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A conceptual study on envisioning digital humanities based on spatio-temporal analyses anthropogenic activities of heritage site: An interactive application

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Abstract

Heritage buildings provide a visual depiction of Malaysian culture and historical elements. Heritage buildings are also living representations of the past. Malacca Town, Malacca, is known to have numerous heritage buildings that are over a century old. The Malaysian government has been working diligently to manage these historical buildings since Malacca was designated as one of the UNESCO World Heritage Sites. However, this research study aims to bridge the gap in understanding human impact on historical sites by integrating digital tools and spatio-temporal analysis and proposes a digital humanities framework that integrates Geographic Information Systems (GIS), spatio-temporal analysis, and interactive web-based storytelling to analyse anthropogenic activities within Melaka's heritage zones. Multi-temporal land-use and land-cover data from 1989 to 2024 were analysed to identify patterns of urban expansion and environmental transformation and the results reveal a substantial increase in developed areas. To support data dissemination and public engagement, an interactive GIS-based web application and story map were developed which enabled users to explore heritage buildings through spatial visualization, historical timelines, and multimedia integration. The proposed framework demonstrates how digital tools can enhance heritage monitoring, support conservation planning, and democratise access to historical knowledge. The significance of this study lies in its innovative approach to analyzing and visualizing the patterns of anthropogenic activities over time, contributing valuable insights to the field of digital humanities and to the advancement of digital humanities by bridging

geospatial analysis with cultural heritage interpretation, offering a scalable approach for sustainable heritage management and citizen science engagement in rapidly developing urban environments.

Keywords: Database design, digital humanities, heritage building, GIS, story map, web mapping

Introduction

Due to various issues such as development and modernisation, the need for heritage management is unquestionably essential. For decades, modernization has resulted in the removal of historic structures in order to make way for urban redevelopment projects (Karam et al., 2017). Digital humanities (DH) is a field that creates new scientific tools, methods, and theories that work across multiple humanities fields. In recent years, digital humanities research has generated interest among scholars who try to understand how computer-driven techniques are able to address the challenges of various traditional research. In recent years, several efforts have been carried out in order to further bridge the gap between digital history and the broader field of DH, combining historical research efforts and methods with multi-disciplinary approaches from the exact and social sciences. Among these is a growing interest in fostering spatio-temporal analysis on a more solid corpus of primary sources taken from the rich heritage of world archives. The spatial expression of human activities is so highly expressed that it is inevitable to neglect it in a historical study. Commencing from the consideration that the detection of the same place (in extended historical research) can change its name several times in the course of history, it is clear that the necessity and convenience of being aware of the spatial and, indeed, geographical expression of historical sources are particularly important and practical. However, despite the emerging and empirical acknowledgement (that is, the first quantitative data are often used only to support theoretically derived claims) that space and time elements linked to human activities can also be considered determinants of history and vice versa, a transversal and long-term historical analysis of anthropogenic activities does not seem to find in digital humanities the same credibility and interest given to diachronic textual analysis.

The study of anthropogenic activities at World Heritage sites is a growing field within heritage management and conservation. Anthropogenic activities, including urban development, tourism, and industrialization, have significant impacts on these sites, often leading to degradation and loss of cultural and historical values. Numerous studies have highlighted the adverse effects of tourism on heritage sites. For instance, Garcia et al. (2021) and Falk and Hagsten (2024) examined how tourism pressures can lead to physical wear and tear, pollution, and changes in local communities' cultural practices. Similarly, Shawabkeh et al. (2023) discussed the challenges of balancing tourism with conservation efforts, emphasizing the need for sustainable tourism practices. Urban development poses another significant threat to heritage sites. Studies by Jerpasen and Swensen (2008) and Kristy (2018) have shown how modern urbanization can encroach on historical areas, causing irreparable damage as well as leading to the loss of historical buildings and landscapes. This encroachment often results from inadequate planning and the prioritization of economic growth over cultural preservation. Industrial activities also impact heritage sites. The research by Rovella et al. (2021) and Cantillo et al. (2024) on the impacts of industrial pollution on historical monuments highlights how industrial emissions can cause structural damage and deteriorate materials, particularly in areas with significant industrial activity. In the context of

Malacca, these anthropogenic pressures are evident. Studies by Jamei et al. (2015) and Ertan and Eğercioğlu (2016) have documented the impacts of tourism and urban development on Malacca's heritage sites, emphasizing the need for integrated management strategies that balance conservation with sustainable development. Heritage buildings serve as tangible representations of cultural identity, historical continuity, and socio-economic evolution. In Malaysia, historic cities such as Melaka reflect a unique convergence of multicultural influences shaped by centuries of trade and colonisation. However, increasing pressures from urban development, tourism expansion, and environmental change have intensified the vulnerability of these heritage assets. Modernisation, while economically beneficial, has often resulted in the alteration or loss of historic structures to accommodate infrastructure growth and urban redevelopment (Karam et al., 2017).

Literature review

Malacca heritage

The history of Malacca started with the Malacca Sultanate era from 1411 to 1511. Later, Malacca was conquered by the Portuguese from 1511 to 1641, under the command of Afonso de Albuquerque. Malacca continued to prosper under Portuguese rule until the Dutch came from 1641 to 1824. The Dutch captured the port and ruled over it until 1824. From 1824 to 1957, the British conquered Malacca through the Anglo-Dutch Treaty. British colonization was the longest compared to others. During World War II, Malacca was occupied by the Japanese from 1942 to 1945 until Malaysia received independence in 1957 and continued with recognition as a UNESCO World Heritage site in 2006. In 2013-2014, the multinational company AkzoNobel aided in the 'restoration' of this heritage by painting all the buildings on the town hall square red, just the same colour that the British had painted these buildings for a small part of the 20th century.

