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Multi-temporal Digital Representation of Morphological Transformations in Old Mosul: A Web-GIS Model and User Experience Evaluation

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Abstract:

This research digitally represents morphological transformations in Old Mosul while tracking surrounding urban expansion on the city's right bank. The study integrates textual sources, historical maps, aerial imagery, and contemporary spatial data within a Geographic Information System (GIS) environment. Cartography sources were georeferenced, digitized, and assessed for special and historical reliability. The analysis compares the extent of the urban area, the size of urban blocks, and the length of the city wall across various time snapshots spanning from 637 to 2020. It also examines transformations associated with the construction of new streets and bridge approaches. The findings are presented via an interactive web platform that facilitates temporal navigation, cross-period comparisons, and the linking of specific landmarks to archival information and imagery. The results reveal an expansion of the urban area beyond the former walled boundaries, occurring alongside the reconfiguration of parts of the existing urban fabric underscoring the importance of distinguishing between the city's physical expansion and the alteration of its historical fabric. The platform's usability was evaluated using 101 survey responses collected through social media. The tools received an average rating of 82.10 out of 100, while the 46 respondents who completed all four understanding items, questionnaire reported an average score of 75.05 out of 100 for their perceived understanding of the city's morphology. An interactive web platform enables temporal navigation, cross-period comparisons, and links landmarks to archival information and imagery. The framework integrates documentation, spatial analysis, and interactive presentation to support education, research, and awareness of Mosul's urban-heritage.

Keywords: historical maps, georeferencing, spatial reliability, visual comparison, user experience.

Statements and Declarations

Funding: No funding was received for this study

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Author contributions: Abdullah Bashar Mohammed developed the methodology, collected and analyzed the data, developed the interactive platform, and wrote the original manuscript. Emad Hani Ismaeel supervised the research and reviewed the manuscript.

Data availability: The interactive platform is publicly accessible at https://abdbasharm.github.io/Mousl-Diachronic-Map/. Historic map sources and attribution information are provided within the platform. Anonymized questionnaire data are available from the corresponding author upon reasonable request.

Ethics approval: The study was approved by the academic supervisor.

Consent to Participate: Participants were informed of the study's purpose and provided written informed consent.

1-Introduction:

The "urban fabric" represents the physical and material composition of a city's urban realm, comprising streets, alleyways, building blocks, open spaces, and the interrelationships between them (Al-Nuaimi, 2018). Historic Islamic cities (such as the old city of Mosul) are characterized by a compact, organic fabric that is highly interconnected and pedestrian-oriented; in these settings, houses are clustered around internal courtyards and linked by narrow alleyways designed for protection and shade (Hassan & Thannon , 2026). This fabric evolves over time, and such transformations can be traced by examining shifts in the relationships between urban blocks, movement networks, and city boundaries. "Morphological change" refers to the ongoing, dynamic processes that lead to the alteration and modification of a city's physical structure and spatial forms over time (Hassan & Thannon , 2026). This evolution is influenced by a variety of factors—including natural and geographical conditions, as well as human, political, economic, and defensive considerations—such as the construction of walls and fortresses, the laying out of new streets, or the replacement of traditional, heritage-based building materials with concrete and steel (University of Mosul, 1991). To track these transformations, multi-temporal analysis enables a scientific comparison of a city's urban and spatial development across successive periods. This is achieved by monitoring changes in city boundaries, expansion patterns, street alignments, and the distribution of building blocks through the direct comparison of various historical maps and plans (al-Rashidi, 2025). Geographic Information Systems (GIS) provide the capability to map and analyze rich, location-based data (Kazouz, 2024), enabling the precise digital representation and analysis of urban changes. Given the rapid evolution of these technologies, maps are no longer merely tools for drawing or static documentation; they have transformed into geographic databases that allow for the simulation of historical urban fabric and the analysis of its structural characteristics—such as movement corridors and distinct digital access points (Yang & Liu, 2025). Previous studies have addressed various aspects of this process, ranging from the textual documentation of the urban environment in Mosul to the development of digital representation methods for historical cities.

1.1- Previous Studies

The studies reviewed in this research are divided between works that dealt with the history of Mosul and the transformations that occurred in its urban fabric and buildings, and works that examine the representation of historical cities and the management of their data digitally. The study (Kemp, 1979) provided rich historical documentation of Mosul's walls, gates, official buildings, markets, and khans. This study provides a historical basis for understanding the architecture of Mosul in the period it discussed, and current research benefits from it in interpreting the elements and transformations represented in the spatial sources. A study (Al-Dewachi et al., 2010) focused on the old Mosul markets area, and the study provided a good understanding of the compositional transformation, but its focus was limited to the markets area without studying the comprehensive morphological development of the entire old city through the series of available historical maps. A study (Marchetti et al., 2023) on the 'Ottoman Mosul Bridge', which focused on the history and documentation of the water bridge and its urban importance, but the study remained confined to the single architectural and historical scope of the bridge, without discussing the impact of the emergence and multiplicity of bridges on the form and development of the internal street network of the old city. A study (al-Rashidi, 2025) on Ismail Haqqi's Ottoman map of 1906 AD, which highlights the map as a rare and historical document. The study's treatment of the map and its historical context is useful in evaluating the source and understanding its content before using it in a multi-period spatial comparison. In addition to studies related to Mosul, other works have addressed the possibilities of building digital representations of historical cities and making them available through interactive interfaces. The study (Münster et al., 2025) addressed the problem of collecting and managing models of urban cities and displaying them in the form of interactive models on the web in light of the limited data available about them, and presented a solution that integrates computer linguistic models to process historical images and integrate them with 3D models accurately and smoothly. As for the study (Farella et al., 2021), it focused on addressing the absence of height information in two-dimensional historical maps to produce multi-temporal urban models with a good level of detail, and proposed a solution based on machine learning to estimate building heights based on geometric parameters with the generation of three-dimensional data and models. The study

(Vaienti et al., 2023) also provided a solution to the problem of the frequent lack of engineering data in historical records and the difficulty of complex manual modeling, from Through the development of an open software library that combines modeling with machine learning to automatically predict floors and roof patterns, and generate 4D city models at an advanced level of detail and in the JASON format. The gap that the research addresses, within the limits of the cross-sectional studies, is the need to integrate historical sources and multi-period maps within a spatial database that allows comparison of urban scale boundaries, blocks, and the movement network in Mosul, while indicating the varying reliability of the sources. The research adds to this by making these representations available via an interactive web platform, evaluating their ease of use, and their perceived usefulness in understanding morphological transformations. The traditional urban fabric of the old city of Mosul (since the city's inception until the year 2020) witnessed successive deep morphological deformations and disintegrations as a result of forced modern planning interventions (the construction of straight streets such as Nineveh and Al-Farouq Streets) and the entry of motorized transportation, in addition to the widespread destruction that befell the historical architectural structure during the liberation battles in 2017 AD (Nováček et al., 2021). The cross-sectional studies provide a historical and methodological basis for analyzing the urbanization of Mosul. The current research stems from the need to collect this knowledge and use it to represent a digital time series that allows comparison of city boundaries and its fabric. The research problem is how to convert heterogeneous cartographic sources into a digital representation that allows reading the change in the morphological shape of the city over the ages and using it to guide and manage information about the preservation of the heritage city and support sound reconstruction plans. To address this problem, the study examines the transformations that can be extracted from historical texts and maps to create an interactive digital representation of them.

This research begins with the following question: "How can historical and spatial sources from various periods be integrated into an interactive digital representation that enables the analysis of the morphological transformations of Old Mosul and the expansion of the urban fabric on the city's right bank?"

The research aims to construct a multi-period geographic database to document the morphological transformations of Old Mosul within the context of its urban expansion, drawing upon historical and spatial sources that vary in their characteristics and reliability. This is achieved by evaluating these sources, georeferencing them, digitizing their components, comparing indicators such as the urban area of city blocks and the length of the city wall, and examining changes in the street network and bridge approaches. Furthermore, the research seeks to make these findings accessible via an interactive web platform, while evaluating its usability and perceived utility among users.

2- Research Methodology

The research involved reviewing historical sources and conducting a comparative spatial analysis to construct a multi-period digital representation, which was subsequently made accessible via an interactive web platform—the user experience of which was also evaluated. The study began by examining textual and cartographic sources to identify periods that could be represented based on available evidence; this process was supplemented by consultative interviews to support historical framing and the interpretation of sources.

Geographic Information Systems (GIS) were employed to spatially reference the cartographic sources by identifying recognizable features and aligning them with a spatial reference framework. QGIS software was used to process spatial data and georeference historical maps, utilizing the "Georeferencer" tool and Ground Control Points (GCPs). Given the varying nature and geometric characteristics of the sources, their spatial reliability was assessed based on several factors: the number and distribution of GCPs; the magnitude and consistency of the transformation residuals resulting from the georeferencing process; and the inherent cartographic nature of each source, including any intrinsic geometric distortions. These reliability categories were used to determine the appropriate level of detail for morphological interpretation—they are not intended to imply a level of positional accuracy comparable to that of precise land surveying. Table 1 outlines the established spatial reliability levels and their implications for the appropriate level of detail for morphological analysis.

