

Framework and Use Case for a Web-Based Interactive Analysis Tool to Investigate Urban Expansion and Sustainable Development Goal Indicators

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Abstract

Land cover changes have been mapped for decades to investigate urban expansion patterns. Under the UN Sustainable Development Goals (SDGs), several indices are employed to interpret urban growth trends quantitatively and comprehensively. However, landowners and the interested public usually have limited insights into these types of information as access to data and software is limited. Static maps and the inability to access special file formats increase the difficulty of viewing and investigating the data. This contribution presents a dedicated, interactive, web-based analysis tool for integrating land cover and land use maps as well as urban expansion indices. The tool's concept, development and functionality are presented, and its general design is reviewed based on an actual implementation case. The setup allows integrating land use and land cover (LULC) change data alongside SDG indicators. The tool's design aims to enhance user accessibility to information on urban expansion indices and LULC. We demonstrate that such a tool can be used to help disseminate results and to improve communication with the public in the context of other use cases.

Keywords:

web gis, land use and land cover change, lulc, urban expansion, sustainable development goals, sdg

1 Introduction

Over recent decades, urbanization has become the primary driver of changes in land use and land cover (LULC). This global phenomenon started on the urban periphery and has brought considerable negative environmental effects, such as air pollution, traffic congestion and water shortages (Arifeen et al., 2021; Brueckner, 2000, 2001). Rapid developments in remote sensing data analysis and GIS techniques facilitate investigating urbanization patterns and its effects, in particular pattern changes in urban sprawl. Such techniques vastly improve processing time and accuracy when it comes to identifying changes in LULC occurring over a given time period, thanks to their coverage of large areas and their short revisiting times. Recently, large

studies of urban areas have been conducted to closely investigate urban expansion (Dewan et al., 2008; Jat et al., 2008; Zhang et al., 2017). To quantify the extent of urbanization and show the sprawl patterns, some use cases have implemented Shannon's entropy and landscape metrics (Shannon, 2001; Shekhar, 2004; Sudhira et al., 2004; Bhatta et al., 2010). As cities have attracted more and more in-migration from rural areas, accelerating urban expansion, some studies focus on the impervious surface dynamics of built-up areas (Barnes et al., 2001; Yin et al., 2011; Sudhira et al., 2004).

For implementing its long-term strategic plan, the UN adopted the 2030 Agenda for Sustainable Development and has been focusing on 17 Sustainable Development Goals (SDGs), with 169 targets using 232 indicators. These indicators are designed to achieve a balance between human development and environmental protection (United Nations, 2014). Among the indicators, 11.3.1 covering Land Use Efficiency (LUE) describes the relationship between urban expansion and demographic change. This indicator is based on the ratio of the Land Consumption Rate (LCR) to the Population Growth Rate (PGR). The latter indicates the rates of population increases and decreases (including migration) in a given area. This derived indicator for urban developments can be incorporated into other indicators that relate to built-up area developments (e.g., 11.7.1, 11.2.1, 11.6, and 11.a.1). It has been proved in several application cases around the world that indicator 11.3.1 can reveal urban expansion dynamics through a close analysis of population growth (Wang et al., 2020; Ghazaryan et al., 2021).

Under the SDG framework, the European Commission has developed a suite of data, called the Global Human Settlement Layer (GHSL), which maps human presence in built-up areas, population distribution and settlement typologies, between 1975 and 2015. The GHSL combines worldwide data derived from satellite images and census data. It can be applied to display urban centres and aggregate their characteristics at a spatial resolution of one kilometre. Another perspective has considered the association between the drivers of urbanization and population increase, leading to the creation of a number of quantitative indices such as the Abstract Achieved Population Density in Expansion Areas (AAPDEA) index. This index can be used to identify population changes in urban areas within a specific period (Schiavina et al., 2019; Steurer & Bayr, 2020).

