Computers & Geosciences 181 (2023) 105462

Contents lists available at ScienceDirect

Computers and Geosciences

journal homepage: www.elsevier.com/locate/cageo

An ontology-based framework for semantic geographic information systems development and understanding

Chiao-Ling Kuo [a,b,*], Han-Chuan Chou [a]

[a] Research Center for Humanities and Social Sciences, Academia Sinica, Taipei, 11529, Taiwan
[b] Department of Geography, National Taiwan University, Taipei, 10617, Taiwan

ARTICLE INFO

Keywords:
Ontology
GIS components
Semantic GIS development
System comprehensibility
WebGIS
Online thematic mapping

ABSTRACT

Geographic information systems (GIS) are a widely used approach for geodata manipulation, analysis, and geoinformation visualization. Although the issue of semantic heterogeneity for GIS applications has been widely addressed, the development of flexible semantic GIS systems can still be improved, and GIS interfaces can be further unified to enhance system understanding among users of various GIS systems. This study proposes an ontology-based semantic GIS conceptual framework that can seamlessly combine ontology models, GIS elements and user actions for semantic GIS application development. In addition, a GIS components ontology that encompasses the five fundamental components of GIS is proposed to integrate GIS elements that can perceive GIS operations and processes semantically and to support customized GIS system designs. Moreover, a semantic WebGIS implementation framework is designed on the basis of the proposed conceptual framework to facilitate semantic WebGIS development. The implementation uses two common application scenarios regarding urban change analysis and user interaction. The former performs semantic retrieval for urban change analysis with system understanding, whereas the latter conducts online thematic mapping with semantic interpretation. The study contributes in terms of innovation in the design of a unified GIS components ontology and successful implementation of a semantic GIS system using the ontology-driven approach, thereby providing a convincing demonstration of the latter and showing the potential for semantic GIS application paradigms.

1. Introduction

Geographic Information Systems (GIS) are a widely used approach for geodata interpretation, processing, analysis, and integration, and are defined as *computer-based information systems that enable capture, modelling, storage, retrieval, sharing, manipulation, analysis, and presentation of geographically referenced data* (Worboys and Duckham, 2004). GIS are advantageous to end users, data providers, and developers in various fields, as those in each field can address and analyze problems from a spatial perspective, such that satisfactory answers will be accompanied by spatial-awareness decisions. For example, end users ranging from domain experts and investigators to unsophisticated users are better able to receive geospatial information or knowledge based on geographic locations and to discover spatial patterns. Data providers such as governmental agencies or social cooperatives and system developers can easily create a whole picture of data coverage and data-driven functionality to foster data quality improvement and interdisciplinary collaboration.

With the advent of computer, internet, communication, and the development of framework technologies as well as the emergence of the OpenGIS perspective, a tremendous number of desktop-based, mobile-based and networked GIS application systems with user-friendly functions have been established by using either commercial or open-source software. Each full-featured GIS system is designed with its own unique characteristics so as to achieve success in the targeted GIS operations. For instance, Google Maps (Google, 2022) proposed by Google, a popular web mapping site and a typical model of GIS, offers geographic information with location-based functionality such as place searching, route planning, and street view service to show one's surrounding environment. In addition, the Web 2.0 revolution promotes collaborative and interactive mapping solutions, and volunteered geographic information (VGI) is produced (Goodchild, 2007). OpenStreetMap (OSM) (Bennett, 2010) is a representative VGI project which provides free and new geodata, and allows adaptive reuse and reproduction, thus leading to increasing interest in data ecosystem diagrams and development of GIS. Openrouteservice (HeiGIT, 2022), an

* Corresponding author. Research Center for Humanities and Social Sciences, Academia Sinica, Taipei, 11529, Taiwan.
E-mail address: kuo@chiaoling.com (C.-L. Kuo).

https://doi.org/10.1016/j.cageo.2023.105462
Received 11 March 2023; Received in revised form 18 September 2023; Accepted 19 September 2023
Available online 21 September 2023
0098-3004/© 2023 Elsevier Ltd. All rights reserved.

OSM-based route service, perfectly exemplifies the emerging trend which establishes route calculation and directions for a variety of end-users such as pedestrians, bikers, motorists, and disabled persons. Furthermore, many domain-specific GIS application systems developed either at the regional or world level are contributing to increasing numbers of benefits in terms of dataset creation, geo-information extraction, pattern discovery, integrated analysis, geo-simulation, etc. (Khashoggi and Murad, 2020; Tomaszewski, 2020; Murray, 2021). The development of GIS systems can considerably benefit geospatial studies and applications. However, GIS adopters including users and developers may suffer from problems associated with usability among GIS systems. Unrau and Kray (2019) have found that GIS systems are most often built for casual user scenarios, and lack sufficient guidance and details of complex interfaces and functionality, thus diminishing their usability. That is, it is often unclear whether those systems provide suitable properties and functionality, as well as meet users' expectations. Both understanding the purpose and contents of a system and distinguishing the purpose and contents of one system from those of another are often challenging. Hence, improving usability and making it easier for users to understand what systems' capacities and purposes are has become increasingly important.

On the other hand, in the field of GIS, conceptualization and abstraction are two common approaches to creating geodata and generating GIS relevant models that often follow domain-specific criteria, so semantic heterogeneities can exist among GIS elements and implementation. To enable semantic interoperability resolving semantic heterogeneities in GIS, many researchers have devoted great efforts over the last two decades to semantic exploitation, from data modelling to GIS system implementation. As ontology is defined as *an explicit specification of a conceptualization* (Gruber, 1995), ontology engineering has become a promising approach to semantic representation and semantic interpretation, allowing widespread domain exports including the GIS field to build ontology models for semantic interoperability. Thus, many GIS-relevant ontologies including geospatial, temporal, metadata, and data quality ontologies as well as specific domain and cross-domain integrated framework ontologies have been proposed (Hobbs and Pan, 2006; Schuurman and Leszczynski, 2006; Wang et al., 2007; Fonseca and Camara, 2009; Lebo et al., 2013; Albertoni et al., 2015, Anna Wagner, 2019; Li et al., 2019). Previous studies mainly focused on in-depth investigations into data and methods and their combinations with semantic representation and operations, but there is room yet for additional improvements in flexible semantic GIS systems development and more unified of GIS interfaces to improve user friendliness for those who use multiple systems. This issue is also echoed by Claramunt (2020), who notes that embedding geospatial ontologies within GIS is still far from straightforward and needs enhancement.

Hence, in this study, a semantic GIS conceptual framework based on ontology engineering for semantic GIS systems development and understanding is proposed. Our proposed semantic GIS conceptual framework is a three-tier architecture that regards ontology as the core in the ontology tier and builds a middle tier responsible for highly automated semantic information generation and transformation between ontologies and actions of users. Therefore, semantic interpretation and operations can be performed on the client applications tier leading to better system understanding for users. In addition, we propose a GIS components ontology consisting of five components which are universally accepted as the definition of GIS components, namely data, software, hardware, method, and user, to perceive GIS-relevant operations and processes at the semantic level. The GIS components ontology embraces an extensible framework with semantic linking that emphasizes the flexibility to integrate GIS-relevant elements to accommodate diversely customized GIS system designs. Users can thus efficiently understand and operate different systems because of a uniform interface between them, and yet use customized systems for distinct purposes as needed. Thus, this study aims at proposing an integrated GIS components ontology with complete semantic linking of GIS potential operational elements supporting cross-systems GIS understanding instead of building domain ontologies on each component in-depth, which has received extensive attention and could be further integrated in our method. Moreover, a semantic WebGIS implementation framework is designed based on the proposed conceptual framework. Implementations offer two common request scenarios toward urban change analysis and user interaction, that is, performing semantic retrieval for the urban change analysis with system understanding and online thematic mapping with semantic interpretation. Our main contributions in this paper are threefold.

- An ontology-based semantic GIS conceptual framework is proposed for seamlessly integrating ontologies and GIS elements as well as user actions to perform semantic information interpretation and transformation for efficient semantic GIS development.
- A GIS components ontology encompassing five GIS components, namely, data, software, hardware, method, and user, is designed for customized semantic GISs leading to improvement of users' understanding and distinction between different GIS systems.
- A highly automated and available semantic WebGIS framework developed based on the proposed conceptual framework with semantic operational procedures is demonstrated to exploit the potential for semantic applications among GIS systems.

The remainder of this paper is organized as follows. Section 2 surveys the literature on GIS-relevant ontologies and ontology-based frameworks for GIS applications. Section 3 presents the methodology regarding design of both a semantic GIS conceptual framework and semantic WebGIS framework as well as GIS components ontology development to achieve semantic GIS interoperability. Implementations with discussion are described in Section 4. Conclusions and recommendations for future work are provided in Section 5.

2. Literature review

Ontology-based approaches to semantic operations in GIS and other fields have been widely exploited. As to geospatial ontologies, in the early years, Wang et al. (2007) designed a *GeographicalSpace* ontology for describing spatial concepts and objects. The GeographicSpace ontology is composed of *SpatialThing*, *SpatialRelation* and *SpatialData* classes, which detail abstract entities, physical entities, geometric shapes, spatial relations and properties of geographic objects. In the same year, W3C Incubator Group published the Geospatial Ontologies (W3C, 2007), which consists of geospatial foundation ontologies regarding geospatial concepts and properties like geospatial features, feature types, toponyms, spatial relationships, coordinate reference systems, geospatial metadata, and geoweb services. Later, Fonseca and Camara (2009) promoted the concept of geo-ontologies which contain both semantic and spatial relations. The NeoGeo Vocabulary (Norton et al., 2012) was then created, a spatial relations ontology based on region connection calculus (RCC) for modelling geographic regions' relations. More recently, the Ontology for Managing Geometry (OMG) (Wagner et al., 2019) has been designed to provide geometric descriptions of objects using three levels of connection methods, thus the geometric shape information, components, and states of building objects can be stored and queried. To further strengthen the representation of the file format of data, the File Ontology for Geometry formats (FOG) (Bonduel et al., 2019) has been built for describing buildings' geometric formats such as DWG and OBJ file formats. In the ontology of geometric primitives specification (Nathalie Abadie, 2019), basic geometric concepts are introduced including feature collection, abstract and concrete classes, which is similar to the General Feature Model defined by OGC. As to temporal ontologies, the OWL-Time ontology (Hobbs and Pan, 2006) is able to describe moment-in-time (time instant) and time period, and facilitates the comparison between two time records.

