

# Chapter 4

## GIS: An Array of Tools for Archaeology



### Preamble

A geographic information system (GIS) is a software system that provides a framework for gathering, integrating, managing, and analysing spatial data. As we have noted earlier, it is often useful to look at multiple satellite images for a given site. These could be images taken by the same sensor on different dates (see Sect. 2.3.6), or from different sensors (see Sect. 3.2.1). GIS software organizes information into layers based on geospatial location, allowing the analyst to integrate data from multiple images, as well as spatial data from other sources such as ground truthing,<sup>1</sup> field observations, old maps, and other historical spatial records. In order to integrate spatial data, it is obviously necessary to ensure that all this data is *georeferenced* (i.e. it is expressed in a common geospatial coordinate system) so that features in one layer are as accurately aligned as possible to their footprint in other layers (Fig. 4.1). Thus, any geospatial analyst must be proficient in georeferencing. In the first part of this chapter (Sect. 4.1), we will discuss *why* georeferencing can greatly benefit archaeological and cultural heritage research. In the second part, we will discuss *how* to georeference the type of spatial data we typically encounter in this domain. We will split this discussion into three parts: georeferencing satellite images (Sect. 4.2), georeferencing historical spatial records (Sect. 4.3), and discussing other kinds of spatial analysis that adds value to research in cultural landscapes (Sects. 4.4, 4.5 and 4.6).

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<sup>1</sup>By ground truthing we mean making direct observation to verify a feature already detected in satellite imagery, whereas field observation includes observing features afresh on the ground (not necessarily as an act of verifying a predetermined feature).



**Fig. 4.1** Georeferenced Survey of India map overlaid over a satellite image. The spatial alignment between the two layers can be seen in the shape of the river

## 4.1 Why Is Georeferencing Useful?

An immediate benefit of georeferencing spatial data is that it facilitates precision measurements. However, the accuracy of these measurements depends on the accuracy of georeferencing and the spatial resolution of the images being used. In the context of studying past settlement patterns, typical measurements of interest include: the latitude and longitude of a specific point of interest (e.g. one that has been or will be investigated at ground level during a site visit), the dimensions of a linear or curvilinear feature (e.g. length of a wall or a street), the area of a feature with well-defined boundaries (e.g. a fort or a tank), and the orientation of a structure or a layout (either relative to other features, or to fixed directions such as geographical north).

Another benefit of georeferencing, particularly for large archaeological explorations or excavations, is that it provides a context in which the location of all material found at the site can be recorded. This systematic recording of spatial metadata is called *geotagging*, and it is a valuable book-keeping procedure (see Sect. 4.4). For example, for the nineteenth-century CE excavations, at the Buddhist monastery Nalanda in Bihar, there are no records of where many of the sculptures and other samples were found. Our study has identified several unprotected mounds in the vicinity of the protected site. We have collected a handful of brick samples from some of these mounds for carbon dating analysis, and each of these samples has been geotagged so that we can associate it with the structure it was part of (Das et al. 2019). Apart from physical materials, spatial metadata can also be gathered for other data collected at the site. For instance, Malik et al. have conducted ground penetrating radar (GPR) scanning of two sites within the fortified area of Vigukot in

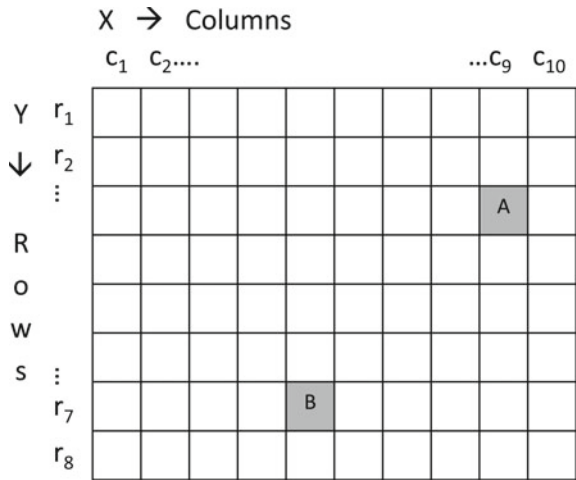
the Great Rann of Kachchh and have identified buried walls that are not visible on the surface at all (Malik et al. 2017). By georeferencing this data, the existence of these walls can be incorporated into the larger geospatial documentation of this site.

Finally, having a georeferenced backdrop of the site and integrating it with other geotagged artefacts and georeferenced layers allows the analyst to visualize some or all the layered spatial data in the form of visualizations such as maps and 3D views, to view the distribution of features within a site’s spatial context (at various scales), to examine the spatial relation between specific features and propose hypotheses for such a relation. Such an integrated information system can assist an analyst investigating cultural heritage by shedding new light on well-studied problems and creating opportunities to ask new questions. We present some examples to illustrate the power of such visualizations. For instance, the density of the artefacts recovered from the archaeological excavation at the ancient Roman site Porolissum in present day Romania has been visualized as a heat map, which has enabled researchers to understand the spatial layout of human activity in the precinct (Opreanu and Lăzărescu 2015). Similarly, the locations of early, mature, and later period Harappan sites were visualized against a background of coarse-resolution multispectral satellite imagery. By doing so, we were immediately able to observe that mature period sites lay in dense clusters along the palaeochannels of what was once a major river (often referred as the River Sarasvati), whereas later period sites clustered closer to the Indus valley. This study used data from two independent sources, the first being georeferenced satellite image showing palaeochannels and the second being geotagged points from latitudes/longitudes available in published literature. As a result, we were able to propose a novel hypothesis: the palaeochannels were active during the mature Harappan period, but they subsequently dried and the lack of water forced later settlements to move closer to the Indus (Fig. 4.2) (Rajani and



Fig. 4.2 Regional distribution of Mature Harappan and Late Harappan sites

**Fig. 4.3** Pixel A at column 9 row 3 and pixel B at column 5 row 7



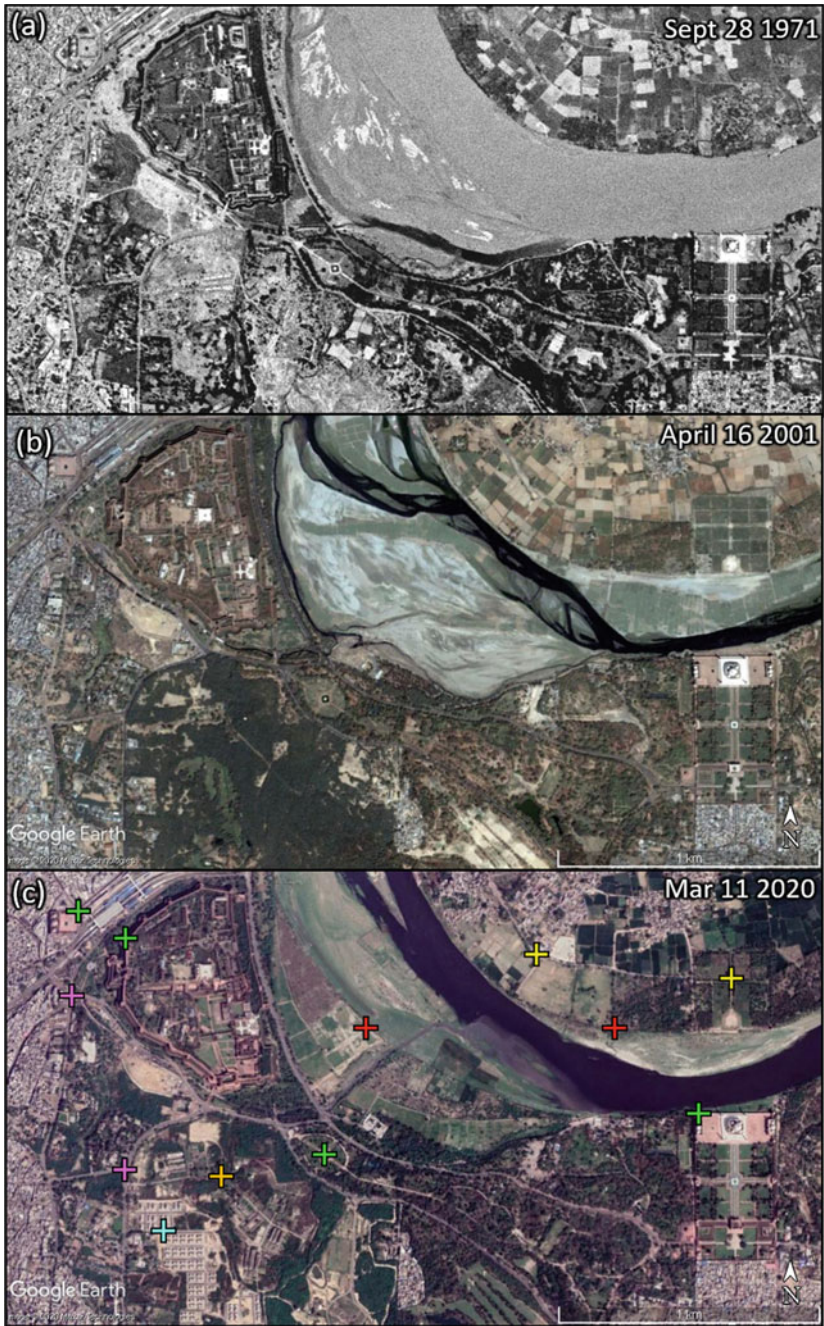
Rajawat 2011). Similarly, by observing the distribution of manmade tanks and a palaeochannel which once drew water from a nearby river in Nalanda’s spatial context (both identified on different images), we have hypothesized a much larger spatial extent for the Nalanda monastery as suggested by other historical records (Rajani 2016).

