain the processes and events behind such — often massive — shifts (Lichtenberger and others 2019). As Gerasa is located in a dry climate zone, environmental DNA has not been included in our approach, but in colder and/or more moist climates this approach should be considered.

As part of an extra-urban research programme, documentation of settlement patterns should be done by mapping all in-situ evidence and surface finds through an extensive field survey and drone survey to give automatic detection of surface finds (Orengo and Garcia-Molsosa 2019). The basis and starting point for the surface surveys should be done in close cooperation with landscape modelling (described below). Furthermore, analysis of LiDAR data enables survey and documentation of prioritized areas.[1] The site documentation should be carried out through geodetic survey, including photogrammetry, laser scanning of selected areas, and collecting surface pottery.[2] As part of the hinterland survey the water installations identified should also be verified and assessed. Besides the extensive field survey, a sample transect should be laid out and surveyed intensively to collect reference data and to test the viability of the LiDAR-based extensive survey approach. Such a transect should be chosen in an area that covers a 500 m broad strip descending from the upper-wadi ridges to the river bed. This would allow for early adjustments in the survey strategy.

The survey data should be included in a GIS dataset. Pottery and surface finds should be analysed for chronological purposes and typology, which will indicate function of the sites.[3] The pottery should also be analysed by statistical quantification and integrated into computational modelling (also see Romanowska, Lichtenberger, and Raja 2021; Romanowska and others 2021). Based on LiDAR (40 cm resolution), drone (sub-cm resolution), and ground truthing, sites should be identified and classified.

Since surface surveys do not give the complete overview and exact chronological span of a site, targeted archaeological excavations in selected areas should be undertaken. These are necessary for a better understanding of the chronology and character of particular sites. Excavations provide access to soil profiles and other undisturbed data archives (e.g. archaeo-botanical and archaeo-zoological data). Therefore, different types of sites should be excavated as examples of the variety in sites and soil profiles. The choice of sites should be based partly on seeking answers to questions of site characterization, partly on the broader relationship to the wadi sediments.

At the same time an urban research programme should be implemented in which systematic cleaning and re-excavation of urban profiles from previous excavations within the city could provide new data that needs to be related to extra-urban stratigraphies. Throughout the ancient site, previously excavated areas (some excavated decades ago) can be restudied with little effort and high-impact results. The profiles should be documented stratigraphically and prepared for taking soil samples. Areas could for example include: the North Theatre profile, the western end of the North Decumanus, the Roman Basilica, and the northern section of the city walls. Some of the profiles are up to 10 m high and indicate catastrophic events. The profiles should be analysed and then related to associated monuments, for most of which data on the building history are available, and the high-definition data already published by the Danish-German Jerash Northwest Quarter Project can also be used as comparative material and serve as a background framework (Lichtenberger and others 2019; 2021).

During the targeted excavations, bone and botanical remains should be systematically investigated. Quantification of these chronologically controlled collections from different areas of the landscape will allow contrasting assessments of land use and land–water resources, complement the soil and sediment-based analyses of land–water resources, and give greater security of interpretation. Similarly, quantification of livestock bone will give an indication of the proportion of milk vs meat production (through analyses of the neonatal component) together with the proportion of land given over to livestock production and the area required for fodder.[4] In both archaeo-botanical and zoo-archaeological datasets an assessment of the changing relative contributions of wild and domestic species should be undertaken.

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[1] See Stott and others 2018 for an integrative approach to LiDAR data from Gerasa.

[2] See Bes and others 2020 for an overview of published ceramics from the region.

[3] See contributions in Lichtenberger and Raja 2020a for the newest research in pottery in Gerasa.

[4] Also see Lichtenberger and others 2018 for proof-of-concept work.

Furthermore, compound-specific stable-nitrogen and carbon-isotope analyses ($\delta^{15}N$ and $\delta^{13}C$) should be undertaken on bone and botanical material to assess whether crops and livestock have been produced on nutrient-enhanced land (Fuller and others 2012; Simpson and others 1997; 1999a).

Local surveys of soils and sediments within the Gerasa urban hinterland identify polygenetic stratigraphies of cambisol, anthrosol (irragric and hortic), and fluvisol soil classes (IUSS Working Group WRB 2015). Working from the principle that soils and sediments reflect the social and physical environments in which they have been formed, these stratigraphies when validated against local ethnographies and environments are millennial-scale records of water dynamics shaping the hinterland, land-use responses, and the evolving significance of Wadi Suf (upper Chrysorrhoas) (Holdridge and others 2017; 2020; 2021; Adderley, Simpson, and Davidson 2006).

