Developing Geoportals and Applications for Singapore Historical GIS

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Abstract: This article presents Singapore Historical GIS, including geoportals and Web GIS applications, developed by the Department of Geography, National University of Singapore. Two types of geoportals have been developed for the dissemination of historical maps for GIS experts and non-GIS users to cope with their different levels of GIS background knowledge. Web technologies and metadata standards employed to implement the geoportals are first discussed. Web GIS applications are then introduced for facilitating spatiotemporal analysis using historical maps based on visual comparisons. In addition, issues relevant to historical GIS, such as intellectual property, data uncertainty, and spatiotemporal analysis, are examined to allow the potential users to understand the capabilities and limitations of this infrastructure.

Keywords: Geoportal, Historical GIS, Historical map, Singapore

1. Introduction

Historical GIS (Geographic Information System) projects have been carried out by various institutes and scholars to collect historical data and conduct spatiotemporal analysis of historical events. Some examples of the historical GIS projects are the National Historical GIS in the United States (https://nhgis.org/), the Great Britain Historical GIS (http://www.port.ac.uk/research/gbhgis/), and the China Historical GIS (http://www.fas.harvard.edu/~chgis/). Historical paper maps are important resources to understand geospatial phenomena over time particularly before the development of remote sensing technologies. Besides, in many tropical regions conditions are such that old satellite images and aerial photographs are often obscured by clouds and other components of the atmosphere, such as smoke particles from biomass burning. Due to the lack of available and suitable historical remote sensing data, historical paper maps present important resources for investigating and understanding temporal changes of geospatial phenomena in countries such as Singapore.

Historical GIS projects generally collect and collate historical spatial data and paper maps, and share the information online. The websites for historical GIS projects are not simply web portals to exhibit paper maps and data but infrastructure where historical data are searchable and sharable by metadata, connecting data providers and data consumers. A typical GIS project workflow consists of data collection and management, data processing, visualization, spatial analysis, and dissemination. For inclusion in a historical GIS, paper maps are collected, scanned, and archived as digital images. The digitalized paper maps are georeferenced by superimposing reference data (e.g., satellite images or authoritative road junction data). After that, historical geospatial features of interests can be extracted from the digitalized paper maps, visualized through GIS tools, and used for analysis. The digitalized paper maps and the analysis outputs can also be shared with users through the Internet.

Most of the historical GIS projects have been carried out to derive spatiotemporal quantitative data (Gregory and Healey 2007) because GIS has been perceived as a tool for conducting research with quantitative approaches. However, the usage of GIS is beyond quantitative approaches (Sheppard 2005). GIS can be considered as a media to deliver geospatial information, and used for qualitative analysis (Sui and Goodchild 2001). One of the examples of qualitative historical GIS is the Valley of the Shadow project comparing two counties, one North and one South, before, during and after the American Civil War (Thomas and Ayers 2003, Gregory and Healey 2007).

As part of an initiative to encourage the usage of GIS with qualitative and quantitative approaches in the humanities and social sciences, the Singapore Historical GIS project in the Department of Geography, National University of Singapore (NUS) has been set up. Singapore is the city exhibiting rapid urban transformation from a colonial city to a major global city, and has attracted interests of social science researchers to study such transformation to not only understand the history and heritage of Singapore but also inform future urban planning. To support such goal, a data repository sharing high-resolution geospatial data over time is indispensable. In addition, it is necessary to provide a means to facilitate broad access to a range of analytical and visualization tools that can be used to identify and examine spatial patterns. Accordingly, the Singapore Historical GIS is intended to enable researchers to focus on data analysis and interpretation, e.g., urban transformation, the pattern of colonial city, and the global financial hub. For our project, Singapore paper maps from 1846 to 2010 have been collected. The historical maps have been archived and shared via web portals. In addition, a number of web applications have been developed to compare multiple historical maps visually.

The remainder of this article is organized as follows. Section 2 illustrates the framework for implementation of the Singapore Historical GIS. Section 3 describes crucial issues in collecting historical maps, processing historical data, and analyzing

