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ORIGINAL ARTICLE

# Historical Spatial-Data Infrastructures for Archaeology: Towards a Spatiotemporal Big-Data Approach to Studying the Postindustrial City

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**Abstract** While the use of geographic information systems (GIS) has become commonplace within the discipline of archaeology, the potential of a big-data approach to GIS is yet to be fully exploited within historical archaeology. Archaeologists inspired by developments in the social sciences and humanities have recently called for new ways of conceptualizing GIS as a process that is more theoretically satisfying and methodologically effective in its applications to archaeology. We respond to these calls by proposing a new approach for GIS in historical archaeology, an historical spatial-data infrastructure (HSDI). We outline the progression from historical GIS to the construction of an HSDI and present a series of case studies that demonstrate how using a spatiotemporal big-data-based approach expands the scale of archaeological inquiry to studying the postindustrial city.

**Extracto** Si bien el uso de los sistemas de información geográfica (SIG) se ha convertido en un lugar común en la disciplina de la arqueología, el potencial de un enfoque de macrodatos para los SIG aún no se ha explotado por completo dentro de la arqueología histórica. Los arqueólogos inspirados por los desarrollos en las ciencias sociales y las humanidades han pedido recientemente nuevas formas de conceptualizar los SIG como un proceso que es más teóricamente satisfactorio y metodológicamente efectivo en sus aplicaciones a la arqueología. Respondemos a estas llamadas al proponer un nuevo enfoque para los SIG en la arqueología histórica, una infraestructura de datos espaciales históricos (IDEH). Esbozamos la progresión del SIG histórico a la construcción de una IDEH y presentamos una serie de estudios de casos que demuestran cómo el uso de un enfoque basado en un enfoque de macrodatos espacio-temporal expande la escala de la investigación arqueológica para estudiar la ciudad postindustrial.

**Résumé** Si l'utilisation des systèmes d'information géographique (SIG) est devenue pratique courante dans la discipline archéologique, le potentiel d'une approche big data quant aux SIG n'est pas encore pleinement exploité dans l'archéologique historique. Les archéologues inspirés par les développements dans les sciences sociales et humaines se sont récemment prononcés en faveur de voies nouvelles pour conceptualiser les SIG à titre de processus plus satisfaisant d'un point de vue théorique et plus efficace d'un point de vue méthodologique dans ses applications à l'archéologie. Nous proposons une réponse à ces attentes sous la forme d'une nouvelle approche des SIG dans l'archéologie historique, à savoir une infrastructure de données spatiales historiques (HSDI—historical spatial-data infrastructure). Nous soulignons la progression à partir des GIS historiques vers la

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construction d'une HSDI, et nous présentons une série d'études cas démontrant comment le fait d'utiliser une approche basée sur le big data élargit la portée de l'enquête archéologique pour étudier la ville post-industrielle.

**Keywords** historical GIS · postindustrial · big data · urban

## Introduction

Geographic Information Systems (GIS) leads something of a double life within the discipline of archaeology. Archaeologists were early adopters of GIS technology (Allen et al. 1990; Aldenderfer and Maschner 1996; Kvamme 1999), and GIS has since established itself as the most commonly used tool for the gathering, management, and integration of spatial data into archaeological research in both cultural resource management (CRM) and academic archaeology (Lock and Pouncett 2017). Despite this broad embrace by the discipline, GIS continues to be a source of theoretical unease. GIS, with its quantitative roots, is sometimes criticized for a tendency towards atheoretical application (Howey and Brouwer Burg 2017b), and its "point and click" ease of use (Kvamme 1999:185) may seem a persistent incongruity in the context of the more self-reflective theoretical environment archaeology inhabits today (Lock and Pouncett 2017). Archaeologists thus seem faced with an unappetizing choice: "either to perceive GIS-related practices in archaeology as atheoretical and having self-evident benefits ... or to dismiss them for the sake of postpositivist counter-modernist research" (Hacıgüzeller 2012:246). This state of affairs has not prevented the growth of GIS in archaeology, nor of computational archaeology approaches in general, but it has led to a chronic "anxiety discourse" among computational archaeology practitioners who remain to some extent unsure of their theoretical ground (Huggett 2013:15). Decades after its initial appearance, computational approaches to archaeology, including GIS, are still broadly spoken of as an emerging field (Huggett 2013).

Historical archaeologists have not as yet contributed much to these discussions. Previous general reviews of archaeological applications of GIS (Aldenderfer 1998; Kvamme 1999; Ebert 2004; McCoy and Ladefoged 2009) or standard texts on the use of GIS or spatial technologies within archaeology (Allen et al. 1990; Aldenderfer and Maschner 1996; Lock 2000; Conolly and Lake 2006) have generally featured few, if any, discussions or case studies that foreground historical archaeology. In a much-needed exception to this status quo, González-Tennant (2016) recently reviewed the use of GIS in historical archaeology and remarked that "[t] he use of GIS is now a core aspect of historical archaeology, but work remains to fully realize the technology's potential for the discipline" (González-Tennant 2016:41); geospatial analysis (such as predictive modeling, viewshed analysis, least-cost path analysis) in historical archaeology, though growing, is still less prevalent than in other archaeological subdisciplines (González-Tennant 2016). This relative lack of experience with geospatial analysis, coupled with the theoretical misgivings mentioned previously, may make historical archaeologists especially prone to seeing GIS as merely a "tool" for data management and, as a result, less engaged with broader discussions of the role of GIS in archaeology. To truly take advantage of GIS, historical archaeology must begin to see GIS as more than simply a *tool*, but as a *process* with appropriate theoretical and methodological foundations (González-Tennant 2016; Howey and Brouwer Burg 2017a:2). Herein we present a methodological approach to GIS for historical archaeological research that facilitates this evolution from tool towards process. Using the postindustrial city as our laboratory, we outline the creation of an historical spatial-data infrastructure that harnesses the spatiotemporal and big-data analytical capabilities of GIS.

### Intersections of Archaeology and Social Science GIS

Archaeology has always been an inveterate borrower of theory (Lucas 2015); with respect to the use of GIS, archaeologists can point toward several promising theoretical developments in the social sciences and humanities that expand the use of GIS as a means to study the past and its influence on the present. The explosion in the use of GIS in geography by the early 1990s led to a tense debate between GIS practitioners and postmodern theorists within the social sciences over two decades ago (Schuurman 2000), resulting in the rise of the subdiscipline of "critical GIS." Critical GIS scholars argue that, in order for GIS-based research to mitigate the issues inherent in a technology with positivist and deterministic origins, GIS-based research in the social sciences must diversify the types of data worked with, how they are collected, and how they are interpreted (O'Sullivan 2006; Schuurman 2017). To meet these critiques, scholars have adopted more democratic or inclusive approaches to GIS-based research, including participatory GIS (PGIS), public-participatory GIS (PPGIS), and volunteered geographic information (VGI) (Craig et al. 2003; Goodchild 2007; Brown and Kyttä 2014; Lafreniere et al. 2019). The result of this process has been the emergence of GIScience, which focused on the conceptualization of GIS as a critical, reflexive process of digital, spatial inquiry, rather than simply the use of software tools (Goodchild 1992; Goodchild and Janelle 2004; Egenhofer et al. 2016). Archaeological research has, of course, always involved spatial thinking (Lock and Pouncett 2017), and GIScience serves as a useful theoretical foundation for archaeologists dealing with challenges unique to working with spatial data in a GIS.

Spatial history and the spatial humanities also represent useful sources of inspiration for archaeologists using GIS. The recent "spatial turn" in the humanities, which sought to foreground concepts of place in humanities research, brought GIS to the attention of humanists. Spatial history involves collaborative historical research that makes use of digital approaches and visualizations to develop unique historical narratives and counternarratives (Knowles and Hillier 2008; Olson and Thornton 2011; Gregory, DeBats et al. 2018a). Following on from this, the spatial humanities (Bodenhamer et al. 2010, 2015; Gregory and Geddes 2014) have begun to develop a theoretical framework for applying GIS and related spatial technologies to mixed-methods inquires. Major themes in spatial-humanities research that should appeal to historical archaeologists using GIS include finding ways to incorporate texts and other nontraditional data sources within GIS (Lafreniere and Gilliland 2015; Donaldson and Gregory 2016); reducing reliance on desktop GIS in favor of the use of more widely accessible Web-based GIS or GIS-like software, such as Social Explorer (<http://www.socialexplorer.com>); further developing the spatiotemporal capabilities of GIS to permit more sophisticated explorations of space-time (Gregory DeBats et al. 2018a); and finding more effective ways to represent the multiply constituted or contingent nature of place (Bodenhamer et al. 2010).

A popular recent development within the spatial humanities has been the emergence of the concept of "deep maps." Bodenhamer et al. (2015) theorize that deep maps embrace multiple forms of media, provide more democratic access to data, better accommodate imprecision and subjectivity of data, and foster the presence of multiple voices and interpretations. While deep maps seek to move beyond the positivist or deterministic constraints of GIS as a "tool," they do still often incorporate GIS in some form as a digital spatial framework within which such maps may be constructed (Ridge et al. 2013; Scarlett et al. 2018; Lafreniere et al. 2019). The ultimate goal of deep mapping is the creation of digital contexts operating at phenomenological scales (Lock 2010) that people may use to create spatial narratives, using the power of information technology to combine complex, varied, "resplendently untidy" sets of spatialized digital information into meaningful representations of place (Harris et al. 2015:224).

Up to this point archaeology has made little more than a token contribution to GIScience, spatial-history, or spatial-humanities literature, and with very few exceptions, such as Hays et al. (2018), most archaeologists remain largely unaware of these fields (Earley-Spadoni 2017). This critique cuts both ways; while historical GIS in particular purports to be an interdisciplinary approach to studying the past through the use of geospatial approaches, its practitioners rarely engaged with archaeologists using GIS (Allen et al. 1990; Kvamme 1995, 1999; Lock 2000, 2003; Conolly and Lake 2006) that developed their own theoretical and methodological approaches over the course of several decades. It is here that historical archaeology is perhaps best placed to take a leading role in meeting recent calls for the wider field of archaeology to be more closely engaged with these new approaches to GIS-based research (González-Tennant 2016; Howey and Brouwer Burg 2017b). Historical archaeology's use of the historical record as a fundamental component of research is an approach shared with other disciplines in the social sciences and humanities that study the past, though historical archaeology contributes its own unique perspective to historical research (Orser 2017).

As archaeologists we need new methodological approaches that apply GIScience to archaeological research and allow us to more usefully represent space and place, and how they change over time, bringing us closer to effective mixed-qualitative/quantitative GIS research and perhaps ultimately to deep mapping. We require a digital framework or infrastructure that can support new types of data, better access to that data (both for collaborative research and the public participation), more effective longitudinal representation and inquiry, and useful juxtapositions of multiple, often conflicting, representations of place. In proposing such an infrastructure, we look to the social sciences and recent developments in historical GIS (HGIS) for our methodological foundation. Researchers in the fields of geography, sociology, history, and historical demography (among others) have developed HGIS as an approach to modeling historical environments, and HGIS holds great promise for historical archaeologists as an innovative means for modeling past environments. The historical record can, in some ways, support more granular models of past environments that complement the detailed environmental data used by prehistoric and classical archaeologists. Our approach to GIS will allow historical archaeologists to exploit this potential more fully.

## GIS, Crises of Representation, and Challenges of Scale

An ongoing theoretical constraint on better representing past environments using GIS has been the "crisis of representation" brought about by the inherent differences between space and place, and seemingly insurmountable difficulties in adapting Cartesian space to human understandings of distance, direction, and position (Lock 2010; Lock and Pouncett 2017:130). This can be seen, in part, as problems with human notions of scale and landscape, where GIS struggles to transition from recoding "analytical scale" to "phenomenological scale" (Lock and Pouncett 2017:131).