Malacca was founded around the early 15th century by Parameswara, a prince of the Srivijaya Kingdom who fled the Majapahit invasion. He chose a strategic location at the mouth of the Malacca River because he considered it an ideal place for maritime trade and defences. This location provides direct access to the Straits of Malacca, a major international trade route. Malacca's location in the middle of the Straits of Malacca made it a global trade centre. The city became a meeting place for traders from China, India, the Middle East, and the archipelago. (Andaya & Andaya, 1982; Wade, 2009) Trading activities created a multicultural residential area around the port, with local people and foreign communities living side by side. The Malacca River became a central element of the city's layout. The river functioned as the main highway connecting the interior to the seaport. The city was divided into two parts connected by a wooden bridge. This bridge also functioned as the main market, with stalls where traders from various nations sold their wares. The river's northern part became a residential area for Chinese and Indian traders, while local Malays inhabited the southern part. The city planning of Melaka was initially heavily influenced by the Hindu-Buddhist concept of Srivijaya. This is reflected in the principle of Mandala cosmology, which regulates the structure of space based on three levels of the world: the sky (spiritual), the earth (human), and the underground (the world of evil spirits). This influence is seen in the placement of important buildings, such as the palace on Melaka Hill, to reflect the hierarchy and cosmological balance. However, when Islam began to enter Melaka due to relations with the Pasai Sultanate, it impacted the development of culture, law, and architecture. Mosques were built in a style that combined Hindu-Buddhist and Islamic traditions. Sultan Muzaffar Shah

officially made Islam the official religion of the kingdom (Brown, 1970; Hall, 2011; Reid, 1993; SarDesai, 1969).

After conquering Malacca in 1511, the Portuguese built the fortress "A Famosa," which became a central element of the city's layout. The fortress replaced earlier local structures such as palaces and mosques. The fortress's location at the foot of Bukit Melaka (now St. Paul's Hill) made it the centre of military and administrative control. The fortress was equipped with a wall surrounding the port area, reflecting the concept of a walled city in medieval Europe. The city's layout shifted from an open model based on rivers and ports to a defensive structure. The Portuguese made Bukit Melaka an administrative and religious centre named as the Church of Nossa Senhora da Annunciada (later known as St. Paul's Church) was built on the hilltop. This church symbolized Portuguese religious power and a base for the Catholic mission. The hillside also included residences for high-ranking Portuguese officials and a military complex. The port remained an important element of the city's layout but was under strict surveillance by the Portuguese military. Warehouses and storage facilities around the port supported the Portuguese-run spice trade. The trading area was crowded with traders from various nations, including the Chinese, Arabs, and Indians, although their activities were now strictly controlled. The city layout retained the pre-existing ethnic segregation, but the Portuguese strengthened their control over the area: Chinese communities lived around the port, near the trading centre. Indian communities, mainly Tamil Muslims, remained active in the textile and spice trade. The Portuguese established settlements for Europeans around the fort. (Boxer, 1977; Hall, 2011; Irwin, 1962; SarDesai, 1969; Subrahmanyam, 2012).

The Dutch colonial period (1641–1795) reflected significant changes that integrated military, administrative, and commercial elements into a more organized city layout. The Dutch retained some elements of the Portuguese layout but also introduced new governance and architectural styles that reflected their systematic approach. The Dutch moved the administrative centre from the top of Bukit Melaka (St Paul's Hill) to the foot of the hill. The Stadthuys building, built in 1650, became the governor's office and the seat of government. It is located at the foot of Malacca Hill, near the port and the primary market. Malacca Hill remained a strategic area for military defence but lost its role as a major administrative centre. The Dutch began to organize the city's layout based on the principles of efficiency and zoning: Streets were designed to be more regular and straight, such as Heerenstraat and Jonkerstraat. Main streets were parallel to the river and the port, supporting trade activities. On the other hand, the Dutch repaired and expanded the A Famosa fort, inherited from the Portuguese. New bastions, named Middelburg and Victoria, were added to strengthen the defences. The residential areas remained divided by ethnicity, reflecting colonial social stratification. The Chinese community settled around the port and trading areas. The Malays lived on the city's outskirts, especially around the river and agricultural land. The Dutch and other Europeans lived in elite areas near the Stadthuys and the fort. Despite the infrastructure improvement, Malacca's role in international trade declined during the Dutch colonial period. This was because the VOC prioritised Batavia (now Jakarta) as its main trading centre. Melaka became a transit port, not a trade centre, as it was during the era of the Melaka Sultanate or the Portuguese era (Hall, 2008; Hussin, 2002).

