UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Department of Geography, Geoinformatics and Meteorology

Evaluating different options of integrating linked data into standard geospatial web services for thematic mapping

by

Wiafe Owusu-Banahene
(Student Number: 11372215)

A thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy (Geoinformatics)

in the
Faculty of Natural and Agricultural Sciences,
University of Pretoria

2015 November

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Abstract

Evaluating different options of integrating linked data into standard geospatial web services for thematic mapping

Candidate: Wiafe Owusu-Banahene **Supervisor:** Professor Serena Martha Coetzee

Degree: PhD (Geoinformatics) **Department**: Geography, Geoinformatics and Meteorology

The open data movement has resulted in many datasets on the web to be freely available for anyone to freely access, use, modify and share for any purpose (subject, at most, to requirements that preserve provenance and openness). The Linked Open Data (LOD) cloud is an example of such an open data repository of attribute data in the form of billions of Resource Description Framework triples on the Web. Visualising such open data in thematic maps provides a powerful spatial analysis tool for planning and decision-making. In this research, several styles of creating web thematic maps by integrating the attributes from the LOD cloud with geometry in a spatial database server were investigated and evaluated. Requirements for a specialised geospatial web service that combines linked data with geospatial data to create thematic maps were specified. Standard technologies were used, motivated by the widespread deployment of standardised web map services in the geospatial community and the widespread publication of alphanumeric data (by statistical agencies) in the LOD cloud. A specialisation of an Open Geospatial Consortium Web Map Service (WMS) that creates web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server was conceptualised. Three integration styles (referred to as design options) for this specialised web service were designed and implemented. The first style integrates linked data with spatial data by an importer. The second and third styles use a middleware and extension of a spatial database server respectively to integrate linked data with spatial data. In each of the three styles, attributes are retrieved from the LOD cloud through semantic queries and only the results of the semantic query are visualised on the thematic map. In this way, the benefits of semantic queries are exploited in the Semantic Web itself and the WMS mapping capabilities are used to visualise the semantic query results on a thematic map by integrating these with geospatial data. The three integration styles are critically evaluated against the specified requirements. This research contributes to understanding the pros and cons of incorporating semantic (linked) data models into standard geospatial web service models to create cartographic products (web thematic maps). This research contributes to bridging the gap between linked data and web thematic mapping.

Keywords: geospatial web service, thematic map, LOD cloud, linked data, integration, OGC Web Map Service (WMS)

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Acknowledgements

To the Most High God be the glory!

With inexpressible gratitude: I would like to thank my supervisor, Prof. Serena Coetzee who spent countless hours, days and weeks to ensure that I bring out the best in me, despite her busy schedule all year long. You really are an inspiration to me! My sincere appreciation goes to the German Academic Exchange Service (DAAD) for the partial funding of the research described in this dissertation. The University of Ghana granted me a study leave with pay; for this, I am grateful. The South Africa-Namibia bilateral project on spatial data infrastructure (2012-2013) provided partial funding for me to attend a conference in Germany in 2013. The said project created an opportunity for me to work with colleagues from Namibia (Dr Martin Hopondoka, Dr Emma Nangolo and Mr Kisco Sinvula), Ghana (Mr Foster Mensah) and South Africa (Prof. Serena Coetzee, Mr Antony Cooper and Miss Victoria Rautenbach); for this I am thankful. It was great working with you all!

To my sweet wife Afua and my children Meroma, Mataya, Melkina and Manuella who were with me during the full time studies in Pretoria, South Africa; I say, ‘Ayekoo’ (translated from Twi as ‘well done’). Without your understanding, unflinching support and co-operation, I could not have come this far. My deepest gratitude goes to my parents: Samuel Kwadwo Wiafe (late) and Juliana Serwaa for giving me the opportunity to be educated amidst their disadvantaged financial circumstances. I cannot forget your support, Dr Ransford Frempong (37 Military Hospital) and my cousin: Dr. Effah Kwabena Antwi (United Nations University, Tokyo, Japan). I appreciate all your efforts!

I would like to make special mention of Miss Victoria Rautenbach who provided administrative assistance all the time. Victoria I am grateful for everything

I am thankful to Dr Daniel Darkey, Sanet Eksteen and Erika Pretorius; staff of the Department of Geography, Geoinformatics and Meteorology of the University of Pretoria, for their support and comments during seminar presentations. To my postgraduate colleagues who worked with me in the same lab, Kisco Sinvula, Ditsela Jeofrey, Noh Teamrat and Sammy Katumba. The fruitful discussions we had in the lab about our research projects had a positive impact on this research.

My gratitude also goes to Prof. Hahns-Peter Baehr, Dr Charlotte Kaempf, Prof. Dieter Prinz and all the postgraduate students of the Master Resources Engineering (2012-2014 intake) at Karlsruhe Institute of Technology, Karlsruhe, Germany for their participation, comments and suggestions during the "Alumni Get Together PhD presentations" in 2013. I would like to also thank Professors Getrude Schaab and Reiner Jaegar of Hochschule Karlsruhe (Karlsruhe University of Applied Sciences), Karlsruhe, Germany for their support during my visit in August, 2013. "Ich bin ihnen sehr dankbar" (I am very grateful).

My siblings, extended relatives, in-laws and some friends especially Mr Oppong Amponsah and Dr Isaac K Nti supported me in diverse ways during this PhD journey. To all of you, I say thank you.

Finally, I would like to express my heartfelt appreciation to Mrs Dakey of Ghana High Commission in Pretoria, Oupa, Moses Maputuma (Bra Moss), Wendy and the family and Violet (University of Pretoria).

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Preamble

Between 2012- 2013 I was involved in the South African –Namibian bilateral cooperation on Namibian Spatial Data Infrastructure for Health. I was part of the team that represented South Africa from the Centre for Geoinformation Science of the Department of Geography Geoinformatics and Meteorology of the University of Pretoria. As part of the project, I led the team in investing the SDI in Ghana resulting in the publication of a refereed book chapter (Appendix C1). Appendix C1 presents the other publication from this project.

During my PhD studies, I was a lecturer for a *Spatial Database* short course organised by the Computer Science Department under the Centre for Continuing Education (CEATUP) of the University of Pretoria in June, 2012.

In 2011-2012, I represented the Department of Geography Geoinformatics and Meteorology of the University of Pretoria on the South African Bureau of Standards (SANS) TC 211 Committee on Geographic Information.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Table of Contents

List of Figures

List of Tables

List of Acronyms

API – Application Programming Interface
CSV – comma separated values
CKAN – Comprehensive Knowledge Archiving Network
GIS – geographic information system
GISc – geographic information science
GTWS – Geospatial Thematic Web Service
HTTP – Hypertext Transfer Protocol
IRI–Internationalized Resource Identifiers
ISO – International Organisation for Standards
JSON – JavaScript Object Notation
LOD – Linked Open Data
NamSDI – Namibian spatial data infrastructure
OGC – Open Geospatial Consortium
OWS – Open Geospatial Consortium Web Service
OWL – Web Ontology Language
SKOS – Simple Knowledge Organisation System
RDF – Resource Description Framework
SASDI – South African spatial data infrastructure
SLD – Styled Layer Descriptor
SOA – service oriented architecture
SPARQL – SPARQL Query Language for RDF
SPARQL Fed – SPARQL Federated
spatial2LOD – spatial database server extension to Linked Open Data Cloud (LOD)
TSV– tab separated values (TSV)
UDDI – Universal Discovery Description and Integration

W3C – World Wide Web Consortium

WCS – Web Coverage Service

WFS – Web Feature Service

WMS – Web Map Service

WSDL – Web Services Description Language

XML – eXstensible Markup Language

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Chapter 1: Introduction

1.1 Background Information and Motivation

Geospatial information can be presented as thematic maps, which typically feature a single distribution or relationship over a spatial background to help locate the distribution being mapped (Tyner, 2010). With the advent of the internet, thematic maps that visualise and communicate information about geographic phenomena are now widely published on the Web. A growing demand for thematic maps (Durbha, King, Shah and Youman, 2009) exists since the increase in the collection and availability of thematic data. In Geographic Information Science (GIScience), development of a theme-specific information system requires spatially represented thematic maps (Sagar, 2010). The growth in data has required an increase in the need to better understand the phenomena associated with the data, therefore requiring, new sources of information, and vigorous ability to integrate data (Janowicz *et al.*, 2013). The increasing volumes of available open data and the need to integrate these into cartographic products over the web motivated this research.

Geographic data is defined as “data with implicit or explicit reference to a location relative to the Earth.” (ISO 19109: 2005). Strictly speaking, spatial data refers to any spatial data, not only to data referenced to a location relative to the Earth, i.e. a three-dimensional representation of a teapot is also spatial data. However, in scientific literature ‘geographic data’, ‘geospatial data’ and ‘spatial data’ are typically used interchangeably and this approach is also adopted in this thesis. A web service is described by Papazoglou (2008, p8) as a self-describing, self-contained software unit available through a network (the internet) and capable of completing tasks, solving a problem or to perform a transaction for a user or application. A geospatial web service is a specialised web service that can process spatial data into geospatial information over the web (Shanming and Jianjing, 2008; Breitman, Casanova, and Truszkowski, 2010). A geospatial web service can take advantage of the statistical data available in the linked open data (LOD) cloud to create thematic maps. Visualising the vast amounts of data available in the LOD cloud as thematic maps, offers a powerful spatial analysis tool for planning and decision-making. This could be done by using geospatial web services to integrate linked open data with geometry in a spatial database server. In this thesis, a thematic map that is created by a geospatial web service is referred to as a web thematic map.

Open data refers to data or content free to use, reuse, and redistribute (subject, at most, to requirements that preserve provenance and openness (Open Knowledge, 2014). Increasingly, Government supports open data with the aim to leverage the potential of publicly funded data (UK Government Open Data, 2013; US Government Open Data, 2014; European Environment Agency, 2014). For instance, the principles of linked data (Berners-Lee, 2006) have been adopted by an increasing number of data providers and application developers leading to the creation of the *Web of data* (Bizer *et al.*, 2009). The Web of data also called the linked open data (LOD) cloud contains enormous data as billions of Resource Description Framework (RDF) triples. The LOD cloud is an example of such a Web of data available as open data over the Web (W3C 2013f; Bizer *et al.*, 2011).

The linked open data cloud is built on standards published by the World Wide Web Consortium (W3C). Relevant standards for this research are:

- The Resource Description Framework (RDF), an encoding for linked data (W3C 2014a, 2014b)
- SPARQL (W3C 2013b, 2013c), a query language for linked data
- SPARQL-Federated Query (W3C 2013a)
- SPARQL Query Results XML (extensible markup language) format (W3C 2013d)
- SPARQL Query Results CSV (comma separated values) and
- TSV (tab separated values) formats (W3C 2013e)

GeoSPARQL (OGC GeoSPARQL 2012), an emerging standard for querying geospatial data encoded in RDF, was not used because according to the needs the geometry is stored in non-RDF format in an object-relational spatial database server. The LOD cloud creates an opportunity for data consumers (Fensel, 2011; Curry *et al.*, 2013) and the potential for representing geo-information in a new and accessible form. Third-party applications are using linked data to enrich or complement its contents (Vidal, Lama, Otero-García and Bugarín, 2014). Methods to display these attribute data over the web are in high demand (Speckmann and Verbeek, 2010).

ISO/TC211[1] Geographic Information/Geomatics (International Standards Organisation (ISO) technical committee) and Open Geospatial Consortium (OGC[2]) set standards in "Geographic information/Geomatics" (Kresse and Fadaie 2010; Coetzee 2011; Fan, M., Fan, H., Chen N., Chen, Z., and Du, 2013). OGC web services standards are created for web applications (OGC, 2013). They (OGC web services) are well specified and their implementations can be tested for conformity (Janowicz *et al.*, 2010). OGC developed many standards for geospatial data exchange, intending to promote interoperability, using web services (Sun *et al.*, 2012). OGC web services accomplished a notable degree of interoperability (Goodchild *et al.*, 2012) and are used in the geospatial community. Two of these standards are used in the implementations of the three integration styles presented in this thesis. ISO/TC 211 and OGC published ISO 19128:2005, Web Map Server Interface (WMS), a specification for a web service that dynamically produces maps from spatially referenced data (ISO19128:2005). It describes a standard interface for requesting maps over the Internet. The OGC's Styled Layer Descriptor (SLD) defines an encoding that extends the WMS standard to allow user-defined symbolization and coloring of geographic features and coverages (OGC Styled Layer Descriptor 2007).

---

[1] ISO/TC211 Geoinformation/Geomatics. Available at: http://www.isotc211.org/ Accessed: 2013/01/23

[2] Open Geospatial Consortium. Available at: http://www.opengeospatial.org/ogc/vision Accessed: 2013/01/23

This research explores using standard geospatial web services to combine geometry in a spatial database with attribute data in the LOD cloud to produce thematic maps. For this research standard technologies were used, motivated by the widespread deployment of standardised web map services in the geospatial community and the widespread publication of alphanumeric data (by statistical agencies) in the LOD cloud.

Spatial databases are efficient and reliable in performing spatial analysis. On the spatial database side, ISO 19125-1:2004, *Geographic information – Simple Feature access, Part 1: Common architecture*, jointly published by ISO and the OGC, applies to this research. The standard describes the geometry object model for spatial data representation in spatial databases (ISO 19125-1:2004). Support for complex geometric data (points, lines and polygons) is well established. Much of the spatial data now in use are stored in spatial databases. Data integration approaches make it possible to combine data from heterogeneous sources into a unified (global) view. For example, the statistical data (attribute data) from the LOD cloud can be joined with geometry in a spatial database to create thematic maps. This research evaluated the various ways of combining linked data from the LOD cloud with geometry in a spatial database to create thematic maps.

Several free and open source geospatial software products are freely available and the source code can be customised or extended. Some of the proved benefits of open source software include cost savings, vendor independence, and open standards (Holmes, Doyle, and Wilson (2005; Von Hagen, 2007; Steiniger and Hunter, 2012). Free and open source geospatial software is now maturing (Steiniger and Hunter, 2013). Due to these benefits, this research sought to use free and open source geospatial software to evaluate how open source geospatial software technology can also benefit from the LOD cloud.

A spatial data infrastructure (SDI) is an enabling platform for facilitating the sharing of data among stakeholders. SDIs are widely used to share, discover, visualise and retrieve geospatial data through OGC web services. The use of OGC web services to integrate linked data from the LOD cloud with geometry in a spatial database server would advance SDI research and developments. This operation will bring to the fore the challenges, requirements and approaches for integrating the LOD cloud as part of an SDI. A current growing interest aims at leveraging linked data to allow global access to spatial data held in SDIs (Abbas and Ojo, 2013, 2014; Janowicz *et al.*, 2010; Granell, Schade and Hobona, 2010). The maturing and benefits of free and open source geospatial software will assist SDI initiatives in developing countries (such as those in Africa).

1.2 Research Description

1.2.1 Problem Statement

The LOD cloud is increasingly populated with volumes of linked data. Spatial data maintained in spatial database management systems are progressively being integrated with enterprise information systems. Spatial databases are efficient and reliable in performing spatial analysis. This research explores the use case where geometry is stored in a spatial database and attribute data needs to be retrieved from the LOD cloud to create thematic maps.

For example; sensors across a country may be measuring phenomena such as temperature, visibility, precipitation, pressure, wind speed, humidity and seismic activities. The data from these sensors may published as alphanumeric linked data, including the name of the location of each sensor, into the LOD cloud. Other statistics such as population, HIV prevalence and economic indicators of a country may also be available as alphanumeric linked data in the LOD cloud. Spatial data such as sensor location (name, northings, eastings and height), land use, all levels of administrative boundaries, environmental and geological may be stored in a spatial database. To create maps showing rainfall patterns, number of sensors for each lowest-level administrative unit, population per environmental zone, natural disaster risk areas, HIV prevalence per administrative unit would require the combination of alphanumeric linked data from the LOD cloud with spatial data in the spatial database.

In cases such as in the example, OGC web services can be used to create web thematic maps by combining the alphanumeric linked statistical (attribute) data available in the LOD cloud, with spatial data in a spatial database to create thematic maps. In its current form though, OGC web services cannot use linked data from the LOD cloud. It is a challenge to use OGC web service to access linked data from the LOD cloud and combine it with existing geometry in a spatial database server to create web thematic maps. The difficulty lies in the fact that the LOD cloud is built on linked data technology using World Wide Web Consortium (W3C) standards while OGC web services are built on OGC standards. For example, linked data is published into the LOD cloud as RDF and can be queried using SPARQL. These standards and OGC web services are heterogeneous for data models. Access and data integration are still obstacles to creating web thematic maps by combining linked data from the LOD cloud with existing geometry in a spatial database. One of the integration challenges stems from the difference in heterogeneous data models.

In this regard, this research explores ways of creating thematic maps by combining linked data from the LOD cloud with geometry stored in a spatial database server in an open source environment.

Recently, there has been a hive of research activity in geospatial linked data (see Chapter 2, Section 2.12) aimed at creating maps from linked data sources. Research efforts focus on representing geographical phenomena as linked data and producing maps from such linked data. The geometry and attributes of a geographical phenomenon is represented in a single (linked data) model (Hartig, Mühleisen and Freytag 2009, Stadler, Lehmann, Höffner and Auer 2012). The work by T. Zhao, Zhang, Wei and Peng (2008) attempt to combine linked data with geospatial data but dissimilar to this research, the flow of data is from the geospatial data sources to the LOD cloud. In the research described in this dissertation, the flow of data is from the LOD cloud to the geometry. Reports of efforts creating maps by combining linked data with data from a spatial database are limited. This research aims to contribute to the latter.

1.2.2 Goal of this Research

The purpose of this research is to investigate and evaluate various ways of creating web thematic maps by combining attributes in the form of linked data from the LOD cloud with geometry in a spatial database server. The goal is to evaluate this in an open data and open source environment.

1.2.3 Research Objectives

The research objectives:

- Review relevant literature and latest technologies:
    - Assess the current knowledge and related work in thematic cartography, ubiquitous cartography, standards based geospatial web services, linked data technology, data integration approaches, spatial data infrastructures and open source geospatial software.
    - Critically evaluate newest technologies, tools and standards in an open data and open source environment.
    - Drawing on the literature review, identify the evaluation criteria (requirements) for integration approaches that combine linked data from the LOD with geometric data in a spatial database to produce thematic maps.
- Design and implement different options of creating web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server.

    This will provide empirical evidence that can be used to compare and evaluate the designs.
- Evaluate the implementations and make recommendations for future work.
    - Critically evaluate the implementations against the evaluation criteria (requirements).
    - Make recommendations for future work.

1.2.4 Limitations of the Research

This research applied to creating choropleth and proportional symbols map. The research did not test the approach for all thematic maps. The aim was to illustrate how an OGC conformant geospatial web service can be enabled to create thematic maps from linked data and spatial data and not to improve on thematic mapping.

GeoSPARQL, an emerging and now *de facto* standard for geospatial RDF is not applied. This was deliberate because the research approach focussed on an OGC conformant web service that consumed primarily attribute data (non-spatial RDF). The attribute data were combined with geometry stored in a spatial database server.

This research aimed at bridging the gap among various technologies, namely OGC and linked data. On the contrary, it was not intended to create technology such as a semantic WMS. Where new programmes (software) were written it was intended to indicate methods by which linked data could be accessed and integrated with a geospatial web service. The research approach sought to benefit human users more than it did software agents. The processes for creating web thematic maps were not fully automated. The method used to integrate LOD as attribute data to geometric features is a join operation, the success of which depends in an overwhelming measure of the normalisation of a unique identifier data in both datasets.

The evaluation framework in this research focussed on how thematic maps can be created by combining linked data with spatial data in a spatial database. This does not include the creation of a service or an application, and benchmarking was not required.

One of the ideas of geospatial semantic web research is to make spatial data available as linked data in the web of data. Unlike geospatial semantic web research, this research combines linked data from the LOD cloud with spatial data in a spatial database to create thematic maps.

1.2.5 Significance of the Research

The research shows several ways that open source OGC conformant geospatial web service can be used to create thematic maps by combining linked data from the LOD cloud with geometry in a spatial database. This research demonstrates how ubiquitous cartography can benefit from the freely available linked data in the LOD cloud. The research highlights ways by that spatial data in spatial databases can be enriched with linked data from the LOD cloud.

In this respect, there is no need to convert the spatial data into a linked data form - a process prone to errors and it is time-consuming.

The availability of linked data in vast quantities in the LOD cloud presents an opportunity for data consumers. One of the characteristics of an ‘ideal’ SDI is that geospatial data can be integrated with many other kinds or sets of data to produce information useful for decision makers and the public, when appropriate (Nebert, 2004). From the perspective of SDI, this research brings forward some choices for integrating heterogeneous sources of data to create useful information. OGC web service in this research makes it easier to transfer the knowledge gained into SDIs development, since OGC technology are widely used in SDIs for discovery, exchange and portrayal of geospatial data and information.

1.3 Scientific Background

The study cuts across the following disciplines: Cartography, Computer Science and Geographic Information Science. This section presents the facets of this research that relates to each discipline.

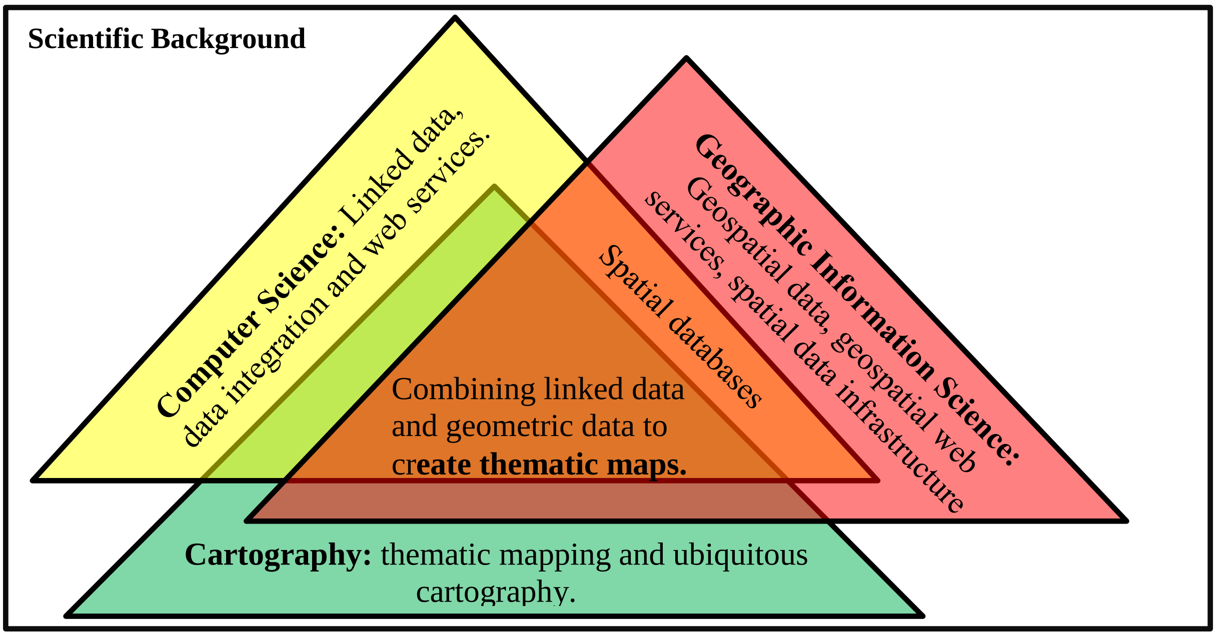


Figure 1: Scientific background to the research described in this study

This research combines aspects of these three disciplines as shown in Figure 1.

1.3.1 Cartography

The discipline of cartography, applies art (design), science and technology to map-making to design and realise these products (Cartwright, Gartner and Lehn, 2009). In Cartwright (2009), science and technology is to provide cartography with the means for providing accurate maps in a prompt and efficient manner. Thematic cartography is a branch of cartography that deals with the production of thematic maps. Slocum, McMaster, Kessler, and Howard (2010) showed that thematic cartography transformed into a true academic discipline during the twentieth century. Thematic cartography, from its beginning in the eighteenth and nineteenth centuries (MacEachren, 1979; Crampton, 2010) has exercised a significant influence on the development and spreading of knowledge (MacEachren, 1979).

Ormeling (2011) in discussing *Cartography and Geoinformation in the 20th and 21st Centuries* indicated that the digital generations have brought ubiquitous cartography in the sense that spatial data can be accessed anywhere at any time. Ubiquitous cartography thrives on the backbone of the internet, the World Wide Web and satellite systems. These technologies are what makes it possible for spatial data to be accessed anywhere at any time. This study falls into thematic cartography and ubiquitous cartography. Thematic cartography is a key of the study in that the research sought to create web thematic, maps from linked data.

Chapter 2 presented thematic cartography in Section 2.2 where thematic mapping principles and techniques are discussed. In the same chapter, ubiquitous cartography is highlighted (Section 2.3), about cartography and technological trends on the web. Ubiquitous cartography has been presented in this research on the technological discourse in the cartographic community from the late 1990s up to the 21st century and beyond. The significant highlights of the discourse appear in topical issues like *Internet cartography*, *cybercartography* and *online cartography*. In Chapter 3, thematic cartography performed a key part in selecting tools suitable for setting up a geospatial web service dedicated to producing thematic maps. In Chapter 4, the map communication model was used to derive the requirements of a specialised geospatial web service that combines alphanumeric linked data with geometry in a spatial database to create thematic maps. Choropleth and proportional symbol maps are examples of thematic maps created with the implementations of the specialised geospatial web service in Chapter 5.

1.3.2 Geographic Information Science

Geographic Information Science (GIScience) deals with the science underlying the computer system for capturing, storing, querying, analysing and displaying *geographically referenced* (geospatial) data. In the foreseeable future, GIScience will likely continue to play critical roles in many fields (ecology, emergency management, environmental engineering and sciences, geography and spatial sciences, geosciences, and social sciences) for solving scientific problems and improving decision-making practices (Wang et al., 2013). Web mapping, data integration, SDI and open source geospatial technology are areas of research in GIScience relating to this study.

According to Alam, Khan and Thuraisingham (2011), the integration of data in a geographic domain is useful in many areas such as business, academic, homeland security and public awareness. This research relates to the integration of data in the geographic domain and shows how linked data can be combined with geometric data to create new geographic information. Data integration of is made possible after data from diverse sources are integrated with a common platform. In this respect, this research throws light on integrating linked data into a spatial database environment before it is combined with geometric data. Section 2.7 and Section 2.8 of Chapter 2 presents current knowledge and gaps on integrating linked data into (spatial) databases. The conceptualisation, requirements formulation and design options, of a specialised geospatial web service that combines linked data with geospatial data to create thematic maps is presented in Chapter 4. It has the topic of integration embedded in them. Each design choice presented in Chapter 5 has its own *integrator* implemented, showing the various approaches for integrating linked data from the LOD cloud into a spatial database server.

In *producing thematic maps over the Web*, T. Auer, MacEachren, McCabe, Pezanowski and Stryker (2011) hints that the next generation of *web mapping tools* will need unique solutions to navigating, querying, displaying, and interpreting millions of data points in time and space. The importance is stressed that, *web mapping tools* be adapted to produce thematic maps associated with these large volumes of data. In this research, aspects of GIScience relating to *web mapping* are presented in Section 2.5 of Chapter 2 where standards based geospatial web services are covered. Generic architecture of geospatial web services are discussed with open source web mapping tools needed to create a web mapping component of a specialised geospatial web service. This combines linked data with geometry in Chapter 4, Section 4.2. In Chapter 4, the geospatial web service is presented. This is because the understanding of the concepts and models upon that geospatial web services are developed is required in analysing, designing, implementing and evaluating the specialised geospatial web service.

Geospatial data the core of GIScience research was explored in the conceptualisation, evaluation of technology, design options and implementations of the specialised geospatial web service as discussed in Chapters 3, 4 and 5. Each stage of the research was presented to prove enhancing a geospatial web service to create thematic maps by combining linked data from the LOD cloud with existing geometry stored in a *spatial database* server. GIScience performed a critical part in finding answers and solutions to the research question and problem posed in this research.

SDI is a key area of GIScience research. In recent times, from the technologies available, increasing volumes of diverse data needs to be integrated with SDIs. Linked data from the LOD cloud is among those diverse data that need to be integrated with SDIs. This research sheds light in this respect, proving integrated linked data into SDIs through geospatial data in a spatial database. The research described in this study shows the potential benefits of using open source software in integrating linked data with geospatial data. SDI has been presented in Chapter 2, Section 2.10. In the same chapter, open source geospatial technology has been presented in Section 2.9 and Section 2.10. The entire Chapter 3 has been dedicated to evaluation of open source geospatial technology suitable for creating the specialised geospatial web service. The various implementations of the web mapping part of the specialised geospatial web service presented in Chapter 5 used open source geospatial software.

1.3.3 Computer Science

The following aspects of this study fall under the discipline of Computer Science: linked data technology, database and web services. Breitman *et al.*, (2010), published as part of the *NASA Monographs in Systems and Software Engineering* series indicates that as the volume of web resources increases rapidly, researchers from industry, government and academia were exploring the possibility of creating a semantic web in that meaning, is made explicit. The authors call the Semantic Web, *the Web of the future*. The Semantic Web is one of the current research areas in computer science.

Hendler (2011) described the "*linked data*" and ontology communities as two communities involved in Semantic Web research. The former focuses more on the scaling and web application used semantic technologies while the latter is interested in expressive ontologies. This study categorise into the *"linked data"* community since it focusses on the retrieval of linked data (RDF) from the LOD cloud and has much less to do with ontology. Many open, distributed, and structured semantic data available on the web has no precedent in the history of computer science (Lopez, Ungerb, Cimiano and Motta, 2013).

The web will continue to be a predominant area for semantic and interoperability, but a linked data movement will need further research on integrating existing data sources (Halshofer and Neuhold, 2011). This study contributes in furthering the research on how non-semantic web applications can integrate linked data from the LOD cloud with (non-linked) geometric data. In this research, linked data from the LOD cloud is considered a by-product of the semantic web (Keivanloo and Rilling, 2014).

In this study, the linked data are presented in Chapter 2 with discussions on the LOD cloud and how linked data are represented, accessed, queried and integrated with an (object-) relational database. Chapter 4 introduces the specialised geospatial web service with the view of showing an approach by that geospatial web services can be enhanced to use the LOD cloud to create web thematic maps from linked data. Chapter 5, Chapter 6 and Chapter 7 further discuss several aspects of linked data on the specialised geospatial web service.

This research relates to other Computer Science (research areas) such as web services, service oriented architecture (SOA) and data integration. Web services and SOA upon that geospatial web services, which are presented in Chapter 2. Data integration concepts are applied in linked data integration into (spatial) database and (object-) relational database to RDF mapping as presented in Sections 2.7 and 2.8. Web services, service oriented architecture (SOA) and data integration are applied throughout the conceptualisation, design and implementations as presented in Chapters 3,4,5,6 and 7.

This study has a significant part of its foundation in Computer Science in linked data technology, databases, web services and SOA.

1.4 Research Approach

This section presented the research approach used in this study.

The research approach starts with describing the conceptualisation of a geospatial web service dedicated to producing web thematic maps from alphanumeric linked data and geometry. The remaining sub-sections present the other stages in the research approach used in finding answers to the research question, in achieving the research objectives and in finding solution to the research problem.

1.4.1 Conceptualising Geospatial Thematic Web Service

After reviewing the state-of-the-art concepts and technologies in the topics of this research, a specialisation of an OGC WMS that creates web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server is conceptualised. In this ‘research the term ‘geospatial thematic web service’ (GTWS) is used for a specialized web service (an OGC WMS) that creates web thematic maps by combining linked data with geospatial data to create thematic maps. The LOD cloud is regarded as ‘just another’ attribute data source. GTWS is used as a model to display methods that an open source geospatial web service could create web thematic maps from heterogeneous sources such as data (attribute data) from the LOD cloud together with geometry stored in a spatial database server. The idea indicated that a geospatial web service (an OGC conformant web service) could create and visualise geoinformation from linked data in the LOD cloud and geometry in a spatial database. The conceptualisation is proven on the principle that: *linked data technology can be integrated with negligible interference to existing information infrastructure, as a complementary technology for data sharing, and was not considered as a replacement for current Information Technology (IT) infrastructure* (O'Donnell, Corry, Hasan, Keane and Curry, 2013). The conceptualisation is discussed further in section 4.2 of Chapter 4.

1.4.2 Critical Evaluation of Technology, Tools and Standards

In this sub-section, the second procedure in the research approach is discussed. This procedure involved the design and implementation of an experiment used to evaluate three state-of-the-art open source web map servers for its suitability in setting up a GTWS. The three web map servers were evaluated against nine different criteria. The web map server that showed superiority in most criteria was chosen for implementing the prototype. Besides the experiments, literature was reviewed to choose other state-of-the-art tools required in setting up a web mapping component of a GTWS. The entire evaluation procedure and the results are presented in Chapter 3.

1.4.3 Identify Requirements and Design Options

In this section, the third procedure in the research approach is presented. This procedure involved the identifying requirements and creating of three, various design options of integrating alphanumeric linked data with geometry in a spatial database server. The requirements were identified from the literature review. Established on the evaluation discussed in sub-section 1.5.2, requirements identified and business process flow modelling, an OGC WMS based geospatial web service was designed consisting primarily of a client, a web map server and a spatial database server. Each design option integrates linked data from the LOD cloud into the geospatial web service environment differently. The designs enabled non-spatial linked data to be accessed from the LOD cloud and integrated with geometry in a spatial database server. An integration mechanism loaded the non-spatial linked data into the web mapping component which creates the thematic map. Styling was applied using OGC SLD. Based on a client's request; thematic maps were created and presented by the WMS to the client. Chapter 4 discusses three design options for integrating linked data with geometry in a spatial database server.

1.4.4 Implementations

In this section, the fourth procedure in the research approach is presented. This procedure involved implementing the three design options options for integrating linked data with geometry in a spatial database server. The tools used in the implementation were established on the evaluation procedure in sub-section 1.5.2. These implementations are presented in Chapter 5. The results are discussed in Chapter 6.

1.4.5 Results and Evaluations

In this section, the fifth procedure in the research approach is presented. With this procedure the design options were analysed and the three implementations evaluated against the requirements and other work. The analysis and evaluations are discussed in Chapters 6 and 7.

1.5 Brief Overview of Chapters and its Contributions

This section describes the remaining chapters in this thesis.

Chapter 2-This chapter gives an overview of the state-of-the-art in scientific background and related work and illustrate how they relate to the research from the disciplines of Cartography, GIScience and Computer Science respectively. The following topics are presented:

- Thematic cartography
- Ubiquitous cartography

- Standards based geospatial web services
- Linked data technology, spatial data infrastructure
- Open source geospatial software

The objective of this chapter is to assess the current knowledge and related work in the following:

- Thematic cartography
- Ubiquitous cartography
- Standards based geospatial web services
- Linked data technology, spatial data infrastructures
- Open source geospatial software

This chapter evaluates the challenges in creating web thematic maps from linked data. In addition to the challenges, this chapter highlights the gap between linked data and the following topics: geospatial web services, web based thematic mapping, open source geospatial software and SDIs.

Chapter 3- This chapter comprises the results of an experiment published as a refereed paper in the proceedings of Geoinformation Society of South Africa (GISSA) Ukubuzana Conference 2012 (Owusu-Banahene and Coetzee, 2012). The objective of this chapter critically evaluated state-of-the-art technologies, tools and standards that will be suitable for developing a GTWS in an open source environment. The qualitative comparison of MapServer, GeoServer and QGIS Server under default settings to ascertain its suitability for creating web based thematic maps using OGC web standards is presented. This chapter shows a procedure used in selecting one of the state-of-the art open source web map servers, needed to set up a GTWS. The procedure led to the choice of an open source spatial database server. This chapter advances the course of selecting open source geospatial software and further shows its use in setting up a geospatial web service.

Chapter 4- Chapter 4 presents the design choices of GTWS. Parts of this chapter consist of papers published as conference proceedings from the 26th International Cartographic Conference, 2013 (Owusu-Banahene and Coetzee, 2013) and one submitted to a journal (Owusu-Banahene and Coetzee, 2014). Here the objectives are 1) to identify the requirements established on literature; and 2) explore various options for geospatial web services to access linked data from the LOD cloud, integrate it with geometry stored in a spatial database server, and produce web thematic maps. Four different options each of that can integrate linked data from the LOD cloud with existing geospatial data to create web thematic maps. Unique identifiers were introduced to simplify the discussion on the various design choices and its implementations, namely: GTWS-1, GTWS-2, and GTWS-3.

Chapter 5- In this chapter, implementations of GTWS-1, GTWS-2 and GTWS-3 are presented. Parts of this chapter comprise a papers submitted to the 26th International Cartographic Conference, 2013 (Owusu-Banahene and Coetzee, 2013) and one submitted to a journal (Owusu-Banahene and Coetzee, 2014). This chapter aims to offer solid experiences of implementation with each design.

Chapter 6- Established on the implementations of Chapter 5, this chapter discusss the results and a critical assessment of GTWS about the results and contributions to scientific research. Analysis of the implementations of design options is discussed. The design options and implementations are evaluated against the requirements. A critical assessment of the GTWS approach is discussed compared with other related work.

Chapter 7- This chapter explores the research described in this research to confirm that the objectives were accomplished. This chapter represents findings and contributions to scientific research and recommendations for future research.

Appendices – This appendices B presents the list of publications resulting from this research. Appendix C shows other publications resulting from other related research projects embarked upon during this PhD study.