## 4.2 Georeferencing Satellite Images

As we shall see, there are multiple geospatial coordinate systems. Hence, even when certain spatial data such as modern satellite images are already georeferenced according to some coordinate system, they may need to be reprojected or even regeoreferenced in another system for compatibility with other layers of spatial information that the analyst wishes to examine. Older satellite images (e.g. Corona satellite images) must be georeferenced before they can be integrated.

An image is a matrix or *raster* of pixels. When a raw image is opened as a raster in GIS software, each pixel is assigned two coordinates: its column number and its row number (Fig. 4.3). The purpose of georeferencing is to transform the image coordinate system to a map coordinate system (i.e. each pixel will be assigned the latitude and longitude of the location it represents). This process requires the analyst to manually provide map coordinates for a small number of pixels (at least 4 to 5), known as ground control points (GCPs). The analyst chooses GCPs from features that can be uniquely identified in the *target* image (i.e. the image to be georeferenced) whose geographic coordinates are known or can be determined from another *source* such as an existing map, or ground-based GNSS measurements, or from geoportals like Google Earth, Google Map, Bhuvan, etc. A chosen GCP should be a sufficiently prominent feature that is not subject to seasonal changes so that it





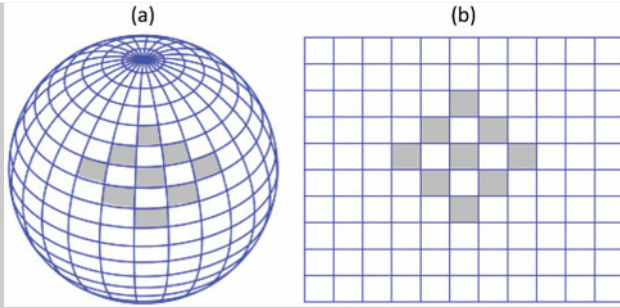
**Fig. 4.4** Environs of Taj Mahal and the Fort at Agra **a** Corona satellite image; **b** and **c** images from two different dates, Google Earth. Several GCPs are marked in (c)

can be identified unambiguously in both the source and the target images. Further, it should be an immovable (preferably permanent) feature, at least over the period between the dates of these images. For instance, Fig. 4.4 shows three images covering the same area. Figure 4.4c has several points marked in crosses of different colour: the green crosses are well-defined corners of structures and pink crosses are road intersections. Both these features are visible in all three images. Hence, if any one of these was a source and the other two were target images, these points would serve as good GCPs. In contrast, the cyan cross represents a structure and the orange cross represents a road intersection that is only visible in Fig. 4.4c. Hence, these features are inappropriate as GCPs for the other two images, even though these are arguably “permanent” features. The yellow crosses represent features that are identifiable only in Fig. 4.4b, c, so these could be used as GCPs if either of these was the source and the other was the target image. However, these would not be useful GCPs if Fig. 4.4a was the target image. The red crosses are on the bank of a meandering river. Since rivers change course, such features are non-permanent features and are therefore not good GCPs. In general, it is better to have a small number of highly accurate GCPs than several inaccurate GCPs. Naturally, the larger the number of highly accurate GCPs, the better the positional accuracy.

After selecting several accurate GCPs, GIS software allows the analyst to assign each GCP a specific latitude and longitude and select references such as the coordinate system, datum, and projection. Given these assignments, the GIS software can automatically compute the latitude and longitude for the vast majority (often millions) of pixels according to one of several image transformations.

Since the earth is not a perfect sphere or even a perfect ellipsoid, there will always be some error in translating image coordinates to real-world coordinates. This error may be smaller for certain transformations. The simplest transformation is a first-order polynomial transformation, which can shift, scale, and rotate images. Linear features in the original image remain linear under such a transformation. If the original image is distorted in more complex ways (e.g. if it is a hand-drawn map), it may be necessary to use higher-order polynomials to correct for such distortions. In general, higher-order polynomial transformations require more GCPs.

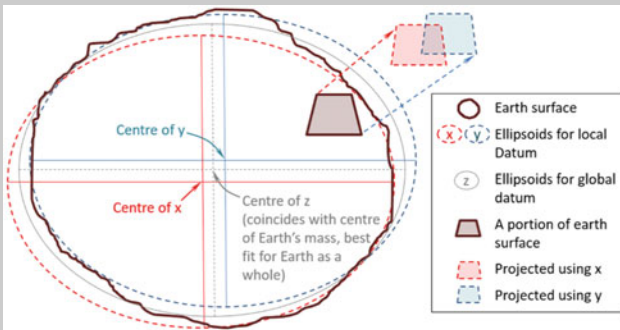
**Box 1** Coordinate system: coordinate systems enable layers of geographic data to use common locations for integration. A coordinate system is a reference system used to represent the locations of geographic features, imagery, and observations such as GNSS locations within a common geographic framework. There are two basic types: geographic and projected (Fig. Box 1a)



**Fig. Box 1** a 3D Geographic and b 2D projected coordinate systems

. The former uses a three-dimensional spherical surface to define locations on the earth, where a point is referenced by its longitude and latitude values. The latter is defined on a flat and two-dimensional surface that is based on the grid of a spheroid or ellipsoid, where locations are identified by  $x$  and  $y$  coordinates on a grid, with the origin at the centre of the grid.

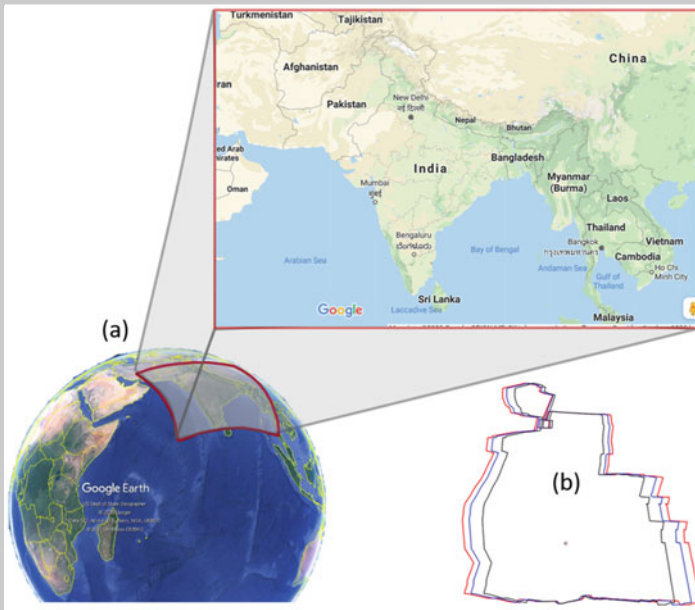
**Box 2** Datum: a datum is a system which allows latitude, longitude, and height to be calculated for any location on the earth's surface. If the earth had been a perfect ellipsoid, this calculation would have been quite simple. Unfortunately, no ellipsoid model fits the earth precisely. Hence, geodesists have traditionally used several different ellipsoids, called local (or regional) datums, each of which is accurate only for certain regions. Figure Box 2



**Fig. Box 2** Diagram showing global versus local ellipsoids. The misalignment between the red and the blue trapezia is due to differences between the two local datums

uses an exaggerated illustration to show how two different local datums *X* and *Y* align closely with different parts of the earth’s surface. Outside these regions, two different local datums can disagree by over 100 m, which is unacceptable. Thus, global (or geocentric) datums such as World Geodetic System 1984 (WGS 84) have been developed (Fig. Box 2). As their name suggests, the centre of global datums coincides with the centre of earth’s mass, and they provide a good fit for the earth as a whole.