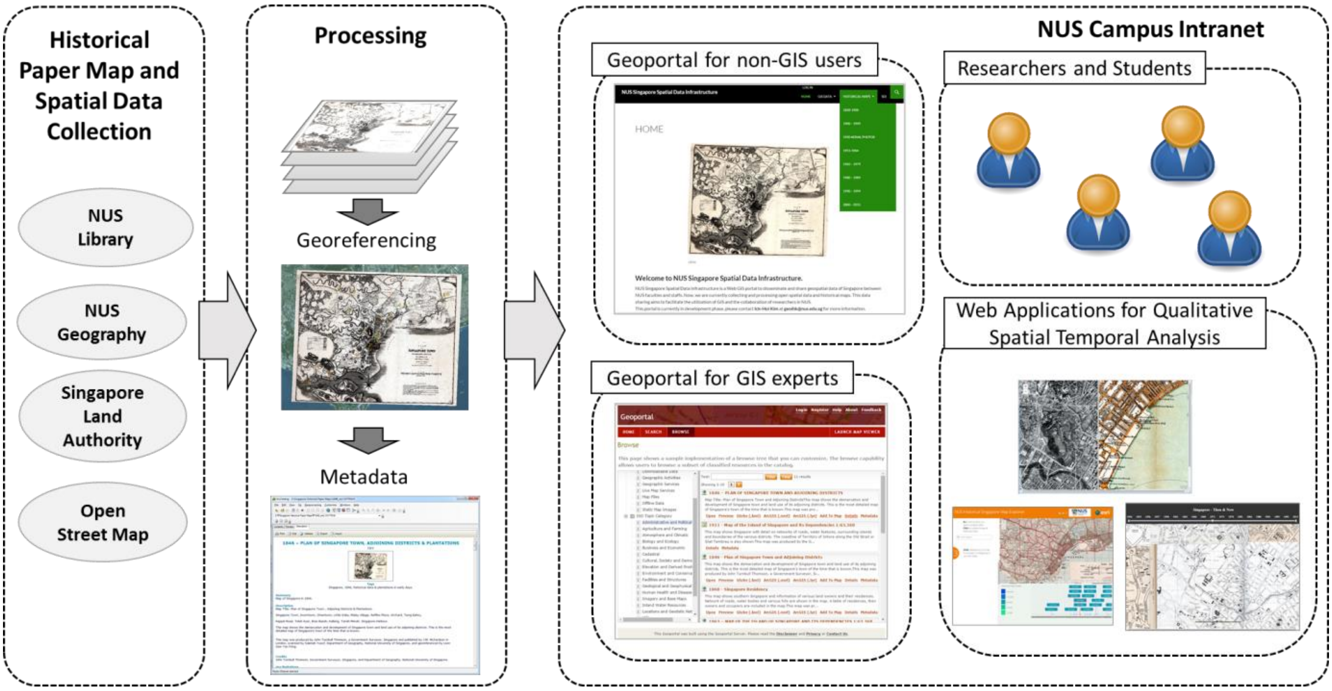

Fig. 1. The workflow of the geoportal for Singapore Historical GIS

spatiotemporal events through historical GIS. Section 4 and Section 5 demonstrate geoportals and Web GIS applications. Section 6 shows worked examples using historical GIS to understand landscape changes. Finally, Section 7 presents the conclusions.

2. The Historical GIS Workflow Components

The workflow components of the Singapore Historical GIS are data collection and processing, dissemination of historical maps, and spatial analysis (Fig. 1). Because the infrastructure includes topographic paper maps provided by the Ministry of Defence, Singapore, there is an intellectual property issue. Hence, the dissemination of the original paper maps has currently been limited to the NUS campus for research and education purposes only. Nevertheless, the geoportals are accessible outside the campus so that users can search and examine low-resolution paper map images and the list of paper maps.

The Map Resource Unit, Department of Geography, NUS, archives more than one hundred Singapore paper maps, including old paper maps, topographic maps, and aerial photos. These paper maps have been scanned into digital form and georeferenced. Georeferencing involves comparing the locations on paper maps with the same locations on geo-corrected satellite images. Then the digitalized paper maps can have spatial information. Metadata, or information on the digital spatial data, have also been uploaded to the geoportal. In the geoportal, the historical maps have been classified by time periods.

For the dissemination of spatial data, many countries and local governments have built web portals. In Singapore, OneMap and Data.Gov.Sg have been developed for sharing spatial data, but neither have provided useful resources for historical analysis. The only useful resource is the set of the Street Directory maps over forty decades provided by OneMap. The maps are high-resolution images and downloadable, but they are not georeferenced. Another government agency dealing with historical maps is the National Archives of Singapore, but only a list of historical maps is provided on the website without spatial information. Thus, to share historical data with spatial information, Singapore Historical web map services have been implemented with ESRI Geoportal Server and ESRI ArcGIS Server.

ESRI Geoportal Server is a free, open source software program for discovering geospatial resources and managing metadata. It is not dependent on ESRI products and is based on international standards. Thus, it integrates seamlessly with other web map services and provides a spatial data clearinghouse framework for accessing to metadata records, catalogs, and web services as well as ESRI ArcGIS map services. The compatibility of ESRI Geoportal Server with ESRI ArcGIS Server as well as standard web map services is the main reason why it has been selected as our geoportal for Singapore Historical GIS. In addition, as stable updates are offered by ESRI in accordance with the updates of related software, such as ESRI ArcGIS Server and Java, the adoption of ESRI Geoportal Server ensures the compatibility of our services to the most recent standards and technologies.

3. Issues of Historical GIS

Web GIS technologies have matured to implement historical GIS on the Internet to share and analyze historical maps. Some issues, however, need to be tackled before disseminating historical GIS to users. These issues are related to intellectual property and methodologies for data uncertainty and spatial temporal analysis.