Classification	Interpretation
High	Stable spatial correspondence, adequate GCP coverage, relatively consistent residuals, and spatial sources with strong geometric characteristics such as aerial imagery or detailed modern maps. Suitable for medium-to-fine morphological analysis.
Medium	Acceptable spatial correspondence but with noticeable geometric uncertainty, distortion, scale limitations, or uneven residuals. Suitable mainly for regional or medium-scale morphological interpretation.
Low	Significant geometric distortion or high residual variation typical of early historical cartography. Used only for broad morphological patterns rather than precise metric measurements.

Table 1 Clarification of spatial reliability levels and their significance

Following the georeferencing of all maps and aerial imagery, digitization was carried out within QGIS. Features were saved as vector layers in Shapefile format and organized chronologically using the "Temporal Controller" tool. Urban elements—such as city blocks, landmarks, circulation paths, walls, the river, and bridges—were digitized into separate layers, based on the content of the source materials. These layers were grouped by time period and linked to relevant descriptive data and available imagery, enabling comparisons across different eras and the tracking of spatial transformations, while accounting for variations in the level of detail provided by the various sources.

The analysis relied on metrics including the total urban area, the area of individual city blocks, and the length of the city wall (in kilometers). For earlier periods, the urban extent was defined by following the path of the city wall as depicted in the source material; for later periods, where urban development expanded beyond the walls, the extent was determined by tracing the outer boundaries of the represented urban footprint. The measurements were confined to the right bank (western side) of the city of Mosul, encompassing both the historic core and subsequent expansions. An increase in the urban area was interpreted as an expansion of the urban fabric—though these modern expansions are not considered extensions of the historic fabric sharing the same characteristics—while also taking into account differences in the criteria used to define boundaries and the specific nature of the source materials.

The Field Calculator in QGIS was used to extract areas and lengths by applying the expressions `$area` and `$length`. The area of each urban block was calculated by aggregating the areas of the polygons defined by the surrounding streets; this includes buildings, open spaces, alleys, and internal pathways contained within those boundaries. Consequently, this area represents the urban units as depicted in the source materials, rather than the building footprints alone or a direct measure of building density. The length of the perimeter wall was determined by tracing its path—digitized as a linear feature—while accounting for variations in map detail and the completeness of its representation. The label "N/A" is used to indicate that a wall length measurement is not applicable for periods following the wall's removal, distinguishing this from cases where data is simply unavailable.

For temporal comparisons, the relative change for each indicator was calculated by subtracting the earlier value from the later value, dividing the difference by the earlier value, and multiplying the result by 100. Furthermore, the share of urban blocks within the urban zone was calculated by dividing the total area of the blocks by the total area of the zone for the same year, then multiplying by 100. This figure represents the proportion of the urban zone occupied by these blocks, rather than a building coverage ratio or a direct measure of urban density. When making comparisons, variations in the level of detail regarding how blocks are represented across different sources are taken into account. The calculated percentages of change represent the total change between the available snapshots—not annual growth rates—given that the time intervals vary. In cases where the initial value is zero, the percentage of change is mathematically undefined. The indicators were complemented by a comparative analysis of transformations in the street network, urban blocks, and bridge approaches, drawing upon historical sources for interpretation.

The outputs were made available via an interactive web-based mapping platform (Web-GIS), following the export of spatial layers from the QGIS environment into GeoJSON format using Python. The platform’s interface was developed using HTML5, CSS3, and JavaScript, utilizing the MapLibre GL JS library for rendering maps and layers. The

interface features a time slider and a spatial comparison mode for analyzing changes between two distinct periods. Furthermore, GitHub was used to host the project files and make them accessible online.

The Google Forms platform was used to create an online questionnaire assessing the platform's usability and its perceived utility in understanding the morphological transformations of the urban fabric of the historic city of Mosul across successive time periods. The evaluation focused on the user experience and the comprehension of changes and relationships between different historical eras and urban elements, thereby complementing the spatial and historical analysis presented in the study. The questionnaire included inquiries regarding the respondents' professional background and prior experience with Geographic Information Systems (GIS) and historical maps. It also featured questions designed to evaluate the historical timeline, visual comparisons, the accessibility of landmarks, and the linking of historical images to their respective locations. Furthermore, the questionnaire addressed the clarity of the city's developmental stages, the understanding of the relationship between its historical and contemporary forms, and the platform's perceived value in preserving urban memory. Open-ended questions were also included to gather feedback, suggestions for further development, and insights into the platform's strengths and weaknesses.

The descriptive analysis of the responses relied on frequencies, percentages, and the distribution of answers, with the total number of valid responses noted for each item. Items that were not applicable or left unanswered by certain participants were neither imputed nor counted as negative evaluations. Responses such as "I don't know" or "not sure" were retained within the descriptive distributions but were excluded from the numerical coding of the respective items. For multiple-choice questions, the percentage for each option was calculated based on the total number of responses, and the "all of the above" option was disaggregated into its constituent components; consequently, the sum of the percentages may exceed 100%. Two separate composite indices were constructed. The platform tool evaluation index comprised six items addressing the timeline, visual comparison, illustration of urban interventions, access to site-specific data, the linking of archival images to their respective locations, and the impact of these features on mental visualization. The perceived morphological understanding index consisted of four items covering the clarity of developmental stages, the relationship between historical and current forms, the tracking of changes in urban elements, and the utility of the platform compared to traditional methods. In the coding scheme for access to site-specific data, the responses "difficult to use" and "unclear" were grouped into the lowest category, while "acceptable" was assigned the middle rank, and "excellent" the highest rank.

To account for variations in response ranges, the items were converted into a standardized scale from 0 to 100. This was achieved by subtracting the lowest possible score from the respondent's score, dividing the result by the difference between the maximum and minimum possible scores, and multiplying by 100. The instrument evaluation index was calculated based on the mean scores of the valid items available for each respondent, while the comprehension index was limited to cases with complete data across its four constituent items. These indices represent summary scores rather than percentages of the total number of respondents. Cronbach's alpha coefficients were calculated using the raw (pre-conversion) scores, based on cases with complete data for the items within each index.

The Kruskal-Wallis test was employed to explore differences in the evaluation and comprehension indices based on the respondent's field of specialization and their level of Geographic Information System (GIS) usage. Spearman's rank correlation was used to examine the relationship between the two indices. The results are presented as exploratory, with the caveat that no adjustments for multiple comparisons were applied. Open-ended responses underwent an initial descriptive thematic coding process; this involved reviewing the text within the context of the corresponding questions, identifying key themes, and creating a log linking each response to its assigned code(s). Multiple codes could be assigned to a single response. Responses suitable for analysis were distinguished from empty entries or those indicating that the respondent had no comments, and the frequency of themes was calculated based on the responses provided.

3- Applying the methodology to the city of Mosul

3.1- The Multiple Historical Periods of the Old City of Mosul

The site upon which the old city of Mosul stands today—long before the Arabs expanded into it with their own construction—was once an Assyrian fortress, referred to by the Arameans as the "Crossing Fortress" (Al-Sufi, Khutat al-Mawsil, 1953). In the seventh century AD, during the era of Caliph Umar ibn al-Khattab, Mosul witnessed the emergence and development of an Islamic misr (garrison city) on the west bank of the Tigris River, opposite the historic city of Nineveh—a development that took place during the period of early Islamic conquest and settlement (Al-Sufi, 1970). Arab tribes were distributed among designated residential quarters, known as (khitat), which were organized around the initial congregational mosque and the governor's residence (dar al-imara) (Al-Hamawi, 1977). Fig. 1 presents a research-based reconstruction of the fortified core of this misr and the associated sites.

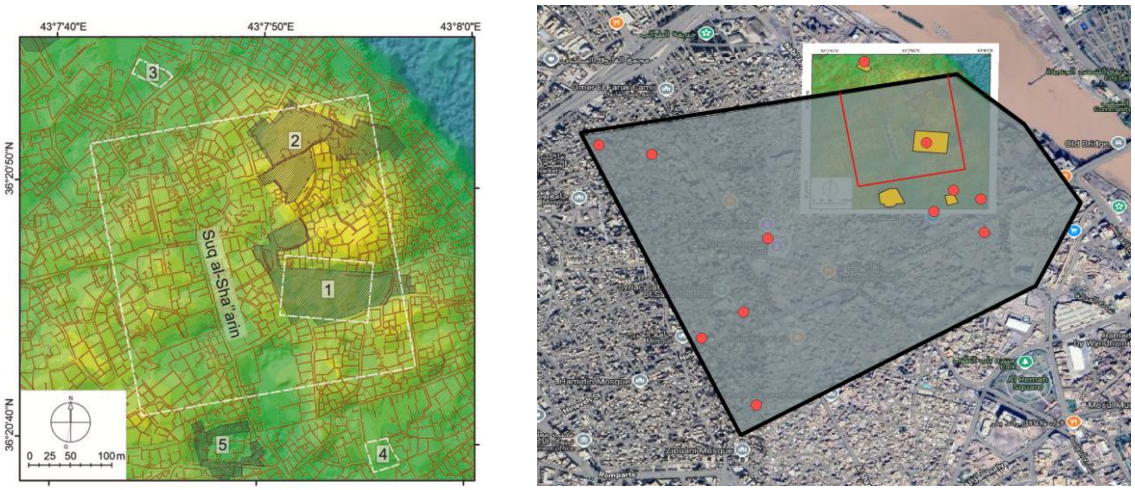


Fig. 1 The Old City of Mosul, detailing the fortified core of the "misr" (the large dashed square) and its associated, hypothesized sites, adapted from (Nováček et al., 2021)