Key to understanding these records are the exceptional luminescence archives contained within these stratigraphies. These can be explored through novel field-based and in-situ luminescence profiling utilizing OSL equipment (Munyikwa, Kinnaird, and Sanderson 2020; Lichtenberger and others 2019). When set in their particle size and mineralogical contexts, variations in luminescence signals — and hence sedimentation processes — characterize and quantify sensitivities and morphological change in sedimentary systems from shorter timescales (<10^2 yrs) to longer periods of time (>10^2 yrs). Spatial statistical analyses of luminescence data integrated with spatial modelling of hinterland processes, including settlement locations and land management, sedimentation effects of the AD 749 earthquake, and regional climate change focused on the late antique Little Ice Age (Bar-Oz and others 2019; Kempe and others 2006) make clear the contributions of extreme events and more gradual changes to sediment dynamics.

Records within soil and sediment stratigraphies also evidence land capabilities and management within the hinterland. Water management, soil fertility, and land covers are all identified through interpretation of soil properties. Soil textural and structural data together with field-measured soil permeameter and particle-size distributions make possible the mapping of soil water-holding capacities across the hinterland and indicate soil water deficits for agriculture (Adderley and Simpson 2006). Management responses to these inherent constraints include macro- and micro-irrigation systems, with their historical patterns of water movement recognized in soil thin sections by distinctive micro-scale textural pedofeatures. These can be observed and quantified using AnalySis image-analyses methods and associated scanning electron microscopy, which enable assessments of irrigation-enhanced crop productivities in the Gerasa hinterland (Gilliland and others 2013a). Measurement of soil-nutrient elements using inductively coupled plasma mass-spectrometry-based analyses — particularly phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), lead (Pb), and copper (Cu) — give definition of nutrient limitations and management enhancements together with polluting impacts in the early hinterland landscape (cf. Adderley and Simpson 2006; Golding and others 2015). Organic materials applied to maintain soil fertility can be identified through sterols, stanols, and bile acids in soils, separating herbivorous and omnivorous animal wastes and indicating intensity of applications (Simpson and others 1998; 1999b). Innovative bio-marker analyses may also be applied to the identification of crop and woodland cover types based on the retention of leaf wax ester analyses in soils, with triterpene methyl ethers emerging as particularly important diagnostic compounds. Of particular interest in the Middle East are the prospects for identifying new leaf waxes unique to fig (*Ficus carica*) and olive (*Olea europaea*), giving a new focus in defining the land-use history of these important cultivated crops.

To set soils and sediments analyses within robust and refined temporal frameworks, detailed ^{14}C and OSL dating can be applied to stratigraphies, guided by the OSL profiling analyses. OSL dating provides a means to directly date buried soil surfaces and sediment movement within polygenetic stratigraphies and offers chronological frameworks for land–water resource dynamics. We have undertaken OSL analyses within Jerash and in Wadi Suf, and although the underlying geology of the region is limestone (which does not contain much quartz), it has been confirmed through micromorphological analyses that soils and sediments of the region hold Holocene aeolian quartz (cf. Lucke and others 2014). Furthermore, pilot field studies and laboratory measurements confirm that these quartz grains hold a luminescence signal (Lichtenberger and others 2019). From this foundation, we have successfully applied OSL-chronology methods to provide historical dates for the formation of Wadi Suf sediments, giving confidence that robust chronological frameworks can be developed for the hinterland area (Lichtenberger and others 2019). Application of OSL in dating earthworks and terraces in the Mediterranean and Near East give further confidence to this approach on a global scale (Beckers and others 2013; Bevan and others 2012; Davidovich and others 2012; Gadot and others 2016; Puy and Balbo 2013; Turner and others 2021). The OSL chronology can be further supported by ^{14}C dating of plant macrofossils, charcoal, and animal bone, dating the materials of the sediment profiles and stratigraphic layers, and it can be refined through Bayesian modelling.

From a Distance: The Meso-Regional Perspective — Multi-Scalar and Multi-Temporal Landscape Modelling of Jerash and Hinterland

The meso-regional perspective should focus on extending the detailed and high-definition social, temporal, and environmental observations drawn from the local perspective across the study area, by modelling the landscape development of Jerash and its hinterland and integrating them with remotely sensed data, geochronology, and Bayesian modelling. Landscape is in the last millennia created by the interaction between people and their environment and, as such, is the sum of the dynamic of natural and anthropogenic processes that shape it over time. This dynamic change rarely erases all evidence of previous conditions, meaning that landscapes represent a continuously evolving palimpsest of past and present land use and events (Ashmore and Knapp 1999). Understanding these processes entails looking for their physical traces and using these to reconstruct how landscape has changed. From such reconstructions we can infer the wider environmental and societal causes driving these changes. In Jerash and its hinterland, this is best achieved using the remotely sensed data, including aerial imagery dating back as far as the First World War and modern LiDAR and satellite data (Stott and others 2018). Each dataset represents a snapshot of the landscape at a particular time, and by analysing them together, we can identify and track processes. Mapping results of recent changes also means that we can exclude them and identify features indicative of relict land use and settlement patterns. Such temporal depth is crucial, as population growth and resultant agricultural intensification and urban development mean that much historically salient detail has been obscured or destroyed (Kennedy 1998; Stott and others 2018).