3.1 Intellectual Property

The topographic maps have been provided through the official publisher of the maps in Singapore, the Ministry of Defence. Based on the map usage agreement with the Ministry of Defence, these topographic maps can be used for research and education purposes only. For users outside the campus, hence, the geoportals provide the list of the historical maps with low-resolution images. Watermarks have been added on the map images to prevent reproduction without permission.

Although additional historical paper maps are found in other government agencies, they cannot be incorporated into our historical GIS because permissions to use those maps are tied to individual projects. For instance, the National Archives of Singapore provides the list of paper maps. Although orders of those maps can be placed through the National Archives of Singapore, since the intellectual property owner is not the National Archives of Singapore, users should contact the original owners, such as the Singapore Land Authority, the Library of Congress, Singapore Maritime Museum, the National Library Board, and the British Library, for reproduction permissions. If users want to use the same maps for another research project, they need to obtain permissions separately.

Concerns over intellectual property are a major obstacle to a wide sharing of the digitalized historical maps and have meant the imposition of restrictions over access to the geoportal. Resolving intellectual property issues is needed if the geoportal for Singapore Historical GIS is to be fully opened up to the general public.

3.2 Data Uncertainty

One of the key issues of historical GIS is data uncertainty (Gregory and Healey 2007). Historical maps are intrinsically less accurate, and data uncertainty is higher than recent maps (Manzano-Agugliaro et al. 2013). Data uncertainty is caused by the less accurate surveying tools, incomplete projection information, and the georeferencing errors associated with mapping in the past. In addition, geospatial features are simplified and generalized for representation on paper maps. This leads to the loss of the details of geospatial entities on the maps and positional inaccuracy of paper maps. The uncertainty of spatial information has been an important issue in GIS (Van Niel and McVicar 2002). Fisher (1999) has classified the nature of uncertainty into three measurements, i.e., attributes, space, and time. Understanding the errors associated with these three measurements is essential because the errors of spatial data can also result in the uncertainty of outputs of spatial analysis. For the historical maps, additional uncertainties arise because paper maps are snapshots of a specific time, and no independent attribute information is usually provided; the latter is often extracted at a later date from the maps themselves.

Fig. 2. Road network junctions for positional accuracy assessment. Red dots and blue dots represent the junctions digitalized from the 1974 paper map and extracted from the present authoritative spatial data respectively.

Positional accuracy is commonly measured with the distances between true locations and recorded locations of corresponding point pairs. Although there is no global standard for positional accuracy, the U.S. National Map Accuracy Standard (United States Bureau of the Budget 1947) provides some references. According to the standard, the threshold used is 1/30 inch for scales larger than 1:20,000 and 1/50 inch for scales smaller than 1:20,000 respectively. This standard has been revised by the U.S. Federal Geographic Data Committee standard (FGDC) in 1998 to the National Standard for Spatial Data Accuracy (NSSDA) (Federal Geographic Data Committee 1998). In the guideline of NSSDA, the minimum number of control points is 20 and a normal distribution of the errors is assumed. This assumption implies no systematic errors and no major outliers; however, the lack of normality is often observed in positional errors (Zandbergen 2008), implying that the positional errors are not pure random errors. Thus, the positional errors in spatial data are the combination of systematic errors and random errors.

An example of the positional error patterns is illustrated in Figs. 2 - 3. Red dots and blue dots (Fig. 2) represent the road network junctions digitized from the 1974 paper map and extracted from the present authoritative road network data respectively. These road junctions are matching junctions that have existed consistently from 1974 to the present. Although regular error patterns (systematic errors) are identified in some areas on the map (Fig. 2), the error patterns are mainly irregular over the map, evident in the error field (Fig. 3) created by the interpolation of the distance errors between two road junctions

Fig. 3. The error field created by the interpolation of distance errors. The map extent is the same as Fig. 2.

(Fig. 2). Systematic errors can be fixed relatively easily, while the correction of random errors is more challenging. Thus, research efforts to further reduce the positional errors of geospatial features in historical maps are desirable so as to alleviate the potential inaccuracy of spatiotemporal analysis using historical maps.

3.3 Spatiotemporal Analysis

Spatiotemporal analysis is one of the main applications of historical GIS (Gregory and Healey 2007). Yet, spatiotemporal analysis is still challenging in the conceptualization of the space-time relationship and the implementation of the spatiotemporal data in GIS.

If vector data are created by digitizing geospatial features from paper maps, the data uncertainty issue discussed above can lead to discrepancies of geospatial features in different temporal snapshots. In addition, administrative boundaries have changed over time, making it difficult to compare and analyze attribute data based on administrative units, because their sizes and shapes have been modified. Furthermore, each map represents similar types of geospatial features with different symbols. For instance, buildings in downtown areas are represented by different symbols, such as black rectangles and grey polygons (Fig. 2). Caution is required when applying the historical GIS, as these inconstant symbolizations complicate spatiotemporal analysis based on historical maps.