During the British colonial period (1795–1957), Malacca underwent significant changes as the British adopted a more modern approach to urban planning, focusing on transport, zoning, and colonial integration. After taking Malacca from the Dutch in 1795, the British demolished most of the A Famosa fort in the early 19th century. This was done to reduce the military threat to the British, as the fort was considered irrelevant to the British defence strategy. Only the Porta de

Santiago, the fort's main gate, remains a relic. With the fort gone, Malacca's urban planning shifted from defence to trade and administration. The British expanded the city into new areas more conducive to commercial and residential functions, including building significant thoroughfares to support mobility and trade. Major roads were widened, including Jalan Jonker (Jonker Street) and Jalan Heeren (now Jalan Tun Tan Cheng Lock). Bridges such as the Tan Kim Seng Bridge replaced the old wooden bridges over the Malacca River, reflecting the influence of modern infrastructure design. The British began reclamation projects along the Straits of Malacca to create new space for economic development. The area became a modern trading centre, with new buildings such as trading offices, warehouses, and markets. The British retained the Stadthuys as the administrative center but built additional buildings for government offices. Around the main square, new buildings were constructed in a typical British colonial style, including administrative offices and an Anglican church. The Malacca River remained the main trading center, but the British expanded the commercial zone inland. Markets and warehouses were placed around the port to support import-export activities. The area around Jonker Street became a more modern centre of trading activities (Hussin, 2002; Ibrahim, Abdullah, Ibrahim, & Murtaza, 2018; Sandhu & Wheatley, 1983)

Digital humanities in heritage

Digital humanities represent an academic field that brings together computation and the humanities. This field of inquiry involves exploring humanities data and finding innovative ways to distribute, interpret, and analyze these data using technology (De Boer & Stork, 2024). This field also includes the process of digitizing texts and developing digital libraries and archives while using methods such as text mining, machine learning, and network analytics to analyse and discover something new (Terras et al., 2013; Wulff, 2018). Digital humanities can be understood as an advanced development of humanities practices in the context of the digital culture's requirements, and introducing digital tools into humanities research can enhance the effectiveness and efficiency of the studies and create more possibilities and innovative output of humanities research.

In the context of digital humanities in heritage, it is a rapidly growing subdiscipline that applies digital technologies and methodologies to culture and heritage practices. This synergy is between quantized tools of computer sciences and contextualising philosophies of humanities sciences to work with material and immaterial aesthetics in new ways. Several features of this intersection are based on recent research findings, including digital humanities visualization (Alessandra Spreafico & Chiabrando, 2024; Jänicke, 2020; Meinecke, 2022), machine learning and cultural heritage (Fiorucci et al., 2020), and documentary heritage (Liao et al., 2020).

Interactive web applications such as digital heritage interfaces are important in disseminating cultural information. These applications made it possible to experience heritage in a virtual and user-friendly way, and they often incorporate multimedia. Web-based heritage platforms offered new possibilities of narrative construction and the audiences' involvement, which would have been impossible with traditional media. For example, use of virtual reality (VR) and augmented reality (AR) is now common in museums and other heritage institutions. These technologies make it possible to develop interactive exhibits that can provide the visitors with an interesting historical experience, hence improved human interaction with heritage (Rodriguez-Garcia et al., 2024; Shafiee Roodposhti & Esmaeelbeigi, 2024).

The use of the 3D Web Geographic Information System (GIS) in the analysis of cultural heritage is, therefore, an improvement in the management and preservation of cultural heritage. GIS technologies complement 3D visualization tools to allow researchers as well as the public to engage with history and archaeology data in ways that are meaningful and educational (Alessandra Spreafico & Chiabrando, 2024; Spreafico et al., 2023). 3D Web GIS is essentially an improvement of the GIS system with the added 3D elements which enables the user to maneuver through a map closer to reality. Traditional 2D GIS returns most of its information on a flat map, and, unlike 3D Web GIS, it is independent of the spatial environment of terrain, structures, and artefacts in 3D space. It is most useful in heritage studies for its capacity for modelling and simulating sites and their associated histories with an impressive spatial accuracy (Auer & Zipf, 2018; Nishanbaev, Erik & McMeekin, 2021).

The use of GIS in heritage studies is not limited to web applications but also in storytelling applications. The area of applying GIS storymaps for heritage is progressing by integrating the GIS with the story map approach to enhance the understanding and communication of cultural heritage. This method relies on the spatial and temporal dimensionality of heritage sites to create engaging and dynamic narratives (Malinverni et al., 2019; Mauro et al., 2021).

GIS approach for storytelling through interactive mapping

Geographic Information Systems (GIS) plays a role in implementing analysis and data visualization with an interactive map platform. The integration of multimedia components with GIS to produce compelling narratives, known as story maps, provides an effective means of communicating intricate spatial information. GIS facilitates the integration of spatial data with written descriptions, photos, and videos (Mokhtar et al., 2023). Historical events can be depicted in conjunction with geographical places, timelines, and associated artefacts, providing a multi-dimensional view (Mohd Yusoff et al., 2024). Furthermore, Esri's Story Maps have been extensively utilized for this purpose, allowing users to integrate cartographic narratives with interactive experiences (Esri, 2023).

In heritage conservation, GIS storytelling has demonstrated its significance in recording and advocating for cultural assets. GIS-based story maps provide a digital archive by mapping heritage sites and connecting them to their historical tales, ensuring accessibility and preservation. In addition, storytelling can also be displayed in interactive 3D visualization (Thöny et al., 2018), which can be embedded and applied for heritage buildings with a combination of historical narratives, archival images, and geographic information to elevate public knowledge and cultivate respect for cultural heritage. These projects can enhance tourism, education, and policymaking, promoting a balanced strategy for conservation and development. Other research by Nishanbaev, Erik and McMeekin (2021) developed a cloud-based web GIS platform that brings together interactive maps, 3D digital models of cultural heritage (CH) sites, and Linked Open Data (LOD) to support richer online exploration of heritage assets. Gao, Yang and Jiao (2022) used interactive GIS mapping in observation of regional habitat quality in rapidly urbanizing Chinese cities due to intensified human activities such as construction expansion, transportation infrastructure, and land-use conversion. Research by Mokhtar et al. (2023) used GIS-based learning tool designed to teach *Sirah* by integrating animated storytelling with geographic visualization. This web application targets school-age learners and aims to make Sirah more engaging by situating events on interactive maps with variety of interesting spatial elements.

