remote sensing

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Review

Google Earth as a Powerful Tool for Archaeological and Cultural Heritage Applications: A Review

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Abstract: Google Earth (GE), a large Earth-observation data-based geographical information computer application, is an intuitive three-dimensional virtual globe. It enables archaeologists around the world to communicate and share their multisource data and research findings. Different from traditional geographical information systems (GIS), GE is free and easy to use in data collection, exploration, and visualization. In the past decade, many peer-reviewed articles on the use of GE in the archaeological cultural heritage (ACH) research field have been published. Most of these concern specific ACH investigations with a wide spatial coverage. GE can often be used to survey and document ACH so that both skilled archaeologists and the public can more easily and intuitively understand the results. Based on geographical tools and multi-temporal very high-resolution (VHR) satellite imagery, GE has been shown to provide spatio-temporal change information that has a bearing on the physical, environmental, and geographical character of ACH. In this review, in order to discuss the huge potential of GE, a comprehensive review of GE and its applications to ACH in the published scientific literature is first presented; case studies in five main research fields demonstrating how GE can be deployed as a key tool for studying ACH are then described. The selected case studies illustrate how GE can be used effectively to investigate ACH at multiple scales, discover new archaeological sites in remote regions, monitor historical sites, and assess damage in areas of conflict, and promote virtual tourism. These examples form the basis for highlighting current trends in remote sensing archaeology based on the GE platform, which could provide access to a low-cost and easy-to-use tool for communicating and sharing ACH geospatial data more effectively to the general public in the era of Digital Earth. Finally, a discussion of the merits and limitations of GE is presented along with conclusions and remaining challenges.

Keywords: Google Earth (GE); archaeological; cultural heritage; remote sensing; Keyhole Markup Language; very high-resolution (VHR); virtual

1. Introduction

Even though remote sensing technology, especially satellite Earth observation, was not originally designed and established for archaeological purposes, it has become an indispensable and powerful tool in Archaeological and Cultural Heritage (ACH) and is being applied for miscellaneous uses [1,2]. Based on the imaging techniques used, the existing spaceborne remote sensing tools in ACH generally can be divided into three types: Multispectral [3–14], hyperspectral [9,15–19], and synthetic aperture radar (SAR) [20–26]. Recent reviews [1,27–31] and chapters [2,32,33] have been published to point out the basic principles and methods that make different remote sensing techniques suitable for ACH and produce some successful results.

In order to identify and document archaeological features successfully, most of the above-mentioned ACH applications were carried out by employing high-resolution and very high-resolution (VHR, defined here as imagery with a spatial resolution finer than five meter) commercial satellite imagery (SPOT, IKONOS, Gaofen, QuickBird, GeoEye, WorldView, TerraSAR, ALOS-PALSAR, TanDEM, and COSMO-SkyMed). These commercial data sources and commonly used practices will most probably continue to play an important role in ACH applications in the future. ACH applications rely on purchased commercial satellite imagery for archaeological prospection—a significant financial burden if large areas are to be assessed [34,35]. Generally, collecting these commercial data is time-consuming and costly, and thus it imposes severe limitations on the size of the area that can be investigated [36]. Existing remote sensing techniques have made it possible to survey, document, and conserve ACH but this far from satisfies the demands of nationwide participation, simple operation, and data sharing from the perspective of public archaeology [3]. In 1999, Schadla-Hall [37] pointed out that public archaeology should consider not only public interest in terms of conservation and documentation of the past, but also ways in which archaeologists can both involve the public and make it possible for them to engage in many of the issues that archaeologists too often debate without reference to them. In short, public participation embodies the peculiarity of archaeology as a public activity together with public benefits. In addition, satellite remote sensing archaeology is a very challenging field for the general public because not only do they lack a good understanding of remote sensing imaging theory, but they also lack the professional skill to use complex image-processing tools, such as that offered by ENVI, ESRI ArcGIS, ERDAS Imagine, and Geomatica. Visualization of ACH data has the great benefit of revealing new insights into the patterns of nature/human-related cultural phenomena and assisting in the understanding of palaeoenvironmental changes and past human activities. Conolly and Lake [38] noted that four typical applications of geographical information systems (GIS) in ACH are the management of archaeological resources, excavation, landscape archaeology, and the spatial modelling of past human behavior [12]. The integration of remote sensing-derived ACH data into a GIS platform could assist in a better understanding and reconstruction of the spatial–temporal dynamics of archaeo-landscapes and associated cultural heritage environments. From this point forward, archaeological GIS will be a useful tool for collating, exploring, documenting, visualizing and analyzing geospatial data in the field of ACH [39,40].

However, traditional GIS tools are expensive and have a steep learning curve [41–43]. In addition, they are less flexible for geo-visualization [44] and it is not easy to operate and integrate huge volumes of data from different sources automatically and seamlessly [43]. To collect, identify, document, manage, share and display ACH data, traditional GIS science and technologies are faced with a big challenge: How to make it easier to realize three-dimensional (3D) visualization and representation of ACH geospatial data from local to global scales. The rapid development of virtual globe technology has provided access to a low-cost (even free) and easy-to-use tools for communicating and sharing ACH geospatial data more effectively to the general public, as well as among engineers and scientists [45,46].

To the scientific community, virtual globes such as GE, NASA's World Wind, ESRI's ArcGIS Explorer, and Microsoft's Bing Maps are not only tools providing huge volumes of freely available imagery and 3D views of the Earth, but more importantly are effective channels to communicate and share data and research findings [43,47,48]. Thousands of papers, chapters, and reports have been published to illustrate the use of virtual globes in diverse fields since the emergence of GE in 2005, and ACH is one of the most popular application fields. This new technology has been introduced and reviewed in a number of peer-reviewed articles [43,47–51] and sessions in academic conferences (e.g., International Symposium on Digital Earth (ISDE), International Committee of Architectural Photogrammetry (CIPA) and the American Geophysical Union (AGU) Fall Meeting). Virtual globes offer researchers a simpler alternative to the traditional GIS tool, leading to increased data sharing while facilitating studies on a global scale [49]. It is now 13 years since the release of GE, and a similar period has elapsed since the release of the earliest of what is now a long list of comparable virtual globes [49,52]. GE provided free or low-cost access to multi-resolution imagery that has opened the world of satellite images to the scientific and general public, and facilitated entertainment, education, and the exploration of new findings [43,53].

GE is increasingly being expanded in a variety of applications from natural sciences to arts and humanities [36]. In the field of remote sensing, GE is popularly used to produce fine thematic maps and validate coarse (MODIS) and medium (Landsat) resolution products such as the global mapping of tree cover and forest [54,55], water bodies [56,57] and urban areas [58,59], which provides a favorable reference for ACH applications. In addition to its direct application in scientific publications, GE is also being used retrospectively by creating and publishing Keyhole Markup Language (KML) files of key findings to supplement scientific publications and broaden the dissemination of knowledge [43,51].

This paper provides new perspectives obtained from practice and the peer-reviewed literature, both locally and internationally, as GE has become more and more popular for use in ACH applications, when combined with the ground-truthing data. In this review, we examine the brief development of GE, which is the most popular 3D virtual globe for both the public and scientific communities, highlight its applications to ACH and discuss the merits and limitations of the current product for global studies. Several possible improvements are identified and proposed at the end.

2. Google Earth

2.1. Google Earth Software

A virtual globe is a 3D software model or representation of the Earth or another solid planet (e.g., the Moon and Mars) with the ability to move around freely in the virtual environment by changing the viewing angle and position [60]. Compared to a conventional globe, virtual globes have the additional capability of representing many different views on the surface of the Earth. These views may be of geographical features, man-made features such as roads and buildings, or abstract representations of demographic quantities such as population. The history and current state of the virtual globe has been introduced and discussed by Yu and Gong [43] in detail. A virtual globe has the ability to (1) explore in a virtual environment, (2) add users' own data and share them with others, and (3) represent natural and man-made features on the surface of the Earth [60]. Virtual globes provide easy access to image and terrain data and user-friendly annotation abilities.

GE (www.google.com/earth/index.html), a geographical information computer application released in 2005, is the most influential and popular virtual globe program. It was originally named EarthViewer 3D and was created by Keyhole, Inc. (Mountain View, CA, USA), a Central Intelligence Agency (CIA) funded company acquired by Google in 2004 [36,43,61]. The GE software can be downloaded from http://earth.google.com/download-earth.html. Table 1 shows the version history of GE. There were three versions of GE, namely GE Free, GE Pro, and GE Enterprise, listed in rising order of supported capabilities. GE Pro was originally the business-orientated upgrade to GE Free and provided customers with additional GIS and remote sensing data importation features, advanced measurement tools, higher data download speeds, and higher resolution printing and movie making. Up until late January 2015, it was available for $399 dollars per year, although Google decided to make it free to the public [61]. GE Pro is currently the standard version of the GE desktop application as version 7.3. GE Enterprise was designed for use by organizations that have satellite imagery or large quantities of geospatial data that need to be deployed in a secure solution. GE Enterprise allowed developers to create maps and 3D globes for private use, and host them through the platform. As of March 2015, Google has retired the GE Enterprise, with support ending in March 2017.

Table 1. The version history of Google Earth (GE) [61].

Version	Date	Changes
1.0	July 2001	The first version of EarthViewer 3D released by Keyhole, Inc. (Figure 1a)
1.4	January 2002	
1.6	February 2003	
1.7	October 2003	
2.2	August 2004	
3.0	June 2005	The first version of GE released after Google acquired Keyhole, Inc.
4.0	June 2006	
4.1	May 2007	
4.2	August 2007	Google Sky was introduced A flight simulator was added
4.3	April 2008	First release to implement KML version 2.2 Google Street View was added
5.0	May 2009	Google Ocean was introduced Historical Imagery was introduced
5.1	November 2009	
5.2	July 2010	Last version to support Mac OS X 10.4 Tiger and 10.5 Leopard
6.0	March 2011	3D Trees were added
6.1	October 2011	
6.2	April 2012	Last version to support Mac OS X 10.5 Leopard
7.0	December 2012	Support for 3D Imagery data was introduced Tour Guide was introduced
7.1	April 2013	Last version to support Mac OS X 10.6 Snow Leopard and Mac OS X 10.7 Lion
7.3	July 2017	GE Pro became the standard version of the desktop program.
9.0	April 2017	An entirely redesigned version of the program, currently only available for Google Chrome and Android.

GE's imagery is displayed on a digital globe, which displays the planet's surface using a single composited image (RGB true colour) from a far distance. After zooming in far enough, the image transitions into different images of the same area with finer detail; these images vary in date and time from one area to the next. The imagery is generally captured by satellite or airborne sensors. The spatial resolution of the imagery ranges from 15 m to 15 cm [61]. For many areas of the Earth, GE uses digital elevation model (DEM) data collected by NASA's Shuttle Radar Topography Mission (SRTM). This creates the impression of a 3D terrain, even where the images are only two-dimensional. GE displays VHR images of the Earth's surface, defined here as images with a spatial resolution finer than five meters, allowing users to see interesting regions and targets at an oblique angle. One reason for the popularity of GE is possibly due to the easy availability of VHR imagery, and because there are often images acquired at multiple dates available for any given location. GE is also now widely used by policy-makers, planners, managers, and the public in both research and teaching in the humanities and social and natural sciences [36].