During the Marwanid period, the governor Al-Hurr ibn Yusuf initiated the "Open Canal" (Al-Nahr al-Makshuf) project (Al-Azdi, 1967). Historians of Mosul generally agree that the canal began near the Monastery of Mar Michael, northwest of the city, passed by 'Ayn Kibrit, and followed the course of the present-day river for a total length of 10 kilometers (Al-Daywahji, 1982). Under the Umayyad Caliphate, Mosul became the capital of the Al-Jazira province, which accelerated the city's urban expansion and transformed it into a major metropolitan center (Sarre & Herzfeld, 1920). During the Atabeg period, the city's built-up area expanded significantly (Al-Nuaimi, 2018), covering approximately 3 square kilometers, while the northern citadel—known as the Citadel of Mosul or "Bash Tabiya"—was converted into a fortified administrative and military complex overlooking the river (Sarre & Herzfeld, 1920). Mosul's defensive structure underwent a transformation following the famous siege by the Persian ruler Nader Shah in 1743 AD, during which he unsuccessfully bombarded the city from the northwest, near the 'Amadiyah Gate (Niebuhr, 1778). Husayn Pasha al-Jalili, the governor (Wali) of Mosul, led a major campaign to rebuild and restore the city's dilapidated walls and strengthen its defensive fortifications, with the cooperation of both its Muslim and Christian inhabitants (Kemp, 1979). A map by Niebuhr, published in 1778, provides a representation of the city's general layout, its walls, and a pontoon bridge; this map is used in research to examine the city's overall spatial characteristics, within the limits of its geometric reliability (Marchetti et al., 2023). Additionally, the Prussian officer and traveler Helmuth von Moltke produced a plan of Mosul in 1838, which illustrates the city's urban reality and its defensive walls (von Moltke, 1841). Both the plan and his accompanying description reveal a contraction in the actual inhabited area: the northern section of the city—within the walls—had become a expanse of ruins and vacant land, while the population and urban activity were concentrated in the central and southern parts (von Moltke, 1841). In 1852, the British Captain Felix Jones conducted a comprehensive topographical survey of Nineveh and Mosul. Jones documented that Mosul's walls, along with their surrounding moat—which measured 20 feet in depth and 50 feet in

width—served as a significant barrier to the city's outward expansion, effectively defining its morphological form by acting as a clear boundary (Jones, 1853).

The 1906 Ottoman map serves as a source for understanding the city's movement network and urban fabric prior to the transformations documented in later maps. Following the First World War, with the arrival of British forces and the establishment of the Iraqi monarchy, Mosul underwent the most significant urban morphological transformation in its history (Sarre & Herzfeld, 1920). A map by Ernst Herzfeld (1919) provides a representation of the city's traditional urban fabric, documenting the initial construction of Nineveh Street, which, by the time the map was drawn, had extended as far as the Clock Church (Sarre & Herzfeld, 1920). In 1944, the population of Mosul was estimated at 100,000 (Marchetti et al., 2023). After 1944, the city experienced massive urban expansion beyond its historic walls, and contemporary neighborhoods were established on the left (eastern) bank; consequently, the old city of Mosul was relegated to the status of an aging, architecturally neglected commercial center (Hassan & Thannon , 2026). Satellite imagery from 1966, 1980, 2003, and 2020 allows for the tracking of urban expansion on the right bank of Mosul, facilitating a comparison of the growth of urban blocks and the street network across these periods, while distinguishing between the historic core and the modern urban extensions surrounding it. Old Mosul suffered unprecedented destruction during the 2017 liberation battles, which resulted in the loss of prominent landmarks—including the Great Mosque of al-Nuri and its leaning minaret, the Church of the Clock, and various other archaeological sites (Nováček et al., 2021). This loss underscores the importance of documenting architectural elements and linking their textual and visual records to their specific locations, while distinguishing between their historical state and the subsequent transformations they have undergone.

Based on the aforementioned historical framework, the history of Mosul—in terms of its urban development and as evidenced by available historical texts and maps of the old city—can be divided into successive time periods. Table 2 summarizes the historical periods that frame this study and illustrates their relationship to the years for which spatial data sources are available:

no	Name of the time period	Timeframe	Key landmarks, textual evidence, and urban transformations
1	The Assyrian Period: The Nucleus of Pre-Islamic Mosul	400BC	1- The Assyrian fortress (the crossing fortress), located on what is now the Al-Qulay'at height. 2- The founding of the hermitage of the monk Mar Isho'yahb (570 AD), leading to the formation of a settlement and the western quarters.
2	Islamic Foundation and Atabeg Expansion	636AD – 912 AD – 1096 AD – 1127 AD	1- Planning of the (misr) (garrison town) and the distribution of tribes around the first mosque and the (dar al-imara) (seat of governance). 2- Expansion during the Seljuk era, including the construction of administrative residences and a (qasr al-imara)

			(palace of governance), alongside further urban development. 3- Expansion under the Atabeg Zengi dynasty, extending 3 km² beyond the old walls, and the establishment of the Bash-Tabiya citadel.
3	The Early Ottoman Period	1778AD	1- The first drawn plan illustrating the morphological layout of the city of Mosul, by Carsten Niebuhr. 2- The siege by Nader Shah and the restoration of the city walls during the era of Hussein Pasha al-Jalili.
4	The Middle Ottoman Period	1838–1852 AD	1- The visit of Helmuth von Moltke and the creation of a map of the city of Mosul. 2- A reduction in the residential area, with the population becoming concentrated in the central and southern parts of the city. 3- The transformation of the northern part of the city into ruins and debris. 4- The visit of Captain Felix Jones and the creation of a detailed map of the city of Mosul, showing its relationship to the ancient city of Nineveh and the Tigris River. 5- The identification of the city wall and a trench measuring 20 feet in depth and 50 feet in width.
5	The Late Ottoman Period and Municipal Organization	1869–1906 AD	1- Establishment of the Mosul Municipality in 1869 2- Precise and detailed documentation of the dense organic urban fabric and public facilities by Ismail Hakki in 1906
6	The Royal Era and the Beginning of Constructing New Streets	1919م - 1944AD	1- Documentation of the urban fabric and the circulation network in the Herzfeld map (1919)

			2- Identification of newly introduced streets and changes in the urban fabric, as represented in the 1944 map
7	Modern expansion and the erosion of the heritage fabric	1966–2020 AD	1- Cutting through major, straight streets 2- Erosion of the city walls and the disappearance of the historic city gates 3- Expansion beyond the city walls into new areas, with construction that deviates from traditional styles 4- Construction of bridges and its impact on the historic urban fabric

Table 2 It illustrates the time periods the city has gone through, including significant events and changes it has experienced, based on the availability of maps and information.

3.2- Sources of maps and images

The selection and establishment of morphological phases are based on two primary references: first, the historically accepted sequence of maps of Mosul, as cited by both Herzfeld (al-Rashidi, 2025) and Karel Nováček (Nováček et al., 2021). Second, the researcher conducted three consultative interviews with experts knowledgeable about the history and urban heritage of Mosul. These discussions addressed the criteria for delineating historical periods, the selection of cartographic and textual sources, and the interpretation of transformations concerning streets, bridges, and landmarks. The interviews underscored the importance of consulting and cross-referencing original sources, linking historical chronologies with extant urban evidence, and acknowledging the limited spatial data available for earlier periods. They also offered diverse perspectives on periodization and documentation priorities. Consequently, these insights were treated as supplementary consultative material for establishing a historical framework and interpreting sources, rather than as a consensus on a single chronological division or an independent verification of the geometric accuracy of the maps. Given the varying nature and geometric characteristics of these sources, their use in comparative analysis necessitated spatial processing and an assessment of their reliability. Table 3 presents the map sources and satellite imagery utilized to represent the historical periods of the city of Mosul.

Name	Map Year	Resource
Karel Nováček	637	*Mosul After Islamic State* https://link.springer.com/book/10.1007/978-3-030-62636-5
Karel Nováček	912	*Mosul After Islamic State* https://link.springer.com/book/10.1007/978-3-030-62636-5
Karel Nováček	1096	*Mosul After Islamic State* https://link.springer.com/book/10.1007/978-3-030-62636-5
Karel Nováček	1127	*Mosul After Islamic State* https://link.springer.com/book/10.1007/978-3-030-62636-5
C. Niebuhrs	1778	*C. Niebuhrs Reisebeschreibung nach Arabien und andern umliegenden Ländern. Zweyter Band.* https://digi.ub.uni-heidelberg.de/diglit/niebuhr1778bd2/0539/image,info
Helmuth von Moltke	1838	https://www.lib.uchicago.edu/e/collections/maps/middleeast19/G7614-M6-1838-M6.html

Flex Jones	1852	https://collections.library.yale.edu/catalog/31923311
Ismaiel Haqi	1906	https://rememberingmosul.org/maps/
E. HERZFELD	1919	F. SARRE UND E. HERZFELD
British Navey	1944	Iraq and the Persian gulf
Satellite Imagery	1966	https://earthexplorer.usgs.gov
Satellite Imagery	1980	https://earthexplorer.usgs.gov
Satellite Imagery	2003	https://earthexplorer.usgs.gov
Map of Mosul	2020	Mosul Heart to Heart book

Table 3 It specifies the sources of the maps and satellite imagery, along with the years represented by each source.