Although these data are accessible for download from public internet resources, distinguishing patterns and differences among various areas and periods during cross-comparisons remains challenging. A number of studies over the years have showcased various developments and implementations of web-based systems that demonstrate dynamic changes in environmental monitoring (e.g., Tsou, 2004; Han et al., 2015; Aye et al., 2016; Pratihast et al., 2016; Gitis et al., 2016; Gobakis et al., 2017; Acedo, 2020). However, general use of such systems on desktop devices may be limited due to the devices' input and format restrictions and environments (e.g., Wei, 2009; Gao & Mai, 2018). Additionally, if no web-based GIS is implemented on the server side, data providers require users to download data in their native format and to deal with them locally. This can easily become a major challenge for accessing large volumes of heterogeneous geospatial data, which – ultimately – leads to a reduction in the value and use of the data.

Such challenges have motivated researchers to develop various approaches and applications for map display. Over the past few decades, web mapping and the use of online geospatial information have evolved rapidly, with web mapping developing towards intelligence capture and data analytics for a wide variety of users and application bases. Traditional mapping methods suffer from limited reproducibility, distribution and data re-use (Neumann, 2017). By contrast, a well-designed web-based application generally includes an overall map design, a ready-to-use data implementation, and additional functions for analysis and exploration, which can be explored interactively by any user (Veenendaal et al., 2017). Such systems have become feasible instruments for publishing and illustrating research data and results, where accessible query functions enable users to make further investigations. Implementing spatial queries can be conducted through static web pages or via a web-server setup with database management at the back end, but the flexibility of these multifunctional systems and access to them may be limited by economic factors and time constraints when commercial desktop mapping software is used. Some of the economic constraints, particularly for government and educational institutions, can be overcome through open-source products (Pesch et al., 2007), though for non-UN members (such as Taiwan) access to open-source products may be difficult.

The limited pixel resolution of the GHSL dataset is a further drawback that makes it difficult for the public and decision makers to obtain detailed spatial information for national planning. This technical shortcoming led to our major motivation: to develop and showcase an interactive web-mapping platform based on open-source products by integrating LULC maps generated for different time slices and including relevant urban indices. At this stage of our project, the data provide snapshots at five-yearly intervals, between 1985 and 2015, of our main study area, Kaohsiung, for further observation of LULC characteristics. The final web-mapping platform is expected to be used as a prototype to disseminate the basic concept under the SDG framework. The aim is that it should be used to map the dynamics of urban expansion patterns, and to better reveal the characteristics of urban sprawl.

With respect to the SDGs, it is important to monitor and measure the dynamics of urban expansion, in order to provide metrics and visual aids for future planning purposes. Our case study focuses on the metropolitan area of Kaohsiung, in southern Taiwan, an important port. Over the decades, population growth and widespread infrastructure development have been witnessed in this area, putting pressure on the surrounding environment.

In Section 2, we discuss a general framework for a web platform design, and the integration of all related data on this platform. An introduction to various practical cases and the interface as a whole are presented in Section 3, where we also discuss the results.

2 Materials and Methods

2.1 General Framework and Data

This [webGIS application](#) (to which access can be made available on request) uses an open-source infrastructure and open standards, based on HTML and Cascading Style Sheets, along with dynamic JavaScript code, to retrieve data from the web-server side. The general design uses a client–server infrastructure, and the web browser can be represented as the client. The

overall architecture, including interactive functions and communication between the different tiers, is shown in Figure 1. The design comprises three tiers: the data storage, and the server- and client-side components. Together, these allow interactive access to mapping functions and data management. The client side comprises the map canvas, design elements, and functionality components shown on the user interface, including layer selection and an interactive toolbar. The server side mainly manages and communicates the requests between the front end and back end. Map data and attribute tables used for display and analysis are managed within the PostgreSQL 13 database management system with PostGIS 3.1 spatial extensions.

Data displayed in this web-based framework describe the dynamics of human development patterns, and include satellite images, pre-calculated LULC maps, and information on urban expansion. The LULC maps for this project were acquired from the preliminary classification results derived from machine learning and deep learning classification algorithms, such as Support Vector Machine, Random Forest and Convolutional Neural Network, covering the period 1985–2015. Data were also acquired from remote-sensing imagery from two earth-observation platforms: the NASA/U.S. Geological Survey (USGS) Landsat 5, and the Satellite pour l'Observation de la Terre 5 (SPOT-5). Processing steps integrate cloud masking and data mosaicking within the Google Earth Engine, where 200 points were manually selected for each land cover type to provide sufficient training data for classification. LULC changes were then mapped (cf. Tsai & van Gasselt, 2022). Classified results with the best accuracy were selected as the representative LULC maps for further investigation, with five categories included: built-up, barren and cultivated areas, water bodies and vegetation. Built-up areas were later extracted as a new layer for the demonstration and calculation of indicators. All the raster files were georeferenced before being published as dynamic layers and image-providing services. Detailed information demonstrating urban expansion is shown along with the LULC maps and demographic changes, with further indices calculated to describe driving forces and sprawl patterns.