4. Implementation of Geoportals

This section describes the implementation of metadata and geoportals for our Singapore Historical GIS project. Two types of geoportals have been developed, one for those with some expertise in GIS and a second for non-expert users. The geoportal implemented with ESRI Geoportal Server is designed to share geospatial data with GIS experts who have knowledge about spatial metadata standards, spatial data categories, and Web GIS technologies. The other geoportal implemented with WordPress is for non-GIS users, because many functions in ESRI Geoportal Server may be challenging for users without a background in GIS.

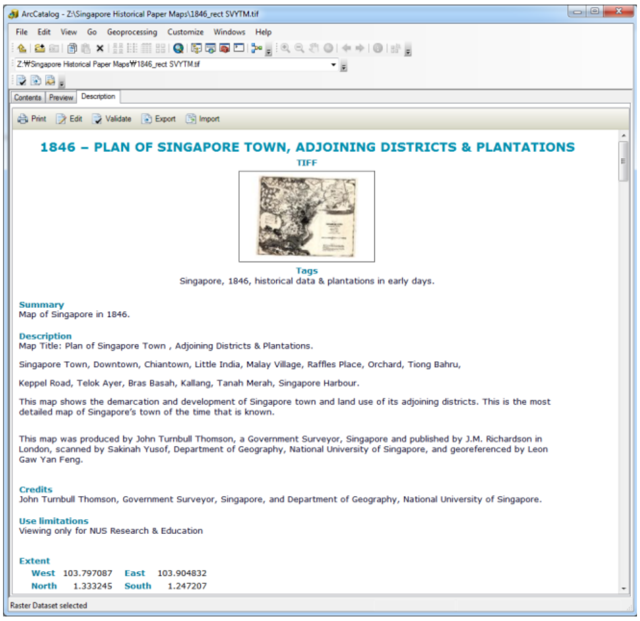

Fig. 4. The metadata editor in ESRI ArcGIS ArcCatalog showing a sample case of the 1846 Singapore Town Map.

4.1 Metadata

To share spatial data, metadata should be posted to and shared through the geoportal. Metadata comprise information about the spatial data, such as who created the spatial data, when the data were created, which areas the data cover, and how and where users can obtain the data. For a metadata standard, the U.S. FGDC Content Standard for Digital Geospatial Metadata (CSDGM), a commonly used standard, has been applied to our project.

The CSDGM consists of seven categories, including identification, data quality, spatial data organization, spatial reference, entity and attribute, distribution, and metadata reference. Each of the seven categories is further divided into dozens of sub-categories. Capturing all categories of the metadata is time-demanding and may not be possible for all historical maps. Consequently, the default option for the metadata editing tool, "Item Description", in ESRI ArcGIS ArcCatalog has been used in the project. This metadata editing tool includes key items to describe the data and allows users to edit part of the metadata categories that are the most important for their geoportal, such as title, summary, description, time period, keywords, credit, use limitations, and geospatial extent. If users want to provide more details, they have the flexibility to expand the categories and add more items. For our project, after selecting the FGDC metadata standard option in ESRI ArcGIS ArcCatalog, a few items based on "Item Description" have been filled, and some important items (e.g., citation and point of contact) have next been added by expanding the categories. A screenshot of the ESRI ArcGIS ArcCatalog metadata editing user-interface is shown in Fig. 4. Metadata should be converted to XML form using the "Export Metadata" tool prior to being exported to ESRI Geoportal Server.

4.2 Geoportal for GIS Experts

The geoportal for GIS experts has been designed and implemented to share spatial information and provide user-interfaces with GIS terminologies relevant to searching spatial data with spatial and non-spatial queries. Implementation has been conducted using ESRI Geoportal Server, a free open source product. Technically, the geoportal can be implemented with the combination of various programs, not limited to ESRI software. The necessary programs are a database management system, the Java Development Kit, Apache Directory Server, Apache Lucene, and Apache Tomcat. Apache Lucene provides functions to index and search spatial data through metadata. The authentication mechanism is based on the Lightweight Directory Access Protocol with Apache Directory Server.

The user-interface displaying the list of maps with metadata is shown in Fig. 5. The metadata created by ESRI ArcGIS ArcCatalog are posted to ESRI Geoportal Server, and an administrator checks the metadata and approves them. Metadata

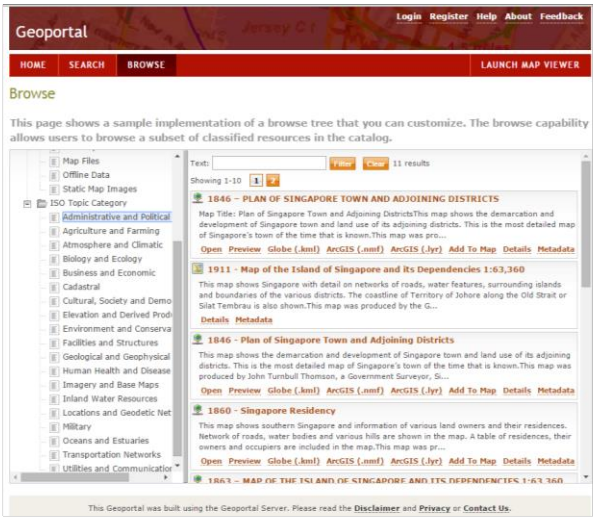

Fig. 5. The list of maps on ESRI Geoportal Server.