3.3- Georeferencing and Assessing the Reliability of Sources

For the purpose of georeferencing, identifiable landmarks—such as the Bashtabiya Citadel, the Shrine of Imam Yahya ibn al-Qasim, the Qara Saray Citadel, the Mujahidi Mosque, the Great Mosque of al-Nuri with its leaning minaret (Al-Hadba), the Shrine of Imam Awn al-Din, the Mosque of the Prophet Jirjis, and the Mosque of the Prophet Shit—were utilized. These sites, which have existed in the city for over 300 years, facilitated the accurate georeferencing of historical maps to their original locations. They allowed for the topographic alignment of these maps within modern coordinate systems, enabling a comparison with contemporary maps to verify the precision and reliability of the spatial projection. Based on the historical context of the city of Mosul, the QGIS software was employed to represent historical information and maps discovered by the researcher. Although these historical maps lacked inherent geographic data, the researcher identified several fixed historical buildings—present across most of the maps—to serve as reference points for georeferencing within the EPSG:3857 (WGS 84 / Pseudo-Mercator) coordinate system. By importing the historical map image and utilizing the "Georeferencer" tool (accessible via the "Layer" menu), the researcher selected a series of reference points to project the map onto its actual geographic location (Fig. 2). For maps dating back to the early foundation of Mosul, the researcher utilized historical buildings that existed at that time and remain in their original locations today; these were sourced from the book (Mosul After Islamic State). Regarding the Islamic foundational period, the research draws upon the findings of Karel Nováček, mapping this era according to the three distinct phases he identified.

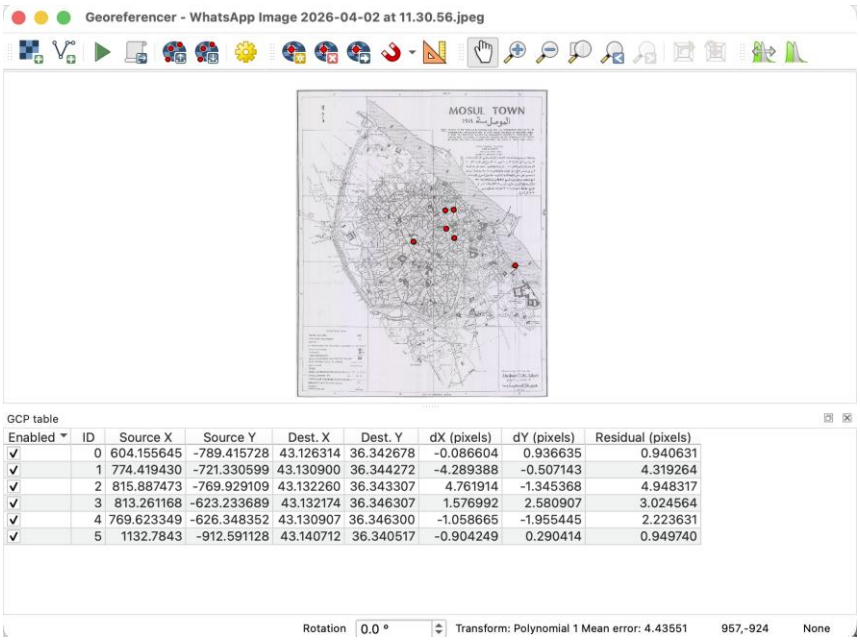
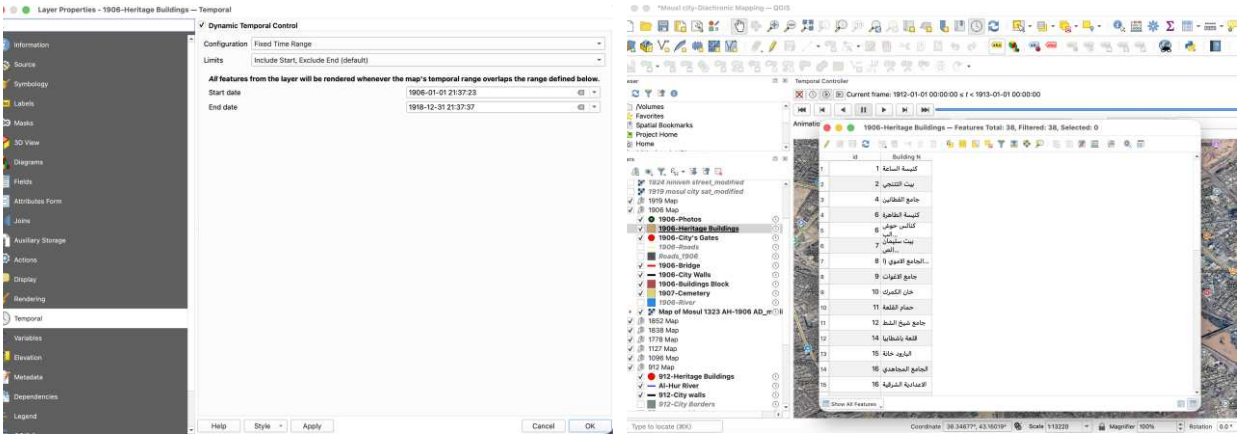


Fig. 2 The image shows the Georeferencing tool window in QGIS. The table within the image displays the coordinates of points that have been georeferenced—mapped to their actual locations—using the EPSG:3857 (WGS 84 / Pseudo-Mercator) coordinate reference system

3.4-Digitizing urban elements and building a database

Using QGIS software, fourteen sets were created, each containing a historical map sourced from its original records. Every set comprises multiple layers, with each layer dedicated to a specific feature—such as movement paths, historical buildings, the city wall, urban blocks (as depicted in the referenced sources), and the course of the river. A digital elevation model (DEM) of the city of Mosul was utilized to identify topographical depressions; these were then compared with historical descriptions of the Al-Hurr River's path near the Monastery of Mar Mikhail (St. Michael) to propose a spatial representation of its likely course. This representation is based on a synthesis of topographical evidence and historical data, with the understanding that the DEM alone is not definitive proof of the river's historical course or its full extent (Al-Daywahji, 1982).

Following the digitization of the historical maps and their georeferencing within the established spatial reference framework, textual data was added to the following layers: historical buildings, city gates, and the city wall. Each historical building and gate was assigned its specific, traditionally recognized name—information intended for future use in an interactive web-based model. Furthermore, the established historical periodization was adopted to construct a timeline using the QGIS "Temporal" tool. Each set was assigned a specific time range, ensuring it appears only during its designated interval; as one period concludes, its corresponding set disappears, and the set representing the subsequent period appears (Fig. 3). This timeline facilitates the organized presentation and interpretation of the maps, which would otherwise be difficult to comprehend if all were displayed simultaneously.



(a) (b)

Fig. 3 Organizing spatial and temporal data in QGIS: (a) managing layers and controlling the display of time intervals; (b) metadata for digitized features

In addition to the layers for buildings, movement paths, and gates, an extra layer has been included containing historical images captured during the previously mentioned time periods. These images are linked to the timeline and appear as points on the map; each point contains a link that allows the images to be displayed within the interactive web experience.

3.5- Diachronic Representation Platform

The platform was developed by exporting processed vector layers—including residential blocks, historical landmarks, roads, the river, walls, gates, and bridges—from the QGIS environment into a web-compatible, open data format (GeoJSON). The user interface was then built using HTML5, CSS3, and JavaScript, leveraging the MapLibre GL JS vector mapping library to ensure fast, seamless rendering of maps and spatial data. The application was designed as an intuitive, interactive web experience, prioritizing high performance and a modern interface, with the programming languages specified in Table 4 utilized throughout the development process.

A "Spatial Comparison Mode" algorithm was developed and integrated with a "Time Slider," enabling seamless navigation between the city's various historical eras. The interactive web experience was structured as a self-contained software module to ensure system stability and facilitate future updates. The interface features a primary display layer—anchored by a contemporary map of Mosul—complemented by a control panel for managing layers such as historical buildings, landmarks, and movement paths. The time slider allows users to transition between successive historical periods. This interface is powered by a dedicated backend script that dynamically fetches GeoJSON data layers corresponding to specific time periods, enabling real-time comparisons between different historical eras. Furthermore, the system provides a documented historical record for each era—enriched with archival imagery—which is instantly accessible whenever a user clicks on a historical landmark. This functionality relies on a data repository bundled with the application, containing all spatial databases in ready-to-use formats for immediate retrieval. The entire project—including the source code, archival images, and platform architecture—has been hosted on GitHub, ensuring it remains permanently accessible via a web link.

Technology / Library	Usage and Primary Role
HTML5	The general structure of the page (index.html), side panels, timeline, and control sliders.
CSS3 (Modern Vanilla CSS)	Interface design, dark colors, interactivity, and selective animations.
JavaScript (ES6+)	Fully programmatic interactive logic (main.js) for data loading, layer filtering, timeline management, and opacity control.
MapLibre GL JS / Leaflet	An interactive map engine for handling GeoJSON vectors, featuring smooth zooming and rotation, as well as the generation of popups.
Python	Preprocessing and exporting data from QGIS.