Over the past 13 years, GE has provided an unprecedented variety of VHR satellite images with a spatial resolution of 1 m or finer. Most GE VHR datasets are widely available at little or no cost, along with user-friendly software for non-specialists. Based on the scientific data shared by Myroslava et al. [62], we digitally reproduced the distribution map of the GE VHR imagery by using ESRI ArcGIS10.3. In GE (Figure 1b), continuous areas of very recent VHR images can be found for India, Australia, the southern part of America, USA, Southeast Asia, and some African countries. There is a pronounced lack of VHR imagery in the high latitudes of the Northern hemisphere (Greenland and northern parts of Russia and Canada), and parts of the Amazon and the Sahara.

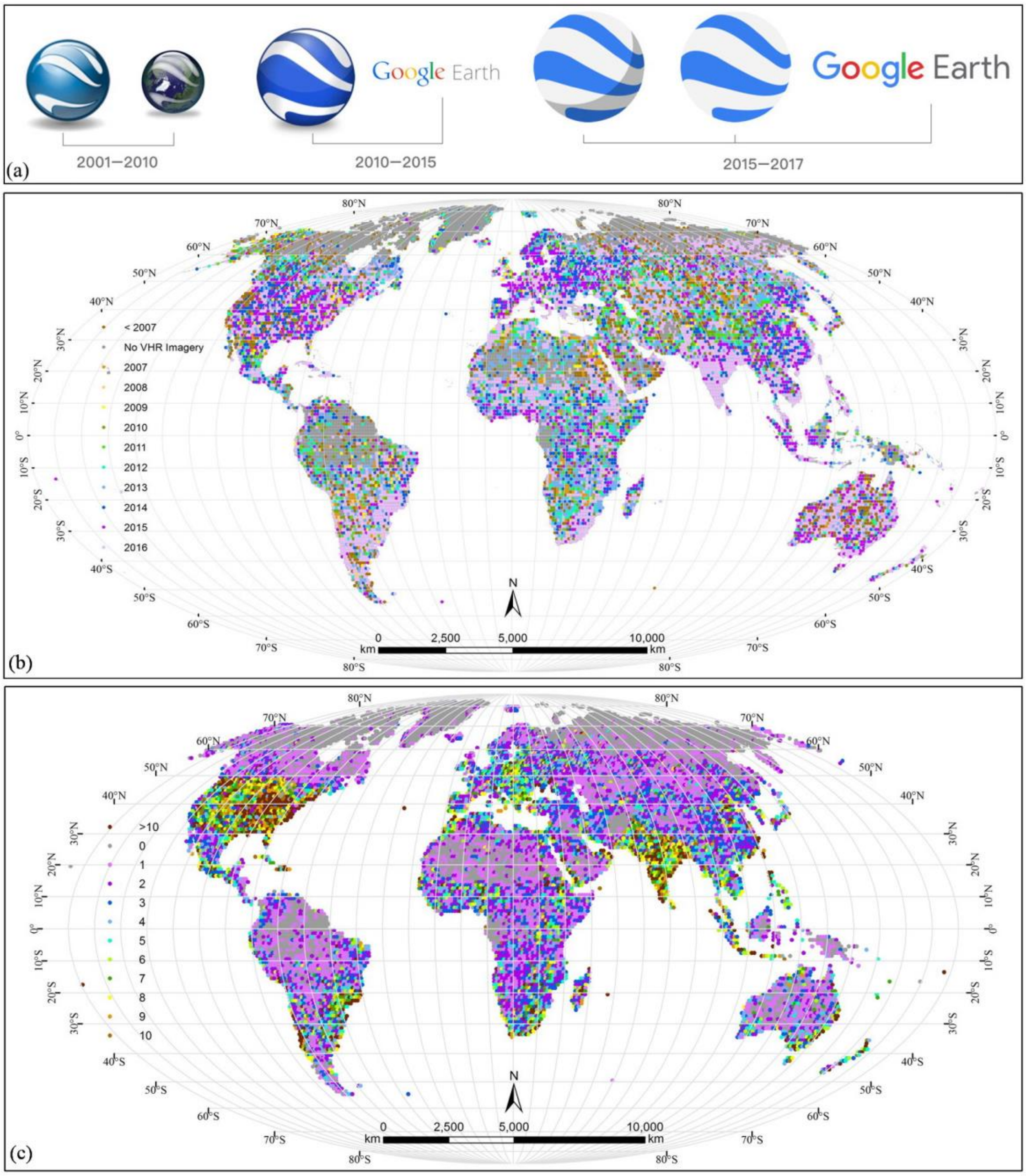

Figure 1. (**a**) The evolution of the GE logo from 2001 to the present; (**b**) the dates of the most recent VHR satellite imagery (<5 m resolution) available in GE as of January 2017; (**c**) the number of VHR satellite image sets available in GE. The original point dataset can be downloaded from https://doi.org/10.1594/PANGAEA.885767 and was collected at a spatial resolution of 1°.

GE VHR imagery is extremely powerful for a range of different ACH applications, from the identification of archaeological anomalies to the monitoring of cultural heritage damage or risks [34,52]. Furthermore, GE provides access to historical imagery, archiving the images as they are added to their system [62]. These historical images represent a valuable source of information for monitoring changes in ACH over time. The user simply navigates to a region of interest then uses the mouse to drag the "historical time slider" left or right [35]. When dragged to the left, the most current satellite image (which is displayed by default) changes to the next oldest image and so on in turn for as many images as are available. As with all the imagery on GE, just what historical images are available depends entirely on GE's database of images [35]. As the historical image sets are from different years, Figure 1c shows the number of VHR image sets available in GE. The areas with the most images available are the USA, India, parts of Eastern Europe and Indonesia, as well as some of the more populated regions of other continents, e.g., the Northern part of China, Southern Brazil, the Eastern coast of Australia and the South-Eastern part of South Africa [62].

2.2. Data Sharing in KML Datasets

Besides the innovative techniques used for 3-D sphere visualization [43,63] and the use of massive remote sensing data of the Earth's surface [62], another technique that is a favorite of the users of GE is Keyhole Markup Language (KML), which is an eXtensible Markup Language (XML)-based open-source language [43,64,65]. This represents a hierarchical data system where geographical objects (Table 2) can be populated in a nested structure [66]. Object styles (e.g., fill colours, line colours, line widths) can be static when they are intended to help users distinguish geographical objects. KML allows user-defined datasets to be overlaid on virtual globes or in GIS software, and GE was the first program able to view and graphically edit KML files.

Table 2. KML geometrical object types.

Object	Description	GE Tools
Placemark	Indication of a specific geographical location	
Points	Discrete points with coordinate and elevation (optional)	
Line string	A list of two or more coordinate values	
Linear ring	Series of coordinates in which the first and last pair of coordinates coincide; can be used to represent the outer or inner boundaries of polygons	
Polygon	Comprises one or many outer boundaries and zero or more inner boundaries	
Multi-geometry	A collection of discrete geometrical objects listed above	
Ground overlay	A 2-D surface laid at a specific elevation or height relative to the ground	

Nowadays, more and more virtual globes and GIS software packages support KML, especially after KML became an Open Geospatial Consortium (OGC) standard in 2008. KML has been the most widely embraced means by which scientific users create dynamic, interactive displays without the need to be GIS experts or computer programmers [64]. Furthermore, a Collaborative Design Activity-based 3D KML model has opened doors to vertical profile rendering in GE. This improves the visualization effects for complex objects (e.g., old buildings and churches) and phenomena (e.g., atmospheric circulation and ocean current). The popularity of GE is probably due to its ease of use [43,49,51], stability [67], and the ability to import, overlay, and visualize geospatial data by converting to the KML file format [43,49,51]. KML has become the standard format for virtual globes, with conversion to this format possible in geo-software such as ArcGIS [68] and Global Mapper [69].

The adoption of KML by scientists and the public is growing rapidly. This shows that it is finding an important niche [65]. It is important to remember that GE and KML do not attempt to replace more sophisticated systems [43,65]. They make it easy for non-specialists to share and visualize simple geospatial data, which can then be operated and produced in other applications if required [36,43]. KML is useful because it bridges the gap between very simple and more complex formats, and provides a much more useful interchange format than the imagery alone since it holds geo-referencing information and allows for the inclusion of links to related information [65]. The most recent version of KML 2.3 contains many new features that are particularly relevant to scientific data, such as large data support and the ability to timestamp features and hence create animations [43,65]. Detailed documentation and tutorials on all KML's capabilities can be found on the official website [70] and will not be reproduced here.

2.3. Google Earth in Literature

GE VHR imagery is used for different purposes but mapping and monitoring is the most frequent thematic area in remote sensing, and map validation—i.e., producing an accuracy assessment of a map [36,62]—is the most commonly found application. As many fine features and small targets—e.g., ships, buildings, roads, aeroplanes, and individual trees—can be seen in VHR satellite imagery, reference datasets for map validation are increasingly being augmented with visual interpretation of GE VHR imagery [54–59,71–74]. At the same time, several public web-based secondary GE applications such as Geo-Wiki [75,76], VIEW-IT [77,78] and Collect Earth [79,80] are using crowd-sourcing to collect and gather datasets for hybrid land-cover maps and validation based on the visual interpretation of GE VHR imagery [62].

To obtain an overview of the growing use of GE in the literature, we searched a widely used electronic database, namely Scopus (http://www.scopus.com/) for the period 1 January 2005 to 31 December 2016. Figure 2 shows a steady increase in the total contributions mentioned by title or abstract that were found when using the search terms "Google Earth" in Scopus, both across general journals (Figure 3) and more specifically in the field of remote sensing.

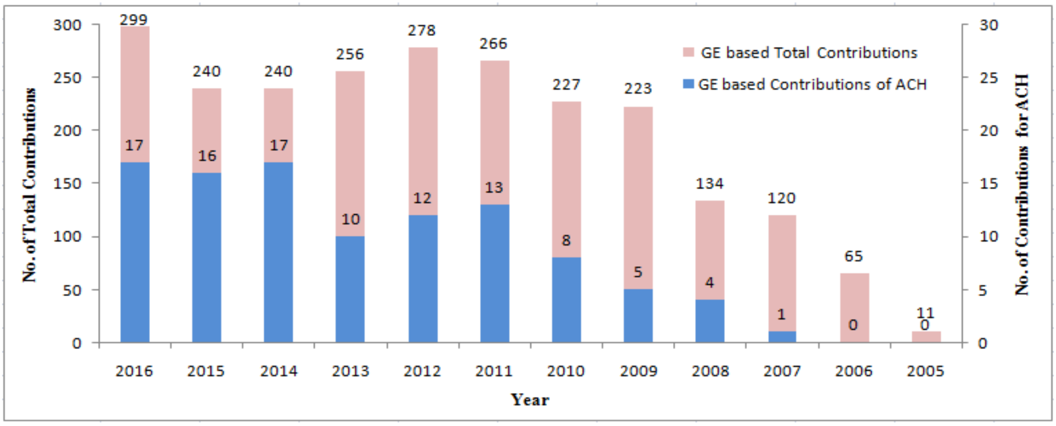

Figure 2. Annual literature counts of contributions introducing GE applications, extracted from the database Scopus published from 2005 to 2016 (last access 15 May 2018).