Any proposed spatial infrastructure must be able to handle the challenges of "scale" in several senses before this transition can be approached:

(1) Geographic Scale: An important aspect of archaeologyis the linkage between everyday, microscale activities and the macroscale phenomena that characterize societies. A spatial infrastructure for archaeology must be able to encompass information about both of these extremes of geographic scale and allow researchers to move across varied geographic scales easily.

(2) Temporal Scale: Handling time within GIS is challenging (Goodchild 2013), and representing change over time is an even greater challenge. Archaeologists need the ability to represent change over time in discernable, accessible ways. It is crucial not only for studying dynamic phenomena in the past, but also for linking phenomena to the present.

(3) The Scale of Big Data: With the quantity of digital data being generated in archaeology growing exponentially (Petrovic et al. 2011), archaeology (and the social sciences generally) are entering the era of big data (McCoy 2017; Thatcher et al. 2018). Working with big data carries with it a multitude of challenges, including the need for greater computational expertise, more transparency in digital-data collection and analysis, and learning to work "ultralongitudinally" across previously separated time periods (Bevan 2015:1481). Within archaeology, this includes the need to be able to handle, analyze, and manipulate growing bodies of digitized historical data, whether they be cartography, records, texts, or visual media.

Addressing such issues of scale is a crucial component of the process of developing a more flexible and robust spatiotemporal, multiscale, spatial digital infrastructure for historical archaeology. We introduce a next-generation HGIS, which we term a historical spatial-data infrastructure (HSDI), and then demonstrate the ways that it may serve as the basis for improving the ways archaeologists handle big data, as well as changing geographic and temporal scale. The HSDI answers the call by González-Tennant (2016) for a more sophisticated employment of GIS in historical archaeology. Our HSDI particularly addresses issues of scale, which represent a challenge to the discipline of archaeology more broadly (Robb and Pauketat 2013) and are a major contributor toward the crisis of representation that has long dogged GIS-based archaeological research.

In the following section we review of the origin, structure, and construction process of an HSDI. This powerful, flexible infrastructure expands the scale of archaeological inquiry in a postindustrial urban environment, demonstrating how the use of an HSDI significantly improves historical archaeologists' capacity for the discovery, visualization, and analysis of large amounts of detailed, historical spatial data in complex contexts. While the focus of our case studies is urban and postindustrial, the basic principles are equally applicable to rural contexts, as evidenced by the work of Van Allen and Lafreniere (2016), though the greater density and accessibility of historical records in urban areas admittedly permits a more fine-grained end product.

## The Evolution of GIS-Based Historical Spatial Research

### Historical GIS

Historical spatial-data infrastructures represent the merging of historical GIS (HGIS) practice with the principles of spatial-data infrastructures (SDI). HGIS is an interdisciplinary application of GIS to the study of the past that arose in the late 1990s and early 2000s (Gilliland 1998; Knowles 2000; Gregory, Kemp et al. 2001; Holdsworth 2003). HGIS has subsequently developed into a distinct subdiscipline at the intersection of history and historical geography (Holdsworth 2003; Knowles 2016; Gregory, DeBats et al. 2018b) and has influenced the development of the emerging field of spatial humanities discussed previously (Bodenhamer et al. 2010; Gregory and Geddes 2014; Gregory, DeBats et al. 2018b). An HGIS typically consists of digitized and spatially referenced cartographic and non-cartographic records, allowing the mapping and visualization of large historical data sets, such as censuses, tax records, boundaries, and gazetteers (Gregory and Ell 2007). The earliest uses of HGIS took the form of national-scale projects, such as the Great Britain Historical GIS (GBHGIS), which began in the UK in the mid-1990s as a project to spatialize existing bodies of historical statistical information and subsequently focused on digitally modeling historical parish-level boundaries so as to facilitate analysis (Gregory, Bennett et al. 2002). Other national HGIS projects followed, including examples focused on China (Bol and Ge 2005), Russia (Merzlyakova 2005), Ireland (Ell 2005), Belgium (Vanhaute 2005), South Korea (Kim 2005), and Canada (St-Hilaire et al. 2007). In the U.S., the Minnesota Population Center developed the National Historical Geographic Information System (NHGIS) to support the need for digitally reconstructed census boundaries for historical population research (Fitch and Ruggles 2003).

HGIS researchers subsequently saw the need to zoom in beyond the large areal units of census geographies, like parishes and counties, to the scale of the individual. The first example of this the was the Montréal l'Avenir du Passé (MAP) Project, an HGIS containing a sample of spatialized census, tax-roll and city-directory data for three time periods (1846, 1880, 2000) in Montreal's history (Gilliland and Olson 2003; Sweeny and Olson 2003). The sample consisted of those households with surnames beginning with the letter *B*, with the data being spatialized at the resolution of individual city lots using digitized and georectified historical cartographic sources. Researchers have used the MAP HGIS to demonstrate that different forms of segregation were lived at different geographic scales (Gilliland and Olson 2010; Gilliland et al. 2011); to trace more clearly the daily lives of women in the industrial city (Gilliland and Olson 2010; Olson and Thornton 2011; Olson 2018); and to understand how events, such as fire (Gilliland 2012) or street widening (Gilliland 2002), impacted urban development in Montreal. DeBats (2008) improved the resolution and increased the scale of HGIS research still further by mapping the entire populations of Alexandria, Virginia, in 1859 and Newport, Kentucky, in 1874 using census, city-directory, voting, and tax records. As with the MAP Project, demographic data are mapped to the lot level. While this HGIS covers just a single year for each city, DeBats (2008) demonstrates the practicability and research value of spatializing entire city-scale historical record sets. DeBats's HGIS research ultimately revealed how wealth inequality manifested itself within complex representations of historical landscapes; it also highlighted the electoral dynamics and political consequences of segregation (DeBats 2011, 2018).

The most recent HGIS research has increased the spatial resolution of HGIS approaches still further. Dunae, Lutz et al. (2011) have constructed an HGIS for the city of Victoria, British Columbia, that spatializes individual census information down to individual building footprints rather than lots, allowing researchers to place people within their actual homes (Dunae, Lutz et al. 2011). To do this they rely, just as historical archaeologists typically do, on fire-insurance plans, which are among the most detailed historical maps available in the historical record (Bloomfield 1982). The resulting HGIS, called the VIHistory HGIS Project, combines the recreation of multiple time periods (1881, 1891, 1901, 1911) with the comprehensive city-scale demographic and geographic coverage of DeBats's HGIS research; the Victoria HGIS additionally includes municipal census data as both a check on and an augmentation of the national census data (Dunae, Lafreniere et al. 2013). Using the Victoria HGIS, researchers have challenged the conventional narrative of Victoria's historical Chinatown as a community closed to outsiders (Dunae, Lutz et al. 2011), "reconstructed the social and domestic spaces" of industrial wageworkers (Dunae, Lafreniere et al. 2013:38), and disproved the longstanding assumption that indigenous peoples simply "vanished" as the city developed (Lutz, Dunae et al. 2013; Lutz, Lafreniere et al. 2018:336).

Most recently, the Imag(in)ing London HGIS (<https://www.historicalgis.com/london-hgis.html>) improves upon the lessons learned during the creation of the HGIS projects focused on Montreal and Victoria by modeling the city of London, Ontario, and its surrounding rural countryside within an HGIS. Lafreniere and Gilliland (2015, 2018) incorporated eight time periods (1855, 1881, 1888, 1907, 1915, 1926, 1958), and a representation of the present-day city) within the Imag(in)ing London HGIS. Imag(in)ing London also achieves full city-scale coverage in its representations of past environments. This includes a detailed model of the built environment: human-made spaces in the city, such as structures, land-use designations, transportation systems, and parks, all digitized and spatialized from historical fire-insurance plans and other cartographic sources. Linked to the built environment are the typical demographic sources used in previous examples, such as the decennial census and city directories, but also new sources, such as small samples of school records, congregational records, and spatialized diaries (Lafreniere and Gilliland 2015). The Imag(in)ing London HGIS allows researchers to uncover small-scale activities, such as daily journeys to work and school, as well as social mobility, either individually or in aggregate (Lafreniere and Gilliland 2020). Doing so reveals the spatial patterning of social phenomena, such as how far from work people of certain occupations tended to live (Lafreniere and Gilliland 2018), the likelihood that children of a given socioeconomic status will be exposed to noxious industrial environments during their walk to school (Lafreniere and Gilliland 2015), the role post offices played in the creation of social networks (Van Allen and Lafreniere 2016), and the changing geography of retailing through the 20th century (Novak and Gilliland 2011). The Imag(in)ing London HGIS not only represents the state of the art in HGIS research, but also a transitional stage towards the development of a fully fledged HSDI, as we will outline below.

## Spatial-Data Infrastructures

We apply SDI principles to HGIS to meet challenges such as these. The U.S. National Research Council (NRC) coined the term "spatial data infrastructure" in 1993 in recognition of the need for national-scale infrastructures for facilitating the creation, use, and sharing of geospatial data, especially within the context of GIS (NRC 1993). The NRC defined an SDI as the "means to assemble geographic information that describes the arrangement and attributes of features and phenomena of the earth," including the "materials, technology, and people necessary to acquire, process, store and distribute such information to meet a wide variety of needs" (NRC 1993:2). A key feature of any SDI is the creation of a collaborative organizational structure for managing knowledge about a particular space and ensuring data interoperability, standards, reliability, and accessibility. The U.S. established an official National Spatial Data Infrastructure (NSDI) by executive order shortly afterwards (Clinton 1994), and by the end of the 1990s numerous other NSDIs had appeared worldwide (Masser 1999).

While these early efforts were explicitly national in scale (Masser 1999), most of the actual data within NSDIs were provided by state and local institutions (Craig 2005). Within a decade states began to adopt the SDI concept themselves, following the lead of several pioneers, such as Minnesota (Arbeit et al. 2004; Craig 2005), and the SDI approach has since come to be applied more broadly to a variety of circumstances in which the need for a framework for the creation, use, and exchange of spatial data is felt (Esri 2010; Masser and Crompvoets 2015, 2018). Within the historical sciences, the SDI *concept* has been used by historical demographers for the creation of big-data historical demographic-research infrastructures, most notably the Canadian Century Research Infrastructure (Gaffield 2007), the North Atlantic Population Project (Ruggles, Roberts et al. 2011; Thorvaldsen 2011), and the Minnesota Population Center's longstanding development and dissemination of very large-scale, yet highly detailed, demographic data, such as the Integrated Public Use Microdata Series (IPUMS) (Sobek et al. 2011; Ruggles, McCaa et al. 2015; Ruggles, Genadek et al. 2017).

HGIS has thus evolved into a sophisticated and effective approach to studying people and their environments in the past from a spatial perspective. While successful as a research approach for geographers, historians, sociologists, and historical demographers, the use of HGIS for studying the past is not without challenges. Chief among these is that researchers have thus far struggled to scale HGIS beyond single specific projects. A lack of established standards for constructing HGIS results in researchers constantly reinventing the wheel (Knowles and Hillier 2008) with each new project, an issue that has also presented itself in archaeological applications of GIS (De Roo et al. 2013; González-Tennant 2016; Gillings 2017). The SDI approach effectively addresses this concern through the establishment of standardized data protocols and data/metadata formats under the leadership of institutions, such as the Federal Geographic Data Committee (<https://www.fgdc.gov/standards>), eliminating the costly and time-consuming construction of a bespoke HGIS infrastructure for each new project.