Population data is provided by the Department of Statistics of the city government, which has been investigated at the level of the administrative district since 1975 (Civil Affairs Bureau, Kaohsiung City Government). This socio-demographic information is released annually, presented in uniform fashion. Two urban expansion indicators, land cover categories and demographic data, are set to the same spatial scale over time. With SDG goals in mind, after combining built-up area expansion with the rate of population increase for two time spans (1985 to 2000, and 2000 to 2015), LUE is calculated using the following formulae:

$$LCR = [\ln(\text{Urb}_{t+n}) - \ln(\text{Urb}_t)] / \Delta t \quad (1)$$

$$PGR = [\ln(\text{Pop}_{t+n}) - \ln(\text{Pop}_t)] / \Delta t \quad (2)$$

$$LUE = LCR / PGR \quad (3)$$

where Δt is the number of years between two time events, t and $t+n$; LCR is the natural logarithm of the proportion of urban areas within y years, and PGR is the natural logarithm value of the population change within y years. The final derived value for LUE is the ratio of LCR and PGR.

The Abstract Achieved Population Density in Expansion Areas (AAPDEA) index is also generated as another reference to describe the socio-demographic changes in the same selected period. This index is calculated using the following equation:

$$\text{AAPDEA} = (\text{Popt} + n - \text{Popt}) / (\text{Urbt} + n - \text{Urbt}) \quad (4)$$

These indicators are pre-calculated and stored in the database for later integration and visualization through dynamic maps or graphs to make the overall display of urban expansion patterns more detailed and interactive. All the data provided are for administrative district units only, as this is the only level available in the population data source.

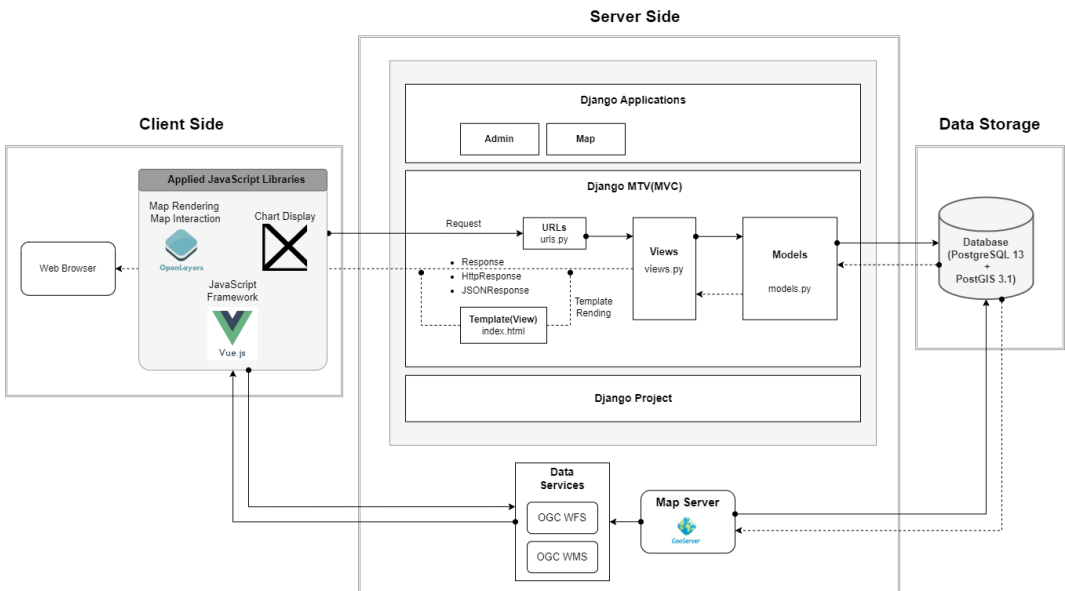


Figure 1: WebGIS System Architecture used within this project.