**Box 3** Projection: the earth is curved, whereas maps are flat (Fig. Box 3).



**Fig. Box 3** Diagrams showing **a** projection from a curved to a flat surface; **b** differences between the boundary of Nalanda’s core zone depending on the choice of projection

Projection is the mathematical process of flattening out the earth onto a piece of paper or computer screen, which uses the latitude and longitude “drawn” on the surface of the earth using a chosen datum. The illustration of Nalanda’s core zone (discussed in Sect. 6.2.3) in Fig. Box 3 shows the distortions that can arise due to different projections in multiple layers.



### 4.3 Georeferencing Historical Spatial Records

In Sect. 4.1, we have discussed several advantages of georeferencing spatial information. For some sites, we are fortunate to have historical spatial records in the form of old maps, archaeological reports, travellers' records, literature, and epigraphy. While it is tempting to try and georeference all such records, this should be avoided when they lack spatial accuracy. In this section, we will discuss examples of records with sufficient accuracy to warrant georeferencing, how to georeference such records (when appropriate), and how to leverage spatial information from historical records with poor spatial consistency.

The idea of representing geographical environments in written forms dates to at least ancient Greece. While early maps were allegorical, the development of geometry had a significant impact on mapping. Greek scholars used geometric principles and techniques to determine the shape and size of the earth and to determine the relative positions of environmental features. Geometrical concepts also led to the development of locational reference systems, such as latitude/longitude. In classical cartography, the positions of stars were used as reference points (Berggren and Jones 2000). The next major revolution in cartography was the trigonometrical survey, where elevated locations on the ground were used as reference points (Keay 2000). Modern mapping technology such as GPS uses the location of satellites relative to specific reference points on earth to locate positions and measure distances (Williams 1994). There were very few accurate copies of early maps (and hence many are lost forever). By the 1900s, however, the development of printing and photography made reproduction far easier and cheaper.

While analysing historical maps, it is necessary to be aware of the methods used in creating them, because each of these methods has limitations that must be accounted for during georeferencing. Maps are historical documents and the standards for producing them (such as what features to include—or even exaggerate—and what to ignore) have evolved over time. Such inconsistencies can pose a challenge (Gupta and Rajani 2020a).

#### 4.3.1 *Maps Made by Trigonometrical Surveys*

Among historical maps, those made using trigonometrical survey and vertical orthographic projection (top-down view) are generally the most spatially accurate: the locations, shapes, and proportions of features they depict are often consistent with identifiable features in georeferenced satellite imagery.

Triangulation was used as a method for drawing local maps to scale in Europe as early as the fifteenth-century CE (Harvey 1987). In 1533, the Dutch mathematician Gemma Frisius published a booklet proposing triangulation as a method for making regional maps. This idea was implemented by cartographers across the Netherlands, Germany, Austria, and England (Andrews 2009), and Willebrord Snell, another

Dutch mathematician, gave us the modern systematic use of triangulation networks (Kirby 1990). By the middle of the seventeenth-century CE, the first such maps for sites in India were created by the Dutch East India Company for their colonies, which included Cananor (Kannur), Cranganor (Fort of Kottupuram south of Kodungalur), and Coylan (Kollam) along the coast of modern-day Kerala (Asia Maior 2006). Over the next century, cartography evolved from producing local maps—including maps of cities and towns of India such as Masulipatnam (Beveridge 1900) and Madurai (Jennings 1755a, b), see Figs. 2.14 and 2.19, by the British and of Pondicherry (*Plan de Pondicherry* 1741) by the French—to maps of whole countries, including France (1745), Great Britain and Ireland (1783 to 1853), and India (1802 to 1871) (Andrews 2009). The latter study, known as the Great Trigonometric Survey of India, served not only the political need of demarcating British territories but also advanced scientific understanding by measuring the height of several Himalayan mountains (including Mt. Everest), and advancing our knowledge of the shape of our planet by carefully studying the earth's curvature along meridian arcs (Keay 2000).

Countries started establishing agencies to standardize mapping practices, such as the Survey of India (SOI) in 1767, the US Geodetic Survey, 1807, Principal Triangulation of Britain began in 1791. These standards evolved in several stages before modern digital maps became the norm. For instance, the shapes of features such as roads, settlement layouts and fort walls in maps made under the aegis of Survey of India can be considered spatially accurate from the nineteenth century onwards, even though standards continued to evolve well into the next century. It is important to keep this in mind when examining maps from this period, as the following examples will show. In 1870, the SOI published a map of Agra, the city that is home to the Taj Mahal, which marks several features with high spatial accuracy, including the river, ravines, ditches, monuments, and localities. However, the map does not mark the two-tiered city walls, which other sources confirm were present at the time (Suganya and Rajani 2020). Similarly, an early twentieth-century SOI map of Bangalore marks *karez*. This terminology, which is of Persian origin, suggests underground tunnels to supply water. However, there are no references to *karez* in the textual literature of this region, or even in other maps of Bangalore from the late eighteenth, nineteenth, and early twentieth centuries. Our investigation into this inconsistency has revealed that, at the time, SOI used the term *karez* to mark any gravity-based underground water porting system (Suganya and Rajani 2018).

Revenue survey maps of India to meet the needs of constructing canals, railways, roads, etc., were separately published (Thuillier and Symth 1875), but in 1878, the SOI took over responsibility for surveying and publishing all maps of India for both civilian and military purposes (Wheeler 1955). The *Manual of Surveying for India...* laid out the rules regarding drawing, finishing, and publishing of maps, stating that all the elements on ground should be marked neatly and clearly, and the symbol should represent and imitate the form and appearance at first look (Thuillier and Symth 1875). Military maps would mark all means of communication (such as railway lines, roads, trails, paths, streams, rivers, and canals), types of shelter for the troops (cities, towns, villages, and isolated houses), sources of water supply (smaller streams, lakes, ponds, large springs, and wells), sources of fuel (woods, orchards, crops, and grass

land), and obstacles to the movement of the troops and form of the ground that are required by the army (Thuillier and Symth 1875; Stuart 1918). Thus, it stated that maps published by the SOI should depict accurate and clear topographical details of all natural, economical, built, transportation, and communication features (Thuillier and Symth 1875; Wheeler 1885).

However, in 1905, a committee consisting officers from civil, military, and the SOI along with advisors from Ordnance Survey of Great Britain reviewed existing maps of India from various circle offices and found that they were deficient in topographical details. In addition, there were inconsistencies in the variety of information they contained and the way in which this information was depicted (Longe 1906). The committee drafted policy and guidelines for rectifying the same (Wheeler 1955). The policy recommended preparing a series of colour maps for the whole of the Indian subcontinent in “one inch to a mile” (1:63,360) scale within 25 years, marking heights in intervals of 50 feet, and using a uniform system of symbols for the whole of India, Baluchistan, North-West Frontier Province, and the adjacent countries (Longe 1906). This system was followed, with minor modifications, until WWII (Wheeler 1955). After India’s independence, the SOI catered to the mapping required to meet the needs of defence, planners, scientists, and for land and resource management. It produced maps in 1:250,000, 1:50,000, and 1:25,000 scales.<sup>2</sup> From the 1980s onward, the SOI has ventured into the phase of generating a digital topographical database for the entire country for use in various planning processes and the creation of geographic information systems.

