

# An interdisciplinary approach to the collapse of the port and degradation of freshwater resources at Panama Viejo (Panama), 1519–1671

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## Abstract

The Archaeological Site of Panama Viejo (Panama) comprises a protected area of 28 km<sup>2</sup> within present-day Panama City, on America's Pacific coast. In 1519, the Spaniards founded the city of Panama Viejo to secure a natural port in an area inhabited by indigenous peoples since at least the eighth century CE. The site, along the coastline and between two rivers, became a principal gateway for goods and people travelling between Europe and Pacific settlements to the east (Realejo) and the west (Trujillo, Lima, Arica). Within one century, however, Panama Viejo's natural port and freshwater infrastructure collapsed, leading to the city's relocation after corsairs attacked it in 1671. This study combines archaeological, geographical and historical analyses to explain how and why human interactions with the local environment made the settlement increasingly untenable.

## KEYWORDS

accretion, DSAS, fresh water, mangrove, Panama Viejo, port

## 1 | INTRODUCTION

### 1.1 | Environmental context

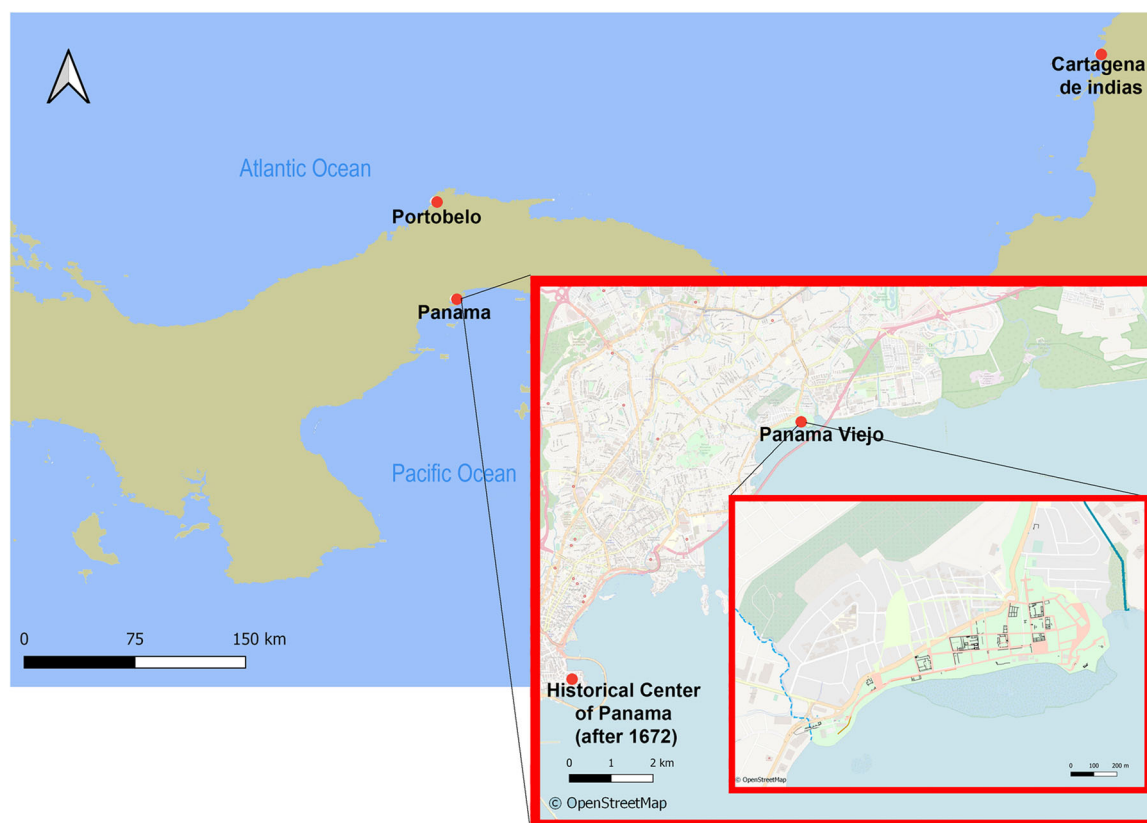
The Isthmus of Panama, located in the intertropical zone near the Equator, between the Atlantic and Pacific oceans (Figure 1), features a hot and extremely wet climate. The mean annual temperature in coastal areas of Panama oscillates between 23°C and 27°C. Two seasons can be distinguished based on the annual distribution of precipitation: a dry season from December through March or April and a rainy season from April to November (Figure 2) (Autoridad Nacional del Ambiente [ANAM], 2010).

Geomorphologically, the archaeological site of Panama Viejo rests on a littoral flatland, or depressed area composed of sedimentary rocks, which are the result of accumulation in a littoral epicontinental platform alternating with very shallow water transitional environments such as tidal flats and salt marshes. The materials are defined by the Tertiary basement, over which Quaternary sediments have been deposited as Travertine (Solano, 2021), which indicates the presence of fresh water along the coast.<sup>1</sup>

<sup>1</sup>All nonmarine limestone depositions, which are composed of calcite or aragonite, formed around seepages, springs and along streams and rivers, and hardly ever in lakes (Pentecost, 2005).

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**FIGURE 1** Location of Panama Viejo's archaeological site on the Pacific coast of the Isthmus of Panama, to the east of the post-1672 settlement.