Chapter 2: State-of-The-Art

2.1 Introduction

This chapter gives an overview of current knowledge in the application area and in the various technologies used in the research described in this study. The overview constitutes a literature survey of the scientific background and related work relevant to this research. The following are presented: thematic cartography, ubiquitous cartography, standards based geospatial web services, linked data, spatial data infrastructures, data integration and open source geospatial software. These areas constitute the aspects of this research from the scientific disciplines of Cartography, GIScience and Computer Science.

The context of this research of work by others in the various topics of this research is presented in this chapter. This chapter highlights the knowledge gaps between existing models (standard based services, open source geospatial software, cartography and spatial data infrastructure) and linked data that support the need for the research presented in this study. This chapter forms the basis of identifying the evaluation criteria (requirements) for integration approaches that combine linked data from the LOD with geometric data in a spatial database to produce thematic maps. Requirements are presented in Section 4.3 of Chapter 4.

2.2 Cartography

2.2.1 Thematic Cartography

Cartography is the art and science concerned with the design, production and the using of maps (Cartwright *et al.*, 2009). The design and production of thematic maps fall under the branch of cartography known as thematic cartography. Thematic maps typically feature a single distribution or relationship over a spatial background to help locate the distribution being mapped (Tyner, 2010). Slocum *et al.* (2010) distinguish between general-purpose maps among maps used to specify the location of spatial phenomena and thematic maps that emphasise one or more geographic attributes.

Figure 2 is an example of a thematic map showing dominant source of water being used by households in a district municipality in South Africa in 2001. The attribute in this case is dominant source of water. Thematic maps constitute a map overlaid with some thematic information. Tyner (2010) summarises the fundamental purposes of thematic maps as:

- To provide specific information about what and how much of something is present in a particular location
- Map information about spatial patterns and to compare the spatial order and organisation
- To present findings to an audience.

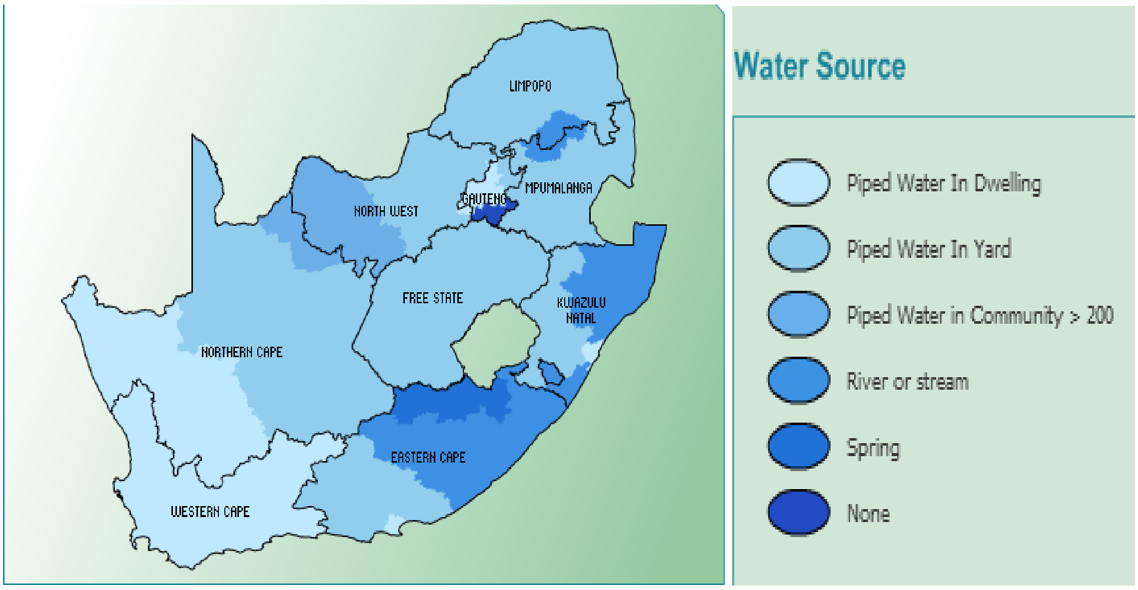


Figure 2: A thematic map showing the dominant source of water being used by households in a district municipality, 2001 (Source: *Statistics South Africa*[3]).

---

[3] http://mapserver2.statssa.gov.za/geographywebsite/index.html

The design and production of thematic maps require understanding map communication (using map communication models), visualisation techniques, statistical data analysis, graphs, cartographic principles (rules) and some mapping techniques. This section highlights the cartographic principles and techniques required to produce thematic maps.

The following represents a summary of principles of cartography incorporated into the design and production of thematic maps as selected from Slocum *et al* (2010).

- *Data classification* involves combining raw data into groups or classes. A unique symbol depicts each class or group. Some methods used in classifying data are *quantiles*, *equal intervals*, *mean-standard deviation*, *maximum breaks*, *natural breaks* and *optimal*. Cartographers use the optimal.
- *Normalisation* involves adjusting raw data for differing sizes of enumeration units. This mapping technique is appropriate when values of a phenomenon changes rapidly at boundaries of enumeration unit.
- *Symbolisation* deals with selecting an appropriate thematic mapping technique. This section discusses the common thematic mapping techniques. The principles used in selecting a particular technique include (but not limited to) considering the *nature of geographic phenomena* (for example; points, lines, areas and volumes) *the levels at which the geographic phenomena can be measured* (nominal, ordinal, interval and ratio) and *the types of symbols that can be used to* represent the spatial data (for example; visual variables).
- *Scale and generalisation-scale* specifies the representative fraction map units to Earth unit. The process of *generalisation involves* reducing the amount of information displayed on a map. Factors that affect generalisation include scale change, map purpose, intended audience and technical constraints.
- *Map projections are* used to project the earth (spherical) onto a flat surface (map). Knowledge of the earth's coordinate system is fundamental to appreciating map projections. Classes of projections include cylindrical, conic and planar. Though a class of projection is constructed, distortion is unavoidable. Some projections minimise

distortion in areal, angular, distance and direction and are called *equivalent, conformal, equidistant and azimuthal* projections. In the past projection transformation was a challenging task, but with computers this task has been trivialised.

- *Proper use of colour* involves understanding how to specify appropriate colours relevant to the map to be produced. Graphic display and choice of colour models (RGB, CMYK, Munsell, HVC and CIE) are also considered under the principle of colour.
- *Cartographic design*-This is a process used by a cartographer to conceptualise and create maps according to the needs of intended map user. The principles of map elements and typography are considered a part of the design principles.

Besides these cartographic principles, there are techniques for displaying thematic maps. Some mapping techniques are choropleth, proportional symbol, dot, isarithmic, dasymetric, multivariate, cartograms and flow maps. The research presented in this research incorporates the principles in the analysis of requirements, the designs and implementations of the various GTWS in creating web thematic maps from linked data. The results of the implementations of all the GTWS applied choropleth mapping and proportional symbol mapping techniques.

Here is an overview of choropleth and proportional symbol mapping techniques.

i. *Choropleth mapping* a technique by that the density or degree of a feature is mapped in enumeration units such as census blocks, census tracts, counties, states, or countries (Crampton, 2010). Data for enumeration units are grouped into classes and either a colour or a gray tone is assigned to each class. In constructing choropleth maps, *normalisation* is important. A choropleth map showing agricultural production (1999-2001) is shown in Figure 3.

ii. *Proportional symbol mapping* is used to create proportional symbol maps with symbols scaled in proportion to the magnitude of data arising from a particular point (true or conceptual) location. The magnitude values can be categorized into a number of classes, each represented by a symbol at a different scale. This technique uses raw data. Figure 4 is a proportional symbol map showing transport sector gasoline fuel consumption of countries.

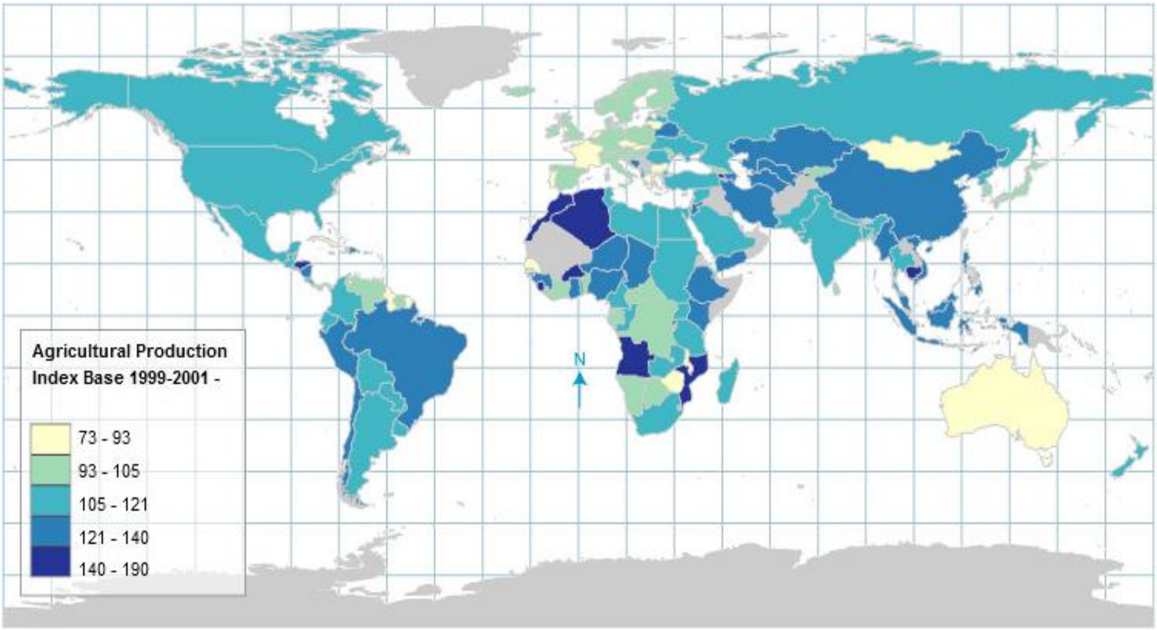


Figure 3: A choropleth map showing agricultural production (1999-2001) of countries (created with *Indiemapper*[4]).

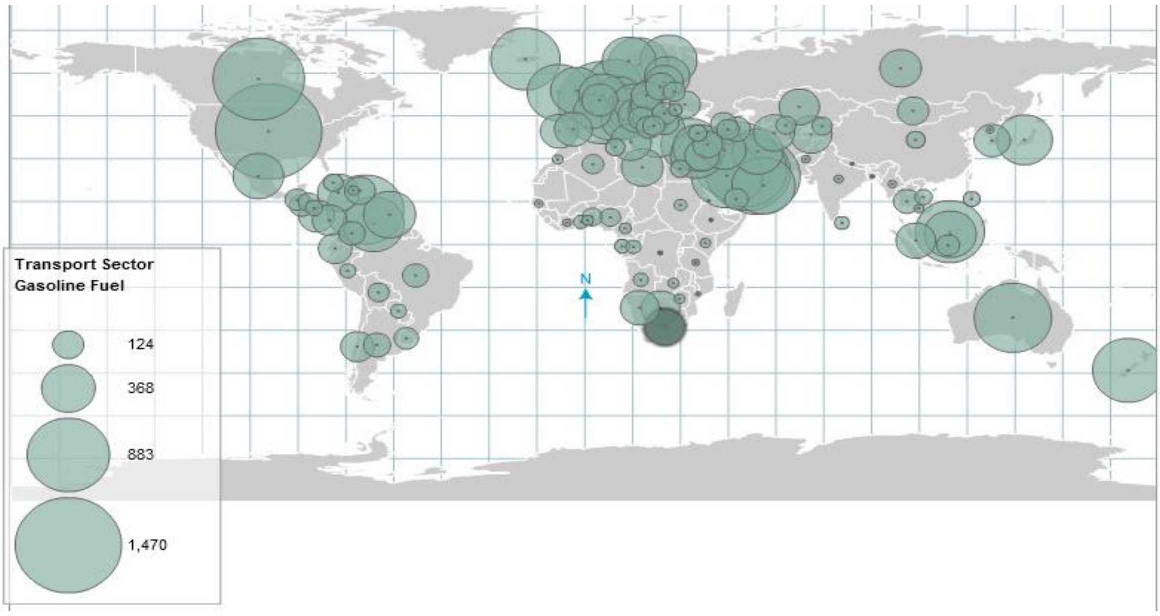


Figure 4: A proportional symbol map showing transport sector gasoline fuel consumption of countries (created with *Indiemapper*).

---

[4] Indiemapper: http://indiemapper.com

2.2.2 Ubiquitous Cartography

Ormeling (2011) in discussing Cartography and Geoinformation in the twentieth and 21st Centuries showed that the digital generations have brought ubiquitous cartography in the sense that spatial data can be accessed anywhere at any time. Ubiquitous cartography thrives on the backbone of the web and satellite systems since these technologies are what makes it possible for spatial data to be accessed anywhere at any time. Around the late twentieth century and beginning of the twenty first century, technological improvements in internet and web technologies introduced new discourse and concepts in cartography.

Cybercartography was introduced in 1997 in a keynote address presented at the International Cartographic Conference in Sweden (Taylor, 2005). Kraak (2001a), defined *Web cartography* as the design, production and using maps restricted to the medium of WWW and further stated in Kraak (2001b) that *Web cartography* is a trend in cartography. Designing maps for the internet and the web, required adjustment among cartographers, even the experienced ones.

In 2003, Richmond *et al.* (2003) also comments about Internet cartography and further explores Internet maps and its use in web-based tourism destination marketing. Krygier (2003) also explores map education in a world of WWW and reveals that most students involved in the literacy education found thematic mapping (choropleth maps of census data) to be much interesting. Herzog (2003) observed that thematic cartography could use the potential of the web to communicate spatial information to a larger audience and concluded that there are many areas where thematic mapping could be applied on the Web. I. Zaslavsky (2003) also introduces Online Cartography and comments that internet cartography has much to do with advances in distributed computing and that with cartographic ontology pages added to the web, one could address many problems of online map creation such as intelligent styling of map elements.

In 2003, Herzog observed that thematic cartography could use the potential of the web to communicate spatial information to a larger audience and concluded that there are many possible applications of thematic mapping to the context of Web. In 2005, Taylor viewed *cybercartography* as cartography's contribution to the knowledge-based economy (Taylor, 2005). Eddy *et al.* (2005) concluded that the aim of cybercartography is to provide better information about the real world and is enhanced and challenged by emerging cyber technologies. Peterson (2005), in looking at the web and computers and the role they play in the interactivity and distribution of maps, remarked that depending on the complexity, spatial patterns on thematic maps can be comprehended in an even shorter time.

Web-based services generate a large quantity of maps and this is expected to increase is expected (Stigmar and Harrie, 2011). An increasing number of map users, experts and non-experts rely on the internet to access cartographic products (de Mendonça and Delazari (2012). Web maps are becoming the *de facto* medium for distributing information because a wide audience takes part through a website (Field, 2012).

To conclude this section it is important to look at another concern Ormeling raised in his conversation (Ormeling, 2011). He predicted that one of the vital concerns for the next 20 years has to do with designing cartographic products for new platforms. Statistical data associated with geographic regions is nowadays globally available in large amounts and thus methods to display these data visually are in high demand (Speckmann and Verbeek, 2010).

The research described in this thesis takes advantage of statistical data for geographic regions (countries) freely available in the linked open data cloud. Studying recent trends of technology such as web services and linked data, this brings to the fore the theoretical and implementation concerns of cartography and thematic cartography as far as web services and the semantic web or Web of data is concerned. This study aimed at contributing to new knowledge around creating cartographic models (thematic maps) from linked data models.

2.3 Standard Based Geospatial Web Services

2.3.1 Web Services

The World Wide Web Consortium (W3C[5]) is an international community where Web standards are developed. W3C introduces Web of services as referring to message-based design established on technologies such as HTTP (Hypertext Transfer Protocol), XML (extensible Markup Language), (Universal Discovery Description and Integration) (OASIS, 2004), WSDL (Web Services Description Language) (W3C, 2007a), and SOAP (Simple Object Access Protocol) (W3C, 2007b). Booth *et al.* (2004) define a web service:

> "*as a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-process able format (specifically WSDL). Other systems interact with the Web service in a manner prescribed by its description using SOAP messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards*".

Banerjee *et al.* (2004) describes three basic parts to a Web services interaction as *discovery and configuration*, the *request* and the *optional response* as shown in Figure 5. UDDI defines a set of services supporting the description and discovery of Web services providers, the Web services they make available, and the technical interfaces which may be used to access those services (OASIS, 2004). WSDL provides a model and an XML format for describing Web services. With the help of WSDL the description of an abstract functionality offered by a service are separated from concrete details of a service description (W3C, 2007a). SOAP is an XML based lightweight protocol aimed at exchanging structured information in a decentralized, distributed environment (W3C, 2007b).

Discovery of Web services can be done for example; through WSDL files or through an UDDI registry or other automated mechanism. The *request* is formulated by SOAP using the WSDL to create and populate the message body. This is channelled through HTTP, (but not

---

[5] W3C: http://www.w3.org/standards/

always) to the URL in the WSDL. The *response* is formulated as SOAP message by the provider agent. The requester agent receives the response and decodes it.

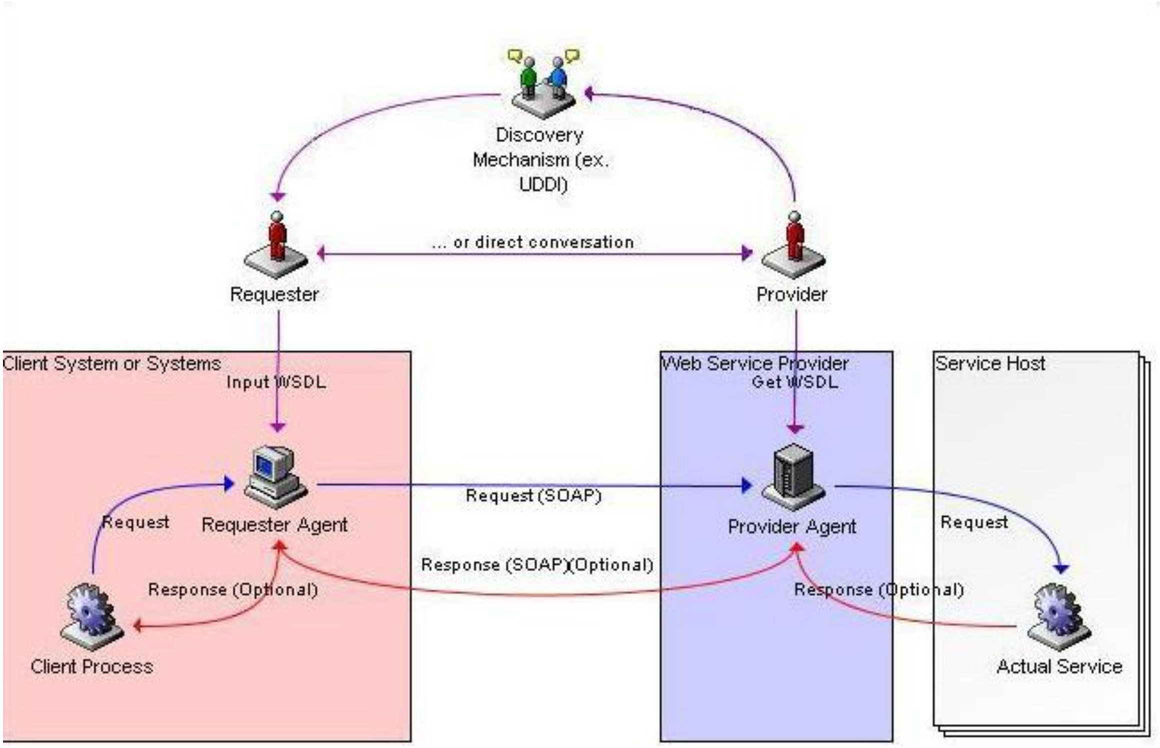


Figure 5: Anatomy of a web service interaction. Purple arrows are the discovery, the blue arrows are the request, and the red arrows are the response. (Banerjee *et al*., 2004)

The key to web services is Service-Oriented Architecture (SOA) (Papazoglou, 2008, p22). SOA is built on the notion of three operations-*publish* (publication of service descriptions), *find*-(finding the service descriptions) and *bind* (binding or invocation of services) (Papazoglou, 2008, p23). SOA is realised through web services (Lund, Eggen, Hadzic, Hafsoe, and Johnsen, 2007; Akıncı, Sesli, and Doğan, 2012). SOA has matured in recent years and provides an interoperable computing infrastructure for conducting advanced distributed geoprocessing tasks (P. Zhao, Foerster and Yue, 2012). The increasing adoption of the (SOA) paradigm enables a scalable Web (C. Yang, Di and Chen, 2012).

2.3.2 Geospatial Web Services

Geospatial web services are web services that process geospatial data (Breitman *et al.*, 2010). (Crampton, 2009; Fritz *et al.*, 2012; Schmidt and Weiser, 2012; Caquard, 2013). A web map server is the imperative part of a geospatial web service that fulfils spatial queries, conducts spatial analysis and creates and delivers maps to a client grounded on a user's request (Peng and Tsou, 2003). A web map server provides support for web services (Steiniger and Hunter, 2012).

Standards allow thousands of applications, vendor solutions, and technologies to be interoperable (OGC, 2011). Standardisation of interfaces to access geographic web services is the door opened to share information among several systems by various producers in an interoperable way (Scianna, 2013). Geospatial web services comply with well-established standards to provide seamless integration with geospatial applications (Maué, Michels and Roth, 2012). Walker Johnson *et al.* (2011), highlight that interoperability is exploited through adopting best practices, using open standards and the use of spatial data infrastructure (SDI). The standardisation of web services interfaces enable easy distribution, integration and interoperable access to a wealth of geospatial resources (Granell, Fernández and Díaz , 2014).

A need existed to identify specific standards to set up GTWS, that can create web-based thematic maps.

2.3.3 Geospatial Web Services Standards

The ISO/TC211 Geographic Information/Geomatics, develops standards for information about objects or phenomena directly or indirectly associated with a location relative to the earth (Kresse and Fadaie 2010; Coetzee 2011) and develops the ISO 19100 series of geographic information standards. OGC is a consortium comprising about 474 members as part of its mission develops international standards for geospatial interoperability.

OGC has published several standards that promote syntactic interoperability through using web services (OGC, 2011; Díaz, Bröring, McInerney, Libertá and Foerster, 2013). OGC standards are technical documents that detail interfaces or encodings and OGC Web

Services (OWSs) are those OGC standards created purposely for World Wide Web applications (OGC, 2014a). OWSs follow the publish-find-bind paradigm in the SOA and defines discovery, description, and binding layers (Yue, Di, Wei and Han, 2013) corresponding to the W3C architecture. OGC has published some OWS including WMS, Web Feature Service (WFS) and Web Coverage Service (WCS). These standards provide means to query, access, communicate, deliver, portray and process geospatial data over the Web in an interoperable manner (Han, Z. Yang, Di and Mueller, 2012; Tian and Huang, 2012; Castronova, Goodall and Elag, 2013). Among the OGC standards, WMS, WFS and WCS are most popular and being used globally (Tian and Huang, 2012). Review of WMS, WFS and WCS follows.

WMS: WMS is a service that produces maps of spatially referenced data dynamically from geographic information (de la Beaujardierre, 2006). The maps generated by WMS are mostly rendered as Portable Network Graphics (PNG), Graphics Interchange Format (GIF), Joint Photographics Expert Group (JPEG) and sometimes as Scalable Vector Graphics (SVG) or Web Computer Graphics Metafile (WebCGM) formats. A WMS defines three operations *GetCapabilities*, *GetMap* and an optional *GetFeatureInfo* (Peng and Tsou, 2003; de la Beaujardierre, 2006). *GetCapabilities* operations returns service-level metadata; *GetMap* returns a map whose geographic and dimensional parameters are well-defined; and *GetFeatureInfo* operation that returns information about particular features shown on a map. WMS is jointly published by ISO and OGC as ISO 19128:2005, Web Map Server interface and OpenGIS Web Map Service (WMS) Implementation Specification (ISO, 2005).

WFS: Vretanos, (2010) defines the WFS specification as specifying the behaviour of a service that provides transactions on and access to geographic features: independent of the underlying data store. It specifies discovery operations, query operations, locking operations, transaction operations and operations to manage stored parameterised query expressions.

WCS: Baumann, (2010), defines WCS as a standard interface and operations that enables interoperable access to geospatial "coverages". It supports electronic retrieval of geospatial data as "coverages" – that is, digital geospatial information representing space or time-varying phenomena.

Lopez-Pellicer, Renterı´a-Agualimpia, Be´jar, Muro-Medrano and Zarazaga-Soria (2011) developed a focused crawler to find available OGC Web services in March 2011. The results showed that most (4305(46.1%) out of 9329) OGC web services found were WMS from Figure 6. OGC implementation statistics (OGC, 2014b) now shows that WMS is the most widely implemented standard among geospatial software products.

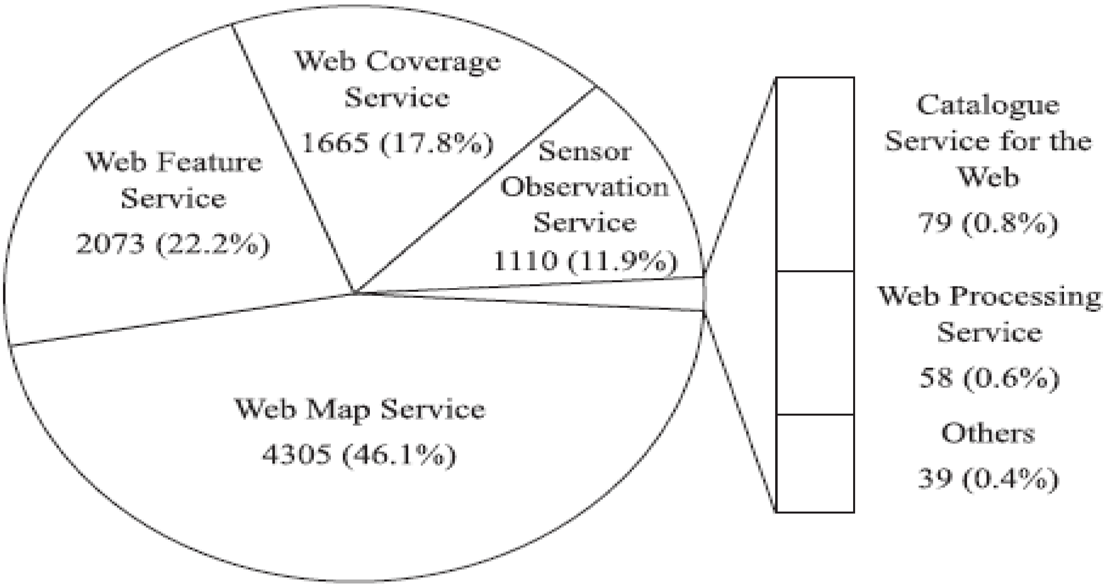


Figure 6: OGC Web service instances classified by specification (Source: Lopez-Pellicer *et al.*, 2011).

To support styling of data sets for display OGC further the *Symbology Encoding (SE) Implementation Specification*. This specification can portray the output of Web Map Servers, Web Feature Servers and Web Coverage Servers (Müller *et al.*, 2006). SE defines an eXtensible Markup Language (XML) encoding that can be used for styling feature and coverage data. There is an OGC standard called *Style Layer Descriptor profile of WMS* that defines the operation, called *DescribeLayer* that fulfils the need to style features of data differently depending on some attribute (Lupp, 2007). This operation returns the feature the several levels specified in the request, and the attributes can be discovered with the

DescribeFeatureType operation of a WFS interface or the *DescribeCoverageType* of a WCS interface. SLD defines how *Symbology Encoding* can be used together with WMS by describing styling using a user-defined XML encoding of a map's appearance (Lupp, 2007).

OGC OWS were developed to integrate geospatial data and services with web-based distributed applications (Evangelidis, Ntouros, Makridis and Papatheodorou, 2014). OGC services cannot be directly connected to the Linked Data cloud (Janowicz, 2012). The research described in this research uses OGC WMS and SLD compliant services. WMS was used atop a web map server to create and visualise the maps. SLD files generated the required style depending on the attributes of the data to form thematic maps.

2.4 Linked Data

2.4.3 Principles of Linked Data

Berners-Lee (2006) outlines the four architectural principles of linked data as:

1. *Use URIs as names for things.*
2. *Use HTTP URIs so that people can look up those names.*
3. *When someone looks up a URI, provide useful information, using the standards (RDF, SPARQL).*
4. *Include links to other URIs, so that they can discover more things.*

The principles of linked data (Berners-Lee, 2006) refer to some recommended guidelines and best practices examples Adida, Birbeck, McCarron and Herman (2013); Archer, Smith and Perego (2009); Berruetta and Phipps (2008) and Connolly (2007) for exposing, sharing, and connecting RDF data by dereferenceable URIs in the Semantic Web (Bizer, Heath, Idehen and Berners-Lee, 2008). Linked data are further empowered by technologies such as RDF (Manola and Miller, 2004), SPARQL (Steve and Seaborne, 2013), OWL Web Ontology Language (OWL) (McGuinness and van Harmelen, 2004), OWL2 (W3C OWL Working Group, 2012), and Simple Knowledge Organisation System (SKOS) (Miles and Bechhofer, 2009). OWL is used to build vocabularies or "ontologies" and SKOS is used for designing knowledge organisation systems. This makes it possible to enrich data with additional meaning, which allows more people (and more machines) to do more with the data.

Linked data technologies use these standards established by the W3C aiming at information integration (König, Dirnbeket and Stankovski, 2013). The primary objective of linked data is on publishing structured data as RDF using URIs to focus on ontological representations or implication (Keivanloo and Rilling, 2014). The motivation to implement linked data spaces is the RDF technology (Galiotou and Fragkou, 2013). Third-party applications are just starting to use linked data to enrich or complement its own contents (Vidal, Lama, Otero-García and Bugarín, 2014).

In this study, RDF and SPARQL are used for the designs and implementations of GTWSs. The GTWSs in its current forms do not use OWL and SKOS. GTWSs use neither ontologies nor designing of knowledge organisation systems. GTWSs are consumers of linked data.

2.4.4 Linked Open Data (LOD) Cloud

These best practices have been adopted by an increasing number of data providers, thus significantly increasing the amount of linked data published (Colomo-Palacios, Stantchev and Rodríguez-González, 2014). After the first discussions of the linked data approach, the amount of linked data published has been increasing rapidly (Bechhofer *et al.*, 2013) leading to create a global data space containing billions of assertions - the *Web of Data* (Bizer, Heath and Berners-Lee, 2009). The emerging *Web of Data* means easier access to data for consumers (Curry *et al.*, 2013).

Efforts by the *Linking Open Data community project* aimed at making open interlinked datasets available on the web have resulted creating the LOD cloud. The most visible application of the linked data principles is the LOD project (Pohorec, Zorman and Kokol, 2013; Dobbins, Merabti, Fergus, Llewellyn-Jones and Bouhafs, 2013). The LOD cloud diagram by Schmachtenberg, Bizer, and Paulheim (2014) is shown in Figure 7. The nodes are the linked datasets and the arrows show interlinks to other datasets in the cloud. One of the main challenging issues is developing applications established on the *Web of Data* (Heath, 2008; Heath and Bizer, 2011; Hausenblas, 2009, 2011).

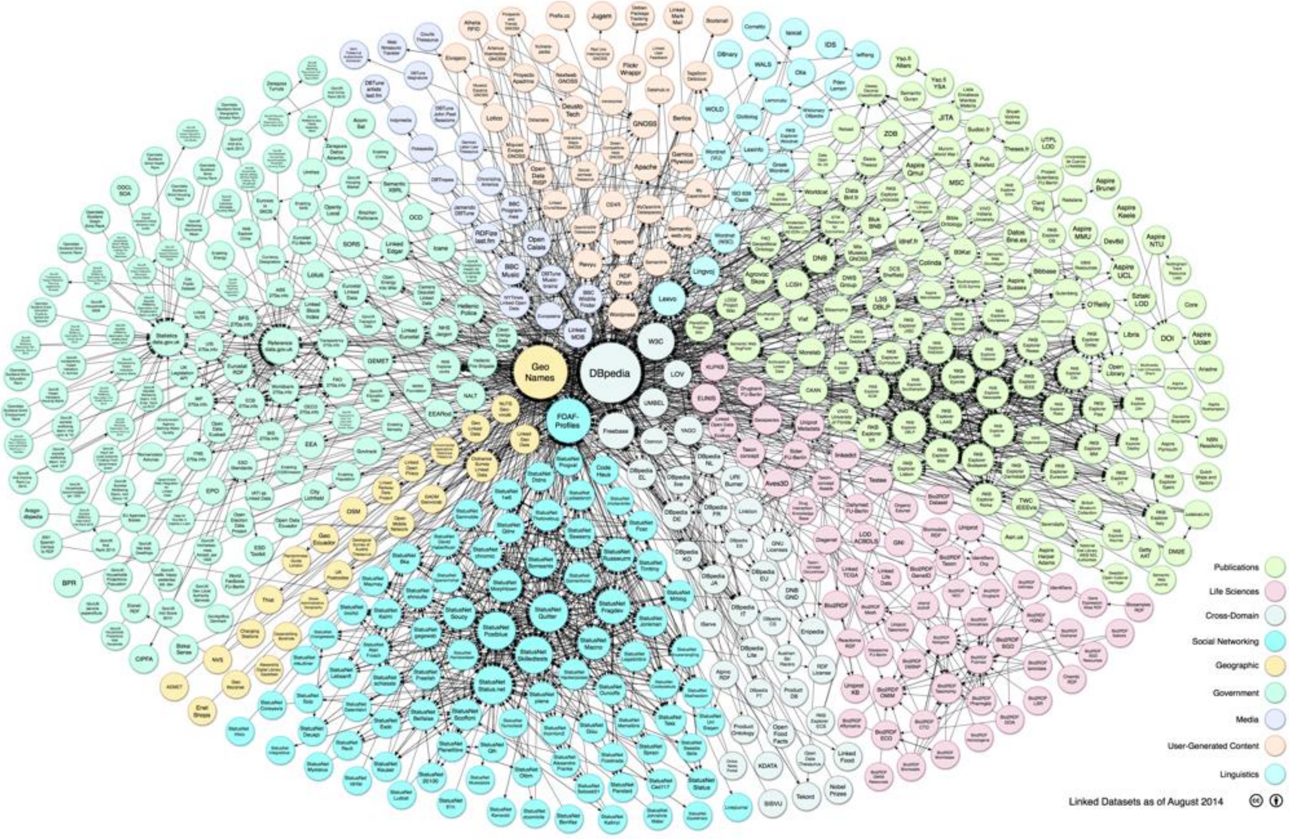


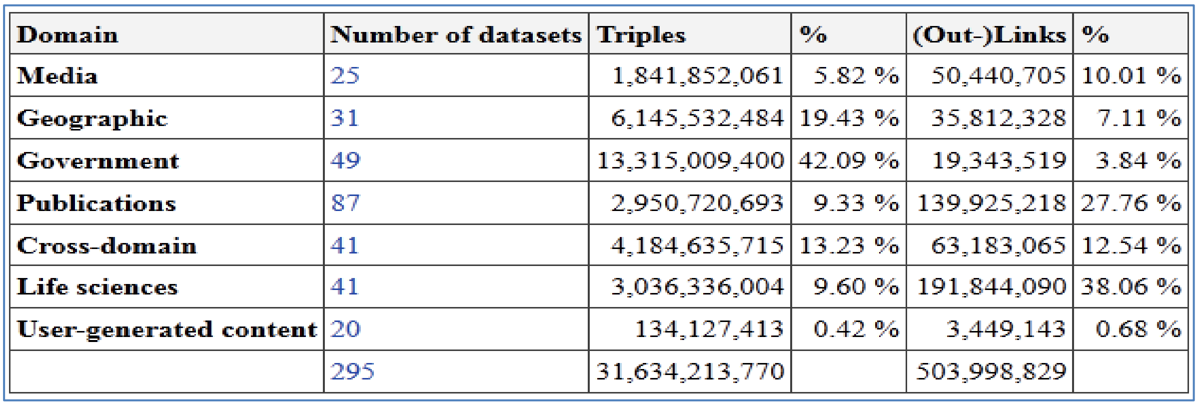
Figure 7: LOD Cloud diagram (Source: Schmachtenberg, Bizer, and Paulheim, 2014)

The *Web of data* also known as the LOD cloud (H. Chen, Yu and J. Chen, 2013; Ballatore, Bertolotto and Wilson, 2013), enhances available attributes as open interlinked datasets. With the LOD cloud, new applications arise, attempting to use information from various data sources (Apanovich and Marchuk, 2013). Linked data (geospatial and non-geospatial) has become one of the new research trends in recent years (Wiegand, Kolas and Berg-Cross, 2010; Janowicz, 2012).

2.4.5 Statistics on the Linked Open Data Cloud

Data sets in the LOD cloud are classified into the following topical domains: geographic, government, media, libraries, life science, retail and commerce, user-generated content, and cross-domain data sets (Heath and Bizer, 2011). Table 1 summarises the number of triples and the amount of RDF links per domain. In September 2011, the LOD cloud contained more than 31 billion RDF triples and around 504 million cross-data set RDF links (Bizer *et al.*, 2011) in Table 1.