### 4.3.2 *Eighteenth and Nineteenth-Century Maps Made Using Other Methods*

Many maps created in the Eighteenth and nineteenth century used a mixture of survey methods. For example, distances between important landmarks may have been measured using triangulation, whereas distances between less important features were recorded as estimated walking distances. These methods have very different margins of error, ranging from a few metres to several kilometres depending on the scale of the map (Hesse 2016). For this reason, such maps are often distorted by attempts to georeference them using standard methods that take all spatial information into account. For such maps, it is important to perform georeferencing using only the well-surveyed points. As an example, let us consider Alexander Cunningham’s *Sketch of the ruins of Nalanda* from 1871 (Fig. 4.5a), one of several such site maps he made in the second half of the nineteenth century. The sizes of each archaeological mound marked on the map and the proportion of distances between them are to scale when compared with respective features identified on georeferenced DEM and Google Earth images (Fig. 4.5b, c). In contrast, the shapes and sizes of the water bodies—Gidi Pokhar, Pansokar Pokhar, and Indra Pokhar—and the roads/paths are

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<sup>2</sup><http://www.surveyofindia.gov.in/pages/view/10-about-us>. Accessed 12 May 2020.

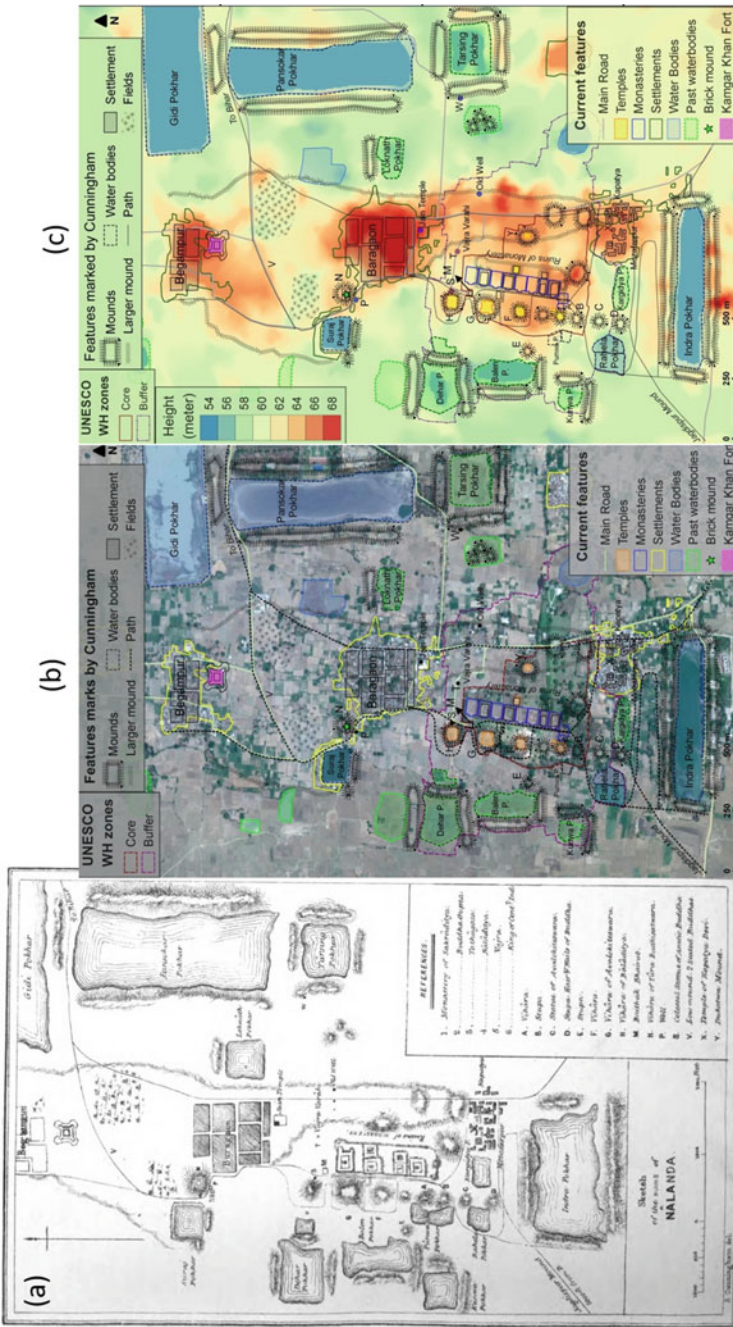


Fig. 4.5 a Sketch of the ruins of Nalanda (reproduced from Cunningham 1871, Plate XVI); b features from the sketch overlaid on a Google Earth image; c the same overlaid on a DEM

filled in the interim spaces. Thus, if we georeference this map using archaeological mounds as GCPs, we will find far less distortion than if we used road intersections or the corners of water bodies. However, even the former approach is challenging since mounds are not one-point features. Instead, we suggest the following approach for such maps. We begin with a georeferenced satellite image of the site. Next, we identify a few reliable points from the map and mark these as a vector layer over the satellite image. (Hence, these points acquire coordinates from the underlying satellite image.) Finally, we use these as anchor points and trace the remaining features from the map by comparing them with visible features on the satellite image. Note that this can be a laborious manual process, but we have found the trade-off between effort and accuracy to be acceptable. In case of Cunningham's Nalanda sketch, we first recognized that the mounds he identifies as H, G, F, A, and Y correspond to the subsequently excavated temples 14, 13, 12, 3 and the Sarai Temple, respectively. We were then able to correlate features C, D, X, and N on Cunningham's sketch with unexcavated mounds identified in the vicinity of the site. Cunningham's features M and T correspond to shrines that are currently used for worship. Having fixed these points, we drew vector shapes to match their depictions in the sketch. Thereafter, the similarities in the arrangement of waterbodies, roads, and settlements became conspicuous. We traced these one by one.

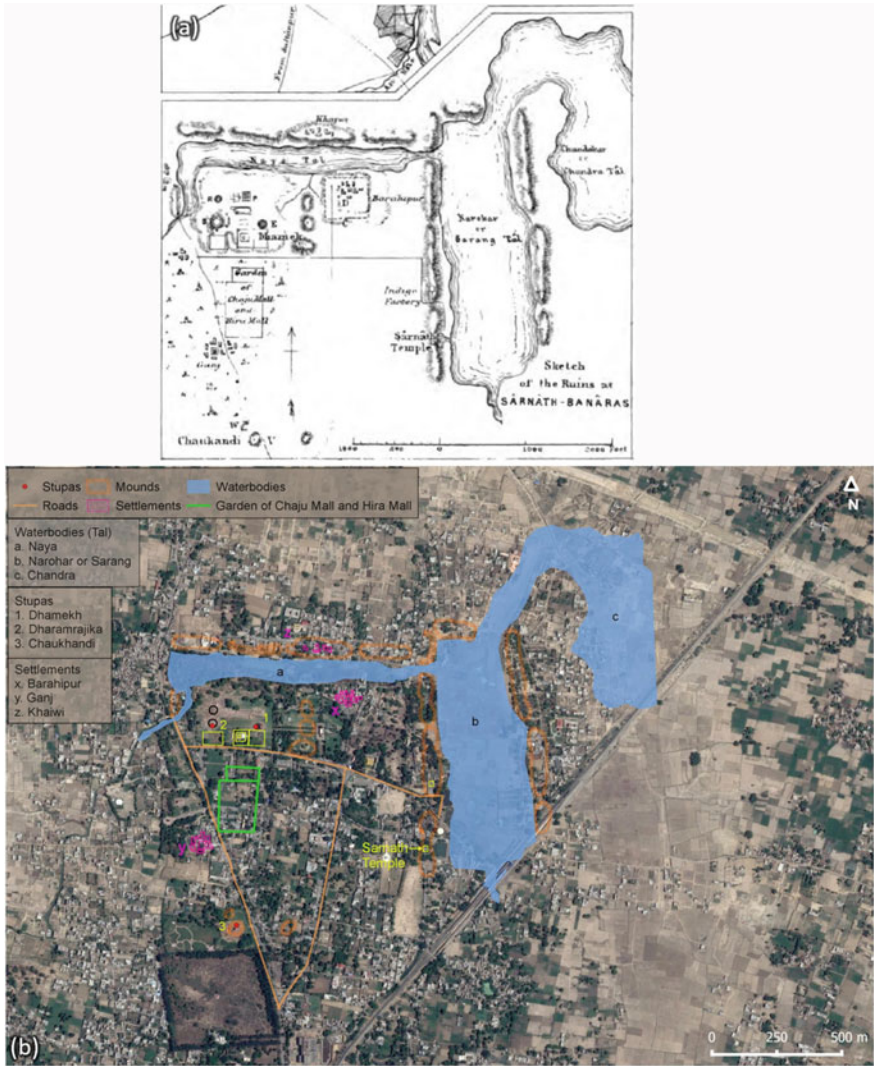
This kind of spatial accuracy in archaeological features depicted in the site maps or sketches made by Cunningham is consistent across the sketches he made of various sites. Figure 4.6 of Sarnath is another example, where the location of Dhamekh, Dharmarajika, and Chaukhandi stupas marked as mounds in Cunningham's map and the location of Saranganatha temple was used to first fix the reference between the sketch and Google Earth imagery. With this in place, the shapes of water bodies and road became conspicuous. We were then able to mark several of the oblong mounds around the three connected water bodies. Finally, we were able to visit these locations for verification, and we found that several of these mounds still exist.