Focusing on characterizing soil and water resources within the catchment area, using well-tested, semi-supervised machine-learning classification approaches (Paloscia and others 2013; Stenberg, Rossel, and Mouazen 2010; Stoner and Baumgardner 1981) on time series of synthetic aperture radar (SAR) and multispectral satellite and aerial photographic data, resources may be mapped. These could be used both to map soil-reflectance properties directly and to identify seasonal changes in vegetation, indicative of long-term water availability. Of particular importance for this, are archival aerial photographs and declassified satellite imagery from the 1960s, as these were acquired before the intensification of ground-water abstraction in the region (Al-Zyuod and others 2015; Salameh 2008).

Recent advances in image processing have made possible the generation of high-resolution 3-D digital terrain models (DTMs) from sequences of archival aerial and satellite images (Risbøl and others 2015; Sevara and others 2018). Using a combination of aerial images and CORONA satellite imagery from the 1960s and 1970s and comparing these to modern SAR- and LiDAR-derived DTMs will provide a comprehensive overview of how topography has changed (Stott, Kristiansen, and Sindbæk 2019; Tapete and Cigna 2019), and provide insight into processes of erosion and deposition. Additionally, the historic DTMs provide topographic measurements before the modern intensification of urban development obscured evidence of diagnostic topographic features indicative of large-scale fluvial, colluvial, and tectonic processes. Using both the historic and modern DTMs, terracing may be automatically identified using a classification of multi-scalar topographic position indices (De Reu and others 2013; Diaz-Varela and others 2014). By using the vegetation analyses from aerial and satellite imagery, it can be deduced which terraces are maintained at a particular time. This information can then be used to identify those that are archaeologically important. Recent work in the area (Boyer 2016a; 2019; Kristiansen and Stott 2020; Stott and others 2018) has revealed a complex system of water abstraction and delivery, dating from the Ottoman period back to Antiquity. At present, these have mostly been destroyed, but using archival imagery these channels and aqueducts can be mapped, and surviving sections identified in the modern data.

Detection of archaeological features is possible with the use of high-resolution LiDAR-derived DTMs, historical photography, and satellite imagery to identify likely sites of settlement. This may initially be conducted using visual interpretation of data, advanced contrast enhancement, and data-fusion techniques (e.g. Doneus 2013; Filzwieser and others 2018; Kokalj and Hesse 2017). These features could then be targeted and ground-truthed for investigation. Subsequently, state-of-the-art spectral and morphological feature detection using convolutional neural networks (Maggiori and others 2017; Nogueira, Penatti, and dos Santos 2017), Support Vector Machines (Mountrakis, Im, and Ogole 2011), and Decision Trees (Belgiu and Drăguț 2016) could