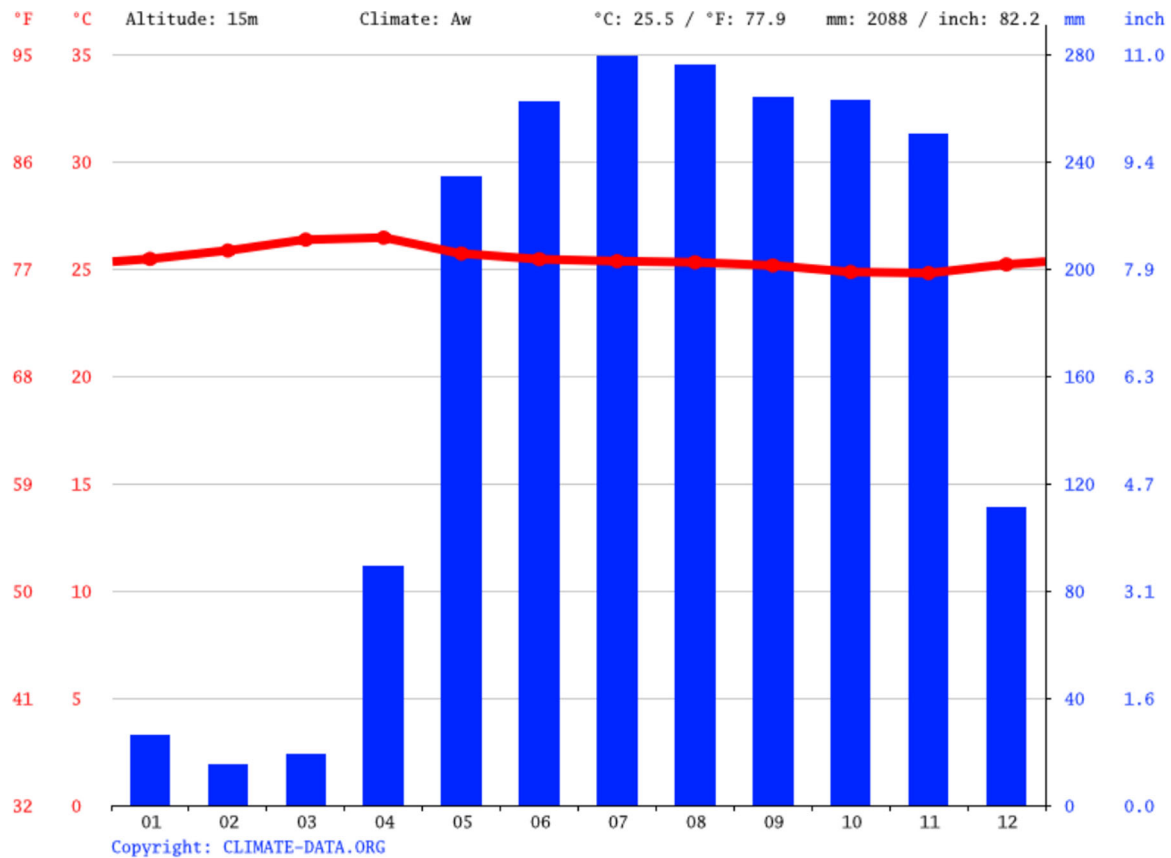
Tidal range and dynamics in the Gulf of Panama have impressed observers accustomed to less dramatic Mediterranean or Atlantic fluctuations since the 16th century. Between 2005 and 2006, the Balboa station in Panama recorded an average tide range of 3.84 m, with a maximum sizigia tide of 4.99 m and a mean tide level of 2.49 m (Lizano, 2009). In the 1520s, the chronicler Gonzalo Fernández de Oviedo described a similar situation (Fernández de Oviedo, 1852, p. 132), with the ocean nearly reaching the city's houses at high tide, yet more than 1.5 leagues (7.2 km) away from them at low tide. Historical records also describe a warm and wet climate, although the mean temperature has probably risen 2–3°C since the 16th century,<sup>2</sup> due to the impact of large-scale construction and global warming. Previous conditions favoured the extension of tropical vegetation, with dry tropical woods and savannah most common in the lowlands (Castro, 2006). Historical records describe the region as rainy, with 'nearly perpetual downpours' from April through December and a relatively dry season or 'summer' from January to April (Audiencia de Panamá, 1607, pp. 53v–54r).

Although its climatic and hydrological conditions have not changed substantially, the area's ecology underwent dramatic changes over the course of one century (Hernández Mora et al., 2021; Martín Rincón et al., 2021). The variety of molluscs identified in the pre-Columbian period infer large beaches of sand and a coastal area composed of a mix of mud and sand with small rocks, as well as mangrove vegetation. Subsequently, the loss of a sandy beach and the diminution of sediment size along much of the coast accompanied a reduction in the number of species of molluscs consumed in Panama Viejo. After the arrival of Spaniards and Africans, 11 species of bivalves and 12 species of gastropods disappeared from Panama Viejo's archaeological record, reflecting the large-scale ecological changes provoked by the settlement's activities, including the probable use of mangrove vegetation for fuel or make-shift construction (Hernández Mora et al., 2021; Martín Rincón & Rodríguez, 2006).

## 1.2 | Archaeological and historical background

The earliest human remains found at Panama Viejo date back to the sixth century CE. Archaeological excavations have documented a small indigenous settlement, ca. 776–1289, to the west of the site, at Morelos Park (Martín Rincón, 2002; Martín Rincón & Arango, 2013; Rosario Capodiferro et al., 2021) (Figure 3). In 1513, the crown of

<sup>2</sup>The presence of plant species such as the *Quercus* at 1000 m of altitude, according to the palynological analyses undertaken at el Valle, 139 km to the west of Panamá Viejo, indicate temperatures 2–3°C lower in the Upper Pleistocene (13,000–10,000 BP) than today. In the Holocene (10,000 BP to the present day), the percentage increases of pollen from species of Gramineae and Cyperaceae that flourish in hot and humid climates (Colinvaux, 1997).



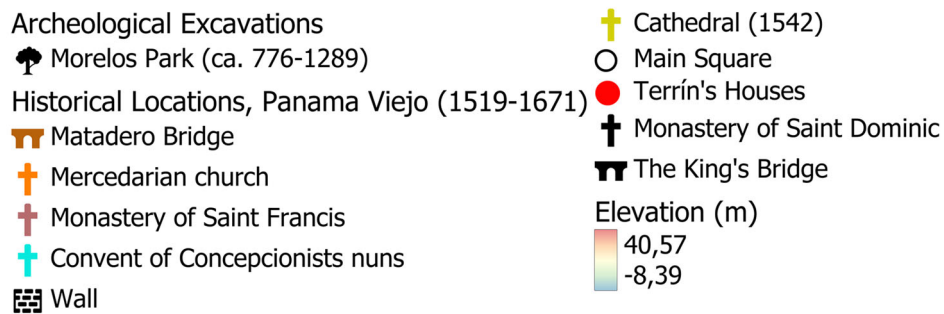
**FIGURE 2** Average monthly temperature and precipitation in Panama City from 1999 to 2019 (Climate-Data.org, n.d).

Castile sent a captain with experience in Granada and North Africa, Pedrarias Dávila, to the Isthmus of Panama with some 1500 soldiers and instructions to found strategic settlements. In particular, the king ordered Dávila to establish ports along the coast to secure trade and transport in and between the oceans discovered. The king recommended that Dávila found cities with ports where ships could dock to load and unload goods and provisions. The ideal sites, moreover, should be healthy and not swampy ('sanos y no anegadizos') and near rivers to facilitate transport inland. Finally, the king emphasised the importance of good water and air quality, with proximity to hills as well as lands suitable for farming (Aragón, 1513).

In accordance with the instructions received, Dávila and his lieutenant, Gaspar de Espinosa, reconnoitred the isthmus for years before selecting a natural harbour in the Gulf of San Miguel as the site to establish the first European settlement on America's Pacific coast. The city extended along the coastline between two rivers, the *Matadero*, also known as *Algarrobo* (Sosa, 1919, p. 91) and today as *Quebrada de Santa Elena* to the west, and the river *Gallinero* later renamed *Río Abajo* (Arroyo, 2015), to the east, as seen in Figure 4. Notwithstanding the difficult climate, the city sustained travel and trade between the Iberian Peninsula, Peru, and Nicaragua. An overland route of 7.5 leagues (36 km) stretched from Panamá Viejo to the Cruces Inn on the Chagres River, which from that point could be navigated in flat boats to the Caribbean.

Limiting the city's inland extension, a swamp behind it emitted vapours that were soon considered unhealthy (Castillero Calvo, 2006, p. 122; Cieza de León, 1554, p. 4v). Herds of cows also pastured close to the city, polluting the rivers (Aram, 2018; Audiencia de Panamá, 1607, p. 54r; Castillero Calvo, 2006, p. 127), which, to make matters worse, overflowed their banks under heavy rains. Serious inundations led to the construction of a wall alongside the shoreline in 1609 (Figure 3) in an attempt to protect the city from the sea after the tides had carried away make-shift houses and a kitchen (Hernández Mora et al., 2021).