When metadata is defined as *data about data*, which provides additional information to elaborate further on the data itself, the development of metadata ontologies has received attention. In the earlier years, (Schuurman et al., 2006) proposed ontology-based metadata extended from the first version of ISO 19115 (Geographic information — Metadata standard) to facilitate dataset-level semantic integration and to achieve the classification of non-equivalent cadastral data. In addition, the Group for Ontology Maintenance within the International Organization for Standardization (ISO)'s Technical Committee 211 (TC/211) has published a series of ontologies (ISO/TC211, 2023) according to ISO series standards such as ISO 19115, ISO 19110 (Methodology for feature cataloguing), ISO 19119 (Geographic information — Services), and ISO 19139 (XML schema implementation), which have been proposed for universal or specific domain representation for geographic information. Moreover, Dublin Core is another commonly used metadata format for describing resources, and the ontology-DCMI Metadata Terms (Core, 2023) have been developed. Besides, in order to improve the ontology search performance, an ontology metadata vocabulary (OMV), which is a metadata standard for describing ontologies, has been designed by Hartmann et al. (2005). Around a decade later, metadata for ontology description and publication (MOD) (Dutta et al., 2015) including field types, authorities, built tools, etc. have been proposed based on 15 metadata ontologies for the same purpose. In the past decade, the focus has been on recording the provenance of data creation or data processing, because capturing the procedure of data processing or system execution gives us more confidence in data quality and application results. In 2013, W3C has proposed the PROV ontology (Lebo et al., 2013), which can be used to represent provenance information, especially among different environments with extendable generic models. Studies like Closa et al. (2017) and Jiang et al. (2018) thus contribute to the provenance description at the dataset, feature and attribute levels, and provenance ontology integration with ISO 19115 lineage, respectively. Furthermore, data quality measurement plays a crucial role for examining and ensuring data quality. W3C has proposed the Data Quality Vocabulary (Albertoni et al., 2015) to describe the quality of a dataset in terms of status, accuracy, completeness, validity, consistency, etc.

To achieve the goal of geographic information integration and geoprocessing, many studies have produced important outcomes on the construction of a system architecture or framework. Fonseca et al. (2002) has proposed an ontology-driven GIS architecture taking ontology as a significant component, which is responsible for the process of knowledge generation. System users thus are able to retrieve corresponding image and vector data via ontology, which is called knowledge use. Wang et al. (2007) designed a geo-ontology reasoning framework based on the proposed geospatial ontologies, in which three layers, a spatial/application server layer, semantic service layer and presentation layer, constitute the framework which extends the aforementioned architecture by Fonseca et al. (2002). Tanasescu et al. (2006) proposed an ontology-based Emergency Management Application (EMA), which is a semantic decision-support system composed of four layers: a legacy system, service abstraction, semantic web service, and presentation layers. In their architecture, the service abstraction layer is composed of web services derived from the legacy system layer where data resources are provided, and the semantic web service layer is responsible for the bridging between service abstraction and presentation layers. Li et al. (2019) developed an ontology-based framework consisting of theme, spatial data, and spatial operation ontologies, combined with designed spatio-temporal analysis rules to generate an automated service chain with reliably reproducible geoprocessing workflow for complex spatio-temporal questions. Other featured ontology-based GIS application systems are presented in recent studies. Wang et al. (2018) has provided semantic retrieval and visualization functionality for local geological time and paleontological information in the North American area based on a geological time scale ontology. In Huang et al. (2020), the authors perform geospatial data semantic integration and visualization of urban bicycling suitability based on their proposed level of service (LOS) and level of traffic stress (LTS ontologies) with semantic constraints and rules.

Collectively, these studies provide substantial details of the ontology design, development and improvement for a wide range of semantic geoprocessing and interoperability. However, getting a better understanding and usability improvement among diverse GIS systems that can aid users to recognize and operate the desired functions among systems has not been investigated. This research aims at proposing an integrated GIS components ontology model that enables flexible semantic linking of potential GIS operational elements; accordingly, a semantic GIS conceptual framework encompassing the proposed GIS components ontology is proposed for seamlessly integrating ontologies, GIS elements and user actions, thus allowing users to easily distinguish and acquire suitable geographic information in the GIS application diagram.

3. Methodology

Based on the aim of increasing GIS interoperability with semantic GIS system development efficiency and improving the system understanding using ontology engineering, in the methodology, we first propose a conceptual framework that incorporates geodata and ontology models with client applications. Next, a GIS components ontology embracing an extensible framework with semantic linking used for semantic GIS application systems is designed and discussed, followed by the development of a semantic WebGIS implementation framework which involves applying the proposed conceptual framework and employing appropriate development strategies to reach universal web-based solutions.

3.1. Ontology-based semantic GIS conceptual framework

The conceptual framework illustrated in Fig. 1 is composed of three tiers: an ontology tier, middle tier, and client application tier, of which the middle tier provides full benefits for the connection between ontology as well as client application tiers, and supports seamlessly extensible semantic data transformation by using ontologies. More details on the role and functionality of each tier are elaborated as follows.

- Ontology tier: an ontology represents a field of knowledge in a formal way, involving the specification of shared vocabularies, relationships, and axioms. The creation of ontologies has received significant attention in the literature to resolve semantic conflicts. In the proposed conceptual framework, the ontology tier stands alone to accommodate flexible import of ontology models based on application purposes. Such a design allows for a system-independent ontologies development, thus enabling more flexible and efficient ontology development.
- Middle tier: this tier plays a key role in constructing semantic GIS systems or services by smoothing integration of ontology models with GIS elements and semantic web relevant technologies, which differs from most current ontology-based approaches that primarily rely on task-oriented programming development to meet specific needs, which is time consuming and inefficient. In the middle tier, data or resource schemas from the local or server side enable mapping with ontology models, and semantic schemas can be generated. Then, semantic data conversion will be performed, which adopts semantic schemas and databases to build resource description framework (RDF) data, and RDF semantic data will be stored in graph databases served as services which provide queryable interfaces for applications. The design of the middle tier improves the effectiveness and efficiency of an ontology-based approach using ontology engineering, which seamlessly combines ontology models and data and provides highly accessible as well as replicable semantic data.
- Client application tier: this tier is designed to be able to query semantic data from the middle tier and allow end-users to display

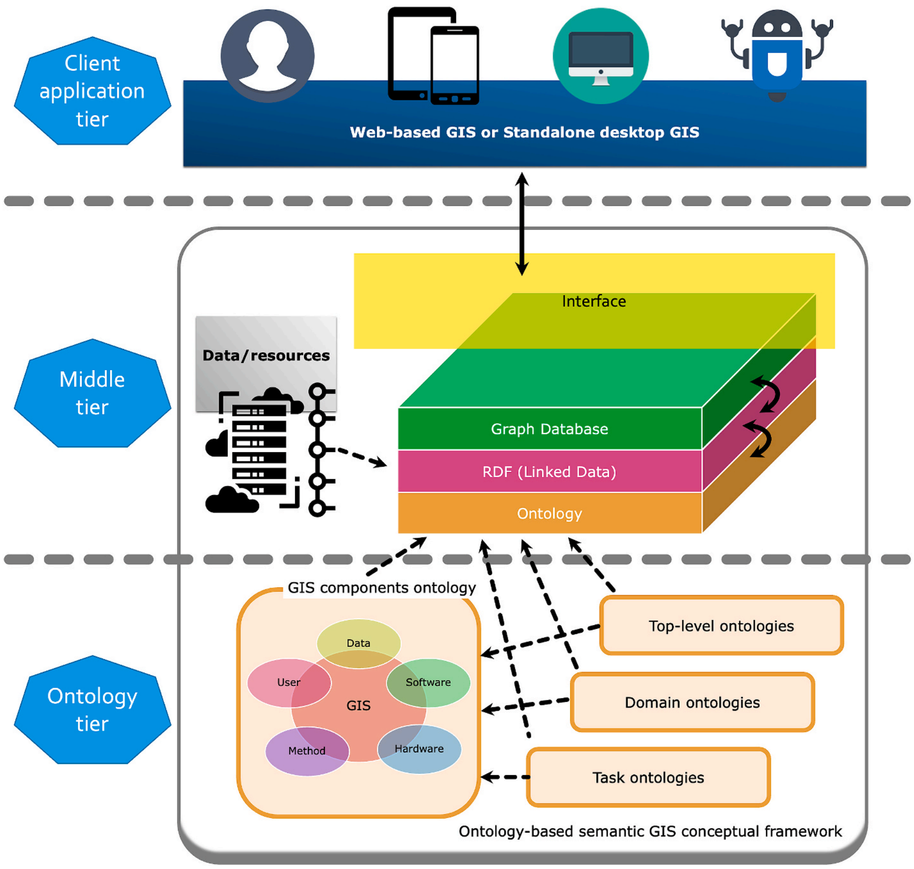


Fig. 1. Ontology-based semantic GIS conceptual framework.

application results using the retrieved data. Queries in this tier support all potential requests from end-users such as manual actions from web functional interfaces or agents' requests that all can retrieve semantic data from the application programming interface (API) provided by the middle tier. Then end-users such as GIS developers or GIS software users are able to further accomplish interactive analysis or visualization by either built-in or self-developed functions.