Table 1: Overview of the number of triples and the amount of RDF links per domain as at September 2011 (Source: Bizer *et al.*, 2011)



Domain	Number of datasets	Triples	%	(Out-)Links	%
Media	25	1,841,852,061	5.82 %	50,440,705	10.01 %
Geographic	31	6,145,532,484	19.43 %	35,812,328	7.11 %
Government	49	13,315,009,400	42.09 %	19,343,519	3.84 %
Publications	87	2,950,720,693	9.33 %	139,925,218	27.76 %
Cross-domain	41	4,184,635,715	13.23 %	63,183,065	12.54 %
Life sciences	41	3,036,336,004	9.60 %	191,844,090	38.06 %
User-generated content	20	134,127,413	0.42 %	3,449,143	0.68 %
	295	31,634,213,770		503,998,829	

Comprehensive Knowledge Archiving Network (CKAN, “The *Data Hub*[6]”) is an open source data management system, used by government and organisations around the world, to provide tools for publishing, distributing, finding and using data (Open Knowledge Foundation, 2014). This is written and maintained by *Open Knowledge*[7], a worldwide non-profit network of people passionate about openness.

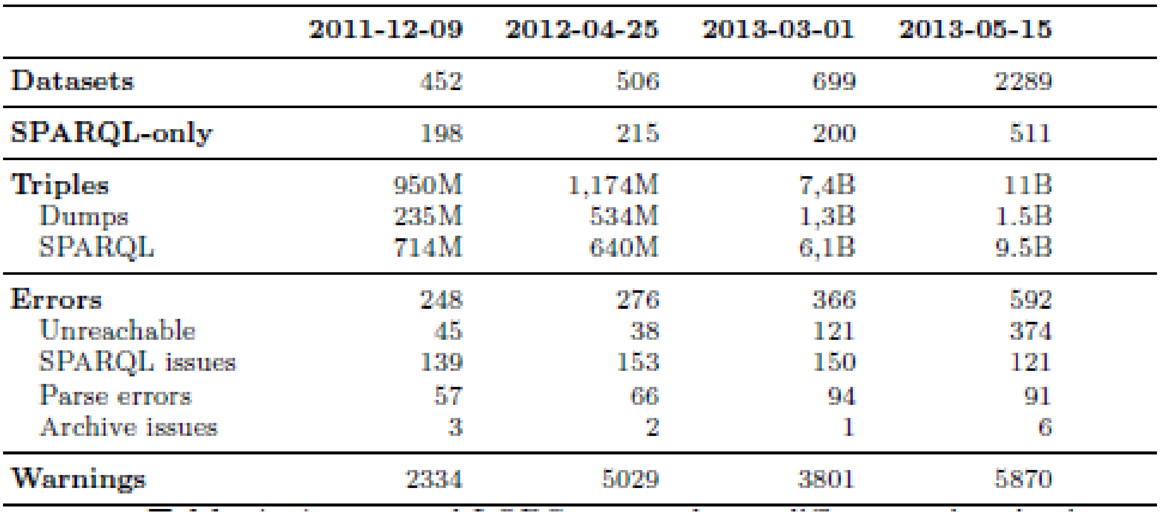
LODStats (see http://stats.lod2.eu/) is a statement-stream-based approach for gathering comprehensive statistics about RDF datasets (S. Auer, Demter, Martin and Lehmann, 2012). One rationale fordeveloping *LODStats* is the computation of statistics for resources from the CKAN (“*Data Hub*"). Ermilov, Martin, Lehmann, and Auer, (2013) presented a web

---

[6] http://datahub.io/about
[7] http://okfn.org/about/

application proven on *LODStats* for collection and exploration of the Linked Open Data statistics. Ermilov *et al.* (2013) evaluated every dataset available by CKAN in one format *LODStats* can handle (i.e. N-Triples, RDF/XML, Turtle, N-Quads, N3). The results of its results in Table 2 show that in May 2013 the *Web of Data* contained 2289 linked datasets and 11 Billion triples. In February 2014, the *LODStats* website[8] shows that the *Web of Data* contains more than 61 Billion triples.

Table 2: Aggregated LODStats results at various points in time (Source: Ermilov *et al.*, 2013)



	2011-12-09	2012-04-25	2013-03-01	2013-05-15
Datasets	452	506	699	2289
SPARQL-only	198	215	200	511
Triples	950M	1,174M	7,4B	11B
Dumps	235M	534M	1,3B	1.5B
SPARQL	714M	640M	6,1B	9.5B
Errors	248	276	366	592
Unreachable	45	38	121	374
SPARQL issues	139	153	150	121
Parse errors	57	66	94	91
Archive issues	3	2	1	6
Warnings	2334	5029	3801	5870

The LOD cloud presents an opportunity for data consumers. The design options and their implementation choices presented in this thesis make it possible for free and open source geospatial software to connect to the LOD cloud to consume linked data.

2.4.6 Representing Linked Data

Information about resources on the Web is represented in RDF (Breitman *et al.*, 2010, Fensel, 2011). RDF makes it possible to write statements about resources with each statement comprising a *triple*. The parts of a triple are the *subject*, represented by an URI or a blank node; the *predicate* or *property*, represented by an URI; and the *object*, represented by an

---

[8] http://stats.lod2.eu/

URI, a blank node, or a literal. Several triples form a graph. RDF is a language for representing information about resources in the WWW (Manola and Miller 2004). It provides a flexible data model (Breitman *et al.*, 2010), allowing RDF data to be serialised in various formats for publication on the Web. Formats include RDF/XML, RDFa, Turtle, N-Triples, RDF JSON (Heath and Bizer, 2011). RDF, is simple to implement, and allows straightforward integration of data from heterogeneous sources (Nečaský *et al.*, 2014).

W3C Geospatial Incubator Group (GeoXG)[9] published: Geospatial Vocabulary defines a basic ontology and OWL vocabulary for representing geospatial properties for Web resources (Lieberman, Singh and Goad, 2007a). This report presents a model for basic feature properties of Web resources and a realisation of these feature property elements as XML and OWL/RDF vocabularies. Geospatial Ontologies, another report by Lieberman, Singh and Goad (2007b), describe geospatial foundation ontologies that can represent geospatial concepts and properties on the worldwide web. GeoRDF[10] is an RDF compatible profile for geospatial information. It defines profiles for points, lines and polygons. The GTWS presented in Chapter 5 consumes non-spatial linked data (attribute data) from the LOD cloud.

2.4.7 Querying Linked Data

Prud'hommeaux and Seaborne (2008) define SPARQL as the query language for RDF. Some linked data providers provide RDF dump or SPARQL endpoint for its linked datasets (Heath and Bizer, 2011). An RDF dump, a large RDF document, contains the RDF graph that makes up the entire linked dataset but a SPARQL endpoint is an HTTP-based query service that executes SPARQL queries over the linked dataset (Hartig and Langegger, 2010). The geospatial thematic web services presented in this research consume non-spatial linked data in RDF through a SPARQL endpoint.

SPARQL is the query language for RDF and can express queries across data stored as RDF or viewed as RDF over middleware (Steve and Seaborne, 2013). SPARQL provides a

---

[9] www.w3.org/2005/Incubator/geo/
[10] www.w3.org/wiki/GeoRDF#Implementation

flexible and extensive way to query RDF data (Aditya and Kraak, 2007). SPARQL query results can be serialised into other formats, such as Extensible Markup Language (XML) (Beckett and Broekstra, 2013), JavaScript Object Notation (JSON), CSV or tab separated values (TSV) (Seaborne, 2013a, 2013b). The SPARQL federated query is an extension for executing SPARQL queries distributed over various SPARQL endpoints (Prud'hommeaux and Buil-Aranda, 2013). GTWS-2 and GTWS-3 use SPARQL federated queries to retrieve attributes (RDF) from the LOD cloud, while GTWS-1 uses SPARQL queries.

OGC published a standard, OGC GeoSPARQL that supports representing and querying geospatial data on the Semantic Web (Perry and Herring, 2012). GeoSPARQL defines a vocabulary for representing geospatial data in RDF. It also defines an extension to the SPARQL query language for processing geospatial data. No need existed to use GeoSPARQL for GTWS in its current implementation because GTWS consumes only non-spatial attributes from the LOD cloud. The non-spatial attributes and point geometric data can be represented as RDF.

2.4.8 Accessing Linked Data

Prud'hommeaux and Seaborne (2008) define SPARQL as the query language for RDF. Some linked data providers provide RDF dump or SPARQL endpoint for its linked datasets (Heath and Bizer, 2011). An RDF dump, a large RDF document, contains the RDF graph that constructs the entire linked dataset but a SPARQL endpoint is an HTTP-based query service that executes SPARQL queries over the linked dataset (Hartig and Langegger, 2010; Jupp *et al.*, 2014; J. Zhao, Miles, Klyne and Shotton, 2009; Villata, Costabello, Delaforge and Gandon, 2013). The geospatial thematic web services consume non-spatial linked data in RDF by a SPARQL endpoint.

2.5 Data Integration

Data integration deals with the problem of combining data from various sources, and providing the user with a unified view of these data (Lenzerini, 2002). Database integration is the process that takes as input a set of databases, and produces as output a single unified description of the input schemas (the integrated schema) and the associated mapping information (Castano and De Antonellis, 1998) as shown in Figure 8.

Lenzerini (2002) formalise a data integration system as follows: $I = <G; S;M>$ where

- I is the data integration system.
- G is the global schema, expressed in a language L_G over an alphabet A_G. The alphabet comprises a symbol for each element of G (for example; relation if G is relational, class if G is object-oriented).
- S is the source schema, expressed in a language L_S over an alphabet A_S. The alphabet A_S includes a symbol for each element of the sources.
- M is the mapping between G and S.

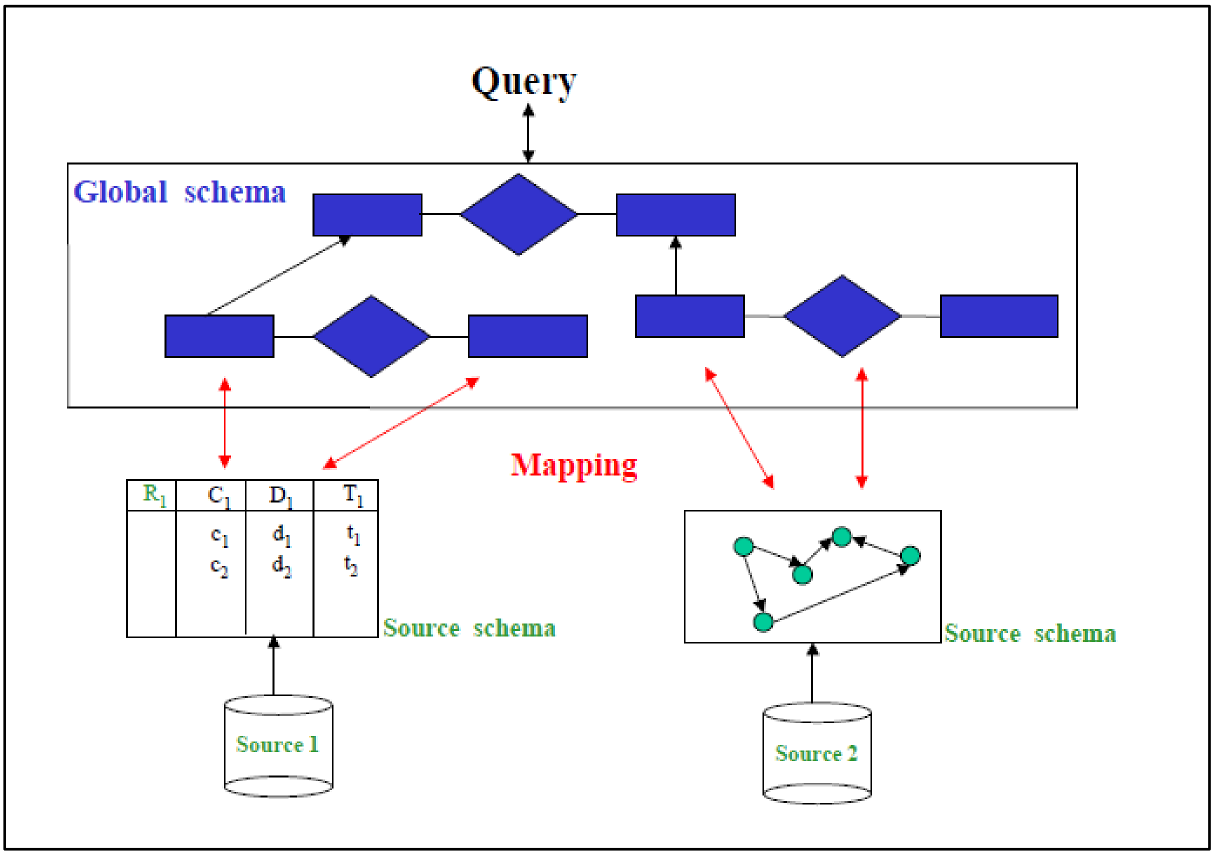


Figure 8: Data integration system (Source: Lenzerini, 2002)

2.5.1 Approaches to Data Integration

The main approaches to data integration are *Local-as-View* (LAV) and *Global-as-View* (GAV) (Castano and De Antonellis, 1998; Halevy, Rajaraman and Ordille, 2006). GAV requires that the global schema is expressed in the data sources whilst LAV requires the global schema to be specified in-dependently from the sources (Lenzerini, 2002). In LAV the relationships among the global schema and the sources are established by defining every source as a view over the global schema.

Lenzerini, 2002 distinguishes the LAV and GAV from the modelling perspective as:

- The LAV approach is based on the idea that the content of each source should be characterised with a view over the global scheme. LAV approach favours the extensibility of the system: adding a new source means enriching the mapping with a new assertion, without other changes.
- The idea proves that the content of each element of the global schema should be characterised with a view over the sources The GAV approach is . GAV approach favours the system in carrying out query processing because it tells the system how to use the sources to retrieve data. Extending the system with a new source is now a problem. The new source may influence defining various elements of the global schema, whose associated views need to be redefined.

In processing queries in GAV and LAV, Calì, Calvanese, De Giacomo, and Lenzerini (2013) highlights the following:

- Processing queries in LAV is similar to query answering with incomplete information and is a complex task.
- Query processing is much easier in GAV approach where answering a query, means unfolding its atoms according to its definitions about the sources.

There is a mixed approach that combines the advantages of LAV and GAV in a mediation language called Global-And-Local-As-View (GLAV) (Halevy et al., 2006; Kwakye, 2011).

Modelling the Web of data requires using the GLAV approach since GAV and LAV are restricted to modelling relations (Friedman, Levy and Millstein,1999).

The Open Data Platform (Mildorf et. al (2014) and the HUMBOLDT project[11] are examples of data integration where *spatial* data is integrated. The Open Data Platform enables users to integrate, harmonise and visualise spatial planning and other data (Mildorf et. al (2014). The HUMBOLDT project provides tools and services aimed at enabling the implementation of a framework for harmonising spatial data and services, under the Infrastructure for Spatial Information in Europe (INSPIRE[12]) Directive (Villa, Molina, Gomarasca and Roccatagliata , 2012).

In this research, the focus is on investigating and evaluating several ways of creating web thematic maps by combining alphanumeric linked data from the LOD cloud with geometry in a spatial database server.

2.5.2 Integrating Linked Data into (Spatial) Databases

Traditional data management applications operate in well-structured information environments and benefit from full-fledged strategies (SQL) that provide the needed functionality to represent, manage and query well-structured data (Yu and Spaccapietra, 2010). Geonames.org[13] (and Gazetteers) does not provide geometries for the location names other than a single representative point (Brisaboa, Luaces, Places and Seco, 2010). A Gazetteer is a geographical dictionary that contains, besides location names, alternative names, populations, location of places, and other information related to the location (Brisaboa *et al.*, 2010).

Many storage mechanisms are available for storing linked data. The first persistent RDF storage mechanisms were built using backing relational databases, with a layer added to translate data back and forth into a relational schema. While this approach provides a solid,

---

[11] http://www.esdi-humboldt.eu/home.html
[12] http://inspire.ec.europa.eu/
[13] http://www.geonames.org/

reliable base upon which to build, performance can be lacking (Kolas, 2008). With the increasing amount of RDF data on the Web, researchers developed specialized architectures for RDF data management named triple stores (Abadi, Marcus, Madden and Hollenbach, 2007; Carroll *et al.*, 2004; Chong, Das, Eadon and Srinivasan, 2005; Neumann and Weikum, 2010; Weiss, Karras and Bernstein, 2008). These store the data in a native form more like RDF, and as a result, provide better performance (Rohloff, Dean, Emmons, Ryder and Sumner, 2007).

Some Semantic Web triple stores are adding spatial indexing, such as *Spatially-Augmented Knowledgebase* (SPAUK) (Kolas, 2008). Meanwhile, in the Semantic Web, the support for geometric data has also increased significantly (Kolas and Self 2007), with the following triple stores supporting this kind of data: OWLIM Standard Edition[14] (OWLIM-SE, previously known as BigOWLIM), Open Sahara [15] , Parliament [16] , AllegroGraph[17] and Virtuoso[18]. Both types are viable storage solutions but this strictly Semantic Web types of system cannot process spatial data efficiently (Kolas and Self 2007).

In the relational database realm, support for complex geometric data (points, lines, and polygons) is already well established. Examples are MySQL[19], PostgreSQL[20], and Oracle[21]. Much of the spatial data now in use is stored in a relational database with additional spatial indices. This technique is efficient and reliable. While a relational database with spatial extensions is useful, it fails to provide the benefits of the Semantic Web as described above (Kolas, 2008).

Since neither a Semantic Web triple store nor a relational database with spatial extensions provides all the functionality that is desired, a new system has come into existence. These systems combine efficient storage of Semantic Web data with efficient storage of spatial data

---

[14] http://www.ontotext.com/owlim/geo-spatial
[15] https://dev.opensahara.com/
[16] http://parliament.semwebcentral.org/
[17] http://www.franz.com/agraph/allegrograph/
[18] http://virtuoso.openlinksw.com/
[19] http://www.mysql.com/
[20] http://www.postgresql.org/
[21] http://www.oracle.com/index.html

(Kolas, 2008). These systems are now being created working in both directions; some spatial data systems are now adding RDF support, such as Oracle. Oracle is discussed further under the section on Related Work.

2.5.3 Relational Database to RDF Mapping Approaches

Converting relational databases to RDF is a significant area of research with several approaches published and many tools available (Stadler, Lehmann, Höffner and Auer, 2012). There is the *W3C RDB2RDF working group*[22], that aims to standardise a database to RDF mapping language (Das, Sundara and Cyganiak, 2012). There are various tools available implementing the surveyed approaches such as *D2R*[23], *Triplify*[24], *DartGrid*[25], *DataMaster*[26], *MapOnto*[27], *METAmorphoses*[28], *ODEMapster*[29], *RDBToOnto*[30], *RDOTE* (Vavliakis, Grollios and Mitkas, 2013), *Virtuoso RDF Views*[31] and *VisAVis*[32]. The reader is refered to surveys (Sahoo *et al.*, 2009; Spanos, Stavrou and Mitrou, 2012) and *overviews*[33] on this topic for further information.

In sub-section 2.9.1 and 2.9.2, the mapping approaches published by the W3C RDB2RDF working group is briefly presented. Sub-section 2.9.3 highlights the mapping of object schemas to relational database schemas. These approaches were explored to find a suitable approach for integrating RDF directly into a spatial database as for GTWS-3.

A Direct Mapping of Relational Data to RDF

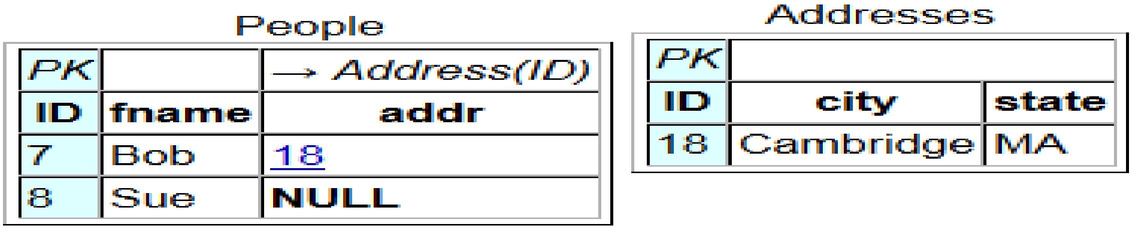
---

[22] http://www.w3.org/2001/sw/rdb2rdf/
[23] http://d2rq.org/d2r-server
[24] http://triplify.org/Overview
[25] http://www.w3.org/wiki/DartGrid
[26] http://protegewiki.stanford.edu/wiki/DataMaster
[27] http://www.cs.toronto.edu/semanticweb/maponto/
[28] http://metamorphoses.sourceforge.net/
[29] http://neon-toolkit.org/wiki/ODEMapster
[30] http://www.tao-project.eu/researchanddevelopment/demosanddownloads/RDBToOnto.html
[31] http://docs.openlinksw.com/virtuoso/rdfviewsrdbms.html
[32] https://code.google.com/p/visavis/
[33] http://esw.w3.org/topic/Rdb2RdfXG/StateOfTheArt

In this sub-section the mapping approach published by the W3C RDB2RDF Working Group in (Arenas, Alexandre, Prud'hommeaux and Sequeda, 2012) is highlighted. The *direct mapping* defines an RDF graph representation of data in a relational database (Arenas *et al.*, 2012). The direct mapping takes as input a relational database (data and schema) and generates an RDF graph called the direct graph. The algorithms compose a graph of relative Internationalized Resource Identifiers (IRIs) that must be resolved against a base IRI to form an RDF graph. Foreign keys in relational databases establish a reference from any row in a table to exactly one row in a (potentially different) table. The direct graph conveys these references, and each value in the row.

For example; the results of applying a direct mapping to relational tables People and Addresses (see Table 3) are shown in Figure 9.

Table 3: People and Address relational tables (Source: Arenas *et al.*, 2012)

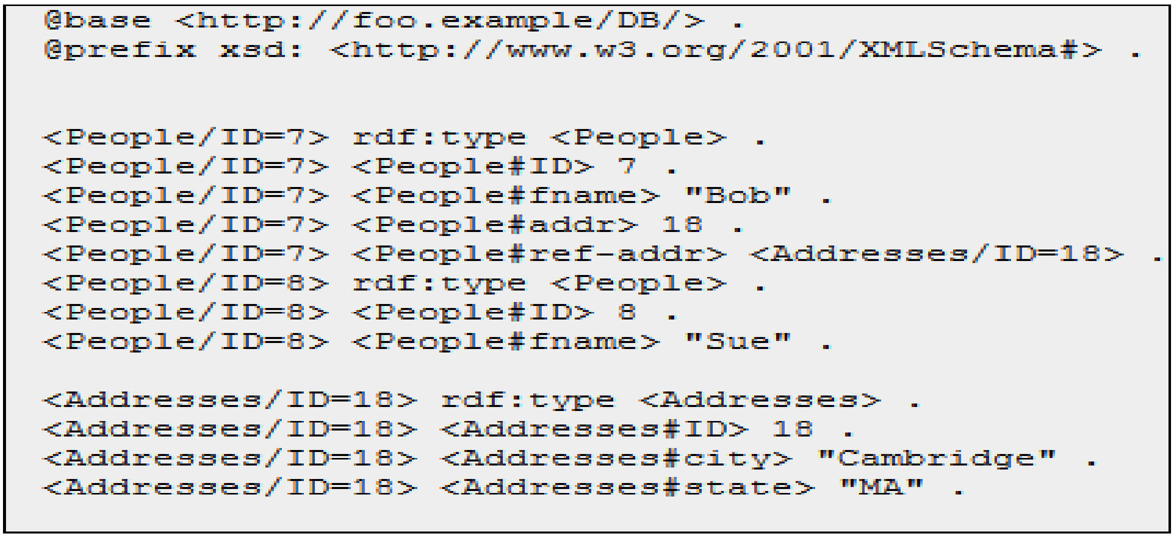


People

PK		*→ Address(ID)*
ID	**fname**	**addr**
7	Bob	18
8	Sue	**NULL**

Addresses

PK		
ID	**city**	**state**
18	Cambridge	MA



```
@base <http://foo.example/DB/> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .


<People/ID=7> rdf:type <People> .
<People/ID=7> <People#ID> 7 .
<People/ID=7> <People#fname> "Bob" .
<People/ID=7> <People#addr> 18 .
<People/ID=7> <People#ref-addr> <Addresses/ID=18> .
<People/ID=8> rdf:type <People> .
<People/ID=8> <People#ID> 8 .
<People/ID=8> <People#fname> "Sue" .

<Addresses/ID=18> rdf:type <Addresses> .
<Addresses/ID=18> <Addresses#ID> 18 .
<Addresses/ID=18> <Addresses#city> "Cambridge" .
<Addresses/ID=18> <Addresses#state> "MA" .
```

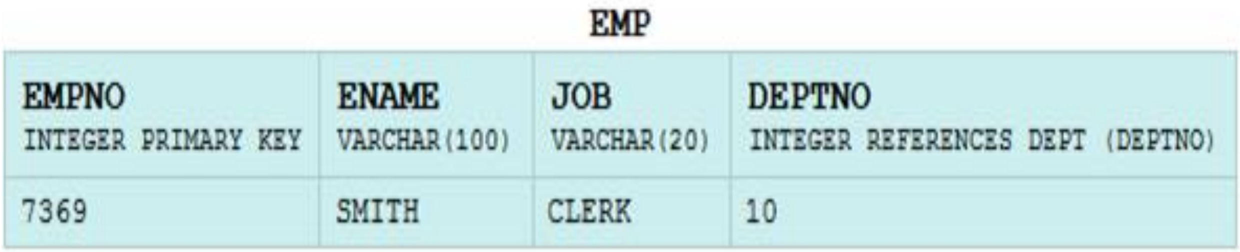
Figure 9: Direct mapping of *People* and *Address* relational tables to RDF (Source: Das *et al.*, 2012).

The *subject:* an IRI formed from the concatenation of the base IRI, table name (People), primary key column name (ID) and primary key value (7). The *predicate* for each column: an IRI formed from the concatenation of the base IRI, table name and the column name. *The values:* RDF literals formed from the lexical form of the column value. Each foreign key produces a triple with a predicate composed from the foreign key column names, the cited table and the cited column names. The object of these triples is the row identifier (<Addresses/ID=18>) for the cited triple.

R2RML: RDB to RDF Mapping Language

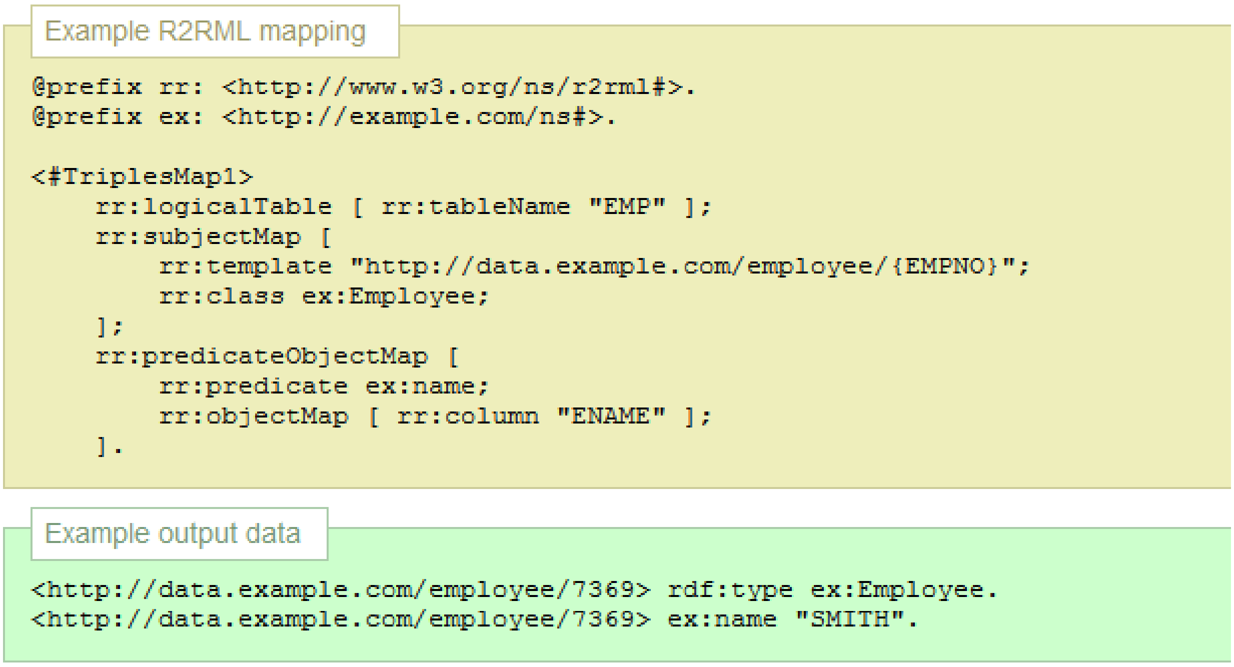
This specification (also published by the W3C RDB2RDF working group) describes R2RML, a language for expressing customized mappings from relational databases to RDF datasets (Das *et al.*, 2012). In the direct mapping of a database, the structure of the resulting RDF graph reflects the structure of the database, the target RDF vocabulary reflects the names of database schema elements, and neither structure nor target vocabulary can be changed. Figure 10 is an example of an output resulting from R2RML mapping of EMP relational table (Table 4).

Table 4: EMP relational table (Source: Das *et al.*, 2012).



EMP

EMPNO INTEGER PRIMARY KEY	ENAME VARCHAR(100)	JOB VARCHAR(20)	DEPTNO INTEGER REFERENCES DEPT (DEPTNO)
7369	SMITH	CLERK	10



Example R2RML mapping

```
@prefix rr: <http://www.w3.org/ns/r2rml#>.
@prefix ex: <http://example.com/ns#>.

<#TriplesMap1>
    rr:logicalTable [ rr:tableName "EMP" ];
    rr:subjectMap [
        rr:template "http://data.example.com/employee/{EMPNO}";
        rr:class ex:Employee;
    ];
    rr:predicateObjectMap [
        rr:predicate ex:name;
        rr:objectMap [ rr:column "ENAME" ];
    ].
```

Example output data

```
<http://data.example.com/employee/7369> rdf:type ex:Employee.
<http://data.example.com/employee/7369> ex:name "SMITH".
```

Figure 10: R2RML mapping of EMP table and example output (Source: Das *et al.*, 2012).

With R2RML conversely, a mapping author can define highly customised views over the relational data. The input to a R2RML mapping is a relational database that conforms to that schema. The output is an RDF dataset [SPARQL] as defined in SPARQL that uses predicates and types from the target vocabulary.

Mapping Object Schemas to Relational Database Schema

How to map object schemas to relational database schemas has been dealt with extensively by (Bourret, 2009). Table 5 is an extract from (Bourret, 2009) of how object-oriented structure could be mapped to relational database structure. In the instance of GTWS, (object-) relational mapping is required when integrating RDF triples directly into a spatial database as is the situation for GTWS-3. GTWS-1 and GTWS-2 use RDF in a serialised format compatible with a spatial database or a web map server.

Table 5: Mapping object-oriented structure to relational database structure (Bourret, 2009).

Object-oriented Structure	**Mapping to relational database structure**
Abstract class	Abstract classes are not mapped unless mapping inheritance. See Inheritance.
Class	Table. This is known as a *class table*. An object is represented by a row in a class table.
Inheritance	(i) The superclass and subclass are mapped to separate tables with a unique key / foreign key joining them. The unique key is in the superclass table. An object is represented by a row in each table.
	(ii) The superclass properties are stored in the subclass table. An object is represented by a row in this table.
Single-valued property with scalar data type	(i). Column in class table. This is known as a *property column*. The data type determines the set of possible data types of the column. (A data type of pointer to void or Object is mapped to BLOB.) A property is represented by a value in a property column.

2.6 Open source Geospatial Software

Several free and open source geospatial software products are freely available and the source code can be customised or extended. Some proved benefits of open source software include cost savings, vendor independence, and open standards (Holmes, Doyle, and Wilson (2005; Von Hagen, 2007; Steiniger and Hunter, 2012). Free and open source geospatial software is now maturing (Steiniger and Hunter, 2013). Due to these benefits, this research sought to use free and open source geospatial software in the implementation of GTWS to evaluate how open source geospatial software technology can also benefit from the LOD cloud.

Several free and open source geospatial software products are freely available and the source code can be customised or extended. Most can be downloaded freely from the internet, for example; from the *sourceforge* (http://sourceforge.net/) website. It allows selected open source geospatial software to be freely distributed, duplicated and passed around. Ramsey (2006, 2007) and also Steiniger and Hunter (2013) presented general reviews of (major) geographical information system (GIS) software projects that develop free and open source software .

The Open Source Geospatial Foundation (OSGeo) is a not-for-profit organisation with a mission to support the development and promote using free and open source geospatial software (see http://www.osgeo.org/). Table 6 illustrates examples of open source geospatial software to those listed on the OSGeo website under the category of web mapping, desktop applications and geospatial libraries. The conceptualisation, design options and implementations of this research has incorporated free and open source geospatial software to connect to the LOD cloud to consume and visualise linked data as web thematic maps. Chapter 3 proves the choice of open source software discussed on critical evaluation of technology.

Open source web mapping technology has proved popular among organisations and groups who can access spatial data and have some programming expertise, but who lack either the desire or the means to pay proprietary software purchase and licensing fees (Hall, Chipeniuk, Feick, Leahy and Deparday, 2010).

Table 6: Examples of categories of open source geospatial software (Source: http://www.osgeo.org/)

Web Mapping	**Desktop Applications**	**Geospatial Libraries**
deegree	GRASS GIS	FDO
Geomajas	Quantum GIS	GDAL/OGR
GeoMoose	gvSIG	GEOS
GeoServer	Opticks	GeoTools
Mapbender		OSSIM
MapFish		PostGIS
MapServer		
Quantum GIS Server		
OpenLayers		
52° North		
ZOO		

2.7 Spatial Data Infrastructures in this Research

A spatial data infrastructure (SDI) is an enabling platform for data sharing- based on a dynamic, hierarchic and multi-disciplinary concept that includes, people, data, access networks, institutional, policy, technical standards and human resources dimensions that aims to facilitate and coordinate the exchange and sharing of spatial data among stakeholders in the spatial data community (Rajabifard, Binns, Masser and Williamson, 2006). An SDI is an evolving concept about facilitating and coordinating the exchange and sharing of spatial data and services among stakeholders from several levels in the spatial data community (Hjelmager *et al.*, 2008, Cooper et al, 2011, 2014).

Geoportals are World Wide Web gateways that organise content and services such as directories, search tools, community information, support resources, data and applications

(Maguire and Longley, 2005) to discover and access geographic Web services (Tait, 2005). They are the most visible part of SDIs (de Longueville, 2010). Today's geoportals are focusing on interoperability through implementing standards for discovery and use of geographic data and services (de Longueville, 2010). SDIs are widely used to share, discover, visualise and retrieve geospatial data through OGC web services (Giuliani, Ray and Lehmann, 2011). OGC web services can be combined to provide a technical infrastructure for an SDI with SOA (Coetzee, 2009).

One characteristic of an 'ideal' SDI is that geospatial data can be integrated with many other kinds or sets of data to produce information useful for decision makers and the public, when appropriate (Nebert, 2004). As a result of current technologies, there are ever increasing volumes of diverse data that need to be integrated with SDIs (Harvey, Iwaniak, Coetzee and Cooper, 2012). Users expect SDI data to be available through new technologies (Coetzee, Harvey, Iwaniak and Cooper, 2013).

Holmes, Doyle, and Wilson (2005) emphasise the potential benefits of using open source software in developing SDIs - money spent on tailoring the software can go towards developing local skills and capacity, no need to pay license fees that tie users to a single vendor. This allows more culturally sensitive solutions instead of an universal answer imposed from the outside (Holmes, Doyle, and Wilson (2005). Von Hagen (2007) attempted to use open source components; based on OGC and ISO standards to help build a Somalia SDI- using the Food and Agricultural Organisation-Somalia Water and Land Information Management (FAO-SWALIM) project. An analysis by Steiniger and Hunter (2012) reveals that for all categories of software used in SDIs a free software product is available. This enables an SDI to be implemented on a limited financial budget, and allows distribution of a proved SDI architecture without legal constraints (Steiniger and Hunter, 2012).

In developing countries, frequently in Africa, the various SDI initiatives such as the Namibian Spatial Data Infrastructure (NamSDI) (Sinvula and Coetzee 2012; Sinvula *et al.*, 2014), the South African SDI (SASDI) (Rautenbach and Coetzee, 2013) and the SDI in Ghana (Owusu-Banahene *et al.*, 2013) will benefit from the technological advances in open source software and integrating linked data into geospatial data sources to create visualisation such as thematic maps. Overall this research seeks to contribute to the technical facet (Cooper *et al.*, 2013) of SDI research.

2.8 Related Work

2.8.1 Creating Thematic Maps

Thematic mapping is not a default functionality of creating maps over the Web (web mapping) but offers further functionalities, such as data exploration and spatial analysis, to the user (Rautenbach, Coetzee and Iwaniak, 2013). In the circumstance of creating thematic maps from linked data over the web, even though utilising linked data to non-tech web users is evident, consumption of linked data is restricted mostly to the semantic web community (Dadzie and Rowe, 2011). There are large volumes of interlinked geospatial data on the *Web of Data*; Loading all these data sets simultaneously is hard for many systems (Van Hage, Wielemaker and Schreiber, 2010).

OGC WMS and SLD have partly set a stage for an open framework for web mapping services (Iosifescu-Enescu, Hugentobler and Hurni, 2010). WMS standardises the way maps are requested over the Internet and how servers describe its data holdings (Kresse and Fadaie, 2010). The SLD specifies how a WMS can be extended to allow user-defined styling (Lupp, 2007). With the current specification of SLD, it is more or less possible to describe thematic maps (Sae-Tang, and Ertz, 2007). OGC technology is widely used in the geospatial community (Farnaghi and Mansourian, 2013) for standards-based interoperability and sharing technology of the Cyberinfrastructure for GIScience (Yue, Gong, Di, He and Wei, 2011). In its current form OGC technology cannot be connected to the LOD cloud.