2.2 Server Side

The server side comprises two parts: web server and map server. The web server is configured using the Django 4.0 framework, a high-level python web framework for the design of web applications. Through a GeoDjango extension setup in the original framework, spatial data can be queried and processed with great ease. This framework follows the Model-View-Controller design pattern, where models are the definitive source of information that is derived from databases and linked to the individual stored tables (Django, 2019). After the models have been registered, users can be authorized to manage, edit and update the models via the admin page. These updates are saved to the database. Through the controller passing requests from the client to models, appropriate data can be queried and processed at the back end. These data can be viewed directly, as JSON or HTTP responses, rendered in the front end. For the map server design, the well-established open-source software Geoserver 2.19.1 is

applied. This software enables users to share and edit geospatial data; the data can be shared publicly as a Web Feature Service 2.0.0 and Web Map Service 1.1.1, by following Open Geospatial Consortium (OGC) standards (Open Geospatial Consortium, 2002, 2006, 2010). In this case study, we published several datasets in the Geoserver environment, to enable requests to be pulled from the client side. These data are transferable using XML, specifying the properties and field of the spatial data. The use of GetCapabilities helps to return the XML in open standard format, which for the client increases the ease of obtaining field data stored in the spatial features. The administrative district/village boundaries can be published as a Web Feature Service and can later be pulled in GeoJSON format for detailed queries.

Another practical use of the tool is to mosaic georeferenced raster data as an ImageMosaic store, which extends the online mapdata services with both spatial and temporal dimensions. This extension greatly enhances the uses of large-scale and long-term data. Our project implements the extension to manage long-term spatial data including pre-processed satellite imagery and classified LULC maps. This allows easier public access to the data online, as interactive maps. The basic map design on this open-source platform is supported by the Styled Layer Descriptor, which allows the user to specify how features should be rendered.

2.3 Client Side

Developing the front end of a web-based system requires a number of libraries and functions to interact effectively; without suitable interaction, conflicts may arise between functionalities. An adaptable framework that allows integration with other libraries or existing projects is beneficial for a user interface setup. In this study, the client side uses Vue.js 2.6.14 as the main framework for developments. Initially, it requires minimal effort to divide elements for development into different components. Development can then take place gradually as the needs arise. This brings advantages for the entire website development, since functions and components are like blocks that can be moved, modified and combined with more flexibility.

Dynamic map rendering and interaction functions are based on the latest version of OpenLayers 6.12.0, an Open Source advanced JavaScript library for the creation of light Web-GIS clients (Hazzard, 2011). It includes a very large API for displaying basics, while other plugins allow additional data filtering and rendering functions, which are also published as reusable APIs. Maps hosted on the server side are pulled through defined OGC standard protocols and passed to the front end. These maps can be displayed and overlaid with defined styles and custom configurations. In addition, through the GetCapabilities support, users can make requests and receive objects in return together with data representing their capabilities.

For higher performance on real-time updates and plot rendering, statistics charts are based on Chart.js 3.7.0 libraries. Drawing on the synchronized tables saved in PostgreSQL databases, data used for demonstration are fetched by specific .ajax commands and then updated during each mount and refresh. The overall environment for interface design and the implementation of the web-based application are HTML-based; Cascading Style Sheets are applied for describing the appearance of interfaces. Graphic icons are retrieved from Font Awesome font repository 4.7.0; the content of modal windows, the navbar and the info buttons rely on Bootstrap JavaScript library 5.0.2. These functional add-ons make the interface user-friendly and reduce the development-time costs. The pre-existing OpenLayers modules enhance the

design of interactive tools in the front end (e.g. map zoom-in and zoom-out, and display of coordinates for the mouse pointer), making them more user-friendly. An extension offered by this study is the combining of OpenLayer modules with custom JavaScript code to enable users to switch between layers and change the opacity. In order to enhance user-friendliness further, `getView` and `getCenter` are employed to develop a Spatial Bookmark function, which allows a geographic location to be stored for future revisiting.