## Towards an HSDI: The Imag(in)ing London HGIS

The Imag(in)ing London HGIS, briefly described previously, represents a transitional move towards the creation of a true HSDI. By creating discrete "stages" of *built* and *social* environment that are then linked together into a highly complex, digital historical infrastructure using geodatabases,[1] Lafreniere and Gilliland's (2015:2) approach brings the scale, robustness, and accessibility of the SDI to GIS-based studies of the past. Reviewing the construction and organization of the London HGIS demonstrates how the merging of HGIS and SDI approaches permits an expansion of the scale of inquiry into past environments.

The Imag(in)ing London HGIS is a high-resolution, longitudinal HGIS recreation of the city of London that covers approximately 163 sq. mi. of urban space, as well as another 900 sq. mi. of surrounding countryside, and features a detailed model of the built and social environments for the period from 1855 to the present. In common with many rustbelt cities of the Great Lakes region, London (Fig. 1) experienced a steady, occasionally rapid, process of industrialization over the course of the 19th and early 20th centuries, followed by a gradually accelerating decline in the latter half of the 20th century. Cities serve as excellent laboratories for GIS-based historical research (DeBats and Gregory 2011) and thus are ripe for the development of the HSDI concept due to their voluminous documentation in the historical and cartographic record and their dense and relatively compact nature. Postindustrial cities are especially challenging, with dynamic processes of industrialization and deindustrialization resulting in highly complex, deeply layered, and often contested histories (Mallach 2016; High et al. 2017); these complex histories are also reflected in their archaeology (Praetzellis and Praetzellis 2004; Rothschild and diZerega Wall 2014; Ryzewski 2015). GIS is already well established as a tool for urban planning and development (Yeh 2005). Access to an HGIS may serve to inform city planners, engineers, and the public alike, enabling these groups to adopt heritage-led development approaches based in evidence that are more likely to be sensitive the historical character or heritage values within a given community.

[1] The HSDI projects outlined in our article make use of the ESRI software ecosystem. However, the HSDI concept itself is emphatically "software agnostic"; all of its essential features may be implemented using open-source tools and data formats.

### The Structure of the Imag(in)ing London HGIS: The Built-Environment Stage

As with any HGIS, the Imag(in)ing London HGIS harnesses the principle that space is a powerful unifying element for conducting more effective historical research. Doing so begins with the digitization and spatial referencing of historical cartographic data to create a "built-environment stage." Historical cartographic sources, such as fire-insurance plans (FIPs), topographic maps, and other cartographic sources, are scanned at high resolution, georeferenced, and stored within a geodatabase. Large map sets using many individual sheets, such as the FIPs and geodetic surveys, are assembled into raster-mosaic data sets, so that the entire set of sheets can be viewed and manipulated as one spatial-data set with seamless borders (Lafreniere and Rivet 2010).

Built-environment features, such as building footprints, roads, and rail lines, are manually digitized from the georeferenced historical cartographic sources as points, lines, and polygon-vector data and stored as feature classes in a geodatabase. Lafreniere and Gilliland (2015) then added relevant attribute data to each feature, such as the building address, number of stories, building material, and any other specific information contained within the cartographic sources (including the name of the company occupying the building, the building's labeled function, the name of a street, or the owner of a section of railroad line). This process is then repeated for additional cartographic sources and

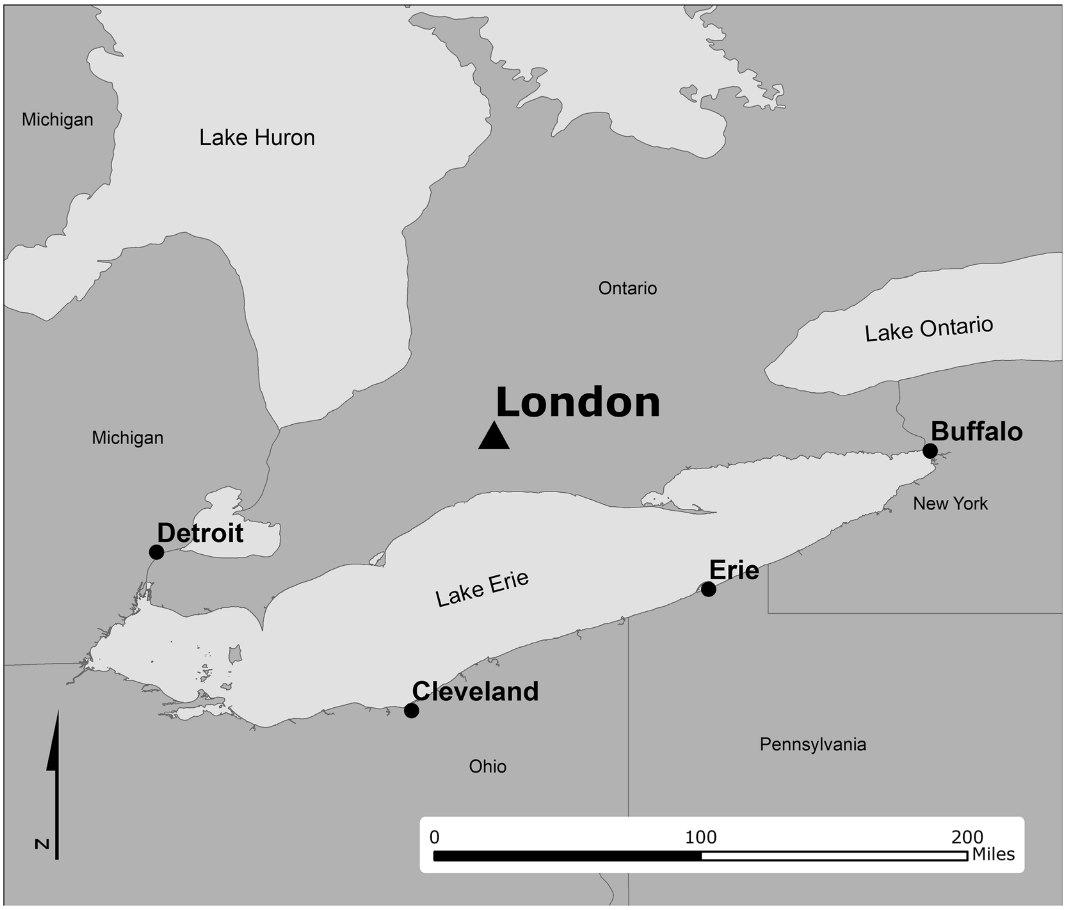



**Fig. 1** Location of London, Ontario, Canada. (Illustration by Dan Trepal, 2018.)

divided into eight time periods or time slices that together cover over 100 years of changes to London's built environment. The HGIS also includes modern building footprints, land-use data, and other urban amenities created for the City of London's municipal GIS. The built-environment stage of the London HGIS contains over 120,000 historical building footprints and thousands of roads and other built-environment features (Fig. 2).

This longitudinal structuring of the built-environment stage permits features of the built environment to be spatially linked through geographic location or proximity, as well as through linked attributes in the geodatabases, such as street addresses, names of occupants, functional descriptions of a building, or details of land use. The historical maps themselves remain present in digital, georeferenced form, providing not only a visual backdrop to the vector data, but also primary sources against which other data may be compared and contrasted when looking for patterns and discrepancies worthy of further investigation. Within the Imag(in)ing London HGIS, the built-environment stage thus represents a longitudinal recreation of London's historical buildings and infrastructure using GIS raster and vector data that can be visualized in either 2-D or 3-D (Novak and Gilliland 2009; Lafreniere and Gilliland 2015; Arnold and Lafreniere 2018).

## The Structure of the Imag(in)ing London HGIS: The Social-Environment Stage

The built-environment stage not only serves as a model of the historical built environment in its own right, but also serves as the basic spatiotemporal framework within the HGIS to which a wide variety of additional data can be linked in the form of additional HGIS stages. The Imag(in)ing London HGIS includes a "social-environment stage" that links a large corpus of historical records containing demographic information on individuals and

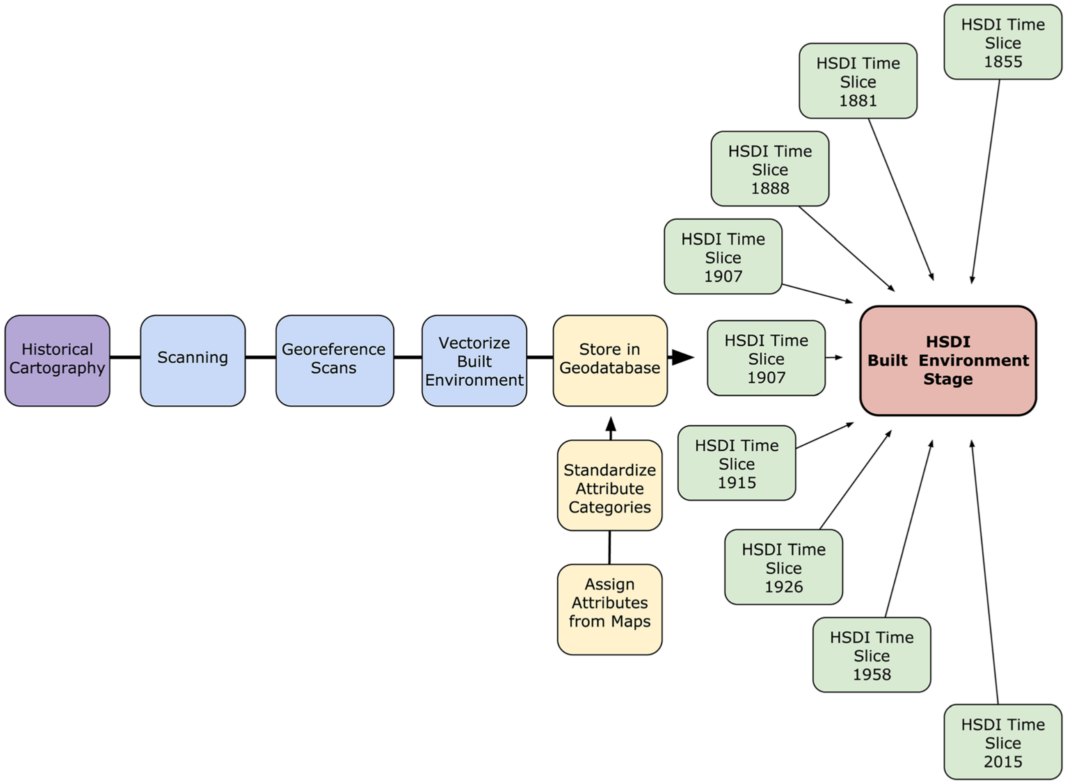



**Fig. 2** Built-environment stage preparation workflow for the Imag(in)ing London HGIS, adapted from Lafreniere and Gilliland (2015). (Illustration by Dan Trepal, 2018.)

groups to the built-environment stage. The social stage itself is anchored by the digitization of historical city directories and decennial census data that match the date of the built-environment stages as closely as possible; see Lafreniere and Gilliland (2015). The city directories are digitally transcribed and then geocoded, with each line (representing an individual) in the directory assigned to a vector point within the HGIS corresponding to the centroid of a building polygon within the built-environment stage that has a matching street address. Thus, the information contained in each year's directory is mapped to the residential addresses identified within the built-environment stage, situating the information within the HGIS in both space and time. Once this process is complete, the contents of the decennial census nearest to each time slice can be added through the use of probabilistic record-linkage software, as explained elsewhere by Lafreniere and Gilliland (2018). Adding further historical sources (such as employee, school, or congregational records) to Imag(in)ing London becomes possible due to the ability to match new data to existing geocoded social-environment data sets by a host of variables, including name, address, or employer. As more data sets are added, this process becomes progressively easier. Once available, this group of data sets collectively allows modeling of a wide variety of detailed social environments in great detail; this includes families, professional or workplace networks, religious communities, schoolmates, and wider kin networks (Lafreniere and Gilliland 2015) (Fig. 3).