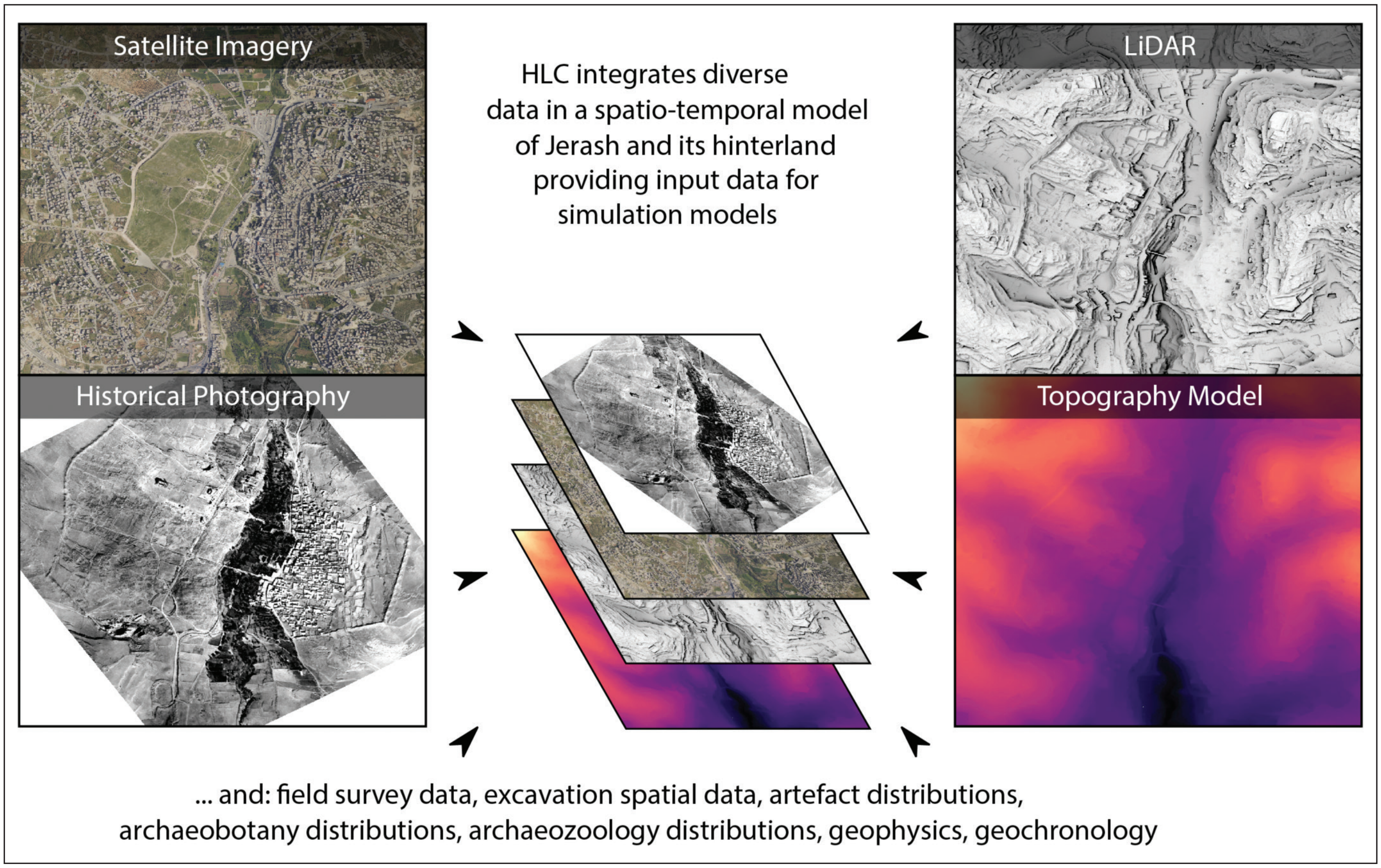

Figure 3.4. Historic Landscape Characterization integrating diverse data in a spatio-temporal model. Illustration by authors.

be evaluated using training data comprising sites identified by field surveys. Developing a toolkit for automatic feature detection and pattern recognition is of great importance for archaeologists globally, as pressure on cultural heritage from climate change, conflict, and development mean we lack the resources to map the ever-accumulating archives of remotely sensed imagery (Bennett, Cowley, and De Laet 2014; Sevara and others 2016). As has recently been shown, this is feasible on national scales in Europe using Random Forests Regression (Stott, Kristiansen, and Sindbæk 2019).

By integrating the data gained from the local and meso-regional investigations and the high-resolution geochronological work described above, it would be possible to derive a Historic Landscape Characterization (HLC) (Fig. 3.4). Historic Landscape Characterization is a method that presents an interpretation of the historic character of entire landscapes (Turner 2006). It was first developed in England (Herring 1998) but has subsequently been used to inform landscape management, planning, and research throughout the UK and elsewhere (e.g. Crow, Turner, and Vionis 2011; Fairclough and Herring 2016; Turner and Crow 2010). An HLC map classifies the entire landscape into a series of GIS polygons, which reflect particular categories or 'types' of historic landscape character. As an approach it is rooted in the holistic concept of landscape outlined by the European Landscape Convention (ELC) (Council of Europe 2000, Articles 1 and 2). It encompasses 'the entire territory' (not only particular points of interest) and the diachronic development (not just specific points in time). On a conceptual scale, we need to devise frameworks that overcome the boundaries between the past and the future, or between researchers and the broader concerns of citizens. On a detailed level, we need to be able to articulate the processes of landscape development and change so they are accessible to researchers from different disciplines. This means overcoming the conceptual, theoretical, and practical divides between them.

All spatial data and previously published data on Jerash and its hinterland (cf. Boyer 2019; Kennedy 2004; Lichtenberger and Raja 2019b; 2019c; Lichtenberger, Raja, and Stott 2019; Lichtenberger and others 2019) could be integrated within a common spatial framework in a PostGIS database, which would facilitate platform sharing and analyses of data across the programme, using both proprietary and Open Source GIS software.