3.2. GIS components ontology

An ontology is the core used to interpret and integrate information correctly in a semantic GIS system. To achieve the development of a semantic GIS conceptual framework, we create a GIS components ontology that refers to a definition of GIS system which is ordinarily accepted, specifying GIS components including data, method, software, hardware, and user components. The GIS components ontology thus can be adopted to identify relevant GIS operations, procedures, and subsequent tasks. Fig. 2 depicts the pipeline of the GIS components ontology development. In the pipeline, questions such as data acquisition, data quality assessments, responsibilities, processing provenance, employed software and hardware, users' profiles and behaviors, etc., related to GIS components are first collected. Next, the GIS relevant questions are analyzed to extract semantic tokens, and structural statements are constructed based on previously extracted tokens with reference to existing ontologies and semantic alignments. GIS components ontology is then created according to structural statements. More details of ontology development are presented as follows. Section 3.2.1 presents the basic criteria of ontology development which elaborates the relationships between the root class, which is *gisc:GIS*,[1] and five components, followed by details of five components discussed in Section 3.2.2 to Section 3.2.5.

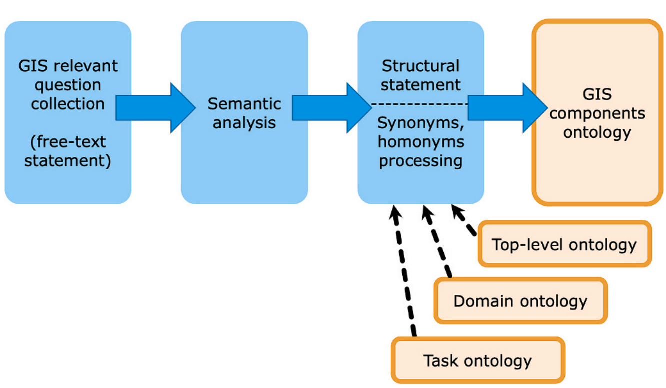


Fig. 2. The pipeline of the GIS components ontology development.

3.2.1. Basic criteria

The five components of GIS are data, software, hardware, method and user. The design of GIS components ontology aims to precisely express GIS components and their interaction and integration, as well as application results among components. The starting point of the ontology is the *gisc:GIS* indicating the GIS components ontology, and the *gisc* (standing for GIS components) is the prefix for the identification of the ontology. The five components with associated elements are thus designed to relate to the *gisc:GIS* according to the following basic criteria, which are also illustrated as Fig. 3.

[1] Text in italics indicates classes, object or datatype properties in ontologies.

- In the data component, *dcat:Resource* and its subclass *dcat:Dataset* from data catalog vocabulary version 3 (W3C, 2023) are adopted to represent materials used in a GIS system; the former is linked by *gisc:hasResourceInfo* and the latter by *gisc:hasDatasetInfo* from *gisc:GIS* to express resources and datasets information, respectively, complying with the data catalog vocabulary ontology.
- As to the method component, most GIS operations are performed based on a theme referring to relevant datasets using specific processing methods, for example, for population density mapping, a spatial join is conducted to obtain the population data for a specific region, which is then used to calculate population density based on the region's area. Thus, *gisc:Method* is created for methods description and linked from *dcat:Dataset* by *gisc:hasMethod*. In addition, *gisc:Method* and *dcat:Resource* link to *skos:Concept* using *gisc:theme* and *dcat:theme*, respectively, to identify the theme of GIS operations.
- Both software and hardware components are fundamental components in a computer-based system, especially in a GIS system. Software refers to programming tools for GIS data manipulation or execution of functions, whereas hardware refers to the machines or devices running the aforementioned performed programs. Many GIS are now available and processed through either client- or server-side functions or services, or the combination of them, enabling flexible and efficient resource acquisition and application development. Thus, to express the processing environment and to enable efficient management of processing in each step, the software and hardware adopted at client or server sides need to be distinguished and presented. Hence, *gisc:Client* and *gisc:Server* are created and linked by *gisc:hasClientInfo* and *gisc:hasServerInfo* from *gisc:GIS* directly. Then, *dctype:Software* designed in the DCMI Type Vocabulary (Core, 2001) and *itsmo:Hardware* proposed in the IT Service Management Ontology (Fagnoni, 2012) are adopted to describe software and hardware from local clients or remote servers by using *gisc:hasSoftware* and *gisc:hasHardware*, respectively. That is, *gisc:Server* and *gisc:Client* both relate to *dctype:Software* and *itsmo:Hardware* to distinguish development environments. In a GIS system, GIS-operated functions such as analysis or visualization functions are important, usually developed by engineers or domain experts using special software. Thus, *dctype:Service* from DCMI Type Vocabulary is adopted and linked by *gisc:hasCreate* from *dctype:Software*. Besides, to clearly describe GIS functions in a GIS system, *dctype:Service* is linked by *gisc:hasFunctions* from *gisc:GIS* directly.
- In the user component, GIS users could be system developers, administrators, data providers, GIS client users, or agents such as robots deployed to execute arranged processing. There have been popular ontologies related to user information description, for example, FOAF (an acronym of friend of a friend) ontology (Graves et al., 2007), presenting users' information such as users' profile, behaviors, activities, or their relationships. Thus, *foaf:Agent* and its subclass *foaf:Person* are adopted such that the former is used to represent the agency information and the latter is able to describe information of human users. In addition, to establish the relationships between the user and the other components for information integration, *dcat:Dataset* is linked to *foaf:Agent* by *dcterms:publisher*. Moreover, to clarify the relationship between users and software, we design *dctype:Servcie* links to *foaf:Person* using *doap:developer* proposed by Wilder-James (2012) and *gisc:hasUser* because users could be developers or users who have relationships with a service from *dctype:Service*.

The above discussion introduces the basic criteria of GIS components ontology development, mainly focusing on the creation of root class, that is, *gisc:GIS*, five components, and their relationships at a high level which directly links to or is linked from the root class or five components. Other details regarding the five components are presented below.

3.2.2. Data component

The data component is designed to describe all spatio-temporal properties, metadata, quality and accessibility information of GIS resources including local and online datasets and services. Thus, the *dcat:Resource* and its two subclasses, *dcat:Dataset* and *dcat:DataService*, are adopted as the core which follow the specification of data catalog vocabulary version 3 (W3C, 2023) to describe all resources included in a system. To distinguish the data type such as raster or vector data, *gisc:dataType* is designed and liked from *dcat:Resource*. Details of the ontology design of the data component are introduced as follows, and the data component ontology model is depicted as Fig. 4.

- Three datatype properties of *dcat:Resource*, *gisc:openSource*, *gisc:dataSourceType*, and *gisc:accessible* are created in which *gisc:openSource* is used to note whether resources involved in a system are for public or private use, and *gisc:dataSourceType* is used to recognize the source types of resources, for example, first- or second-hand data. In addition, *gisc:accessible* is designed to describe the accessibility of

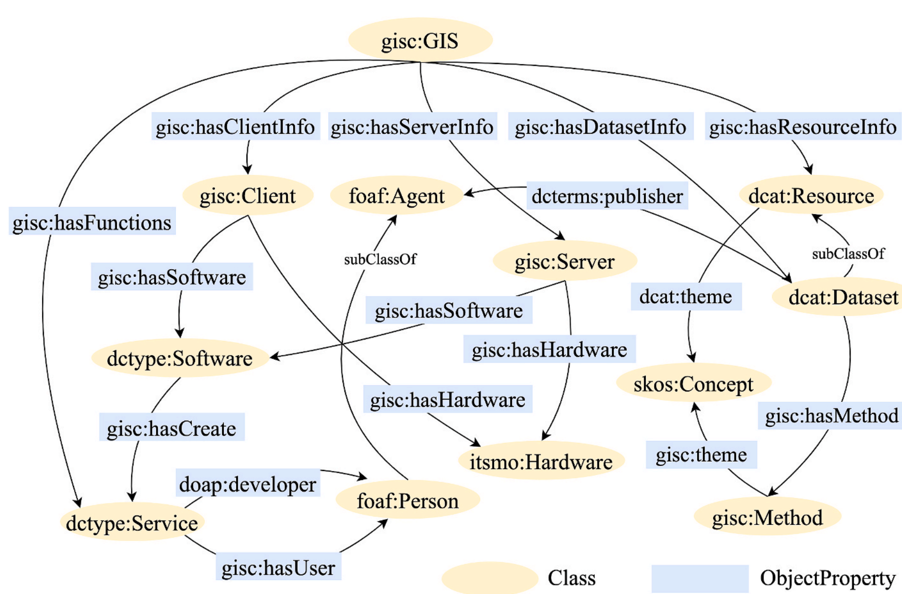


Fig. 3. GIS components ontology—a high level portion of ontology which applies the basic criteria.

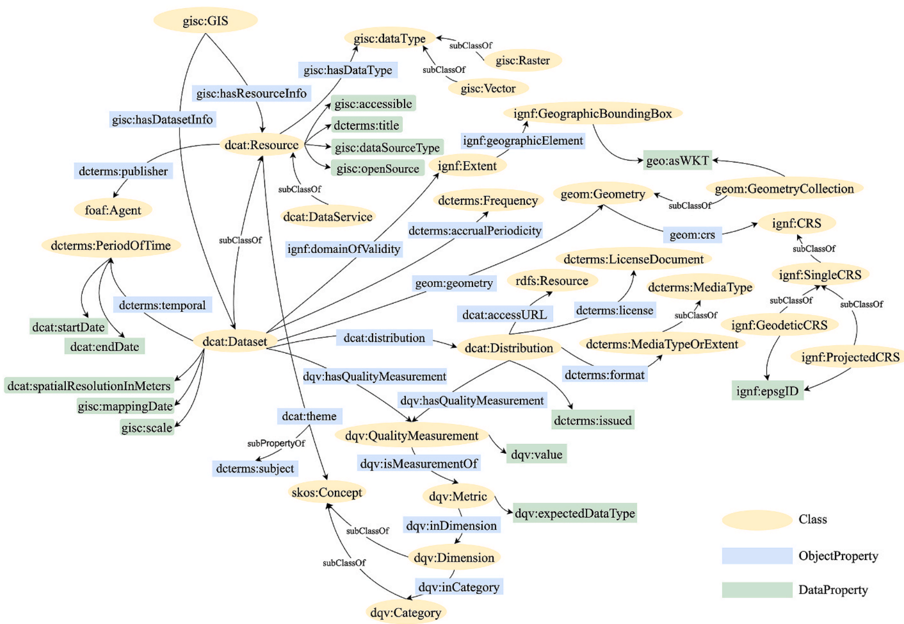


Fig. 4. Data component ontology.

data. As to the mapping information of dataset, *dcat:spatialResolutionInMeters* is used to describe the spatial resolution of dataset in meters. Moreover, *gisc:mappingDate* and *gisc:scale* are created to record the mapping time and the scale of dataset.