(Rautenbach *et al.*, 2013) describes the present, thematic cartography over the web as one requiring complex processes with the current implementations of existing OGC web services. GTWS uses WMS and SLD to create thematic maps from linked data in the LOD cloud. It offers mechanism for connecting WMS to a web map server to the LOD cloud. GTWS further shows how linked data can be combined with geometry to create thematic maps over the Web.

2.8.2Linked Data Web Mapping Applications

In this section *map4rdf*[34] , *Researchers Map*[35], *DBpedia Mobile*[36], *Spatial@LinkedScience Interactive Tool*[37] and *LinkedGeoData Browser*[38] linked data web mapping applications related to GTWS are described. The reader is shown how GTWS differs from these applications. Related work is subsequently described in this section.

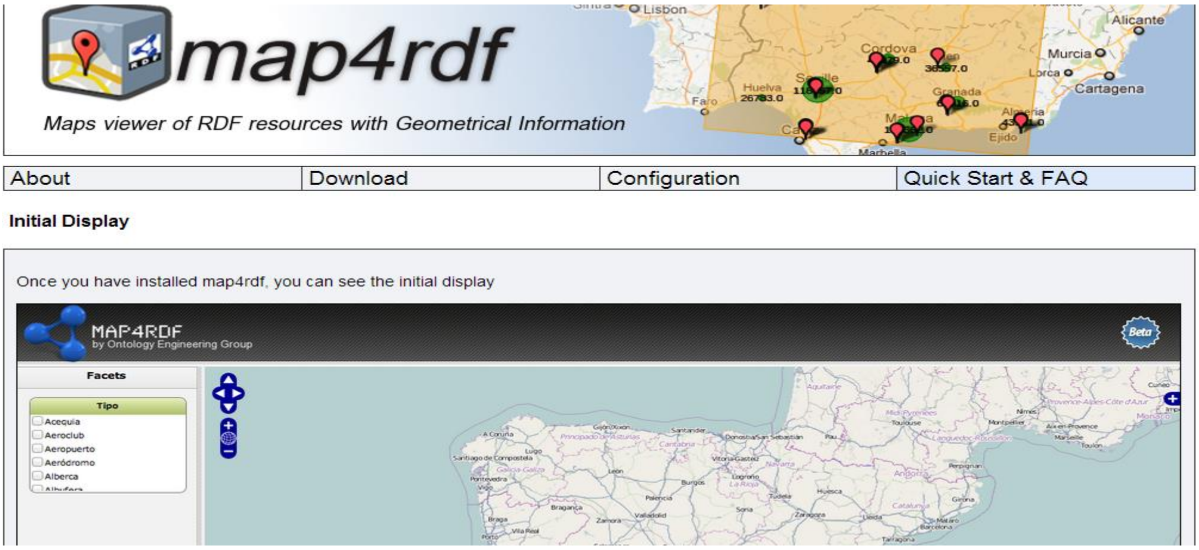
map4rdf is a mapping and faceted browsing tool that can be configured with a SPARQL endpoint to provide exploration and visualisation of RDF resources enhanced with linked data based geometric information (see Figure 11). It provides geospatial and geometrical visualisation using *Google Maps*[39] and *OpenStreetMap*[40].

Researchers Map is a linked data mash-up application that provides a map of the work place of professors of the German database community (Hartig *et al.*, 2009).

The *DBpedia*[41] datasets have been extracted from Wikipedia and comprise of 1.89 billion pieces of RDF triples. *DBpedia Mobile*, of that a web page is shown in Figure 12, is a location-centric client for the Semantic Web. Based on the current GPS position of a mobile device, DBpedia Mobile renders a map containing information about nearby locations from the DBpedia dataset. Geographic locations are now available for 300,000 of DBpedia's 2.18 million “things”.

---

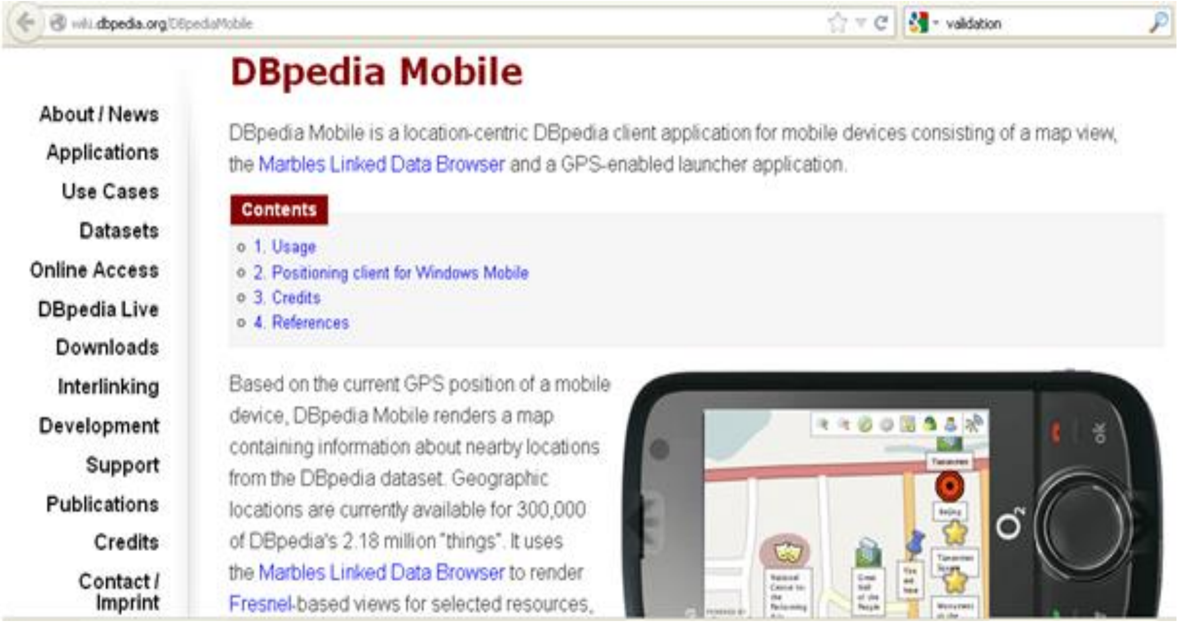
[34] http://oegdev.dia.fi.upm.es/projects/map4rdf/
[35] http://researchersmap.informatik.hu-berlin.de/
[36] http://wiki.dbpedia.org/DBpediaMobile
[37] http://spatial.linkedscience.org/)
[38] http://linkedgeodata.org/LGDBrowser
[39] http://maps.google.com
[40] www.openstreetmap.org
[41] http://wiki.dbpedia.org/Datasets



Initial Display

Once you have installed map4rdf, you can see the initial display

Figure 11: Homepage of map4rdf (Source: http://oeg-dev.dia.fi.upm.es/map4rdf/)



DBpedia Mobile

DBpedia Mobile is a location-centric DBpedia client application for mobile devices consisting of a map view, the Marbles Linked Data Browser and a GPS-enabled launcher application.

Contents
- 1. Usage
- 2. Positioning client for Windows Mobile
- 3. Credits
- 4. References

Based on the current GPS position of a mobile device, DBpedia Mobile renders a map containing information about nearby locations from the DBpedia dataset. Geographic locations are currently available for 300,000 of DBpedia's 2.18 million "things". It uses the Marbles Linked Data Browser to render Fresnel-based views for selected resources.

Figure 12: DBpedia Mobile's web page (Source : http://wiki.dbpedia.org/DBpediaMobile)

Spatial@LinkedScience Interactive Tool (see Figure 13) is a linked data based interactive web mapping tool developed by Carsten Keßler, Krzysztof Janowicz and Tomi Kauppinen to access all papers ever published in significant Geographic Information conferences:

GIScience [42] (international conference on geographic information science), COSIT [43] (Conference on spatial information technology), ACM SIGSpatial [44] (Association for Computing Machinery international conference on advances in geographic information systems), and AGILE[45] (Association for Geographic Information Laboratories for Europe conference). ***Spatial@linkedscience*** is a community-driven effort to create methods, vocabularies, tools and data for showing how and why spatial information can efficiently be used in scientific settings. The application was developed as part of the Spatial@linkedscience initiative[46].

Showing all data – no filters active

Figure 13: *Spatial@linkedscience* interactive tool

Another example of a linked data based application is the *LinkedGeoData browser* that can display data from *LinkedGeoData*. The *LinkedGeoData browser* (shown in Figure 14) is a facet based browser and editor for *LinkedGeoData* that allows browsing of the world by

---

[42] http://www.giscience.org/
[43] http://www.cosit.info/
[44] http://www.sigspatial.org/sigspatial-conferences
[45] http://www.agile-online.org/
[46] http://linkedscience.org/spatial/

using a ‘slippy map’ (Stadler *et al.*, 2012). Once a facet or a particular facet value has been selected, matching elements are displayed as markers on the map and in a list.

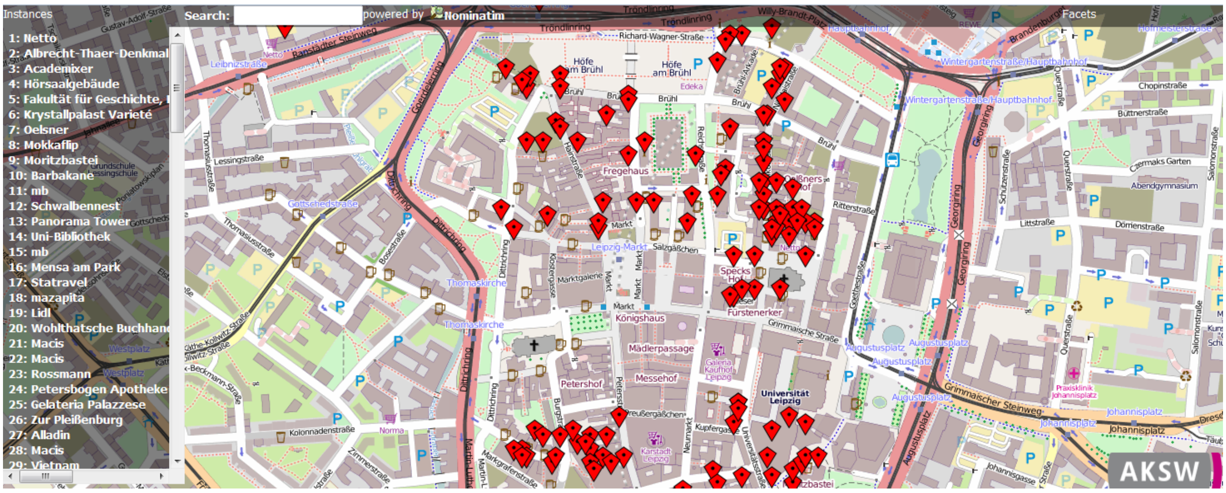


Figure 14: *LinkedGeoData browser* (Source: http://browser.linkedgeodata.org/)

map4rdf provides visualisation tools for a single source of geospatial RDF data and *Researchers Map* is constructed solely based on queries executed against the Web of data (Hartig and Langegger, 2010), while GTWS combines non-spatial linked data (attributes) from the LOD cloud (first source) with geospatial data in an SDS (second source) to produce thematic maps. *DBpedia Mobile*, *Spatial@linkedscience* and *LinkedGeoData browser* provide visualisation and editing tools for geospatial linked data, GTWS sought to create visualisations as thematic maps by combining linked data models with object relational models (spatial data) in a geospatial web service environment. GTWS creates visualisations for heterogeneous data - linked and non-linked alike.

All the related work described above uses only Semantic Web technology, whilst GTWS combines semantic web (linked data) and OGC compliant technologies. In another work, T. Zhao *et al.* (2008) integrate spatial data available through OGC WFS and in databases into the Semantic Web: ontological queries are converted to WFS queries and executed against the spatial data. This work also combines Semantic Web (linked data) and OGC models, but the flow of data is from OGC models to Semantic Web. In contrast, his research shows how existing WMS can retrieve attributes from the LOD cloud and integrate them with spatial data to create thematic maps.

A Similar work by Jones, Kuhn, Keßler, and Scheider (2014) implements an OGC WFS compliant service as an adapter that listens to WFS requests and converts these requests into SPARQL queries. This adapter requires current GIS to have access to geographic LOD datasets, using its implementation of WFS. Unlike the adapter, this research integrates alphanumeric linked data from the LOD cloud with spatial data in a spatial database to create thematic maps. The current design options use OGC WMS for visualisation of the thematic maps.

2.8.3 Integrating Linked Data into (Spatial-) Databases

The RDF store in Oracle is built on top of the Oracle Spatial Network Data Model (NDM), in that a network or graph captures relationships among objects using connectivity (Alexander and Ravada, 2006). RDF graphs are modelled as a directed logical network in NDM. In this network, the subjects and objects of triples are mapped to nodes, and predicates are mapped to links that have subject start nodes and object end-nodes. A link represents a complete RDF triple. A key feature of RDF storage in Oracle is that nodes are stored once – regardless of the number of times, they participate in triples. A new link is always created whenever a new triple is inserted. Figure 15 illustrates how an RDF graph of three RDF triples: <S1, P1, O1>; <S1, P2, O2>; <S2, P2, O2> is modelled.

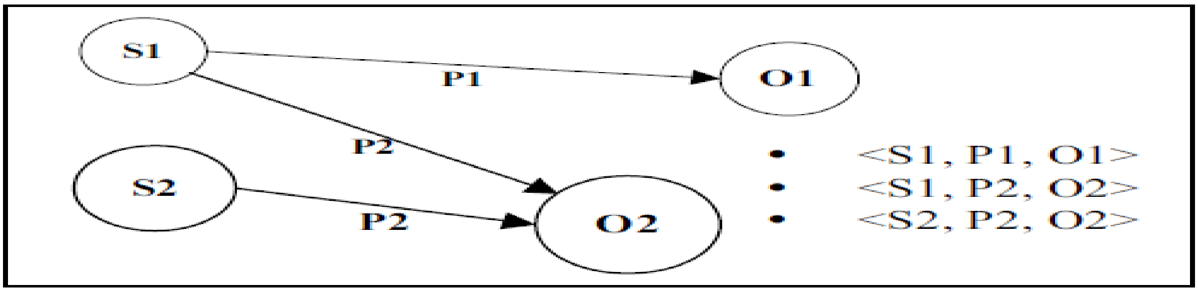


Figure 15: RDF graph in Oracle (Source: Alexander and Ravada, 2006)

Atlas (Kaoudi and Koubarakis, 2013) is a system built on top of the Bamboo distributed hash table (DHT) (Rhea, Geels, Roscoe and Kubiatowicz, 2004) for the distributed storage, update and querying of RDF data and RDFS ontologies. When a node wants to store RDF(S) data, it submits it as an RDF(S) document. The document can be in either RDF/XML or RDF/N3 format. This document is decomposed into a collection of RDF triples. Each triple of form (subject; predicate; object) is stored in Atlas three times, once for its subject, once for its predicate and once for its object. As URIs and literals may comprise of long strings, a mapping dictionary similarly to centralised RDF stores has been implemented (Chong *et al.*, 2005; Neumann and Weikum, 2010). URIs and literals are mapped to integer identifiers and triple storage and query evaluation is performed using these identifiers. Each node stores the triples it receives in its local database

Converting relational databases to RDF is a significant area of research with several approaches published and many tools available. Instead of focussing on converting/representing RDF in RDB, the research presented in this research shows the efficiency of spatial databases in handling spatial analysis can be combined with available linked datasets in the LOD cloud to create thematic web maps. Integrating RDF triples directly into a spatial database as in the instance of GTWS-3, follows a simple relational database approach of storing RDF. The RDF triples (Subject (S), Predicate (P), Object (O)) are stored in relations as tuples comprising of <S, P_1, O_1, P_2, O_2, P_3, O_3 …P_K, O_K> as shown in Table 7. S is the unique ID of the resource later used to join the existing table containing the geometric objects in a spatial database as shown in Table 8. Table 9 is created after joining the geometric object table to the relational table containing the RDF triples.

Table 7: Representing RDF triples in a relational database

S	P_1	O_1	P_2	O_2	P_3	O_3	…	P_K	O_K

Table 8: Table containing geometric objects in a spatial database.

OID	UID	geometry

Table 9: Table created after joining the geometric object table to the relational table containing the RDF triples.

OID	geometry	S(=UID)	P_1	O_1	P_2	O_2	P_3	O_3	…	P_K	O_K

The reliance on relational representations of RDF means that GTWS can take advantage of 35+ years of research on efficient storage and querying, industrial-strength transaction support, locking and security (Bornea *et al.*, 2013).

GTWS-3 is an example of a *linked data based web cartographic concept* of creating thematic maps by accessing alphanumeric linked data from the LOD cloud through a direct connection of a spatial database server extension.

With the approach described in this research, the spatial database server and the WMS used to visualise the thematic maps are not modified. The LOD cloud is treated as if it is just a new external data source (a big database with new data representation) required for creating thematic web maps in the era of ubiquitous cartography.

2.9 Conclusion

The following topics are presented: thematic cartography, ubiquitous cartography, standards based geospatial web services, linked data, spatial data infrastructures, data integration and open source geospatial software. These areas constitute the aspects of this research from the scientific disciplines of Cartography, GIScience and Computer Science. This chapter reveals the gap among existing models (standard based services, open source geospatial software, cartography and spatial data infrastructure) and linked data. The combination of the vast quantities linked data available in the LOD cloud and the efficient spatial analysis capabilities of spatial database is beneficial to data consumers such as including GTWS. This chapter provides a basis for identifying the evaluation criteria (requirements) for integration approaches that combine linked data from the LOD with geometric data in a spatial database to produce thematic maps. Each design choice of GTWS adopts a different integration approach in creating a global view of the autonomous data sources: linked data from the LOD cloud and geometric data from a spatial database.

In its current form OGC web cannot be directly connected to the LOD cloud. Apart from the work by T. Zhao *et al*. (2008) and Jones *et al*. (2014), related work focuses on Semantic Web models. The research described in this research focus on creating thematic maps by integrating linked data from the LOD cloud with geospatial data held in a spatial database. This research uses OGC models to visualise the thematic maps created from the resulting integrated data. This research may benefit workers who use standards from the Open Geospatial Consortium (OGC) and the World Wide Web Consortium (W3C). From the perspective of SDI, this research contributes to how open diverse sources of data, such as linked data can be integrated with existing spatial data managed in national and regional SDIs. This research also shows the potential of using open source software in SDIs.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Chapter 3: Evaluation of Technologies, Tools and Standards Related to Open Source Geospatial Web Services

This chapter is an extended version of a refereed conference paper published as: Owusu-Banahene, W., and Coetzee, S. (2012, October). *An evaluation of the suitability of open source web map servers for setting up a geospatial thematic web map service*. GISSA Ukubuzana 2012, Ekurhuleni, South Africa.

3.1 Introduction

The objective of this chapter is to (critically) evaluate state-of-the-art technologies, tools and standards that will be suitable for developing a GTWS in an open data and open source environment. An experiment was set up to evaluate the ease of setting up a geospatial thematic web service in three open source web map servers, namely: MapServer, GeoServer and QGIS Server. Literature was further reviewed to evaluate open source spatial database servers. The work described in this chapter evaluates the ease of setting up a geospatial thematic web service in three open source web map servers, namely: MapServer, GeoServer and QGIS Server. In our current research, this chapter shows the procedure used in selecting one of the contemporary open source web map server, that meets the requirements of this research.

This section attempts to provide a method to answer this suitability question with comparison of three open source web, namely: MapServer, GeoServer and QGIS Server. This section is placed in the research objective to identify and select a state-of-the-art web map server suitable for GTWS. Open source web map servers were used for this research since this source code is open and allows modification when the need arises.

There have been ongoing attempts to test the performance of open source web map servers. This evaluation was not intended to test the performance of these web map servers, nor to run compliance tests. It was aimed at doing a qualitative assessment of each web map server, using the same client under the default set up, according to the following criteria: ease of installation, ease of cartographic workflow, level of support for displaying web maps, types of output formats supported, level of quality of web maps, types of input data that can be used, level of support for styling, adherence to OGC standards and quality of the user documentation. Results proven on the criteria are presented. The evaluation criteria of the three WMS servers focus primarily on their suitability to produce web maps, since the web map servers were not required to support linked data.

3.2 Overview of Three Open Source Web Map Servers

In this section, an overview of the ages and approaches of the three open source web map servers-namely: *GeoServer*[47], *MapServer*[48] and *QGIS Server*[49], used in this evaluation are presented.

GeoServer is written in Java that and runs in an integrated Jetty or Apache Tomcat web server environment (Steiniger and Hunter, 2013).

MapServer, originally developed in the mid-1990 at the University of Minnesota, written in C (UMN, 2013), runs as a Common Gateway Interface (CGI) application in the Apache web server environment (Steiniger and Hunter, 2013). *QGIS Server* is a fast CGI/CGI written in C++ (ETH, 2009; QGIS, 2013).

QGIS Server started as QGIS mapserver, initially developed as QGIS mapserver by the Institute of Cartography, ETH, Zurich. QGIS mapserver's code was included in the QGIS SVN repository as of August 2010 (ETH, 2009) and has been part of *QGIS*, open source Geographic Information System (GIS) software.

---

[47] http://geoserver.org/display/GEOS/Welcome
[48] http://www.mapserver.org/index.html
[49] http://www.qgis.org/en/site/

MapServer is the oldest followed by GeoServer with QGIS Server been recent (Anselin, 2012; Steiniger and Hunter, 2012).

3.3 Related Work

P. Yang, Cao and Evans (2007) tested the performance of various WMS servers and analysed the test to find performance patterns. In another study (Birgoren and Gumusay, 2010), performance tests of ArcGIS Server, Geoserver and Mapserver software have been made with Internet Explorer where they were set up on the same computer and same geographic data introduced to software. Similar performance tests have been conducted to compare the performance of GeoServer and MapServer (Aime and Deoliveria, 2008; Aime andMcKena, 2009). In (Aime and McKena, 2010) the performance of MapServer, Geoserver, and Mapnik were compared, and various back-end data sources, such as PostGIS and Shapefiles. In this research, the aim was to run neither performance test nor compliance test but to do a qualitative comparison of MapServer, GeoServer and QGIS Server under default settings to find out its suitability for creating web-based thematic maps using OGC web standards. At the time of writing the study, to the knowledge of the author, comparable tests for suitability of web map servers in creating thematic maps have not been done for these map servers.

3.4Evaluation Procedure and Results

Approach for comparing the three web map servers are presented in this section. First criteria to assess the suitability of a map server for creating thematic web maps are set. Secondly, a procedure for evaluating each criterion was designed and implemented. Finally, the latest releases (at the time of performing the tests) of MapServer, GeoServer and QGIS Server were compared against the criteria. The input data comprised a shapefile obtained from the South African 2001 Census data and a raster image obtained from (ETH, 2009). The shape file contained data on the provinces in South Africa. Figure 16 is a snap shot of the spatial data as visualised with QGIS Desktop. In this section, the criteria, the procedure for evaluating each criterion and the results are discussed in the subsequent sub-sections.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

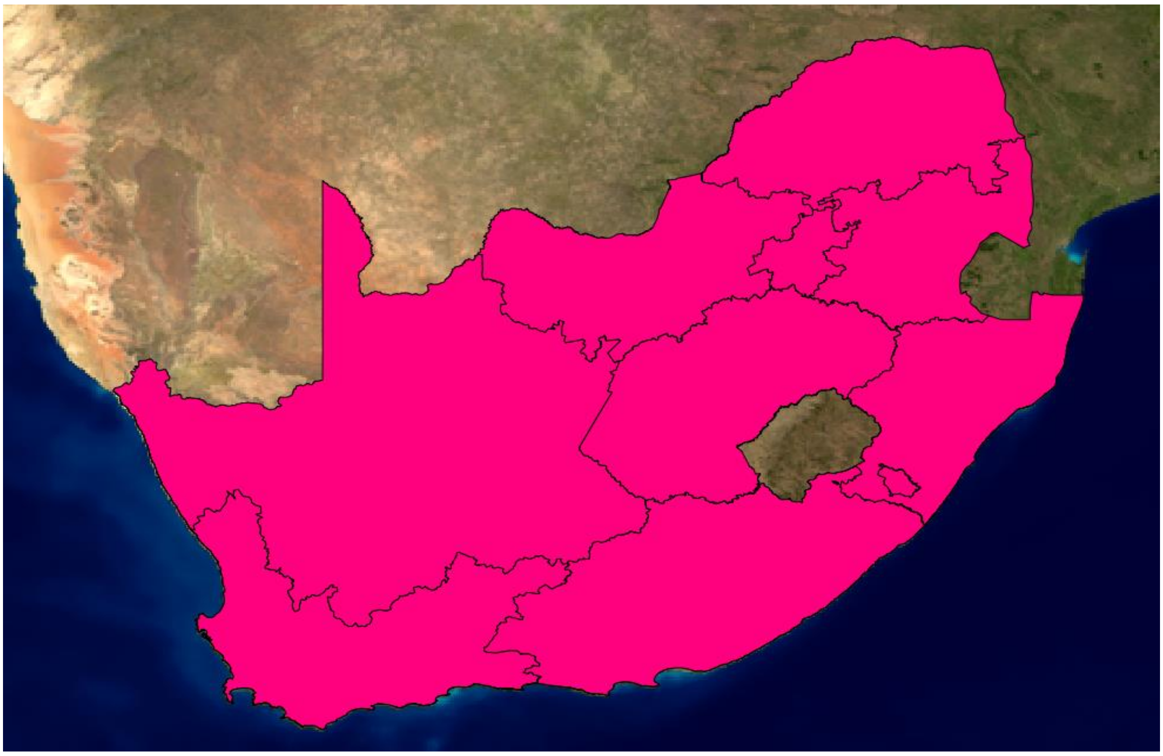


Figure 16: Input data for the evaluation of web map servers

Criteria for evaluation

The following criteria to compare the web map servers were set: ease of installation, ease of cartographic workflow, level of support for displaying web maps, types of output formats supported, level of quality of web maps, types of input data that can be used, level of support for styling, adherence to OGC standards and quality of the user documentation. Table 10 shows the mode of evaluation and justification for each criterion.

Table 10: Mode of evaluation and justification for each criterion

Criterion	**Mode of evaluation**	**Justification**
Ease of installation	Follow documentation to set up WMS on same computer using default settings	To assess ease of deployment by a novice user
Ease of cartographic workflow	i)Load same data to each WMS, ii) Run GetCapabilities requests and iii) Run GetMap requests from same Web browser iv) Qualitative analysis of i) to iii)	To assess the ease of carrying out cartographic design
Level of support for displaying web maps	Analyse level of support for various versions of WMS	The GTWS will use WMS to display web maps
Level of quality of web maps	Analyse the quality of WMS output	To assess the quality of web maps
Types of output formats supported	Analyse number of output formats supported by WMS	To assess level of support for cartographic reproduction
Types of input data that can be used	Analyse documented support for input data	To assess the range of input data that can be supported.
Level of support for styling	Analyse documented support for SLD and SLD extensions	To assess the level of support for creating thematic information.
Quality of user documentation	Analyse information pertaining to the web map server from official websites, links on the official website to other sources of information and user manuals	To assess how accessible, how helpful and how usable the documentation were.
Adherence to OGC standards	Analyse OGC statistics	The GTWS is OGC standards based service and therefore adherence to OGC standards is a requirement.

3.4.1 Ease of Installation

In addition to Google Chrome (19.0.1.1084.56m) web browser, Table 11 shows the web map servers installed on a workstation with Windows 7 Ultimate operating system. It was just enough to follow the documentation for GeoServer, MapServer and QGIS Server respectively to install the map servers. For GeoServer, no further configuration was required to set up WMS. The map server used for windows (ms4w) to install MapServer required no configuration as well to set up WMS. In the case of QGIS Server after installing with

OSGeo4W further configuration was required as copying *.dll files into its appropriate directories. Installation is easiest in GeoServer and MapServer.

Table 11: Open source web map servers installed.

Software	**Version**	**Release date**	**Package used**
MapServer	6.0.3	8 May 2012	MS4W
GeoServer	2.1.4	4 June 2012	Windows installer
QGIS Server	1.7.4	November 2011	OSGeo4W

3.4.2 Ease of Cartographic Workflow

The author assessed the ease of carrying out cartographic design with each web map server. The procedure was as follows:

i) Same data was loaded to each WMS

ii) GetCapabilities requests were run

iii) GetMap requests from same web browser were made to each WMS

iv) Q analysis of steps i) to iii) were performed

Figure 17 shows the conceptual design of the set up used to analyse the cartographic workflow. With the same input spatial data, a QGIS project file was created to be used by QGIS Server, mapfile was also created to be used by MapServer. For GeoServer the input data was loaded into a data directory followed by creating of workspace and a data store. Appropriate WMS requests (GetCapabilities and GetMap) were sent from same Google Chrome 19 Web browser to each WMS. The responses; Response$_m$, Response$_g$ and Response$_q$ from MapServer, GeoServer and QGIS Server respectively were compared. In Figure 17, the arrows starting from the input data through to the WMSs to the responses indicate the cartographic workflow.

From Figure 17, the number of steps required to load data to WMS in MapServer, GeoServer and QGIS Server were three, four and two respectively. For someone new to the three map servers, the steps in GeoServer could be completed quicker than in MapServer and QGIS Server. The reason is that a mapfile has to be edited in the occasion of MapServer and QGIS project file has to be created for QGIS Server. GeoServer provides a graphical user interface that makes it easier and quicker to load data into WMS and also run GetCapabilities and GetMap requests. Cartographic workflow is the easiest in GeoServer.

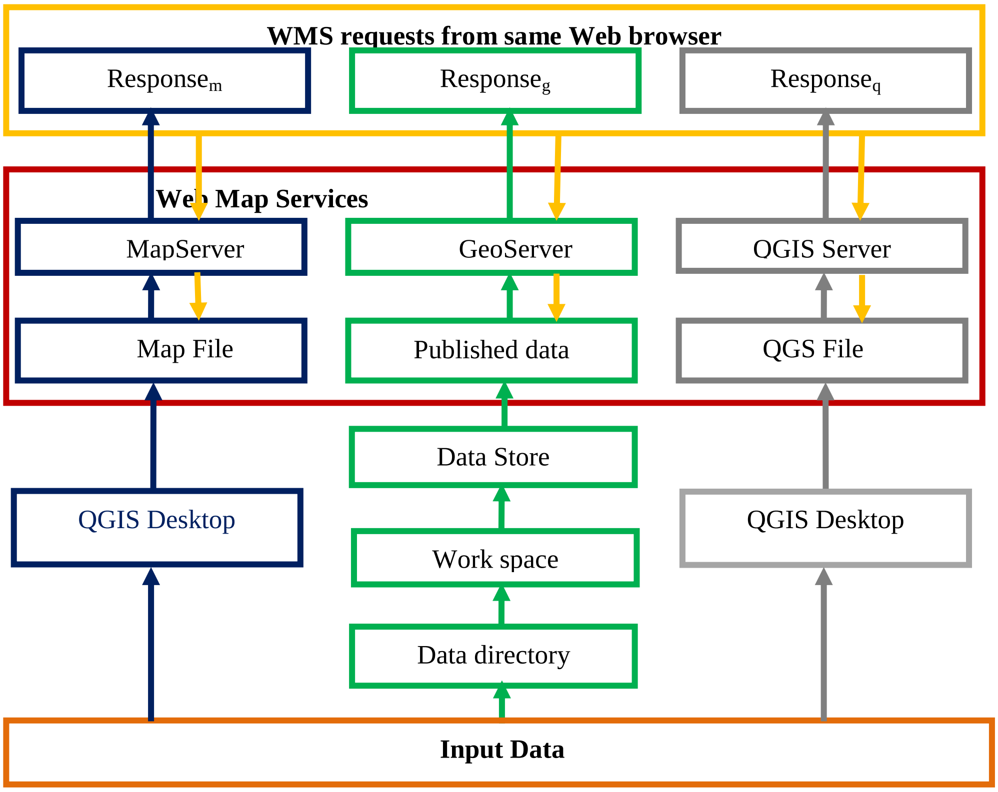


Figure 17: Conceptual design of the set up for analysing the ease of cartographic workflow

3.4.3 Level of Support for Displaying Web Maps

Since the GTWS will use WMS to display maps, it was important to find out which versions of WMS were supported by each web map server. If WMS is set up correctly, the service will respond to a WMS GetCapabilities request with an XML document (de la Beaujardierre, 2006). The WMS 1.3.0 standard (de la Beaujardierre, 2006) indicates the following in response to GetCapabilities request:

a) If VERSION parameter is not specified, the server shall respond with the highest version it supports.

b) If VERSION parameter is specified that the server implements, the server shall send that version.

c) If VERSION parameter is specified that the server does not support, the server shall respond with output that conforms to a version it does support, as determined by the following rules: i) If a version unknown to the server and higher than the lowest supported version is requested, the server shall send the highest version it supports that is less than the requested version. ii) If a version lower than any of this known to the server is requested, the server shall send the lowest version it supports. iii) If the client does not support the version sent by the server, it may either cease communicating with the server or send a new request with a different version number that the client does support.

In lieu of this, the following GetCapabilities requests were run for Geoserver: "*http://localhost:9090/geoserver/wms?request=getCapabilities*",MapServer:"*http://localhost /cgi-bin/mapserv.exe?MAP=C:/ms4w/apps/trial.map&SERVICE=WMS& VERSION=1.3.0& REQUEST=GetCapabilities*"andQGISServer:"*http://localhost/cgi-bin/qgis_map_server/ qgis_map_serv.cgi?SERVICE=WMS &REQUEST=GetCapabilities*". Similar requests with different version numbers were made. Table 12 shows the number of versions of WMS supported. Analysis from Table 12 shows that all three map servers supported WMS 1.3.0, but MapServer supports more versions.

Table 12: Various versions of WMS supported.

	GeoServer				**MapServer**				**QGIS Server**			
WMS version	1.3.0	1.1.1	1.0.0	1.1	1.3.0	1.1.1	1.0.0	1.1	1.3.0	1.1.1	1.0.0	1.1
Supported?	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No
Versions supported	2				4				1			

3.4.4 Level of Quality of Web Maps

The level of quality of web maps was evaluated by assessing the quality of WMS output formats for each web map server. A single *GetMap request* aimed at retrieving two layers (*shapefile* and *tiff*) from one WMS in a particular output format was sent to each WMS map server at a time. Six *GetMap* requests were run for each WMS representing six (6) various output formats. These six output formats are those specified by the WMS 1.3.0 standard (de la Beaujardiere, 2006) namely: Graphics Interchange Format (GIF), Portable Network Graphics (PNG), Joint Photographics Expert Group (JPEG), Tagged Image File Format (TIFF), Scalable Vector Graphics (SVG) and Web Computer Graphics Metafile (WebCGM).

In all 18 GetMap requests were run. The response of each request was compared with the input data as visualised in QGIS Desktop. The idea was to explore whether all two layers will appear in the web browser and if they did was the quality of the response same as input? The results were tabulated for each format as shown in Table 13. During the cause of making the request, utmost care was given to ensure that the requests were correct according to the WMS standard.

The following *GetMap* request, will retrieve a png formatted map from MapServer- *http://localhost/cgi-bin/mapserv.exe?service=wms&version=1.3.0&request=GetMap &layers=earth,PR_SA &styles =default&crs=EPSG:4326&bbox=14.091,-39.0758,34.1167,-21.854 &width=600&height=600&format=image/png&transparent=TRUE&map= C:\ms4w*

\apps\saprovinces.map&. A similar *GetMap* request to retrieve same png map from QGIS Server looks like this *http://localhost/*cgi-bin/qgis_map_server/qgis_map_serv.cgi? service =WMS&*version=1.3.0&request=GetMap&layers*=earth20120225173140855,PR_SA20120225173128727*&styles=default,SingleSymbol&crs=EPSG:4326&bbox=16.4549,-34.833, 32.8913,-22.126*&width=600&*height=600&format=image/png& transparent=TRUE* . For GeoServer, this *GetMap* request will also retrieve a png formatted map, http://localhost:9090/geoserver/saprovince/wms?service=WMS&version=1.3.0&request=GetMap&layers= saprovince: earth, saprovince:PR_SA &styles=raster,polygon&bbox=-34.8330, 16.4549,-22.1260,32.8913&width=600&height=600&srs=EPSG:4326&format=image/png& transparent=TRUE.

Table 13 shows the *GetMap* responses. Analysis of GetMap responses from Table 13 reveal that GeoServer and MapServer supported all six formats with QGIS Server supporting two. Geoserver had all four output formats (PNG, JPEG, GIF and TIFF) having the same quality as the input. In the case of MapServer, two output formats (PNG and TIFF) had the same quality as the input. GeoServer shows superiority in the number of output formats that had the same quality as the input data. All three map servers supported PNG format. The output map in PNG format had same quality as the input data. Figure 18, Figure 19 and Figure 20 show the output map in PNG from MapServer, QGIS Server and GeoServer respectively.