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Method and study area

The project will begin with an extensive literature review and data collection from various historical and geographical sources. Using GIS and other digital tools, the collected data will undergo spatio-temporal analysis to map and visualize the patterns of anthropogenic activities. The methodology will be applied to a carefully selected historical site, ensuring comprehensive and detailed analysis. The final phase will involve creating interactive visualizations and developing a GIS-story map for citizen science engagement. Figure 1 shows the methodology of the study.

The research is expected to produce a detailed spatio-temporal analysis of anthropogenic activities at the selected historical site, providing valuable insights into human impacts over time. A significant outcome will be the development of a GIS-story map, which will serve as a tool for public engagement and contribute to the preservation and management of historical sites. This project will advance the field of digital humanities and demonstrate the potential of digital tools in historical research and citizen science.

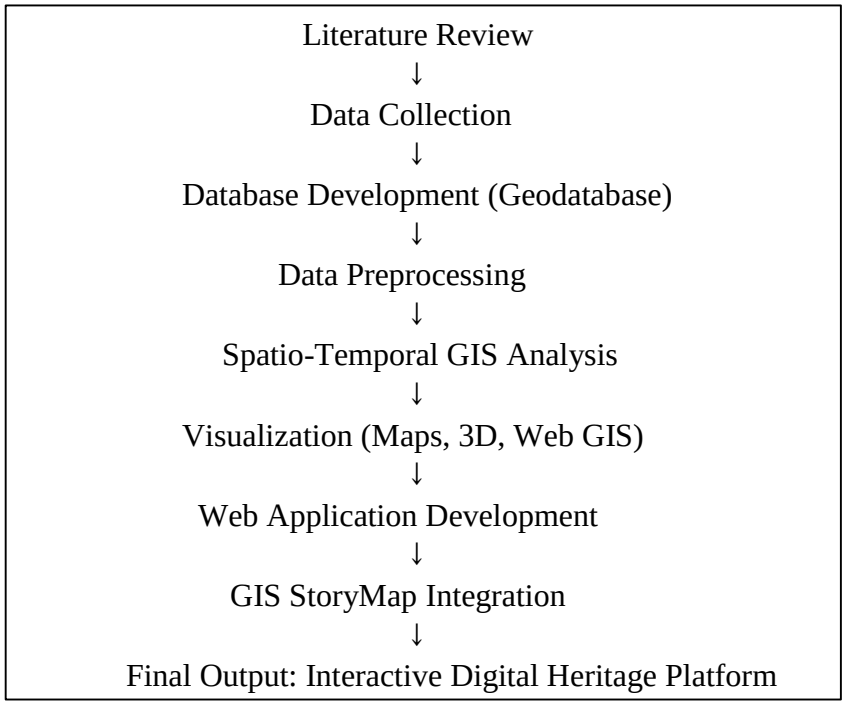

Figure 1. Flow of methodology

There are different approaches and methodologies that contribute to performing a historical analysis. Among the most exploited methodologies, there are the archaeological approach that finds ancient sources to be exploited, the scientific historical method, the philological approach, and documentary methodologies, both in traditional paper form and in electronic and digital form, with methods and techniques of the Digital Humanities. Nowadays, new progress in technology allows us to potentially exploit a consistently higher number of sources, especially spatio-temporal sources. For example, the greater availability of digital maps (ancient and modern), along with the increasingly widespread discipline of Geographical Information Science (GISci), contribute to increasing the awareness that where human activities occur, when they take place, what happens

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and what is left are important clues to understand human history and the context of our current society from a primarily spatial point of view.

At this stage, archival research, historical records, archaeological data, and geographical information systems (GIS) will be performed. The study area is located at the UNESCO World Heritage Site of Malacca with an estimated land area of 288.1 hectares (Figure. 2). The study area is divided into two heritage zones: the core zone with 45.3 hectares and the buffer zone with 242.8 hectares of total land area. Melaka, Malaysia, are remarkable examples of historic colonial towns on the Straits of Malacca that demonstrate a succession of historical and cultural influences arising from their former function as trading ports linking East and West. These are the most complete surviving historic city centre on the Straits of Malacca with a multi-cultural living heritage originating from the trade routes from Great Britain and Europe through the Middle East, the Indian subcontinent, and the Malay Archipelago to China.