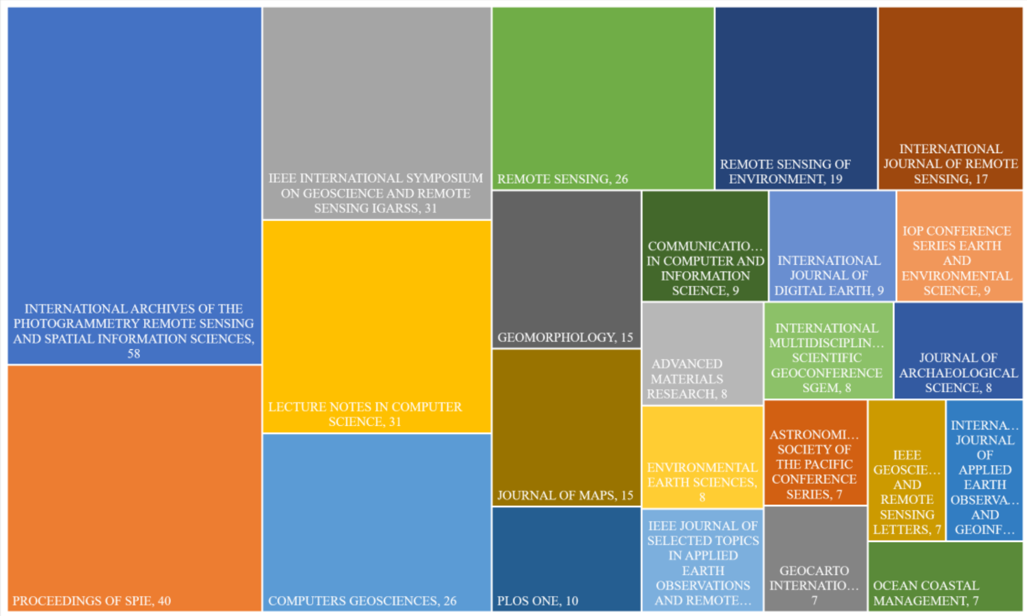

Figure 3. A treemap of GE-based papers published in Top 25 journals, and *J. Archaeol. Sci.* is 15th. The numbers behind the journals' titles represent the counts of published contributions. The search was conducted on 15 May 2018.

Encouragingly, GE is now widely used by planners, policy-makers and the public in both research and teaching in the humanities and social sciences. For instance, Parks [81] used GE to represent the possibility of visualizing the geopolitical, territorial, and structural conditions of the Darfur crisis. Chang et al. [82] proposed using a combination of GE and GIS mapping technologies in a dengue surveillance system for developing countries. Yang et al. [83] mapped the rural population distribution in the Lake Tai basin, Eastern China, based on the VHR imagery from GE. Trujillo et al. [84] used GE to extract fish cages in the Mediterranean Sea and found that the reliability of recent FAO farmed fish production statistics for the Mediterranean as well as the promise of GE to collect and ground truth data. Since the launch of GE in the mid-2005, a steady increase in publications related to ACH applications has been noted (Figure 2). While GE does not provide multispectral information, it allows for rapid surveys and the detection of even small cultural heritage sites and subtle archaeological traces [35,36,85–88], which is a huge step forward in terms of archaeological applications.

3. GE Based ACH Applications

In many ACH applications, GE VHR imagery has already been used instead of high-cost commercial VHR remote sensing data [34–36,52,85–90]. Moreover, GE offers data at diverse scales of interest, from small monuments to archaeo-landscapes, and cultural relics. Following Yu and Gong [43], this review updates and summarizes GE-based ACH applications into five general categories: Visualization and data integration; data collection and exploration, validation and reference; ACH monitoring and assessment for decision-making; 3D modelling for virtual tourism; and communication and dissemination of research results.

3.1. Visualization and Integration of ACH Data

Visualization is a function with a number of purposes depending on which data are to be visualized [43]. These data include not only a digital elevation model (DEM), remote sensing imagery, and thematic layers provided by GE itself, but users' own vectors, rasters, and overlapping 3D models. In the era of Digital Earth and Big Data, a large volume of ACH data will be produced and gathered, so the major problem that faces us at present is how to represent the key information to the public and stakeholders in a simple and plain style. For ACH, written records (e.g., chronology, history, material, and value) and photos are the primary means by which researchers capture information from sites and their surroundings. These types of important information are without strong readability and are thus difficult for the public to imagine and understand. The public prefers to be provided the exact locations of ACH in GE, rather than two-number strings of geographical coordinates. How do we show the information of ACH sites more intuitively for the public? KML is a key tool for visualizing data in 1D/2D/3D/4D in GE.

Geospatial data consist of two parts: Spatial coordinates and property tables. In this context, GE is an excellent tool which offers a "Properties" dialogue box every time a user selects a targeted object. Take the UNESCO-WHC World Heritage Sites (WHSs) list as an example. As of July 2017, 1073 sites are listed: 832 cultural, 206 natural, and 35 mixed properties, in 167 states [91]. Included sites are generally organized and represented in five formats (XLS, GEORSS, RSS, XML, and KML). XLS is the most popular format with the public and scientific communities, especially for statistical analysis of World Heritage Sites [92], and will be updated by UNESCO-WHC after the annual Session of the World Heritage Committee. However, GEORSS, RSS, and XML formats often have substantial content but a counterintuitive interface. Additionally, a KML format was provided by UNESCO-WHC, but the data were only updated to 2014.

In this review, we produced the latest (updated to 2017) WHS list in KML format (KML S1) by coding and extracting the items from the latest XLS sheet data and linking and visiting the photo collections from the UNESCO-WHC website [91]. For instance, the WHS list by country lists Mexico as the home of the seventh largest number of sites with 34. The public then only knows that Mexico has 34 WHSs and can read their tedious descriptions in the XLS file as well as the GEORSS, RSS, and XML files, but it can learn more about sites from the KML file in GE: For example, exact locations, general situations, photos, and spatial distribution features. The Tropic of Cancer effectively divides Mexico into temperate and tropical zones. By browsing the KML file in GE, it can be found that most WHSs are concentrated to the south of the Tropic of Cancer (Figure 4); in particular, the cultural properties and distribution patterns of the sites are maybe closely related to the terrain and landforms [93].

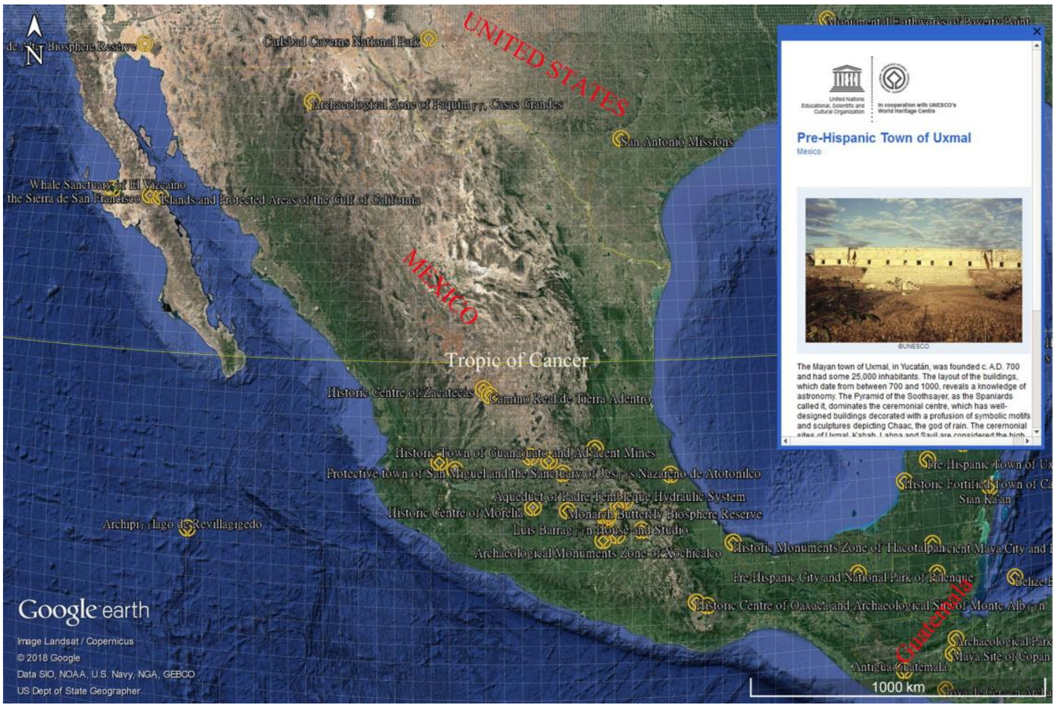

Figure 4. Visualization of Mexico's WHSs in GE. The original EXCEL file can be downloaded from http://whc.unesco.org/, copyright © 1992–2017 UNESCO/World Heritage Centre.

The key advantage of GE is the use of KML to ease the integration of multisource datasets from different providers and simultaneously to visualize and identify relationships for use in subsequent quantitative investigations [43,62]. ACH applications need the integration of heterogeneous georeferenced 1D/2D/3D/4D data from local computers or obtained 'on the fly' from distributed sources owing to the demands of comprehensive archaeological understanding and knowledge discovery. For GE, usually these data are in KML format. Here, this review proposes a case study of part of the Great Wall (Figure 5a) in Northwestern China that was explored in the early 20th century by many famous archaeologists and geographers who made many great discoveries and uncovered its mysteries. The work of these expeditions served different roles and provided clues to researchers seeking to find unknown sites. The most famous explorers were Stein [94] and Hedin [95], and their precious investigation reports and archaeological maps (Figure 5b,c) play important roles in understanding the changes that have occurred in the Middle East and Central Asia in the past century, especially in terms of land use and land cover (LULC) [12,96,97].