Table 13: Quality of WMS GetMap responses

Formats Tested	**GeoServer**		**MapServer**		**QGIS Server**	
	Supported	Same quality as input	Supported	Same quality as input	Supported	Same quality as input
png	Yes	Yes	Yes	Yes	Yes	Yes
jpeg	Yes	Yes	Yes	No	Yes	No
gif	Yes	Yes	Yes	No	No	No
tiff	Yes	Yes	Yes	Yes	No	No
Svg+xml	Yes	No	Yes	No	No	No
WebCGM	Yes	No	Yes	No	No	No
Total Yes	6	4	6	2	2	1
Total No	0	2	0	4	4	5

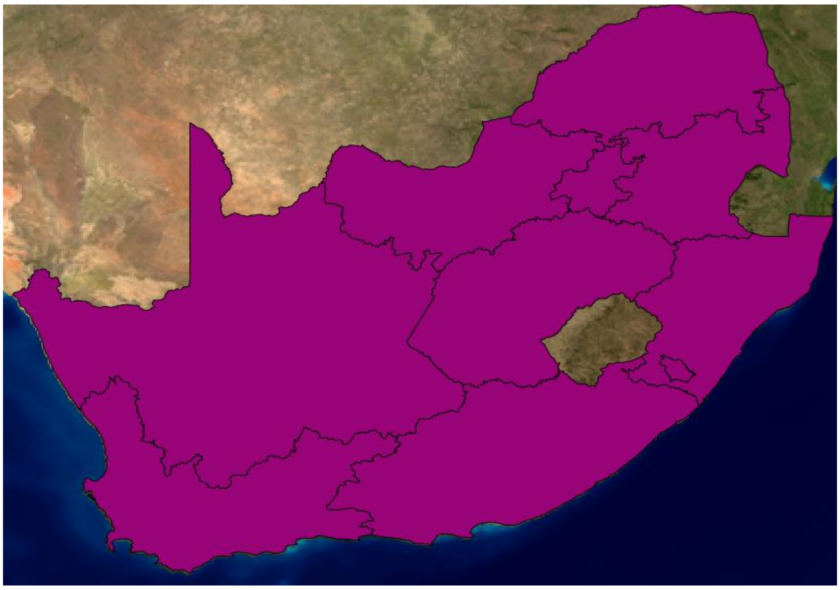


Figure 18: Map in PNG from MapServer

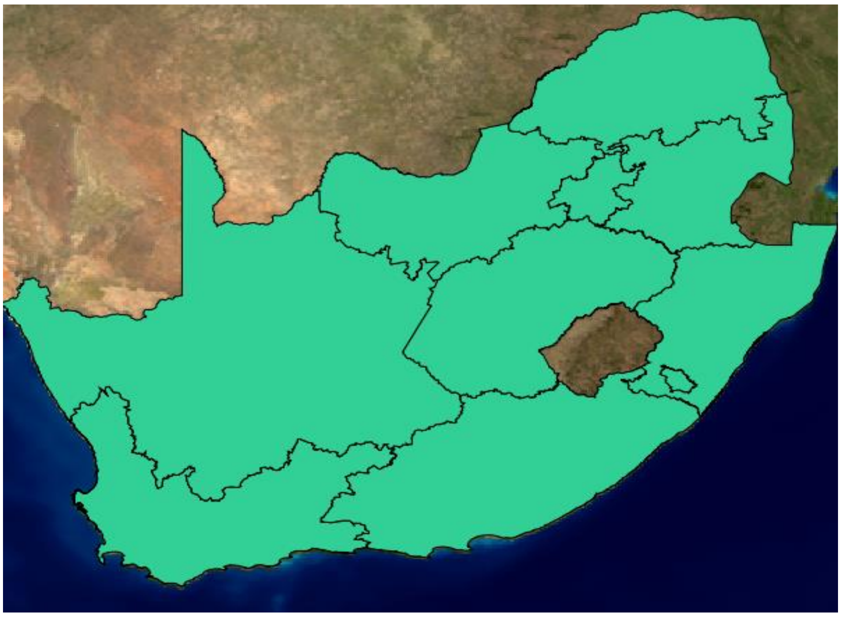


Figure 19: Map in PNG from QGIS Server.

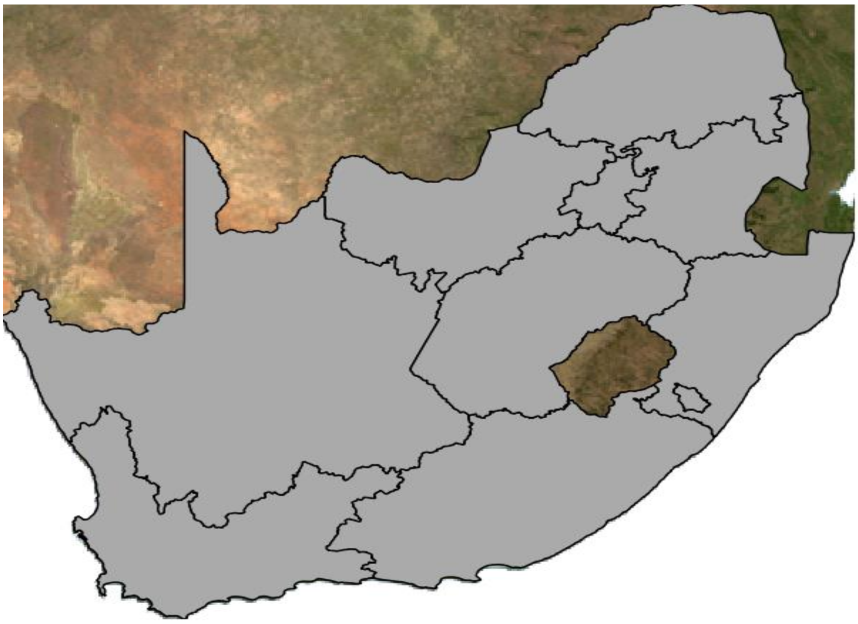


Figure 20: Map in PNG from GeoServer.

3.4.5 Types of Output Formats Supported

The response to a WMS *GetCapabilities* request is an XML file. The XML file contains information about the output formats supported by the WMS' *GetMap* request. For example; , the following extract from a *GetCapabilities* response from MapServer shows that nine (9) various output formats (indicated as bold) are advertised as supported:

```
<GetMap>
 <Format>image/png</Format>
 <Format>image/jpeg</Format>
 <Format>image/gif</Format>
 <Format>image/png; mode=8bit</Format>
 <Format>application/x-pdf</Format>
 <Format>image/svg+xml</Format>
 <Format>image/tiff</Format>
 <Format>application/vnd.google-earth.kml+xml</Format>
 <Format>application/vnd.google-earth.kmz</Format>
 <DCPType>
     <HTTP>
     <Get><OnlineResource xmlns:xlink="http://www.w3.org
 /1999/xlink" xlink:href="http://localhost/cgi-
 bin/mapserv.exe?map=C:/ms4w/apps/saprovinces.map&"/>
     </Get>
       <Post>
     <OnlineResource xmlns:xlink="http://www.w3.org/1
 999/xlink" xlink:href="http://localhost/cgi-
 bin/mapserv.exe?map=C:/ms4w/apps/saprovinces.map&"/>
     </Post></HTTP>
 </DCPType>
</GetMap>
```

The output formats supported by WMS 1.3.0 were analysed. The Venn diagram in Figure 21 is the result of the comparison of output formats supported by *GetMap* requests. It could be seen from Figure 21 that GeoServer advertised 14 output data formats followed by MapServer with nine and QGIS Server with two. Two data formats were common to all three map servers. GeoServer ranks highest in the number of output formats supported by *GetMap*.

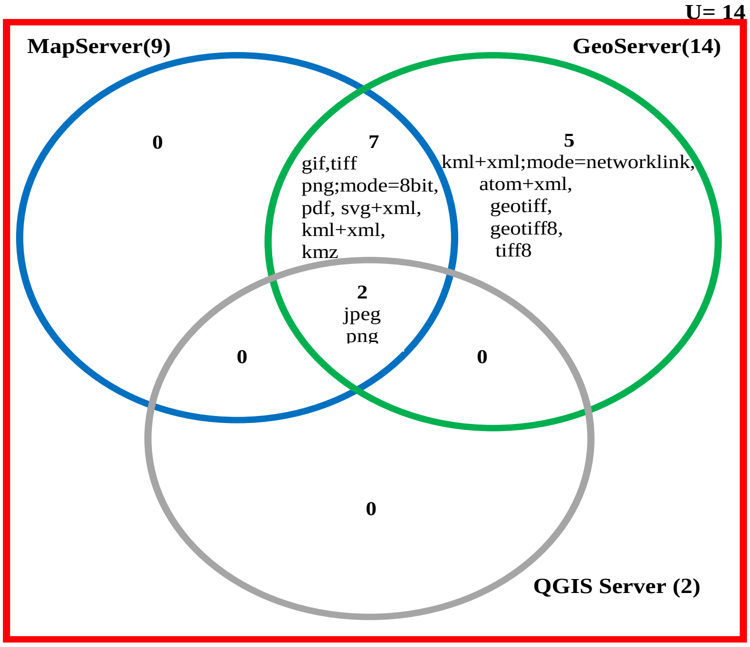


Figure 21: Venn diagram showing number of output formats supported by GetMap requests.

3.4.6 Types of Input Data Supported

Documented input data was extracted from the following urls http://mapserver.org/input/index.html#input,http://docs.geoserver.org/stable/en/user/data/index.html and http://www.qgis.org/ en/about-qgis/features.html for MapServer, GeoServer and QGIS Server respectively. Documented input data from these sources were compared with documented data in the respective user manuals. Table 14 shows the input data supported by the three web map servers.

Table 14: Types of input data

Item	MapServer	GeoServer	QGIS Server
1	ArcInfo	Application Schema Support	PostGIS
2	ArcSDE	ArcGrid	SpatiaLite
3	DGN	ArcSDE	OGR
4	Erdas .LAN/.GIS	DB2	ESRI shapefiles
5	ESRI File Geodatabase	External Web Feature Server	MapInfo
6	ESRI Personal Geodatabase	External Web Map Server	SDTS
7	ESRI Shapefiles (SHP)	GDAL Image Formats	GML
8	GDAL	GeoTIFF	GDAL
9	GIF	GML	GRASS
10	GML	GTOPO30	WMS
11	GPS Exchange Format (GPX)	H2	WFS
12	Inline	Image Mosaic	WMS-C
13	JPEG	Image Mosaic JDBC	WFS-T
14	KML	ImagePyramid	
15	MapInfo	Java Properties	
16	MSSQL	Microsoft SQL Server and SQL Azure	
17	MySQL	MySQL	
18	NTF	Oracle	
19	OGR	Oracle Georaster	
20	Oracle Spatial	PostGIS	
21	PNG	Pregeneralized Features	
22	PostGIS	Shapefile	
23	S57	Teradata	
24	SDTS	VPF	
25	SpatiaLite	WorldImage	
26	TIFF/GeoTiff	Directory of spatial files	
27	USGS TIGER		
28	Virtual Spatial Data		
29	WFS		

Figure 22 shows the number of input data formats. It can be seen from Figure 22 that MapServer support twenty various data formats followed by GeoServer with twenty six and QGIS Server with thirteen. On the basis of these documented data MapServer shows superiority for types of input data supported.

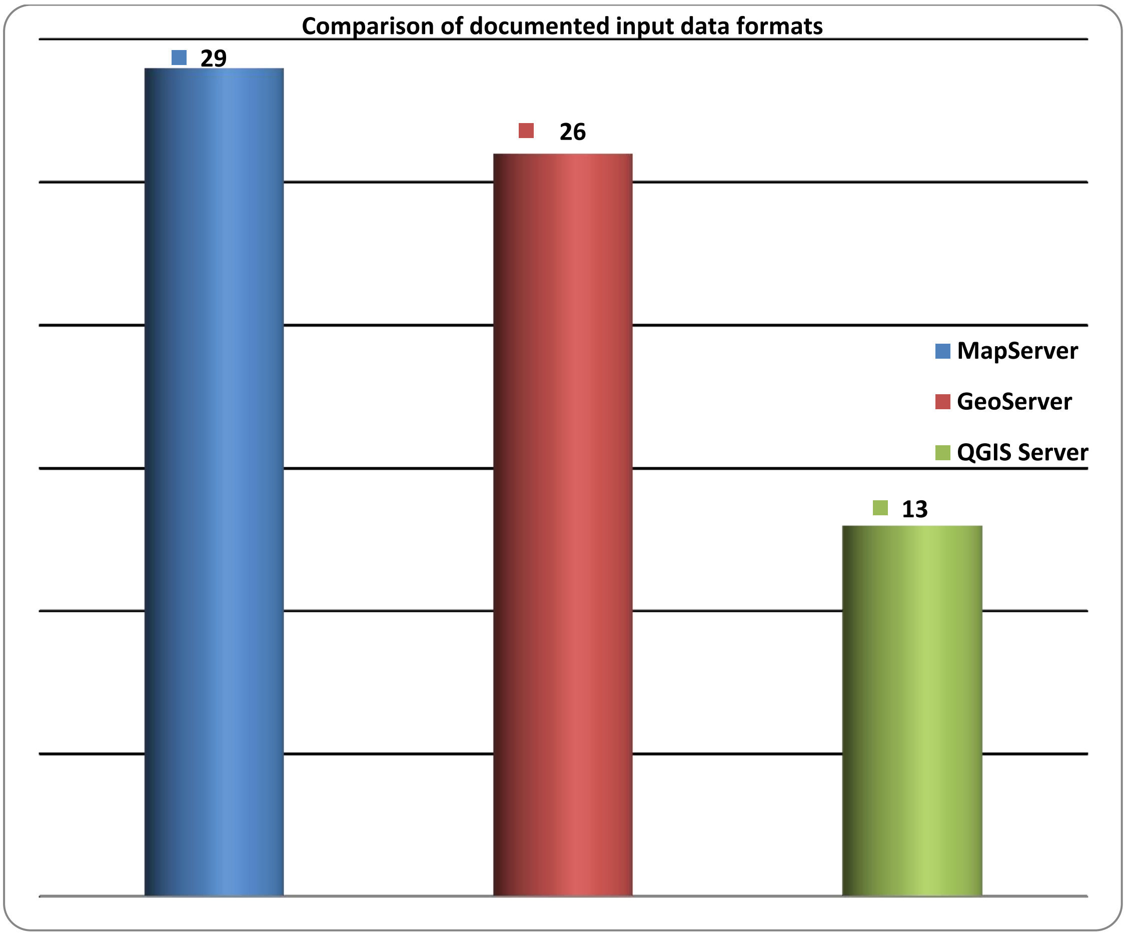


Figure 22: Number of input data supported.

3.4.7 Levels of Support for Styling

The level of support for styling was assessed as an indication of each web map server's the level of support for overlaying thematic information over web maps. This was our measure of the potential of each web map server to create thematic maps. Documented information regarding SLD and SLD extensions supported by each map server were obtained from these urls and checked with user manuals. The urls and manuals used are as follows; Mapserver: http://mapserver.org/ogc/sld.html and The MapServer Team (2012), GeoServer: http://docs.geoserver.org/stable/en/user/styling/index.html,http://docs.geoserver.org/stable/en/

user/styling/sld-extensions/index.html and (GeoServer, 2012); and for QGIS Server: http://www.qgis.org/about-qgis/features.html#server.

Table 15 shows that all three map servers support SLD but MapServer has no SLD extensions whilst GeoServer and QGIS Server have SLD extensions. Figure 23 indicates that GeoServer has four extensions to SLD and QGIS has two extensions. GeoServer supports more SLD extensions.

Table 15: Documented support for SLD and SLD Extensions.

	MapServer	**GeoServer**	**QGIS Server**
Support for SLD?	Yes	Yes	Yes
SLD Extensions	None	Geometry transformations in SLD	Cartographic extensions to SLD
		Point symbology in GeoServer	Exchange of cartographic rules with the GetStyle operation
		Parameter substitution in SLD	
		Specifying symbolizers sizes in ground units	

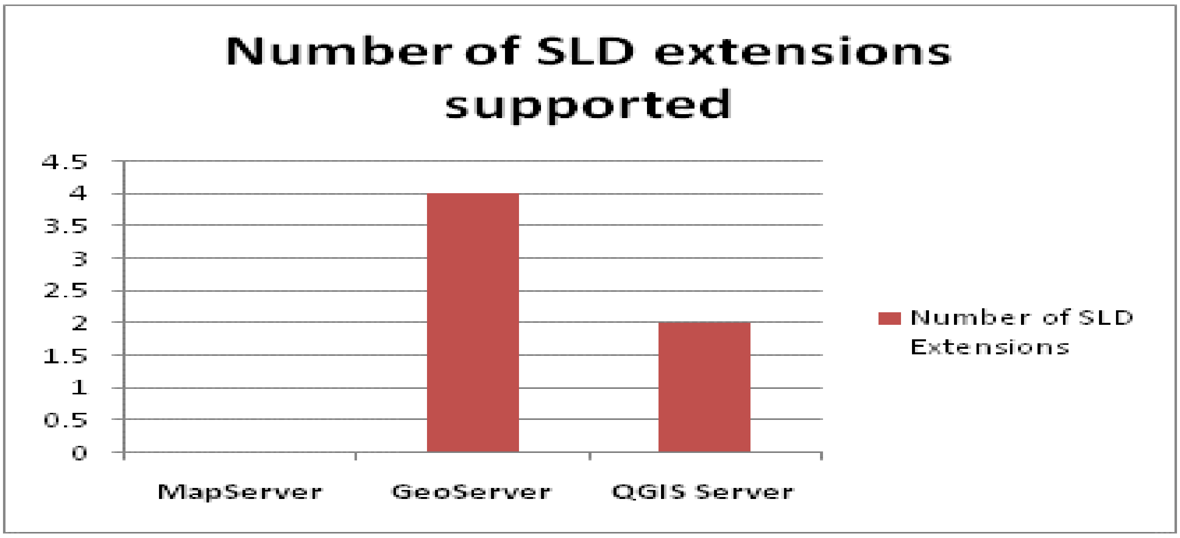


Figure 23: Number of SLD extensions supported.

3.4.8 Adherence to Standards

OGC statistics (OGC, 2012a; OGC, 2012b) were analysed to evaluate the adherence to standards of different WMS and SLD implementations. OGC classifies implementations as one of the following:

- **I:** The version of the software implement that particular version of WMS or SLD.
- **C**: The version of the software complies with that particular version of WMS or SLD.
- **Nil:** No information was found for the version of the software on OGC's website (OGC, 2012b).

At the time of the analysis, there were no implemetations of type 'C'. Table 16 shows that QGIS Server 1.7.4, released in 2010, implements WMS 1.3.0 and WMS 1.1.1 but does not implement SLD. GeoServer 2.1.3, released in December 2011, implements WMS 1.0, WMS 1.1.1, WMS 1.3.0, SLD 1.1.0 and SLD 1.0. MapServer 6.0.0, released in May 2011, implements WMS 1.0, WMS 1.1.1, WMS 1.3.0, SLD 1.1.0 and SLD 1.0. Since GeoServer 2.1.3 and MapServer 6.0.0 implement more standards (WMS and SLD) than QGIS Server 1.7.4, GeoServer and MapServer show greater adherence to OGC WMS and SLD standards.

Table 16: OGC WMS and SLD statistics of the current and previous versions of web map servers (Source of data: OGC, 2012c)

			OGC Specifications							**OGC Implementated Date**
Product	**Release date**	**Type**	**WMS 1.1.1**	**WMS 1.0**	**WMS 1.1**	**WMS 1.3.0**	**SLD 1.1.0**	**SLD 1.1**	**SLD 1.0**	
GeoServer 2.1.4	2012-June	Server	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
MapServer 6.0.3	2012-May	Server	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
QGIS Server 1.7.4	2011-Nov.	Server	**I**	Nil	Nil	**I**	Nil	Nil	Nil	2012-04-12
GeoServer 2.1.3	2011-Dec.	Server	**I**	**I**	Nil	**I**	**I**	Nil	**I**	2012-02-08
MapServer 6.0.0	2011-May	Server	**I**	**I**	Nil	**I**	**I**	Nil	**I**	2011-05-12

3.4.9 User Documentation

With the quality of user documentation was the focus was on how much, how accessible, how helpful and how usable the documentation were. Information about documentation was gathered from official websites, links on the official website to other sources of information and user manuals. There is documentation available for all map servers and are all-accessible. User manuals of MapServer and GeoServer have much helpful and useful information. QGIS Server has inadequate information in the user manual with other sources of information being fragmented and takes time to coordinate the information. MapServer and GeoServer rank highest in terms quality of documentation.

3.5 Summary and Analysis of Results

A summary of the results of our comparison of MapServer, GeoServer and QGIS Server are presented in Table 17. For any criterion, the web map server that ranks highest based on our evaluation of that criterion is shown with a tick "√" .

MapServer and GeoServer are easier to install compared with QGIS Server. Cartographic workflow in QGIS presents fewer steps but GeoServer appears attractive because of the ease with that one can complete the loading of data and of running WMS GetMap requests. Tests for WMS versions supported shows that MapServer supports three previous WMS versions followed by GeoServer with one and QGIS Server with none. Mapserver supports more WMS versions (current and previous put together). MapServer indicates superiority in the total number of requests capabilities advertised and all its requests supported POST and GET methods.

Table 17: Summary of results

Criterion	**MapServer**	**GeoServer**	**QGIS Server**
Ease of installation	✓	✓	
Ease of cartographic workflow		✓	
Level of support for displaying web maps	✓		
Types of output formats supported		✓	
Level of quality of web maps		✓	
Types of input data that can be used	✓		
Level of support for styling		✓	
Adherence to standards	✓	✓	
User documentation	✓	✓	

All the three map servers support SLD but MapServer has no SLD extensions whilst GeoServer and QGIS Server have SLD extensions GeoServer supports more SLD extensions. GeoServer advertised fourteen various output data formats that can be supported by its GetMap, this is followed by Mapserver with nine and QGIS mapserver with two. Seven formats were common to GeoServer and MapServer. Yet, there were no formats common to GeoServer and QGIS Server. There were also no formats common to MapServer and QGIS Server. GeoServer ranks highest in the number of output formats supported by its GetMap. QGIS Server and GeoServer ranks highest regarding output formats supported by GetFeatureInfo. Overall GeoServer shows superiority in output formats supported by WMS requests.

Overall analysis of the output shows that GeoServer shows superiority in the number of output formats that had same quality as input data. For all the three map servers, PNG output format was supported; it displayed all the layers and had the same output quality as the input. The results of comparing the documented input data formats indicated that MapServer documented support for twenty-nine various data formats followed by GeoServer with twenty-six and QGIS Server with thirteen. Based on these documented data MapServer supports more input data.

Results of documented SLD and SLD extensions showed that all three map servers support SLD but MapServer has no SLD extensions whilst GeoServer and QGIS Server have SLD extensions. GeoServer support four various extensions to SLD. QGIS also has two SLD extensions and GeoServer documents support for more SLD extensions. WMS and SLD statistics and show that for WMS total implementation for WMS is higher than SLD but compliance to WMS and SLD are very low. In the particular occasion of the current versions of GeoServer, MapServer and QGIS Server used in this experiment, none of them was acknowledged compliant with either OGC WMS or SLD. GeoServer showed greater adherence to OGC WMS and SLD standards. MapServer and GeoServer ranks highest in documentation. Overall, GeoServer showed superiority for most criteria.

3.6 Choice of Spatial Database Management System

GeoServer was selected as WFS connector between SMILEX (Spatial Mobile Information and Location based Experience) software and PostgreSQL database with PostGIS spatial database enabled (Rafoss, Sælid, Sletten, Fredrik, and Engravslia, 2010). In developing a task controller (TC) prototype uses multiple external services such as WFS during a spraying operation, Kaivosoja, Jackenkroll, Linkolehto, Weis and Gerhards (2014) implemented high performance data storage for multidimensional data, PostgreSQL database with a PostGIS extension. Kaivosoja *et al.* (2014) used Geoserver as one application to publish and view data (and metadata) according to ISO- and OGC-standards. Bastin, Buchanan, Beresford, Pekel, and Dubois (2013) presented an example of a Web-based solution proven on free and open source software (PostGIS and GeoServer) and standards (including Web Map Services, Web Feature Services and) to support assessments of land-cover change. An existing PostGIS database was coupled with GeoServer gives access to Landsat GLS data by WMS (Bastin *et* *al.*, 2013). For the development of a *geospatial web service application for emissions inventory spatial allocation* (Gkatzoflias, Mellios and Samaras, 2013), all the required geospatial and emission data were stored in a PostgreSQL object-relational database by using the PostGIS.

Based on the literature reviewed in this section 3.6, PostgreSQL with PostGIS spatial database extension was chosen for the design and implementation of GTWS. The literature reviewed showed that PostgreSQL with PostGIS have been used with GeoServer to power OGC based web services.

3.7 Conclusion

This chapter shows a critical evaluation of state-of-the-art technologies, tools and standards that will be suitable for developing a GTWS in an open data and open source environment. Three open source web map servers were assessed according to the following criteria: ease of installation, ease of cartographic workflow, level of support for displaying web maps, types of output formats supported, level of quality of web maps, types of input data that can be used, level of support for styling, adherence to OGC standards and quality of the user documentation. The following have been presented: a short literature review, definition of cartographic workflow and design and implementation of a procedure for evaluating each criterion has been presented. The various approaches and ages of each piece of web map server in this evaluation were acknowledged.

The results show that installation is easiest in MapServer and GeoServer. Cartographic workflow is easiest in GeoServer. MapServer shows superiority in the level of support for displaying web maps. GeoServer supports the most output formats. The quality of output of web maps in GeoServer is higher. MapServer supports the most input data forms. GeoServer documents more support for styling. MapServer and GeoServer rank highest in the quality of user documentation. In choosing a state-of-the-art web map server for geospatial thematic web services, GeoServer is preferred since it showed superiority for most criteria. The criteria can be further enriched with criteria that evaluate level of support for cartographic principles such as scale, normalisation, classification and map projection. The level of support for thematic mapping techniques can also be evaluated.

Based on the literature reviewed under section 3.6, PostgreSQL with PostGIS have been used with GeoServer to power OGC based web services in several geospatial applications. PostgreSQL with PostGIS spatial database extension was chosen for the design and implementation of GTWS.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Chapter 4: Design Options for Geospatial Thematic Web Service

The GTWS-1 and GTWS-2 design options are part of refereed papers published as: Owusu-Banahene, W., and Coetzee, S. (2013). *Integrating linked open data into open source web mapping.* 26th International Cartographic Conference (ICC). Dresden. International Cartographic Association (ICA) and Owusu-Banahene, W., and Coetzee, S. (2014). Three integration styles for combining attributes from the linked open data cloud with geospatial data for web thematic mapping. *Submitted*.

4.1 Introduction

Chapter 4 provides information about various designs of a GTWS. This chapter draws on the literature review (described in Chapter 3) to: i) conceptualise GTWS (section 4.2) and ii) identify the evaluation criteria (requirements) for integration approaches that combine linked data from the LOD with geometric data in a spatial database to produce thematic maps (section 4.3). The objective of this chapter is to present the designs for the various design options of creating web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server. Unique identifiers have been introduced to simplify the discussion on the various design choices and its implementations, in this chapter and the rest of the research: GTWS-1, GTWS-2 and GTWS-3. The various design choices are described in section 4.4 in this chapter.

4.2 Conceptualisation of GTWS

The GTWS was conceptualised as having three components namely: The *web mapping* (geospatial web service), *integrator* and *linked data* as shown in Figure 24. The *web mapping* component is an OGC model (web service on top of a web map server) connected to an object-relational model (spatial database) and can create cartographic models (web thematic maps). The *linked data* component conversely, comprised linked data model namely, the LOD cloud acting as linked data (RDF) source, queries (SPARQL, SPARQL Federated), linked data based software (linked data servers, linked data stores), tools (linked data based middleware) and services such as, SPARQL endpoint (or SPARQL service). The *integrator* is a programme (or script) that provides the mechanism for integrating linked data into the spatial database aiding flow of linked data from the linked data component to the web-mapping component.

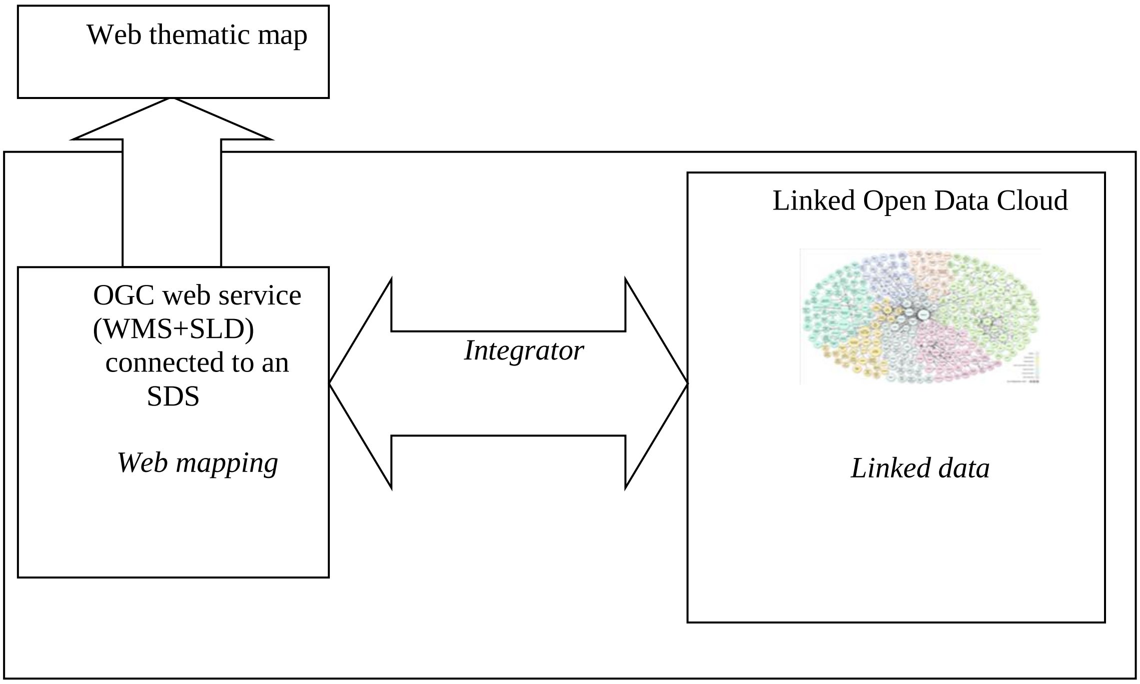


Figure 24. Diagram showing the conceptualisation of a GTWS.

The notion was to demonstrate that existing technology (web mapping, spatial database and implementations of OGC standards) could create and visualise new information by combining geometry with attributes from linked data in the LOD cloud. The GTWS treats the LOD cloud as if it is just a data source (with new representation) that can be integrated with existing web mapping services. By design, GTWS combines geometric data in a spatial database server with non-spatial linked data from the LOD cloud and styling (SLD) to produce thematic web maps as shown in Figure 25.

GTWS is needed in occupances where: 1) An existing WMS has to be migrated to using linked data, 2) Statistical agencies publish statistical data as linked data to the LOD cloud and

3) Geospatial data is too big to be accessed over the web and or it is already available locally. It is pleasant to create thematic maps from all the attribute data available on the Web.

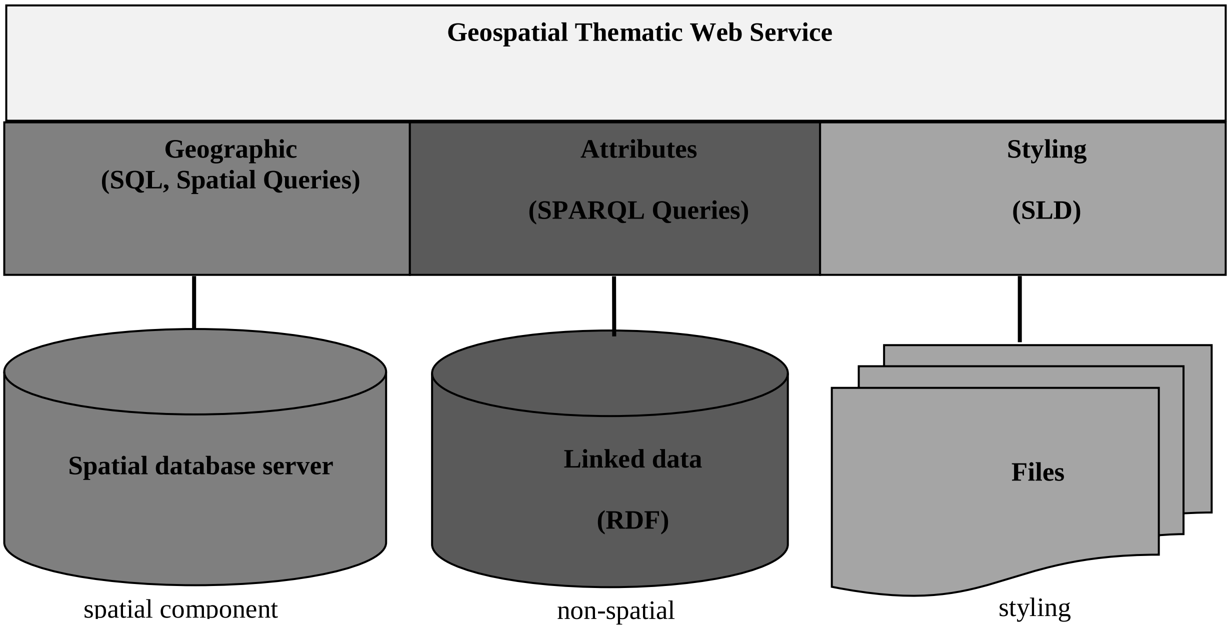


Figure 25: Spatial, non- spatial (attributes) and styling components of GTWS (Source: Owusu-Banahene and Coetzee, 2013).

4.2.1 Utilising Open source Geospatial Software to Access and Integrate Linked Data from the LOD Cloud

In this sub-section the current relationship between open source geospatial software and the LOD cloud and the proposed approach to improving the relationship are presented. As indicated previously, the main challenge to consuming linked open data is the difficulty with that open source geospatial software accesses and integrate linked data from the LOD cloud.

From Figure 26, open source geospatial software cannot integrate linked data. The relationship can be described as disjoint. Four approaches are proposed, shown as bold in Figure 27, by that, open source geospatial software can access and integrate linked data from the LOD cloud. From Figure 27, the first approach considers using existing linked data models (data, queries, services and software). The second approach considers developing extensions to existing open source geospatial software (web mapping, desktop and geospatial libraries), such that they can connect to the LOD cloud. The third approach uses the development of new open source geospatial software. With the fourth approach, entirely new open source software has to be developed from scratch. The four approaches are not mutually exclusive though.

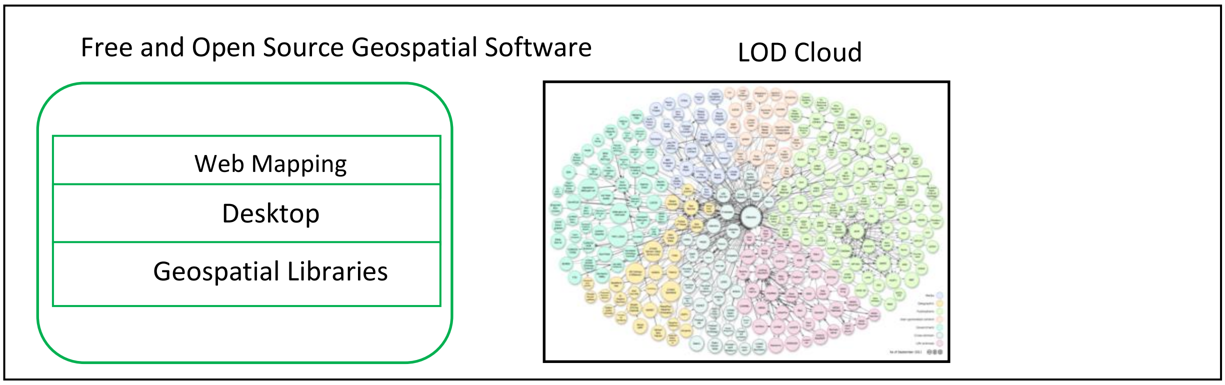


Figure 26: The current relationship between free and open source geospatial software and the LOD cloud.

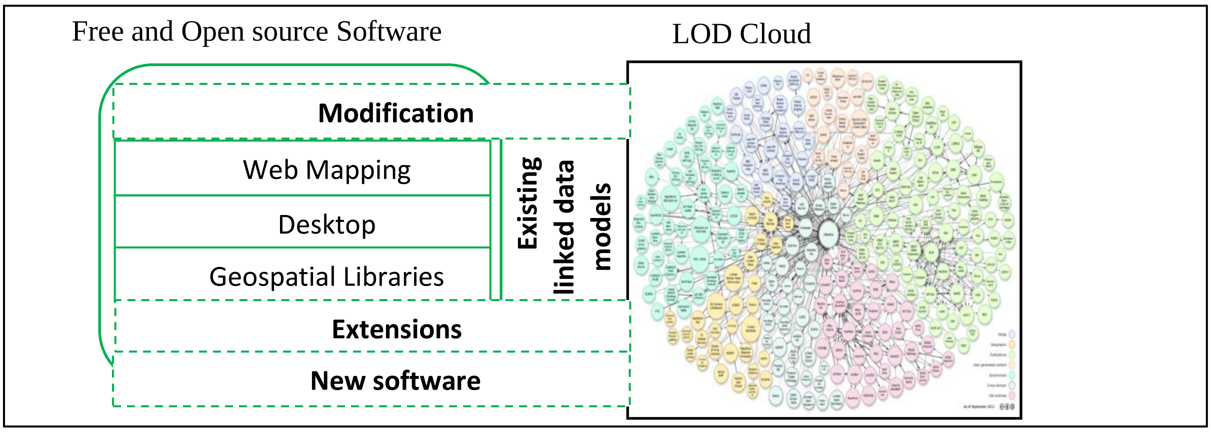


Figure 27: Approach to developing free and open source geospatial software to use the LOD cloud.

The research described in this thesis, used the existing linked data models. The development of extensions were incorporated into the designs and implementations of

GTWS. GTWS-1 and GTWS-2 used existing linked data models to access the LOD cloud. GTWS-3 used extension to existing open source geospatial software.