- Spatial information delivers where data or resources are located on a certain coordinate system and what the geometric shape is. Users then enable spatial analysis or geoprocessing. Thus, it is necessary to record the spatial information of data in the ontology. The designs related to spatial information descriptions mainly refer to data catalog vocabulary version 3 (W3C, 2023) that has provided common concepts regarding spatial information such as geometry, extent, coordination reference systems, etc. Hence, the *geom:Geometry* linked from *dcat:Dataset* is used to describe the spatial coverage or location based on a specified coordinate system which could be a geodetic or projected coordinate reference system. Thus, the *ignf:CRS* from coordinates reference systems ontology (Forestière, 2019) is adopted, and the *ignf:CRS* has a subclass, *ignf:SingleCRS*. In addition, the *geom:GeometryCollection*, a subclass of *geom:Geometry*, is used to record geometric shape of geodata using Well-known text (WKT) format. To clarify the types of coordination reference systems, two subclasses of *ignf:SingleCRS*, that is, *ignf:GeodeticCRS* and *ignf:ProjectedCRS*, are used for CRS representation. Furthermore, the *ignf:Extent* is used to describe the spatial extent of data, which links to the *ignf:GeographicBoundingBox* class to record the extent of data by WKT format.
- Time is a kind of annotation in data that represents when data are created or what period of time is valid for data. The design regarding time of data is based on the data catalog vocabulary version 3 (W3C, 2023) as well. Thus, the *dcterms:PeriodOfTime* is used to describe the time information of data.
- As to the data quality description, data update frequency shows how often data are updated, which is a significant index to measure data quality. Hence, the *dcterms:Frequency* linked by *dcterms:accrualPeriodicity* from *dcat:Dataset* which has been proposed in the data catalog vocabulary version 3 (W3C, 2023) is used to represent the frequency of data updates. In addition, data quality information in terms of the stability and availability of GIS functions and applications are needs to be recorded to ensure the quality of a GIS system. Thus, *dcat:Dataset* is related to the *dqv:QualityMeasurement* to present data quality measurement results by using the *dqv:Metric*, and the *dqv:Metric* links to the *dqv:Dimension* to indicate dimensions of quality measurements such as performance, reliability, conformance, durability, serviceability, and perceived quality. Moreover, the *dcat:Distribution* linked from *dcat:Dataset* is adopted to detail the access URL, license, and format which are designed as the *rdfs:Resource*, *dcterms:LicenseDocument*, and *dcterms:MediaTypeOrExtent* in which *dcterms:MediaTypeOrExtent* is a subclass of the *dcterms:MediaType* to describe types of media.
- Datasets are adopted for a specific usage and analysis based on a theme. The *skos:Concept* is used to describe a GIS application's topic. The *dqv:Dimension* and the *dqv:Category* are two subclasses of *skos:Concept*, identifying the application themes.

3.2.3. Method component

The method component describes GIS relevant analysis methods and algorithms for raster and vector data in which both are ordinary GIS data models. Thus, *gisc:Method* is created to represent GIS methods and contains two subclass, *gisc:rasterMethod* and *gisc:vectorMethod*. The *gisc:rasterMethod* is used to present processing methods for raster data, encompassing several subclasses such as *gisc:aspect*, *gisc:slope*, *gisc:hillshade*, *gisc:contour*, *gisc:elevation*, *gisc:viewshed*, etc. Furthermore, the *gisc:vectorMethod* is designed to describe processing methods for vector data, having subclasses such as *gisc:buffer*, *gisc:shortestPath*, *gisc:nearestNeighbor*, *gisc:cluster*, *gisc:hotspot*, etc. Both *gisc:rasterMethod* and *gisc:vectorMethod* are extendable. GIS users can adopt GIS method to perform GIS analysis and functions to generate results. To record the results, *gisc:result* is designed and linked from *gisc:Method* as well as linking to *skos:Concept*, which is allowed to retrieve the provenance information with its theme in a processing procedure. In addition, the *gisc:result* is extendable, for example, *gisc:thematicMap* is one of processing results in GIS. Fig. 5 delineates the ontology.

3.2.4. Hardware and software components

Hardware and software components are fundamental development environments that provide support for GIS systems with spatial-temporal analysis, geodata manipulation and integration, visualization, etc. In modern GIS infrastructure, especially the innovative web-based technology involved, the use of software and hardware can be divided into client and server-side operations. Identification of the hardware and software operated from the client- or server-side aids in

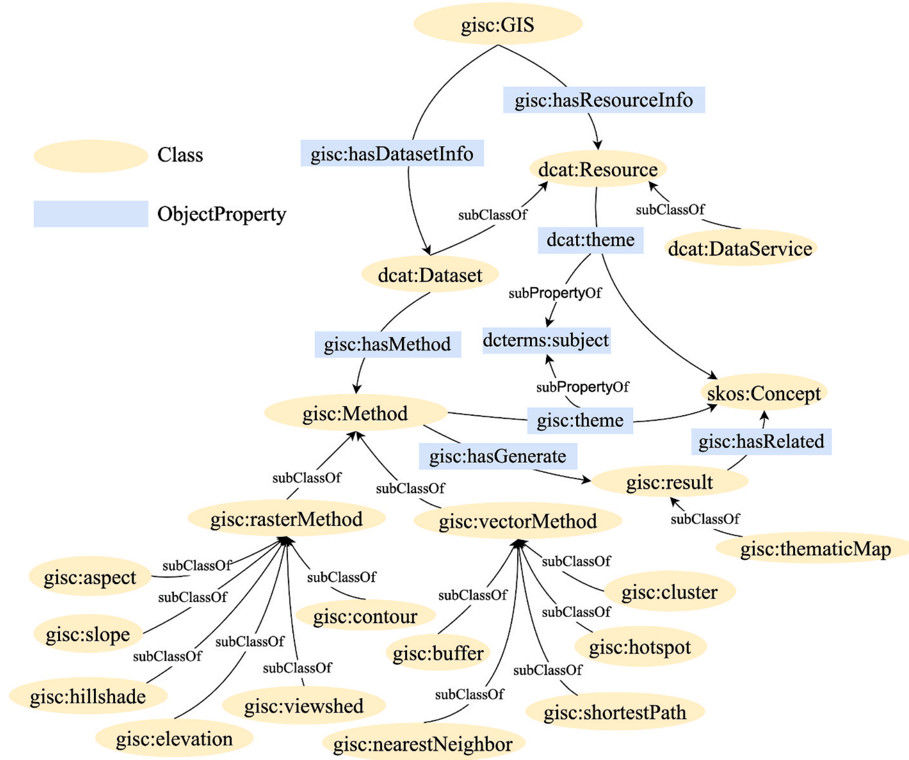


Fig. 5. Method component ontology.

improving performance of GIS development and applications. Thus, *gisc:Server* and *gisc:Client* are created and are linked to *gisc:GIS* directly, and both link to *itsmo:Hardware* and *dctype:Software*, which have been discussed in Section 3.2.1. More information about the design of the two components is described as follows. The ontology model is illustrated in Fig. 6.

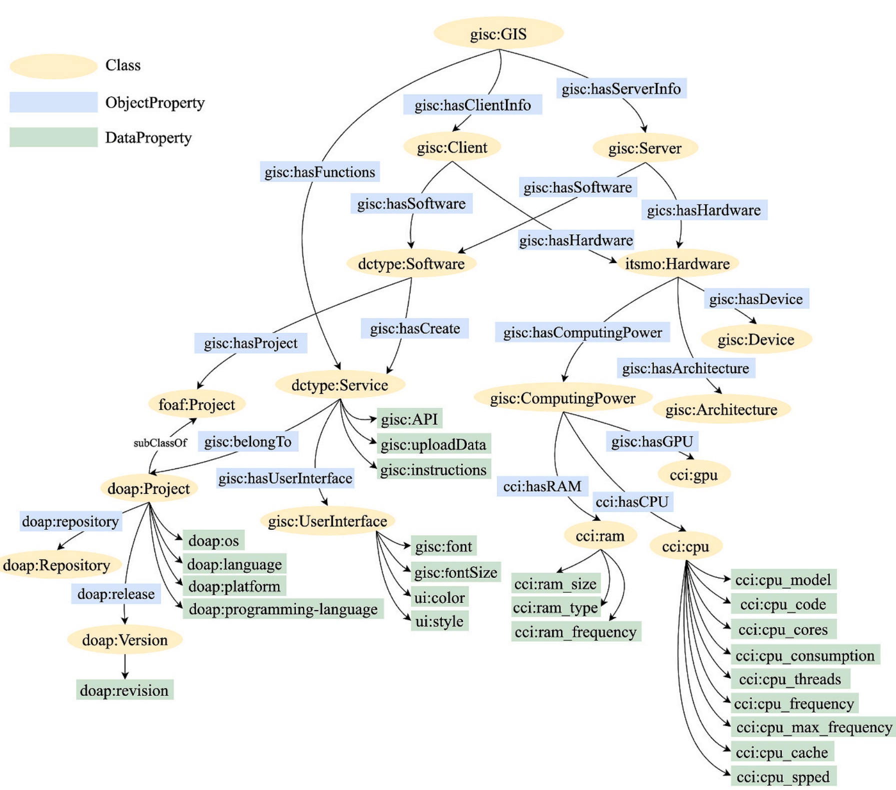


Fig. 6. Software and hardware component ontology.