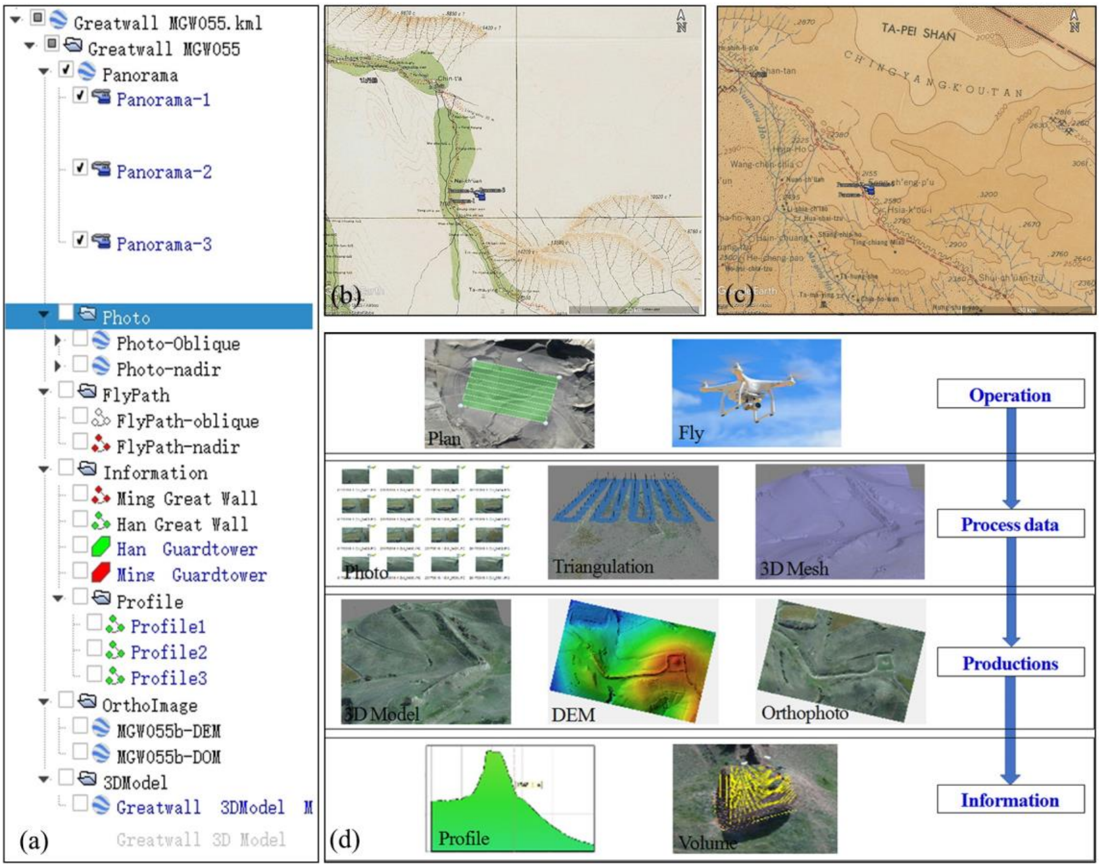

Figure 5. The integration of geospatial data of the Great Wall in Northwestern China. (**a**) The overall tree structure of KML layers in GE; (**b**) the archaeological maps made by Stein [94]; (**c**) the archaeological maps made by Hedin [95]; and (**d**) the operation flowchart for our UAV investigation. We deleted the photo layer in the supplementary file (KML S2) owing to the volume being too large to submit for peer review.

An unmanned aerial vehicle (UAV) investigation of the Great Wall was carried out by the authors (Figure 5d). All of the original and processed data (courses, photos, triangulation, and mesh), final products (orthophotos, 3D scene and DEM) and derivative information (profiles and volumes) were saved in KML format (KML S2). The public and scientific peers can download and reproduce these in order to integrate these data with the archaeological maps. Stein's and Hedin's archaeological maps (KML S2) were used in this case; these can be downloaded from the Japanese National Institute of Informatics (http://dsr.nii.ac.jp). By browsing in GE, it was easy to find that Hedin's archaeological map of our proposed pilot area was more detailed than Stein's (Figure 5b). We were unable to find any marks showing the linear traces of the Great Wall in Stein's map but they are present in Hedin's map (Figure 5c). In future research based on data visualization and integration in GE and the LULC specific situations established by GE VHR imagery, it will be possible to use UAV data and archaeological maps to deduce historical LULC changes in the past century along the Great Wall.

In addition, GE easily allows the public to make a comparison between similar ACH sites in different geographical units or similar sites in a similar geographical unit [12] because the multiple resolution and seamless mosaic remote sensing images in GE provide comprehensive Earth surface background information. In particular, terrain, and geomorphological information as well as land use and land cover [35,52,98] data are included.

3.2. Data Collection and Exploration for ACH Prospection

Investigating known and unknown ACH sites is the initial purpose for remote sensing archaeology, especially in remote and untraversed regions. Generally, spatially explicit ACH data collection requires systematic field surveys equipped with positioning instruments. This can be limited by budget considerations, difficult access, a lack of positioning instruments, or even a lack of positioning signals in densely wooded areas or mountainous regions [36]. Such a data collection process benefits from the use of VHR images in GE that provide local to global coverage [43]. However, it should be noted that the image quality and acquired data may or may not be suitable for quantitative research purposes at certain locations [36,85]. For data collection, in most cases, these images provide useful information directly; but for some cases, image processing is required [36,43].

For ACH surveys at a local scale, GE has usually been used for fine interpretation of small sites or archaeo-landscapes together with GIS tools. Kennedy and Bishop [99] and Thomas et al. [100] used GE VHR imagery to identify archaeological sites in Saudi Arabia and Afghanistan, respectively. Hritz [101] combined GE and declassified CORONA data to survey the cultural relics in the Southern Balikh valley, Syria. Sadr and Rodier [102] found that GE VHR imagery and GIS allowed for detailed studies of the distribution of stone-walled relics in the Suikerbosrand Nature Reserve of Southern Gauteng Province in South Africa. Here, we provide a case study of an investigation of the spatial pattern and morphology of ancient stone tidal weirs (STWs) (KML S3) located on tidal flats of the Penghu Islands, China using GE VHR images from different time periods [103,104]. The STWs, simplified and abstracted as LineString objects, were drawn out in GE Pro. Figure 6 shows a distribution map of the STWs. Compared with costly field and airborne surveys, the GE-based method not only identified 91.04% of STWs from the ground-truthing references but required less time and was more efficient [103]. The arbitrary timing of GE images means that STWs cannot all be observed at the same time. In this case study, over 50 STWs were still missed using GE, mainly due to their being submerged by seawater, and we could not find images acquired at suitable times for them in GE.

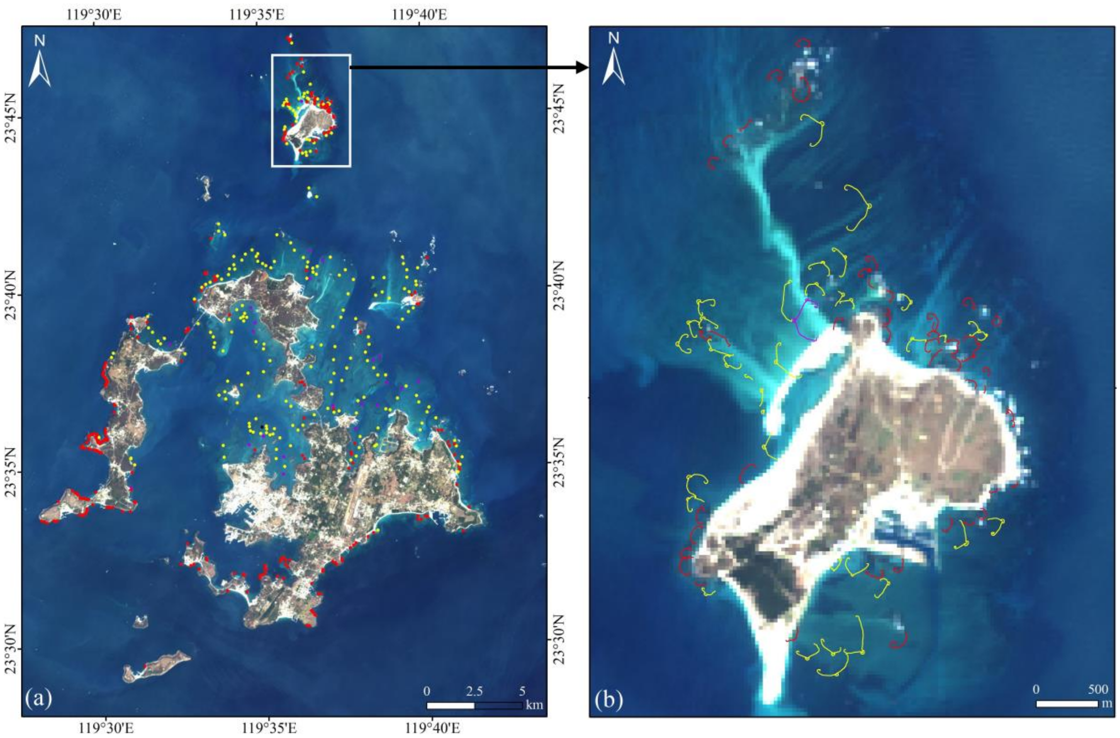

Figure 6. (**a**) Spatial distribution map of Stone Tidal Weirs (STWs)on Penghu Islands, China; (**b**) close-up image of (**a**) in Chipei Island. The red, yellow and violet represent the arched, single-room and double room STWs, respectively. (The base map is the Landsat-8 OLI image, which can be downloaded from http://www.usgs.gov).

For ACH surveys at a regional or global level, GE has generally been used to provide a full-cover inventory of the special ACH sites that are scattered across vast regions or even across borders. For instance, based on visual inspection and interpretation, Stinson et al. [105] used GE VHR imagery to offer a new, large-scale assessment of active and inactive ancient irrigation system of Karez in Central and Southern Afghanistan, providing a major and much needed revision of Karez data that have not been updated in print for 50 years. Olof Pedersén produced a preliminary set of placemarks for GE of a selection of the most important archaeological sites in the Ancient Near East (http://www.lingfil.uu.se/research/assyriology/earth/). Kempe and Al-Malabeh [106] used GE VHR imagery of the Harrat Desert, Jordan, and Saudi Arabia to uncover the structure, distribution, and function of the desert kites, which are prehistoric stone gazelle-hunting structures. Brown Vega et al. [107] used GE VHR images and historic aerial photographs to identify hypothesized prehispanic fortifications in a macro-region along the Peruvian coast. Their remarkable results demonstrate the feasibility, in terms of time and cost-efficiency of using fine spatial resolution imagery that is freely available for viewing in GE. A global inventory of desert kites was released online by an interdisciplinary research team from France [108]. This global inventory, including 5809 inventoried kites, is a freely-accessible work, including published data, personal communications, and investigations done on VHR imagery from GE.