Bayesian statistics which include archaeological information, OSL, and the radiocarbon ages should be generated and combined in a framework to construct robust high-definition chronologies for each profile or trench, from both urban contexts and the hinterland (e.g. Borić and others 2018; Sanjuan and others 2018). The stratigraphical information either in terms of Harris matrices (trenches) or depth information (sediment profiles) could then be used to inform Bayesian models (Bayliss and Ramsey 2004; Blaauw and Christen 2011). Summarizing activity plots based on all ^{14}C and OSL dates from the riverine hinterland would then allow for using kernel density estimation (KDE) within a Bayesian framework (Ramsey 2017). The KDE analysis can provide information on periods with enhanced hinterland activity. For the sediment cores, Bayesian depth-to-age models should be informed with accumulation rates inferred from OSL profiling using BACON (Blaauw and Christen 2011).

Zooming Out: Locating Jerash in a Meso-Regional and Global Context

Expanding perspectives developed in the local and micro-regional settings with an integrated view to the meso-regional and global-history contexts (Troebst 2012; Lichtenberger 2021) is crucial. Therefore key debates on the balance between environmental and human agency in the Anthropocene in the context of the semi-arid/arid Near East (e.g. Clarke and others 2016; Haldon and others 2018; Harper 2017; Huntington 1915; Issar and Zohar 2007; Izdebski and others 2016; Rosen 2007; Wilkinson 2003) and on the broader level of global history (e.g. Brooke 2014; Chakrabarty 2009; 2015; Contreras 2017; Huntington 1915; Lieberman and Gordon 2018; Van de Noort 2013) must be addressed. They can be approached through four areas of study: narratives of Near Eastern history and climate; meso-regional settlement history and water systems in comparative perspective; the role of climate as a case study of global historical developments; and semi-arid regions globally (Lichtenberger and others 2021).

Narratives and theories about the development of the Near East are an important backdrop for the study of any ancient city there. Historical scholarship rests on the insight that history, as opposed to the past, is constituted by narratives (Carrard 1992; Rüsen 2005; Veyne 1971). This is an important way of structuring data.[5] It is crucial, however, to be aware of the pitfalls embedded in such approaches. Data manipulation and presentation bias are hard to spot and unconsciously done when generating grand narratives. Our notions of Near Eastern history remain influenced e.g. by deeply rooted preconceptions of biblical, Greek, Roman, and Islamic pasts of perceived global significance. A way of tackling this is providing a critical overview of the narratives of Gerasa and the region between the second-century BC foundation by the Seleucids and the resettlement in the Ottoman period. Cases include the Hellenistic urban expansion (Cohen 2016), Roman rule (Butcher 2003; Haldon 2016), the Jewish War (AD 66–70) (Lichtenberger 2018), the establishment of Provincia Arabia in AD 106 and the debated impact of the Antonine and Justinianic plagues (Haldon and others 2018; Harper 2017; Newfield 2018a; 2018b), as well as the late antique Little Ice Age (Büntgen and others 2016; Newfield 2018a; 2018b). They continue with the Arab conquest, transition from Umayyad to Abbasid rule (Bulliet 2009; Ellenblum 2012; Haldon 2016; Preiser-Kapeller 2018; Walmsley 2012), the Little Ice Age during the Mamluk period (Behringer, Lehmann, and Pfister 2005; Raphael 2013; Xoplaki and others 2018), and nomad–settled interaction and the rise of Suf as an Ottoman regional administrative centre (Lewis 1987; Rogan 2002). Studies done on this background should not focus exclusively on climate, but relate to published climate-history timelines as well as the new and consolidated ones resulting from the work done on regional climate records. Such studies would provide a high-resolution timeline feeding into the synthetic part of such a research programme and the assessments of the balance between environment and agency in shaping the development of Jerash.

Mapping access to water in the meso-region, west of the Euphrates and east of the 400 mm isohyet, to establish the hydrological context for Jerash and the Decapolis, allowing investigation of the role of water in determining patterns of historical settlement, communication, and geopolitics would be a crucial study to undertake. Using Soviet military maps in 1:50,000, 1:100,000, and 1:200,000 scales, every water source can be mounted in a GIS: well, spring, and cistern/reservoir (*GUGK*; Seland 2019). While these maps do not give complete information, they are recognized for their accuracy and quality (Kent 2017). In contrast to the alternatives offered by national agencies, they provide a standardized and comprehensive dataset across borders, supple-

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[5] See e.g. Andrade 2013; Ball 2016; Issar and Zohar 2007; Millar 1993; Sartre 2001; Sommer 2018 on the Near East.

menting the fine-grained data gathered by survey on the ground. Earlier work has verified the accuracy of these maps (Meyer 2017; Meyer and Seland 2016), which have also been checked against satellite imagery to exclude modern drilled wells (associated with visible pumps and fences) and mandate and Second World War maps, to reconstruct the premodern availability of water. Data may also be vetted against the structures archaeologically mapped during the fieldwork as well as published material (e.g. Royal Jordanian Geographic Centre 2013). It will feed back by providing data on density of water that can be aligned with the distribution of archaeological sites and identify 'hot' and 'cold' zones of past human activity based on maximum entropy modelling (cf. Meghan, Palace, and McMichael 2016). While aerial and satellite archaeology has produced astonishing results in the Near East (e.g. Bewley and others 2016; Kennedy 2011; 2017; Kennedy and Bishop 2011; Poidebard 1934), the Cold War maps have never been systematically utilized.