- GIS systems must be run with suitable hardware and software environments. Sometimes GIS applications even run only in specified environments. The design of hardware information includes system architecture, running devices, and computing resources, which explains what hardware environment is adopted. Thus, the *gisc:Architecture* is created to describe GIS system architecture such as a centralized or distributed structure, and *gisc:Device* is created to describe machine devices like desktops or pads to operate GIS systems. In addition, the *gisc:ComputingPower* is designed to express the computing ability of a GIS system, and *cci:cpu*, *cci:gpu*, and *cci:ram*, proposed in the Ontology for Cloud Computing instances (W3C, 2023), are used to record information about the CPU, GPU and RAM in a GIS system.
- GIS applications such as functions and services are developed mostly based on certain software tools, and therefore those applications need to run in appropriate software and hardware environments. From the perspective of development, using *dctype:Software* and *dctype:Service* to present how services such as functions are created and applied. For example, an online mapping function described by *dctype:Service* is developed by a JavaScript library like OpenLayers (2023) that is described by *dctype:Software* from a server-side environment using *gisc:Server.*
- On the other hand, from the perspective of use, GIS functions and services are available by using a client-side web browser, for example, Google Chrome. So, Chrome is described by *dctype:Software* from a client-side environment using *gisc:Client.* In addition, to elaborate the user interface and functionality of services from *dctype:Service*, *gisc:UserInterface* and several datatype properties like *gisc:API*, *gisc:uploadData*, and *gisc:instructions,* which are extendable and are used to express the characteristics of functions provided by the service, are designed.
- As *dctype:Service* sometimes may be developed according to a plan or a project, *doap:Project,* a subclass of *foaf:Project,* proposed in the project vocabulary (Wilder-James, 2012) is adopted and is linked by *gisc:belongTo* from *dctype:Service* to represent what services are developed belonging to what projects. In addition, to express the relationships between software and project, *dctype:Software* links to *foaf:Project* using *gisc:hasProject.*

3.2.5. User component

GIS users encompass system users, developers, data providers such as responsible agencies, and agents such as machine robots or automation services. The design of user component adopts *foaf:Agent* and *foaf:Person* for describing the above types of users, as has been discussed in Section 3.2.1. To further identify users and record the number of visitors in a GIS system, *foaf:Person* and *dctype:Service* contain *gisc:identity* and *gisc:visitors*, respectively, to identify users from server-side records. Fig. 7 displays the user component ontology.

Based on the discussion above, Table 1 lists all existing ontologies and vocabulary with the prefix and URI adopted in the design of the GIS component ontology; the complete GIS component ontology are provided in Appendix A.

3.3. Semantic WebGIS implementation framework

WebGIS is an efficient approach for geodata manipulation, analysis and visualization through the Internet, facilitating real-time geodata integration and interoperability. We hence develop a semantic WebGIS

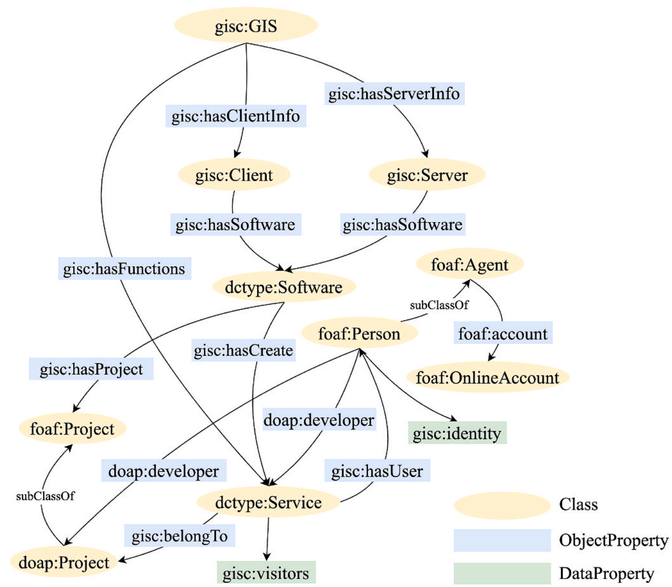


Fig. 7. User component ontology.

Table 1
Existing ontologies and vocabulary adopted in the GIS components ontology.

prefix	URI	prefix	URI
gisc	http://gisc.sgis.tw/gisc#	geom	http://data.ign.fr/def/geometrie#
cci	http://cookingbigdata.com/linkeddata/ccinstances#	geo	http://www.opengis.net/ont/geosparql#
dcat	http://www.w3.org/ns/dcat#	ignf	http://data.ign.fr/def/ignf#
dcterms	http://purl.org/dc/terms/	itsmo	http://ontology.it/itsmo/v1#
dctype	http://purl.org/dc/dcmitype/	owl	http://www.w3.org/2002/07/owl
doap	http://usefulinc.com/ns/doap#	skos	http://www.w3.org/2004/02/skos/core#
dqv	http://www.w3.org/ns/dqv#	ui	http://www.w3.org/ns/ui#
foaf	http://xmlns.com/foaf/0.1/		

implementation framework based on the proposed conceptual framework introduced in Section 3.1 to enable online semantic GIS applications, integrating ontology engineering smoothly with geospatial information and web technologies as well as database management systems. Fig. 8 illustrates the semantic WebGIS implementation framework which is composed of the three tiers, including the ontology tier, middle tier, and client applications tier, in which the ontology tier is established by the proposed GIS components ontology. In the middle tier, first, ontology integrates with remote databases through the ontology mapping to the data processing step that uses a mapping tool such as Map-On (Nemirovski and Nolle, 2017) to generate the R2RML (RDB to RDF mapping language) file (Consortium, 2012; Vaisman and Chentout, 2019) that specifies the relationship between data schemas with ontologies. Second, semantic RDF datasets can be generated and stored in a graph database such as GraphDB (Li et al., 2022) to provide an API interface for semantic data access. The design of the middle tier

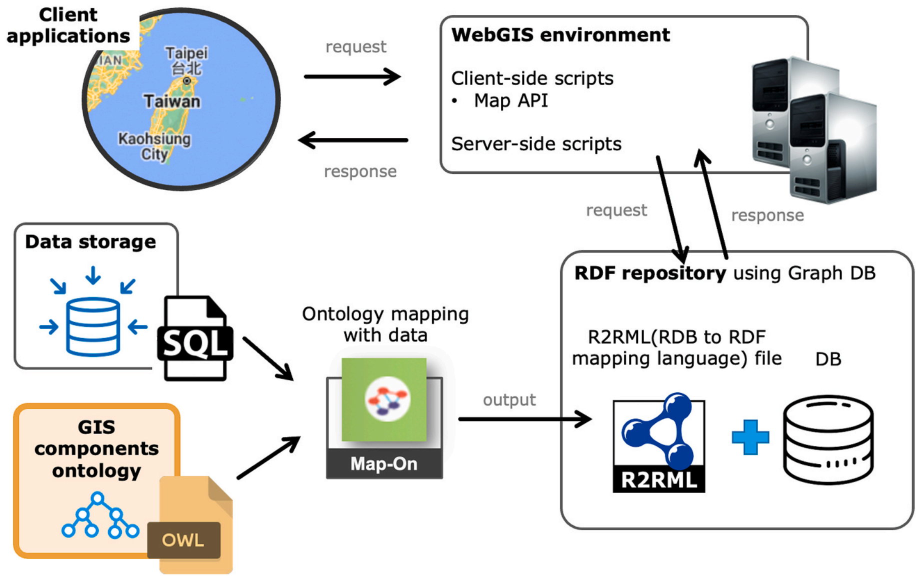


Fig. 8. Structure of the semantic WebGIS implementation framework.

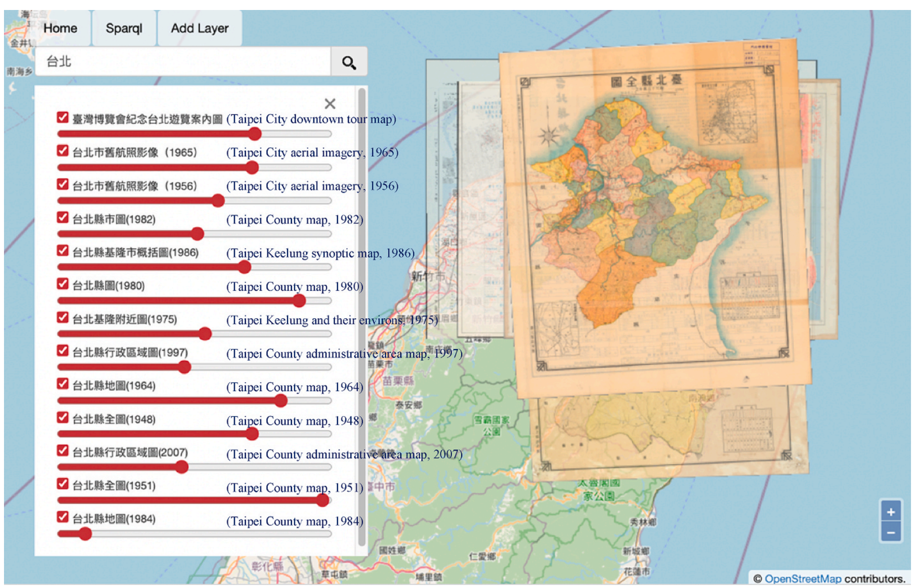


Fig. 9. Implementation of semantic WebGIS: a semantic query using “台北”(Taipei).

assists in seamless and automatic semantic RDF data conversion and data accessibility through integrating ontology mapping tools, RDF generators and graph databases. In the client applications tier, the semantic WebGIS interactive map is developed by using web programming and map APIs or libraries such as OpenLayers (2023) that supports user semantic retrieval and interaction, for example, online mapping with visualization.