At the same time, archaeological and historical evidence points to Panamá Viejo's increasingly difficult access to potable water. The city promoted the construction of a well on the Main Square (Castillero Calvo, 2010; Mendizábal, 1999), which would have been in use until approximately 1570, based on the debris subsequently deposited in it (Linero Baroni & Muñoz Álvarez, 2018; Mendizábal, 1999). By 1607, the city obtained fresh water mainly from one of the Abajo River's tributaries, 'Las Lavanderas' (Antonelli, 1586; Tejeda & Antonelli, 1591), whose name suggests that it also served for washing clothes. Under such circumstances, Panamá's inhabitants had to walk at least one-half league to obtain fresh water—frequently, a task assigned to the enslaved—or to purchase it from water sellers. In response to this situation, some of Panamá Viejo's elite institutions, including its Monastery of Saint Dominic and Convent of Conceptionist nuns (Figure 3), invested in structures to catch and store rainwater (Linero Baroni & Muñoz Álvarez, 2018; Suárez, 2013). A request in the 1630s



**FIGURE 3** Location of the landmarks in Panama Viejo mentioned in the text. Background adapted from a DEM (1:5000) 4343 III SW (from the Tommy Guardia Geographical Institute) and from a map of the Archaeological Site of Panama Viejo (courtesy of the Architecture Department, Patronato Panama Viejo). DEM, digital elevation model.



**FIGURE 4** Illustration of the Gallinero River, also named the Abajo River, alongside Panama Viejo, Spain. Ministry of Defence. Archivo Histórico de la Armada Juan Sebastián de Elcano. 011-A-11. 'Plano hidrográfico y geográfico del Reino de Tierra Firme' (Rodríguez, 1744).

to build a public fountain in the city went unfulfilled (Castillero Calvo, 2010, p. 202).

After 1671, the ancient city was abandoned, and Panama Viejo became a small village with a marginal population. Private interests took over its ruins in the early 20th century, with local populations establishing themselves around the area beginning in the 1930s. The archaeological site, which became a park in 1960, was seen as having tourism potential and managed by the Instituto Nacional de Cultura, with an important part of the area belonging to the National Police, National Guard and Defense Forces in succession. Finally, 1995 marked the foundation of the Patronato de Panamá Viejo, which cares for the site, promoting research, museums and other outreach activities (Arroyo, 2016). Meanwhile, Panama's urban development, especially the formation of the Panama Viejo neighbourhood and the construction of the Fiftieth Anniversary Road, have affected the course of the *Abajo River* and *Quebrada de Santa Elena*, altering their relationships to the site.

This study combines archaeological, geographical and historical analyses to explain how and why human interactions with the local environment made the settlement founded in 1519 increasingly untenable, resulting in its abandonment after 1671. Its interdisciplinary approach proposes a contextualised interpretation of the complex interactions between humans and the natural environment in the early urban development on America's Pacific coast.

## 2 | MATERIALS AND METHODS

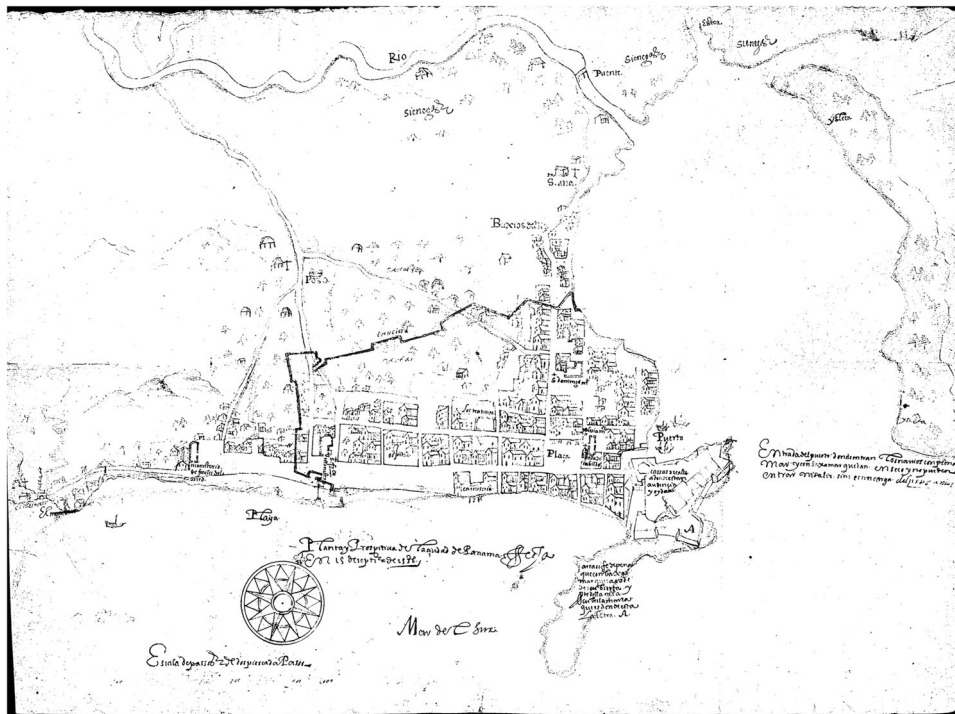
Historical, archaeological and geophysical methods have been applied to assess the impact of Panama Viejo's early foundation on its land and seawater resources, particularly in relation to the supply and management of drinking water, alongside the performance of its port and coastline dynamics. Specific historical documents allude to aspects of the complex problem of hydrographic resources at precise times and make it possible to document—without necessarily explaining—their evolution. Historical records conserved in repositories, particularly the Archivo General de Indias in Seville, Spain, offer a plethora of data that complement historical cartography and offset its limitations. With respect to Panama Viejo, such limitations include the lack of any maps before 1586, when historical sources already allude to the progressive loss of the port, as well as flooding and difficulties obtaining potable water. Complementing such historical data, archaeological evidence of the same developments has been assembled from excavations in Panama Viejo since 1996, documenting the relocation of both the Cathedral and Mercedarian Church some 500 feet away from the coast, the abandonment of a well in the Main Square, c. 1570, the construction of a wall along the coastline against flooding in 1609 (Audiencia de Panamá, 1608) (Figure 3) and evidence of additional constructions to capture rainwater in the 17th century. An online, interdisciplinary database developed since 2016 makes it possible to analyse the results of specific archaeological excavations alongside the relevant historical documentation, dating architectonic elements encountered with greater precision than

previously possible (An ARTery of EMPire, 2015; Aram et al., 2020). Subsequently, temporal and spatial projections of archaeological and historical data in GIS make it possible to connect different finds and begin to construct a narrative of change over time from a more holistic, less fragmented perspective.