Furthermore, collecting archaeological data from GE VHR imagery is an important task that should be carried out before any further processing [36,96]. Automatic archaeological feature extraction techniques save time and manpower but are not very successful except at an extremely limited range of spatial scales and spectral contrasts [109]. Automatic extraction of archaeological features is not a trivial task due to the complexity and subjective perception of target objects [110]. While automatic extraction is not yet popular, it is one of the major directions for GE archaeology in the future, as in Lasaponara and Masini [111]. All of the above-mentioned case studies found that the use of GE for the data collection and exploration of ACH sites has enormous potential when dealing with sites with diverse scales that are otherwise largely inaccessible on the ground. In short, VHR images captured from GE are only RGB renderings that may not be usable for quantitative research but are still interesting for visual data collection and exploration.

3.3. Validation and Reference of ACH Interpretation

On the one hand, for archaeological remote sensing, GE VHR images have been widely used to validate archaeological research findings derived from medium-high resolution imagery. Similar to data collection, validation of the surface objects presented in the images that are treated as real 'ground truth' should be conducted with care [43] when using GE VHR images. Many ACH applications use these images as ground-truthing data [12,14,89,111–115]. Luo et al. [12] confirmed the Landsat-derived potential medieval post stations in wasteland by browsing and interpreting the VHR images in GE (Figure 7), which is used to digitally reconstruct the royal road to ancient Dunhuang. Tapete and Cigna [115] validated the collapse feature in the citadel of Aleppo captured by Sentinel-2 by using the GE VHR image acquired on the same date, which shows the same collapse feature and allows a finer delineation of the footprint of the damaged area to match the satellite-based assessment [116]. On the other hand, GE VHR images have usually been used to serve as references (corroborative evidence) for supporting research results that were generated from commercial VHR multispectral imagery [12,14,36,89] and SAR images [25,26,117].

Undoubtedly, relative to commercial VHR multispectral imagery, GE is a very effective, low-cost and readily accessible tool that provides a direct perception of the geographical area with a relatively good spatial accuracy [89]. Comparing the VHR SAR images with the GE VHR optical imagery, many of the archaeological features in the SAR are visible also in the visible data, but in some cases are not so clearly delineated [25,26]. Chen et al. [117] identified linear archaeological traces of the Han Great Wall based on 1-m resolution TerraSAR-X Spotlight data, and proposed that SAR remote sensing contributes more to finding buried archaeological objects than optical remote sensing when considering GE VHR imagery. An integration and comparative analysis of the use of optical and SAR technologies in the prospecting of ACH sites will become part of the mainstream remote sensing archaeology.

As we argued at the beginning of this review, ground-truthing is crucial to remotely investigation due to satellite imagery can be deceptive and misleading [12,88]. The further discussion on ground-truthing issue will be given in the Section 5.

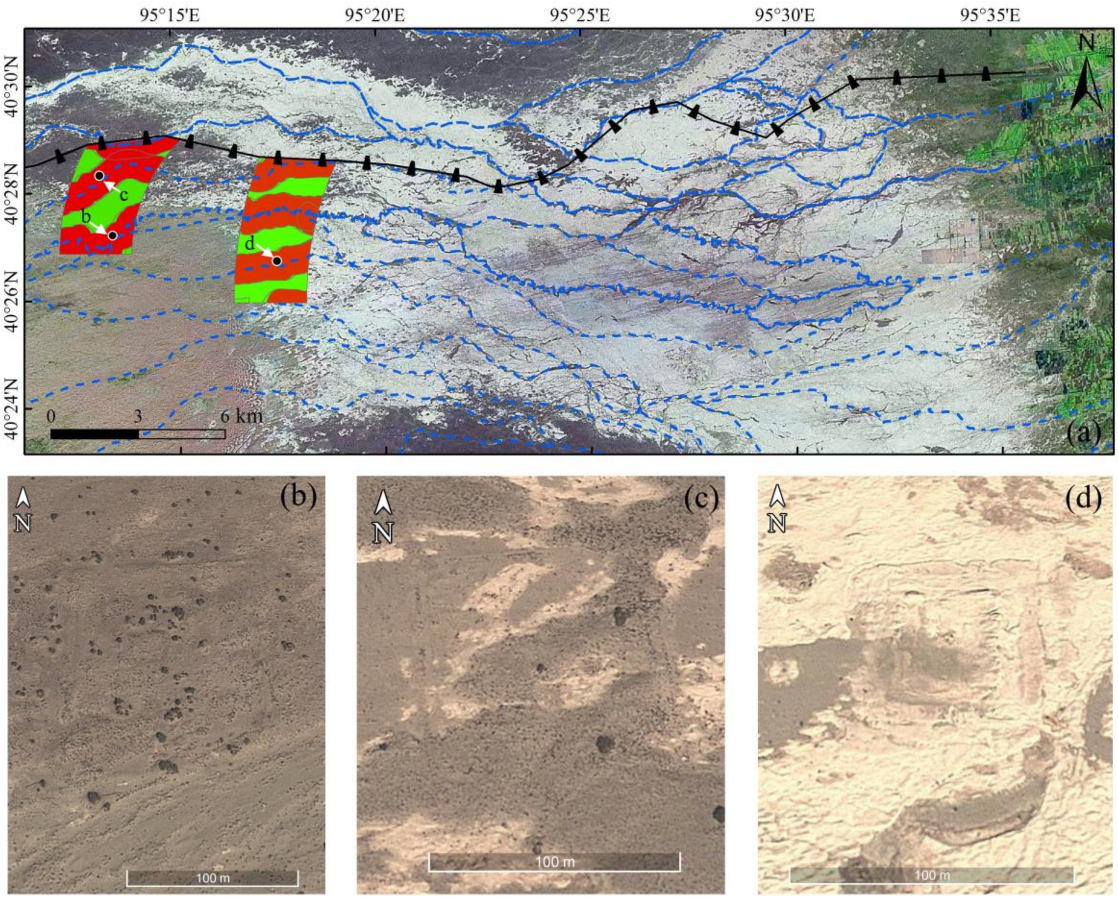

Figure 7. Medieval post stations in Dunhuang. (**a**) Prospective sub-areas to medieval post stations based on Landsat image interpretations and GIS analysis, red and green areas represent the high and low archaeological potential, respectively, blue dotted lines indicate dried and buried channels, and the black line indicates the Great Wall of Han Dynasty; (**b**–**d**) GE VHR images from September 2013 (© 2018 Digital Globe) of post station sites.

3.4. Monitoring and Assessment for Decision-Making Support of ACH Management

For sustainable development and management, change monitoring and assessment of ACH sites is essential for managers and policy-makers. Since the GE 5.0 version, GE has been updated with new features, including a dataset of historical imagery that can be accessed through the "historical time slider" control (Figure 8) [35]. A test of this feature using the Rome Historic Centre revealed imagery going as far back as 1945, but another test viewing Old Peking, showed that 2001 was the oldest image available (Figure 8). Thus, one potential application of GE to ACH site management is the possibility of monitoring and assessing changes over time [35].

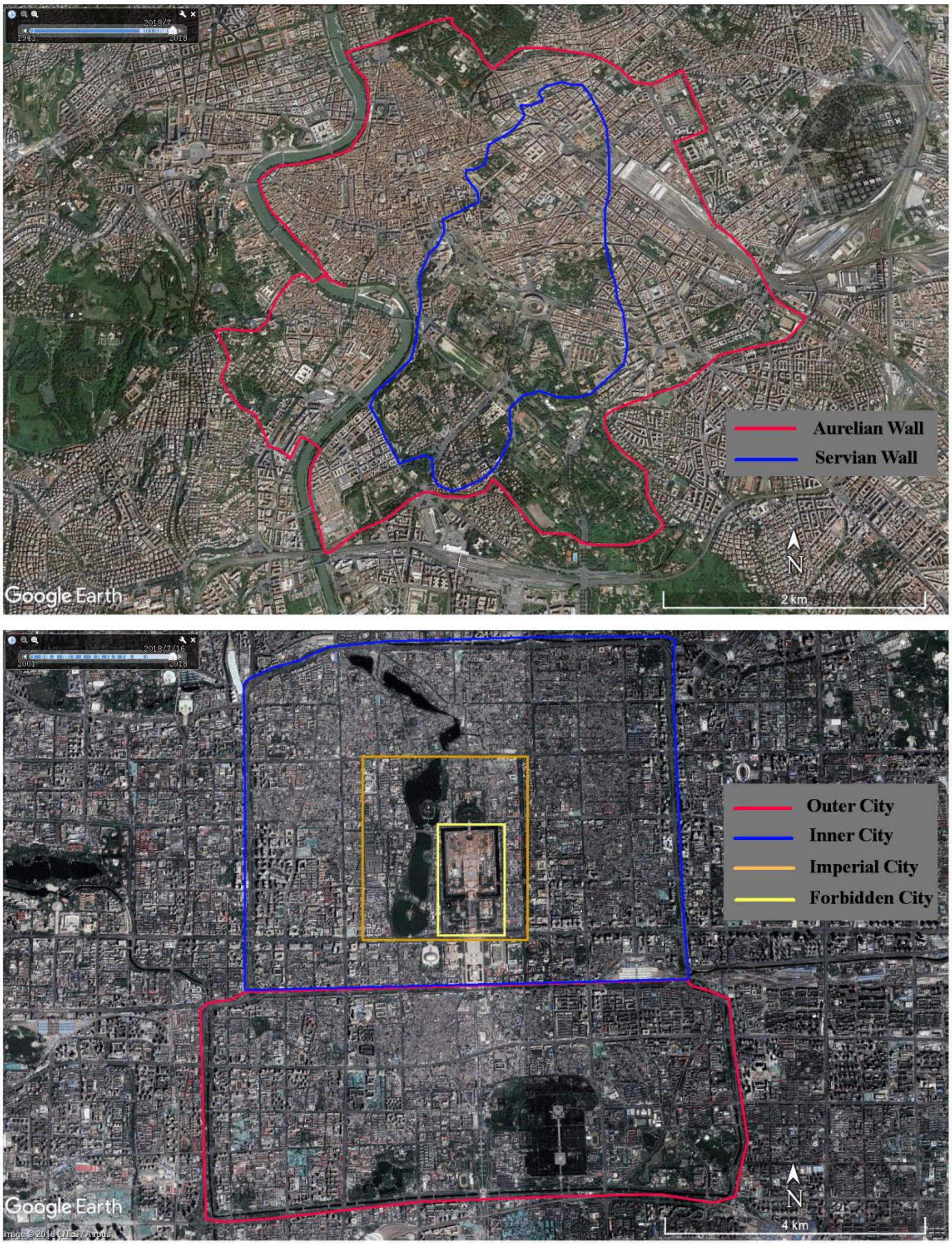

Figure 8. GE Historical image view of the Rome Historic Centre (**top**) and Old Peking (**bottom**) obtained using the "historical time slider". Imagery © 2018 Digital Globe.