4.3 Identifying Requirements

4.3.1 Map Communication Model in the Linked Data Context

A map communication model conceptualises basic steps in communicating cartographic information to a user (Dodge, Kitchin and Perkins, 2009). A map communication model was adapted from Slocum *et al.* (2010) for linked data from the LOD cloud with separate geometry in a spatial database server as shown in Figure 28.

Slocum *et al.* (2010) presents the following map communication model (shown as boxes and arrows depicted with light gray in Figure 28).

1. *Consider how the real world phenomenon might look like.*
2. *Determine the purpose of the map.*
3. *Collect data appropriate for the map's purpose*
4. *Design and construct the map*
5. *Determine whether users find the map useful and informative*

For this research, the map communication model by Slocum *et al.* (2010) was adapted to illustrate the steps required to combine attributes from the linked open data cloud with geospatial data in a spatial database server to create web thematic maps. The steps were adapted as follows. The steps in the adapted model are shown as dark gray boxes and black arrows.

1. *Consider how the real world phenomenon might look like.* This is done by a cartographer so it was not included in our adapted model.

2. *Determine the purpose of the map*. This is presented in our adapted model as **Step 1. Select a theme.** A user selects a theme for the thematic map to be created. For

example; , population density of all countries in the world.

3. *Collect data appropriate for the map's purpose*. This became *Step2* adapted model and was expanded to include the three sub-steps required for data collection:

   Step 2.a) Collect appropriate linked data (attributes) from the linked open data cloud, for example; the population sizes of countries

   Step 2.b). **Identify relevant geometry in a spatial database server, for example; country boundaries.**

   Step 2.c) Combine the attributes with the geometry, for example; by linking country boundaries with corresponding population sizes through a unique identifier such as the country name.

4. *Design and construct the map* was taken as *Step3* expanded into five sub-steps described below. Note the feedback loop to step 3, that allows refinement of the thematic map, if required.

   Step 3.a) Choose a thematic mapping technique, for example; the choropleth mapping technique can be selected to show differences in population density.

   Step 3.b) If required, normalise the data, for example; by calculating the population densities of countries as a ratio of population to area.

   Step 3.c) Depending on the choice of the user, the data may be presented as classified or unclassified. For classified data, classes are created according to an appropriate data classification method, for example; population densities could be classified into two classes where one class includes population densities below a certain value and the other class population densities greater than or equal to that value.

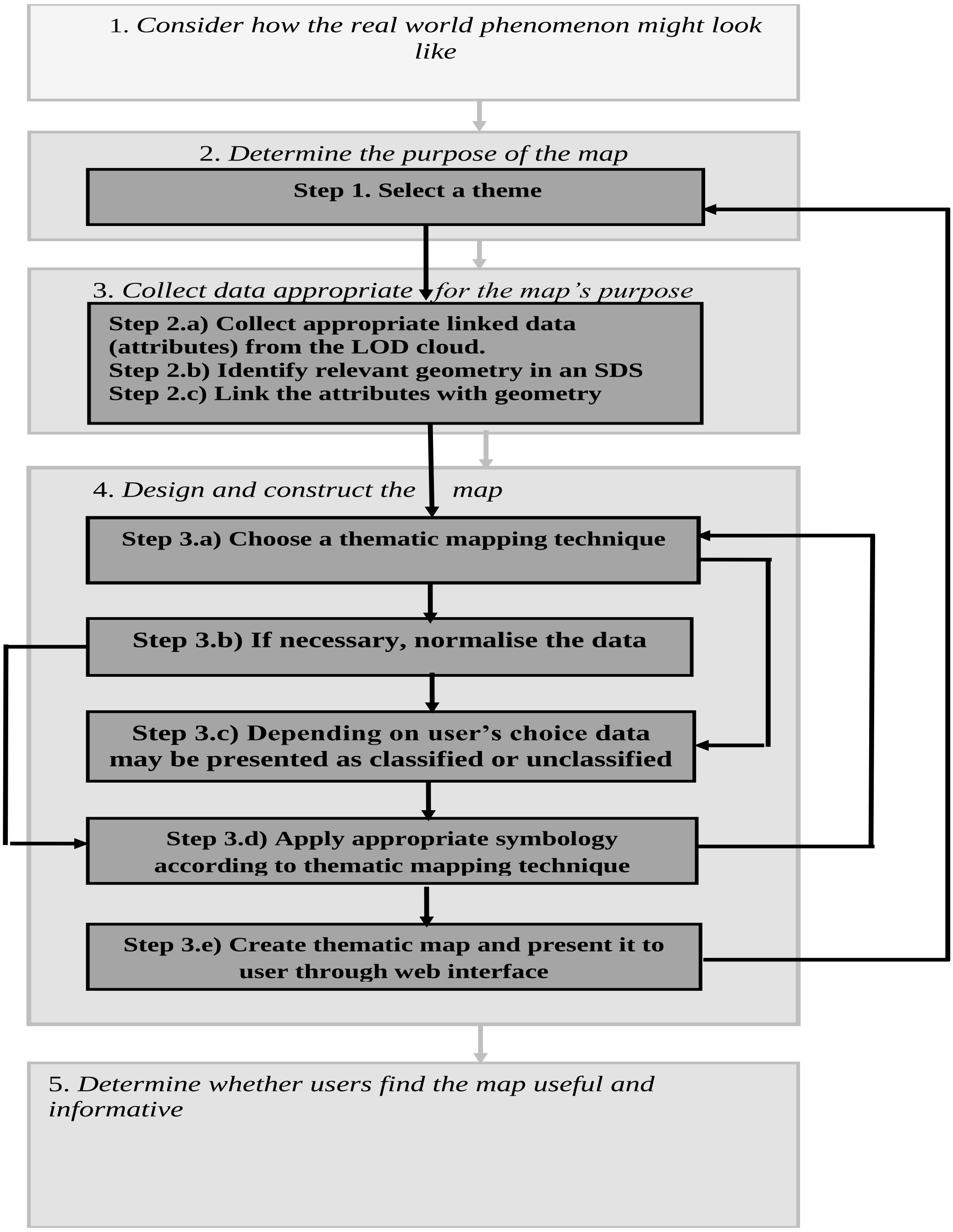


Figure 28: A map communication model in the context of linked data, adapted from Slocum *et al.* (2010).

Step 3.d) Appropriate symbolisation applies to the data according to the choice of thematic mapping technique, for example; for a choropleth map a different colour is assigned to each class.

Step 3.e) Finally, the thematic map is created and presented to the user through a web interface.

5. *Determine whether users find the map useful and informative*. This was included in the adapted model as a feedback loop from Step 3.e to Step 1. The feedback loop allows refinement of the thematic map if he does not find the map useful and informative.

4.3.2 Requirements

The requirements describe a web service that combines attributes from the LOD cloud with geometry in a spatial database server to produce thematic maps. The modified model with the review of literature (see Chapter 2) and critical evaluation of technology in Chapter 3 formed the basis for identifying requirements for GTWS described in this section. GTWS-1, GTWS-2 and GTWS-3 described in Section 4.4 met these requirements. Eight requirements for a web service that combines attributes from the linked open data cloud with geometry in a spatial database server to produce thematic maps are described below. The requirements were identified with reference to the adapted map communication model.

Requirement 1. A client shall request a thematic map from a web map server (the client sends a map request to the service).

Requirement 2. A client shall specify a theme and a thematic mapping technique in a map request (see steps 1 and 3.a).

Requirement 3. The service shall identify the attributes to be used for the theme in the linked open data cloud (see step 2.a).

Requirement 4. The service shall identify the geometry to be used for the theme in a spatial database server (see step 2.b).

Requirement 5. The service shall combine the attributes with the geometry (see step 2.c).

Requirement 6. The service shall normalise and classify data as required (see steps 3.a and 3.b).

Requirement 7. The service shall apply symbology appropriate for the specified thematic mapping technique (see step 3.d).

Requirement 8. The service shall create a thematic map image and return it to the client (see step 3.e).

In addition, to the requirements above, for this research standard technology for web mapping, linked data and spatial databases were to be used. This requirement is motivated by the widespread deployment of standardised web map services in the geospatial community and the widespread publication of alphanumeric data (by statistical agencies) in the LOD cloud.

The process flow for GTWS based on these requirements and the interactions (request and response) in the geospatial web service needed to create thematic maps are further described in sub section 4.4.3. ***Requirements*** 3-5 distinguish GTWS from any other web service that creates maps.

4.3.3 Process Flow Modelling

Figure 29 shows the process flow model of GTWS based on ***Requirements*** 1-8. The client sends a request for a thematic map to the service (requirement 1). The client specifies the theme and thematic mapping technique as part of the request for a thematic map (requirement 2). The service identifies the attributes to be used for the theme in the linked open data cloud (requirement 3). After this, the geometry to be used for the theme is identified in a spatial database server (requirement 4). Based on requirement 5, the service combines the attribute with the geometry.

GTWS receives a request for a thematic map. The service checks if there is a need for normalisation and normalises the data if required. If there is no need to normalise the data, the service checks if the data has to be classified (requirement 6). If the data has to be classified (requirement 6). Subsequently the service creates appropriate classes (requirement 6) else, it applies symbolisation to the data (requirement 7). Finally, the service creates the thematic map and sends it back to the client in a web browser (requirement 8).

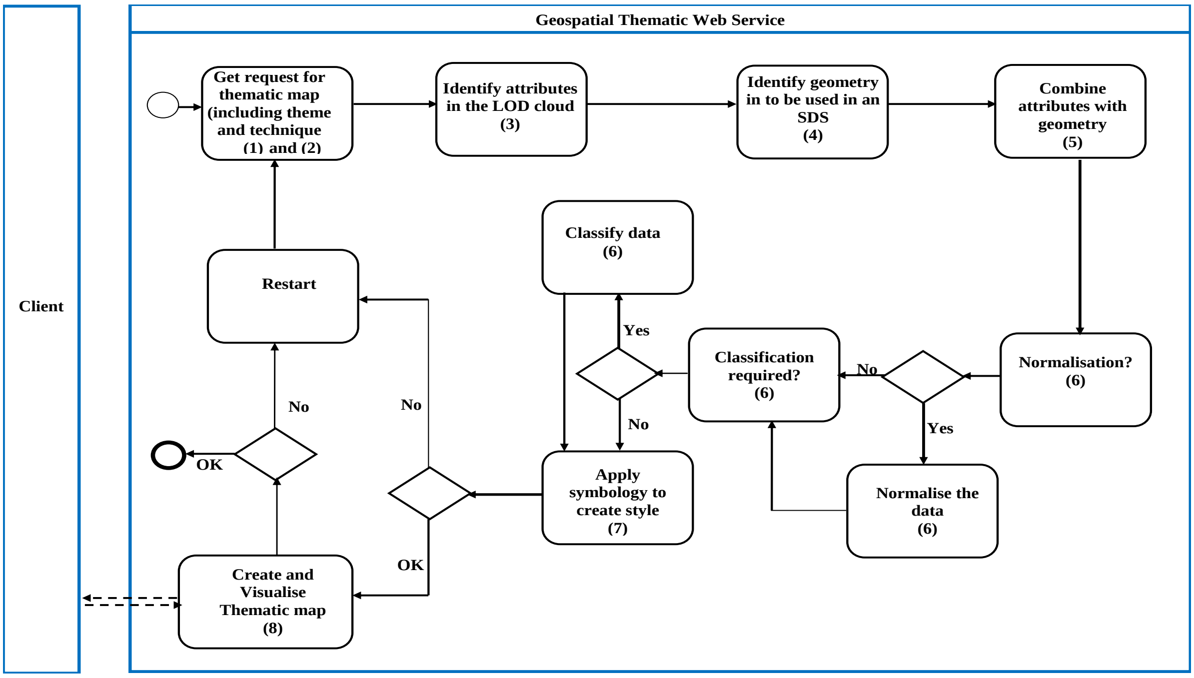


Figure 29: Process flow model for GTWS.

4.4 Design Options

In this section, a geospatial thematic web service (GTWS) is introduced. Three different ways of creating web thematic maps by combining alphanumeric linked data from the LOD cloud with geometry in a spatial database server are presented, namely: GTWS-1, GTWS-2 and GTWS-3. Each option integrates attributes from the LOD cloud in a different way: GTWS-1 integrates attributes from the LOD cloud by storing results of SPARQL queries intermediately and importing them into a spatial database server; GTWS-2 does so through a spatial database server connected to a linked data server by middleware; and GTWS-3 connects directly to the LOD cloud by an extension to the spatial database server.

The three different design options illustrate how an OGC model (WMS-SLD) hosted by a web map server can produce cartographic models (web thematic maps) by combining linked data models (attributes from the LOD cloud) with geo-relational models (geometry in a ***spatial database server)***. The web mapping component of GTWS (shown in Figure 30) is a typical generic architecture of a geospatial web service comprising a client as a web browser, a web map server and a ***spatial database server***. The web map server provides support for WMS and SLD. SLD offers support for styling, to meet *requirements 6* and *7*. The ***spatial database server*** stores geometry and provides data manipulation functionality to meet *requirements 3* and *5*. The data in the ***spatial database server*** is published to the web map server.

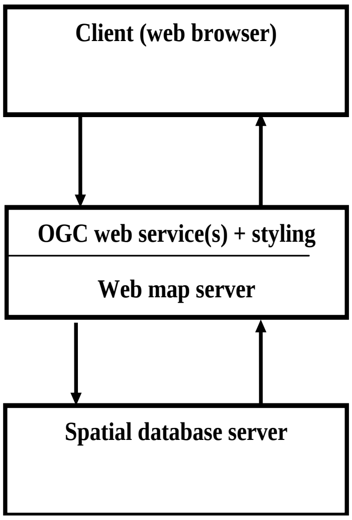


Figure 30: Generic architecture of the web mapping component.

A request for a thematic map is made from the client to the web map server that applies styles, and sends a thematic map to the user by WMS, thereby satisfying requirements 1, 6 and 8. In the subsequent subsections, the three design choices for retrieving attributes from the LOD cloud to meet requirements 4 and 5 are presented. The various design options are described in detail in this section. Unique identifiers: GTWS-1, GTWS-2 and GTWS-3 have been introduced to simplify the discussion on various design options.

4.4.1 GTWS-1: The Importer

The GTWS-1 design option follows an *importer* approach, as shown in Figure 31. Linked data from the LOD cloud is retrieved by executing SPARQL queries directly against a SPARQL endpoint (*query editor*) of a linked dataset. The responses to the queries (the attributes) are stored temporarily as files in an appropriate format such as CSV that can be integrated with a spatial database without requiring an RDF to relational mapping. A script, the *sql importer,* loads the files containing the attributes into a spatial database so that the attributes can be linked to stored geometry and used by the web mapping component. The *sql importer* creates a table in the spatial database server; copies the data in the CSV file into the table; and then creates a JOIN between the said table and the table containing the geometry previously stored in the spatial database server.

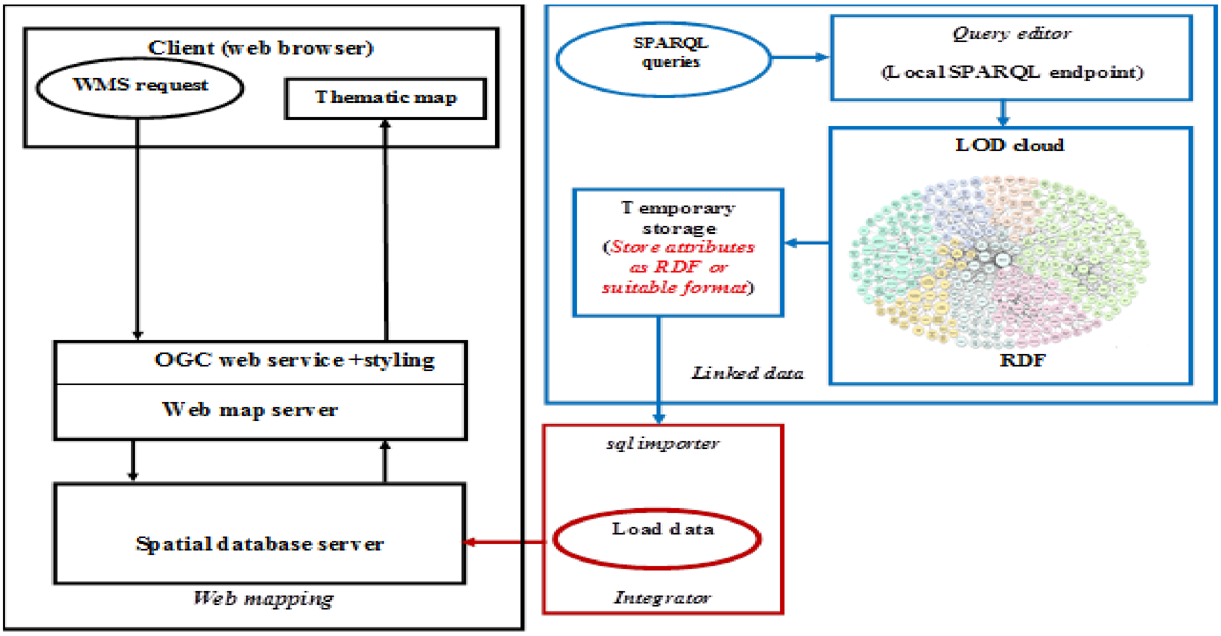


Figure 31. GTWS-1: *Importer*

4.4.2 GTWS-2: The Middleware

In the GTWS-2 design option, referred to as the *middleware,* attributes from the LOD cloud are accessed by generic SPARQL service and integrated with geometry through a linked data server connected to a spatial database server through middleware. The middleware acts as the *integrator* and can be a database connectivity driver, such as ODBC, JDBC or a wrapper. The middleware has the capability of allowing linked data from the linked data server to be migrated into a spatial database server. The migration of the data from the linked data server into the spatial database server ensures that the linked data is accessed in a form that can be integrated with the geometry in the spatial database server. Figure 32 shows this design option.

The linked data server is an RDF store (including RDF-mapped relational database) with or without a SPARQL endpoint. Figure 32 shows this design option. The linked data server is an RDF store (including RDF-mapped relational database) with or without a SPARQL endpoint.

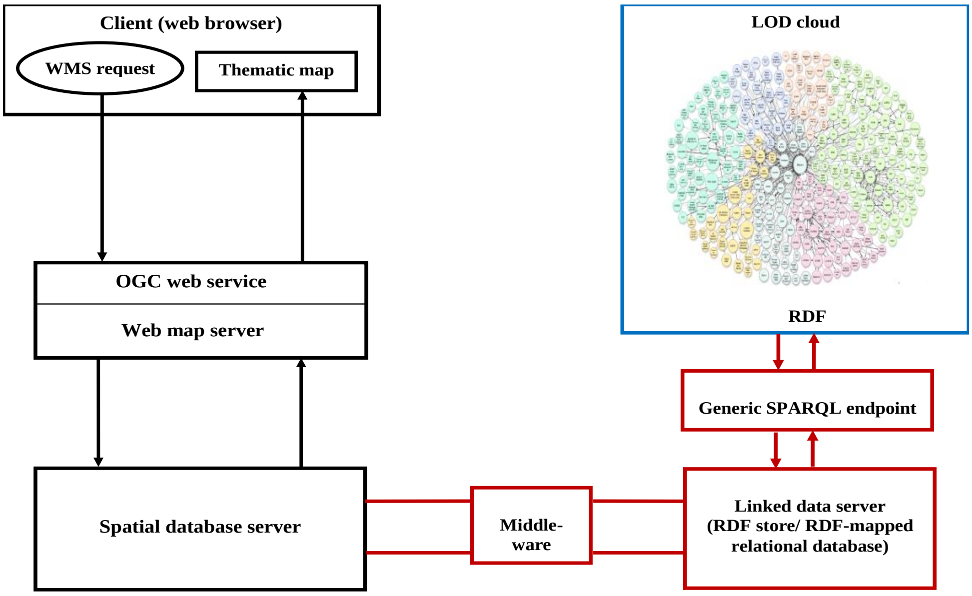


Figure 32: GTWS-2: The *middleware*

GTWS-2 retrieves attributes from the LOD cloud by SPARQL federated queries against a generic SPARQL endpoint. The SPARQL query results (in an RDF serialised format) are stored on the linked data server and integrated with a spatial database server by the middleware. The web mapping component can create thematic maps by combining the attributes with geometry stored in the spatial database.

4.4.3 GTWS-3: The Extension

In the GTWS-3 design option, the spatial database server connects directly to the LOD cloud through a query enabled extension, as shown in Figure 33. RDF triples (attribute data) are accessed directly from a remote SPARQL service and integrated with geometry in a spatial database. The extension to a spatial database server is called in this research a *spatial database server extension to LOD cloud (spatial2LOD).* A *spatial2LOD* retrieves RDF triples (attribute data) from a remote SPARQL service and integrates them with existing geometry in a spatial database. In its simplest form the *spatial2LOD* is a linked data query interface that enables an application to process SPARQL and SPARQL-FED queries to a remote SPARQL service. *spatial2LOD* utilises application programming interfaces or frameworks for building semantic web applications that provide a programmatic environment for querying linked data from the LOD cloud.

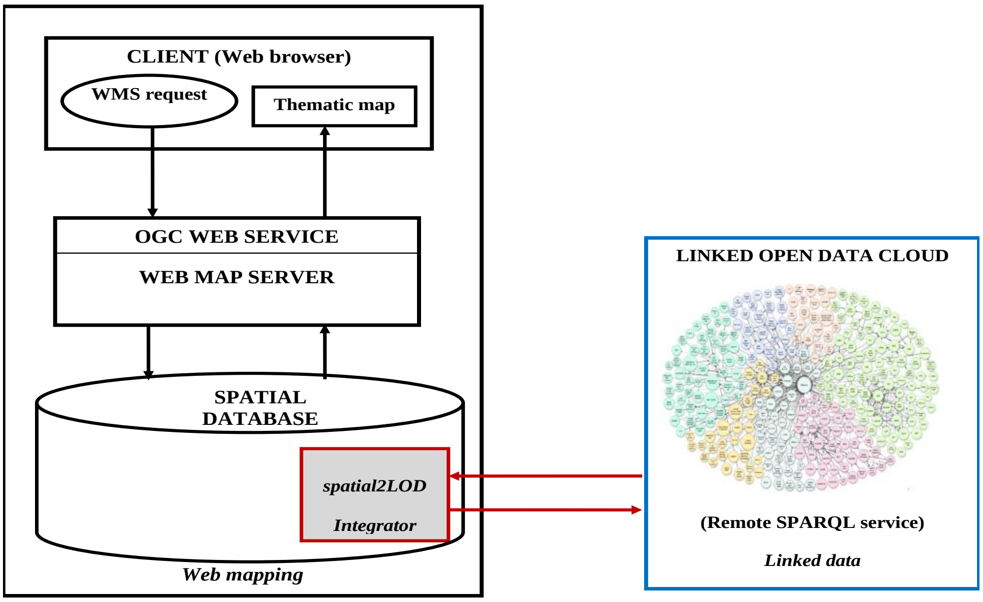


Figure 33: GTWS-3: *extension*

Figure 34 shows the architecture of the *spatial2LOD*. *spatial2LOD*consists of a lightweight application implementing an *RDF query interface* and a *loader*. Non-semantic geometric objects are stored in the spatial database along with a unique identifier (UI). The *RDF* query *interface* enables the application code to process SPARQL and SPARQL-FED queries to retrieve RDF triples from a remote SPARQL service. The *loader* provides connectivity to the spatial database allowing RDF triples to be integrated with the spatial database. Integrating RDF triples into a spatial database requires the mapping of RDF to (object-) relational database. Any of the mapping approaches discussed in section 2.3 could be used to represent RDF triples in the spatial database. GTWS-3 uses the *direct mapping of RDF to relational database* approach to integrate RDF triples into the spatial database.

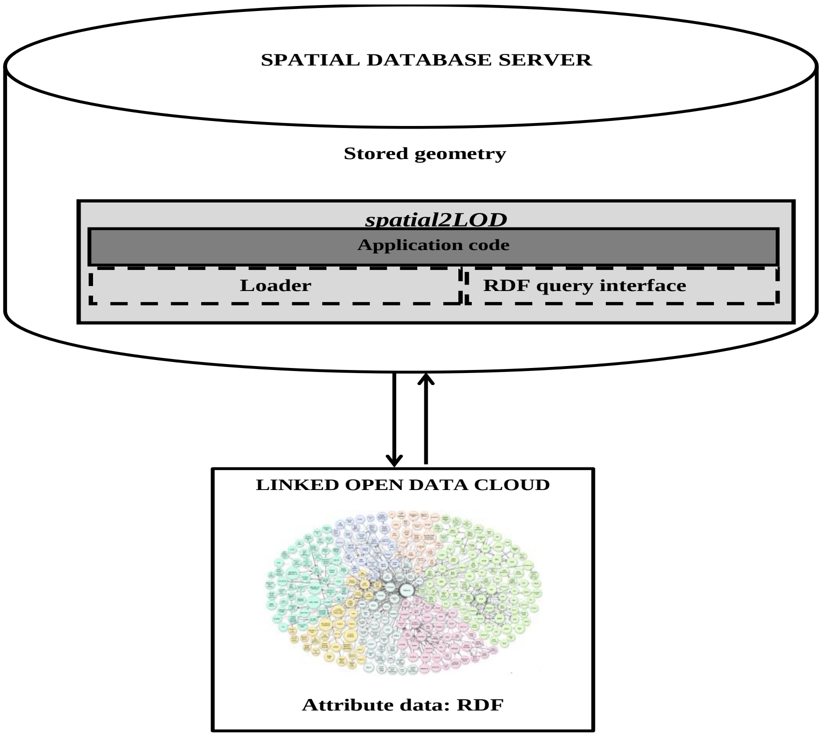


Figure 34: Architecture of spatial database extension to LOD cloud (*spatial2LOD*)

GTWS-3 in its generic form uses *spatial2LOD* to query attributes (RDF) data from the LOD cloud and integrates it (RDF data) into a spatial database. Similar to GTWS-1 and GTWS-2, a client makes a request for thematic map to a web map server that hosts an OGC web service and styling. The web map server makes a request for geometry and attributes data from a spatial database. Style is added to the geometry and attributes data to create a thematic map, portrayed back to the client by the OGC web service.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Chapter 5: Implementations

The implementations of GTWS-1 and GTWS-2 are part of refereed papers published as: Owusu-Banahene, W., and Coetzee, S. (2013). *Integrating linked open data into open source web mapping.* 26th International Cartographic Conference (ICC). Dresden. International Cartographic Association (ICA); and Owusu-Banahene, W., and Coetzee, S. (2014). *Three integration styles for combining attributes from the linked open data cloud with geospatial data for web thematic mapping . Submitted.*

5.1 Introduction

This chapter offers the implementation of the various options of creating web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server. The implementations of GTWS-1, GTWS-2 and GTWS-3 are presented. This provides empirical evidence that can be used to compare and evaluate the designs. The implementations are integrated with existing open source geospatial software. The results from these implementations are case studies with actual data input, processing and output showing thematic maps with two different thematic mapping techniques - choropleth and proportional symbols. The maps were prepared with data retrieved directly from the LOD cloud, without any evaluation of the quality of the data. In some cases the data quality is severely lacking, e.g. not all landlocked countries are included in the data. The focus in this research is not on the quality of data for integration, therefore the maps were prepared with this data, even if the quality was poor. In future work, evaluation of the data quality will have to be addressed before integration into an SDI (see also 7.4.5).

The following software packages were selected based on the critical evaluation of technology and review of literature in Chapter 3: GeoServer 2.1.4, PostgreSQL 9.1.4 and PostGIS 2.0. GeoServer was required to set up a WMS, that provided support for styling through SLD and SLD extensions, and to establish a direct connection to the PostGIS database. PostGIS is a spatial extension to the open source PostgreSQL object-relational database management system. The packages were chosen after a critical evaluation of available technologies and a review of literature. The summary of findings from the review showed that GeoServer and PostgreSQL/PostGIS were the most suitable free and open source geospatial software for web mapping. The implementations and results of GTWS-1, GTWS-2 and GTWS-3 discussed in sections 5.2, 5.3 and 5.4 illustrate how linked data is accessed from the LOD cloud and integrated with geospatial data to create thematic maps. This chapter contributes to bridging the gap between linked data and web thematic maps.

5.2 Implementation of GTWS-1

Figure 35 is a high-level architecture showing the main components of GTWS-1: the *importer*. The linked open data access-and- integration mechanism is shown in red. The *query editor* was DBpedia's SPARQL endpoint. Linked open data in RDF were requested from *DBpedia's Virtuoso Query Editor*[50] . The query response (RDF) was serialised and stored temporarily as CSV files. The *integrator* was implemented as SQL scripts (*importer*). These SQL scripts provided the mechanism through that linked data were fed into the web service environment. In this section, results of thematic maps created with GTWS-1 are presented using linked data from DBPedia since DBpedia[51] is part of the LOD cloud.

---

[50] DBpedia Virtuoso Query Editor: http://dbpedia.org/sparql
[51] DBpedia: http://wiki.dbpedia.org/Interlinking

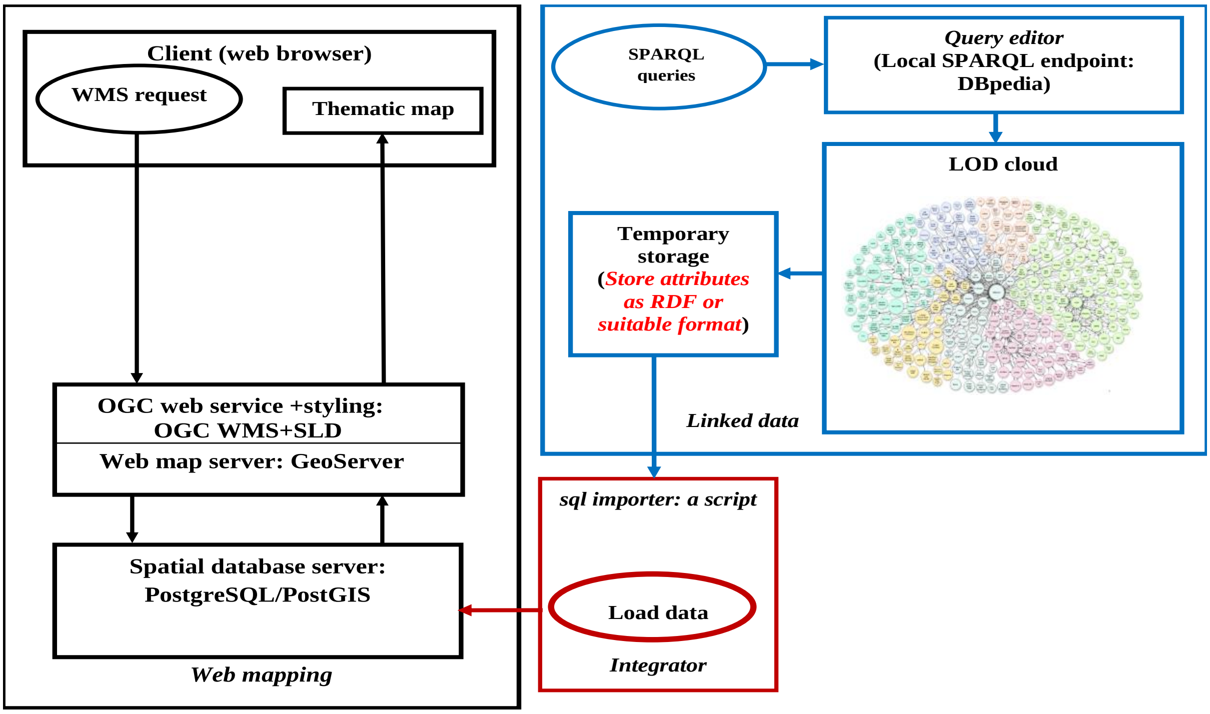


Figure 35: Implementation of GTWS-1: The *importer*.

5.2.1 *Assessing RDF from the LOD Cloud*

SPARQL queries were executed against the DBpedia OpenLink Virtuoso SPARQL end point to retrieve all names population and population density per square kilometre of all landlocked countries in the world (see Appendix A.1 for the SPARQL query). The result of the SPARQL query in RDF/XML is shown in Appendix A.2. The same SPARQL query results were serialised and stored in a CSV file (see Appendix A.3) to allow for integration into the spatial database by SQL script. The first row with the headings was deleted to allow for consistency in data type when the data in the file is later copied into a PostgreSQL table. A section of the CSV file is shown below. The first, second and third values represent country name, population and population density, respectively:

```
Ethiopia,82101998,74
Afghanistan,29835392,44
Uzbekistan,29559100,61
Nepal,29331000,199
```

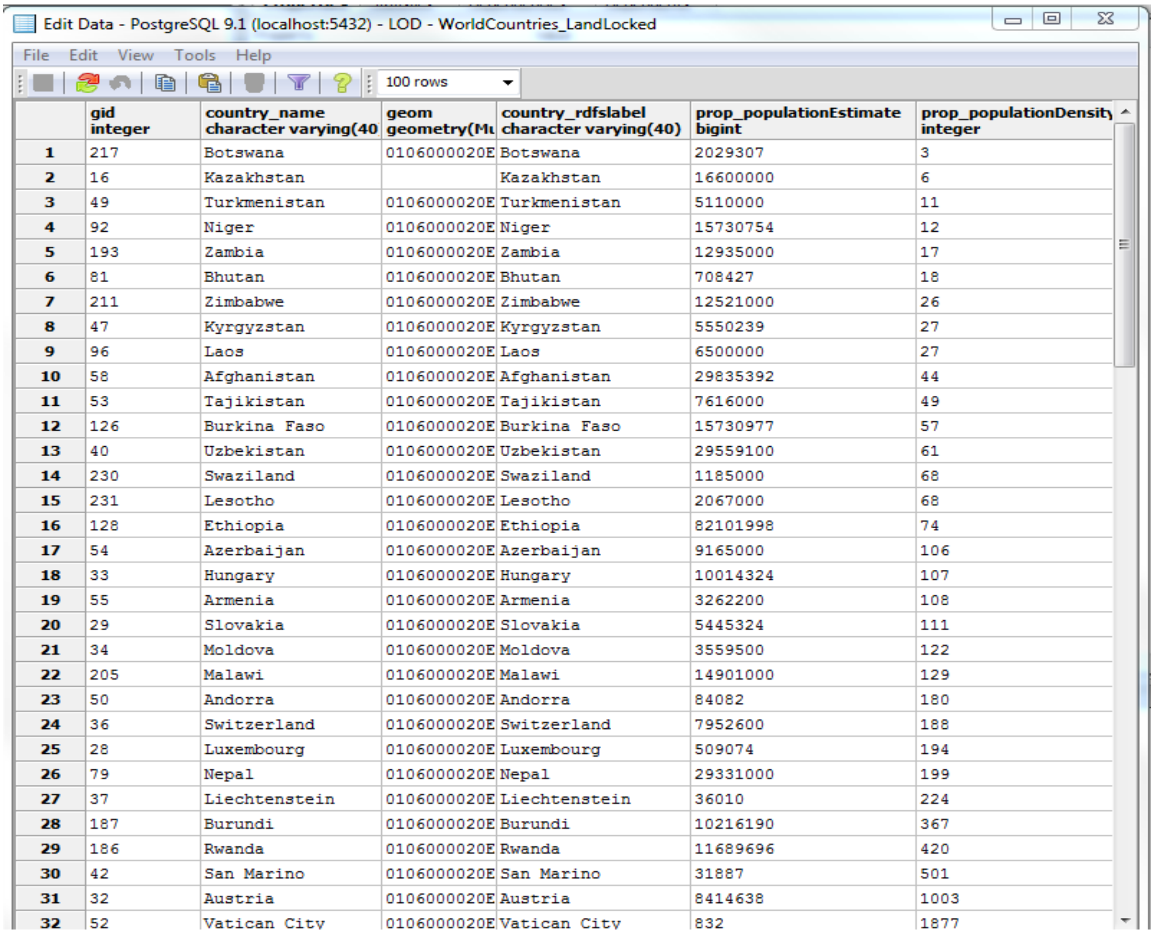
```
Kazakhstan,16600000,6
Burkina Faso,15730977,57
Niger,15730754,12
Malawi,14901000,129
Zambia,12935000,17
Zimbabwe,12521000,26
Rwanda,11689696,420
```

5.2.2 *Loading Results of SPARQL Query into Spatial Database*

A spatial database in PostGIS called LOD with a table (World_Countries) containing the names of countries and its geometric data was created. The *integrator* was implemented using SQL script (*importer*, see Appendix A.4) to pursue the following:

1. Create a table called LandLocked in *LOD*.
2. Copy the data in the CSV file into the relation created in PostgreSQL;
3. Create another table WorldCountries_LandLocked by a JOIN between the two tables World_Countries and LandLocked.

Figure 36 is a screen shot of the table WorldCountries_LandLocked in the PostGIS database.