4. Implementation and results

This section implements the proposed semantic WebGIS framework based on the proposed GIS components ontology using two common application scenarios for accomplishing GIS system understanding and semantic operations. The first is urban change analysis with semantic retrieval on georesources, tile services, and system environment to prove the concept; the second is online thematic mapping to present highly automated semantic processing with user interaction. These scenarios are presented in Sections 4.1 and 4.2, respectively. Section 4.3 provides the discussion.

Tile services that provide base layers or thematic maps are powerful services often used to enrich GIS applications (e.g., spatial recognition and customized mapping with visual applications). In this study, approximately 3500 layers that was originally published in a historical tile service website (https://gis.sinica.edu.tw/tileserver/wmts), including historical topographic maps, aerial photos, and historical thematic maps, such as forests, rivers, administrative regions, disaster areas, etc., are adopted as study materials for the urban change analysis. These layers are built as RDF data (including properties, such as tile name, identification number, image format, levels of tiles, extent of tiles, etc.) using the approach introduced in Section 3.3. Simulated data about clients are converted to RDF. Moreover, population data from open data are used in the online thematic mapping. Both cases are performed by a self-developed WebGIS system based on an open-source JavaScript library, i.e., OpenLayers. Details of the experiments are described as follows:

4.1. Urban change analysis in Taipei

To demonstrate the importance of the proposed concept with GIS component ontology, several user cases with semantic retrieval and operations that improve system understanding are implemented. The homepage of the semantic GIS system is shown in Fig. 9, and it allows users to send semantic queries to find the desired geoinformation. Fig. 9 shows the results by a simple semantic query using “台北”(Taipei). More semantic operation results are verified with SPARQL queries presented as follow.

Query 1 retrieves all available data provided by a GIS system if the results fulfill the application purpose. Lines 10–11 specify datasets associated with a GIS system in the *gisc:GIS* entity and present their detailed information, such as the title and theme from the d*cat:Resource* entity, which is necessary for association and is used in the thematic constraints. Lines 17–21 prescribe the spatial and thematic constraints to filter the results. The spatial constraints include two types of expressions: geometric shapes and place name by strings (e.g., 臺北, 台北, and Taipei), adopting a synonym searching method to resolve the naming heterogeneity. The example results shown in Table 2 provide related datasets, including historical and contemporary resources for the purpose of application, indicating that the system is available. Otherwise, the system is considered unavailable for work when data are not returned. Users can further examine and choose the appropriate resources, such as suitable data type (e.g., image data), for the change analysis. For example, the use of historical data for long-term change analysis (e.g., over 20 years) is more reasonable than that of contemporary data (mapping within a year) in the case. When a given question is extensive, the situation regarding uncertainty of data accessibility is encountered commonly in practice. Thus, the design helps users realize the capability of a GIS system and determine whether to use a system during the early stage.

Query 1
SPARQL query for retrieving data with temporal and thematic information for the urban change analysis in Taipei.

```
1   PREFIX : <http://gisc.sgis.tw/gisc#>
2   PREFIX dcat: <http://www.w3.org/ns/dcat#>
3   PREFIX dcterms: <http://purl.org/dc/terms/>
4   PREFIX geo: <http://www.opengis.net/ont/geosparql#>
5   PREFIX geof: <http://www.opengis.net/def/function/geosparql/>
6   PREFIX ignf: <http://data.ign.fr/def/ignf#>
7   PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
8   SELECT DISTINCT ?Resource ?Title (MIN(?Mapping_Date) AS ?Mapping_Year) ?Period ?Theme
9   WHERE {
10    ?system :hasResourceInfo ?Resource.
11    ?system :hasDatasetInfo ?dataset.
12    ?dataset rdfs:subClassOf ?Resource;
13              dcterms:temporal ?Period;
14              :mappingDate ?Mapping_Date;
15              ignf:domainOfValidity/ignf:geographicElement/geo:asWKT ?wkt.
16    ?Resource dcterms:title ?Title;
17                dcat:theme ?Theme.
18    BIND("POLYGON ((121.57098050500008 25.197168116000057, 121.665934308000018 25.02987789300004,
    121.601234532000049 24.960889626000039, 121.457161441000039 25.107735761000072, 121.57098050500008
    25.197168116000057))" AS ?taipeiWKT)
19    BIND (geof:sfIntersects(?wkt, ?taipeiWKT) as ?f)
20    VALUES (?synonymLabel) { ("臺北"@zh) ("台北"@zh) ("Taipei"@en) }
21    FILTER (?f = true || contains(STR(?Title), ?synonymLabel))
22  }
23  GROUP BY ?Resource ?Title ?Period ?Theme
24  ORDER BY ?Mapping_Year
```

Table 2
Result for Query 1 (samples).

Resource	Title	Mapping_Year	Period	Theme
Resource1	日治二萬分之一台灣堡圖(明治版) (Hōzu Genzu, in the Meiji era)	1904	Japanese ruled period	Historical
Resource2	台北市舊航照影像 (Taipei City aerial imagery, 1956)	1956	Japanese ruled period	Historical
Resource5	Topographic map in Taipei	2022	ROC period	Contemporary

Query 2 finds datasets from the period of Japanese rule for the purpose of urban change analysis. The results shown in Table 3 are filtered from Query 1 to present more specific information of resources for the analysis, including their scale, positional accuracy, theme type, and data type (only samples of metadata and data quality information are given here).

Query 3 finds resources with tools and environmental requirements for hardware at clients when conducting change analysis. The results (see Tables 4 and 5) show that both resource 1 and resource 2 are available at client 1. They can perform the feature detection and feature extraction functions of the GeoAI method, which includes Geospatial artificial intelligence models like object detection and object extraction for georesources, respectively. By contrast, resource 2 is unavailable due to limited data accessibility and insufficient hardware resources (e.g., limited Web bandwidth and lack of graphic cards) at client 2. The design assists users to realize the usability of a GIS system and its capability at a client, thus providing the potential for finding alternative solutions based on the detected parameters of the client and server-side environment.

Query 2
SPARQL query for retrieving data during the period of Japanese rule with map information for the change analysis in Taipei.

```
PREFIX : <http://gisc.sgis.tw/gisc#>
PREFIX dcat: <http://www.w3.org/ns/dcat#>
PREFIX dcterms: <http://purl.org/dc/terms/>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX geof: <http://www.opengis.net/def/function/geosparql/>
PREFIX ignf: <http://data.ign.fr/def/ignf#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT DISTINCT ?Resource ?Title (MIN(?Mapping_Date)
AS ?Mapping_Year) ?Scale ?Positional_Accuracy ?Map_Type ?Data_Type
WHERE {
  ?system :hasResourceInfo ?Resource.
  ?system :hasDatasetInfo ?dataset.
  ?dataset rdfs:subClassOf ?Resource;
          :hasMethod ?method;
          :mappingDate ?Mapping_Date;
          :scale ?Scale;
          dcat:spatialResolutionInMeters ?Positional_Accuracy;
          ignf:domainOfValidity/ignf:geographicElement/geo:asWKT ?wkt.
  ?Resource :hasDataType ?Data_Type;
            dcterms:title ?Title.
  OPTIONAL {
     ?method :theme ?mdt.
     ?method :hasGenerate ?Map_Type.
  }
  BIND("POLYGON ((121.57098050500008 25.197168116000057, 121.665934308000018 25.02987789300004,
      121.601234532000049 24.960889626000039, 121.457161441000039 25.107735761000072, 121.57098050500008
      25.197168116000057))" AS ?taipeiWKT)
  BIND (geof:sfIntersects(?wkt, ?taipeiWKT) as ?f)
  VALUES (?synonymLabel) { ("臺北"@zh) ("台北"@zh) ("Taipei"@en) }
  FILTER (?f = true || contains(STR(?Title), ?synonymLabel))
  FILTER contains(STR(?mdt), 'Change_Analysis').
}
GROUP BY ?Resource ?Title ?Scale ?Positional_Accuracy ?Map_Type ?Data_Type
ORDER BY ?Mapping_Year
```

Query 3

SPARQL query for identifying the accessibility, operational functions, and environments of the retrieved data in Query 2.

```
PREFIX : <http://gisc.sgis.tw/gisc#>
PREFIX cci: <http://cookingbigdata.com/linkeddata/ccinstances#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?Resource ?Accessible ?Method ?Tool (IF(bound(?S_gpu), "GPU", "") AS ?Env_Requirement)
(CONCAT( IF(bound(?S_gpu), "Server", ""), "/ ", IF(bound(?C_gpu), "Client", "")) AS ?Computing_Side)
(IF(bound(?Computing_Side), IF(contains(STR(?Accessible),"Yes"),"Yes", "No") , " No ") AS ?Available_on_Client)
WHERE {
  ?system :hasResourceInfo ?Resource.
  ?Resource :accessible ?Accessible.
  ?system :hasDatasetInfo ?dataset.
  ?system :hasServerInfo ?Computing_S.
  ?Computing_S :hasHardware/:hasComputingPower/:hasGPU ?S_gpu.
  OPTIONAL {
    ?system :hasClientInfo ?Computing_C.
    ?Computing_C :hasHardware/:hasComputingPower/:hasGPU ?C_gpu.
    FILTER contains(STR(?Computing_C), "client1").          // alter as client2 to obtain information at client 2
  }
  ?dataset rdfs:subClassOf ?Resource;
           :hasMethod ?Method.
  ?Tool rdfs:subClassOf ?Method.
  ?Method :theme ?mdt.
  FILTER contains(STR(?mdt), 'Change_Analysis').
}
```

4.2. Online thematic maps mapping

Creating a thematic map for statistical data with spatial analysis is a promising approach for discovering geospatial information and patterns. An online thematic mapping tool to generate thematic maps with semantic interpretation is developed to demonstrate the feasibility of the proposed semantic GIS framework. In the online semantic thematic mapping procedure, users can upload geodata with statistical properties and offer a thematic map's information following the rules of the GIS components ontology, for example, the title of the thematic map and time of creating a map. Then, the thematic map with semantic properties can be automatically generated and stored in an RDF repository that is available to support semantic operation afterwards.