GE VHR imagery can be used to monitor land-use and land-cover changes [98,118] and have also been widely used to monitor and assess the changes in ACH sites [35,36]. In this way, GE can help in the understanding of sites and their surroundings because they are able to acquire not only multi-sensor VHR imagery but also long-term time series of historical data. Evidence of looting, one of the main problems affecting ACH throughout the world [111,119–125], is generally difficult to see when standing on a site; however, in VHR remote sensing images, looting pits often appear with great clarity [25,120], and unless they are ploughed over, can remain visible for decades [120]. Lasaponara and Masini [111] proposed an automatic data processing tool for the identification of looting areas in Peru and Syria based on the use of GE images. Contreras and Brodie [121] traced illegal looting at archaeological sites in Jordan and showed that the use of publicly-available VHR data provided by GE allows for the effective quantification and monitoring of looting at essentially no expense. Parcak et al. [124] used GE satellite imagery from 2002 to 2013 to examine archaeological sites across Egypt to map looting trends, and completed a comprehensive report quantifying the total amount of looting in Egypt.

Recently, GE VHR imagery was used to track heritage loss across Syria and Iraq [126–132] and to assess the damage to Syria's WHSs caused by ISIS and the Syrian civil war [128,129,132]. The results of this analysis indicated that more than one quarter of the archaeological sites exhibited severe damage, including five of the six Syrian WHSs and six of the 12 Tentative WHSs [130]. A well-known example is the Hellenistic/Roman site of Dura Europos on the West bank of the Syrian Euphrates (Figure 9). The site was submitted to the Tentative World Heritage List in 1999 but was resubmitted as a joint property with the site of Mari in 2011 [130]. Less than a third to half of the city has been excavated so far. During the three years (2011–2014) that separate the two GE VHR images (Figure 9) that were analyzed, the site was subject to extremely heavy looting. A long history of pre-war looting extending back several decades is visible in an early 2011 GE VHR image (Figure 9a) of the site, but in 2014 (Figure 9b), the site was further damaged by looting, with thousands of new holes visible across the entire site [120]. Most of the public applications capture the perceptual and qualitative aspects of the looting at the site; the professional applications generally focus on the quantitative and rational aspects of the changes. Figure 9b shows that, inside the ancient city wall, the disruption was so extensive that counting individual looting pits was impracticable—the pits overlap so that it is impossible to distinguish one pit from another. Beyond the ancient city wall, the density of looting was lower but still severe, with scores of individual pits scattered throughout the area, as shown in Figure 9b.

Some specialists have attempted to count each visible pit manually [120,121,131,132], while others have sought to calculate the total looted area of the sites [25,130]. We opted for a simpler method in which looting was identified in ENVI 5.3 by using the change-detection tool [133]. Figure 9c shows the changes caused by looting between 2011 and 2014. Furthermore, the results were converted into a KML file (KML S4) for data sharing and communication, to satisfy the demands of public perceptual cognition through browsing the site in GE. Almost the same results were provided by UNITAR's satellite-based assessment, which showed that, within the city wall of Dura Europos, an area of approximately 0.38 km^2 was destroyed by looting and 76% of the walled-city had been damaged by April 2014 [130]. The above results could provide crucial information for the Syrian administration and UNESCO to make the right decisions for protecting the country's heritage, which is still in dire straits. Global communities and organizations condemned ISIS's atrocities, and the danger to Syria's heritage drew international calls for an end to the crisis. UNESCO launched the Emergency Safeguarding of Syrian Heritage Project [134], one of whose aims is to provide technical support for the establishment of a police database of looted artefacts.

Sometimes, essential information or important clues from GE VHR imagery that affects the judgement and decisions of policy-makers is derived. For instance, in the GE VHR image of Dura Europos from 2 April 2014, four vehicles (red circles in Figure 9e) were observed among the ancient Roman ruins near the looting areas, suggesting that the disturbances at the site may have been ongoing at that time. From Figure 4, it was seen that Mexico's WHSs are concentrated South of the Tropic of Cancer. Thus, we can imagine that Mexico's policy-makers may be inclined to nominate new sites that lie to the north of this. Thus, GE can be used to support decision-making by direct ACH data visualization [43].

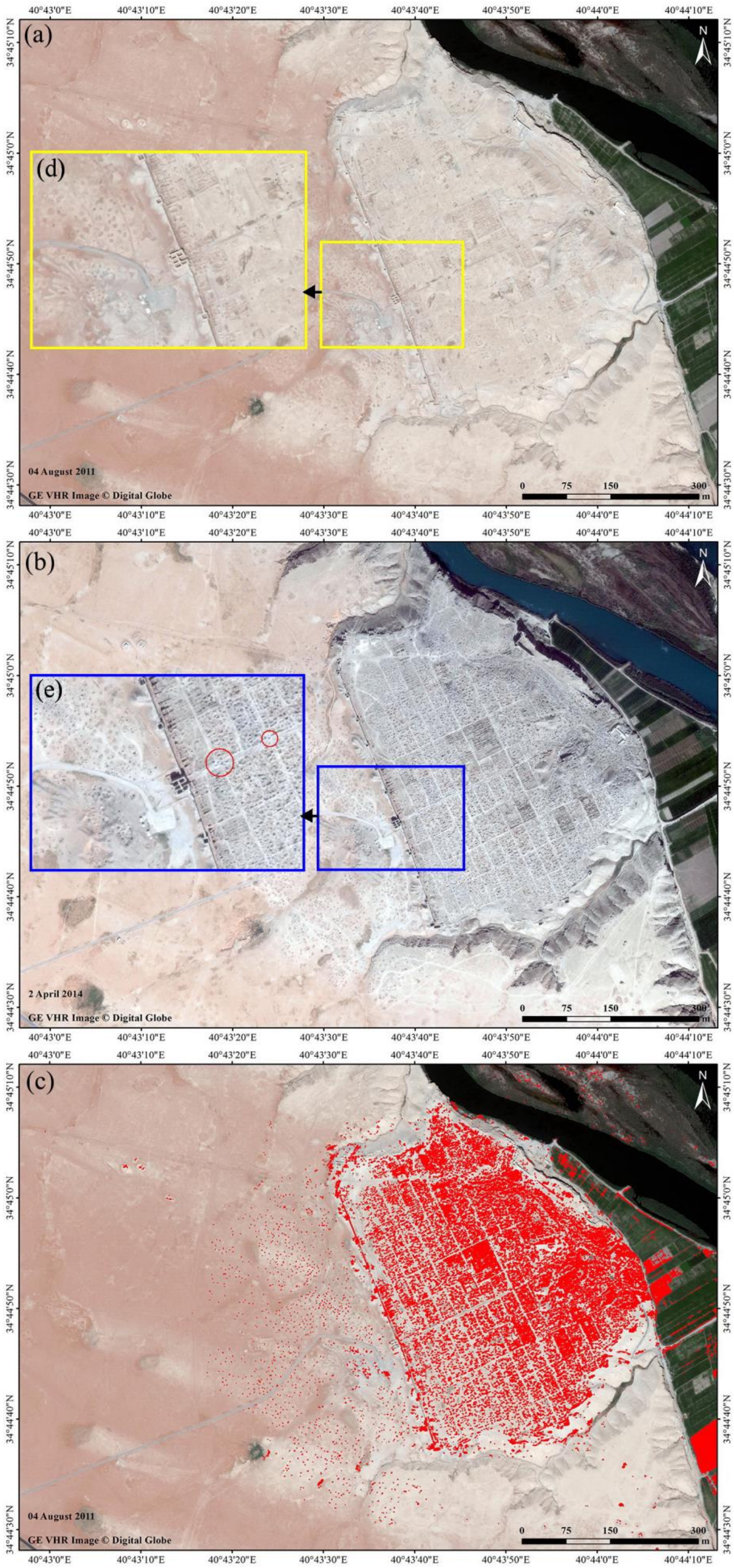

Figure 9. Dura Europos, eastern Syria, as it appears in images from August 2011 and April 2014. (**a**) Dozens of decades-old looting holes are visible in a close-up around the Palmyrene Gate; (**b**) The image from April 2014 shows a renewed phase of severe, war-related looting with fresh pits clearly visible in the same area; (**c**) The GE VHR image from 2011 was displayed with detected looting changes in red; (**d**) Close-up image from 2011; and (**e**) Close-up image from 2014. Imagery © 2018 Digital Globe.

3.5. 3D Modelling and Virtual Tourism at ACH Sites

Two kinds of modelling needs to be distinguished: One is the construction of static 3D models (such as those models in the '3D buildings' layer in GE), another is the modelling of dynamic phenomena/processes [43]. The former is the meaning of 'modelling' in this review. GE is simply based on 3D maps, with the capability to show 3D ancient buildings and structures (such as the Roman Colosseum (Figure 10), which consists of users' submissions using SketchUp, a 3D modelling program software.) Thus, based on the 3D model, virtual tours in GE offer an expanded chance to make ACH sites more accessible for a broader audience [135]. GE Pro Version 7.3 provides several virtual tours as examples. The Forbidden City case was described in this review as a pilot (KML S5).

The user can set up a tour of a set of placemarks and the GE will start a fly-through visit to each site in turn. This is a very useful capability for sharing multiple sites of interest among collaborators. It also has the potential for use in education at a variety of levels. By applying 3D flight tools, archaeologists can enrich a virtual 3D tour of interesting sites by integrating multiple georeferenced thematic digital layers (including remote sensing interpretations, archaeological maps, topographical maps, digital terrain models, historical aerial photos, and field pictures) [136,137]. Beck [86] and Gonzalez-Delgado et al. [138] have given cautiously optimistic overviews of GE, and they see GE as a significant resource and tool for 3D-visualization and interpretation of ACH sites. They highlight as positive GE's potential for providing tours and entertainment to both experts and mass audiences.

Figure 10. A sky-view 3D image of the Historic Centre of Rome (Roman Colosseum-centred view) for ACH virtual tourism. Imagery © 2018 Digital Globe.

It is noteworthy that Google released a virtual reality version of GE for Valve's Steam computer gaming platform on 16 November 2016. GE VR allows users to navigate using VR controllers and is currently compatible with the Oculus Rift and HTC Vive virtual reality headsets [61]. One day, GE VR will revolutionize the entertainment industry and include virtual ACH tourism. In addition, let us not forget that GE Street View displays 360° panoramic street-level photos of selected cities and their surroundings, which are precious materials for virtual tourism. These photos, taken by cameras mounted on cars, can be viewed at different scales and from many angles, and are navigable using arrow icons imposed on them [61]. GE Street View is more applicable to cultural heritage sites in urban areas. GE's Street View application gives 360-degree panoramic photographs of any location in a number of cities and is perhaps the most controversial of Google's projects [34].

3.6. Communication and Dissemination of ACH Data and Results

GE is a powerful platform for communication and dissemination, which refers to the sharing of geospatial data, information, and knowledge with non-specialists or among archaeologists by using proper visualization in KML format, especially in the field of ACH training and education. Conroy et al. [41] laments the late adoption of GIS by paleontologists and proposes that GE might remedy the situation. Ur [87] emphasizes the potential of GE for archaeological research, but most important is GE's usefulness in the classroom—he states that this is its most promising aspect [35].