Long-term LULC changes and the expansion of built-up areas are visualized through the adaptation of the Web Map Service Time example, where layers can be smoothly reloaded when changes are requested through an interactive slider. Administrative districts and village boundaries are acquired from a self-published Web Feature Service in Geoserver and rendered on the map. Further implementations and functions to combine queries have also been developed. After pre-calculated urban indices saved in the databases have been linked, users can query detailed figures and trends of statistical graphs through `onClick` based on the spatial units. All the above design functions have been integrated in the toolbar for users.

3 Implementation Cases and Results

This paper presents a more interactive approach to visualizing urban expansion patterns, through a user-friendly interface for online data access. The approach was tested by randomly picked students who were not familiar with the topic in-depth. A practical assignment and questionnaire were handed out, and contributions were anonymized upon return. Participants' feedback highlighted the user-friendly nature of the guides and the accessibility and clarity of the overall design of the website. Tips and guides for users appear in a pop-up window when the user first accesses the system, before they start to investigate the different functions (see Figure 2). The information covers basic functionalities, such as layer selection, the use of a dynamic slider to identify various spatial and temporal services, and how to query statistical graphs to identify changes. The application includes all five of the core functionalities that were originally planned, as shown in Figure 3. Map navigation is provided by interactive pan, zoom and mouse-click actions. Users are able to switch basemaps and add customized spatial bookmarks via various functions presented in the toolbar. Additional LULC map tiles and other dynamic layers can be added to the map canvas. The current view can be saved as an image for output, distribution or further analysis.

In this paper, the effectiveness of the web-based design as a whole will be summarized in two applications in order to demonstrate real-world examples and to cover the indices for measuring urban sprawl characteristics.

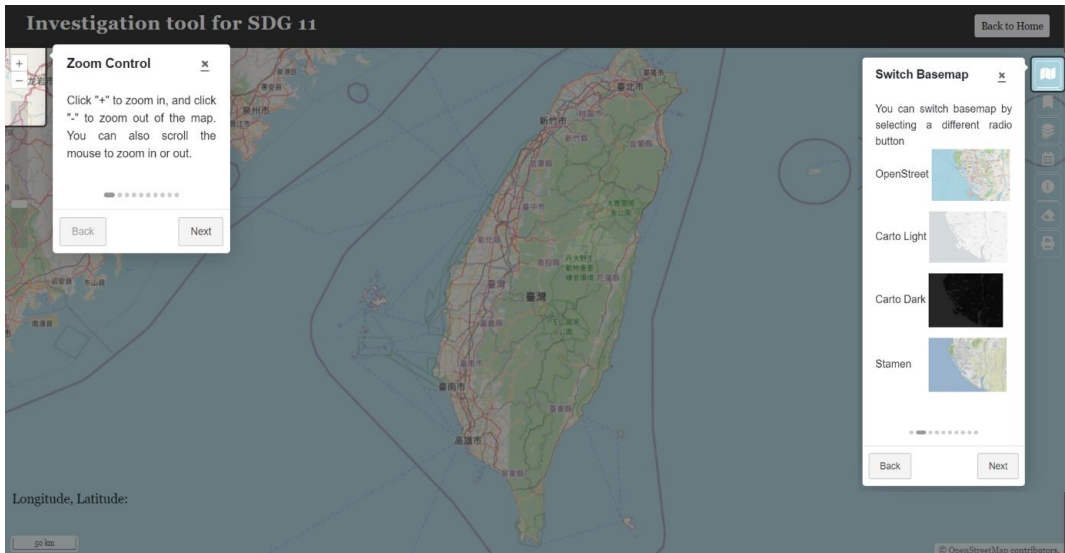


Figure 2: WebGIS System.