Taking another step in this direction, the analysis of historical maps and modern aerial photographs in a GIS-based Digital Shoreline Analysis System (DSAS)—accessible with ArcGIS (University license)—made it possible to identify and interpret changes in coastline position and port evolution over time. Geophysical images obtained by an archaeological team based at the University of Tübingen (Germany) in 2006 were also reviewed with the aim of locating the remains of wells. Unfortunately, however, geophysical prospection did not extend to the area along the coastline, and 20th-century interventions in the area, including the construction of simulated wells, rendered the results of such prospectations inconclusive (Patzelt, 2015). These recent interventions, which interfered with visible archaeological structures, also rendered aerial prospectations inadvisable. On the other hand, on-site alterations did not directly impact the coastline, which could be examined in aerial photographs.

Among other parameters, the DSAS GIS modelling tool calculates rate-of-change statistics from multiple historical shoreline positions and provides very informative results. This automated method for establishing measurement locations performs rate calculations, gives the statistical data necessary to assess the rates of change and offers a beta model of shoreline forecasting (Himmelstoss et al., 2021). The technology has been applied to analyse erosion and accretion processes in different areas of the world, yet rarely to specific historical information. Temitope D. Oyedotun first employed the software with historical data from Crantock Beach in Southwest England (Oyedotun, 2014). In 2019, Hindle et al. tried to understand the position and evolution of Florida's coastline over time since 1875, using topographic maps from the United States's National Oceanographic and Aerial Administration (Hindle et al., 2019). Both surveys concurred on the feasibility of using DSAS software to assess the long-term morphodynamic behaviour of the coast.

For the present research, the historical shoreline positions have been obtained from historical maps of Panama Viejo executed by royal engineers Juan Bautista Antonelli on 10 September 1586 (Figure 5) and Cristóbal Rodá, between 28 February and 7 April 1609 (Figure 6), as well as aerial photographs of the Archaeological Site from January 1971 (shows the coast of the current Archaeological Site of Panama Viejo), October 1983 (shows the mouth of Abajo River and the estuary) and May 1996 (shows the coast of the current Archaeological Site of Panama Viejo) preserved at Panama's Tommy Guardia National Institute of Geography. The Mercator Universal Transverse projected coordinate system, used for georeferencing and rectification, also permitted the coastline's digitisation and analyses carried out in the DSAS. To implement the measurements with DSAS, the Datum NAD 27 zone N17 (EPSG: 26717), which corresponds to Panama, was chosen.



**FIGURE 5** Map of Panama City dated 10 September 1586. Spain. Ministry of Defence. Archivo Histórico de la Armada Juan Sebastián de Elcano. 013-D-17. 'Planta y perspectiva de la ciudad de Panamá.' 10 September de 1586. Bautista Antonelli.

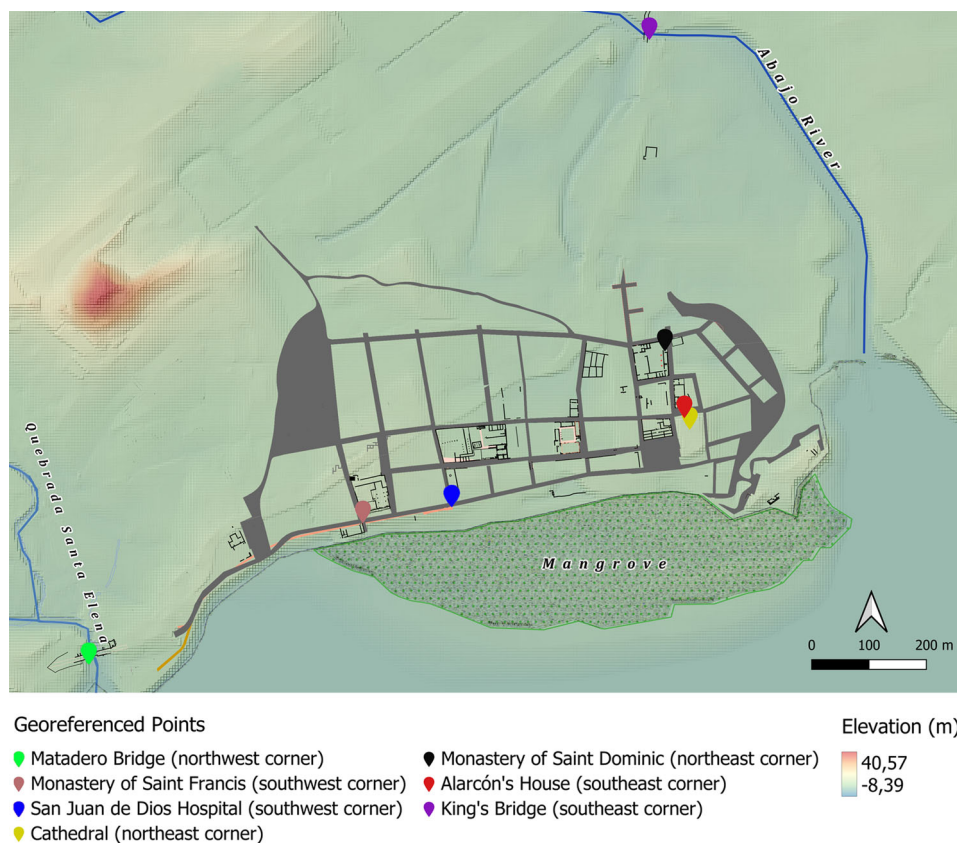


**FIGURE 6** Map of Panama Viejo with the Royal Houses, drawn by the engineer Cristobal Rodá between 28 February and 7 April 1609. Spain. Ministry of Culture and Sports. Archivo General de Indias. MP-PANAMA, 27 (Rodá, 1609). 'Plano de la ciudad de Panamá y sitio donde están las Casas Reales y la Isla de Perico y demás islas'.

Taken as control points, the archaeological site's architectural structures represented a robust set for the georeferencing process, as these features appear in different representations of the area, with various points lying near the coast. In all, seven control points have been taken (Figure 7). Some of the aerial photographs show only part of the archaeological site without

including all of the points mentioned. Thus, the previous identification of seven points of reference assured the presence of a minimum of four points in each image used to perform the geo-referencing.

The average error (RMS) for each georeferenced image (raster document) follows:



**FIGURE 7** Location of georeferenced control points. Background adapted from a DEM (1:5000) 4343 III SW (from the Tommy Guardia Geographical Institute) and from a map of the Archaeological Site of Panama Viejo (courtesy of the Architecture Department, Patronato Panama Viejo). DEM, digital elevation model.

1. Map of Panama City by Juan Bautista Antonelli (Figure 5) in September 1586, RMS: 129.743.
2. Map of Panama City of Cristóbal de Rodá (Figure 6) made between March and April 1609, RMS: 176.187.
3. Aerial photograph, January 1971, RMS: 9.84086.
4. Aerial photograph, March 1983, RMS: 1.53826.
5. Aerial photograph, May 1996, RMS: 2.33605.

The baselines used in the analysis are idealised so that all transects have the same point of reference, leading to measures that are easier to interpret. The maximum search distance from the baseline was 1000 m, and the spacing transect was 100 m.

It is important to consider the dates of the different shorelines since their position could vary by approximately 2–7 m, depending on the season (Lizano, 2015). In addition, the ample tide fluctuations induce significant variations in shoreline positions during each cycle, as can meteorological conditions at the time of map or image production, although unknown.