At present, most ACH applications are centrally focused on GE as a tool for visualization and demonstrate how easy it is to share 1D/2D/3D/4D visual information about archaeological finds online. GE can not only be used to assist, encourage and improve users' experiences in visualization, data collection and integration (http://whc.unesco.org/en/news/570), and for virtual tours (https://www.youtube.com/watch?v=MqMXIRwQniA), but can also be implemented to help archaeologists communicate and disseminate data about interesting targets. Currently, enormous amounts of geospatial data are now available in KML format. On this point, GE has amazing potential for use in ACH from formal applications to popular science. GE is proving to be an innovative and flexible medium for communicating information and awareness about ACH sites. For instance, click on the World Heritage List layer (KML S1) and placemarks will pop up, each marking the location of an included site. Click on a specific placemark, and a pop-up window appears with text and image content about the site (Figure 4).

4. The Merits and Limitations of GE

Several papers have partly discussed the potential, limitations, and ethics of the use of GE for ACH applications [34–36,86–89]. Myers [35] provided an in-depth discussion of the ethical concerns inherent in the use of VHR satellite images, as GE might be seen as a panoptic viewing technology that touches on the issues of privacy, censorship, and sovereignty. Kaimaris et al. [89] made a comprehensive comparative analysis of the archaeological content of the VHR imagery in GE. These authors found that GE is a very effective, low-cost, and readily accessible tool that provides a direct perception of a geographical area with a relatively good spatial accuracy. However, a systematic assessment of the current trends in GE for ACH has not yet been carried out alongside a review of the existing opportunities for other scientific and technological fields in Earth science [43].

4.1. Comparative Analysis with Other Virtual Globes

It is now 13 years since the launch of GE, and a similar period has elapsed since the release of the earliest of what is now a long list of comparable virtual globes, including NASA's World Wind (worldwind.arc.nasa.gov/), ESRI's ArcGIS Explorer (www.esri.com/-software/arcgis/explorer/), Microsoft's Bing Maps (www.bing.com/maps), CAS's Digital Earth Prototype System, Wuhan University's GeoGlobe, Digitnext's VirtualGeo (http://virtualgeo.diginext.fr/EN/), and Unidata's Integrated Data Viewer (www.unidata.ucar.edu/software/idv/) [49]. Virtual globes offer researchers or non-specialists a simpler alternative to traditional GIS tools, leading to increased data sharing while facilitating studies on a global scale [139]. Besides GE, World Wind, and ArcGIS Explorer are the two most widely used globes.

World Wind is different from a 3D globe such as GE because it is not an application. Instead, it is a software development kit (SDK) that enables users to create standalone applications in which users' own data and models can be presented in the context of a multi-resolution model of a globe. Several globes similar to World Wind have been developed, for example, LocaSpace Viewer (http://www.locaspace.cn/index.jsp), Virtual Ocean (http://www.virtualocean.org/) and Geosoft Dapple (http://dapple.geosoft.com/default.asp). ArcGIS Explorer comes equipped with a series of analytic tools via ArcGIS Server, which supplies mapping and GIS capabilities via ArcGIS Online for ESRI's web and client applications. However, while most virtual globes are cross-platform applications, ArcGIS Explorer runs only on Microsoft Windows platforms, requiring. NET and Internet Explorer [43]. World Wind and ArcGIS Explorer, aimed primarily at the scientific community, need professional skills, and experience to design and operate, but GE is easy to use both for the general public and specialists. In turn, compared to World Wind and ArcGIS Explorer, a unique shortcoming of GE is its lack of extendibility, especially for spatial analysis.

4.2. Merits of GE for ACH Applications

It is beyond the scope of this review to describe all of the features of GE. Full documentation, tutorials, and other materials are available at http://earth.google.com. However, several notable advantages of GE for use in ACH applications are detailed below.

(i) User-friendly virtual globe software with an easy-to-use interface. GE provides great opportunities for public participation in archaeological prospection and cultural heritage management. The public can survey and browse the ACH site by using the measuring and flight tools in GE, respectively. All of the targets can be abstracted as geographical objects (points/lines/polygons) by using the geometric tools in GE. Users can directly label interesting features and upload related photos and videos by using the desktop application, even on-the-spot by using the mobile app from a smart phone or pad [140].

(ii) GE has sufficient horizontal positional accuracy for searching and locating ACH sites. An evaluation of horizontal positional accuracies for GE's images gives a 40 m root mean square error calculated from 436 points chosen worldwide [71]. Thus, for archaeological fieldwork, GE can be used in place of Global Positioning System (GPS) instruments as a navigational tool because it provides comprehensive Earth surface background information, especially in the trackless wilderness. It also indicates that GE VHR images are sufficient for site validation, which is a difficult-to-accomplish requirement in large-scale prospecting [43].

(iii) Freely accessible multi-temporal and multi-resolution remote sensing imagery in GE promotes scientific research in archaeological prospection (investigation) and cultural heritage management (monitoring, assessment, and decision-making) by providing base data. The VHR and seamless mosaic remote sensing images in GE have an irreplaceable advantage for archaeological investigation, even on a global scale, which is a cost saving.

(iv) Easy visualization is another significant merit. GE allows simultaneous access to diverse types of data (text, image and video), making it well-suited for the different purposes of ACH applications (management, education, training, and communication). KML, in combination with GE as a visualization platform, can be of great value once archaeological research has ended as it allows researchers to disseminate their results to the general public.

(v) Up-to-date thematic layers deepen the understanding of the ACH site and its surroundings. For instance, the layers of 3D models and 360° panoramic street-level photos in GE could support virtual cultural heritage tourism and find clues that could allow the rediscovery of archaeological knowledge.

GE is well suited, but not perfectly so, for use in ACH applications, especially for quantitative research on a large scale. There exist several limitations: The inconsistent quality of remote sensing images, a lack of metadata for the original imagery, insufficient capability for quantitative measurement, a lack of analytical tools, security, and ethical issues, etc.

4.3. Limitations of GE

4.3.1. The Inconsistency of Remote Sensing Image Quality in GE

As analyzed above in Section 2.1, a widely mentioned inadequacy of GE is that it does not provide universal VHR coverage (Figure 1). While some archaeological prospection might still be possible at lower to medium resolutions [5,9,10,17,141], for most situations, archaeologists' use of GE is dependent on the free availability of VHR imagery [35,36]. Besides, for much of the Earth's surface, GE uses a digital elevation model (DEM) collected by NASA's Shuttle Radar Topography Mission (SRTM) [61]. GE uses SRTM data of at least one arc-second resolution for the USA but three arc-seconds for most of the rest of the world. Therefore, in areas of extreme topography, images may contain a greater distortion error [43]. Another problem is embodied in inconsistent acquisition dates and different temporal frequencies. Despite the sources of VHR imagery in GE (WorldView, GeoEye, SPOT, QuickBird and Pleiades) being extensive, the updating frequency does not meet the demands of urgent ACH applications, for example, monthly archaeological looting change analysis. Updating of undeveloped regions, which is usually the focus of archaeological applications, is often slow (Figure 1), especially in desert areas.

4.3.2. The Lack of Quantitative Measurements and Spatial Analysis in GE

Generally, images from GE are processed for visualization purposes and are not suitable for further analysis because multispectral channels of remote sensing data are not supported [89] and there is then no temporal flexibility in the image acquisition [141,142]. GE images are only RGB composites, so the users are not looking for true DNs of the original images. The NIR band, one of the indicators of crop marks, is also not available and the original spatial and radiometric resolution is reduced [36,89]. Quantitative measurements of geometric and topographic parameters (areas, volumes, peaks, contours, profiles, slopes, aspects, curvatures, buffers, and view-sheds) are not possible without recourse to additional software and datasets. In other virtual globes, such as LocaSpace Viewer, those parameters can be computed. Spatial analysis plays a key role in ACH applications [12,38,41]. Until now, GE has supported only a small portion of what a full GIS software package does in its applications. GE's functionalities need to be integrated with analytical tools for spatial analysis while facilitating the sharing of geospatial data among its users [43].

4.3.3. Ethical Issues Related to the Use of GE in ACH Applications

GE could be described as a sort of 'global panopticon' [143] in which the viewer sees all but those who are viewed see nothing and, importantly, do not know if and when they are being watched [34]. Three key ethical issues of privacy, censorship, and copyright are raised through the availability of GE, which shows VHR imagery of the houses we live in and sensitive facilities equally. Through GE, users now have affordable and uncomplicated virtual access to military and security regions and to private land [52]. Myers's [34] and Thomas et al.'s [100] surveys are two projects that show how GE can be used by archaeologists to investigate areas that are usually off-limits to the archaeologist [35]. In addition, the sovereignty of geospatial ACH data is often obscured and overlooked [34–36]. The usefulness of KML in effective data sharing and visualization is obvious. However, the associated risks need to be considered before applying these techniques [43,52,144].

5. GE-Based ACH Applications: Trends and Perspectives

5.1. Towards Big Remote Sensing Data

GE continually updates its coverage, and there has been a marked improvement since its release in 2005. The problem of low-resolution coverage is also gradually becoming less of an issue [35]. GE's optical images cannot be used in quantitative ACH applications (e.g., the spectral analysis of crop marks), but are still interesting for archaeological object recognition [111] and visual applications (e.g., pattern recognition and computer vision methods). If GE provided metadata for optical imagery (coordinates, date/time, spectrum, and solar elevation angle), users could mine more of the ACH objects from the imagery. Taking archaeological shadow-marks at a low solar elevation angle for instance, the shadow length of the archaeological remains could be measured in GE, and if GE provided the solar elevation angle, we could accurately calculate the height of the remains.

At the same time, we need to acknowledge openly that VHR SAR imagery remains an issue. For buried ACH features, GE VHR optical imagery generally fails to reveal significant detail, which can negatively affect archaeological interpretation [115]. If the dates of VHR SAR data were nearly simultaneous to those of the VHR optical images in GE, they would be ideal for further analysis of the complementarity of optical and SAR data in a specific case [25,117], especially for buried features. To solve the data inconsistency problem, a conventional approach is for users to build their own databases using multiple, credible datasets [43]. For ACH applications, such databases can be built by integrating satellite remote sensing imagery, aerial photography, UAV data, on-site measurements, and digital historical maps that require further processing. Considering the uneven coverage of historical imagery in GE, where necessary, a combination of GE and other remote sensing data, such as CORONA imagery [113,145] or historical aerial photos [114,146], for example, could be used to track changes over long time periods. This use of GE and other data could make major contributions to how assessments and interventions at threatened archaeological sites are made [36,100,130,147]. Erosion [148], encroaching development (e.g., urbanization and agricultural land use) [5,105,149], looting [131], and other taphonomic processes [34,150] could be tracked and quantified.