Table 4 Technologies and libraries used in the interactive web platform, with an explanation of their roles within the platform

3.6- Administering the questionnaire and preparing evaluation data

Participants were invited to complete the questionnaire via social media platforms—specifically the "Mosul Heritage Foundation" (Turath al-Mosul) pages on Facebook and Instagram—as well as on LinkedIn, ensuring accessibility for a diverse range of users across different platforms. Respondents were asked to explore the interactive platform—accessed via a link provided within the questionnaire—before answering the questions. This exploration was open-ended, with instructions embedded within the platform to guide users on how to navigate and interact with it. A total of 101 responses were collected between September 8 and September 18, 2026. Questions regarding "morphological understanding" were added while data collection was already underway; consequently, these were not available to participants who completed the questionnaire prior to this addition. As a result, there were 48 responses for the item concerning the clarity of the urban fabric's developmental stages, while the remaining items—covering general understanding, comparison with traditional methods, and shifts in perception—each received 46 responses.

Applying the calculation criteria outlined in the methodology, the index for evaluating the platform's tools incorporated 101 responses, each containing valid answers for at least four out of the six items. For the index of "perceived morphological understanding," complete responses across all four relevant items were provided by 46 participants.

4- Results

4.1- Results of the assessment of spatial quality and historical reliability of sources

The assessment of the sources reveals variations in spatial and historical reliability, as shown in Table 5. These variations affect the level of detail that can be achieved when comparing different periods. Consequently, the following quantitative indicators should be interpreted in light of these characteristics—particularly when comparing sources that differ in terms of their level of detail and geometric distortions.

Spatial source	Year	Source type	GCPs	Transformation	QGIS-reported mean error	Max residual	Spatial / georeferencing reliability	Historical / source reliability
Nováček et al.	637	Scholarly reconstruction	5	Polynomial 1	4.377	5.060 px	Medium	Medium
Nováček et al.	912	Scholarly reconstruction	8	Polynomial 1	0.710	0.726 px	High	Medium
Nováček et al.	1096–1127	Scholarly reconstruction	7	Polynomial 1	1.085	1.331 px	High	Medium
Niebuhr	1778	Original historical map	8	Polynomial 1	44.681	47.356 px	Low	High
Moltke	1838	Original historical map	8	Polynomial 1	143.901	199.214 px	Low	High

Jones	1852	Original historical topographic map	8	Polynomial 1	36.356	50.590 px	Medium	High
Ismail Haqqi	1906	Original historical urban map	6	Polynomial 1	44.812	51.777 px	Medium	High
Herzfeld / Mosul Town map	1919	Original historical urban map	6	Polynomial 1	4.436	4.948 px	High	High
British military map	1944	Original historical urban map	7	Polynomial 1	19.934	24.280 px	Medium	High
Historical aerial photograph	1966	Historical aerial photograph	10	Polynomial 1	9.602	10.547 px	High	High
Historical aerial photograph	1980	Historical aerial photograph	10	Polynomial 1	7.592	19.485 px	High	High
Source-georeferenced map / imagery	2003	Historical aerial photograph	N/A	Source georeferencing retained	N/A	N/A	High	High
Mosul Old City Map	2020	Contemporary urban / heritage map	7	Polynomial 1	6.198	7.968 px	High	High

Table 5 Evaluating cartographic and pictorial sources in terms of spatial and historical reliability

The research-based reconstructions for the early periods are classified as having a medium level of historical reliability. Their spatial reliability, meanwhile, ranges from medium—in the case of the map for the year 637 AD—to high for the maps representing the years 912 AD and 1096–1127 AD. This classification must be understood in the context of their nature as scholarly reconstructions rather than contemporary maps of the periods they depict.

In contrast, the maps by Niebuhr (1778) and Moltke (1838) are rated as having high historical reliability but low spatial reliability. The maps from 1852, 1906, and 1944 are classified as having medium spatial reliability and high historical reliability. This demonstrates that a source's historical value does not necessarily imply an equivalent level of geometric accuracy; consequently, one must exercise caution when interpreting subtle differences in boundaries and areas across various temporal snapshots.

The map from 1919, the aerial photographs from 1966 and 1980, and the map from 2020 all exhibit both high spatial and high historical reliability. As for the 2003 source, its original georeferencing was retained; therefore, no new ground control points or transformation residuals were generated for it within the scope of this study.

The results of this assessment serve to define the parameters for comparing different periods. The georeferencing residuals—expressed in pixels—should not be taken as an independent metric of absolute spatial accuracy. Furthermore, differences observed between measurements cannot be interpreted as actual urban changes without first accounting for the nature, level of detail, and reliability of the respective sources.

4.2- Changes in the extent of the urban area

This section presents the measured changes in the urban extent, block area, and length of the city wall across the selected time snapshots. The measurements are limited to the right bank (western side) of the city of Mosul, encompassing both the historical core and subsequent urban expansions. The calculated rates of change represent comparisons between each time snapshot and the preceding one, rather than annual growth rates (see Table 6).

Year	Source	City Area (km²)	Total Urban Block Area (km²)	Outer Wall Length (km)	Area Change (%)	Wall Length Change (%)
637	Nováček et al. reconstruction	**1.365**	—	**4.770**	Baseline	Baseline
912	Nováček et al. reconstruction	**1.907**	—	**5.383**	**+39.64%**	**+12.86%**
1096	Nováček et al. reconstruction	**2.704**	—	**6.740**	**+41.82%**	**+25.21%**
1127	Nováček et al. reconstruction	**3.599**	—	**7.673**	**+33.09%**	**+13.84%**
1778	Niebuhr	**2.962**	**2.066**	**6.391**	**−17.70%**	**−16.71%**
1838	Moltke	**3.793**	—	**9.198**	**+28.05%**	**+43.92%**
1852	Felix Jones	**3.411**	**1.675**	**6.939**	**−10.08%**	**−24.56%**
1906	Ismail Haqqi	**3.540**	**2.331**	**7.277**	**+3.78%**	**+4.88%**
1919	Herzfeld	**3.554**	**2.233**	**4.780**	**+0.41%**	**−34.32%**
1944	British military map	**7.559**	**2.758**	**N/A**	**+112.68%**	**N/A**
1966	Historical aerial photograph	**17.848**	**9.070**	**N/A**	**+136.11%**	**N/A**
1980	Historical aerial photograph	**21.447**	**10.800**	**N/A**	**+20.16%**	**N/A**
2003	Pre-georeferenced spatial source	**45.862**	**27.842**	**N/A**	**+113.84%**	**N/A**
2020	Mosul Old City Map	**71.110**	**49.003**	**N/A**	**+55.05%**	**N/A**

Table 6 Changes in urban extent, urban block area, and city wall length across the selected temporal snapshots

Note: The symbol "N/A" in the "wall length" column indicates that the measurement is no longer applicable following the removal of the wall—as per the documentation adopted for this study—and does not signify a loss of data.

Measurements derived from reconstruction maps for the early periods indicate an expansion of the urban area: from 1.365 km² in 637 AD to 1.907 km² in 912 AD, followed by 2.704 km² in 1096 AD, and 3.599 km² in 1127 AD. Subsequent maps show fluctuations in the measured area—ranging from 2.962 km² in 1778 AD to 3.793 km² in 1838 AD—before reaching 3.554 km² in 1919 AD. These variations should be interpreted in light of the discrepancies among historical sources and their varying degrees of spatial reliability—particularly in instances where assessments revealed limitations regarding geometric alignment.

A clear change in the size of the urban area is evident between 1919 and 1944; the area increased from 3.554 km² to 7.559 km²—a growth of 112.68%, according to the measurements used. This expansion continued, reaching 17.848 km² by 1966—an increase of 136.11% compared to 1944. This reflects the growth of the measured urban footprint to include city extensions beyond its former walled boundaries, while distinguishing these modern expansions from the historical core.

In more recent periods, the urban area reached 21.447 km² in 1980, followed by 45.862 km² in 2003, and 71.110 km² in 2020. The growth between 1980 and 2003 was approximately 113.84%, while the increase between 2003 and 2020 was approximately 55.05%. The figure for 2020 represents the urban area defined specifically on the right bank; it does not account for the total area of the city of Mosul (across both banks) nor the historical urban fabric alone. In parallel with the expansion of the urban area, the measured surface area of the city blocks increased from 2.233 km² in 1919 to 2.758 km² in 1944, then to 9.070 km² in 1966 and 10.800 km² in 1980, reaching 27.842 km² in 2003 and 49.003 km² in 2020. These figures indicate an increase in the total area occupied by the blocks defined by the surrounding streets. Since these block polygons encompass buildings, open spaces, alleys, and internal passageways, this increase cannot be interpreted as a direct measure of the building footprint or density.