A large set of Cunningham's maps for sites across north and east India were published in the early reports of ASI. By understanding their limitations, choosing GCPs, and tracing features with care, valuable spatial information for these sites can be extracted from such maps if one is willing to invest in the manual effort.

### 4.3.3 *Sea Charts and Maritime Maps*

Portolan charts or sea charts also fall into the category of historical spatial records. These navigation maps were made in Europe from the thirteenth-century CE onwards because major trade routes used the sea, marine channels and navigable rivers. Portolan charts were based on realistic descriptions of harbours and coasts as suggested by the word *portolan*, which comes from the Italian adjective *portolano* meaning "related to ports or harbours" (Rajani and Kasturirangan 2013). These charts identify relatively permanent features such as forts, temples, and hills that were visible on the coast at the time along with coastal geomorphological features such





**Fig. 4.6** a Cunningham’s sketch of the ruins of Sarnath (reproduced from Cunningham 1871, Plate XXXI); b the same overlaid on a Google Earth image

as river-mouths, mud-flats, spits, and bays. An example of a Portolan chart of the seventeenth century of the present Tamil Nadu coast is shown in Fig. 4.7. The coastal structures marked on this chart are also visible on Google Earth and Bhuvan satellite imagery. Section 2.3.7 discusses a portion of this Portolan chart which shows details of Mahabalipuram which aided in understanding why the site had the toponym Seven Pagodas. These charts and the features marked in them (coastline, places, hills, buildings, and trees) are often not to scale. But these were made very systematically



**Fig. 4.7** **a** Dutch Portolan chart (1670) from the archives of the Royal Geographical Society, London; **b** the corresponding coastal stretch on Google Earth marking a few common locations

with the then state-of-art techniques. We believe that these charts represent a largely untapped resource of immense value for studying coasts. One can derive more meaningful information from these charts if they are analysed in context of the status of knowledge in relevant fields at the time, and with awareness of the limitations in the methods used for creating them (Gupta and Rajani 2020a).

#### 4.3.4 *Paintings and Freehand Drawings*

There are several historical records that present spatial information graphically, but in a manner that is too inaccurate for georeferencing. Nevertheless, for sites where no other forms of spatial records are available, it is sometimes possible to extract valuable information from such resources. The analysis tends to be very different for each site, but we can articulate two general principles. First, even if the analyst cannot trust the proportions and distances depicted in these maps or paintings, the *relative arrangements* of features (particularly neighbouring features) are often reliably captured. Second, features common to multiple historical spatial records can help establish valuable spatial information, even if these records are individually

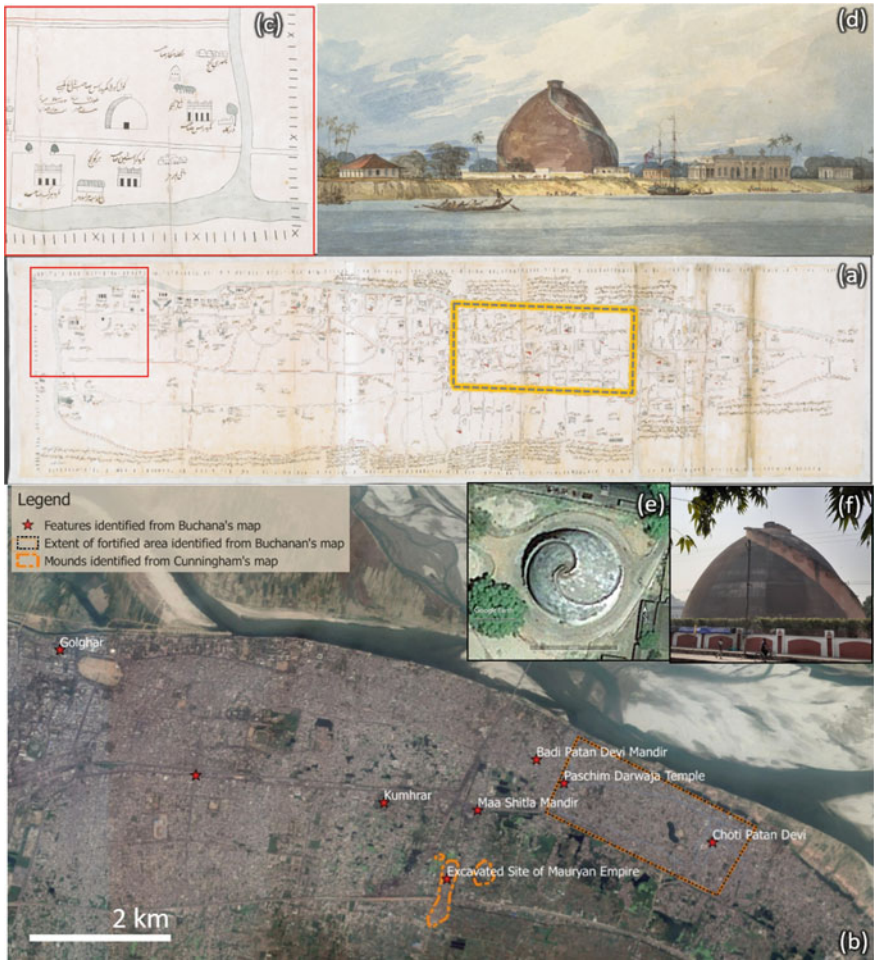
spatially inaccurate. We illustrate these principles with two examples that also highlight the site-specific nature of the analysis one must expect in settings with limited accuracy of spatial data.

**Patna:** among Francis Buchanan’s diaries from the Bengal survey (1807–2014) is an unpublished map from 1812 of Patna, today the capital of Bihar state in India (Buchanan 1812) which was made by an assistant and has annotations in Persian (Jackson 1925). Patna is depicted as a linear settlement running along the bank of the River Ganga. The map marks a rectangular fort north-east of the settlement (see Fig. 4.8a), several roads, temples, and important landmarks. At ground level, it was difficult to discern the fort even when Buchanan visited. He records: “the fort in the north-east corner of the city is now so overrun with modern buildings that its form can be no longer distinguished, nor could I perceive any remains, except some old gates”. Buchanan also noted an inscription on the fort wall attributing its erection to Feroz Jung Khan (Jackson 1925), although Cunningham later stated that the fort was built by Sher Shah Suri (a theory which supports Cunningham’s argument that Patna was Palimbothra based on renovation of the old ruined fort by Sher Shah Suri) (Cunningham 1880). However, Cunningham does not provide a map or any other spatial evidence for where this fort was located. A comparison of the map (Fig. 4.8a) and the satellite image (Fig. 4.8b) reveals substantial changes to the land-cover. As a result of these changes, it is impossible to identify a sufficient number of GCPs to georeference this map.