## Realizing the HSDI Concept: The Copper Country HSDI

The technical demands of the Imag(in)ing London HGIS, with its large geographic coverage and use of a wide variety of sources, led to the development of the dual built-environment/social-environment stage approach and the establishment of clear workflows and protocols for the production of a sophisticated HGIS (Lafreniere 2014; Lafreniere and Gilliland 2015). This structure foreshadows the SDI approach, but it has been

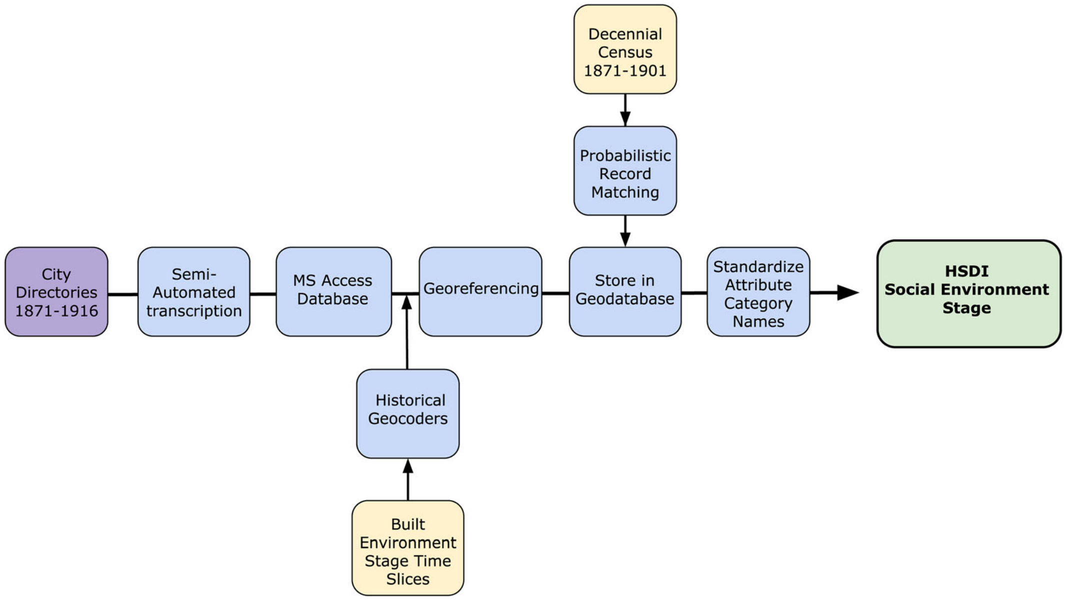



**Fig. 3** Social-environment stage preparation workflow for the Imag(in)ing London HGIS, adapted from Lafreniere and Gilliland (2015). (Illustration by Dan Trepal, 2018.)

left to a recently launched HGIS project, the Copper Country Historical Spatial Data Infrastructure (CC-HSDI), to formally embrace the SDI concept for HGIS research for the first time (Trepal and Lafreniere 2018). CC-HSDI is a fully featured HSDI that covers the Copper Country region of Michigan's Upper Peninsula, comprising Keweenaw, Houghton, and portions of Baraga and Ontonagon counties. Beginning in the 1840s, large-scale exploration and development of a unique deposit of pure or "native" copper in the Lake Superior basin grew, through a series of booms, into the world's most productive copper-mining region by the 1870s (Krause 1992). The region's mining industry entered a slow decline after World War I, with the last large-scale mining ending during the 1960s (Lankton 1991). Today, Copper Country exists as a postindustrial landscape of former boom towns surrounded by a rural hinterland with an economy dependent on service industries and tourism. The project area includes several substantial towns covering about 50 sq. mi. and numerous smaller villages set within over 2,000 sq. mi. of rural, mostly forested land covered with thousands of mining-related archaeology sites, such as mine openings, transportation-infrastructure remains, ruined mills, and large waste deposits (Fig. 4).

CC-HSDI improves upon the stage-based approach of the Imag(in)ing London HGIS in the following four crucial aspects; these may be considered the distinguishing features of an HSDI vs. an HGIS, and together they permit the three expansions of scale mentioned previously:

(1) Flexibility of Inquiry: Whereas the Imag(in)ing London HGIS was originally conceived as a tool to support a specific research question (historical social mobility in London), CC-HSDI is designed from the start as a general purpose, interdisciplinary set of tools, data, and approaches to historical spatial research that will support research into many different research questions. Providing such flexibility begins with the composition of the research team; CC-HSDI is the result of a collaborative effort of over a dozen researchers with expertise in historical geography, historical GIS, public history, historical architecture, heritage management, archaeology, education, enterprise spatial-database management, software engineering, Web-based GIS, citizen science, and software human-interactive design. This is precisely the kind of interdisciplinary collaboration and cross-disciplinary training that archaeologists have recognized as essential for more effective use of GIS and exploitation of the digital humanities within archaeology (González-Tennant 2016; Brouwer Burg 2017; Earley-Spadoni 2017).

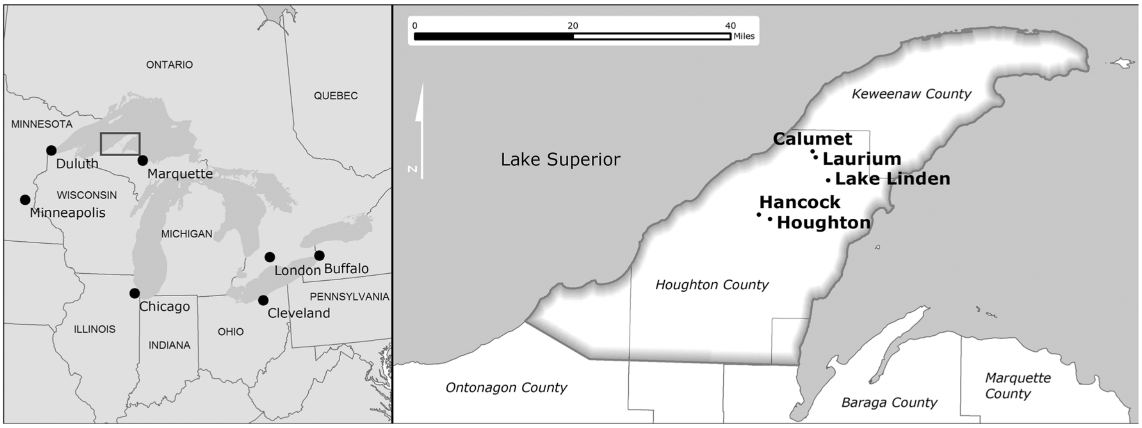



**Fig. 4** Copper Country Historical Spatial Data Infrastructure (CC-HSDI) Project area. (Illustration by Dan Trepal, 2018.)

(2) Comprehensiveness: The earlier manifestations of HGIS models described previously were built around specific data sets to answer specific questions or sets of questions. CC-HSDI not only incorporates a wider variety of historical big-data sources and types than previous implementations of HGIS, it is also intended to grow indefinitely, as new bodies of historical data or new types of sources become available, whether that be through further digitizing projects or the availability of new sensor technologies or crowdsourced data. Further, an HSDI can easily link to open-source government data through the use of APIs or Representational State Transfer (REST) URLs, as exemplified by the Scholars Portal (<https://scholarsportal.info/>), an SDI that provides access to a wide variety of data contributed by 21 university libraries within the Canadian province of Ontario. An HSDI is built with a suite of historical geocoders, gazetteers, and text-parsing tools that allows researchers to quickly include nearly any source they locate in an archive or research repository in accurate time and space. For example, CC-HSDI incorporates much larger bodies of school records than the Imag(in)ing London HGIS and also introduces tens of thousands of digitized and spatialized individual employee records, semiannual physical exams, and epidemiological data produced by historical mining companies and hospitals within the Copper Country.

(3) Spatiotemporal Robustness: CC-HSDI supports spatiotemporal data exploration and analysis. While the Imag(in)ing London HGIS (and other HGIS models) contains numerous time slices, these were primarily designed for looking at cross sections, or "snapshots," of time. CC-HSDI's structure is explicitly designed so that data within the infrastructure are interlinked through both space and time using a combination of several different shared attributes. In particular, built-environment features are tracked through a combination of spatiotemporal-coexistence and -attribute data that record when changes are made to a structure, such as an addition to a building or the construction of a railroad-spur line. Sociodemographic data, such the census, city directories, and company and school records, are georeferenced within the actual building footprints of the residences, businesses, factories, and institutions representing the time period of the source material. Individuals are then linked to their various social environments, such as the rest of their families, their neighborhoods, their workplaces and classrooms, and also linked (when possible) to their records in other historical data sets from the same period in time, as well as forward and backward in time. HSDIs are therefore designed explicitly to study change over time in built and social environments at a variety of spatial scales, rather than simply looking at certain phenomena at discrete times and places in the past (Fig. 5).

(4) Accessibility: The core of CC-HSDI consists of several enterprise geodatabases that can be accessed by the entire CC-HSDI research team, academic collaborators, and, most importantly, the general public using the Internet. The public face of CC-HSDI is represented by the Keweenaw Time Traveler (KeTT) Project, the primary goal of which is to offer the public

access to CC-HSDI's historical big data through a user-friendly Web interface (Scarlett et al. 2018). This is a public-participatory historical GIS (PPHGIS) project in which the public are collaborators, rather than passive receivers of information (Lafreniere et al. 2019). Anyone may use the Web interface to help build CC-HSDI through digitization and transcription of historical maps (georeferenced and served over the Web by the KeTT team), as well as contributing their own spatially referenced oral histories and historical photographs (Scarlett et al. 2018). The KeTT user interface itself has been created in collaboration with the public through a series of design *charrettes* and outreach events that have provided valuable feedback. Public archaeology is often still conceptualized in terms of site-based outreach and engagement (Richardson and Almansa-Sánchez 2015); an HSDI-based, publicly oriented Web interface, such as the KeTT, can bring sophisticated models of past environments to a much wider group of participants, allowing the public to explore and interact directly with historical big data and even contribute to the HSDI's expansion. Between the design charrettes and the PPHGIS components, an HSDI can be used as a tool to meaningfully engage the public in the "construction of knowledge," a crucial component of public archaeology that is all too often not achieved in practice (Richardson and Almansa-Sánchez 2015:202).

The result of these improvements is a true historical spatial-data infrastructure that links voluminous, yet disparate, components of a region's historical record in time and space within a Web-accessible platform. The facility with which an HSDI handles the challenges of geographic-scale, temporal-scale, and the scale of historical big data permits an effective big-data-based approach to the study of past built and social environments from multiple disciplinary perspectives. Ongoing developments in the ability of geodatabases to handle wider varieties of media ensure that any piece of historical information can be incorporated, so long as it can be linked to a person, place, or object within the HSDI. In the next section we use several brief case studies to highlight how to begin to expand the scale of archaeological research by improving historical archaeologists' capacity to discover, visualize, and analyze historical data. This expansion of geographic, temporal, and data scale is accomplished in three different ways, each of which is demonstrated briefly using examples from the postindustrial and urban landscapes of the Imag(in)ing London HGIS and CC-HSDI.

## Expanding Scales of Archaeological Inquiry: Examples from Imag(in)ing London HGIS and CC-HSDI

Using an HSDI helps address challenges of scale in historical archaeology in several aspects. It can move flexibly between extremes of geographic scale, it supports effective representations of change over time (temporal scale), and it provides archaeologists access to a big-data scale representation of historical environments by digitizing, spatializing, and interlinking the historical record.