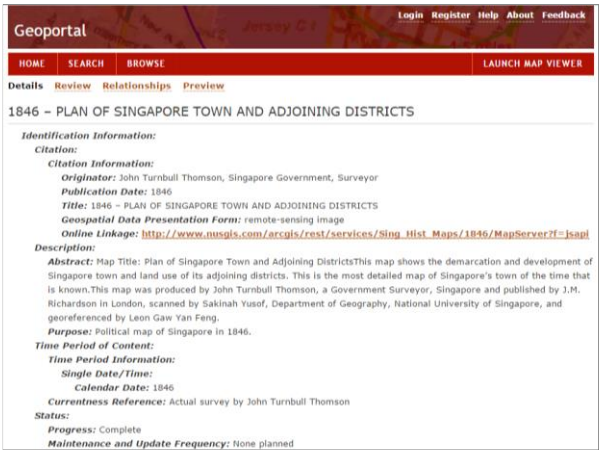

Fig. 6. An example of the metadata of the 1846 Singapore Town Map on ESRI Geoportal Server. "Time Period of Content" is under "Identification Information."

are then registered to the server, and become searchable through the geoportal. Based on the information provided by the metadata, users can obtain the information about how to download the data or how to contact the data provider. In addition, ESRI Geoportal Server can allow data publishers to edit the metadata online. An example of the user-interface for the metadata of the 1846 Singapore Town Map is illustrated in Fig. 6. Users of the NUS campus can access images via the NUS Intranet, while those outside the NUS campus can search the list of historical maps via the URL: http://www.nusgis.com:8080/geoportal.

4.3 Geoportal for non-GIS Users

The geoportal for those with little experience of GIS has been implemented with WordPress, a well-known content-management system. The paper maps are classified based on the year of map production. In this geoportal, the items describing the historical maps include the summary, the description, and the credit (Fig. 7). Most of the details about the maps are described under the description section, such as the place names

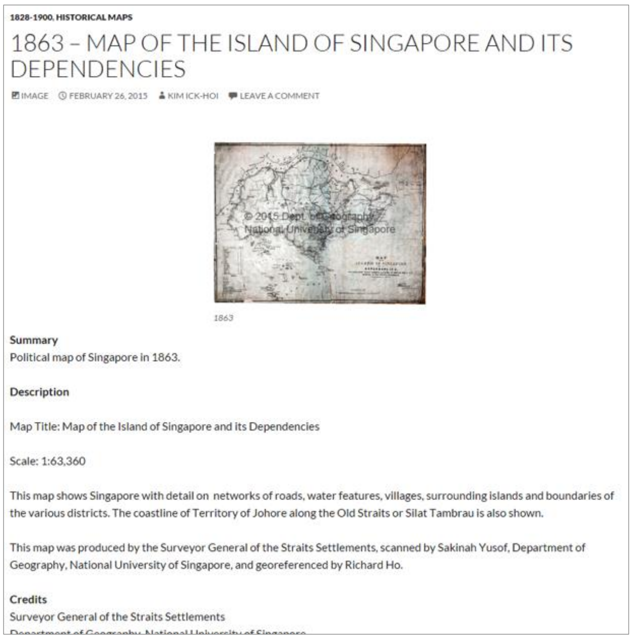

Fig. 7. The map description on the geoportal implemented with WordPress for the non-GIS users.

covered in the paper maps, the legends provided by the maps, and the scale.

The geoportal is accessible outside the NUS campus via the URL: http://www.nusgis.com/hgis. Intellectual property conflicts may arise because the geoportal for the non-GIS users is designed eventually to be accessible beyond the NUS campus. To circumvent any potential conflicts, at least for the time being, thumbnail images and low-resolution images with watermarks are provided through the geoportal as references to the original paper maps. This is similar to how the National Archives of Singapore provides the list of the maps through its website.

5. Web GIS Applications for Historical GIS

An approach to avoid the data uncertainty and the quantitative spatiotemporal analysis issues discussed in Sections 3.2 and 3.3 is to conduct qualitative analysis based on the visual comparison of historical maps. With a visual comparison, the concerns about data uncertainty issues closely relevant to the quantitative spatiotemporal analysis can be alleviated. This section presents Web GIS applications for spatiotemporal analysis with a visual comparison.

5.1 Map Swipe

The Map Swipe (Fig. 8) is an efficient way to interactively compare two historical maps of different years. The Map Swipe template provided by ESRI has been customized to analyze the landscape change in Singapore. To provide the Web GIS application via the Internet, Web GIS services should be built first. For the web services, the digitalized paper maps are registered to ESRI ArcGIS Server as image services. Then the service URLs are added into the Map Swipe template. Users of the Map Swipe can move the vertical slide bar side to side and compare the differences between two time periods to analyze the temporal changes of the landscapes.