In fact, the only structure we can identify with some certainty is Golghar (Brown 2005), a dome-shaped granary<sup>3</sup> built in 1784 that is maintained by the Directorate of Archaeology, Bihar (see Fig. 4.8c, e, f). Extracting further spatial information from such maps necessarily involves a degree of guesswork. On the satellite image, we can identify the location of a temple that bears the name *Paschim Darwaza* (western gateway). Although there are no remains of the fort in its vicinity today, we can surmise from the temple’s name and from the location of the fort’s western gate relative to the river and Golghar as depicted on the map that this temple was near the western gate. As noted in Sect. 2.3.3, roads tend to develop adjacent and parallel to fort walls, and we find such a road near the *Paschim Darwaza* temple leading to the river. In fact, we can identify roads that may have corresponded to all four sides of the rectangular fort (Fig. 4.8b). As further confirmation, the rectangular area within these roads is also slightly higher than the surrounding area (see the DEM in Fig. 4.9), consistent with the hypothesis that the development in this area sits atop the remains of a rectangular fort.

Thus, despite the lack of accurate spatial information in this map, it is valuable for analysis. Note that the map does have a rough scale along its edge (Fig. 4.8a, c), with the distance between evenly spaced cross marks subdivided into ten segments by vertical marks. The accuracy of this scale is questionable, and the map does not mention the unit of distance. However, thanks to the preceding analysis, it is possible to test the accuracy of this scale, for instance, by comparing ratios between the fort’s length, breadth, and the distance between Golghar and the fort’s western wall as

<sup>3</sup><http://yac.bih.nic.in/Da-02.htm#Golghar>. Accessed 12 May 2020.



**Fig. 4.8** **a** Plan of Patna from Buchanan’s record (1811–2012) with the fort marked in yellow (© British Library Board; WD2090, 2090); **b** the corresponding region on Google Earth showing Patna and the features identifiable from the plan; **c** a portion of the plan showing Golghar; **d** a painting from 1814 showing a view of Golghar from the river; **e** Google Earth imagery of Golghar; **f** a recent ground photo of Golghar

represented on the map against the same ratios as measured on the georeferenced satellite image. If these ratios prove to be similar, our confidence in the spatial fidelity of this map would grow and could lead to further insights.

A painting of the Golghar (Smith 1814) dating from 1814 shows the view from the river as well as several other buildings around the domed structures which are also marked on the Persian map (Fig. 4.8d). Using these as pointers, we could identify the extent of Patna when Buchanan visited and also the fort marked in the map (Das and Rajni 2020).



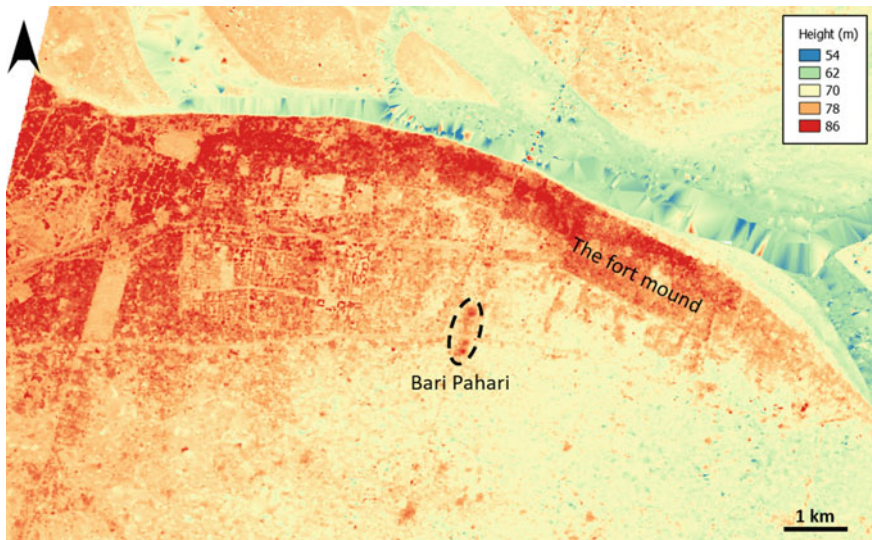
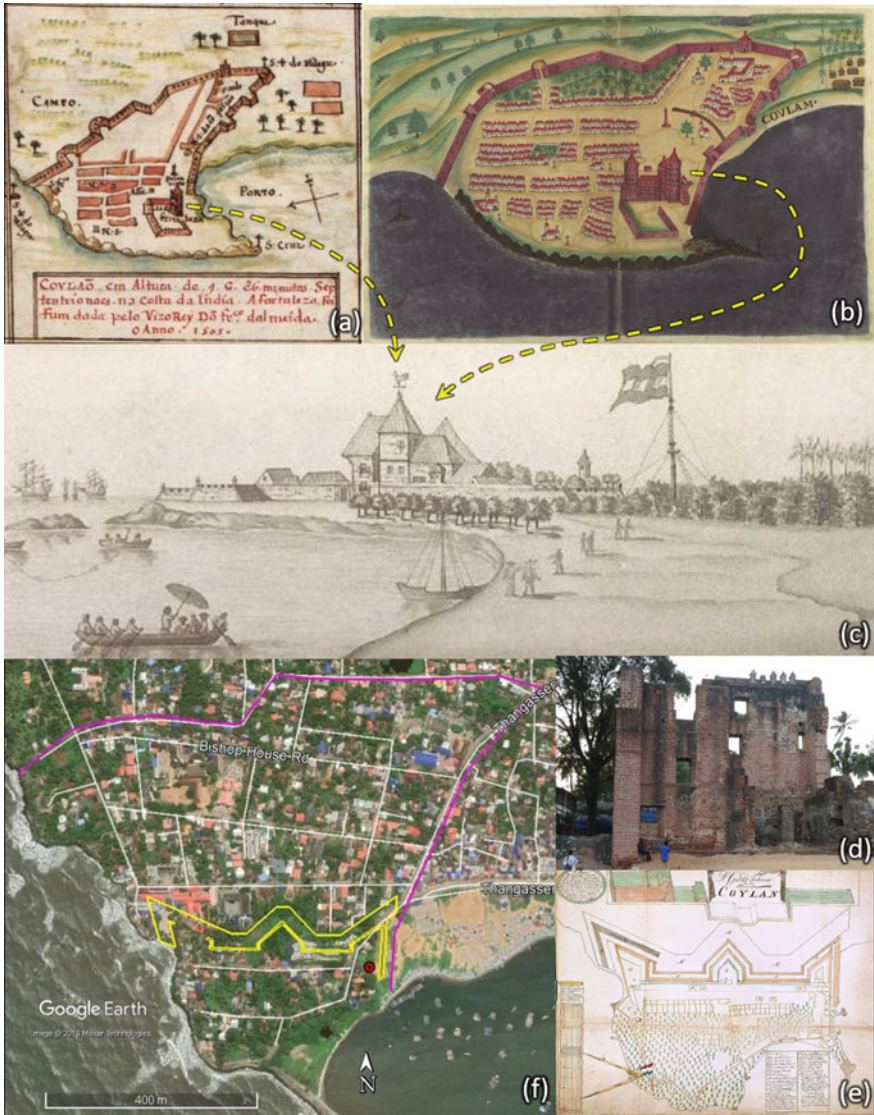


Fig. 4.9 DEM of Patna showing the elevated area of the rectangular fort

**Kollam:** two Portuguese atlases dating from 1630 and 1635 illustrate several port sites on India's west coast (Albernaz et al. 1630; Bocarro 1635). The forts and other buildings are depicted in an oblique or isometric view. Both these atlases have almost the same set of sites but the latter, probably used the former but is not a facsimile, and both are not to scale. Figure 4.10a shows the port of Kollam (*Covlao*) from the earlier atlas and Fig. 4.10b shows the same port (*Covlam*) from the later atlas. The former map includes details such as the title, labels, and direction, whereas the latter omits these but shows greater architectural details. Figure 4.10c is a pen and brush drawing entitled *View of the fort at Coilan* by Johannes Rach, made between 1760 to 1780. This drawing shows the bay as viewed from the east (facing west), centred on the three-storeyed structure that is also prominent in Fig. 4.10a, b. Based on this evidence, we hypothesize that this corresponds to the three-storeyed ruins of the central tower (Fig. 4.10d) of the Fort St. Thomas (Forte de São Tomé, also known as Tangasseri Fort) protected by the Archaeological Survey of India (Innes 1997). The location of this tower is marked with a red circle in the satellite image Fig. 4.10f. We also have a planimetric Dutch map made in 1687 by Hans Georg Taarant/Tarand and Laurens Nicolaesz Duyrendaal (Fig. 4.10e) (Taarant and Duyrendaal 1687).