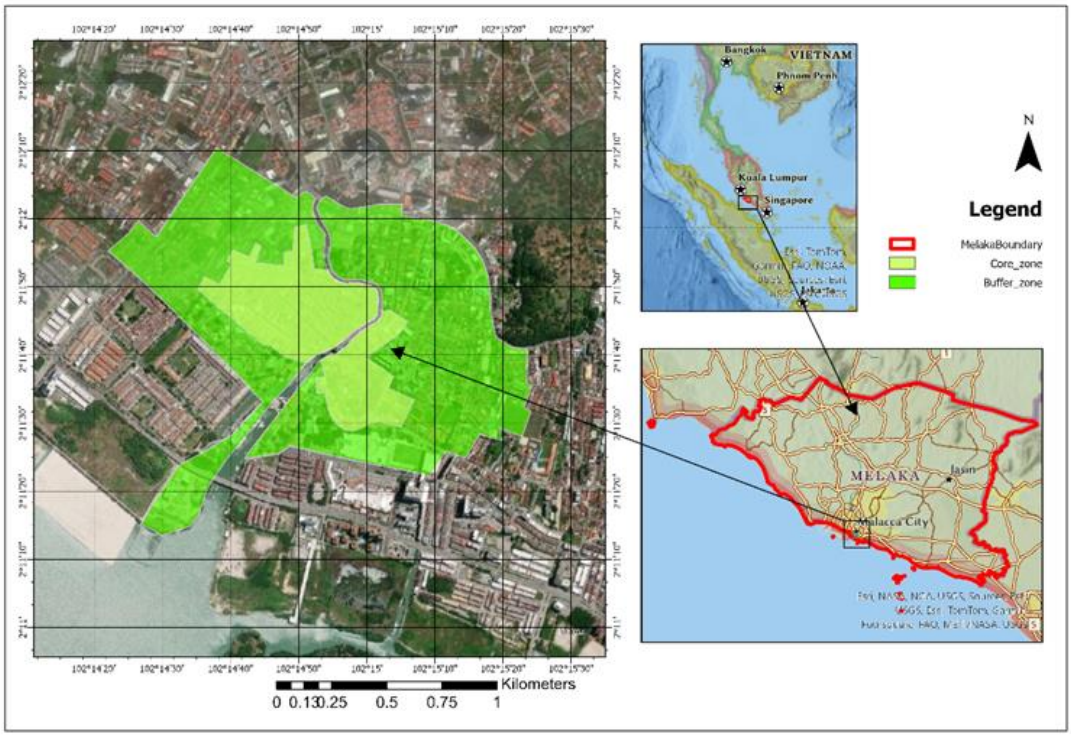

Figure 2. Malacca core area and buffer area

Both towns bear testimony to a living multi-cultural heritage and tradition of Asia, where the many religions and cultures met and coexisted. The study area in Figure. 2 was chosen based on the state government's aspiration to transform the city of Malacca into a truly "living heritage city." The remarkable number of heritage buildings as well as its architectural and characteristic features have made UNESCO consider Malacca one of the World Heritage Sites in Malaysia.

Data collection

There are two types of data sources in this study. Firstly, the primary data is from collecting and organizing data from responsible agencies and secondary data is from fieldwork surveys. The

basemap of the database is from satellite images which are gained from open sources. The images are crucial for reference in helping update the fieldwork survey of historical buildings. Land use maps will also be provided from satellite imagery for a 10-year gap from 1989 to 2024.
Table 1 listed the proposed data to be used to develop the interactive website application in monitoring digital humanities based on spatio-temporal analysis of anthropogenic activities.

Table 1. Proposed data

Data	Format
Building use information	Pdf file and shapefile
Heritage zone boundary	Polygon-vector
Road	Polyline-vector
Land use	Polygon-vector
Basemap	Tiff

a. Heritage and attractive places using GIS visualization approaches

Geographic Information Systems (GIS) have emerged as a powerful tool in heritage studies, enabling researchers to capture, analyze, and visualize the intricate relationships between cultural and historical assets and the dynamic factors that shape them. This approach is especially valuable for studying anthropogenic activities in heritage and attractive places, where human interactions with the environment impact both preservation and visitor experience. The significance of GIS in this field lies in its capability to synthesize complex datasets such as land use changes, visitor traffic, and environmental stressors into cohesive visual representations that support actionable insights (Moylan et al., 2009).

A primary strength of GIS visualization is its ability to map tourist flows, helping identify high-impact zones within heritage sites. These visualizations guide sustainable visitation policies by pinpointing areas most affected by human traffic. Additionally, temporal GIS visualizations, including time-lapse maps, offer valuable insights into how anthropogenic factors such as urban expansion or industrial pollution have altered landscapes over time (Pérez-del Hoyo et al., 2020). Such insights are invaluable for conservation efforts, as they allow researchers to observe evolving patterns of human interaction and provide a strong foundation for informed decision-making in heritage preservation. Through these tools, GIS contributes to a digital humanities approach that emphasizes both cultural preservation and accessibility.

b. Digital tools

Software and technologies to be used. There are three products of ESRI proposed to use for this study. The choice of using ArcGIS products by ESRI in this study is because it is very influential in Malaysia and has an excellent reputation and experience in GIS industries. Not just that, the products are integrated and compatible with each other. ArcGIS Field Maps are selected as mobile apps for data collection during fieldwork. But due to limitations of these mobile apps which could not perform map processing and spatial analysis, platform software such as ArcGIS Pro will be used. Lastly, ArcGIS Online Experience Builder is used as a web-based application and a medium to share data from the user hardware to another software.

c. Web-based application method

Basically, the development of interactive web applications started with understanding the needs and studying the information of the study area. Later, the user requirement analysis (URA) will be conducted based on the questionnaire to the related people within the study area. Data collection from the related agency and the designation of the database system will be the next stage in developing the web application. Data gained from the related agency needs to be managed and go through a data cleaning process in terms of the attributes and the spatial data. At the final stage, the development of the database system will be performed with the results and output which are maps from the analysis and information.

At the final stage, the development of the database system will be performed with the results and output which are maps from the analysis and information. Figure 3 shows an example of data extracted from the satellite imagery. Some information of the latest data such as land use and buildings of the study area are directly gained from satellite imagery or aeriel photograph. In this related study, the data of the surrounding area will be updated through satellite imagery.