Fig. 10 displays the results of the mapping of the population density of 22 cities and counties in Taiwan in September 2022. As to the mapping procedure, when uploading a GeoJSON file that contains cities' geometry and the population number, simultaneously, users are asked to type in fundamental information such as the id, title and created time of the thematic map (Fig. 10(a)). Then, the thematic map can be generated by selecting the correct column of properties, for example, population density (Fig. 10(b)). Finally, the information associated with the thematic map is semantically applicable. Thus, Query 4 retrieves the mapping results with its operational provenance, including used data, mapping time, mapping method, and the running side of thematic map generation shown as Table 6. The details of mapping processing offer quality and reproducible potentials for more precise geoprocessing results. In addition, a highly automated semantic GIS system development with semantic operation is demonstrated.

Table 3

Result for Query 2 (samples).

Resource	Title	Mapping_Year	Scale	Positional_Accuracy	Map_Type	Data_Type
Resource1	日治二萬分之一台灣堡圖(明治版) (Hōzu Genzu, in the Meiji era)	1904	1/20,000	5 m	Topographic map	Image
Resource2	台北市舊航照影像(Taipei City aerial imagery, 1956)	1956	N/A	10 m	Aerial image	Image
Resource5	Topographic map in Taipei	2022	1/5000	1 m	Topographic map	Image

Table 4

Result for Query 3 of client 1.

Resource	Accessible	Method	Tool	Env_Requirement	Computing_Side	Availabl_on_Client
Resource1	Yes	GeoAI	Feature detection	GPU	Client/Server	Yes
Resource2	Yes	GeoAI	Feature extraction	GPU	Client/Server	Yes

Query 4
SPARQL query for the information of thematic mapping, including the used maps and relevant operations.

```
PREFIX : <http://gisc.sgis.tw/gisc#>
PREFIX dcterms: <http://purl.org/dc/terms/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?Thematic_Map ?Used_Data ?Theme_of_Map ?Mapping_Date ?Running_Side
WHERE {
  ?system a :GIS.
  ?system :hasClientInfo ?Running_Side.
  ?system :hasDatasetInfo ?dataset.
  ?dataset rdfs:subClassOf ?Resource;
        :mappingDate ?Mapping_Date;
        :hasMethod ?method.
  ?method :hasGenerate ?Thematic_Map.
  ?Thematic_Map :hasRelated ?Theme_of_Map.
  ?Resource dcterms:title ?Used_Data;
}
```

4.3. Discussion with limitations

The implementations successfully present the feasibility of an ontology-based semantic WebGIS system that smoothly integrates ontologies with GIS systems from client and server-side operations, thereby interpreting GIS elements clearly. The framework provides improved system understanding for users, such as realizing whether available data are offered and how data can be processed by using appropriate tools in a system, as well as the potential processing capability for different clients. In addition, real-time semantic operation with highly automated semantic interpretation and transformation is demonstrated in the online thematic mapping case, leading to increased opportunities for ontology-based semantic GIS development.

The novelty of the study is evident in the design of a uniform interface that comprehensively integrates GIS components with user interaction. However, a customized GIS system created for specific applications is often developed on the basis of the required software and hardware environments set to meet the purpose of an application. A limitation of this study is that if the included domain ontologies are insufficient, then the understanding and usability of the system are limited. For example, for the building safety analysis task, relevant ontologies must be integrated into the framework. When only building elements are included and no safety policies are provided, the safety assessment for buildings cannot be achieved.

5. Conclusions and future work

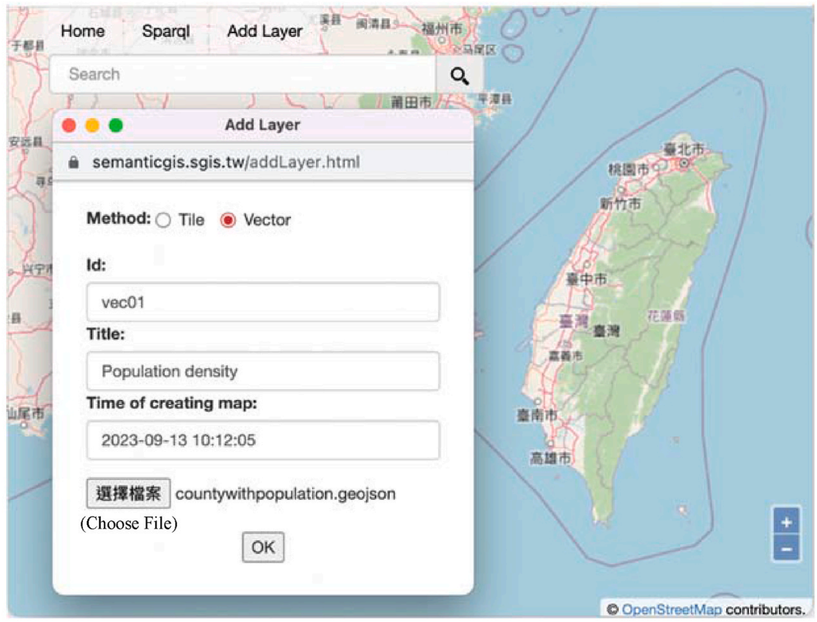
To resolve semantic heterogeneity and improve understanding and usability among diverse GIS systems, this study proposes an ontology-based semantic GIS conceptual framework comprising a three-tier architecture that combines ontologies, geodata, and development environments smoothly for the development of standalone and web-based semantic GIS applications. A remarkable accomplishment of this work is that a GIS component ontology model composed of five fundamental components of GIS that enables flexible semantic linking of potential GIS operational elements is designed to identify GIS knowledge, thus supporting GIS semantic operations. In addition, on the basis of the proposed conceptual framework and the GIS component ontology, a semantic WebGIS implementation framework is developed, and two experimental tests, including urban change analysis with system understanding and online thematic mapping with semantic interpretation, are conducted. The experiments perfectly demonstrate the feasibility and potential of the proposed framework, which helps strengthen ontology-based solutions and semantic GIS development paradigms. Future research may be conducted to establish estimation methods based on the GIS component ontology and measure the difference and similarity among GIS systems that enable users to distinguish GIS systems efficiently, with desired georesources and functionality benefiting GIS applications.

Code availability section

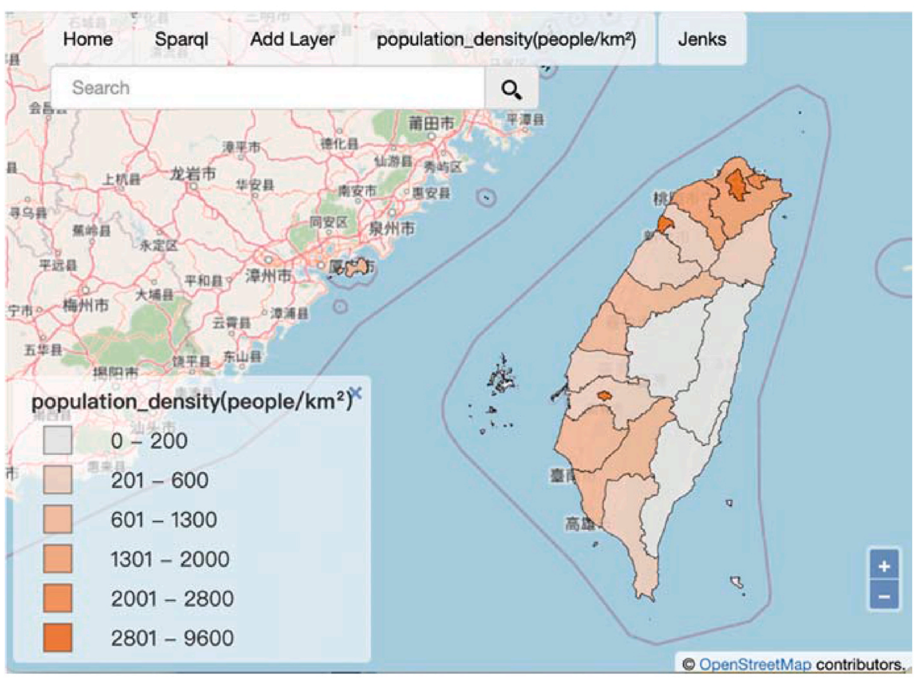
Name of the code/library: Semantic GIS.
Contact: kuo@chiaoling.com.
Program language: JavaScript, PHP.
Source codes are available at: https://gitops.tw/journal/semantic-gis.

Table 5
Result for Query 3 of client 2.

Resource	Accessible	Method	Tool	Env_Requirement	Computing Side	Available on Client
Resource1	Yes	GeoAI	Feature detection	GPU	Server	Yes
Resource2	No	GeoAI	Feature extraction	GPU	Server	No



(a)



(b)

Fig. 10. Mapping of the thematic map using semantic WebGIS: (a) the user interface for uploading files for thematic map mapping; (b) the result of the thematic map (taking the choropleth map of population density of Taiwan in September 2022 for example).

Table 6
Result for Query 4 (samples).