Data harvested from maps are aligned with historical, ethnographic, and archaeological records, and data from local archaeological fieldwork could form the basis for case studies on connectivity, settlement, subsistence, and political borders in the region. The hypothesis, made testable by the application of formal network modelling, is that availability and control of water strongly influenced not only subsistence patterns, territories (partly tribal), and communication but also imperial strategies of control. Thus, this approach can provide nuance and challenge prevailing views on the geopolitical dynamics of the region, which arguably do not sufficiently incorporate the environmental dimension (Edwell 2008; Holt 2014; Lewis 1987; Masters 2013; Millar 1993; Rogan 2002; Walmsley 2012). Case studies will inform the synthesis and include city territories in the Decapolis, the Roman frontier, and the line between agricultural settlement and nomad land in the Islamic period. In this way, the long-term history of Jerash and its hinterland could be situated in a comprehensive hydrological regional framework. Such data will be available and transferable to other settlements in the Near East for further comparison, testing, and analysis.

New high-resolution climatic records for the region could also be developed. Recently, limestone caves were discovered in Al Daher, close to Jerash (Kempe and others 2006). This potential archive has not been used for palaeo-climatic studies despite similar caves around the world having revealed sub-annual records of palaeo-climates (e.g. Bar-Matthews, Ayalon, and Kaufman 1998; Orland and others 2009; Wang and others 2017). By testing the cave data and sediment data against each other and aligning these new combined data with the chronological record resulting from the local and meso-regional perspectives and known historical events, such as the AD 749 earthquake and the impact of the global summer cooling of 43 BC, AD 536, 543, and 627 (Büntgen and others 2016; Sigl and others 2015) one could study correlation between climate change and historical change in Jerash with sub-annual resolution, adding to the growing body of high-profile regional studies of climate–history interaction (Bar-Oz and others 2019; Lawrence and others 2016; Manning and others 2017; McConnel and others 2018). These integrated, high-resolution (annual to decadal) assessments can then feed into the Agent-Based Modelling as outlined below.

Establishing correlation is, however, only a first step. Scholarship addressing contemporary climate change underlines the importance of how scientific knowledge makes its way into media and politics (Hulme 2015; Schmidt, Ivanova, and Schäfer 2013; Seland 2017; Tvinnerheim and Fløttum 2015), and how scientists create narratives about climate change (Sörlin 2009). As any notion of change over time entails assumptions of causality (Rüsen 2005), this insight is a condition for serious investigation into the extent that climate change might have had a role in shaping the history of Jerash and the broader region. Archaeology and history have been slow to take up this challenge, and most studies arguably continue to concentrate on establishing correlation as much as or more than explaining causation (Kaufman, Kelly, and Vachula 2018; Vogelaar, Hale, and Peat 2018). Just as past climate cannot be studied directly, but needs to be observed through proxies, past scholarship is a valuable and understudied source of data for which historical weather–society interrelationships are available in different historical settings (Jusupović and Bauch 2020). Adding a theoretical dimension to the study of climate–history interaction will provide a baseline for understanding the role of climate change, not only in the case of Jerash and other parts of the Near East but also in the context of global history. The vast published scholarship on the role of extreme weather events and climate change in archaeological and historical processes may be quantitatively assessed by applying approaches of systematic review and meta-analyses (e.g. Moher and others 2009; Uman 2011). Online corpora and databases such as Google Books, Google Scholar, Scopus, and Web of Science can be mined to identify texts that connect climate and societal change (e.g. van Bavel and others 2019; Marx, Haunschild, and Bornmann 2018; Seland 2020). Within this corpus, the most important studies can be identified by means of citation network analyses (e.g. Brughmans 2013). These studies may be qualitatively assessed in order to identify influential scholarly models of climate–society interaction in the region. Together these results could be used to review the role of extreme weather events and climate change in the longue-durée development of Jerash, and would also have relevance to any other study of climate and historical change in global history by offering quantified and testable information on the causal mechanisms that operate between climate change and historical change. In this way, work on Jerash is informed by current debates in global historiography, while also feeding back empirical perspectives to that tradition, where applying empirical data on global and general scales remains a fundamental challenge (Crossley 2008; Lichtenberger and others 2021). Bringing together published climate data (e.g. Bar-Mathews, Ayalon, and Kaufman 1998; Klein 1982; Lemcke and Sturm 1997; McCormick and others 2013; Schoell 1978; Wang and others 2017; also NOAA) with new records, timelines, and meta-analyses, these can be applied to the settlement history of Jerash, the hinterland, and the Decapolis region. Moving beyond traditional narratives of ecological (neo-)determinism and anthropocentrism (Contreras 2017; Issar and Zohar 2007; Rosen 2007; Van de Noort 2013), this will allow for a balanced narrative integrating climate change, environment, and socioeconomic and geopolitical factors.