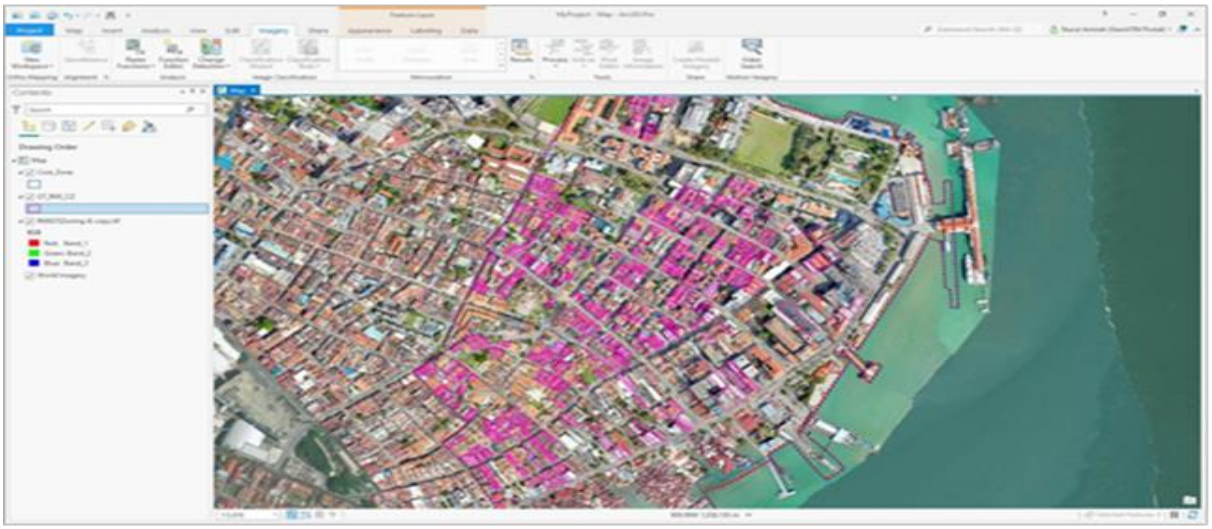

Figure 3. Example of data extraction from land use layer

d. Malacca heritage storytelling development

Storytelling is one of the methods that contains the story flow that has been transformed into digital information. One of the popular approaches to digital storytelling is ArcGIS Storymap, which is license software provided by ESRI. In story map development, the ADDIE model is an essential framework for creating an interesting learning environment. Aldoobie (2015) states that by implementing the ADDIE model's processes, instructional designers, content creators, and educators can create an effective and successful instructional design. The ADDIE model serves as a framework for developing effective instructional designs and is extensively utilized within the instructional design field. The ADDIE paradigm comprises five phases: analysis, design, development, implementation, and evaluation.

Firstly, for the analysis phase, a feasibility study is needed to determine the content material of the storytelling that is suitable and needs improvement. This phase focuses on analysing the

issues related to content and system application development. Secondly, during the design process, the interface for the sitemap, storyboard, multimedia element, and educational game can be created before the application is developed.

This design methodology is essential and includes visual elements, including graphics, text, video, and other necessary materials. To ensure that learning organizations perform more systematically and align with appropriate material, it is essential to develop multimedia prototype content that is meticulously customized to the needs of educators and learners. In addition, it is suggested to embed the geography elements such as distance, area, location, route, direction, and coordinate. Next, in the development phase, the GIS map, multimedia elements, audio, and subtitles for the video were created. This phase has four tasks: developing the prototype's interface, sound recording, scripting text, and incorporating multimedia components into the prototype. ArcGIS Online, Cap Cut, and a voice changer can be used during the development period. Furthermore, it involves iterative assessments, storyboarding, interface design, and content modification. Then, the story map application is implemented for the end user to help them become familiar with all the functionalities and the content of the video. At this phase, the end user's ability to recognize the characters, plot, location, issue, and flow of the story will be tested. For the heritage storytelling, the evaluation process is not implemented to gain user acceptance feedback.

Results and discussion

This section outlines the findings and analysis of the study, concentrating on three important elements: land-use and land-cover changes in Malacca from 1989 to 2024, Web-Based Digital Visualization, and the Malacca Story map for Heritage Buildings. The analysis emphasizes the integration of geospatial tools and digital storytelling in comprehending and conserving Malacca's heritage while evaluating alterations in its landscape over time.

a. Landuse and landcover changes in Malacca from 1989 to 2024

Figure 4 shows the landcover classification map of the study area, which includes the UNESCO buffer zone of Malacca heritage city for years 1989, 2009, and 2024. Four landcover classes, including water, developed area, barren land, and shrubland, were analyzed. From Table 2, it can be observed that the area has continuously developed, where the water bodies area decreased from 1144.578 hectares in 1989 to 492.403 hectares in 2024, while the developed area grew from 534.031 hectares in 1989 to 1331.892 hectares in 2024. This indicates that Malacca City, specifically way from a 2-kilometre radius of the UNESCO buffer zone, had been developed nearly double in size for the past 35 years.

Table 2. Area in Hectares for each landcover class for year 1989, 2009 and 2024

	Area (Hectares)		
Class	**1989**	**2009**	**2024**
Water	1145.578	876.663	492.403
Developed	534.031	1153.795	1331.892
Barren	134.981	186.206	197.466
Shrubland	837.993	435.909	630.621

Figure 4. Landcover classification map of the study area from 1989 to 2024 with 2-kilometre buffer from the UNESCO buffer zone

b. Web-based digital visualization

Developing interactive visualizations through interactive web applications and analysis on the patterns of anthropogenic activities at a historical site using spatio-temporal analysis are one of the proposed outputs. At this stage, all the data will be gathered and displayed in the attribute table interface that was developed based on the URA and data analysis stage. The interactive web app is published in ArcGIS Online, and the public can access the interactive web application. A simple homepage design for the Georgetown interactive web app which has a brief description about the interactive website demonstrated in Figure 5. The homepage is the first interface of the web app before the user enters the master page of the web app. The 'Get Started' button will proceed the user to the main page. Figure 4 shows the example of an interactive web application for George Town Penang Heritage. The master page is divided into two parts, namely the map and the tabs shown in Figure 5(a). The user interface provides the map with a sizable section on the left side for data presentation and exploration. As usual in web mapping applications, the map can be paned and zoomed, reset map orientation, a toggle to pan or rotate 3D map, a full-screen option, a measure distance tool, and a search bar for users to use and explore. While for the tabs, there are different sections consisting of 'About','Explore the Data' and 'Heritage Buildings'. The user can click on a different tab to access additional related information.