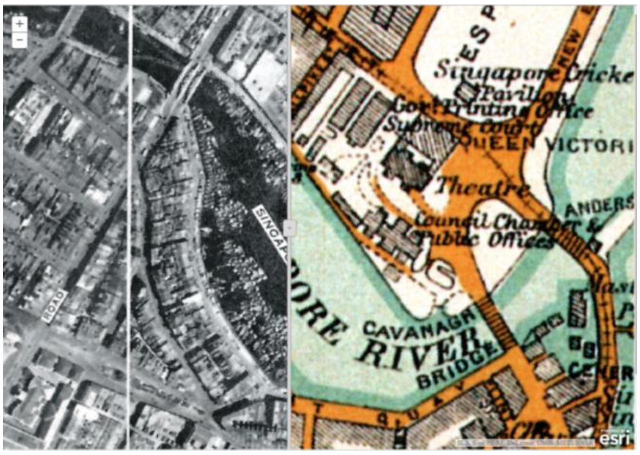

Fig. 8. The Map Swipe to compare the downtown area of Singapore in different time periods, with the 1950 aerial photo on the left and the 1910 paper map on the right.

5.2 Map Explorer

Inspired by the USGS Historical Topographic Map Explorer and the Yosemite National Park Map Collection applications, using the same template, the Singapore Historical Map Explorer (Fig. 9) has been developed to facilitate browsing of the scanned and georeferenced collection of historical maps. This Web GIS application allows users to identify a location of interest by searching for a location or clicking on the map. The application then retrieves a list of maps with coverage over the area of interest and presents them chronologically in an interactive timeline chart in the form of thumbnails. Users can then filter the maps based on scale and select maps of their interest for viewing. The function to change the opacity of the maps helps users to observe the differences between maps. For each of the maps, an URL to download the data is available for authorized users.

The backend technology supporting the application comprises map services, image services and feature services enabled by ESRI ArcGIS Server. Raster data sets derived from historical maps have been incorporated into an ArcGIS File Geodatabase format and managed through an ArcGIS mosaic data set. The ArcGIS mosaic data set has then been published to ESRI ArcGIS Server as an image service, which provides access to the historical maps through a web service. Polygons representing the coverage footprint of each map have been extracted from the mosaic data set and published to ESRI ArcGIS Server as a feature service. The application identifies the list of maps to be loaded onto the timeline by comparing the intersection of the polygon geometry from the feature service with the user's location of interest. An image of the map raster is automatically requested through the image service when a user clicks on an item on the timeline.

5.3 Singapore Then and Now

The Singapore Land Authority has scanned multiple editions of Street Directory maps published since 1954, and provides

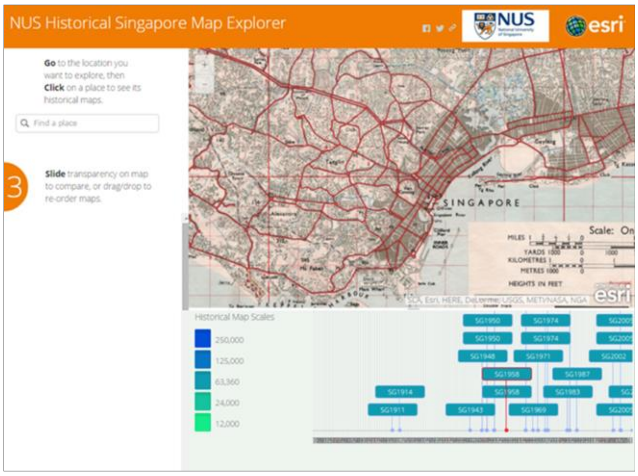

Fig. 9. Singapore Historical Map Explorer.

them for viewing and download through its OneMap web application. There are various numbers of images in each edition, from around 70 map images in the earlier editions to more than 100 map images for the later ones. With the Street Directory maps, the Singapore Then and Now Web GIS application (Fig. 10) has been developed for users to navigate the maps. To implement this web application, we have georeferenced the hundreds of scanned images using a semi-automated georeferencing approach by calculating the positions of the images at the boundary.

Once all the 18 editions have fully been georeferenced, they have been pieced together and published as map services through ESRI ArcGIS Server. The time slider at the top of the Web GIS application (Fig. 10) allows users to easily browse these editions of the Street Directory maps by sliding through the years and to compare the temporal changes of road networks and landmarks. These old maps overlay on top of the basemap of present day Singapore, which offers users an opportunity to observe changes through the years at any location. There are plans to add in feature editing functionalities to allow users to trace and digitize features from these old maps into vector data for their download.