We claim that it is of importance to generalize from local high-definition modelling to semi-arid localities, which hitherto have not been treated in a high-definition manner, with a view to creating geographically weighted variability-modelling toolkits for prediction (Mehrotra, Bardhan, and Ramamritham 2019; Wren and others 2019). This would extend general involvement in existing work on human influences on water systems, major socio-environmental change, and the effectiveness of responses (Gilliland and others 2013a; 2013b; Nelson and others 2016; Strickland and others 2018). Therefore it would be necessary to include a considerable extant body of historical water- and land-management studies from Sahelian Africa (Adderley and others 2004; Baier 1976), Roman North Africa (Liverani 2003), Central and South Asia (Harris 2011; Wordsworth 2018), the American South-West (Homburg and Sandor 2011; Wienhold 2013), and elsewhere (Harrower 2010), and at the broader level of global history (Ertsen and others 2014; Ingram and Hunt 2015; Issar 2004). Key data themes which would arise from these sources include characterizing the interactions between urban and hinterland areas, assessing the environmental resource base, defining the scale-range of water-management systems and defining socio-political contexts. Comparative analyses of these criteria against those from Jerash will enable identification of commonalities and contrasts and enable new model variants to be developed for semi-arid regions.

Synthesis: Integrating Perspectives

Where archaeology and science, technology, engineering, and mathematical (STEM) sciences struggle to go from the plethora of data to robust historical narratives, historical scholarship has been hard pressed to integrate scientific and archaeological results in explanations of historical change. Our answer is to integrate data and hypotheses into qualified, quantified, and formalized narratives, facilitating complex systems modelling aimed at reconstructing the sources of the city's sustainability and robust responses to natural and political crises. Agent-Based Modelling provides a particularly powerful technique for the integration of different strands of evidence into one coherent framework, which can then be used to infer and test models of human, societal, and environmental change (Axtell and others 2002; Lake 2014; Romanowska and others 2019; Wilkinson, Gibson, and Widell 2013). The interaction between climate change, urban development, landscape management and use as well as settlement patterns, and societal change is a complex system driven by a mosaic of interacting mechanisms and feedback loops. Water management is a primary technique for buffering environmental risks and climatic uncertainty. However, it is also costly, requiring strong formal and informal institutions and significant personpower. Thus, the interplay between climate fluctuation, population size, and socio-political organization needs to be modelled in relation to each other and within a formal environment of mathematical frameworks (Kohler 2012; Mitchell 2009).

Two related simulations could be developed in the case of Jerash. A model of subsistence and demography of the Jerash region would provide a baseline of the changes in environmental affordability of the Jerash hinterland and its population dynamics over time. Secondly, a wide range of factors and scenarios can be explored in a model of societal responses in the face of both climatic and political upheavals. To probabilistically estimate the yearly yield of the Jerash hinterland, two computational modelling techniques can be applied: 1) environmental niche modelling and 2) the soil-productivity modelling framework. The niche simulation method focuses on determining the spatio-temporal extent of land suitable for production of a given crop, given the environmental characteristics of the area. This is done using geostatistical techniques, in particular kriging, which interpolates between known data points. Its utility has been demonstrated on both local and continental-scale applications (Bocinsky and others 2016; d'Alpoim Guedes and Bocinsky 2018).

Environmental niche modelling can provide good first-order approximation of the trends in the annual yield of the Jerash hinterland. However, to reconstruct the full picture of environmental interactions, agricultural productivities, and soil legacies over extended time periods, the CENTURY soil-dynamics model can be applied (Adderley and Simpson 2005; Adderley, Simpson, and Vésteinsson 2008; Adderley and others 2000; Simpson and others 2002), parameterized with data drawn from the local and micro-regional perspectives. Following the methodology developed by Charlotte T. Lee and Shripad Tuljapurkar (2011), this should be coupled with an age-structured demographic model (Leslie Model) that will enable one to infer the patterns in population dynamics (Rees and Ellner 2009). These models should be tested against independent data trends, such as archaeo-zoology and archaeo-botany proxies, settlement size, and historical records. The results will thereby be directly comparable to models (d'Alpoim Guedes and Bocinsky 2018; Varien and others 2007) developed for other parts of the world (e.g. the American South-West, Central and South Asia, and Sahelian Africa), enabling the scaling up of a site-specific focus to a global perspective.