The Explore the Data tab was displayed in Figure 5(b) where it specifies any user that wants to look in detail at the attribute table of heritage building features. The 'Download Geodatabase' button is for users that need the data in the ESRI shapefile. While for the 'Heritage Buildings' tab, it contains panels that show each category of heritage buildings with brief information. The map will automatically change according to which category of heritage building is shown on the panel, as shown in Figure 5(c) and Figure 5(d) shows the panel in the 'Heritage Buildings' Tab which describes heritage buildings that are found in George Town. Apart from that, a 'see heritage photos' button will directly bring the user to a second page that focuses on highlighting photos of the study area. Once the user clicks the bookmark, the map will navigate to the location of the bookmark. Users can also click on the heritage building feature that is displayed in the map. A pop-up window will show the attribute of the building, and the 'back to main page' button was provided for users to view the main page again.

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Figure 5. Heritage Homepage a) Main Page, b) Building Heritage Description, c) 3D building and d) Heritage photo and pop-up menu

c. Malacca story map for heritage building

The development of the heritage story map emphasizes Malacca's heritage history and timeline using text and geospatial datasets. The map illustrates several scenes from the Malacca heritage story, seamlessly integrating the necessary elements, as shown in Figure 6. The map arranges the building's position according to the era of its heritage existence and the years of its establishment. The navigation panes consist of i) Heritage Timeline, ii) Discover Malacca: A Journey Through Time, iii) Malacca Through the Ages: A Comparison of Old and New Maps, and iv) Malacca's Architectural Evolution: A Journey Through Era.

The heritage timeline provides an overview of the development and existence of Malacca's heritage buildings by highlighting significant events, milestones, and time periods. The timeline began with the founding of Malacca in 1400 by Parameswara, a Sumatran prince, and continued until the formation of Malaysia in 1963. Modern buildings emerged to promote tourism in Malacca State after the establishment of Malaysia. In a separate section, the "A Journey Through Time" tab showcased the years of existence of heritage buildings, accompanied by visuals from the geospatial mapping platform. This platform pinpointed the current locations of these buildings, commencing with the Malacca Sultanate Palace in 1403 and concluding with Hang Tuah's Well in the 1930s. This has been visualized in sequence to show the movement of the development of the heritage building from the Malacca Sultanate Era (1400s–1511) to the Post-Independence and Modern Era (1957–Present) as in Figure 6(d). Additionally, the swipe block facilitates a visual comparison between the classic 1854 map, the Pharoah Map of Malacca, Malaysia (Geographicus, 2024), and the current Malacca basemap. To compare the two maps, use the slider tool (Figure 6 (b), while Figure 6(c) explores the rich architectural heritage of Malacca, spanning centuries of history and cultural influences. This express map highlights significant eras, showcasing iconic buildings that define Malacca's journey from its Sultanate period to the post-independence era.

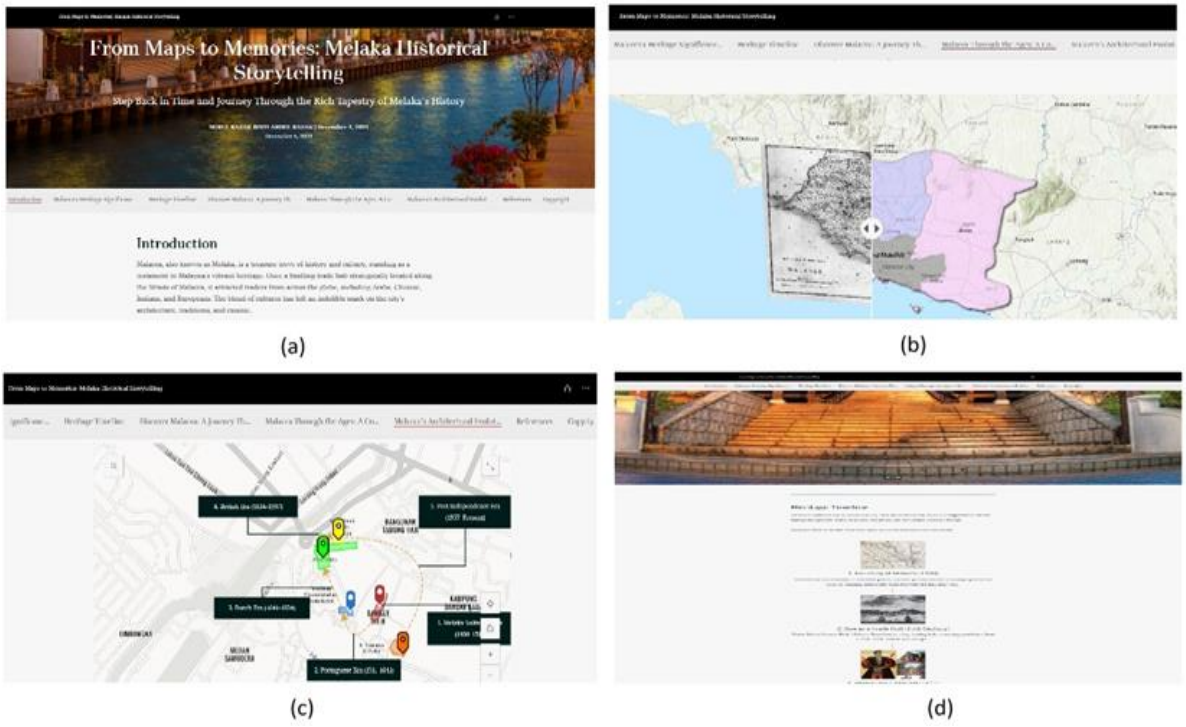

Figure 6. Heritage of Malacca Storytelling a) Main Page, b) Maps Comparison, c) Era Journey and d) Timeline