The shoreline obtained from Antonelli's design produces outlier features since an important amount of land represented on it lay under the sea by 1609—the mangrove covered the remains of that peninsula when it had regrown in 2006 (Figure 8). The prominent spit-like morphology that is represented normal to the shoreline,

while of geomorphological interest, was omitted from the projections to avoid distortion of the rate of change in the DSAS analysis, which focussed on the shoreline related to the port area. The results obtained from the analysis carried out with the DSAS are refined and supported by the information obtained from historical documentation and archaeological excavations.

### 3 | RESULTS

#### 3.1 | Erosion of the coastline and loss of the port

The DSAS provides a quantitative result for the evolution of the historical shoreline and harbour. First, the digitalisation of Panama Viejo's shorelines (Figure 9) revealed the significant modification of the coastline and, even more importantly, the total loss of the estuary due to the tidal deposition of sediment. Between 1586 and 1609, the shoreline receded approximately 80 m. Given the lack of precision typical in early maps, such figures should be taken as merely indicative of a process the settlement catalysed. However, by 1983, the shoreline had accreted 200 m, and by 2021, the envelope had extended to 195 m (Figure 10). Applying the DSAS model makes it possible to understand the coastline's behaviour. The erosion process

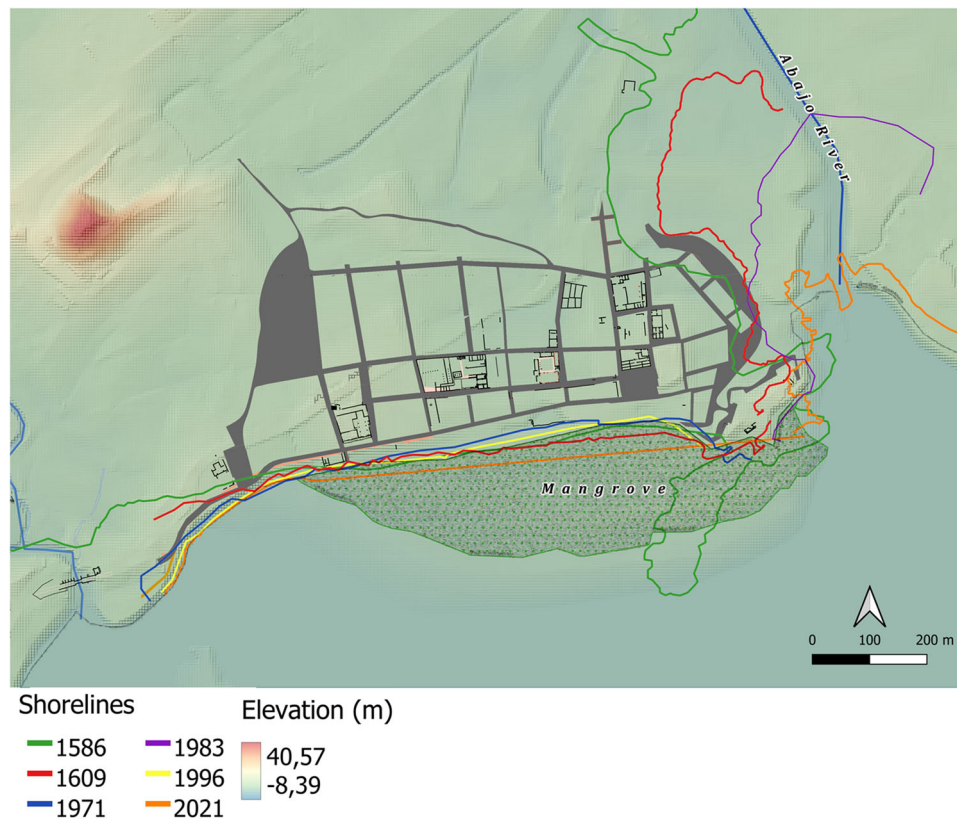


**FIGURE 8** Evidence of erosion along the coastline includes the disappearance of the peninsula that Antonelli drew in 1586 (a), and whose remains were visible underwater in the aerial photo from 2004 (b). Covering these remains, the mangrove regrew after 2006. The irregular form of the historical map (a) is a consequence of the rectification process to adapt the image to reality.

appears very evident along the beach, especially near the port and the mouth of the estuary, with an accretion process at the coastline's other extreme (Figure 11). Moreover, some 29,840 m<sup>2</sup> appear to have been lost between 1586 and 1609 in the intertidal zone (Figure 8).

Since the oldest historical map of Panamá Viejo dates to 1586, archaeological and archival evidence complement the DSAS model with information about processes that began 67 years earlier. With respect to the pre-Hispanic period, more intensive settlement and transport patterns catalyse the area's transformation after 1519. Archaeological evidence of early erosion includes the displacement of churches initially built alongside the ocean some 500 m inland, coinciding with the disappearance of a 'street of the beach' mentioned in the historical documentation from the 1520s by the time of Antonelli's representation (Hernández Mora et al., 2021). The

first documented mention of Panamá Viejo's port dated from 1526, when Francisco Pizarro, Hernando de Luque and Diego de Almagro paid sawyers, carpenters, and other professionals to build two vessels there for 10 months (Pizarro et al., 1526). In 1537, the King echoed reports about the loss of the port due to careless dumping of sand the ships required for ballast in the harbour (Charles I/V, 1537). Two years later, the Audience of Panamá promulgated a list of ordinances aimed to stop the port's deterioration, including fines for dumping rubbish or ballast in the harbour or for leaving timber in it. Ships could stay at port for only 2 months and had to pay fines beyond that time. Furthermore, the government ordered sand dredged from the estuary and a bastion constructed with trash from the city (Audencia de Panamá, 1539; Mena García, 1992, pp. 62–68). According to the authorities: 'one of the main causes of damage to the port is the unloading of wood that is brought by sea and left a long time in