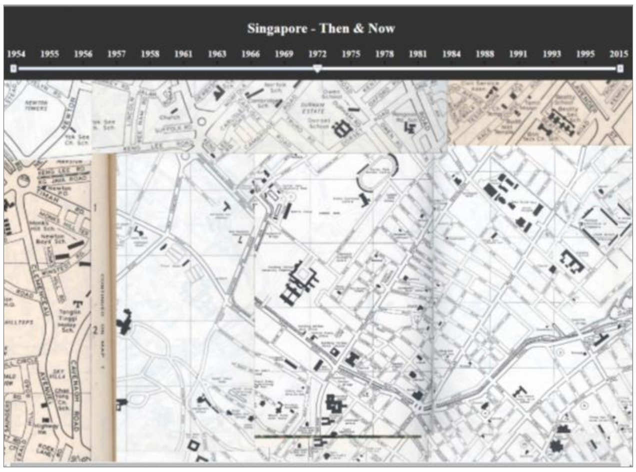

Fig. 10. The Web GIS application, Singapore Then and Now, allows users to easily browse various editions of the Street Directory maps prepared by the Singapore Land Authority.

6. The Case Study: Singapore Landscape Change Analysis by Visual Comparisons

Most researchers utilize GIS with quantitative methods to analyze landscape changes from natural environments to built environments (Antrop 2004, Bender et al. 2005, Tucci et al. 2010, Lloyd et al. 2012). A variety of digital spatial data sets - e.g., satellite imagery, administrative boundary, and land use – have been collected, processed, and analyzed over the years. For long-term periods, historical paper maps have been utilized by scanning, georectifying, and digitizing. For some geographers, however, landscapes can be read as text including symbolic imagery, social relations, and material cultures. GIS can also contribute to a better understanding of the context in which a map was produced. Qualitative GIS is a research approach based on the critiques about conventional GIS supporting quantitative analysis. Our case study demonstrates how GIS can support qualitative approaches to understand landscape changes in Singapore through historical maps.

The method employed in our project is straightforward and relatively easy to follow, and does not require expertise in complex statistical or spatial analysis procedures. The method here extends grid index comparison (mosaics of cells) and graphic symbols (line and color) (San-Antonio-Gómez et al. 2014). The following is worked examples. Grid index has been created and overlaid on the downtown area of Singapore where the first colonialists established a settlement (Fig. 11), and it has been applied to other historical maps (Fig. 12). Solid lines and dashed lines have been employed to represent respectively, either the presence or absence of the features in historical maps (Figs. 13-14).

Multiple time period maps have been analyzed to identify changes in housing types and the area around the Singapore River. Overcrowding and a high density of housing have been a factor throughout much of Singapore's history, and have contributed in the past to poor public health, including a high incidence of infectious diseases such as tuberculosis (Yeoh 2003). Changes in housing types and density are evident in Singapore through a comparison of the historical maps for a part of Chinatown shown in Fig. 13. In most of the historical maps, the housing types are not represented; only the 1893 paper map shows the details of the housing types at the time. In the 1893 paper map, there is no space between houses, but narrow spaces (backlanes) are shown in the 1950 aerial photo and the 2015 satellite image (Fig. 13).

For analysis of changes of the Singapore River, historical maps show that the tributaries identified in the 1846 and 1893 maps have disappeared and have been replaced with roads (Fig. 14). The small island in the river on the grid cell 20 that can be identified in the 1950 aerial photo has been connected to the riverside, and the river between the island and the riverside has been changed to a road. Then, in the 2015 satellite image, only the mainstream of the Singapore River exists. This transformation of the Singapore River shows the morphological

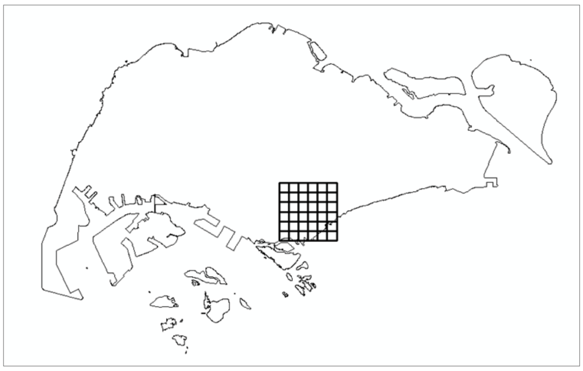

Fig. 11. The downtown area in Singapore with a grid index. Historical maps within the grid index are compared in Fig. 12.