Most recently, Google launched a new online product—Google Earth Engine (GEE)—which makes petabytes of trusted satellite imagery available worldwide [43,46]. While the freely-available Landsat and Sentinel imagery provided within GEE is not of sufficient spatial resolution to adequately conduct the precise ACH analyses described here in References [46,151], the cyber-infrastructure provided within the GEE still represents an advantage compared to similar, intensive analyses carried out on less powerful machines with other geoprocessing software. Liss et al. [151] evaluates the potential role that GEE can play in the future of archaeological research using additional WorldView-2 VHR imagery. In the future, if original VHR imagery could be made freely accessible in GEE, as with today's Landsat imagery, a new chapter for ACH applications will open.

5.2. Towards an Analysis-Enhanced Virtual Globe

An indirect but simple approach to improving the analytical capability of GE is taking ACH outputs from external analysis tools to do further archaeological visualization and documentation [41,82,102,103]. Novel tools and add-ons to existing software packages for spatial analysis that can export their analyses to KML files are increasingly being developed [43]. For instance, users of ESRI's ArcGIS and ITT's ENVI can now export or convert their vector and raster layers directly into the KML format. The analytical capabilities of GE can also be augmented through Web Services integration [42,46]. This integration will provide analysis-enhanced virtual globes to help the understanding of ACH sites and their surroundings. The primary uses of Web Services in ACH applications aim to provide data, data analysis, and interactive control.

The Open Geospatial Consortium (OGC) [152] publishes a suite of specifications for standard Web Services (Web Map Service (WMS), Web Feature Service (WFS) and Web Coverage Service (WCS), Web Processing Service (WPS), and Catalogue Service for the Web (CSW)) for accessing geospatial data. These Web Services make a large number of geoprocessing functionalities easily accessible to researchers as if they were from their local resources [43]. The WMS is the most popular and is also the simplest since it produces images that do not require further interpretation. Blower et al. [153] proposed a demonstration system that enhances WMS support in GE by combining a periodically refreshed NetworkLink with an interactive website that is displayed in GE's built-in web browser to provide extra controls and displays effectively. While it is still an early prototype, their system has the potential to turn GE into a fully-featured WMS client. Web services integration is more suitable for the general public because it combines the visualization and communication power of GE with the powerful analysis functionalities of geospatial web services to help users investigate various ACH sites in an environment that provides natural and intuitive user-experiences.

Noteworthily, some virtual globes provide the means to have their analysis capabilities extended through custom plug-ins. ArcGIS Explorer can be extended through a. NET SDK. NASA World Wind is an open source and can be written in Java SDK, allowing easier customization and even embedding of the World Wind application in other pieces of software, including websites [153]. GE is a closed-source application and does not currently have a mechanism for the community to develop plug-ins to add functionality beyond that provided by KML.

Besides, the newly released GEE allows for the processing, analysis, and interpretation of remote sensing data using high-performance tools based on online parallel-processing platforms. GEE is a cloud-based platform providing access to petabytes of satellite imagery for global-scale analysis that is in development [54]. Combining a massive database with the parallel computation power of Google's infrastructure facilitates, a quick and easy analysis of satellite data at any scale, opening new avenues for research in a number of fields [154–156]. GEE has crucial potential for supporting specialists with automatic classification, detection, and documentation at a global scale—tasks that are often onerous and expensive. While limited cases of ACH research [46,151] are available currently, this is a promising tool that both the public and specialists could apply at any scale.

5.3. Towards a Harmonious Virtual Environment

GE has low barriers to entry, which leads to ethical issues not only in ACH research but in all application fields. As it is easy to operate and free to access by the general public, GE might aid looters as much as it helps archaeologists [87] since placemarks in GE are easily shared online and can be loaded with relative ease on to a handheld GPS device. Public users and even specialists will very likely placemark sites of interest or suspected interest in this virtual globe, which might reveal confidential information consciously or unconsciously. Take the declassified nuclear weapon test sites as an example: Most of these are located in remote no-man's lands, such as the Nevada Desert (USA), Semipalatinsk Steppe (former Soviet Union), Taklamakan Desert (China), Great Victoria Desert (UK), and Sahara Desert (France) [157], which are often hotspots of public or professional browsing for archaeological purposes [158,159]. The fact is that GE VHR images of those secret facilities have caused much concern among governments that feel threatened by such exposure [35].

There are two suggestions on how to control and solve this issue: One is to affirm copyright or sovereignty; the other is to strengthen management. With regard to the copyright issues, Google, as an example, released permission guides for using remote sensing imagery and geoinformation from GE and other related products. For a single KML file provided by institutions or individual suppliers, adding appropriate copyright text or watermark images into content as comments is recommended by Yu and Gong [43]. In terms of risk management, more prescriptive approaches (e.g., morally or legally binding rules and standards), which guide or drive the presentation of visualization material according to shared principles or standards [144], should be designed to provide safeguards against or limits to threats to visualization and communication in GE.

5.4. Towards a Down-to-Earth Archaeological Tool

Undoubtedly, GE is a very effective, low-cost, and readily accessible tool that provides direct perception of the ACH sites' geographical situations with a relatively good spatial accuracy. It is the major reason that GE was widely opened to the public and specialists. In addition to concerns over security and ethical issues, over-reliance on GE VHR remote sensing imagery might lead to the danger that archaeologists become too remote from the people that they are researching [34,35,160]. The characteristics of archaeological features strongly depend on vegetation cover and phenology, pedology, soil types, and topography [14,96]. It can be said that archaeological features create spatial anomalies, but those that have spatial anomalies may not be the archaeological features. After all, a remote sensing image is both an abstraction and a particular, situated representation [161–163].

For example, in May 2016, a 15-year-old Canadian teenager, William Gadoury, claimed that he discovered a lost Mayan city in the southern Yucatán Peninsula in Mexico using ancient star maps and GE VHR images [164]. However, several archaeologists and remote sensing experts have expressed scepticism at Gadoury's findings, saying that the feature shown in the satellite-based photos, lacking ground-truth investigation, is merely an abandoned corn field based on the experience of their previous Maya research projects [165]. What is more, they argue that the Maya people, although good astronomers, probably did not choose to settle in areas based on the positions of the stars. However, there is no denying that the teenager's discovery is a square-shaped mark resulting from a spatial anomaly in the forest cover.

At least three points can be learned from the above mentioned fierce controversy: (i) GE is a powerful tool for archaeological prospection in remote and unexplored regions; (ii) historical materials (written records, ancient maps, oral stories and legends) are crucial clues that should be investigated before archaeological investigation of unknown sites is carried out; (iii) ground-truthing is the key to remote sensing archaeology, and researchers have to be able to confirm what they are identifying in a satellite image or other type of scene. GE is not a straightforward substitute for field archaeology and should ideally be integrated with ground-truthing and expert knowledge both to the public and to specialists. Where this is not possible, caution must be used when putting forward interpretations of sites and features.

Thus, each spatial anomaly observed should be ground-truthed and assessed to be a positive or negative identification by the presence of ancient material remains [32,107]. Generally, spatial anomalies marked in GE as placemarks are exported as a KML file. This file can be converted and imported into GPS instrument [107], which is used to navigate to the anomaly. False positives can be defined as anomalies that, when ground-truthing, were not ACH sites. False negatives can be defined as failure to identify positive anomalies using remote sensing imagery. It is certain that GE alone cannot identify all ACH sites in a given region. Take mountainous areas as an example, due to the existence of shadows and terrain distortions, the anomalies often cannot be identified from remote sensing imagery but can be identified in field survey. Those field anomalies can be considered as a measure of false negatives. The GE based archaeological prospecting is ideally a two-pronged approach that entails image interpretation followed by ground-truthing, or field survey of anomalies [107,163].

For ground-truthing, the Unmanned Aerial Vehicles (UAVs), ground spectroscopy, geophysics prospection, and boring survey can be used alone or in combination to valide the results of GE based ACH applications. In addition, it is worthy to note that many small, weak, buried, specific architectural, and (sub) surface details are not detectable in satellite remote sensing imagery viewed in GE [107]. UAVs can be used to collect centimeter-level VHR data that is typically captured at the site or site scale to support the detailed mapping of remains either on the surface or with some surface expression e.g., sub-surface remains affecting spectral response or resulting in topographic features [166]. Field spectroradiometers can be used to provide calibrated and accurate reflectance measurements since these instruments are often accompanied by a calibrated Lambertian surface [167,168]. For instance, in order to develop specific linear transformations for the enhancement of crop marks, vegetation, and soil using multi-spectral satellite images, Agapiou et al. [169] proposed an alternative methodology based on simulated data taken from ground spectroradiometer. Multi-frequency Ground Penetration Radar (GPR), as a popular geophysical tool, can produce 3D full-waveform maps of the subsurface [14,166]. Kadioglu et al. [170] used polarized microscope, confocal Raman spectroscopy and GPR methods, to identify the buried remains, rock types, and minerals in Turkey. Archaeological boring can be used to map the stratigraphic sequences on the basis of color, compactness, and the inclusions contained in the soil, and then can be used to detail confirmation of the results produced by the remote sensing and GPR surveys [171].

6. Conclusions

GE, an outstanding demonstration of virtual globes, provides users a simpler alternative to traditional GIS tools, leading to increased visualization and communication of ACH geospatial data while facilitating research both at the local and regional scales. GE is of particular interest for specialists and the public as it combines three key components of archaeological research: Objects, space, and time. GE provides long time-series of free-access VHR imagery. Multisource datasets in KML format can be easily integrated and shared in GE. Since the introduction of KML 2.3, georeferenced and textured 3D models can be added to any KML file and visualized in the virtual context provided by GE. Furthermore, the fourth dimension—i.e., time—can be added by using time stamps or time spans. In the era of Digital Earth, sharing of geospatial information about ACH sites could extend well beyond scientific communities to the general public, which has very limited or no technical skills and computing resources—the vision of an information food chain extending all the way from science to policy-making seems almost within reach.

GE provides advanced new tools and procedures for carrying out archaeological prospection and assisting cultural heritage management. This review has presented not only a comprehensive review of the application of GE to ACH applications, but also of the merits and limitations of using GE. It has been demonstrated that GE has a strong ability to document ACH and provides new insights for scientific management and use. The role that GE plays in the field of cultural heritage tourism as a virtual platform has also been discussed. A wide range of applications supports the great potential of GE, but at the same time, the variety of cases presented is evidence that there is still need for harmonization efforts. The current generation of GE has already established an interactive 1D/2D/3D/4D virtual environment that enables the public and archaeologists to conduct their activities and research in a more natural and intuitive environment. For future ACH applications, it can be expected that GE will become even easier to use, providing practical and efficient tools with excellent analysis capabilities from local to global scales.

Supplementary Materials: The following are available online at https://zenodo.org/record/1438214#.W64S2LgRWUk, KML S1: Data Visualization of World Heritage Sites, KML S2: Data integration of Great Wall, KML S3: Investigation of Stone Tidal Weirs in Penghu Islands, KML S4: Looting changes in Dura Europos between August 2011 and April 2014, KML S5: Virtual tourism of Forbidden City.

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