Discussion

This study proposes the design and development of an interactive web application for heritage buildings and to create detailed and interactive visualizations, including maps and 3D models, culminating in a GIS-story map designed for citizen science. This map will engage the public and facilitate community contributions to historical research in Malacca Town as part of initiatives for sustainable development in Malacca as well as assist in managing heritage resources efficiently. In addition, the user of the GIS story map can engage directly with the storyline which can be displayed through video and graphics.

There are countless opportunities for managing, conserving, and preserving our heritage resources because GIS technology now has so much to offer. It is important to note that creating interactive web applications involves more than just purchasing and setting up GIS hardware and software. The implementation phase must be viewed as a process rather than a step if it is to be successful. The process is proposed which will be started with analysis of the user requirements, followed by database development, analysis and ended with user evaluation testing.

In democratization of historical data, GIS will help transform the way people access and understand historical data. Previously, historical information in Melaka was often locked away in archives, books, and academic documents that were difficult for the general public to access. With GIS, spatial data such as historical maps, important locations, and documentation of historical sites can be integrated and presented visually through story maps. This allows various parties, from students to tourists, to view the locations of historical sites directly on a digital map, explore additional information such as historical texts, images, and multimedia, and access this data anytime through online devices, making history more inclusive and accessible to everyone.

Story maps combine GIS data with visual elements such as interactive maps, photos, videos, and narrative texts. This provides a much more engaging experience than reading a traditional history book. In Melaka, these visualizations can include, among others, changes in spatial planning from the Melaka Sultanate era to the Portuguese, Dutch, and British colonial eras. The placement of iconography of historical sites such as Stadthuys, A Famosa, Jonker Street, and St. Paul's Church. Narration of the role of the Melaka River in shaping the city's economy and society in the past. This visualization helps users understand the relationship between geographic location and historical context, creating an immersive and personal experience.

Melaka has a long history as a multicultural world trade center. Its historical narrative involves communities such as Malay, Chinese, Indian, Portuguese, Dutch, and British. GIS and story maps enable the inclusion of these perspectives so that no voice is left out of the city's history, especially in Showing maps of specific community settlements, such as Kampung Portuguese and Kampung Cina, and their contributions to the development of the city and visualizing important locations of various religious and cultural traditions, such as mosques, temples, and churches.

With GIS technology, information about Melaka's historical sites can be permanently documented. This is important because many historical sites are threatened by urbanization and climate change. GIS enables preservation in several ways: by creating a detailed digital record of the location, architecture, and historical context of a historic site, providing tools to monitor the physical condition of a site over time, and using this data to support conservation efforts and more sustainable urban planning.

Conservation and Repositories of Data, heritage site management, data management, data conservation, and data repositories are important in preserving and utilizing information related to Melaka's historical sites. Using GIS in this context focuses on integrating the spatial and temporal dimensions of heritage sites to facilitate their management and preservation.

Effective data management in GIS involves collecting, organizing, and updating data related to heritage sites. One of the main challenges is integrating data from various sources, including geographic, archaeological, and historical data. Malinverni et al. (2019) emphasize the importance of geodatabases in combining various types of spatial and non-spatial data, which allows for a more comprehensive analysis of heritage sites. This geodatabase allows for more structured multi-source data management, thus providing deeper insights into the sites being managed.

Data conservation involves preserving digital data containing important information about heritage sites to maintain them long-term. Data digitization is an important first step to ensure that site-related data can be accessed more widely. Cuca et al. (2011) pointed out the importance of data standardization in GIS, which enables interoperability between different GIS platforms and software. In addition, Hafez (2019) emphasized the need to build an integrated heritage information system to facilitate the storage and maintenance of data in an organized manner. This system should allow regular updates and protect data from damage or loss through regular backups and durable data formats.

Centralized data storage facilitates organized access for academics, management, and the public. Richards et al. (2013) stated that a sound information system for digital heritage preservation should allow various parties to access data with straightforward access controls. This data repository should allow open access to non-sensitive data, thus supporting collaboration and the use of data in various research and applications.

GIS is important in managing heritage site data through spatial information. This technology allows a better understanding of site changes over time and supports site preservation

and management more effectively and efficiently. Ciksi et al. (2019) showed that using GIS in heritage management allows for better site preservation and monitoring planning, especially in sustainability.

Conclusion

The researcher anticipates that this study will be beneficial to the general public, local authority, heritage organizations and any other related field. Interactive web application can act as a prototype of future web application development for local authorities with limited financial budget and no coding specialist required. Interactive websites are also capable of becoming efficient tools that can be used to facilitate data sharing, decision-making, encourage public participation in heritage management, conservation, monitoring the digital humanities, investigate the patterns of anthropogenic activities and the preservation process. A proper database development can greatly reduce conflict of data and resources such as redundancies, difficulties in finding data, limited storage, and more.

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