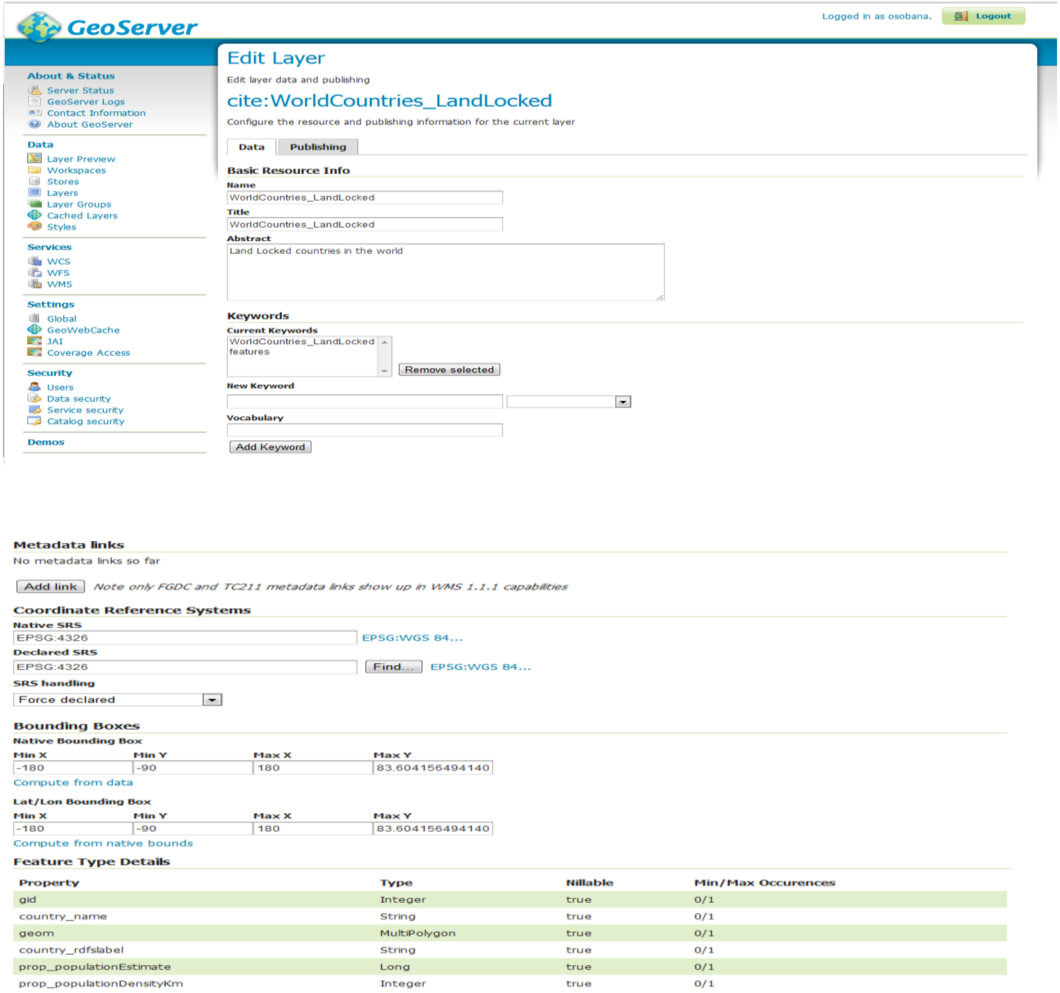
	gid integer	country_name character varying(40	geom geometry(Mu	country_rdfslabel character varying(40)	prop_populationEstimate bigint	prop_populationDensity integer
1	217	Botswana	0106000020E	Botswana	2029307	3
2	16	Kazakhstan		Kazakhstan	16600000	6
3	49	Turkmenistan	0106000020E	Turkmenistan	5110000	11
4	92	Niger	0106000020E	Niger	15730754	12
5	193	Zambia	0106000020E	Zambia	12935000	17
6	81	Bhutan	0106000020E	Bhutan	708427	18
7	211	Zimbabwe	0106000020E	Zimbabwe	12521000	26
8	47	Kyrgyzstan	0106000020E	Kyrgyzstan	5550239	27
9	96	Laos	0106000020E	Laos	6500000	27
10	58	Afghanistan	0106000020E	Afghanistan	29835392	44
11	53	Tajikistan	0106000020E	Tajikistan	7616000	49
12	126	Burkina Faso	0106000020E	Burkina Faso	15730977	57
13	40	Uzbekistan	0106000020E	Uzbekistan	29559100	61
14	230	Swaziland	0106000020E	Swaziland	1185000	68
15	231	Lesotho	0106000020E	Lesotho	2067000	68
16	128	Ethiopia	0106000020E	Ethiopia	82101998	74
17	54	Azerbaijan	0106000020E	Azerbaijan	9165000	106
18	33	Hungary	0106000020E	Hungary	10014324	107
19	55	Armenia	0106000020E	Armenia	3262200	108
20	29	Slovakia	0106000020E	Slovakia	5445324	111
21	34	Moldova	0106000020E	Moldova	3559500	122
22	205	Malawi	0106000020E	Malawi	14901000	129
23	50	Andorra	0106000020E	Andorra	84082	180
24	36	Switzerland	0106000020E	Switzerland	7952600	188
25	28	Luxembourg	0106000020E	Luxembourg	509074	194
26	79	Nepal	0106000020E	Nepal	29331000	199
27	37	Liechtenstein	0106000020E	Liechtenstein	36010	224
28	187	Burundi	0106000020E	Burundi	10216190	367
29	186	Rwanda	0106000020E	Rwanda	11689696	420
30	42	San Marino	0106000020E	San Marino	31887	501
31	32	Austria	0106000020E	Austria	8414638	1003
32	52	Vatican City	0106000020E	Vatican City	832	1877

Figure 36: WorldCountries_LandLocked table created in a PostGIS spatial database.

5.2.3 *Connecting the PostGIS Database to GeoServer and Publishing the Data*

The PostGIS spatial database (LOD) was connected to GeoServer. After a successful connection all the tables contained in the spatial database were available to GeoServer to allow the data in the tables to be published GeoServer's WMS 1.3.0. The table WorldCountries_LandLocked was published as a new layer in WMS 1.3.0. The WMS 1.3.0 parameters; BoundingBox (BBOX) that specifies the area on Earth been mapped and Coordinate Reference System (CRS) for the layer were specified. GeoServer computed the BBOX as from the data as -180, -90, 180 and approximately 83.604 and extracted a Spatial Reference System (SRS) code EPSG:4326 for the CRS. The layer can be visualised by sending a valid GetMap request to the WMS 1.3.0. Figure 37 is a section of GeoServer's Edit

Layer user interface showing WMS 1.3.0 parameters; BBOX and CRS as specified for the layer WorldCountries_LandLocked.



Logged in as osobana.

Edit Layer

Edit layer data and publishing

cite:WorldCountries_LandLocked

Configure the resource and publishing information for the current layer

Basic Resource Info

Name: WorldCountries_LandLocked

Title: WorldCountries_LandLocked

Abstract: Land Locked countries in the world

Keywords

Current Keywords: WorldCountries_LandLocked
features

New Keyword:

Vocabulary:

Metadata links

No metadata links so far

Note only FGDC and TC211 metadata links show up in WMS 1.1.1 capabilities

Coordinate Reference Systems

Native SRS: EPSG:4326 EPSG:WGS 84...

Declared SRS: EPSG:4326 EPSG:WGS 84...

SRS handling: Force declared

Bounding Boxes

Native Bounding Box

Min X	Min Y	Max X	Max Y
-180	-90	180	83.604156494140

Lat/Lon Bounding Box

Min X	Min Y	Max X	Max Y
-180	-90	180	83.604156494140

Feature Type Details

Property	Type	Nillable	Min/Max Occurences
gid	Integer	true	0/1
country_name	String	true	0/1
geom	MultiPolygon	true	0/1
country_rdfslabel	String	true	0/1
prop_populationEstimate	Long	true	0/1
prop_populationDensityKm	Integer	true	0/1

Figure 37: GeoServer's Edit Layer user interface for the layer WorldCountries_LandLocked.

5.2.4 *Creating Styling for Choropleth Maps*

Figure 38 shows the results of a GetMap request to the WMS 1.3.0 to retrieve the WorldCountries_LandLocked layer. At this stage, GeoServer applies a default style to the layer. A new style (XML) was created based on OGC's SLD to create choropleth map showing landlocked and non-landlocked countries. The styling was based on assigning different colours to polygons based on attribute data classification. See Appendix A.5 for the content of the SLD file.

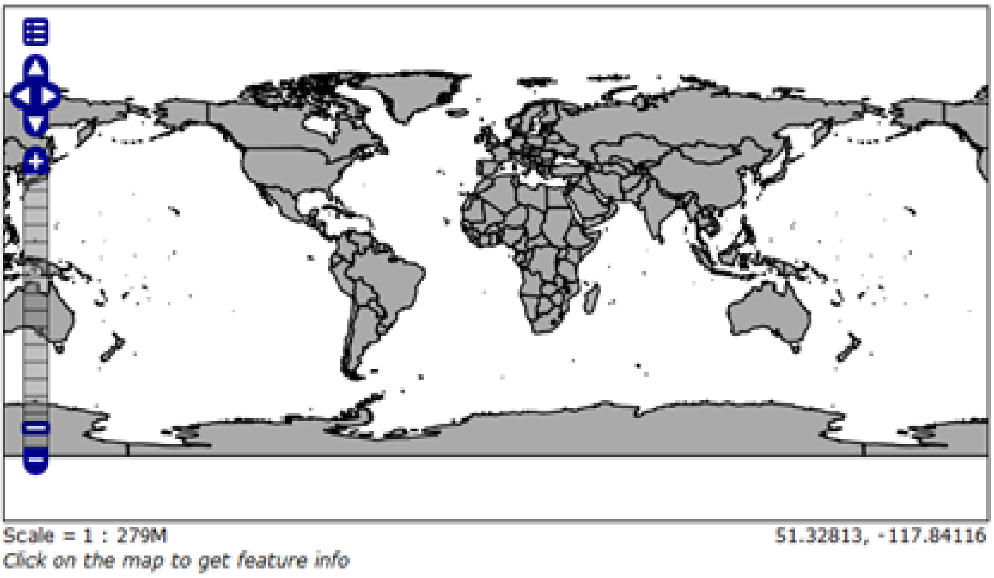


Figure 38: The results of a GetMap request to the WMS 1.3.0. (Source: Owusu-Banahene and Coetzee, 2013).

Figure 39 is the resulting choropleth map showing landlocked and non-landlocked countries after applying the style to the WorldCountries_LandLocked layer. Another SLD file was created and added as a new style. When this was applied to the same WorldCountries_LandLocked layer a new choropleth map showing the population density (per square kilometre) of landlocked countries resulted. Figure 40 shows the choropleth map.

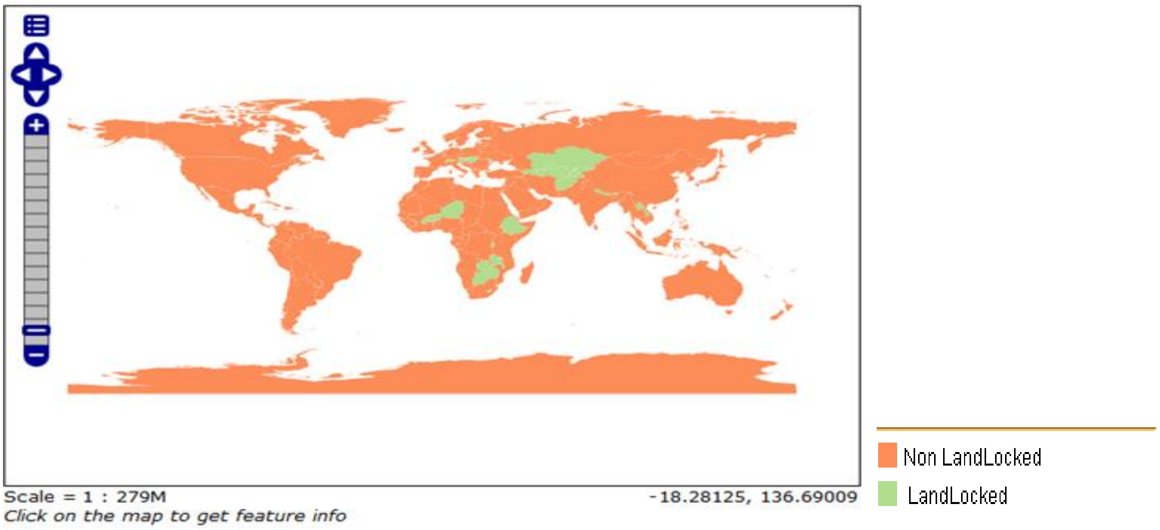


Figure 39: Choropleth map showing landlocked and non-landlocked countries in the world. (Source: Owusu-Banahene and Coetzee, 2013).

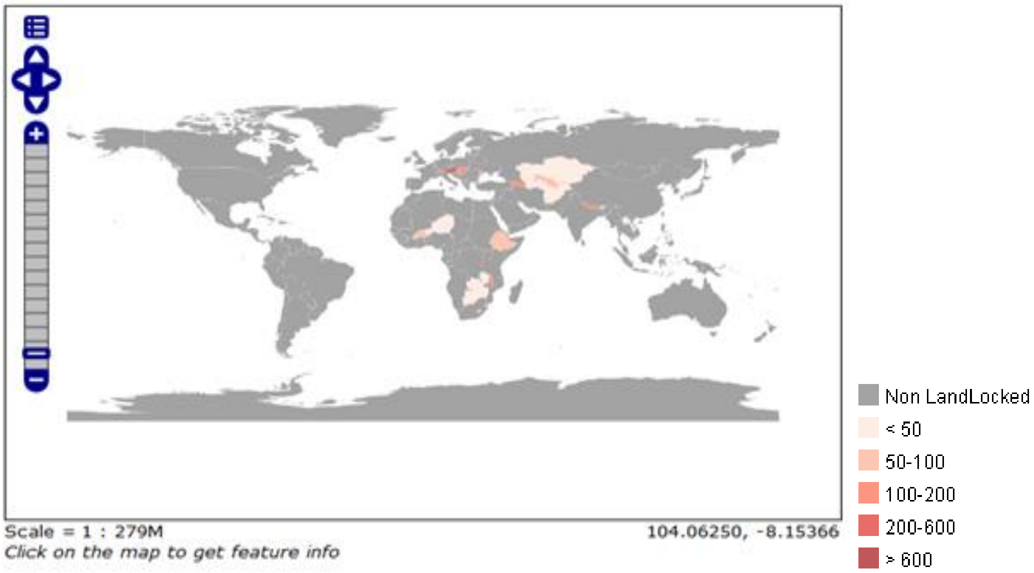


Figure 40: Choropleth map showing population density (per square kilometre) of landlocked countries in the world. (Source: Owusu-Banahene and Coetzee, 2013).

5.2.5 *Creating a Proportional Symbol Map*

This sub-section presents a proportional symbol map showing nominal gross domestic product (GDP) per capita of countries in the world was created. A similar procedure like the one discussed in sub-section 5.2.4. The differences in the approach for creating proportional symbol maps are that a new SPARQL query to DBpedia for the intended nominal GDP per capita of countries are made. The SQL script was also modified. Different sizes of point-based symbol (circle) were applied to distinguish between GDP per capita based classes. The size of a circle for a particular class is proportional to the size of another circle representing another class. The classification was proven on the GDP per capita range. The style (SLD file) created for the proportional symbol map is shown appendix A.6. Figure 41 is the proportional symbols map showing nominal GDP per capita of countries in the world.

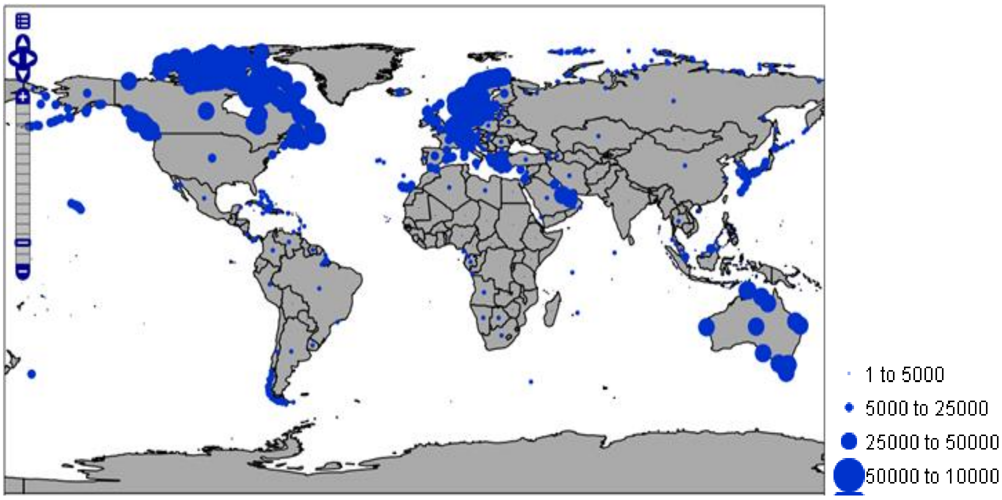


Figure 41: Proportional symbols map showing nominal GDP per capita of countries in the world (Source: Owusu-Banahene and Coetzee, 2013).

5.3 Implementation of GTWS-2: The *Middleware*

Figure 42 shows the implementation of GTWS-2. The OpenLink Virtuoso Universal Server was used as a linked data server. The geometry was stored in a PostGIS. The PostGIS database was connected to a Virtuoso database by a Virtuoso ODBC driver. Tables in the Virtuoso database were migrated by an ODBC data source name (DSN) to PostgreSQL tables with the help of the ESF database migration toolkit[52]. The PostgreSQL tables were linked to geometry in the PostGIS database by unique identifiers and published to GeoServer. GeoServer provided the web map server functionality and support for WMS and SLD.

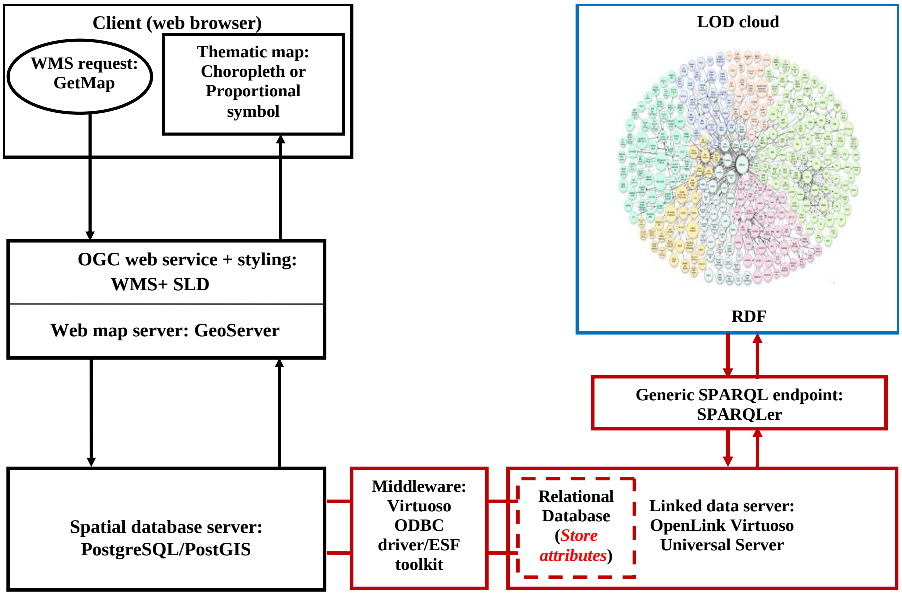


Figure 42: Implementation of GTWS-2: *middleware.*

The proportional symbol and choropleth maps created with the GTWS-2 implementation are shown in Figure 43 and Figure 44. The proportional symbol map in Figure 43 shows the percentage of gross domestic product (GDP) from agriculture per country in 2010, and the choropleth map in Figure 44 shows World Bank statistics of CO_2 emissions per capita per country in 2008. Geometric data of countries in the world was stored in a PostGIS database while attributes (GDP from agriculture per country in 2010) were retrieved from the LOD cloud by executing SPARQL federated queries to the *World Bank Linked Data*[53] SPARQL service (SPARQLer) at http://worldbank.270a.info/sparql. The responses to the queries (attributes) were serialised as CSV and stored as tables in the Virtuoso database.

---

[52] http://www.easyfrom.net/

[53] World Bank Linked Data: http://worldbank.270a.info/about.html

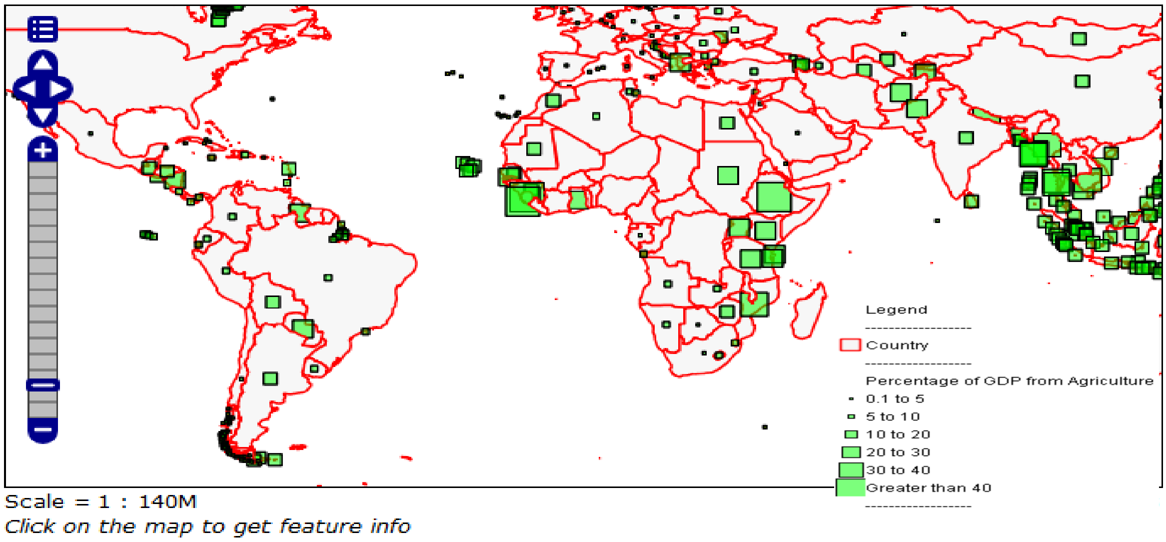


Figure 43: A proportional symbol map showing percentage of GDP from agriculture per country in 2010 created with GTWS-2: the *middleware*.

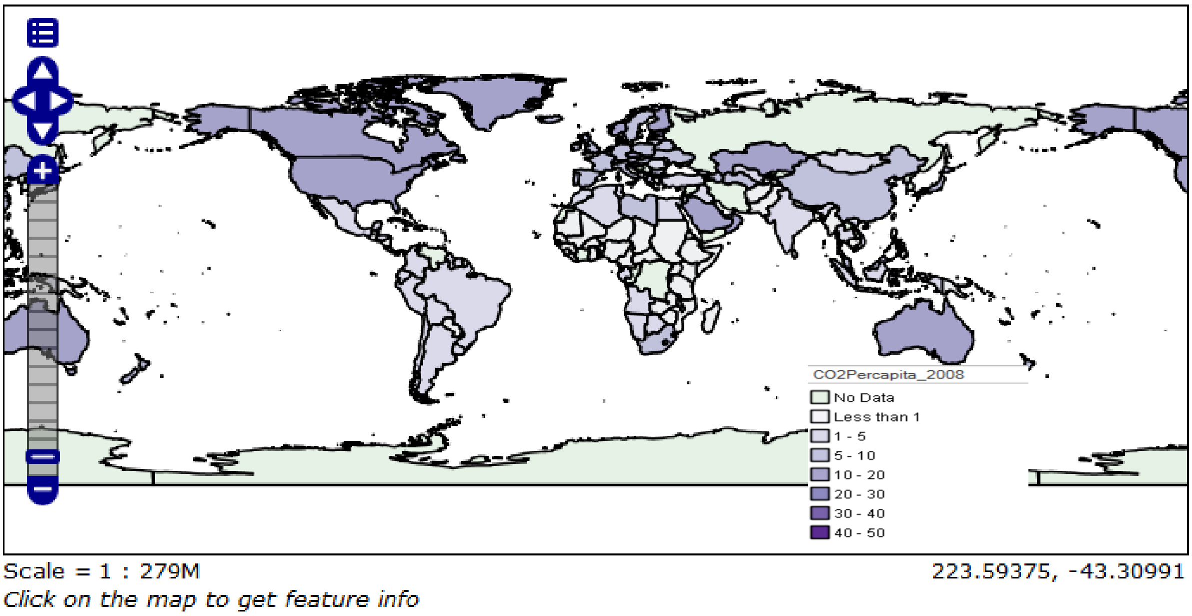


Figure 44: A choropleth map showing CO_2 per capita per country in 2008 created with GTWS-2: the *middleware*.

The tables were migrated into PostgreSQL and linked to the geometry in the PostGIS database by the unique country name. The PostGIS database was published to GeoServer. SLD files styled (normalise, classify and symbolise) the data (global view of the geometry and attribute) in the spatial database server. SLD files were applied as styles to the layers to create the choropleth and proportional symbol maps. Map requests were sent from the browser to the WMS to retrieve the thematic maps.

5.4 Implementation of GTWS-3

The implementation of GTWS-3 requires the creation of *spatial2LOD*. *spatial2LOD* is an *RDF query interface* that enables the application code to process SPARQL and SPARQL-FED queries to a remote SPARQL service. *Apache Jena*[54] (simply Jena) is a Java framework for building Semantic web applications that provides a programmatic environment for RDF and SPARQL among others (Yue *et al*., 2011). The Java framework comprises several application programme interfaces (APIs) for processing RDF (Apache Software Foundation, 2013(a)). The *RDF query interfaces* for GTWS-3 was created using ARQ. ARQ is a query engine application programme interface (API) for Jena that supports the SPARQL (Apache Software Foundation, 2013(b)) and SPARQL-FED for querying remote SPARQL service (Apache Software Foundation, 2013(c)). Since Jena is a Java framework the application and other components of *spatial2LOD* was implemented in Java.

Figure 45 shows the implementation of *spatial2LOD* comprises a lightweight Java application code, an *RDF query interface* and a *loader*. The Java application code queries a remote SPARQL query service in the LOD cloud by an *RDF query interface*. The *loader* provided a Java Database Connectivity (JDBC) to a PostGIS spatial database allowing RDF triples to be integrated with the spatial database. SQL and Spatial SQL queries are executed by the application code to the PostGIS spatial database. GTWS-3 that used *spatial2LOD* to query RDF data from the LOD cloud and integrating it into geometry stored in a PostGIS spatial database as illustrated in Figure 46 is presented.

---

[54] http://jena.apache.org/

For this implementation of *spatial2LOD* the direct mapping of RDF to relational database approach (see section 2.3) was employed to integrate RDF triples into the PostGIS spatial database. Geometric objects representing countries were first stored in a PostGIS along with country names. A SPARQL query was executed programmatically by the *RDF query interface* to retrieve country names and number of ethnic groups of countries from DBpedia. The results set (all the query solution) was formatted as eXtensible Markup Language (XML) based on the SPARQL query result XML format (Hawke, 2013) and cached locally on the server machine.

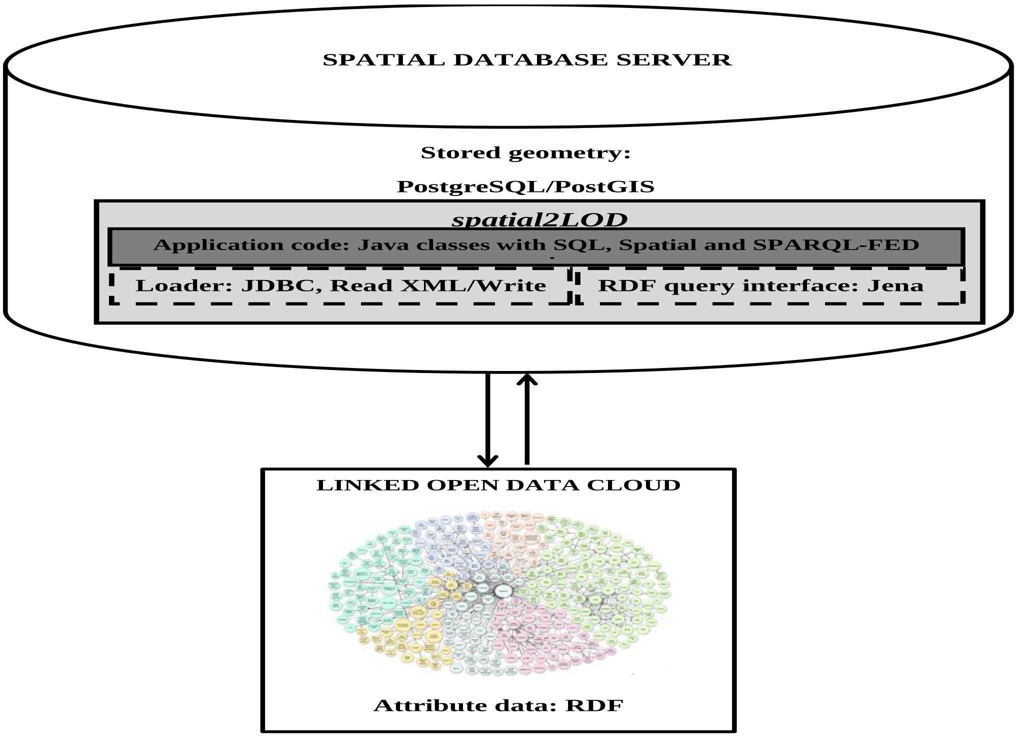


Figure 45: Implementation of spatial database extension to LOD cloud (*spatial2LOD*).

The *loader* creates a table in PostgreSQL and reads the content of the XML into it (table). Each row in this table is a triple. The unique id of the table, in this case the name of the country is the *subject* of the triple. The column headers represent the *predicates* and the column values represent the *objects* (values). After populating the table, the *loader* creates a new table in PostGIS by joining the table containing the geometry of countries with the table containing the triples. The tables are joined by the unique identifiers (country name). Tables in the PostGIS spatial database are published to GeoServer, a web map server.

A client makes a request for a thematic map to GeoServer, that hosts an OCG WMS and SLD. GeoServer adds style to the geometry and attributes data to create a thematic map portrayed to the client by the WMS. SLD files styled (normalise, classify and symbolise) the data in the spatial database server. Figure 47 is a choropleth map (created with GTWS-3) showing human development index (HDI) of various countries in the world using RDF triples from DBpedia.

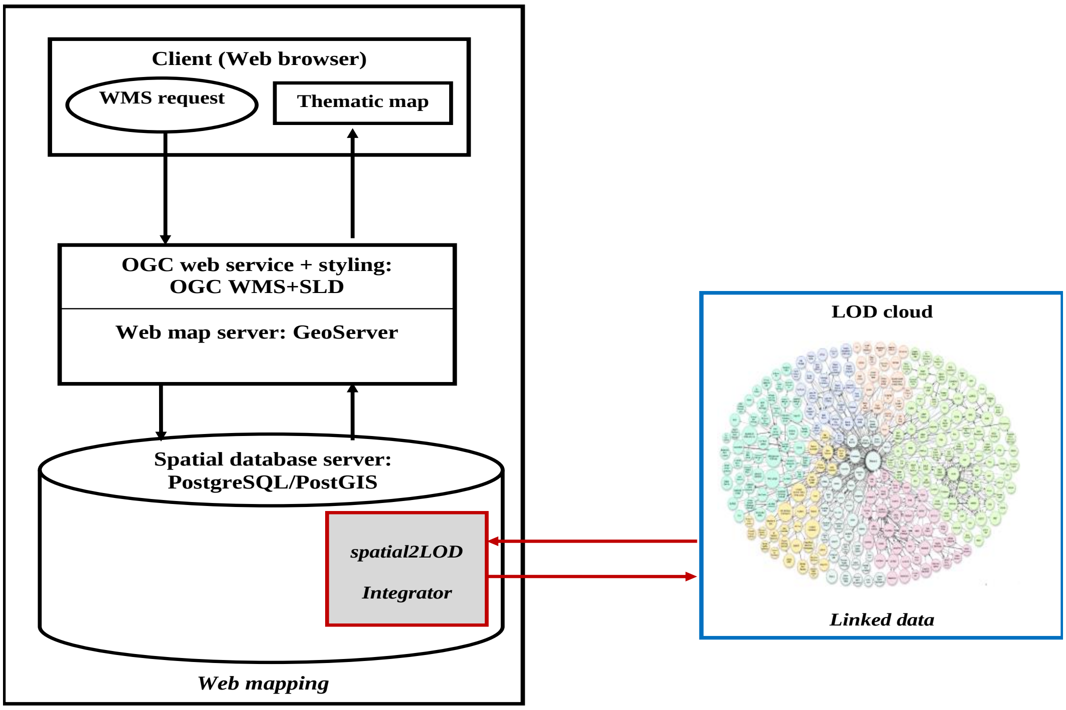


Figure 46: Implementation of GTWS-3: the *extension*.

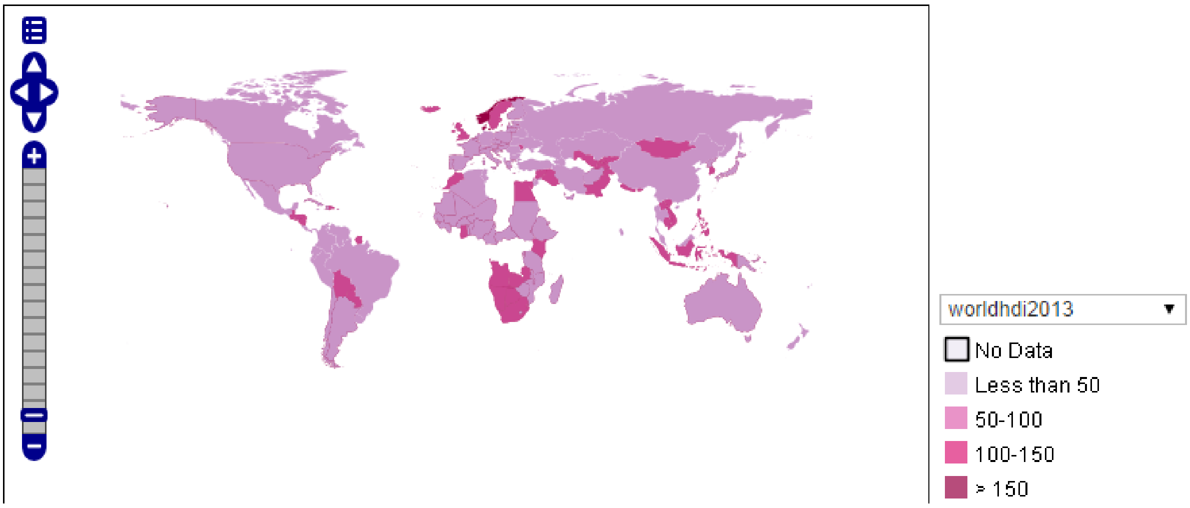


Figure 47: Choropleth map (created with GTWS-3) showing human development index (HDI) of various countries in the world using RDF triples from DBpedia.

Chapter 6: Results and Discussion

6.1 Introduction

The objectives of this chapter are to compare the design options and to critically evaluate the designs and implementations against the evaluation criteria (requirements presented in Chapter 4). Each design options GTWS-1, GTWS-2 and GTWS-3 is evaluated against the requirements in Section 6.2. The evaluation of the implementations of the design options compared to the requirements is presented in section 6.3. The evaluation highlights how the requirements are met by the designs and implementations. In Sections 6.4 and 6.5, the design options and implementations are discussed respectively. The discussions highlights the various ways of creating web thematic maps by combining alphanumeric linked data from the LOD cloud with geometry in a spatial database server. Comparative issues of the GTWS approaches: GTWS-1, GTWS-2 and GTWS-3 are discussed in section 6.5. The comparative issues are the research findings. Analysis and evaluation of the research findings are presented in Section 6.6.

6.2 Evaluation of the Design Options against the Requirements

This section gives an overview of how the requirements are met by each design option as shown in Table 18. In GTWS-1, GTWS-2 and GTWS-3, a client can make a map request from the web map server hosting the service. The first requirement, *a client shall request a thematic map from a web map service* (the client sends a map request to the service), is met by all three design options. A client sends a map request to retrieve a thematic map. The client specifies the theme and thematic mapping technique through style in the map request.

The client can request maps and styles that the service advertises. The requirement: *a client shall specify a theme and a thematic mapping technique in a map request* is met by the design options. The requirement that the *service shall identify the geometry to be used for the theme in a spatial database server* is satisfied by all three design options. In each design option the geometry from the spatial database server are published as layers to the web map server that is hosting the service as pertains generally in web mapping.

Table 18. Evaluation of the design options against the requirements.

Requirement	**GTWS-1**	**GTWS-2**	**GTWS-3**
1. A client shall request a thematic map from a web map service (i.e. the client sends a map request to the service).	map request	map request	map request
2. A client shall specify a theme and a thematic mapping technique in a map request (see steps 2 and 4.1).	Specified as style in a map request	Specified as style in a map request	Specified as style in a map request
3. The service shall identify the geometry to be used for the theme in a spatial database server (see step 3.1).	Geometry is published to service	Geometry is published to service	Geometry is published to service
4. The service shall identify the attributes to be used for the theme in the linked open data cloud (see step 3.2).	Service has no direct access to LOD cloud.	Service has oblique access to LOD cloud through linked data server.	Service has translucent access through extension of the spatial database server.
5. The service shall combine the attributes with the geometry (see step 3.3).	Done by importer.	Done by middleware	Done by spatial database server extension
6. The service shall normalise and classify data as required (see steps 4.1 and 4.2).	Done by styling	Done by styling	Done by styling
7. The service shall apply symbology appropriate for the specified thematic mapping technique (see step 4.4).	Done by styling	Done by styling	Done by styling
8. The service shall create a thematic map image and return it to the client (see step 4.5).	Done by web map server hosting a service	Done by web map server hosting a service	Done by web map server hosting a service

Each design option accesses attributes from the LOD cloud differently. In GTWS-1, the service has no access to LOD cloud. A human agent is required to interact with the LOD cloud. Service has oblique access to LOD cloud through linked data server in GTWS-2. With GTWS-3, the service has translucent access through extension of the spatial database server. The requirement; *the service shall identify the attributes to be used for the theme in the linked open data cloud*, is now met by the design option though not transparent.