Here again, the available historical spatial records are too inaccurate to georeference. However, since we know the coordinates of the three-storeyed structure in these figures, we can look for patterns in satellite imagery to identify the walls of the inner fort (Fig. 4.10e) and the outer fort (Fig. 4.10a, b). The moat surrounding the inner fort has left traces in the form of positive crop marks (Sect. 2.3.2), but these are challenging to identify because several modern buildings obscure the shape. However,





**Fig. 4.10** **a** Map of *Covlao* in Albernaz et al. (1630) (Geography and Map Division, Library of Congress, USA); **b** a map of *Covlam* in Bocarro (1635) (Biblioteca Nacional, Portugal), **c** the drawing *View of the fort at Coilan* by Rach (1760–80) (National Library of Indonesia); **d** the ruins of Fort St. Thomas in Tangasseri, Kollam, photographed in Dec 2018; **e** a map of *Coylan* in Taarant and Duyrendaal (1687) (Nationaal Archief, Netherlands); **f** Google Earth, Maxar Technologies, 10 June 2018, the fort from **e** is marked in yellow, the wall from **(a)** and **(b)** is marked in pink, and the location of the structure in **(d)** is marked with a red dot

we were able to confirm our hypothesis when we visited these locations for ground-truthing and found evidence of ruins of the fort wall and adjacent depressions of the moat (Gupta and Rajani 2020b). We were unable to detect crop or soil marks corresponding to the walls of the outer fort. However, the pattern is well preserved in the roads (shown in pink) in Fig. 4.10f, including the distinctive V-shaped indentation seen in Fig. 4.10a, b. As noted in Sect. 2.3.3, a road may merely run parallel to (not on top of) former fort walls. Considering the proportions of distances from various parts of the inner fort, we believe that the roads highlighted in pink run outside the walls of the outer fort.

Our analysis of Kollam demonstrates that historical paintings such as Fig. 4.10c are valuable sources of spatial information. For sites in India, we believe that the wealth of paintings and drawings made in the eighteenth and nineteenth centuries CE (most famously by Thomas and William Daniell; Mitter 1977) are a largely untapped resource.

### 4.3.5 *Textual Sources*

We briefly note that valuable spatial information can sometimes be recorded in textual form. While textual descriptions of features rarely mention geographical coordinates, they can refer to nearby features whose locations can be ascertained. As an example, Buchanan noted in 1812 that to the west of a tank called Dhigi, on the outskirts of Nalanda, he saw a large mound with fragments of bricks. He added that on the north end of this mound was the village of Begampur (Rajani 2016). Based on this textual evidence, we have identified this feature as the squarish mound to the north of Nalanda seen in Fig. 3.16c.

## 4.4 **Geotagging: Conducting Field Surveys and Integrating Field Data**

As noted in Sect. 4.1, geotagging can be more valuable than a “mere” book-keeping exercise. Hence, this section summarizes points that must be kept in mind while conducting field surveys to maximize the benefits for subsequent spatial analysis.

Objects that can be identified on georeferenced satellite images are effectively geotagged already. When objects that cannot be identified on such images (e.g. because they are too small or are covered by vegetation) are identified at the site, their location can be recorded using a handheld GPS or any other satellite navigation system that provides geospatial positioning anywhere in the world. Modern smartphones have inbuilt receivers to determine latitude, longitude, and altitude to

within a few metres of accuracy. (High-precision devices can even achieve precision in centimetres.)

Many archaeological sites are in remote areas, and they are often overgrown with scrub or buried in accumulated dust or silt. Navigating to such sites without familiar reference points (buildings, intersections, etc.) is often tricky, and even available reference points can be camouflaged. Hence, it is advisable to preload points of potential interest at the site (identified ahead of time using georeferenced satellite images) and use the real-time moving maps provided by handheld devices to navigate to these points. It is also useful to log the track, not only to help retracing steps (and revisiting the site later), but because such a log imposes a natural sequence for the order in which features were geotagged. Such a log (which includes timestamps) can greatly simplify the task of integrating data gathered on multiple devices such as cameras.

This usage of satellite navigation (sat nav) played an important role in our geospatial and ground-based archaeological survey at Talakadu, situated at a hairpin bend on the River Kaveri in the Indian state of Karnataka. Over the last few centuries, annual monsoon winds have carried fine sand from the point-bar deposit towards the old settlement, burying it to depths of 2–30 feet. Prior excavations by the Directorate of Archaeology and Museums of Karnataka and the University of Mysore in 1992–1993 had explored less than 1% of the sand-covered area.

There are five well-known temples in this area—Vaidyeshvara, Kirtinarayana, Maralesvara, Pataleshvara, and Chaudesvari—which were constructed between the tenth and fourteenth centuries CE. The first three temples can be readily identified in optical satellite images because they are exposed above the surface, but the latter two temples are hidden under trees. We geotagged the exact locations of the hidden temples and of all the excavation sites. By correlating information from the excavation of specific trenches with larger landscape features identified by analysing the site's spatial context using satellite imagery, we could contextualize information from multiple sources and scales and interpret appropriately (Rajani et al. 2012). This site is further discussed in Sect. 5.4.

## 4.5 3D Landscape Visualization

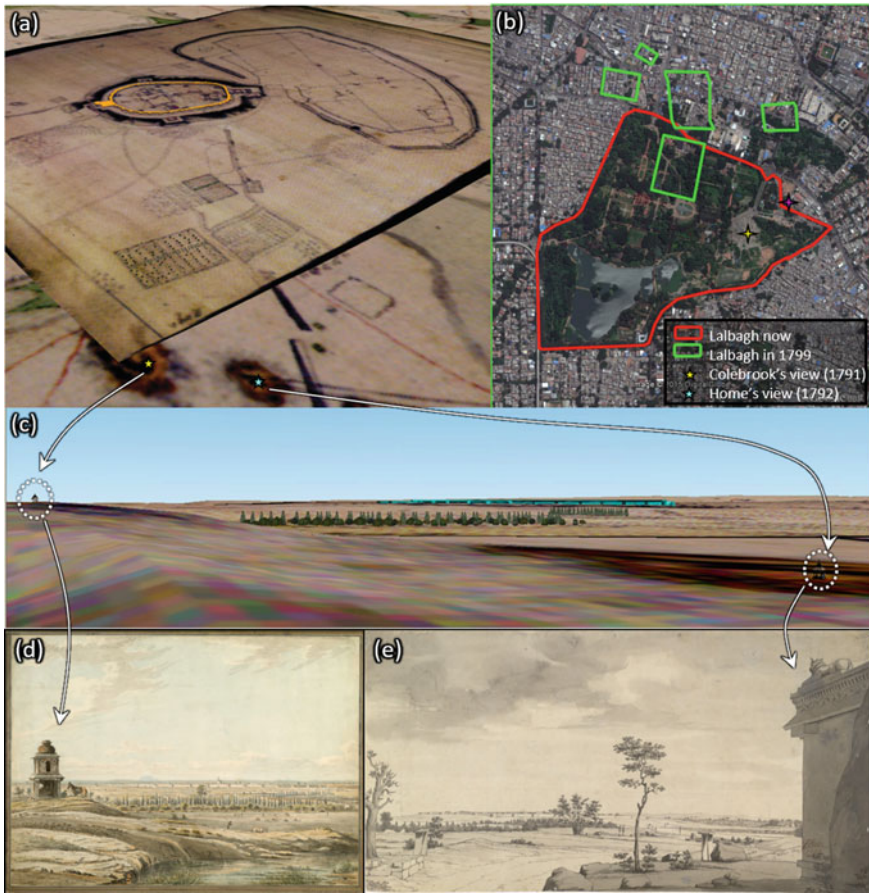
Creating a virtual reality 3D landscape visualization can enable the analyst to simulate visualization of the terrain as it would have appeared in the past. This capability of GIS is best demonstrated in the visualization of the Seven Pagodas of Mahabalipuram in Sect. 5.5 to propose a novel hypothesis for the name of this site. Another application is to create “then vs. now” scenes of the same landscape viewed from the same location. Figure 4.11 shows such a simulation of the hill fort of Chitradurga in the Indian state of Karnataka. Perspective views of the hill fort from old paintings (Fotheringham 1801) were simulated using DEM, which conspicuously displays the changes in land use in the vicinity of the hill fort (Nalini and Rajani 2012).