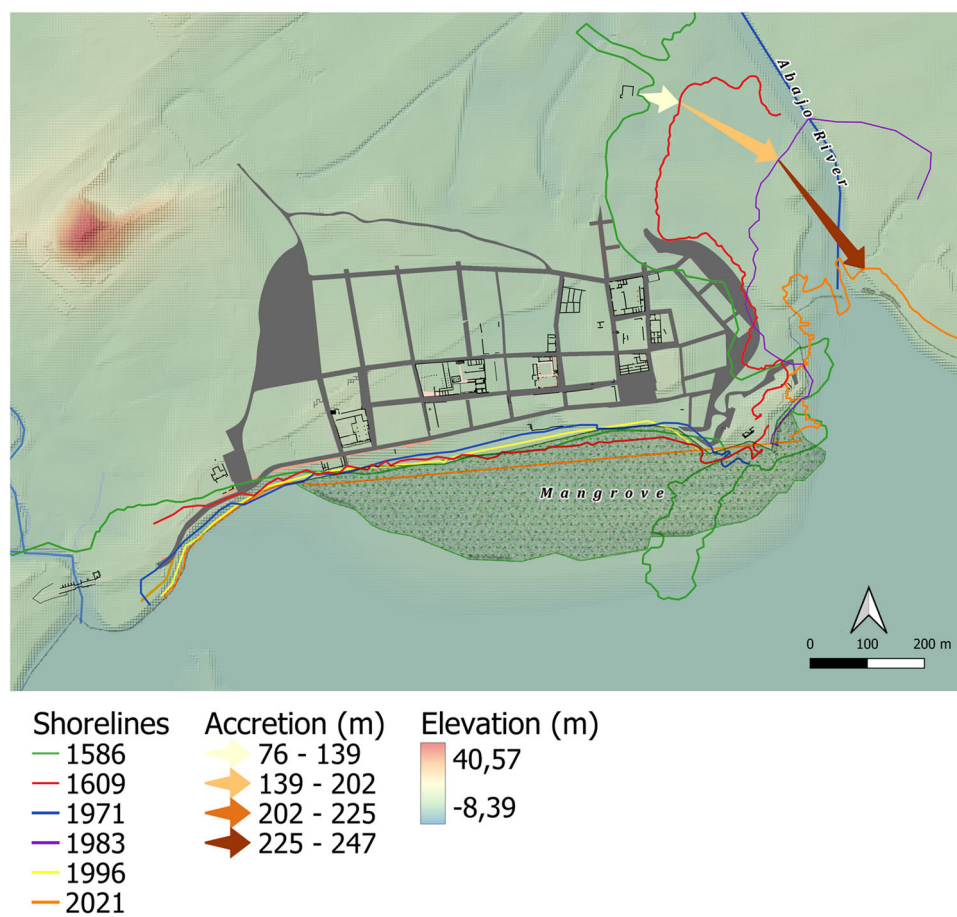
**FIGURE 9** Different shorelines digitalised from historical maps from 1586 (green line) and 1609 (red line) and aerial photos from 1971 (blue line), 1983 (purple line), 1996 (yellow line) and 2021 (orange line). Background adapted from a DEM (1:5000) 4343 III SW (from the Tommy Guardia Geographical Institute) and from a map of the Archaeological Site of Panama Viejo (courtesy of the Architecture Department, Patronato Panama Viejo). DEM, digital elevation model.

the said port, retaining the sand carried in by the sea'; in addition to the 'waste and viscosities from the ships' and from the city, the ballast and the sand pulled by the vessels accumulated in the estuary. Meanwhile, a bastion of garbage was envisioned to limit the sea's erosive effect (Audiencia de Panamá, 1539; Mena García, 1992, pp. 62–68).

Yet Panama's harbour continued to lose depth. Although vessels with 250 barrels had entered the port in previous years, by 1546, they could only carry 30 casks (Philip [Prince, subsequently King Philip II], 1546). One year later, the King mandated measures to clean and repair the port, and some buildings close to the harbour were relocated (Philip [Prince, subsequently King Philip II], 1547). One visitor in 1554 found the harbour ideal for small vessels, although larger ships could only enter and leave it at high tide (Cieza de León, 1554, p. 4r). By 1584, efforts to maintain the port included further restrictions on its use: the town council banned ships with tonnage over 3000 arrobas from entry, requiring them to dock at Perico island, 2–3 leagues (9.7–14.5 km) from Panama Viejo, which became known as 'Puerto Perico' in contrast to the original port or 'Tasca' (Tejeda & Antonelli, 1591). Notwithstanding such restrictions, sand and waste continued blocking the harbour, so that only flat boats could enter it (Audiencia de Panamá, 1607, p. 54r).

### 3.2 | The deterioration of freshwater resources

Alongside erosion of its coastline and loss of its port, Panama Viejo suffered from a common issue in water resource management: an excess of input at some locations and times of the year, followed by scarcity at locations and times of consumption. Evidence of a pre-Hispanic settlement suggests the presence of drinking water in the area at the time, from the *Abajo* or *Gallinero* river and its tributaries, as corroborated by the ground's geological formation. As early as 1538, however, the city government requested a fountain to bring fresh water into the settlement (Isabel of Portugal, Queen of Castile, Empress, 1535). The main source of drinking water for the inhabitants of Panama Viejo had been the river to the east of the settlement, whose pollution by cattle led to increased illnesses, according to complaints registered in 1551 (Charles I/V, 1551). The population also consumed water from the River of the *Lavanderas* (Washerwomen) to the north of the city (Antonelli, 1586), which ran dry in the summer months, leaving most people dependent on a well with poor-quality water in the same vicinity, some 1000 paces (1.393 km, Galán, 1984) to the north of the city (Tejeda & Antonelli, 1591). By 1607, the situation had only grown worse, especially in the winter months, when the water supply became murky and contaminated by cattle (Audiencia de Panamá, 1607, pp. 53r–53v).

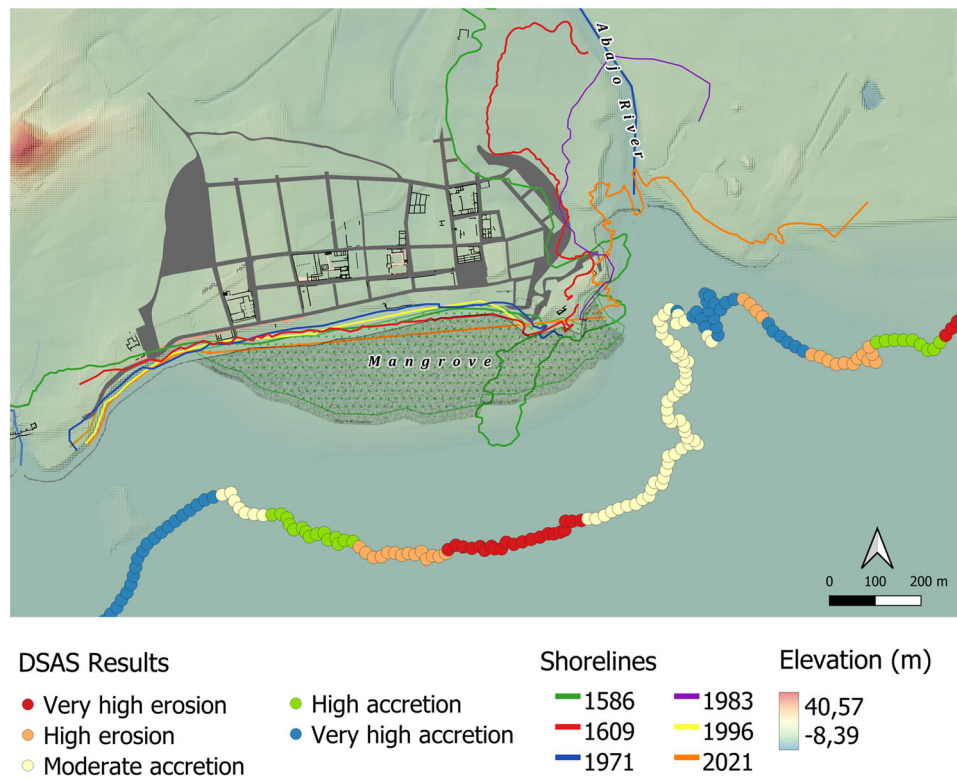


**FIGURE 10** Accretion of the port from 10 September 1586 (green line) until 2021 (orange line). This map compares the shoreline from 1586, 1609 (red line), 1983 (purple line) and 2021. The extension of land between these lines has been calculated to understand the rate of the accretion of the harbour. However, the tides can also influence the line positions. Background adapted from a DEM (1:5000) 4343 III SW (from the Tommy Guardia Geographical Institute) and from a map of the Archaeological Site of Panama Viejo (courtesy of the Architecture Department, Patronato Panama Viejo). DEM, digital elevation model.