### Example 1: Augmented Geographic Scales of Research in London

For example, the HSDI aids in the construction of narratives that flesh out and contextualize the microhistories of archaeological sites. Historical archaeologists often construct micronarratives based upon the former occupants of the sites they study (Orser 2017). These may differ from micronarratives constructed by historians because, as Rebecca Yamin has argued, while historians are often selective in their use of documentary evidence, "archaeologists seek to include as much of the data as possible" (Yamin 2001:167). Yamin explored the use of semi-fictionalized narratives as a means to create alternative narratives for an archaeological site or within a historical neighborhood, narratives that came closer to an insider's view of these historical places (Yamin 2001).

An HSDI is especially useful for the crafting of microhistories around archaeological sites and their former occupants with the aid of historical big data, and to link those microhistories to broader historical and spatial contexts. Historical archaeologists often find the incorporation of microhistories into broader narratives challenging (Cantwell and diZerega Wall 2001; Mayne and Murray 2001). The HSDI allows the bridging of this gap in scale and, at least with respect to the historical record, and supports the

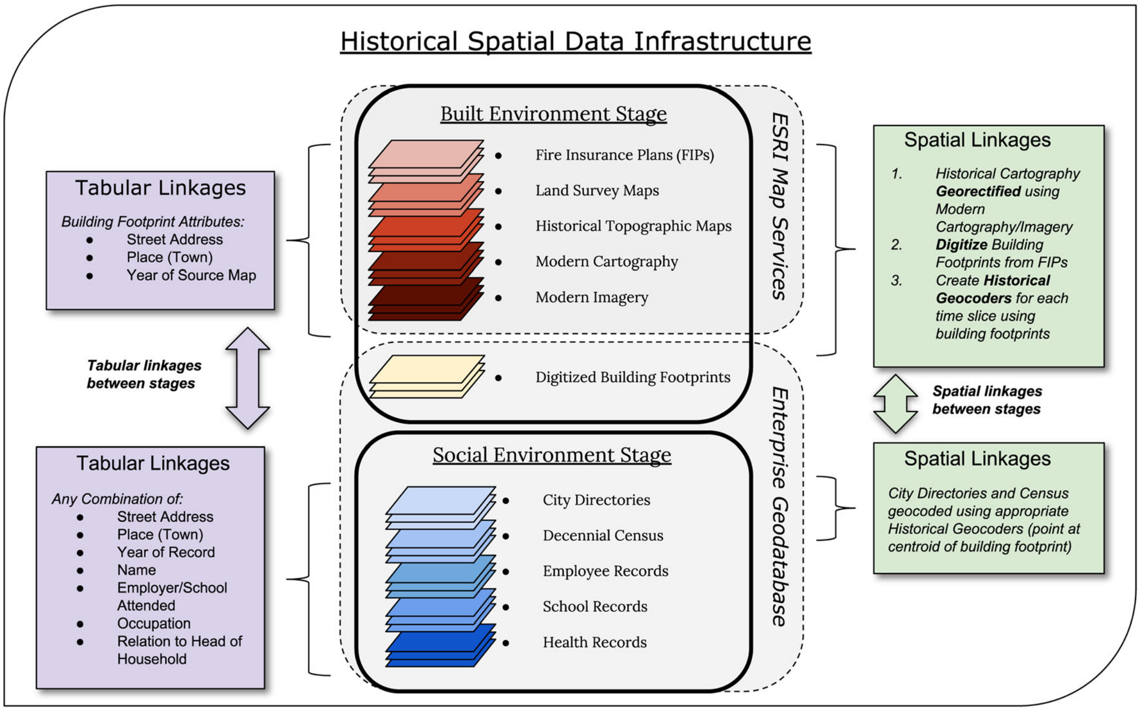



**Fig. 5** Multiple data linkages within an HSDI. (Illustration by Dan Trepal, 2018.)

more comprehensive use of data Yamin (2001) mentioned, while still leaving plenty of room for the construction of engaging, evidence-based narratives of daily life.

The Imag(in)ing London HGIS incorporates a big-data set of detailed records of individual activities useful for narrative building, including 12 personal diaries that have been transcribed, parsed, and spatialized within the Imag(in)ing London HGIS. Here we use the example of the diary of Richard Matthews to show how the HSDI provides a link between archaeology-scale microhistories (Fig. 6) and broader historical contexts. Matthews, a London postal clerk and father of six, kept a diary for 36 years. The Imag(in)ing London HGIS contains a spatialized two-year extract of this diary covering the period 1881–1882; 90% of the events and 70% of the people mentioned in the diary for that period have been successfully geocoded and linked to the other data sets within the Imag(in)ing London HGIS (Lafreniere and Gilliland 2015).

Richard Matthews's diary, as spatialized within the HSDI, provided an extremely detailed historical spatio-temporal environment within which we could contextualize the results of a hypothetical archaeology investigation at the Matthews' home site within his neighborhood (Fig. 7). Reverend J. Allister Murray, who occasionally preached at Matthews's church, lived less than a block away, at 356 Queens Street. William Scott Philips, one of Richard Matthews's fellow employees at the post office, lived on the same block as Matthews; they occasionally shared their morning commute. The spatiotemporal information within the diary is highly detailed; we know, for instance, that on Thursday, 5 October 1882, Richard's wife, Jane, received a visit at 9:35 A.M. from her friend and neighbor Elizabeth Raymond, a music teacher. Looking at the previous weeks' worth of entries, we can easily imagine them discussing other recent events in the diary, such as Richard mixing up his dates and missing his lodge meeting, the recent renovations to their church, and a comet that appeared in the sky that week.

Zooming out spatially, an archaeological investigation at the Matthews' house lot could further benefit from the Imag(in)ing London HGIS by connecting the archaeology to the Matthews family's actual life events and routines at broader spatial scales. Matthews recorded his daily commute and work routine in some detail. He also recounts, and through the linked big-data sets we can map and better observe, the variety of other activities, such

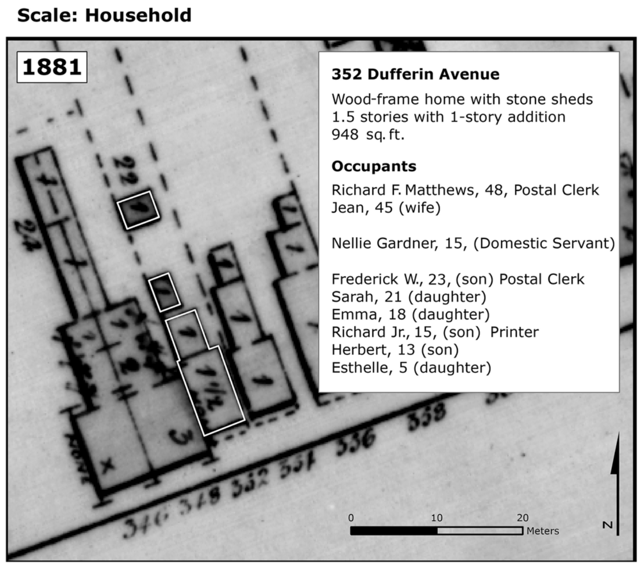



**Fig. 6** Visualizing microscale HSDI data: Richard Matthews's family and home in London, Ontario. (Illustration by Dan Trepal, 2018.)

as his membership in the Ancient Order of United Workmen, picnics in the suburbs, dining out, attending a lecture on Roman history, and where and when he voted in local elections. We can also spatially flesh out the Matthews family's social spaces from the diary by mapping visits to and from the family home; the HSDI allows us to visualize events as they played out on the historical landscape over a period of time. We can thus link the Matthews family's spatial stories more broadly to the city of London. Finally, these micronarratives can also be focused on material culture itself. We can track some of Richard consumption patterns by tracing where and when be purchased his clothes, had his hair cut, and did his Christmas shopping (Fig. 8). It also provides clues as to his material surroundings at home and at work. This record of consumption and material culture can serve as a valuable comparative with the archaeological record if we were to excavate Matthews's house or the post office in which he worked. This dialogue between what was recorded and what remains in the archaeological record can aid us in asking more fruitful questions about what each body of evidence is telling us and better identify where each might be biased or incomplete.

While diaries such as that of Richard Matthews only exist for a handful of people in the city, such sources each reference hundreds of other individuals, most of whom may be linked by name, address, and other attributes to personal records in other data sets within the HSDI. The census and directory data within the HSDI allow us to quickly and easily learn about all of these people: their age, sex, workplace, occupation, and ethnicity, and that of their families and even their family's friends, relatives, and coworkers. Matthews's work at the post office links him to over 700 other postal employees in London for whom we know their workplace duties, wages, employment histories, where they live, their family composition, etc. Church records contextualize Matthews's religious life through the activities of his parish at the Dundas Street Centre Methodist Church. With the HSDI we can quickly visualize and explore a highly complex web of social interactions and spatial movements around Richard Matthews and his family; thus, each diary may serve as the foundation for hundreds of microhistories beyond that of the original author and as links to hundreds of other historical or archaeological sites.

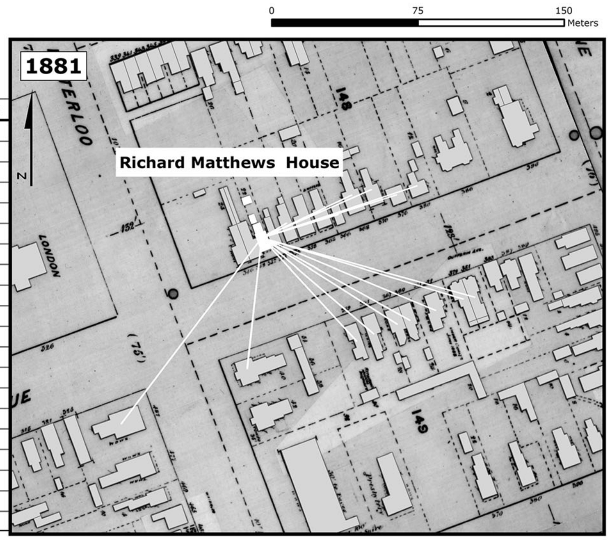
This approach is, of course, also applicable to many other detailed historical sources, such as school and employment records, that may contain notes of events and routine activities, or sales ledgers or private account books that record consumption patterns. Archaeology and historical research may even become more closely intertwined on occasion when archaeologists find documentary evidence within an historical structure itself or within subsurface

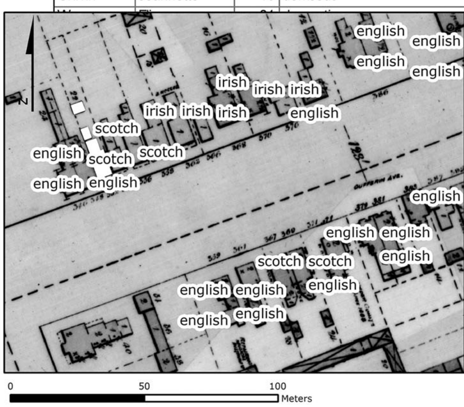
**Scale: Neighborhood**

Richard Matthews's Neighborhood

***Social Environment Data***

| surname | firstname | AGE | occupation | tenure |
|---|---|---|---|---|
| Craig | Albert | 32 | travelling agent | bds |
| Craig | Alvin | 29 | travelling agent | bds |
| Robertson | William | 23 | student | bds |
| Barker | Maria | 42 | seamstress | res |
| Ball | George | 38 | plasterer | res |
| Evans | William | 41 | pianomaker | bds |
| Benson | Wm | 41 | piano tuner | res |
| Irvine | George | 22 | moulder | bds |
| McAulay | William | 39 | merchant | res |
| Craig | Samuel | 34 | manager | res |
| Evans | Richard | 35 | letter-carrier | bds |
| Evans | Goodisson | 27 | letter-carrier | bds |
| Irvine | Richard | 56 | landing w aiter | res |
| Craw ford | Andrew | 48 | janitor | res |
| Brydges | Charles | 46 | insurance and real estate | res |
| Cody | Charles | 64 | inspector | res |
| Fairburn | James | 53 | engine driver | res |
| Griffin | Jeannette | 16 | domestic | bds |
| | | | | bds |
| | | | | res |




| Building_ID | Street_Number | Street | Use | Type | Stories | Building_Material |
|---|---|---|---|---|---|---|
| 4762 | 396 | Dufferin | Dw elling | Residential | 1 | Brick |
| 4750 | 389 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4749 | 387 | Dufferin | Dw elling | Residential | 1.5 | Wood |
| 4765 | 386 | Dufferin | Dw elling | Residential | 2.5 | Brick |
| 4748 | 383 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4745 | 381 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4768 | 380 | Dufferin | Dw elling | Residential | 1 | Brick |
| 4742 | 379 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4770 | 376 | Dufferin | Dw elling | Residential | 1 | Wood |
| 4741 | 371 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4771 | 370 | Dufferin | Dw elling | Residential | 2.5 | Brick |
| 4740 | 369 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4772 | 368 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4739 | 367 | Dufferin | Dw elling | Residential | 2 | Brick |
| 4773 | 366 | Dufferin | Dw elling | Residential | 1 | Wood |

***Built Environment Data***

**Fig. 7** Contextualixing the Matthews household and home within its neighborhood. (Illustration by Dan Trepal, 2018.)

deposits, such as the ledgers Brace (Brace and Ellens 2015; Brace 2016) found while documenting the Blue Bird Inn in Detroit. Using the HSDI, spatial or tabular searches can be used to quickly locate people, places, and events recorded in those sources, construct micronarratives of activities and people associated with the site, and then link them to other people, places, and events in the city.