**Fig. 4.11** **a** Old painting “View of Chiteldroog from the east, 1801” (© British Library Board; WD581, 581); **b** a simulation of the view depicted in the old painting using DEM and Google Earth Image

This technique also provided unique inputs for studying the history of the landscape of the Lalbagh Botanical Garden in Bangalore. In 1760, Hyder Ali established a garden, which was later expanded by his son Tipu Sultan. After Tipu was defeated and killed in 1799, the stewardship of Lalbagh passed through several British Superintendents until Indian independence. The popular assumption was that gardens laid out by Hyder and Tipu are contained within its present boundaries (Fig. 4.12b). Two maps: (i) *Plan of the fortress of Bangalore, 1791* and (ii) *Plan showing the position of the British Troops round the Pettah, March 1791*, together show five distinct plots (Fig. 4.12a). These maps have other features (fort, roads, and bunds) which aided in georeferencing them to identify the corresponding area of the plots on satellite images. Shortly after the capture of Bangalore by Cornwallis’ Army in 1791, a number of official and amateur British army draughtsmen, surveyors, and artists, painted scenes showing what they called the “Cypress Garden”: (1) *East view of Bangalore, with a small shrine and a dismounted horseman in the foreground, and cattle grazing beyond (1791)* by Robert Hyde Colebrooke (Fig. 4.12d) (2) *Southerly view of Bangalore (1792)* Claude Martin, (3) *East View of Bangalore with the Cypress Garden (1792)* by Robert Home (Fig. 4.12e), and (4) *East view of Bangalore, with the cypress garden (1792), from a pagoda* by James Hunter. These four paintings show the Bangalore *Kote* (fort) structure with bastions at the far end, and rectangular patches of greenery with rows of cypress trees in the foreground (although from these paintings it is difficult to discern the exact number of plots). The first among these paintings show the Kempegowda watchtower, and the third shows a temple (both their locations are known) in the extreme foreground, which suggests the artist was close to these structures and illustrated the view visible from this point. Using these locations as references, we created virtual 3D views of the landscape similar to that depicted in the paintings (Fig. 4.12a, c). This further supported our identification of the former plots. Using this kind of geospatial analysis together with Buchanan’s account stating that Hyder’s gardens were watered from a nearby tank while Tipu’s gardens used mechanized water transport (Buchanan 1807), we could





**Fig. 4.12** a 3D perspective showing the maps of (1791) and the location from where painting by Colebrook (d) (© British Library Board; WD4461, 4461) and Home (e) (© British Library Board; WD3775(5), 5) were made; b Google Earth image showing the original and present layout of Lalbagh; c a simulated view that is similar to view in paintings made by Colebrook and Home

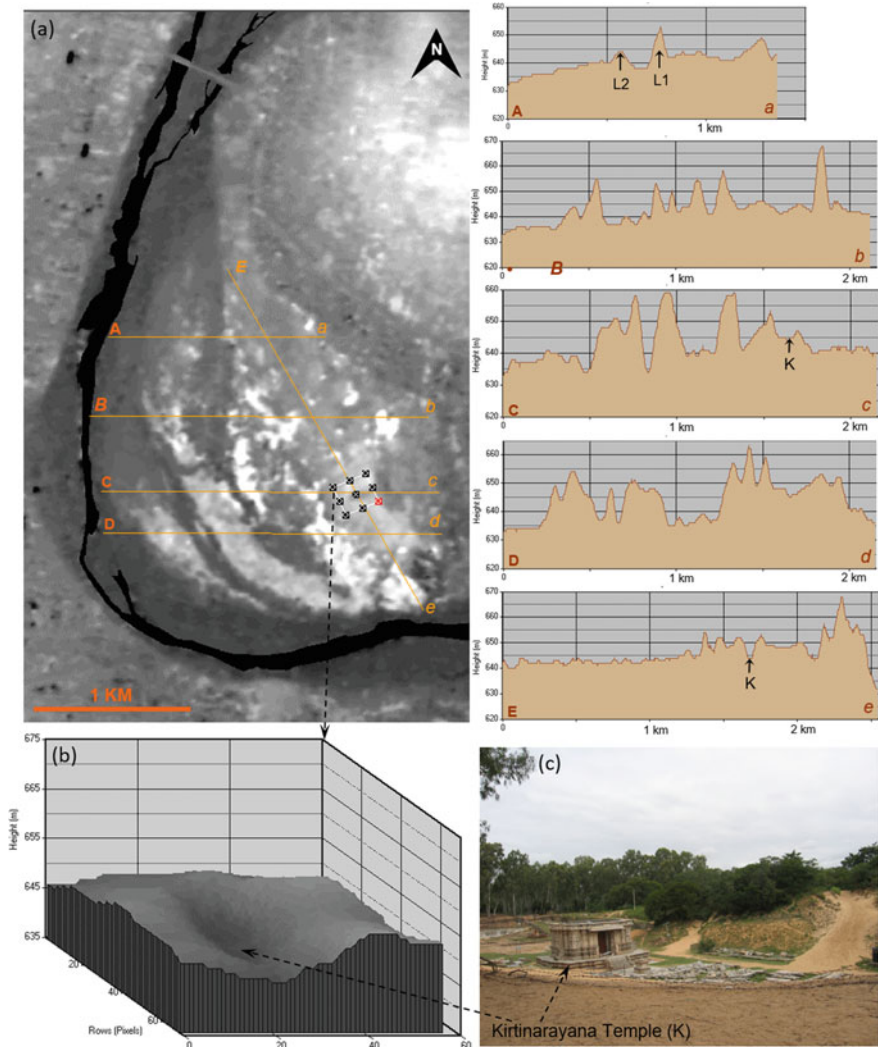
speculate which of the plots were laid out by Hyder and which by Tipu based on their proximity and slope from nearby tanks. Our study has analysed old maps, old paintings, satellite images, and simulated views similar to those recorded in paintings using 3D virtual GIS and found that Hyder and Tipu’s gardens comprised of five distinct plots and only one of these garden plots overlap with the modern Lalbagh (Iyer et al. 2012).



### 4.6 Other Kinds of Spatial Analysis and Modelling

GIS facilitates many kinds of spatial analysis, and we present a few illustrative examples here. For a comprehensive review, we suggest Verhagen (2018).

GIS can extract 2D and 3D surface profiles from the DEM layer. As an example, Fig. 4.13 shows such profiles for Talakadu (discussed in more detail in Sect. 5.4).



**Fig. 4.13** a DEM generated using Cartosat-1 Stereo pair of Talakadu along with selected spatial profiles; b a surface profile of the area around Kirtinarayana temple; c a ground photo of Kirtinarayana temple and surrounding sand dunes

Here, the analyst has drawn 5 transect lines A to E (Fig. 4.13a) across the landscape. GIS can create graphs to visualize the undulations along these lines as pixel frequencies. By selecting an area, the software can similarly create a 3D profile (see Fig. 4.13b). At a site such as Talakadu, which has significant sand accumulation, such an analysis can estimate the volume of sand that must be cleared prior to excavation. Further, one can exaggerate the display of differences in heights represented by the DEM so that the analyst can recognize patterns in undulations more easily.

Using input from a DEM, an analyst can mark a specific vantage point and GIS can generate a viewshed map for a given radius. This creates a layer which indicates which points are visible from the vantage point or occluded due to elevations along the line of sight to the vantage point. This tool is typically used in military and telecommunication applications to identify locations for specific facilities, but it has interesting applications for managing archaeological sites as well. For example, by generating visibility maps for a 350 m radius around five monuments at Badami (Rajani et al. 2009) and six monuments within the Chitradurga fort (Nalini and Rajani 2012), we identified areas that could be selected for developmental activities while preserving the aesthetic views from these monuments, which we recognize as part of their heritage value.

A final interesting example is by Gillespie et al. (2016), who have developed a predictive model using eight environmental parameters to identify 121 possible locations in the Indian subcontinent where inscriptions of the Ashokan era may lie.

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