The *Quebrada de Santa Elena* was also affected by the seasons and intensity of rainfall. According to the President of Panama's Royal Tribunal, the river could be crossed during the dry season but not during the rainy season due to the tides, downpours and flooding streams that discharged into the *Quebrada*. In 1617, the water's force destroyed a wooden bridge that used to cover the river (Enríquez de Sotomayor, 1617). Once the bridge had been rebuilt in stone, petitions resurfaced for a fountain that would supply the city with fresh water. The Tribunal's President described the practice of washing clothes in the river and the land dragged into it by the winter rains as polluting its waters (Enríquez de Sotomayor, 1637). In 1646, the city emphasised the expensive, arduous and dangerous labour of obtaining drinking water, which had even been 'taken at knifepoint' and caused many disasters (Cabildo de Panamá, 1646). Finally, one of the arguments for moving Panama City after 1671 entailed its lack of potable water, since the water that passed through the lower, swampy terrain accumulated many illnesses (Junta de Ministros, 1672).

#### 4 | DISCUSSION

A natural port and access to potable water, two main criteria for Panamá Viejo's foundation in 1519, became causes for its relocation 150 years later. The presence of a natural port in an estuary that sheltered ships loading and unloading goods, with fresh water available in the vicinity, fulfilled royal instructions issued for the settlement of towns and cities in 1513 (Aragón, 1513; Hernández Mora et al., 2021). Within 20 years of Panama's foundation, however, the port began to have problems because of deposits of garbage and other materials that arrived from the city and the ships that entered it (Charles I/V, 1537). In an attempt to maintain the harbour and prevent its loss, the local council issued ordinances to prohibit ship caulking and repair in the port, as well as the dumping of rubbish and wood, which boosted the accumulation of sand and stone deposits (Audiencia de Panamá, 1539). In spite of such regulations, the harbour continued to silt up (Philip [Prince, subsequently King Philip II], 1546). On route to Peru in 1554, one chronicler recorded a difference of five *brazas* (8.35 m) of water from high to low tide, which uncovered a beach of over one-half



**FIGURE 11** Erosion and accretion on the coastline and harbour of Panama Viejo, revealed by Digital Shoreline Analysis System (DSAS). Background adapted from a DEM (1:5000) 4343 III SW (from the Tommy Guardia Geographical Institute) and from a map of the Archaeological Site of Panama Viejo (courtesy of the Architecture Department, Patronato Panama Viejo). DEM, digital elevation model.

league (2786 m) (Cieza de León, 1554, p. 6). In the following decades, ships' tonnage continued to increase, forcing most of them to dock offshore at the island of Perico (Núñez de Silva et al., 1585) and send their goods into Panama Viejo on small boats. This labour was not easy: the vessels berthed in Perico had to transfer their cargoes into flatboats that could enter the port alongside the city in a trajectory characterised by a strong swell in the waves, leading to the loss of ships (Mena García, 1992, pp. 62–68; Tejeda & Antonelli, 1591).

Panama's foundation had impacted its surroundings and led to major changes in the landscape. It introduced a new type of settlement to America's Pacific coast: the city. The model port city, forged in the Mediterranean and the Atlantic, supported the construction of larger, more complex ships and buildings, mainly of wood. Activities associated with these cities, such as maritime commerce, required additional trades, such as carpentry and caulking, practised in Panamá Viejo from at least 1526 (Pizarro et al., 1526), alongside farming, cattle raising, butchery, tanning and other trades necessary to package goods as well as to supply the ships. Some of these activities became registered in the site's toponymy, as in the case of the *Matadero* River, named for the slaughterhouse on the west bank of today's *Quebrada de Santa Elena*.

The new settlement's typology, together with the new land uses, had the direct and early consequence of the deforestation of its surroundings, especially the area's mangrove vegetation, which virtually disappeared (Hernández Mora et al., 2021; Martín Rincón &

Rodríguez, 2006).<sup>3</sup> The loss of mangrove vegetation and plant cover, in general, exacerbated the impact of torrential rains frequent in the area and led to increased erosion, particularly of the coastline and rivers surrounding the city.

The analysis of Panama's coastline highlights this erosion, as seen in Figure 11. This figure could suggest a high level of sedimentation to the west of the city, at the present-day mouth of the *Quebrada Santa Elena*, probably due to the deposit of sediments transported by the river itself. Continuing eastward, very high erosion became visible on the shore, with the area most affected in the 16th century being reoccupied by mangroves after 2006 (Castillo, 2009). The sediment carried by the *Quebrada Santa Elena*, as well as the fine materials likely entrained by waves along the coastline after mangrove's removal, flowed towards the estuary. The process produced the high level of accretions recorded in the DSAS and noted in the historical documentation. At the same time, the port appears impacted by the mouth of the *Abajo* River, which also carried sediment while producing an erosive effect that kept the estuary active.

The understandable human reaction to coastal vulnerability and flooding exacerbated the erosive processes identified. The city's letter of 1537 and ordinances of 1539 noted the impact of sand pushed by the boats and the waves, which accumulated around wood

<sup>3</sup>Mangroves did not return to Panama Viejo until 2006.

left on the beach, as well as 'garbage and slime' from the city and the ships, which even dumped ballast into the estuary (Mena García, 1992, pp. 62–68).

Another result of the accumulation of sediment and trash entailed a local proliferation of catfish (*Sciades dowii*) and sea bass (*Centropomus* spp.). These species typically inhabit the tidal areas of rivers and ravines and littoral regions with muddy foundations and brackish water. After 1570, a study of the faunal remains discarded in the well of the Terrín houses on Panamá Viejo's Main Square (Figure 3) identified eight individuals of each species, with a total biomass of 67 k, representing 34% of that of the fish documented (Jiménez & Cooke, 2001). The presence of these species signals the eutrophication of waters near the city by the late 16th century. A greater amount of residue would have favoured the proliferation of bacteria and other microorganisms that constitute their ideal habitat. Overall, 75% of the bones documented pertained to species typical of shallow waters such as tidal areas, mangrove swamps and the mouths of rivers, also including marine catfish (*Ariidae*), jackfish (*Carangidae*) and tripletakes (*Lobotidae*). Another species, the weakfish (*Cynoscion squamipinnis*), usually found where estuary waters mix with the open sea, prefers to avoid murky, shallow areas. Finally, the identification of 18 freshwater turtles (*Trachemys scripta*) and 27 common toads (*Bufo marinus*) would appear to signal fresh water in the vicinity of Panamá Viejo (Jiménez & Cooke, 2001), even when the well in its Main Square (Figure 3) was used for refuse, 1570–1600.