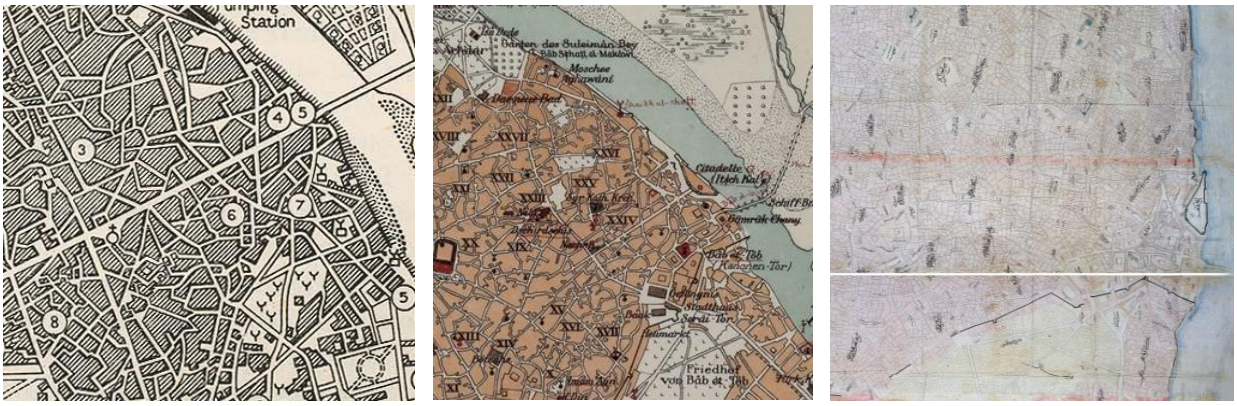
As for the length of the city wall—based on its representation in various maps—it measured 4.770 km in 637 AD and 7.673 km in 1127 AD; it was recorded at 9.198 km in 1838, compared to 4.780 km in 1919. These figures reflect the lengths of the paths as depicted and measured in each respective source; therefore, the differences between them are not, in themselves, sufficient to definitively establish the extent of the wall's actual expansion or the removal of specific sections. In the data entries from 1944 onwards, the designation "not applicable" indicates that the wall was no longer present—having been removed—according to the definition adopted in this study.

4.3- Spatial Transformations

Building on the assessment of changes in surface area, this section examines the locations and nature of spatial transformations by comparing street networks, block boundaries, and the placement of bridges—as well as their integration into the urban fabric—across different time periods. These changes are presented based on the elements depicted in the available sources, while accounting for variations in the level of detail and spatial reliability among the maps.

4.3.1- Transformations of the Street Network

The cutting of streets through the existing urban fabric emerged as a significant spatial transformation in the old city of Mosul. Notable examples include the axis of Nineveh Street—extending from Bab al-Jisr to Ra's al-Jadda—as well as Al-Farooq Street, and subsequently, Ghazi Street and Khalid ibn al-Walid Street. The morphological significance of these interventions lies in the way these thoroughfares cut across a pre-existing urban fabric, altering the boundaries of city blocks and the connections between traditional narrow alleys and the newly created streets. In examining these cases, a distinction is made between the documented history of the interventions and the changes observable in available maps. For instance, a 1906 map shows no trace of Nineveh Street; the circulation network was instead characterized by a web of narrow, winding alleys. By 1919, the beginnings of Nineveh Street appear, extending as far as the vicinity of the Clock Church—a development halted by the onset of the First World War (Al-Daywahji, 1982). Finally, a 1944 map reveals the full completion of Nineveh Street, alongside the clear presence of Al-Farooq Street; both serve as major thoroughfares that cut entirely through the old city of Mosul (Fig. 4).



1944 AD 1919 AD 1906 AD

Fig. 4 A comparison of the street network in Old Mosul based on maps from 1906 *(Haqi, n.d.)*, 1919 *(Sarre & Herzfeld, 1920)*, and 1944 *(Godfrey, 1944)*

4.3.2- The impact of bridges and their approaches

In addition to the construction of streets within the Old City, the impact of roads leading to bridges played a significant role in reshaping parts of the urban fabric on the right bank. The approaches to the Fifth Bridge serve as a clear example of this transformation; the creation of an access route to the bridge necessitated the excision of portions of the existing urban fabric and altered the boundaries of the city blocks along its path. A comparison between 1980 and 2003 reveals that a substantial part of the Al-Mashahda district in Mosul was carved out to

accommodate the bridge's route and its approaches. Consequently, the intervention was not limited to the construction of a river crossing; its spatial impact extended into the neighborhoods through which the access road passed.

This phenomenon can be analyzed by examining shifts in the continuity of the urban fabric, the boundaries of city blocks, and their relationship to the newly introduced axis of movement. The conclusions drawn from the digitized layers are limited to changes in these spatial units; they do not extend to quantifying the number of individual houses demolished, as the city blocks represented in this study encompass buildings, open spaces, and internal alleyways, rather than the footprints of individual structures.

4.3.3- A spatial reading of the hypothesized course of the Al-Hurr River

A digital elevation model (DEM) was analyzed—informed by historical descriptions referenced in the study—to propose a course for the Al-Hurr River in the vicinity of Deir Mar Mikhail, extending toward the city. Fig. 5 illustrates the spatial relationship between the topographic depression and the hypothesized river course within the reconstruction of this historical phase. This alignment serves as supporting spatial evidence for the reconstruction; however, it does not, in itself, constitute definitive proof of the river's history, the stages of its transformation, or its connection to the Tigris River.

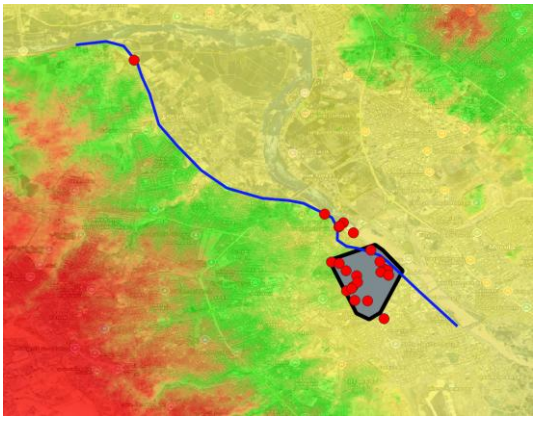


Fig. 5 A reconstruction of the hypothetical layout of Misr al-Mawsil in 912 AD, showing the Nahr al-Hurr originating near Deir Mar Mikhail in the north. The Digital Elevation Model (DEM) illustrates the relationship between the topographic depression and the hypothesized course of the Nahr al-Hurr

4.4- Platform outputs

The platform allowed the display of historical layers within an interactive interface that combines temporal transition, control of spatial content, and comparison between periods. Its outcomes are to allow exploring the distribution of urban elements in each period, comparing their representation between two selected periods, and linking the spatial elements to the information and images available about them. This section presents these capabilities as functional outcomes of the platform, while the next section addresses users' evaluation of its ease of use and perceived usefulness.

The timeline allows you to examine the historical period and view the associated spatial layers, while the control panel allows you to show and hide layers depending on the exploration topic. Thus, the user can focus on the distribution of blocks, movement paths, fences, and landmarks, then move between periods to follow the difference in the representation of these elements according to the sources available for each period (Fig. 6).

The comparison mode allows you to display two selected historical periods and compare the spatial elements represented in them. This function provides a means to explore the changing boundaries of the urban scale and the relationship of streets to blocks, linking the spatial results presented in the previous section to the possibilities of

browsing them within the platform. Reading the differences remains linked to the level of detail and availability of data in each period, as the absence of an element from one of the classes does not necessarily mean its absence historically.

The cartographic display is complemented by the availability of descriptive and historical information and archival images associated with landmarks when selected, according to the content available for each landmark. This allows the item to be read within its geographical location and historical context, and to combine its representation on the map with the documentary material associated with it.

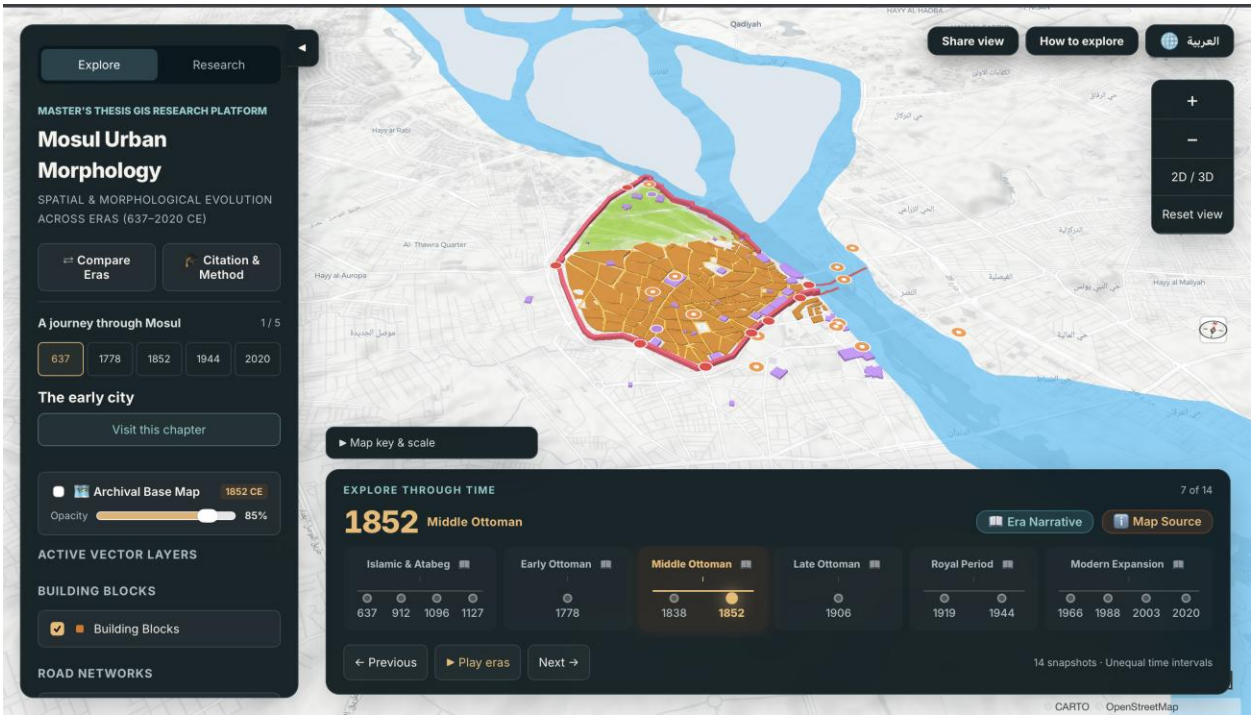


Fig. 6 The interactive platform interface, featuring a timeline at the bottom and a control panel on the left side of the screen

4.5- Results of user evaluations of the platform and its perceived usefulness

Following the presentation of the platform's functions and the outputs of its interactive comparison tool, this section outlines the results of a user evaluation concerning the platform's ease of use and its perceived utility in understanding the morphological transformations of the Old City of Mosul. The findings are organized as follows: sample characteristics and prior user experience; evaluations of interactive functions and the perceived understanding of urban changes; and, finally, anticipated areas of application and suggestions for further development. The number of responses for each item is indicated alongside its respective results.