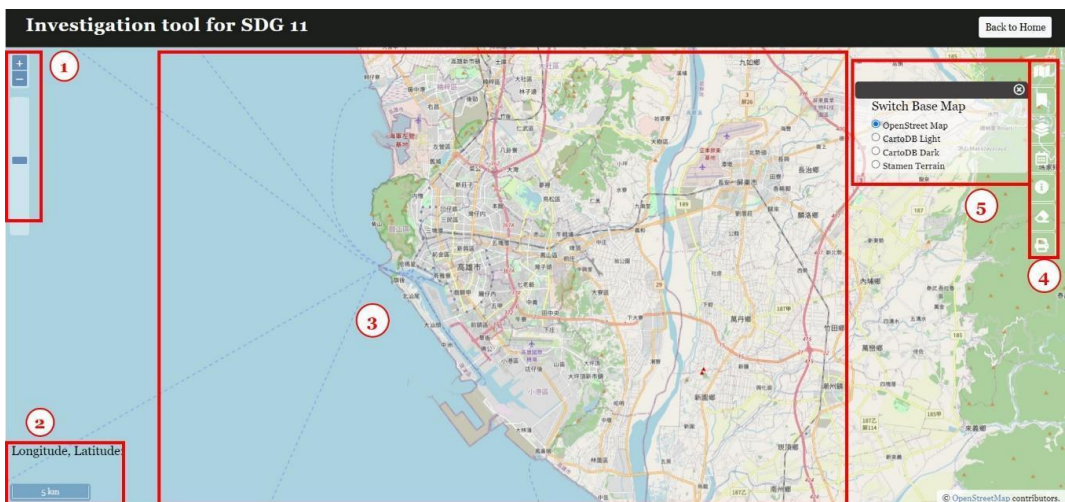


Figure 3: The user interface; 1: zoom controls; 2: coordinates of mouse pointer and scale bar; 3: map canvas; 4: function toolbar; 5: function windows

3.1 Land Cover Change

Preclassified LULC maps are locally hosted on Geoserver, and are accessible to view on the system as shown in Figure 3. Here, five different land use or land cover classes, represented by the standard land classification colours, are shown: built-up area, barren land, cultivated land, water bodies, and other vegetation. While it would have been possible to generate more classes, these five are of special interest in the current project. For ease in comparing temporal

changes in land cover and land use, an interactive slider was added. The user can drag the slider, which allows a real-time update and the loading of new LULC maps. We would like to emphasise the potential of this web tool to visualize different time periods.

The base data characteristics, such as accuracy, are discussed in Tsai & van Gasselt (2022). The white square in Figure 4 draws attention to a coastal area in Kaohsiung City that covers an area of approximately 300 km². Snapshots of this area spanning 30 years, between 1985 and 2015, can be seen in Figure 5. Significant changes in land cover can be observed, in particular the increase of built-up areas and barren land. Up to around the year 2000, most land was used for ponds or fish farms, which then gradually vanished and became development areas. Much of the cultivated land also became urbanized, while the increased area of barren land poses challenges, as it could potentially cause further pressures on the natural environment and vegetation.

For long-term analysis in particular, a dynamic investigation using the time slider can help to identify patterns and defects of, e.g., policy developments. While here 5-year time slices have been incorporated, any other time frame is feasible, as long as it is reasonably well supported by the underlying data. Animation, with individually set frame rates, is another possibility.