Example 2: Augmented Temporal Scaling

Societies and their environments are always dynamic; while researching a static "snapshot" of the past will always be useful, archaeologists are also concerned with revealing and understanding change over time. As mentioned previously, incorporating the passage of time into GIS-based research has long been a challenge, and the methods proposed to meet this challenge differ depending on the kinds of questions being asked and the timescales involved. For archaeologists, the tracking of change through time starts at some point in the past and typically ends at some other point in the past or, perhaps, in the present. Many promising methods for collecting space-time data, such as the use of GPS transponders to track the movement of people or the locational data available from Twitter (Goodchild 2013), are not useful for archaeologists, whose subjects have often been dead for generations. For archaeologists, subjects are tracked through combinations of archaeological and historical evidence. Tracking change through time by means of a rich, mutual contextualization of spatial historical big data can be accomplished within an HSDI, and this approach is adaptable to the needs of archaeologists. To illustrate, we return to CC-

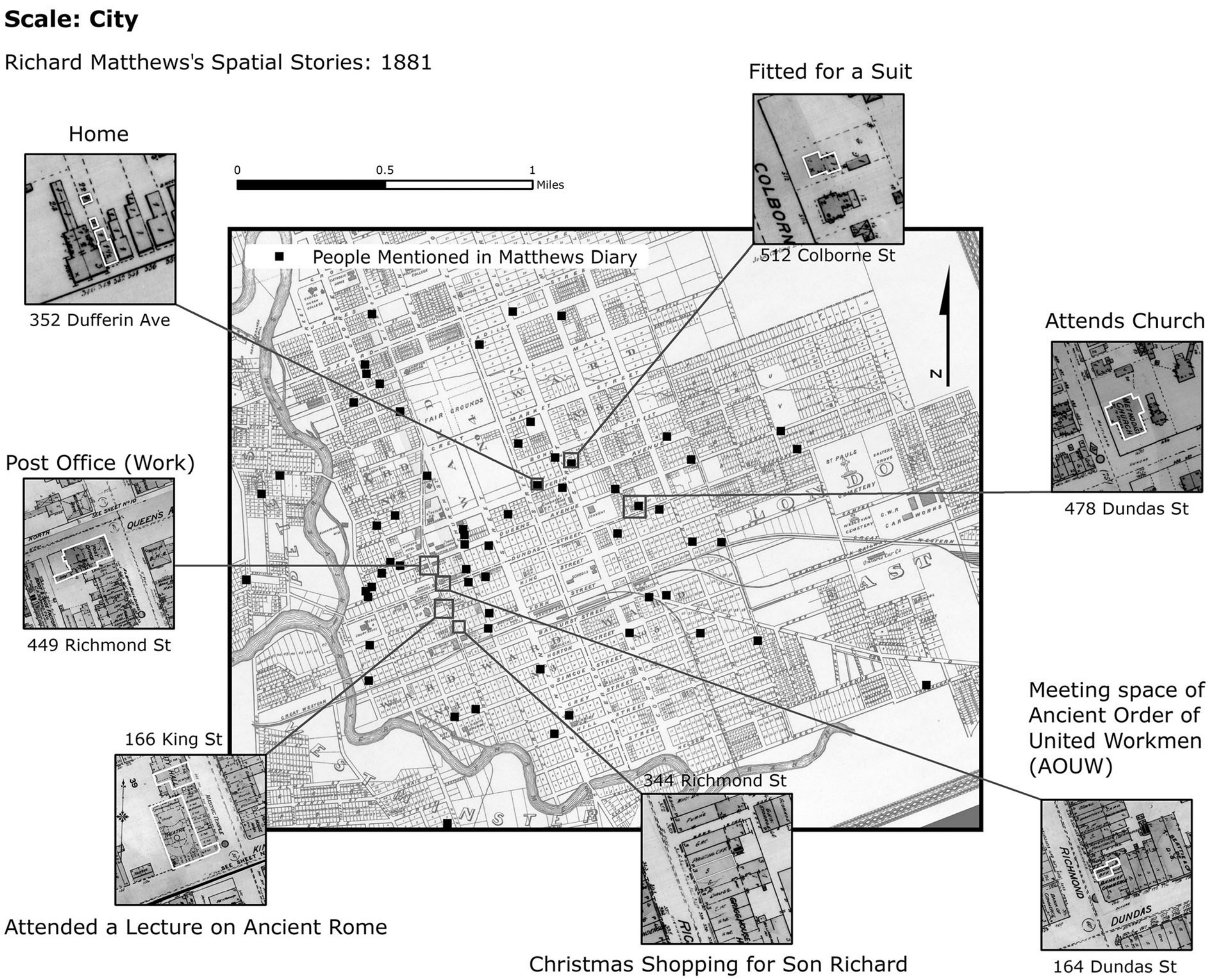



**Fig. 8** Contextualizing Richard Matthews's activites at the city scale. (Illustration by Dan Trepal, 2018.)

HSDI to observe how it permits longitudinal linkages between data; CC-HSDI relies on both tabular and spatial linkages of data between different time periods.

Within CC-HSDI, each object within the built-environment stage can be located using a variety of tabular queries (Table 1). During the digitization process, each building footprint is assigned a unique ID number that remains the same across time slices until the building is altered, demolished, or moved. In such cases, a new unique ID number is assigned that denotes the historical date on which the change to the structure occurred. Each unique ID number thus corresponds to a discrete structural "state" of one component of the built environment that may persist over time in the form of multiple polygons originating from different time periods that occupy the same space and have the same ID, even though the address and the occupants may change. This allows for the quick identification of either persistence or change in the physical state of a building across time within the tabular data. Secondly, each building footprint in the HSDI is assigned a street address, date, and place (typically a town or county name) from its cartographic source. Built-environment information can be filtered for objects containing that attribute or group of attributes, such as outbuildings at the same address, and can also call up any social-environment state data (such as census, city-directory, school, or employment data) linked to that address from any time period covered by CC-HSDI. Finally, each building-footprint polygon is assigned a unique global ID within CC-HSDI enterprise geodatabase, ensuring that every individual "object" within CC-HSDI's global built-environment stage is assigned a unique identifier. In each case, these tabular queries are useful for exploring the contents of multiple historical data sets covering a dense urban environment.

A more powerful way to visualize multiple objects across time is accomplished using the ability of the HSDI to spatially select and visualize data. Spatial queries are especially useful for tracking change over time because they can aggregate all of the available data within a flexibly defined location regardless of date or data type and without relying on tabular linkages, which must be constructed before they can be used. Spatial selections based on the intuitive visualization of the data within GIS are made within the GIS GUI using standard spatial-selection tools. In this way new patterns in the data that may not be evident when looking at tables of historical data can be visualized and identified. This is also useful when address or occupant data are incomplete or missing, or a building never had an address assigned in the first place. The latter is often the case for industrial buildings within a larger complex, as exemplified by the copper-mill complexes built by the Calumet & Hecla Mining Company in Lake Linden within CC-HSDI. Using the HSDI, a specific mill complex, part of a complex, or a combination of the industrial complex and surrounding residential neighborhood can be visually identified and then selected from the built-environment data. Changes to the built environment or linked tabular data may be observed through time without having to rely on multiple tabular queries across time slices (Fig. 9). With geographic space as a constant, a given place can be visualized as either a moment in time or as a palimpsest of cumulative built-environment information recorded in the HSDI's data sets.

**Table 1** Key attributes: CC-HSDI built-environment stage data

| Identifier Type | Links To |
|---|---|
| Join ID | Same building-footprint "state" in different time slices |
| Street address | All other HSDI data with matching address information |
| Date | All other HSDI data in same HSDI time slice |
| Place | All other HSDI data in same "place" (usually town name) |
| Global ID | Unique for each building footprint polygon in HSDI |

The ability to visualize and explore cumulative phenomena, such as the formation of a postindustrial landscape, is especially powerful when the temporal depth of CC-HSDI is explored at the larger geographical scales discussed previously. Entire urban areas, such as the neighboring towns of Houghton and Hancock, can be observed at multiple scales as they developed through time, in both 2-D and 3-D, and with any combination of historical built and social data toggled on and off as desired (Fig. 10). This grants the ability to observe the changing landscape dynamically from multiple visual perspectives and within different contexts while retaining the individual-scale resolution of the spatial and tabular data. This way of observing historical environments echoes Torsten Hägerstrand's (1970) time-geography approach, a diagrammatic visualization of the movement of people through space and time. Time geography has recently seen a resurgence as the power and capability of computer-based geographic-research methods has improved (Sui 2012; Castree et al. 2013). The HSDI approach improves on the basic concept of time geography by allowing researchers to track complex movements of people through space and time using genuine historical big data to represent its subjects and their large- and small-scale contexts.