4.5.1- Sample characteristics

The analysis encompassed 101 survey responses from individuals with diverse professional backgrounds. The largest group consisted of those in architecture and architectural conservation, accounting for 45 responses (44.6%). This was followed by respondents in academic teaching and research (across unspecified disciplines) with 14 responses (13.9%), and those in medical and health-related fields with 10 responses (9.9%). The remaining responses were distributed across various engineering, technical, and humanities-related fields, among others.

There was notable variation in prior experience with spatial tools and resources. Seventeen respondents (16.8%) reported using Geographic Information Systems (GIS) regularly, while 23 (22.8%) indicated that they never use them.

Regarding historical maps, 21 respondents (20.8%) reported using them regularly, whereas 17 (16.8%) stated they never use them. The remaining responses for both categories fell between "occasional" and "limited" use.

4.5.2- Evaluating the platform's ease of use and functionality

Table 7 presents the distribution of user responses regarding the ease of use of the platform's tools and functions.

Item	Highest grade	Intermediate grade	Lowest grade	I don't know
Easy navigation through the timeline	(%71.3) 72	(%23.8) 24	(%5.0) 5	—
The effectiveness of visual comparison layouts	(%61.4) 62	(%32.7) 33	(%1.0) 1	(٪5) 5
Clarifying the impact of major urban interventions	(%59.4) 60	(%37.6) 38	(%1.0) 1	(٪2) 2
Clear access to website data	(%66.3) 67	(%29.7) 30	(%4.0) 4	—
The value of linking archival images to their locations	(%61.4) 62	(%34.7) 35	(%4.0) 4	—
The Impact of Images on the Construction of Mental Representations	(%68.3) 69	(%28.7) 29	(%1.0) 1	(٪2) 2

Table 7 Distribution of user responses regarding the platform's ease of use and functionality (n=101)

Note: The cells display the number of responses and the percentage calculated based on a total of 101 responses. "Don't know" responses were retained in the descriptive distribution but were not treated as negative evaluations, nor were they included in the numerical coding for the index.

Seventy-two respondents (71.3%) selected the highest rating category for the ease of navigating the timeline, while 67 respondents (66.3%) chose the highest category for accessing location-based data. Regarding visual representation, 69 respondents (68.3%) selected the highest category for the effectiveness of historical images in facilitating mental visualization, and 62 respondents (61.4%) chose the highest category for the effectiveness of visual comparison. Conversely, five respondents (5.0%) selected "don't know" when evaluating the visual comparison feature; such responses do not, in themselves, constitute a negative assessment of the functionality. The mean composite index for the evaluation of the platform's tools was 82.10 out of 100, with a standard deviation of 18.06. This index summarizes the evaluations of the six items related to the platform's functions and represents a score on a standardized scale, rather than a percentage of respondents.

4.5.3- Understanding of morphological transformations

Following the assessment of the platform's functions, a further set of questions addressed its perceived utility in clarifying the developmental stages of the urban fabric, understanding the relationship between historical and contemporary forms, and tracing the emergence, transformation, and disappearance of urban elements. There were 48 responses regarding the clarity of developmental stages, while the other items—concerning the understanding of urban forms, comparisons with traditional methods, and shifts in perception—each received 46 responses. Consequently, percentages were calculated based on the number of responses available for each specific item (see Table 8). The lower number of responses for these items, relative to the total sample size, is due to their inclusion after the data

collection process had already begun—a point noted in the methodology; therefore, these results reflect only those respondents who provided answers to these specific questions.

Item	n	Very great extent	Great extent	Intermediate	Low
Clarity of the stages of urban fabric development	48	(%35.4) 17	(%50.0) 24	(%12.5) 6	(%2.1) 1
The relationship between the historical form and the current form	46	(%37.0) 17	(%47.8) 22	(%13.0) 6	(%2.2) 1
Track the appearance, change, and disappearance of elements	46	(%41.3) 19	(%39.1) 18	(%19.6) 9	0

Table 8 Distribution of responses regarding the perceived understanding of morphological transformations

Note: Percentages were calculated based on the number of responses available for each item: 48 responses for the item regarding the clarity of developmental stages, and 46 responses for each of the items concerning the relationship between historical and current forms, and the tracking of changes in urban elements.

Forty-one out of 48 respondents (85.4%) indicated that the platform helped them understand the developmental stages of the urban fabric to a "large" or "very large" extent. The corresponding figure for understanding the relationship between historical and current forms was 84.8% (39 out of 46), and 80.4% (37 out of 46) for tracking the emergence, transformation, and disappearance of urban elements.

When compared to studying maps and images individually, 44 out of 46 respondents (95.7%) perceived the interactive, sequential representation to be superior to varying degrees; one respondent noted no clear difference, while another preferred traditional method.

Regarding shifts in their prior perception of the city's development, 41 out of 46 respondents (89.1%) reported a change: 25 (54.3%) described this change as "clear," while 16 (34.8%) indicated that it occurred "to some extent." Conversely, five respondents (10.9%) reported no change in their perception. The mean score for the composite index of perceived morphological understanding was 75.05 out of 100, with a standard deviation of 20.61, based on 46 respondents. This index incorporates four items addressing the clarity of developmental stages, the relationship between historical and current forms, the tracking of elemental changes, and the perceived utility compared to traditional methods. This score reflects the respondents' assessment of the perceived benefit and does not constitute a direct measure of the actual amount of knowledge acquired.

4.5.4- Perceived educational, research, and documentation value

The user experience assessment was supplemented by a survey exploring the anticipated areas of benefit from the platform, including university education, historical and archaeological research, public awareness, and reconstruction and urban preservation projects (see Table 9). The questionnaire also addressed the perceived value of documenting destroyed landmarks in preserving the city's urban memory.

Field	Frequency	Percentage %
Academic Teaching and University Education	93	92.1
Specialized Historical and Archaeological Research	85	84.2

Field	Frequency	Percentage %
Raising public awareness and documenting spatial memory	82	81.2
Reconstruction and Urban Preservation Projects	78	77.2

Table 9 Expected areas of benefit from the platform, according to participants' responses

This was a multiple-choice question, with percentages calculated based on 101 responses. Academic teaching and university education emerged as the primary areas where the platform is expected to be useful (92.1%), followed by historical and archaeological research (84.2%). Respondents also identified public awareness, the documentation of spatial memory, and projects related to reconstruction and urban preservation as key areas, with 81.2% and 77.2% of responses, respectively. Regarding its documentary value, 94 respondents (93.1%) indicated that documenting destroyed landmarks via the platform contributes to preserving urban memory. While this result reflects the users' appreciation for the platform's potential documentary value, it does not, in itself, serve as a measure of whether preservation has been achieved or sustained.

4.5.5- Qualitative observations and suggestions for improvement

The quantitative results were supplemented by an analysis of open-ended responses, which shed light on aspects of user understanding and identified needs for further platform development. Thirteen respondents provided detailed feedback on aspects that became clearer to them after using the platform. Five responses highlighted urban expansion and city boundaries across different historical periods; four focused on urban fabric, building masses, and their relationship to urban planning; and four noted the value of direct temporal comparisons. Additionally, three responses addressed the street and road network, while another three focused on historical landmarks and their locations.

Regarding the section for comments and suggestions, 29 responses contained content suitable for analysis, representing 28.7% of the total responses. Key development proposals included simplifying the interface and reducing visual clutter (mentioned in eight responses), incorporating 3D representations (seven responses), and expanding the content, as well as the geographical and historical scope (six responses). Other feedback touched upon improving color-coding, enhancing image browsing and comparison features, ensuring mobile compatibility, and optimizing performance and loading speeds.