Conclusion

As outlined in this article, water, climate, cities, and their hinterlands are interrelated micro-systems, which in the past were dependent and influenced by each other, bringing issues such as vulnerability, uncertainty, adaptation, long-term sustainability, and fluctuations to the forefront. We discussed the value of taking a long-term historical perspective on the evolving balance between environment and human agency in managing access to water in a semi-arid environment on micro-regional, meso-regional, and global levels by suggesting an agenda for investigating such entangled aspects of the human past. Given the current pace of climate change and human-driven deterioration of environments and fresh-water resources, a better understanding of the evolution of the urban–riverine hinterland relationship within long-term frameworks and spanning centuries or even millennia is urgently needed. This is especially the case in semi-arid environments, where seasonal and long-term fluctuations in water availability together with competing urban and hinterland requirements have made decision-making and management, from the individual to the collective, vital for the long-term sustainability of communities.

One of the best available sources of information on the benefits, effectiveness, and challenges of long-term water-management strategies is the study of the effectiveness of such practices in the past. Applying high-definition archaeological, historical, and scientific data, scaling up from a case-study approach to its global history implications and offering a long-term perspective on the shifting balance between environment and human agency in managing riverine hinterlands in semi-arid regions, may give us a more nuanced understanding of past urbanism. By dismantling disciplinary boundaries, we can activate data in archaeological and historical research and create empirical and testable narratives on a global-history scale through computational modelling. Drawing on ancient Gerasa/Jerash's rich body of archaeological and historical data together with science-based environmental archives, we have here used it as a showcase to unlock new perspectives on the dynamics of human relationships with water over millennia (Lichtenberger and others 2021).

With an approach as described above we have suggested a new agenda for examining the interrelations between urban landscapes and their riverine hinterlands. If implemented in fieldwork projects it provides a profound new understanding of socio-environmental interdependencies in semi-arid regions by addressing two major research objectives set out in the introduction to this article, namely 1) identifying societal, environmental, and climatic pressures on water and related land resources in semi-arid regions at different scales (local, regional, and global) together with their long-term causes and effects, and 2) exploring and evaluating the diversity, effectiveness, and sustainability of water-, land-, and urban-management responses at different spatial and temporal scales to such socio-environmental pressures in semi-arid regions. In summary such an approach will in the case of Gerasa/Jerash achieve the objectives through the unique multi-scalar approach described above and summed up here:

- Performing integrated high-definition archaeological fieldwork, archaeological science, remote sensing, and environmental science research focused on the site of Jerash and its riverine hinterland, which offers a uniquely well-preserved test case for the study of centuries-long changes of socio-environmental interdependencies in a typical urban settlement in a semi-arid region.

- Benchmarking results, in this case from Jerash, against published archaeological and palaeoenvironmental data from other sites in the Near East and beyond.
- Studying the extreme weather and climate-change history of the wider semi-arid Near Eastern region surrounding Jerash through spatial analysis and historical mapping, and contextualizing this region within global-climate and human-history models and narratives.
- Computational modelling of the changes in demography, subsistence, and water-management strategies in local, regional, and global semi-arid contexts, enabled and validated through high-definition archaeological, historical, and environmental data representing Jerash and its wider region's centuries-long history.

Through such an integrative approach it will be possible to set out how dynamic resource management in the past leaves legacies that influence future prospects for communities in contrasting social and environmental contexts, and to identify those factors that influence the success or failure of communities in semi-arid regions. Furthermore, such an approach seeks to identify early warnings of tipping points in socio-environmental systems that are predictors of major social, environmental, and climate changes and to recognize innovation and adaptation in resource management that mediates against negative and enhances positive social, environmental, and climate changes. Key characteristics that define the relationship between cities and riverine hinterlands, and society and the environment can be identified by pulling together results from across the core themes. Furthermore, the approach allows for generalization from a high-definition study to localities and regions which have not been considered from a high-definition perspective, developing toolkits for effective assessments of significant socio-environmental changes in a range of semi-arid socio-environmental contexts.

The integrative agenda approach presented here holds the potential of significantly enhancing future research and policy perspectives in resource management for semi-arid regions globally facing increasingly intense water- and land-resource pressures. More broadly it could contribute to the development of synergistic approaches where high-definition humanities and STEM disciplines are integrated to enable investigation of how resource-management decisions made by past populations allowed negotiation of climate fluctuations, political upheavals, and catastrophic events over centuries-long time spans.

Abbreviations

GUGK	*Glavnoye Upravleniye Geodezji i Kartografii*, quadrants i36–37, j36–38, h36–37, various scales (Moscow: GUGK, 1980).
NOAA	NOAA, National Centers for Environmental Information: National Oceanic and Atmospheric Administration <https://www.ncdc.noaa.gov/cdo-web/datasets>.

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