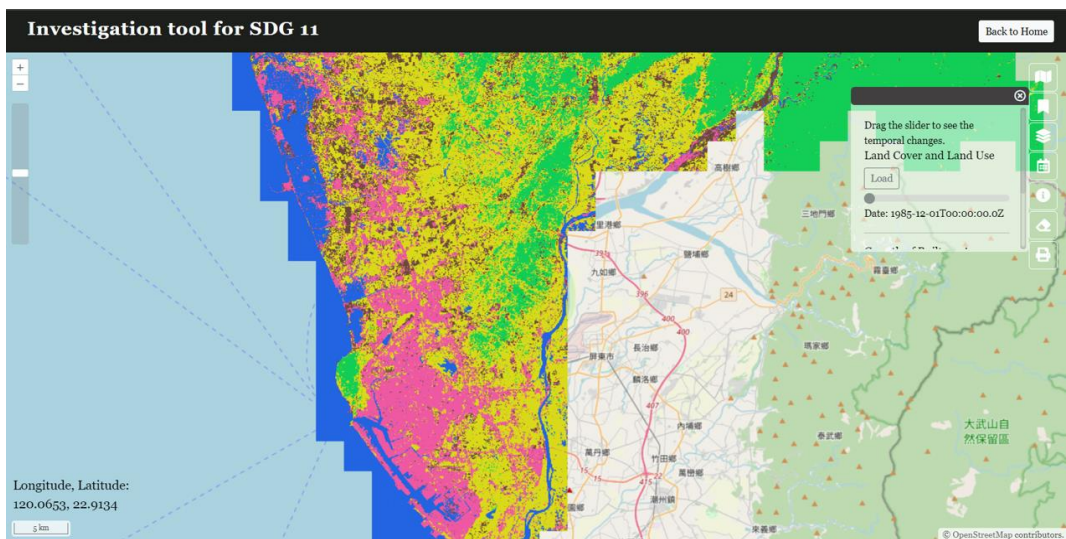


Figure 4: Land use and land cover classes (pink: built-up areas; brown: barren land; yellow: cultivated land; blue: water bodies; green: other vegetation)

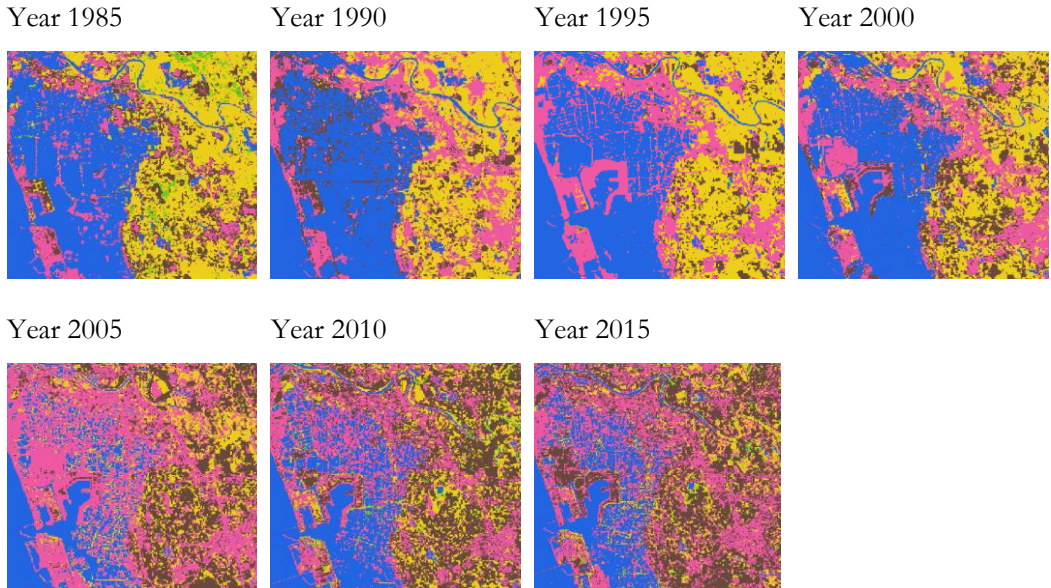


Figure 5: Temporal changes, between 1985 and 2015, of the area highlighted by the white square in Figure 4.

In accordance with the SDG framework, LUE and AAPDEA values were pre-calculated as representative indicators for interpreting the correlations between demographic and land cover changes. In this system, they are combined in the ‘statistics’ tab, which is embedded in the toolbar. Visiting this page allows population growth and temporal changes for the city as a whole to be viewed in the interactive graph, situated bottom right. Both the population and the proportion of barren land show a rising trend, while areas of vegetation decrease significantly in size. The rate of change in built-up areas fluctuated between 2005 and 2015, but overall the rate itself was higher than the initial value. The fluctuation can be attributed to significant development in the municipality of Kaohsiung, which led to extensive building projects within the city but also to reconstruction and local greening projects both in- and outside the main built-up area.

In the ‘function configure’ window (e.g. no. 5 in Figure 3), users can select the radio button to define spatial units for a detailed query. After specifying the area unit (administrative district or village), corresponding geographic data are loaded into the map canvas, and feature information is shown. Three navigation tags covering population, SDG indices and urban expansion indices (such as Shannon’s entropy index) are shown in this window. Users may select different administrative districts on the map canvas to view detailed information, including synchronized graphs.