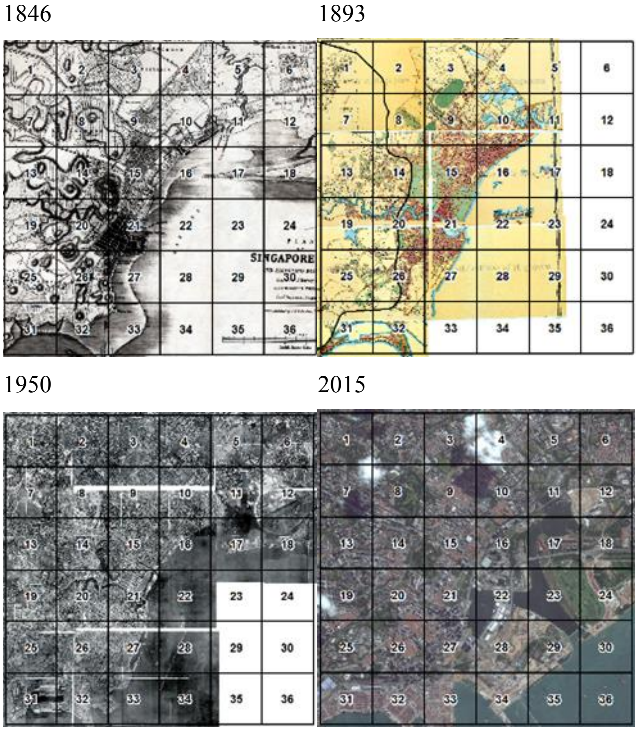

Fig. 12. Historical maps of four time periods with the grid index. The 1846 and 1950 maps are from the Map Resource Unit of NUS, while the 1893 map is from the Survey Department Collection, courtesy of the National Archives of Singapore. ESRI Imagery Basemap of 2015 is included.

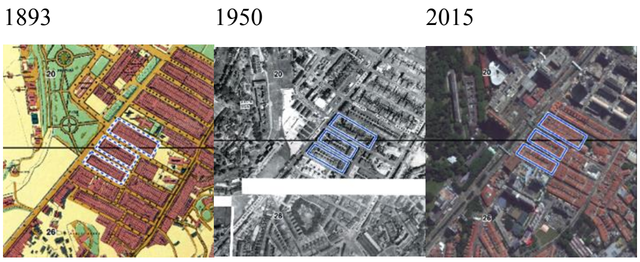

Fig. 13. Historical maps showing the different housing types in Chinatown, Singapore. Solid line and dashed line rectangles indicate the presence and the absence of backlanes respectively.

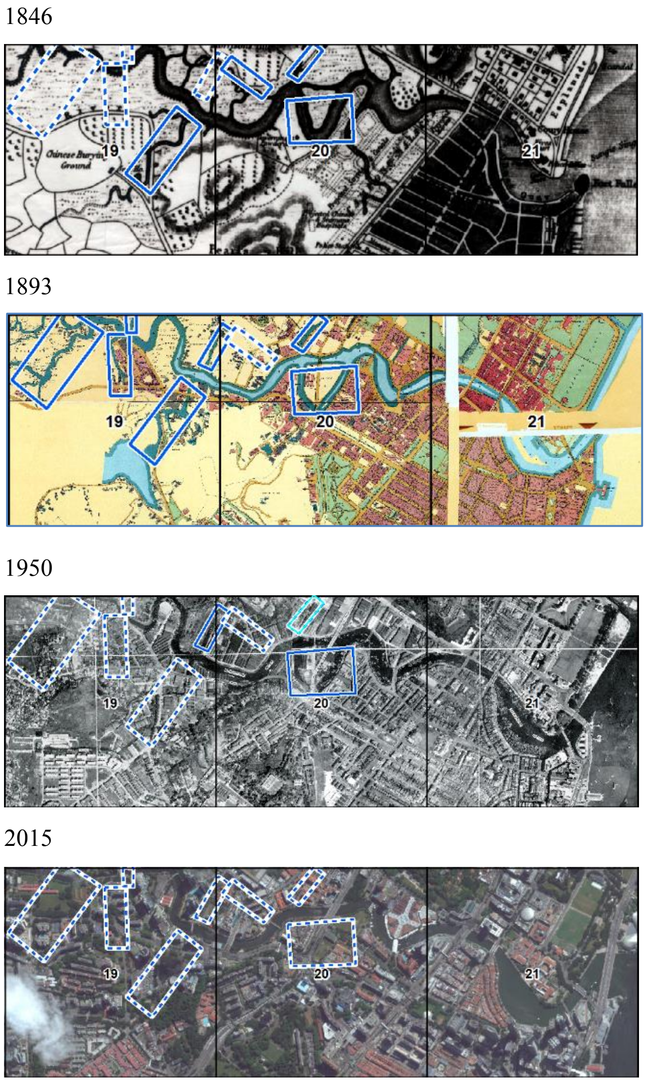

Fig. 14. Singapore River of four time periods. Solid line and dashed line rectangles indicate the presence and the absence of the Singapore River tributaries respectively.

changes and increasing demands on road networks due to urban growth.

The examples above illustrate the change of housing types and urban transformation respectively. The visual comparison allows us to revive footprints that have been modified and have disappeared on the current landscape. It can help us to understand the dynamics of historical footprints as well as landscape changes from natural environments to built environments.

7. Conclusions

This article discusses the processes of implementing the geoportals and applications and the issues for the Singapore Historical GIS. Web GIS applications for visual comparisons demonstrate the possibilities of employing qualitative spatiotemporal analysis for understanding the temporal change of the geospatial phenomena in Singapore. While data uncertainty and spatiotemporal analysis issues are known GIS issues not limited to historical GIS, the issue of intellectual property remains a main challenge for collecting and sharing historical maps for a wider range of users. It is hoped that these issues will be resolved with the advancements in GIS technologies and the cooperation with government agencies.

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