An HSDI thus provides archaeologists with a powerful approach to visualizing and exploring historical big data across space and time while looking for patterns and relationships between people and things. The HSDI can, however, also be used to support spatiotemporal analysis. A final example, this time from the Imag(in)ing London HGIS, demonstrates further how HSDIs may be usefully employed for analysis by archaeologists studying postindustrial cities, where they must cope with the large physical scale of industrial systems, processes, and sites, and the complex development of the landscape over time. The Imag(in)ing London HGIS can be used to visualize the postindustrial landscape in ways that reveal their cumulative process of formation. To demonstrate this, we use information concerning historical industrial-building use contained within the

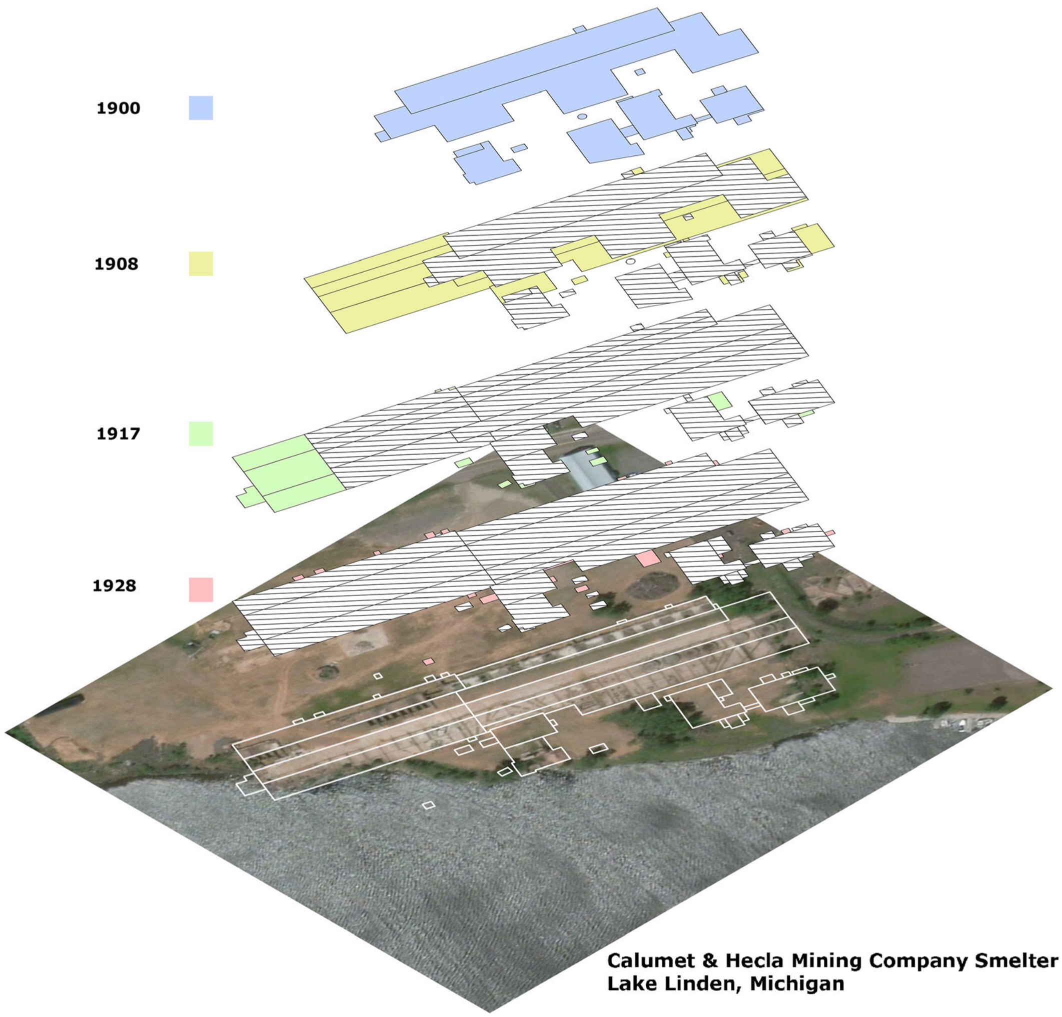



**Fig. 9** Portion of the Calumet & Hecla copper-mill complex in Lake Linden, Michigan. Spatial queries can be used to locate changes to the industrial site across time without relying on tabular linkages across multiple data sets. Similar queries could highlight removal of building elements as well. (Illustration by Dan Trepal, 2018.)

Imag(in)ing London HGIS's data sets to generate a high-resolution spatial model of industrial land-use intensity over time. Using historical descriptive information present in both the built- and social-environment stages, we manually classify all building footprints from all time periods within the built-environment stage into broad land-use categories based on conventional zoning-classification systems in use across North America (Hirt 2014). Each footprint then receives a base industrial-activity intensity rank (Table 2). In the case of commercial- and industrial-building footprints, the data from the built- and social-environment stage usually include either the name of the occupant or the chief function of each building (such as "stable") or, in the case of a manufacturing operation, the type of products produced ("Cigar Factory," for example). This allows the presence of specific types of industrial activity or activities within specific building footprints to be inferred.

The base intensity rank is multiplied by the area of each industrial building to obtain the final intensity ranking. The footprint of each building is calculated and multiplied by the building's number of stories to produce the building's area. Once this ranking is generated, the polygon shapefile is converted to a raster, with each pixel (cell) containing an intensity value. A cell falling on open ground will have a low ranking, while a cell within an area featuring industrial activity will

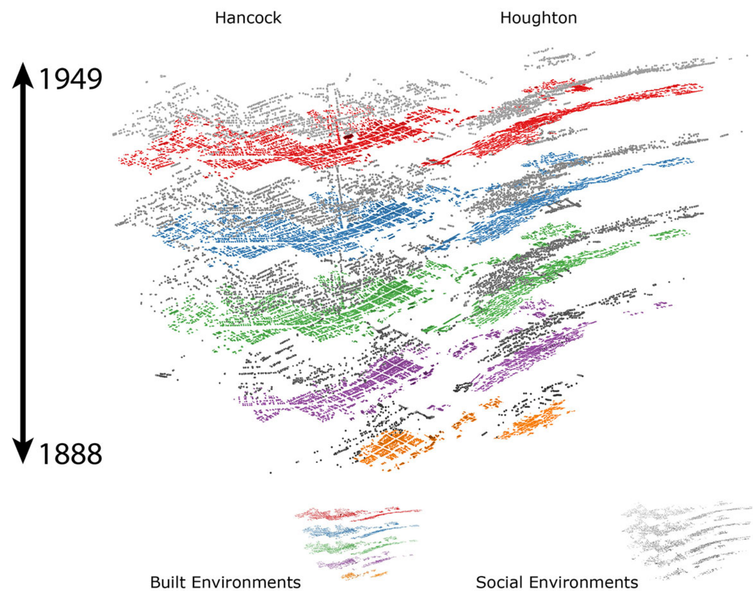



**Fig. 10** Landscape-scale changes in the built environment of the adjacent Copper Country towns of Houghton and Hancock can be interactively and recursively explored using CC-HSDI, without sacrificing the benefits of the high resolution of the constituent historical big-data sets. (Illustration by Dan Trepal, 2018.)

receive a high ranking. We repeat this process for each time slice, so that the rankings for each cell of each of the resulting rasters can be summed in ArcGIS. Adding the values in corresponding cells for each time slice is what gives this map of activity temporal depth, resulting in a new raster representing the cumulative intensity of industrial activity within the study area across the full temporal scope of the Imag(in)ing London HGIS. This allows the intensity rankings to be visualized as an interpolated surface, revealing patterns of cumulative industrial activity on the landscape (Fig. 11).

Cumulative Industrial Intensity of a Given Building = (Land-Use Classification Intensity × Number of Years of Activity) × (Building-Footprint Area × Number of Stories)

**Table 2** Zoning-based land-use classifications with intensity rank

| Base Intensity Classification | Rank | Examples |
|---|---|---|
| Open land | 1 | Municipal park, school playground |
| Residential | 2 | Single-family home, apartment building |
| Commercial | 5 | Retail business, strip mall |
| Light industrial | 6 | Creamery, printer |
| Infrastructure | 7 | Electrical substation, railroad trestle |
| Medium industrial | 8 | Lumber mill, textile manufacturer |
| Heavy industrial | 9 | Steel manufacturer, pesticide manufacturer |

By comparing this model with modern land-use maps and imagery, archaeologists can quickly identify industrial complexes or districts that may be of particular interest, to search for sites of comparative intensity across the city or to compare the intensities of multiple sites. This aids in quickly assessing the extent of past industrial landscapes manifesting in the present—revealing a city-scale landscape of intensive, persistent, historical industrial activity on numerous sites that are either "lost," partially extant, adaptively reused, or, in a few cases, still active. Specifically, archaeologists looking at a particular type of industry can quickly identify within the HSDI where all such operations were located within the city, when they were active, and, by comparing this data with the modern municipal GIS data within the London HGIS, the current occupation or use of each site. This model could even be taken into the field and aid in reflexive, iterative explorations of the postindustrial landscape at every stage of archaeological research, bringing the archive to the field in a more effective way than was previously possible (Arnold et al. [2020]).

Time represents a crucial component of archaeological provenience, and digital historical environments such as an HSDI must be able to facilitate the visualization of time not only in discrete moments, but as dynamic processes taking place at varying spatial scales.

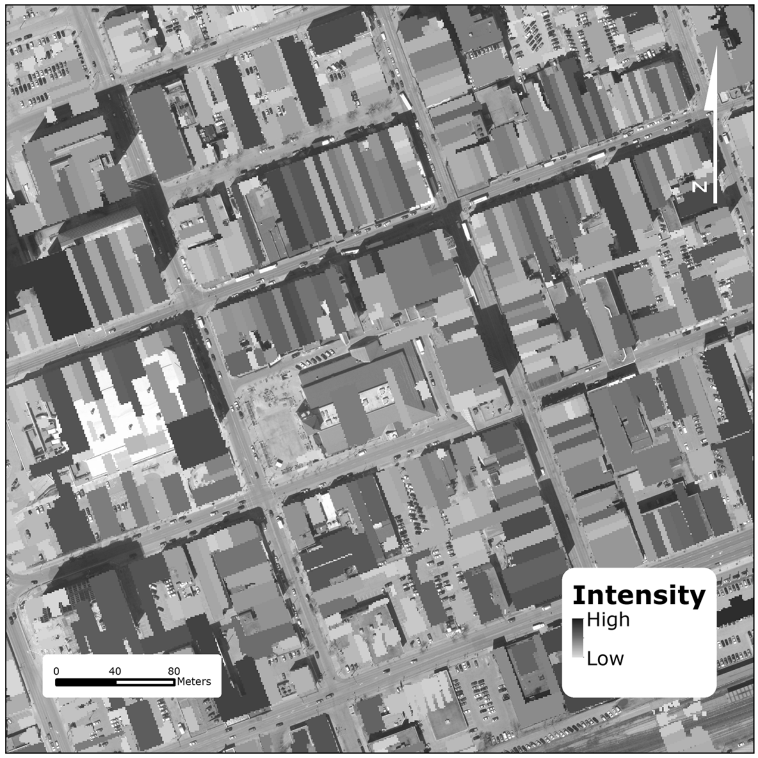



**Fig. 11** Cumulative industrial activity intensity in downtown London, Ontario, from 1888 to 2018. (Illustration by Dan Trepal, 2018.)

Tabular linkages in the geodatabases are important ways to link data sets across time. However, spatializing historical big data is the most powerful way to link disparate pieces of information across time, not only between various periods in the past, but also between the past and the present. Any contemporary information about the built and social environment of the Copper Country can be linked via the HSDI to a vast pool of historical data through geographic location, maintaining the crucial link between the past events being represented and studied on the one hand, and the contemporary physical landscape, the cumulative result of all of those past phenomena, on the other.

Example 2: Embracing the Scale of Big Data

The ultimate promise of the application of historical big data to historical archaeology is the development of more rigorous linkages between different scales of inquiry, from the microscale to the neighborhood, district, city, region, and beyond, through the exploration and analysis of historical environments within an HSDI. Recently Kintigh et al. (2014) described grand challenges for archaeology that include the need for better computational infrastructure for modeling historical and ancient phenomena at larger geographic and temporal scales; scale remains a major challenge (Robb and Pauketat 2013). These challenges, as well as the challenges of reconciling different modes of space and representation when using spatial digital approaches (Lock and Pouncett 2017), are also relevant to historical archaeologists, yet little conversation about them has taken place thus far within historical archaeology. General discussions of big-data issues within archaeology, such as the "avalanche" (Petrovic et al. 2011:56) or "deluge" (Bevan 2015:1473) of incoming archaeological data or the future role of geospatial big data (McCoy 2017), still tend to focus on more ancient contexts in their case studies. While the timescale of historical archaeology might be narrower and the types of evidence available somewhat different, it is past time for historical archaeologists and digital, historical big data to become part of the growing conversation about how to better integrate big-data-based computational approaches within archaeology.