All data described above are pulled and rendered in the front end in real time. For example, in Figure 6, the orange area is the administrative unit of Taoyuan district. Two graphs showing AAPDEA and LUE illustrate that, overall, the population grew in the period 1985 to 2000, and declined in the subsequent period (2000 to 2015) – that is, the most significant growth

took place in the years before 2000. It can be seen that this interactive map design provides users with a visual aid for comparing different spatial units and different time slices. As all data have been integrated and can be visualized via graphs, the demonstration has the potential to be truly comprehensive.

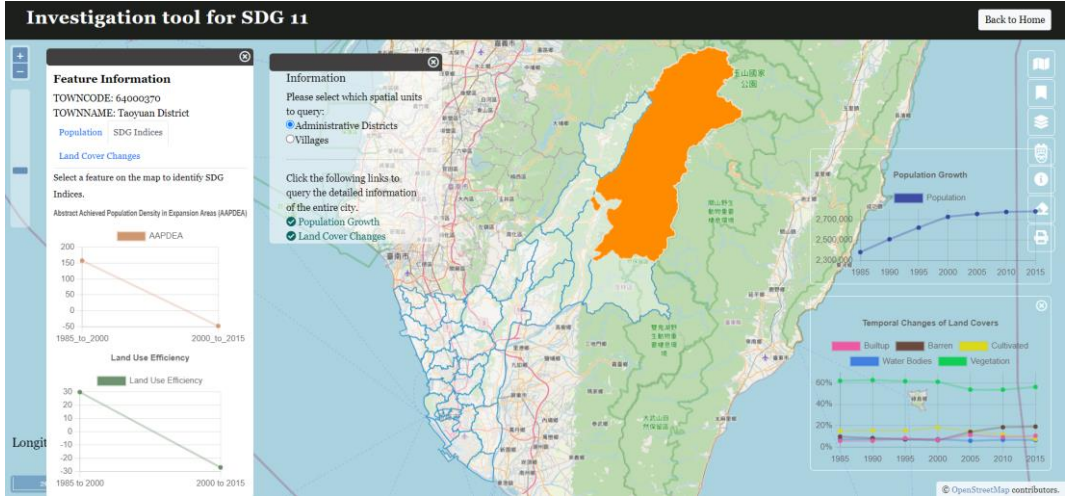


Figure 6: Queryable features for investigating urban expansion characteristics.

4 Conclusion

The rapid growth of metropolitan areas and increasing populations around the world pose significant challenges for society. Along with a growing awareness of these challenges, the importance of a more sustainable environment has entered public consciousness in recent years. The UN's goals are partly based on indicator metrics, and earlier studies have shown the importance of indices to assess and monitor land cover changes and urban expansion. A number of recent studies (Wei, 2009; Gao & Mai, 2018) have highlighted the limited data accessibility on user devices, which could potentially restrict information provision, in particular for comparative analysis and decision making. This study tries to address some of these limitations by providing a web-based application that includes structural back-end and front-end components on the software side. In conjunction with the support of a map server and libraries of interactive maps, the capability for real-time operations and excellent map data rendering qualities can be demonstrated. The system enables users to gain better access to tools that allow comparison between various spatial units, such as districts, townships or counties, and over time. The two applications presented here demonstrate interactive querying for information on land use and land cover changes, as well as urban expansion indices. Interactive features combined with graphs generated from synchronized data pulled from the back end allow for a richer display of statistics and data querying.

We aim to disseminate our work more widely in order to advocate for the inclusion of sustainable development indicators. The functionality presented here should enhance user

access to these indicators by combining different levels of information. The information can also be transferred to other study areas in order to gain further insights into development trends and the impact of policies.

Overall, this study has highlighted an integrated web-based design and a practical use case, presenting a setup that allows integrating LULC change data alongside SDG indicators. It can be taken as a reference for similar studies as well as a guide to extract urban expansion information within the SDG framework. It provides a comprehensive and interactive approach for data access, at national or municipal level. Furthermore, the integrated design of the framework is not limited to the implementation of indicators of SDG 11 specifically, but may also, by allowing web-based spatial visualization, serve for knowledge dissemination with reference to SDG goals more broadly.

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