The disappearance of the mangrove reflected in the faunal analyses is also seen in the changing formation of the soil: sandy beaches characterised Panamá Viejo's coast through the 1520s, while today, this area is mainly composed of sludge (Martín Rincón & Rodríguez, 2006). This fining of beach face materials coincides with a tidal flat now covered by (usually very fine) materials released from degraded or removed mangroves. Hence, the increased role of tidal forces carrying finer sediments more efficiently to an already shallower environment accelerates siltation in the low-energy end of the sediment transport cell (the harbour).

Thus, the successive processes of deforestation, erosion, sedimentation and contamination at Panamá Viejo silted up the estuary and rendered its port increasingly useless. In addition to the physical infill, loose sediments altered the salt content of part of the Abajo Rivers' waters (Parra & Restrepo Angel, 2014). The removal of vegetation, which slows the erosive effect of tides and waves, would have left the earth beneath it totally exposed to these elements (Autoridad Nacional del Ambiente & Autoridad de los Recursos Acuáticos de Panamá [ANAM-ARAP], 2013; Muñoz Vallés et al., 2012; Sierra González, 2012). Further effects included the destruction of a natural barrier against waves and tides (ANAM-ARAP, 2013; Muñoz Vallés et al., 2012; Sierra González, 2012) and the loss of potable water near the city.

The port's process of sedimentation, perceptible in historical maps and aerial photographs, also emerges from the analysis of historical documentation. Although boats laden with up to 250 barrels had docked in Panamá Viejo in previous years, orders issued in 1546 indicated that no ship carrying more than 30 barrels

(Philip [Prince, subsequently King Philip II], 1546) could enter the port. One year later, the last recorded efforts to protect and conserve the port included orders to remove structures built close to it (Philip [Prince, subsequently King Philip II], 1547). None of the measures taken, however, made the port viable. In 1584, ships with cargoes weighing 4–5 thousand arrobas (45–47 thousand kg) were prohibited from entering 'the Tasca' and ordered to dock at Perico Island. From there, merchandise would be transported to the city on small boats and unloaded at the 'Tasca' (Ramírez de Quiñones, 1538).

The construction of a wall along the shoreline in 1609 to prevent flooding (Figure 3) (probably due to an increased surge in the meteorological tide due to severely low atmospheric pressure) would only channel more debris into the estuary and mouth of the Abajo River, making its waters muddier and saltier (Parra & Restrepo Angel, 2014). Panamá Viejo registered its first request for a fountain with drinking water in 1538, 1 year after providing evidence of the port's degradation. The introduction of new land uses, including the pasturing of cattle, processing of their meat and hides, the dumping and accumulation of urban waste and the residues of caulking undoubtedly added to the rivers' contamination. Further pollution resulted from washing clothes (Enríquez de Sotomayor, 1637) in the Lavanderas River. In other words, the city's principal water supply gradually became increasingly contaminated. With erosion of the coastline, water also may have become increasingly salinized and contaminated in the city's wells, including one on the plot of the 'Terrín Houses' (Figure 3), which was used to deposit garbage after 1570 (Lineró Baroni & Muñoz Álvarez, 2018).

In less than one century, Panamá Viejo lost its main sources of potable water. Its residents had to travel at least one-half league to reach the Lavanderas' River or, if it were dry, 1000 steps to access a well with poor-quality water in the vicinity. Alternatives included the purchase of water, sometimes also of dubious quality, from water-sellers or the construction of systems to collect and store rainwater, such as a series of channels and troughs in the monastery of Saint Dominic (Figure 3) built approximately in 1597 (Lineró Baroni & Muñoz Álvarez, 2016). Panamá's Conceptionist convent (Figure 3), founded at a distance from the coastline in 1594, initially relied on a well for water. By 1621, however, the nuns built a large reservoir (*aljibe*) to collect rainwater (Suárez, 2013). Similarly, a large cistern is visible among the unexcavated mounds on the blocks occupied by the Monastery of Saint Francis (Figure 3). The need for such initiatives to ameliorate a deteriorating situation was confirmation in the proposal to build a fountain one-half league from the city to quench its population's thirst. The situation, moreover, was affected by the separation of the crowns of Castile and Portugal, which led to a shortage in the enslaved labour used to haul water and even propitiated violence to obtain it (Cabildo de Panamá, 1646).

Due to the abundant pluvial regime and the complexities of water management, Panamá Viejo's inhabitants alternatively suffered from scarcity and an overabundance of water. DSAS and historical analysis, employed together, indicate that coastal deforestation and silting-up of the city's port in the 16th century also impacted its water supply. A dearth of potable water, while especially notable during the

summer months, entailed an increasing hazard that contributed to the reputation—and reality—of Panamá Viejo as an unhealthy settlement.

## 5 | CONCLUSIONS

Interdisciplinary research, manifested in the use of geographical, historical and archaeological tools, suggests a possible relationship between the loss of Panamá Viejo's port and the decreased portability of the *Abajo* River's water. Panamá Viejo's impact on its environment made what had been an ideal settlement in 1519 untenable by 1671. The concentrated, urban population's intensive use of wood for fuel, as well as the construction of huts, buildings and ships, led to the immediate area's deforestation. Removal of the mangrove along the coast, compounded by other urban and port activities, catalysed rapid silting of the estuary adjacent to the city. There followed the salinisation and contamination of sources of drinking water, including the *Abajo* and *Quebrada Santa Elena* rivers and a number of wells. By 1671, the city had become known as difficult to access by sea, unhealthy, and lacking potable water.

The loss of the city's port in the 16th century exacerbated the salinisation and contamination of its freshwater supply. In addition to the collapse of its port and the degradation of its freshwater resources, the sea had claimed part of the coastline and even a peninsula of land (Figure 8). Creative responses to an increasingly critical situation included the construction of a seawall along the coast to prevent flooding (Figure 3), as well as a large reservoir and a cistern to store rainwater, which undoubtedly enhanced the security and incomes of the elites who invested in them. While attending to immediate interests, such initiatives also offset health hazards associated with contamination and salinisation of the city's water supply.

The Hispanic monarchy, which entertained the idea of building a canal across the isthmus of Panama as early as 1534 and again in 1588, confronted the collapse of Panamá Viejo's port at the height of its commercial activity. Although engineers provided useful maps and recommendations, ultimately, the mangrove proved more effective than their designs for preserving the port. Panamá City changed dramatically from its foundation in 1519 to its relocation in 1671. The new site, chosen to avoid flooding, also provided better access for ships and to potable water, at least initially.

### AUTHOR CONTRIBUTIONS

**Miriam Martos:** Conceptualisation; investigation; writing—original draft; methodology; visualisation; software; formal analysis; data curation; project administration; validation; resources. **Bethany Aram:** Investigation; funding acquisition; methodology; visualisation; writing—review and editing; project administration; supervision; resources; formal analysis; data curation; writing—original draft. **Gonzalo Malvarez:** Investigation; methodology; visualisation; writing—review and editing; software; data curation; supervision; resources; formal analysis; writing—original draft.

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at <https://artempire.cica.es>, thanks to the Agencia Digital de Andalucía and the Centro Informático Científico de Andalucía.

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