The development of the HSDI approach presents historical archaeology with its own unique entrée into this discussion. Geospatial big data serve as the basic building blocks of an HSDI and, as demonstrated previously, presents a geographically and temporally flexible digital infrastructure of the kind called for more broadly within archaeology. It is also ideally suited to the time periods historical archeologists study. This is not merely a new way to organize and store spatialized historical data, but also a big-data-based historical environment within which spatial historians study the past. Historical archaeologists, as users of the historical record in their own right, can and should benefit from the potential benefits of spatial-history approaches.

In the previous two examples, we have touched upon the various linkages between specific data sets and demonstrated the robust geographic and temporal scaling that HSDI can support. Data linkages are both tabular and spatial, easing the task of identifying individual objects, groups of objects with shared attributes, or spatial patterning, all at a variety of scales. Here we wish to emphasize the comprehensiveness afforded by these linkages as well as the modularity of this approach. This is especially evident in the social-environment stage of CC-HSDI, where the geocoded city directories and census data serve as a spatialized digital lattice for the incorporation of virtually any other historical data that can be linked to a person, household, address, workplace, or even more generalized locations. The HSDI approach mutually contextualizes all of its constituent data on the built and social environments within space and time; with it an historical landscape can be modeled, using the historical record, to a degree impossible outside a big-data project (Fig. 5). Such environments are useful for more efficient large-scale spatiotemporal querying of the historical record for the purposes of archaeological site location, the generation of research designs, or the formulation of research questions.

A simple illustration of this can be made using CC-HSDI's social-environment data. As an active mining region, the Copper Country attracted a large immigrant population, with nearly a quarter of residents in the five largest towns in the area being foreign born in 1920. Of these towns, Calumet, which contained the largest concentration of underground-mining activity, had the highest proportion (33%) of immigrants in its population in 1920, over a third. For archaeologists seeking to contextualize the experience of immigrant labor within the broader community, CC-HSDI provides a convenient and powerful tool for querying the broad spatial patterning of immigrants within CC-HSDI. This allows archaeologists to contextualize their study area within those broad patterns, but also to zoom in to look at detailed contexts of potential sites at the household and individual level thanks to CC-HSDI's capacity to support the rapid aggregation and disaggregation of historical big-data record sets.

For example, if one zooms in from the regional-scale visualization to the scale of a street in the town of Hancock in 1917 (Fig. 12), the neighborhood can be contextualized by looking at the national origins and occupations of the residents there. The data are displayed using a prototype Web interface currently under development for CC-HSDI, known as the Keweenaw Time Traveler (<http://www.keweenawhistory.com>). For an archaeologist using CC-HSDI, historical-data exploration and visualization may be useful for the purposes of site location, as argued by White (2013); more than that, it is also an excellent aid to the iterative construction of microhistories of a person, household, or neighborhood during the fieldwork and post-field analysis stages of the archaeological research process. Ultimately, big data provide a freedom of movement within the historical record that cannot be achieved by even the most rigorous traditional historical-research methods, as the HSDI's depth of data and temporality permit a flexibility of contextualization that allows a continuous shifting in frame of reference in space and time. The same location can be viewed from multiple spatiotemporal perspectives or similar patterns formed by the interaction of several types of evidence in multiple times and places can be sought. This represents a far more interactive, flexible, and comprehensive approach to the historical record than the methods archaeologists typically employ.

## Conclusion

With GIS firmly established within archaeology, the continuing challenge archaeologists face is to understand how best to use it and similar computational methods in ways that will benefit archaeology and, through archaeology, the public. It has already proven itself indispensable for basic data recording and mapping; this will likely remain the most common application of GIS among archaeologists for the foreseeable future. The value of GIS as a means to conduct certain types of complex spatial analyses is also well established—though less so in historical archaeology. Recent discussions of the role of GIS in archaeology

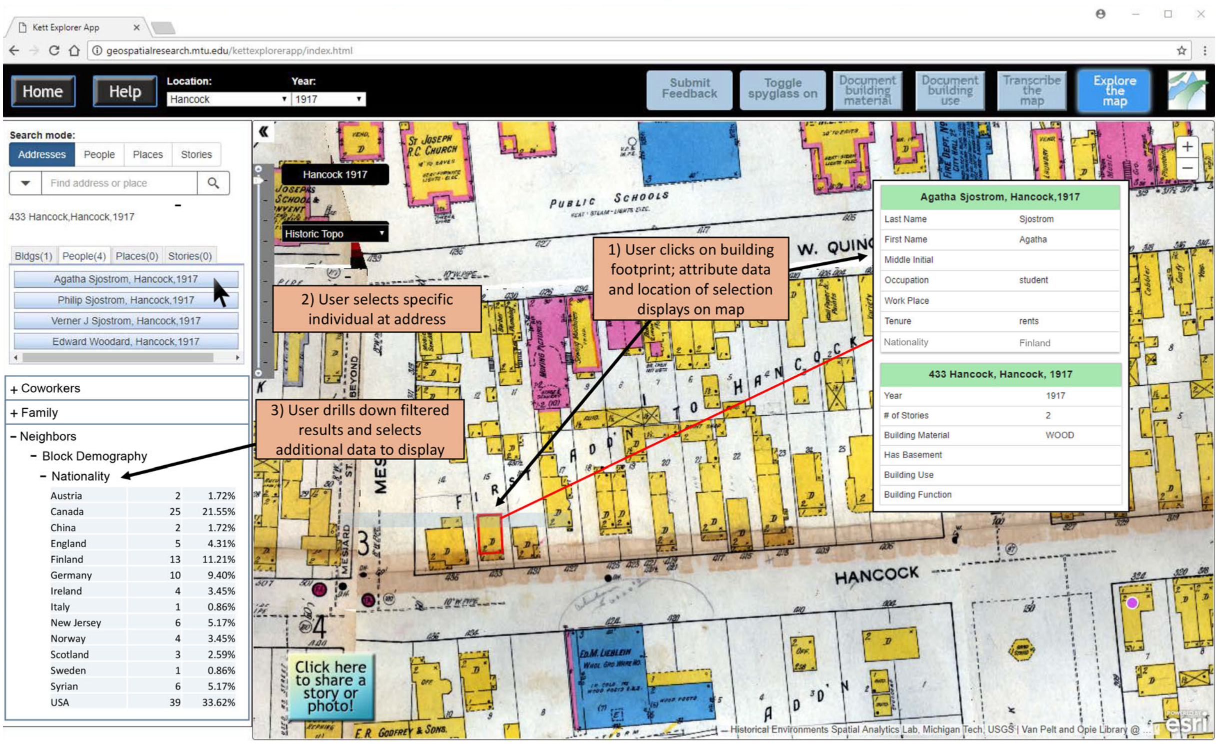



**Fig. 12** Contextualizing the immigrant experience in space and time at the neighborhood scale. (Illustration by Dan Trepal, 2018.)

have suggested it is capable of much more than this, however. In particular, several of the most recent discussions of the use of GIS in archaeology (González-Tennant 2016; Howey and Brouwer Burg 2017a, 2017b) have concluded that GIS needs to move from being seen as a tool to being considered a practice or process; they have also argued that engagement with the ways other disciplines use GIS, such as the digital humanities and GIScience, will grant archaeologists access to useful new theoretical and methodological tools for improving the value of GIS to archaeology.

We argue that a crucial early step in the transition of archaeological GIS from tool to process is the establishment of methodologies and infrastructures such as an HSDI that can support the necessary interdisciplinary blending of the methodologies and theoretical tools of spatial history, digital humanities, and archaeology. These powerful, flexible spatial-data infrastructures can serve to lower disciplinary barriers, as well as the barriers between qualitative and quantitative forms of inquiry, as they move well beyond the limitations of static representations in academic paper publications and represent dynamic, interactive, iterative spatial approaches to the study of historical environments.

The ultimate outcome of this engagement may be the development of large-scale, longitudinal deep maps for archaeology that can support traditional GIS tasks, such as data collection, storage, and management, as well as rigorous geospatial analysis, but yet, most importantly, are also capable of better representing lived experience and a sense of place. HSDI thus may support a hermeneutical approach (Mayne and Murray 2001) to historical archaeology in which historical and archaeological data are iteratively contextualized at different scales though all stages of the research process; this work may also involve creating imaginative, narrative components (Yamin 2001) or the use of virtual reality and collaborative digital storytelling (González-Tennant 2018).

Achieving these goals requires the close collaboration of archaeologists, historians, digital humanists, geographers, GIScientists, and others, such as computer scientists, software engineers, and cartographers. Our research demonstrates a case study of such a collaboration. Using space as the fundamental integrating element, we have demonstrated how archeologists working in postindustrial urban contexts may apply the HSDI approach to expand the scale of archaeological inquiry into historical environments by taking advantage of its facility in handling geographic scales, temporal scales, and working with big data more generally. Historical archaeology may, in turn, contribute to spatial history and the digital humanities its own unique perspective on the past, its manifestation in the present, and, perhaps most importantly, convey the value of material culture and archaeological landscapes to other disciplines. Public Web access to HSDIs like the Keweenaw Time Traveler brings these past environments to the public and represents another useful conduit for the wider dissemination and exchange of archaeological knowledge.

Of course, doing archaeology requires resources, and those resources differ depending on whether archaeology is being conducted under the rubric of academia, federal agencies, nonprofit organizations, or for-profit CRM. The HSDI approach we advocate requires substantial, long-term institutional support and cooperation with a range of other disciplines and is clearly not within the reach of every archaeologist, anthropology department, or CRM firm. It is not our intention to suggest that every archaeologist ought to start building an HSDI; rather, we wish to demonstrate the potential of the HSDI concept to archaeology in general, and historical archaeology in particular, and to encourage groups of researchers, CRM firms, or cultural institutions to collaborate with each other to secure the necessary resources to build and share these infrastructures. The CC-HSDI is accessible by the general public, and the research team maintaining it has also made the HSDI available to the academic community, regional nonprofit organizations, and local municipalities. Our intention is to make the infrastructure as easily and widely accessible as possible. While the entire contents of CC-HSDI is freely available, questions of how to provide access to costly, restricted-access, and/or sensitive data (de Kleijn et al. 2014; Kitchin 2014) are a shared concern with all SDI projects and will require further evolutions of the HSDI interface and sharing model as those types of data are incorporated. Despite this, we demonstrate that a highly complex, fully functioning HSDI can be built with unrestricted public data, and public data will continue to serve as the foundation of the project.

Finally, as archaeologists we must remain mindful of the delicate balance required during any application of computational methods to the study of our own past. It is appropriate to summon the oft-quoted chestnut by George Box: "[t]here is no need to ask the question 'Is the model true?' If 'truth' is to be the 'whole truth' the answer must be 'No'. The only question of interest is 'Is the model illuminating and useful?'" (Box 1979:203).

As we archaeologists work to improve the complexity and rigor of our modeling of past environments, it is important to remember that the best we can hope for are more useful or illuminating models, not perfection or "truth." HSDI is intended to substantially augment, not replace, existing approaches to understanding the historical record and the complex dialogue between historical and archaeological evidence that is so fundamental to historical archaeology. Given what archaeologists have achieved using GIS thus far, we believe this is a worthy and achievable goal. The embrace of an HSDI approach to GIS in historical archaeology is a search for new and better questions, rather than the search for answers or "truthful" models per se. By making use of increasingly flexible, comprehensive, temporally robust, and accessible historical digital infrastructures, we seek to make available new perspectives on the data with which we have to work by augmenting our established approaches. GIS itself will likely continue to live a double life within the broader discipline of archaeology for some time to come; its status as an indispensable tool continues to be consolidated by technological improvements while the debate over its potential as a process is, in some ways, only just heating up. Recent applications of GIS continue to percolate from interdisciplinary spaces within the social sciences, however, and historical archaeology will benefit from participation in these more expansive approaches to the process of GIS.

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**Compliance with ethical standards**

**Conflict of Interest** The authors declare that they have no conflict of interest.

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