4.5.6- Internal consistency and exploratory analysis of assessments

The internal consistency of the items for the two indices—evaluation of platform tools and perceived morphological understanding—was examined using Cronbach's alpha coefficient. The coefficient was 0.780 for the first index and 0.859 for the second, based on the complete cases for the items in each scale, as shown in Table 10:

The Scale	Number of items	n	Cronbach's alpha
Evaluating the platform's tools	6	93	0.780
Perceived morphological	4	46	0.859

Table 10 Internal consistency of the platform tool evaluation indices and perceived morphological understanding

Spearman's rank correlation analysis revealed a positive relationship between the platform tools evaluation index and the perceived morphological understanding index, with a correlation coefficient of 0.733 ($n = 46$; $p < 0.001$). This indicates that higher ratings for the platform tools were associated with a higher level of reported morphological understanding; however, this correlation does not establish a causal relationship.

The Kruskal-Wallis test showed no statistically significant differences between specialization groups regarding either the platform tools evaluation index ($p = 0.530$) or the perceived understanding index ($p = 0.737$). Similarly, no significant differences were observed based on the level of GIS usage, with p-values of 0.419 and 0.865 for the two indices, respectively. These findings should be interpreted within the context of the analysis's exploratory nature; the absence of statistically significant differences does not confirm that the groups are equivalent.

5- Results and Discussion

5.1- Urban expansion and transformations of the urban fabric on the right bank

A chronological comparison reveals an expansion of the urban area on the right bank beyond the former walled boundaries—most notably between the snapshots taken in 1919, 1944, and 1966. Interpreting this transformation requires distinguishing between the city's overall expansion and changes to its historical fabric; an increase in the total urban area signifies the spread of development into new zones, but it does not imply an expansion of the historical fabric itself—that is, the original urban morphology. Consequently, the urban area as of 2020 encompasses both the historical core and modern expansions on the right bank; it should not be misconstrued as representing "Old Mosul" or the city in its entirety (across both banks).

An analysis of these spatial extents, alongside internal transformations, reveals two distinct levels of change: the outward spread of the urban footprint beyond previous boundaries, and the reconfiguration of parts of the existing fabric—driven by the construction of new streets and bridge approaches. The expansion of the urban area can occur simultaneously with the carving away of historical urban blocks or the alteration of how traditional alleyways connect to newly established traffic arteries. Therefore, changes in total area alone are insufficient to explain morphological transformation; one must also consider the specific locations of interventions and how they relate to the boundaries of urban blocks and the street network.

Nevertheless, the significant time gaps between these snapshots make it difficult to trace the continuous trajectory of change or to pinpoint the exact timing of individual interventions based solely on the maps. Furthermore, such comparisons are influenced by variations in the nature and reliability of the source materials, as well as the shift in how the urban extent is defined—using the city walls as a boundary for earlier periods, versus the outer limits of the built-up area for later periods. Accordingly, the results are interpreted as shifts between the states represented in the available sources, with historical documentation used to explain their causes and chronological sequence—without attributing the expansion solely to the removal of the walls.

5.2- The Value of Diachronic Representation in Interpreting Morphological Transformations

The platform's contribution lies in aggregating temporal layers, metadata, and archival imagery within an interactive environment that enables users to navigate between—and compare—different historical periods. This framework facilitates the interpretation of relationships between urban elements within their spatial and temporal contexts, linking quantitative data regarding spatial areas to specific changes in streets, city blocks, and landmarks. The value of this presentation remains contingent upon the quality of the source material and the inherent limitations of its reconstruction; consolidating these sources into a single interface does not eliminate variations in their original accuracy or level of detail.

User feedback reflects a positive reception of the platform's exploratory capabilities: 71.3% of respondents assigned the highest rating to the ease of navigating the timeline, while 61.4% gave the highest rating to the effectiveness of comparing different periods. However, because the evaluation assessed the platform's overall user experience—encompassing all its functions—it is not possible to isolate the specific contribution of each individual feature to the user's understanding.

Regarding the questions on comprehension, 44 out of 46 respondents indicated that the interactive, sequential representation was—to varying degrees—superior to studying maps and images in isolation. Furthermore, 41 out of 46 respondents reported that their prior perception of the city's evolution had shifted. A correlation was also observed between the rating of the platform's tools and the user's perceived level of understanding, with a Spearman's rank correlation coefficient of 0.733. While these findings consistently point to the utility reported by users, the conclusions remain subject to the limitations of self-assessment; correlation does not imply causation, and these responses do not constitute a direct test of the knowledge acquired or the historical accuracy of the reconstruction. The open-ended feedback indicates that, while the overall assessment is positive, there are specific areas for improvement—most notably simplifying the interface, reducing visual clutter, enhancing image display, and ensuring mobile compatibility. The feedback also highlights the importance of organizing content so that users can focus on the comparisons they need to make. Furthermore, the suggestion to incorporate 3D representations points toward a potential future development; however, this would require the availability of appropriate resources, as well as a clear indication of the level of certainty regarding the reconstructed elements.

5.3- Scope of the study and areas for its development

The results of spatial analysis are contingent upon the nature of the available sources, which vary in scale, level of detail, and geometric reliability. Historical maps, research-based reconstructions, and aerial imagery do not provide equivalent levels of information; discrepancies between them may reflect differences in representation rather than actual urban change. Furthermore, georeferencing residuals—calculated at the pixel level—do not, in isolation, constitute an independent assessment of metric accuracy. Consequently, conclusions regarding general trends of change are more robust than those concerning precise spatial details, particularly when derived from less reliable sources.

The significance of the measurements is defined by the spatial units employed. The "urban extent" encompasses the historical core and subsequent expansions, while the "block area" includes buildings, open spaces, and internal alleyways; it does not represent the building footprint alone, nor does it allow for the quantification of demolished structures or the direct measurement of building density. Additionally, the irregular time intervals between sources limit the ability to pinpoint the exact timing and detailed trajectory of urban transformations, necessitating the use of supplementary historical documentation when interpreting specific interventions.

As for the user evaluation, it relied on voluntary participation via online platforms and free exploration, without standardized tasks or fixed durations. Therefore, the results may be influenced by participants' prior interest in the subject, their varying levels of expertise, and the specific conditions under which they used the platform; the sample is not statistically representative of all potential users. The evaluation was based on self-reported responses following use of the platform, without the inclusion of cognitive testing—such as pre- and post-tests—or a comparison group. Consequently, the conclusions are limited to perceived utility and cannot definitively establish the extent of learning or attribute it causally to the platform.

Furthermore, questions regarding morphological understanding were added during the data collection phase; thus, they were not presented to the initial respondents. There were 46–48 responses to these questions, compared to 101 total responses in the overall sample. Therefore, the results from these specific questions cannot be automatically generalized to the entire dataset. Additionally, responses indicating a lack of knowledge were excluded from numerical calculations; the index for evaluating the tools was calculated based on the items available for each response, while the understanding index was limited to complete cases. This necessitates caution when interpreting these two indices, given the differences in their respective calculation bases. Moreover, statistical comparisons should be viewed as exploratory, as no corrections for multiple testing were applied.

Future research could refine this study by verifying historical representations through expert review and independent sources, expanding the spatial documentation of urban interventions, and conducting an evaluation of the platform that incorporates specific tasks alongside performance and comprehension metrics measured both before and after

use. Additionally, future work could involve testing interface enhancements and the accessibility of imagery across various devices, as well as monitoring the platform's application in education, research, and urban preservation to assess its practical utility over a longer timeframe.

6- Conclusions and Recommendations

The research concludes that integrating historical maps and textual sources into a multi-temporal geographic database enables the organization of disparate evidence and facilitates spatial comparisons of urban transformations in Mosul. Its contribution lies in linking the reconstruction of urban elements with the extraction of quantitative indicators, while providing an interactive web-based platform for exploration—all while acknowledging the varying reliability of sources and the limitations in their interpretation.

The comparison highlights the necessity of distinguishing between the expansion of the urban footprint on the right bank (the western side) and the evolution of the historical fabric within it. Modern expansions beyond the former walled boundaries do not represent a continuation of the historical fabric with the same characteristics; furthermore, an increase in total area alone does not reveal internal transformations, such as those resulting from the construction of new streets or bridge approaches. Consequently, interpreting morphological change requires combining area-based indicators with a spatial analysis of the relationships between urban blocks and the circulation network.

The platform enables users to navigate between different historical periods, manage layers, perform spatial comparisons, and link urban features to available information and imagery. An analysis of 101 responses yielded an average score of 82.10 out of 100 for the evaluation of the platform's tools, while 46 respondents who completed all four items related to morphological understanding reported an average score of 75.05 out of 100. These findings underscore the perceived utility of the interactive visualization among respondents, though they do not constitute proof of the accuracy of the historical reconstructions, nor do they serve as a causal measure of the knowledge acquired. The research recommends utilizing the platform as a supporting tool for teaching the history of architecture, urban planning, and urban morphology. It offers activities that enable students to compare historical periods and track changes in city boundaries, street networks, urban blocks, and landmarks. Furthermore, the research suggests using the platform for studies concerning the history of Mosul and its urban transformations; it serves as a means to organize spatial evidence and explore the relationships between various elements, while emphasizing the importance of consulting original sources and critically assessing their varying degrees of reliability.

The research also proposes making the platform available to entities involved in heritage and urban planning, to assist in identifying historical sites when preparing conservation and reconstruction studies—provided that such analysis is supplemented by field surveys and detailed documentation. Additionally, the platform could be employed in exhibitions and cultural or educational activities focused on the history of Mosul, allowing a broader audience to explore the city's transformations and landmarks, while fostering engagement between academic and heritage institutions and the local community.

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