Thematic_Map	Used_Data	Theme_of_Map	Mapping_Date	Running_Side
Choropleth map	Population density	Population density	2023-09-13	Client

Authorship contribution statement

Chiao-Ling Kuo: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing—original draft, Writing—review and editing, Visualization, Supervision, Project administration and funding acquisition, Han-Chuan Chou: Methodology, Software, Validation, Investigation, Data curation, Visualization, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

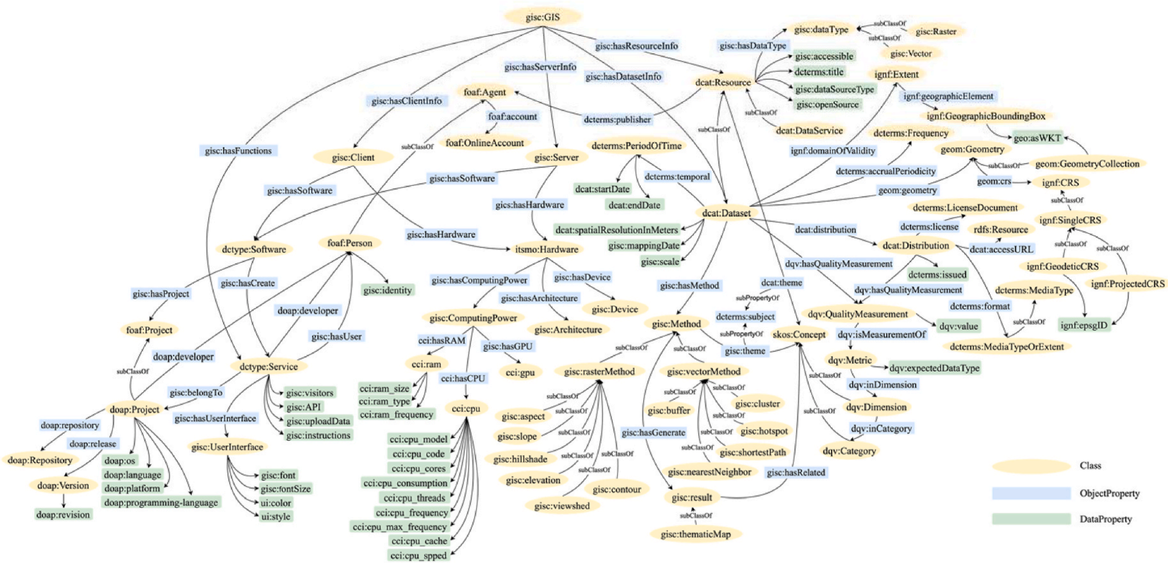
Data availability

All data used are already publicly available.

Acknowledgments

This work was supported by the National Science and Technology Council (NSTC), Taiwan, under grant number NSTC 110-2121-M-001-001-.

Appendix A. GIS components ontology



References

Albertoni, R., Isaac, A., Guéret, C., Debattista, J., Lee, D., Mihindukulasooriya, N., Zaveri, A., 2015. Data Quality Vocabulary (DQV). W3C Interest Group Note. World Wide Web Consortium (W3C).

Anna Wagner, M.B., Pauwels, Pieter, 2019. OMG: ontology for managing geometry. from. https://www.projekt-scope.de/ontologies/omg/archive/0-3/.

Bennett, J., 2010. OpenStreetMap. Packt Publishing Ltd.

Bonduel, M., Wagner, A., Pauwels, P., Vergauwen, M., Klein, R., 2019. Including Widespread Geometry Formats in Semantic Graphs Using RDF Literals. 2019 European Conference on Computing in Construction. European Council on Computing in Construction.

Claramunt, C., 2020. Ontologies for geospatial information: progress and challenges ahead. Journal of spatial information science-JOSIS 20, 35–41.

Closa, G., Masó, J., Proß, B., Pons, X., 2017. W3C PROV to describe provenance at the dataset, feature and attribute levels in a distributed environment. Comput. Environ. Urban Syst. 64, 103–117.

Consortium, W.W.W., 2012. R2RML: RDB to RDF Mapping Language.

Core, D., 2001. DCMI Type Vocabulary.

Core, D., 2023. DCMI metadata terms. from. http://purl.org/dc/terms/.

Dutta, B., Nandini, D., Shahi, G.K., 2015. MOD: metadata for ontology description and publication. In: International Conference on Dublin Core and Metadata Applications.

Fagnoni, E., 2012. A Dictionary for Some IT Service Management Subjects.

Fonseca, F., Camara, G., 2009. Geo-Ontologies. Manual of Geographic Information Systems. Madden, M. ASPRS Press, Bethesda, MD.

Fonseca, F.T., Egenhofer, M.J., Agouris, P., Câmara, G., 2002. Using ontologies for integrated geographic information systems. Trans. GIS 6 (3), 231–257.

Forestière, I. N. d. l. I. G. e, 2019. Ontology of Coordinates Reference Systems.

Goodchild, M.F., 2007. Citizens as sensors: the world of volunteered geography. Geojournal 69 (4), 211–221.

Google, 2022. Google Maps. Retrieved 2022/10/25, from. https://www.google.com.tw/maps.

Graves, M., Constabaris, A., Brickley, D., 2007. Foaf: connecting people on the semantic web. Cataloging Classif. Q. 43 (3–4), 191–202.

Gruber, T.R., 1995. Toward principles for the design of ontologies used for knowledge sharing? Int. J. Hum. Comput. Stud. 43 (5–6), 907–928.

Hartmann, J., Sure, Y., Haase, P., Palma, R., Suarez-Figueroa, M., 2005. OMV–ontology Metadata Vocabulary. ISWC.

HeiGIT, 2022. openrouteservice. from. https://openrouteservice.org/.

Hobbs, J.R., Pan, F., 2006. Time ontology in OWL. W3C working draft 27, 133.

Huang, W., Kazemzadeh, K., Mansourian, A., Harrie, L., 2020. Towards knowledge-based geospatial data integration and visualization: a case of visualizing urban bicycling suitability. IEEE Access 8, 85473–85489.

ISO/TC211, 2023. Ontology representations of geographic technology standards. from. https://def.isotc211.org/ontologies/.

Jiang, L., Yue, P., Kuhn, W., Zhang, C., Yu, C., Guo, X., 2018. Advancing interoperability of geospatial data provenance on the web: gap analysis and strategies. Comput. Geosci. 117, 21–31.

Khashoggi, B.F., Murad, A., 2020. Issues of healthcare planning and GIS: a review. ISPRS Int. J. Geo-Inf. 9 (6), 352.

Lebo, T., Sahoo, S., McGuinness, D., Belhajjame, K., Cheney, J., Corsar, D., Garijo, D., Soiland-Reyes, S., Zednik, S., Zhao, J., 2013. Prov-o: the prov ontology. W3C recommendation 30.

Li, W., Song, M., Tian, Y., 2019. An ontology-driven cyberinfrastructure for intelligent spatiotemporal question answering and open knowledge discovery. ISPRS Int. J. Geo-Inf. 8 (11), 496.

Li, W., Wang, S., Wu, S., Gu, Z., Tian, Y., 2022. Performance benchmark on semantic web repositories for spatially explicit knowledge graph applications. Comput. Environ. Urban Syst. 98, 101884.

Murray, A.T., 2021. Contemporary optimization application through geographic information systems. Omega 99, 102176.

Nathalie Abadie, G.A., 2019. Ontology of geometric primitives. from. http://data.ign.fr/def/geometrie/20190212.en.htm#overv.

Nemirovski, G., Nolle, A., 2017. Map-On: a web-based editor for visual ontology mapping. Semantic Web 8 (6), 969–980.

Norton, B., Vilches, L., León, A., Goodwin, J., Stadler, C., Anand, S., Harries, D., Villazón-Terrazas, B., Atemezing, G., 2012. Neogeo vocabulary specification-Madrid edition. Public draft. February. from URL: http://geovocab.org/doc/neogeo.

OpenLayers, 2023. OpenLayers. Retrieved 5 March 2023, from. https://openlayers.org/.

Schuurman, N., Leszczynski, A., 2006. Ontology-based metadata. Trans. GIS 10 (5), 709–726.
Tanasescu, V., Gugliotta, A., Domingue, J., Davies, R., Gutiérrez-Villarías, L., Rowlatt, M., Richardson, M., Stinčić, S., 2006. A semantic web services GIS based emergency management application. In: International Semantic Web Conference. Springer.
Tomaszewski, B., 2020. Geographic Information Systems (GIS) for Disaster Management. Routledge.
Unrau, R., Kray, C., 2019. Usability evaluation for geographic information systems: a systematic literature review. Int. J. Geogr. Inf. Sci. 33 (4), 645–665.
Vaisman, A., Chentout, K., 2019. Mapping spatiotemporal data to RDF: a SPARQL endpoint for Brussels. ISPRS Int. J. Geo-Inf. 8 (8), 353.
W3C, 2007. W3C geospatial ontologies. from. https://www.w3.org/2005/Incubator/geo/XGR-geo-ont-20071023/.
W3C, 2023. Data Catalog Vocabulary (DCAT) - Version 3 from. https://www.w3.org/TR/vocab-dcat-3/.
Wagner, A., Bonduel, M., Pauwels, P., Uwe, R., 2019. Relating Geometry Descriptions to its Derivatives on the Web. 2019 European Conference on Computing in Construction. European Council on Computing in Construction (EC3).
Wang, C., Ma, X., Chen, J., 2018. Ontology-driven data integration and visualization for exploring regional geologic time and paleontological information. Comput. Geosci. 115, 12–19.
Wang, Y., Dai, J., Sheng, J., Zhou, K., Gong, J., 2007. Geo-ontology Design and its Logic Reasoning. Geoinformatics 2007: Geospatial Information Science. SPIE.
Wilder-James, E., 2012. Description of a project vocabulary. from. https://github.com/ewilderj/doap.
Worboys, M.F., Duckham, M., 2004. GIS: a Computing Perspective. CRC press.