Similarly, the requirement that states that *the service shall combine the attributes with the geometry* is met in each design options differently. Attributes are combined with geometry by *importer, linked data server* and *extension to spatial database server* in GTWS-1, GTWS-2 and GTWS-3 respectively. In all three design options, the attributes are combined with the geometry during the process of integration in the spatial database.

In all three design options, the web map server creates the thematic maps according to the map requests from the client. The normalisation, classification and symbology are specified as styles and used by the web map server (hosting the service) to present thematic maps to the client. The following requirements are satisfied: *the service shall normalise and classify data, as required; the service shall apply symbology appropriate for the specified thematic mapping technique;* and *the service shall create a thematic map image and return it to the client*. These three requirements are met but the normalisation, classification and symbology are done with the help of the developer who manually creates the styles.

6.3 Evaluation of the Implementations against the requirements

Table 19 gives an overview of how the requirements are met during implementing each design option. In GTWS-1, GTWS-2 and GTWS-3, a client can request for a thematic map from the web map server (GeoServer) hosting a WMS. The first requirement, *a client shall request a thematic map from a web map service* (the client sends a map request to the service), is met by all three design options. A client sends WMS requests to retrieve a thematic map. The client specifies the theme and thematic mapping technique a style in the WMS request.

The client can request maps and styles that the WMS advertises. The requirement: *a client shall specify a theme and a thematic mapping technique in a map request* is met by all the design options. The requirement that the *service shall identify the geometry to be used for the theme in a spatial database server* is satisfied by all three design options. During implementing each design option the PostGIS tables are published as layers to the web map server (GeoServer) hosting the WMS.

Table 19. Evaluation of the implementations of GTWS-1, GTWS-2 and GTWS-3 against the requirements.

Requirement	GTWS-1	GTWS-2	GTWS-3
1. A client shall request a thematic map from a web map service (i.e. the client sends a map request to the service).	Specified as WMS request.	Specified as WMS request.	Specified as WMS request.
2. A client shall specify a theme and a thematic mapping technique in a map request (see steps 2 and 4.1).	Specified as style in a WMS request.	Specified as style in a WMS request.	Specified as style in a WMS request.
3. The service shall identify the geometry to be used for the theme in a spatial database server (see step 3.1).	PostGIS tables are published to GeoServer (hosting WMS).	PostGIS tables are published GeoServer (hosting WMS)	PostGIS tables are published to GeoServer (hosting WMS)
4. The service shall identify the attributes to be used for the theme in the linked open data cloud (see step 3.2).	OGC WMS has no access to LOD cloud. A human agent is required to interact with the SPARQL end point.	OGC WMS has access to LOD cloud through Virtuoso Universal server.	Service has access through extension (spatial2*LOD*).
5. The service shall combine the attributes with the geometry (see step 3.3).	Done by SQL script.	Done by Virtuoso ODBC driver/ESF toolkit	Done by spatial database server extension (spatial2*LOD*)
6. The service shall normalise and classify data, as required (see steps 4.1 and 4.2).	Done by OGC SLD files	Done by OGC SLD files	Done by styling OGC SLD files
7. The service shall apply symbology appropriate for the specified thematic mapping technique (see step 4.4).	Done by OGC SLD files	Done by OGC SLD	Done by OGC SLD files
8. The service shall create a thematic map image and return it to the client (see step 4.5).	Done by GeoServer hosting a WMS	Done by GeoServer hosting a WMS	Done by GeoServer hosting a WMS

In GTWS-1, the service has no access to LOD cloud. A human agent is required to interact with the SPARQL endpoint. The WMS has oblique access to LOD cloud through Virtuoso Universal Server in GTWS-2. With GTWS-3, the WMS has transluscent access through extension of the spatial database server (*SDSE2LOD*). The requirement; *the service shall identify the attributes to be used for the theme in the linked open data cloud*, is met by the design option though not transparent.

The requirement that states that *the service shall combine the attributes with the geometry* is met differently in each design options. In all three design options, the attributes are combined with the geometry during the process of integration in the spatial database. The web map server (GeoServer) hosting WMS only accesses the global view of the heterogeneous data (geometry and attributes) from the spatial database server (PostGIS). Attributes are linked to geometry by a unique identifier; the country name in the research described in this thesis. If the country names stored with the geometry do not exactly match the names used in the LOD cloud, the corresponding attributes are not included in the table join. This problem can be overcome for country names by using standardised codes for country names as published in ISO 3166-1, Codes representing names of countries and the subdivisions – Part 1: Country codes. For other geographic features (rivers, water bodies, roads, addresses). Standardised codes or names are not essentially published, that could cause a join with a low percentage of matching identifiers. Intervention would subsequently be required to improve the join. For example; , semantic technologies could be used to match the features in the two datasets.

In all three design options, the web map server (GeoServer) hosting WMS creates the thematic maps according to the WMS requests from the client. The normalisation, classification and symbology are specified as OGC SLD files and used by the web map server (hosting the WMS) to present thematic maps to the client. The following requirements are satisfied: *the service shall normalise and classify data, as required; the service shall apply symbology appropriate for the specified thematic mapping technique;* and *the service shall create a thematic map image and return it to the client*. These three requirements are met but the normalisation, classification and symbology are done with the help of the developer who manually creates the SLD files.

6.4 Discussion of the Design Options

The design options GTWS-1, GTWS-2 and GTWS-3 presented in Chapter 4 represent a model in that the spatial object is the starting point, and from there retrieving attributes as linked data, and linking these attributes to corresponding spatial objects by unique identifiers. In this manner, the design options represent a model by that - linked data from the LOD cloud is integrated with geospatial data in a spatial database for thematic mapping through a geospatial web service environment. The linked data from the LOD cloud is treated as if it were ‘just another’ data source in a geospatial web service environment. The three design options follow various approaches to closing the gap between (object-relational) spatial databases and the LOD cloud.

6.4.1 Discussion of GTWS-1: the Importer

The GTWS-1 design option is suitable when linked data is retrieved once-off from a single linked data source in the LOD cloud. Specialised software, such as a linked data server, is not required, but an *importer* has to be developed to integrate the attributes into the spatial database server. The importer is an sql script that creates a table in a spatial database server; copy data in a CSV file into the table; and then joins the table and another table containing the geometry previously stored in the spatial database server. The mapping between the linked data model and the object-relational spatial data model is done by the developer from the SPARQL service. From the web mapping perspective, the linked data model is accessed transparently from the LOD cloud. The conversion from linked model to object-relational spatial model is oblique to the web map server (service). This is similar to converting a shapefile into a spatial database: a practice still prevalent in the geospatial community.

6.4.2 Discussion of GTWS-2: the Middleware

GTWS-2: *the middleware*, the linked data were retrieved from the LOD cloud by a linked data server connected to a spatial database server. GTWS-2 uses an intermediate linked data server. The *middleware* allows linked data from the linked data server to be migrated into a spatial database server. Migration of data from the linked data server into the spatial database server is performed by the middleware. The middleware facilitates that linked data is accessed in a form that can be integrated with the geometry in the spatial database server.

The conversion from linked data to relational data is done by a migration toolkit on the server. From the geospatial web environment point of view, only object-relational data is accessed. Access once again, to linked data and the mapping between linked data model and the object–relational spatial model are oblique to the web map server (service). The linked data was stored on the linked data server and integrated with a spatial database server by the middleware. This is also a familiar approach where attribute data in one database management system is migrated into a spatial database by middleware such as database connectivity. GTWS-1 and GTWS-2 use an approach familiar to the geospatial community to integrate linked data from the LOD cloud without requiring the development of new software. Linked data is accessed and integrated by non-programmatic models.

6.4.3 Discussion of GTWS-3: the Extension

GTWS-3: *the extension* is a spatial database server extension connecting directly to the LOD cloud referred to as *spatial2LOD*. spatial2LOD is a linked data query interface that enables an application code to process SPARQL and SPARQL-FED queries to a remote SPARQL service. The spatial2LOD utilises application programming interfaces or frameworks for building Semantic web applications that provide a programmatic environment for querying linked data from the LOD cloud.

The extension therefore retrieves RDF triples (attribute data) from a remote SPARQL service and integrates them with existing geometry in a spatial database. In this way the LOD cloud itself was treated as another database with attribute data that can be integrated with a spatial database. The uniqueness of GTWS-3 is using an extension to enhance a spatial database server to exploit data in a format 'traditionally' unknown to the spatial database server. From the geospatial web environment perspective, object-relational data and linked data (attributes) are accessed. Access to linked data and the mapping between linked data model and the object–relational spatial model are translucent to the web map server (service) but transparent to the spatial database server. This approach is also similar to the geodatabase model. GTWS-3 uses an approach that requires the development of new extensions (software).

The design options treat linked data from the LOD cloud as if it were one of those data sources in a geospatial web service environment. The opportunities and main hindrances to implementing LOD enabled open source geospatial web services are presented. These designs presented opportunities for developing further research in integrating the LOD cloud with existing geospatial web services.

6.5 Discussion of the Implementations

The implementations use existing web services when they integrate RDF data with a spatial database. The implementations of the GTWS-1, GTWS-2 and GTWS-3 show various options of creating web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server. These implementations provide empirical evidence used to compare and evaluate the designs.

6.5.1 Discussion of the Implementation of GTWS 1: the Importer

GTWS-1: *the importer* presented in section 4.4.1, retrieves linked data from the LOD cloud by executing SPARQL queries directly against a SPARQL endpoint. An sql script, loads the files containing the attributes into a spatial database so that the attributes can be linked to stored geometry and used by the web mapping component. The importer was implemented using SQL script (importer, see Appendix A.4) to accomplish the following: 1. Create a table called LandLocked in LOD. 2. Copy the data in the CSV file into the relation created in

PostgreSQL; 3. Create another table WorldCountries_LandLocked by a JOIN between the two tables World_Countries and LandLocked.

This design option is suitable when the linked data has to be retrieved from a single linked data source in the LOD cloud. Specialised software, such as a linked data server (Virtuoso Universal server), is not required. One limitation of this design option is that the integrator has to be written for each instance of imports of linked data from the temporary storage to the spatial database server.

6.5.2 Discussion of the Implementation of GTWS 2: the Middleware

GTWS-2: *the middleware* retrieves attributes from the LOD cloud by SPARQL federated queries against a generic SPARQL endpoint. Tables in a linked dataserver (the Virtuoso database) were migrated by an ODBC data source name (DSN) to PostgreSQL tables with the help of the ESF database migration toolkit. The ODBC DSN utilised through the ESF migration toolkit acted as the *middleware*. The SPARQL query results (attributes) are stored in one of the RDF serialised formats on the linked data server and integrated with a spatial database server by the middleware. The geometry in the PostGIS spatial database were linked to PostgreSQL tables by unique identifiers and published to GeoServer. Web thematic maps were created by combining the attributes with geometry stored in the spatial database server.

6.5.3 Discussion of the Implementation of GTWS 3: the Extension

GTWS-3: *the extension* is presented in section 4.4.3. GTWS-3 enables a spatial database server to integrate linked data directly from the LOD cloud as RDF triples into non-linked geometric data. The extension is an RDF query interface that enables the application code to process SPARQL and SPARQL-FED queries to a remote SPARQL service using Apache Jena application programme interfaces (APIs) for processing RDF and SPARQL-FED for querying remote SPARQL service. The extension consisted of a lightweight Java application code, an RDF query interface and a loader. The application code queries a remote SPARQL query service in the LOD cloud by an RDF query interface. The loader provided a Java Database Connectivity (JDBC) to a PostGIS spatial database allowing RDF triples to be integrated with the spatial database. SQL and Spatial SQL queries are executed by the application code to a spatial database. GTWS-3 shows how a data tier of a geospatial web service can be enabled to consume linked data directly from the LOD cloud. Unlike GTWS-1 and GTWS-2 that use CSV, GTWS-3 integrates RDF triples thereby keeping the triples intact. GTWS-3 enables a spatial database server to integrate linked data directly from the LOD cloud.

6.6 Discussion of Comparative Issues

The gap between the LOD cloud and web mapping: Linked open data can be accessed through a SPARQL endpoint or RDF dumps. These sources are now outside the open source web mapping environment. Access, data conversion and data integration are some main challenges in creating thematic maps with linked data on-the-fly since SPARQL end point cannot be accessed directly from the web mapping environment. Open source web mapping software and tools have to be modified to use linked open data directly and be able to process SPARQL queries against data in the LOD cloud to overcome these challenges.

Missing data: All three implementations integrate attribute with geometry in a spatial database server. Attributes were linked to geometry by a unique identifier such as a unique country name. There is missing data in cases where the values of identifiers do not match. With GTWS-2 it is challenging if attributes have to be retrieved from multiple sources since those sources may have various representations for country names.

Time: The time it takes to retrieve the attributes from the LOD cloud and convert the linked data model into object-relational spatial model differs. Even though no benchmarks were done, we observed that it took less time to retrieve attributes from a local SPARQL endpoint (GTWS-1), then to retrieve the attributes with SPARQL federated queries from a generic SPARQL service (GTWS-2). GTWS-3 retrieves the attributes and integrates them directly into the spatial database. Future work could do automation and benchmarking for each design option.

Linked data access and integration compared to existing geospatial models: Unlike GTWS-1 and GTWS-2 that use CSV, GTWS-3 integrates RDF triples thereby keeping the link elements intact. In GTWS-1 linked (attribute) data is imported into a spatial database. This can be compared to importing (any) attributes in a CSV file into a spatial database. In GTWS-2 a connection is set up to the linked data server to link attributes from the server to geometry in the spatial database. This is comparable to the geo-relational model where attribute data in a database management system is linked to geometry in another database (or file). GTWS-3 is in some ways comparable to the geodatabase model where attributes and geometry are stored in a single spatial database. The difference is that the attributes are not strictly in object-relational form, but stored as triples in a relational table. The implementations of GTWS-1, GTWS-2 and GTWS-3 show that web mapping and OGC models have to be improved to visualise linked data as thematic maps over the Internet on-the-fly.

Creating thematic maps in real time: Firstly, on-the-fly creation of web thematic maps with GTWS-1, GTWS-2 and GTWS-3 is challenging in the sense that SPARQL queries are now not an integral part of a WMS request. WMS can be improved to handle linked data by making the linked data model and processing an integral part of it. A WMS will be able to advertise a linked data source as one of its data holdings. A client can request a map from a WMS using the advertised linked data source. The WMS is expected to be able to create the map using the linked data.

Secondly, linking the attributes to geometry, normalising, classifying and symbolising the data in real time are challenging. For GTWS-1, an SQL script was written to import the attributes stored in a file into a spatial database server. GTWS-2 implemented its own linked data server that stores attributes retrieved from the LOD cloud. The linked data server was connected to the PostGIS database by a user open database connectivity (ODBC) data source name (DSN). A toolkit has to be run to migrate the attributes from the linked data server to the PostGIS database. In each approach, the normalisation, classification and symbolisation are done with the help of the developer who manually creates the SLD files.

Suitable use case: Each of the three design options can be suitable under a different use case. GTWS-1 is suitable under use case where investment in linked data server technology does not require the prerequisite. GTWS-2 implemented a linked data server that stores attributes retrieved from the LOD cloud. GTWS-3 requires extending a spatial database server. In an incident where attributes have to be retrieved from multiple sources in the LOD cloud, GTWS-2 and GTWS-3 are more suitable because SPARQL federated queries (GTWS-2) can be executed by the generic SPARQL endpoint to remote SPARQL services compared to a local SPARQL endpoint that has been designed for a particular data source. GTWS-3 is even more suitable since the linked data can be retrieved from the LOD cloud and integrated directly into a spatial database.

Unlike the spatial data systems adding RDF support (sub-section 2.8.3), the research described in this research shows how existing geospatial web services can incorporate new data sources without the need to re-develop new data processing and visualisation models from scratch. GTWS-3 requires investment into the development of extension to a spatial data base server but GTWS-1 and GTWS-2 do not. GTWS-3 will be easier to automate compared to GTWS-1 and GTWS-2 since the extension offered support for processing SPARQL federated queries.

In GTWS-1, GTWS-2 and GTWS-3 linked data from the LOD cloud is integrated with geospatial data for thematic mapping in a geospatial web service environment. The spatial object is at the centre and attributes from RDF repositories or SPARQL endpoints are linked to it by a unique identifier. The linked data from the LOD cloud is treated as if it were 'just another' data source in a geospatial web service environment. The three design options follow various approaches to closing the gap between (object-relational) spatial databases and the LOD cloud.

Linked data integration and open source geospatial paradigm: An open source geospatial environment for the implementations proved to be suitable for the following reasons:

1. Open source geospatial software is customizable since its source code is open. Extensions is easier to be developed (as in GTWS-3) by anyone interested.

2. Most open source geospatial software already implements open standards such as OGC web services standards. OGC web services standards are internet/web-based similar to those implemented by the semantic web (LOD cloud) notably, Uniform Resource Identifier/Locator (URI/L), HyperText Transfer Protocol (HTTP), eXs tensible Markup Language (XML) and Multipurpose Internet Mail Extensions (MIME).
3. The same programming languages, software development environment and tools used in developing open source geospatial software are used in developing semantic web technology such as the LOD cloud.

It must be highlighted that the technical knowledge and understanding the intricacies of the linked data technology may limit the development of these LOD enabled open source geospatial applications to apply the Web of Data – a view shared by Dadzie and Rowe (2011).

Main challenges to creating thematic maps from linked data on-the-fly: Data access, conversion and integration are the main challenges using WMS to create thematic maps with linked data on-the-fly. Firstly, a SPARQL endpoint cannot be accessed directly from the geospatial web mapping environment; and second, web map servers cannot consume RDF data directly, and it has to be converted and integrated with a spatial database. A web map server cannot use the linked data model and cannot process queries proven on the linked data model. Simultaneously, web map servers in its current form cannot process the mapping of linked data to object-relational spatial data model. It is possible though, that a web map server is modified to be able to retrieve linked data directly from the LOD cloud. A standard WMS enumerates a finite number of styles in that images can be generated from Layers. These cannot be configured by the end user (Blower *et al.*, 2013).

It is expected that geometry will be available in spatial databases into the foreseeable future and that there is a need to integrate semantic web with existing technologies, such as those described in this chapter. The design and implementations show that harnessing linked data to spatial objects will be beneficial. The work by T. Zhao *et al.* (2008) confirms this need. The purpose of the work is to illustrate how spatial data can be integrated with (new) attributes from the LOD cloud to produce thematic maps. The attributes are retrieved from the LOD cloud through (potentially complicated and intricate) semantic queries – only the result of the semantic query is used on the thematic map. In this way, the benefits of semantic queries are exploited in the Semantic Web itself and the OGC WMS is used to visualise the semantic query results by integrating these with existing geospatial data.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Chapter 7: Conclusion

7.1 Introduction

Summary of results and contributions are presented in this chapter with a view on how the objectives set out were accomplished, the research question answered and solution to the problem found. Recommendations for future research are also discussed in this chapter.

7.2 Summary of Findings

In Chapter 2 the relevant literature and state-of-the-art technologies are reviewed. The review assesses the current knowledge and related work relevant to this research. The following are presented: thematic cartography, ubiquitous cartography, standards based geospatial web services, linked data, spatial data infrastructures, data integration and open source geospatial software. These areas constitute the features of this research from the scientific disciplines of Cartography, GIScience and Computer Science. The chapter reveals the gap between web thematic mapping, standards based geospatial web services, spatial data infrastructures, open source geospatial software and linked data. Additional research is required to show how this gap can be closed. Chapter 2 further provides a basis for identifying the evaluation criteria (requirements) for integration approaches that combine linked data from the LOD with geometric data in a spatial database to produce thematic maps.

Apart from the work by T. Zhao *et al.* (2008) and Jones *et al.* (2014), related work described in Chapter 2 uses only semantic web technology. The research described in this thesis aims to create thematic maps by integrating linked data from the LOD cloud with geospatial data held in a spatial database. This research may benefit Cartography, GIScience and Computer Science especially in using existing geospatial models and linked data models for thematic web mapping. From the perspective SDI, this research will contribute to how open diverse sources of data, such as linked data can be integrated with existing spatial data managed in national and regional SDIs. This research also shows the potential of using open source software in SDIs.

Chapter 3 shows a critical evaluation of state-of-the-art technologies, tools and standards that will be suitable for developing a GTWS in an open data and open source environment. In choosing the state-of-the-art webweb map server suitable for this research, GeoServer is preferred since it showed superiority for most criteria. The criteria can be further enriched with criteria that evaluate level of support for cartographic principles such as scale, normalisation, classification and map projection. The level of support for thematic mapping techniques can also be evaluated.

Chapter 4 concludes on the literature review (described in Chapter 3) to identify the evaluation criteria (requirements) for integration approaches that combine linked data from the LOD with geometric data in a spatial database to produce thematic maps. The chapter presented the designs for the various options of creating web thematic maps by integrating alphanumeric linked data from the LOD cloud with geometry in a spatial database server. This chapter exploit existing cartographic models (see section 2.2 and sub-section 4.3.1.) and geospatial models (see sections 2.3, 2.6, 2.7, 4.2, 4.4 and Chapter 3) in the design of a geospatial web service that creates and visualises thematic maps from linked data models (see sections 2.4, 2.5, 4.2, 4.4). Using the models in designing GTWS-1, GTWS-2 and GTWS-3 could benefit Cartography, GIScience and Computer by showing various choices of integrating linked data models (Computer Science) into existing geospatial models (GIScience) for thematic mapping (Cartography).

In Chapter 5, the implementations of GTWS-1, GTWS-2 and GTWS-3 are presented.

The GTWS-1 design option is suitable when linked data is retrieved once-off from a single linked data source in the LOD cloud. The mapping between the linked data model and the object-relational spatial data model is done by the developer from the SPARQL service. From the web mapping perspective, the linked data model is accessed transparently from the LOD cloud. The conversion from linked model to object-relational spatial model is oblique to the web map server (service). GTWS-2 uses an intermediate linked data server. The conversion from linked data to relational data is done by a migration toolkit on the server. From the geospatial web environment point of view, only object-relational data is accessed. Once more, access to linked data and the mapping between linked data model and the object–relational spatial model are oblique to the web map server (service). GTWS-3 enables a spatial database server to integrate linked data directly from the LOD cloud as RDF triples in the spatial database. While the LOD data is presented as triples, from the geospatial web environment point of view, the data is accessed as if it were object-relational data (translucent access). The mapping between linked data model and the object–relational spatial model is translucent to the web map server (service).

Chapters 4 and 5 provided the empirical evidence used to compare and evaluate the designs and the implementations. The implementations are developed with existing open source geospatial software. The results from these implementations are case studies with actual data input, processing and output showing thematic maps with two different thematic mapping techniques - choropleth and proportional symbols. The implementations and results of GTWS-1, GTWS-2 and GTWS-3 show that the gap between current standards based geospatial web services, SDIs, open source geospatial software, and the linked data. Some improvements to current geospatial web services are required in the design of geospatial web service to visualise linked data as thematic maps over the internet on-the-fly. These improvements are required in the design of geospatial web services (such a semantic based WMS) and in the implementation level (GeoServer's WMS). For instance, the current WMS can be re-designed to respond to linked data based queries. Similarly, web map server such as GeoServer can be modified to publish data based on linked data models as layers to WMS.

Chapter 5 further highlights that there are various approaches to extending current GIS functionality to incorporate linked data from the LOD cloud. This research has shown that there are situations in that existing *non- semantic web technology based applications* need to consume linked data. For instance, increasingly, governments are supporting open data as a means to leverage the potential of publicly funded data, such as the UK Government Open Data; US Government Open Data; and European Environment Agency open data initiatives. Visualizing the vast amounts of data available in the LOD cloud as thematic maps would provide a powerful spatial analysis tool for planning and decision-making. One could do this by using geospatial web services to integrate linked open data with geometry in a spatial database server.

Chapter 6 critically evaluate the designs and implementations against the evaluation criteria (requirements). In the same Chapter 6, it was indicated that geometry will be available in spatial databases into the near future and that there is a need to integrate semantic web with geospatial web services technologies, such as those described in this research. The design and implementations show that harnessing linked data to spatial objects will be beneficial. The attributes are retrieved from the LOD cloud through (potentially complicated and intricate) semantic queries – only the result of the semantic query is used on the thematic map. In this way, the benefits of semantic queries are exploited in the Semantic Web itself and the OGC WMS is used to visualise the semantic query results by integrating these with existing geospatial data.

All the eight requirements were met differently by each design option. In all three design options, the web map server (WMS) creates the thematic maps according to the WMS requests from the client. The normalisation, classification and symbology are specified as OGC SLD files and used by the web map server (hosting the WMS) to present thematic maps to the client the normalisation, classification and symbology are done with the help of the developer who manually creates the SLD files. A standard WMS enumerates a finite number of styles in that images can be generated from layers. The end user cannot configure this. There is the need to improve existing web mapping and OGC technologies that make them query, store and process linked data from the LOD cloud.

It was shown in Chapter 6 that future work could do automation and benchmarking for each design option. Linked data access and integration in this research were compared to existing geospatial models such the geo-relational and geo-database. It was discussed that an open source geospatial environment for the implementations proved to be suitable. Data access, conversion and integration are the main challenges using WMS to create thematic maps with linked data on-the-fly. The generalised use case for each design option was presented in Chapter 6 as follows. Case 1: no investment in linked data server technology (GTWS-1), Case 2: investment in linked data technology (GTWS-2 and GTWS-3), Case 3: attributes have to be retrieved from multiple sources in the LOD cloud (GTWS-2 and GTWS-3), case 4: linked data has to be retrieved from the LOD cloud and integrated directly into a spatial database (GTWS-3).

The research described in this thesis contributes to the future of Cartography, GIScience and Computer Science by way of enabling existing geospatial data processing and visualisation models to accommodate new data sources without developing entirely new models. Use cases will benefit where efficient storage and processing of spatial data and less efficiency is required for storing RDF triples. There are cases where geospatial data has to be combined with a less bulky amount of linked data to create new geoinformation. In such a situation there is no need to store numerous triples and there is no need to add RDF support to existing spatial databases. For example; creating web thematic maps from linked data with GTWS requires only statistical data to be retrieved from the LOD cloud.

This research contributes to bridging the gap between linked data and web thematic maps. The research shows how existing geospatial web services can benefit from the Semantic Web without transforming geospatial web services geospatial data into the semantic form. The research presented in this thesis shows that there are various approaches to extending existing geospatial data processing and visualisation models to incorporate linked data from the LOD cloud.

7.3 Summary of Contributions

The main results from this research and contribution to scientific research in the disciplines of Computer Science, GIScience and Cartography are presented in this sub-section.

7.3.1 Further Research Questions

This research has led to other questions that can be investigated through further research. These questions are explained under Section 7.4. These questions include:

1. *How can the client (web browser) be enhanced to create web thematic maps from linked data?*
2. *What are the novel ways of creating dynamic visualisations with linked data from the LOD cloud using GTWS? How can this process of creating dynamic visualisation from the LOD cloud be automated?*
3. *What are the modifications required to make OGC web services interoperate with linked data technology?*
4. *What are the new requirements for GTWS to integrate linked data from the LOD2 Cloud?*
5. *Can the LOD/LOD2 cloud be a part of SDIs of the future?*
6. *Is there a need to develop entirely new open source geospatial software that can process both linked and non-linked data?*
7. *How can GTWS create thematic maps with data from the Internet of Things?*

7.3.2 Design Options

The three designs were implemented in this research. Each design contributes to understanding a particular use case of combining geospatial web services geospatial data with other data unknown existing geospatial web services. The designs show the options for existing geospatial web services to integrate linked data from the LOD cloud.

7.3.3 Utilising Linked Data from the LOD Cloud in the Same Way as Other Geospatial Data

Geospatial web services now consume ‘traditional geospatial data’ represented in data formats such as has been shown in Table 14. This research has indicated that linked data represented as RDF could be used in geospatial web services geospatial systems just like the other data represented in Table 194. GTWS-1, GTWS-2 and GTWS-3 are showing various ways by that data from the LOD cloud can be combined with geometry in a spatial database server.

7.3.4 Benefits and Drawbacks of Existing Geospatial Models

The research applied existing geospatial models such as OGC web service styling, spatial database systems and web map servers in the designs and implementations of all the GTWS options. In doing so this research brings to the fore the drawbacks of these existing models in the uptake of linked data. For example; this research highlights some improvements that can be made to make these models linked data consumers. Simultaneously, these technologies have benefitted from several years of research and development and are robust. Using these geospatial models in the research described in this thesis stands to benefit from all these years of research and development.

This research brings to the fore some challenges involved in creating thematic maps by combining heterogeneous data – linked data and geospatial data. Existing geospatial models (OGC web services, open source geospatial software, spatial data infrastructure) have to be modified to overcome these challenges, to consume linked open data directly and be able to process SPARQL queries against data in the LOD cloud.

7.3.5 Setting the Stage for Dynamic Visualisation of Linked Data as Web Thematic Maps

The GTWS prototypes investigated in this research set up the stage for dynamically visualising linked data as web thematic maps. This research highlights the requirements and challenges for creating dynamic visualisations of linked data from the LOD cloud as web thematic maps. The LOD cloud keeps growing with data each day and geospatial web services geospatial data will stay with us in the foreseeable future. Use cases will benefit where up-to-date geographical information has to be harnessed from combining data from heterogeneous sources (linked and non-linked).

7.3.6 Potential of Open Source Geospatial Software in the Uptake of Linked Data

The gap between open source geospatial software and the LOD cloud has been presented in section 4.2.1. Open source geospatial software is neither able to use linked data nor connect to the LOD cloud. The relationship can be described as disjoint. This research advances the course of developing open source software and shows its use in consuming linked data from the LOD cloud.

7.3.7 Extending the Current Architecture of Geospatial web service to Integrate Linked Data from the LOD Cloud

This research contributes to the development of the future of internet GIS or Cartography by designing a geospatial web service to create web thematic maps by combining alphanumeric linked data with geometry in a spatial database. The designs illustrate how existing architectures in the internet GIS can be turned into linked data consumers. The designs implemented in the research described in this thesis, bring to the fore, the various approaches to extending existing web mapping architecture to incorporate the LOD cloud.

Considering a client-web map server (web service)-spatial database architecture of a geospatial web service (as discussed in section 4.4), this research highlights the approaches to extending this architecture to integrate linked data from the LOD cloud. GTWS-1 presented in sections 4.4.1 and 5.3 operates by an *integrator* to extend the geospatial web service architecture. In the same light, GTWS-2 discussed in sections 4.4.2 and 5.4 functions through a middleware to integrate linked data from the LOD cloud. As presented in sections 4.4.3, 4.4.4 and section 5.5 GTWS-3 extend the geospatial web service architecture through the spatial database server and web map server extensions respectively. The possibility to extend the client component of geospatial web service architecture will be explored in future work.

7.3.8 Bridging the Gap between Linked Open Data and Web Thematic Mapping

The literature review in Chapter 2 presented a detailed background introduction to the web-based thematic cartography and the gap between linked data and the web thematic maps, that strongly supports the topic of this research. With the conceptualisation, requirements formulation, design options (all in Chapter 4) and the implementations of GTWS, this research has contributed in bridging the gap between web thematic mapping and the LOD cloud.

7.3.9 Integrating Linked Data into Spatial Data Infrastructure

From the SDI perspective, this research contributes to i) understanding open source geospatial software and ii) the integration of linked data into geospatial data sources to create visualisation such as thematic maps. Overall this research seeks to contribute to the technical facet of SDI research. The various SDI initiatives in developing countries, especially in Africa, such as the Namibian Spatial Data Infrastructure (NamSDI), the South African SDI (SASDI) and the SDI in Ghana will benefit from this research.

7.3.10 Ubiquitous Cartography in the Context of LOD Cloud

The concept, development and trends of ubiquitous cartography-‘cartography everywhere at any time’ have been presented in Chapter 2 (section 2.4). This research contributes to the discourse of ubiquitous cartography from the context of integrating the LOD cloud into cartographic based geospatial web services such as GTWS. GTWS also adds to tackling one of the crucial issues in cartography for the next 20 years-designing cartographic products for new platforms (as predicted by Ormeling).

7.4Future Work

7.4.1 Extending the Client to Integrate Linked Data

The various options for creating web thematic maps by combining linked data from the LOD cloud with geometry in a spatial database has been presented in Section 7.3. Additional work is required in extending the client (of a Geospatial web service) such as web browsers, geospatial web clients (*Open Layers*[55], *GeoExt*[56], *GeoExplorer*[57]) to create web thematic

---

[55] http://openlayers.org/

maps from the combination of geospatial web services geospatial data and linked data from the LOD cloud.

7.4.2 Dynamic Visualisation and Automation

As discussed in section 7.3, this research has set the stage for dynamic visualisation of linked data as web thematic maps. More research is required to create the needed automations for GTWS such that web thematic maps from the LOD cloud directly and on-the-fly in real or near real time. *How can this process of creating dynamic visualisation from the LOD cloud be automated?*

7.4.3 Modifying OGC Web Services for Linked Data Consumption

The research described in this thesis applied OGC WMS and SLD to serve and portray thematic maps to a client. The role of OGC technology in creating dynamic visualisations with heterogeneous data-from existing geospatial data and linked data from the LOD cloud cannot be over emphasised. For example; WFS and WCS can be modified in a way that they can be connected directly to the LOD cloud. Additional research into modifying existing OGC web services to accommodate linked data technology will be required. For example; , a WMS request can embed SPARQL (and SPARQL federated) queries to retrieve linked data directly from the LOD cloud and create thematic maps on- the-fly. Added work on GTWS will be required to use GEOSPARQL (Chapter 2, Sub-Section 2.6.5), one of the OGC standards. This research will lead to creating interoperability between OGC technology (web services) and W3C linked data technology such as SPARQL and RDF.

---

[56] http://geoext.org/
[57] http://suite.opengeo.org/docs/latest/geoexplorer/

7.4.4 Integrating Linked Data from the LOD2 Cloud

GTWS now consumes linked data from the LOD cloud. The GTWS research can be extended to consume linked data from the *LOD2*[58]- a large-scale integrating project co-funded by the European Commission and other linked data sources such as this will be desirable.

7.4.5 Making the LOD Cloud a Part of SDIs

The LOD cloud is a potential source of geospatial data that can be used in an SDI. The LOD cloud contains data from government (and other official sources) and non-official sources. Integrating the LOD cloud as part of SDIs will require more research in data quality, data security, policies and standards. Specifically, it is important to evaluate the quality of the LOD before using it to prepare thematic maps.

7.4.6 Developing Entirely New Open Source Geospatial Software

Two approaches were proposed, shown in Figure 21, by that open source geospatial software can connect to the LOD cloud to use linked open data. These approaches are: 1. creating extensions to existing open source geospatial software and 2. developing entirely new software that can use linked and non-linked data. This research used the first approach in the implementation of GTWS-3 (Chapter 5, Section 5.5). Future work on GTWS can use the second proposed approach of creating entirely new open source geospatial software (web map server, desktop, spatial database servers and geospatial libraries) that can consume linked and non-linked data.

7.4.7 Enabling Geospatial Web Services to Accommodate Internet of Things

The *Internet of Things* (IoT) (Ashton, 2009), represents a vision in that the Internet extends into the real world embracing everyday objects (Mattern and Floerkemeier, 2010). Internet of Things (IoT) will comprise billions of devices that can sense, communicate, compute and potentially actuate (A. Zaslavsky, Perera and Georgakopoulos, 2013). Data streams coming

---

[58] http://lod2.eu/Welcome.html

from these devices will challenge the traditional approaches to data management and contribute to the emerging paradigm of big data (A. Zaslavsky *et al.*, 2013). The question is will it be relevant for GTWS to create web thematic maps from the data resulting from the *Internet of Things*?

References

Abadi, D. J., Marcus, A., Madden, S. R., and Hollenbach, K. (2007, September). Scalable semantic web data management using vertical partitioning. In *Proceedings of the 33rd international conference on Very large data bases* (pp. 411-422). VLDB Endowment.

Abbas, S., and Ojo, A. (2013). Towards a Linked Geospatial Data Infrastructure. In *Technology-Enabled Innovation for Democracy, Government and Governance* (pp. 196-210). Springer Berlin Heidelberg.

Abbas, S., and Ojo, A. (2014, January). Applying Design Patterns in URI Strategies--Naming in Linked Geospatial Data Infrastructure. In *System Sciences (HICSS), 2014 47th Hawaii International Conference on* (pp. 2094-2103). IEEE.

Adida, B., Birbeck, M., McCarron, S., and Herman, I. (Eds.). (2013). *RDFa Core (1.1) Syntax and processing rules for embedding RDF through attributes*. Second Edition. W3C Recommendation 22 August 2013. W3C. Retrieved from: http://www.w3.org/TR/rdfa-syntax/

Aditya, T., and Kraak, M.-J. (2007). A search interface for an SDI: implementation and evaluation of metadata visualization strategies. *Transactions in GIS*, *11*(3), pp. 413-435.

Aime, A., and Deoliveria, J. (2008). *Comparing the Performance of Open source Web Map Servers*. Retrieved from: http://presentations.opengeo.org/2008_FOSS4G/

Aime, A. andMcKena, J. (2009, October). WMS Performance Shoot Out. A presentation at *Free and Open source Software for Geospatial (FOSS4G 2009).* Sydney. 20-23 October. Retrieved from: http://2009.foss4g.org/presentations/

Aime, A., and McKena. J. (2010, September). Web Mapping Performance Shoot Out. A presentation at *Free and Open source Software for Geospatial (FOSS4G 2010).* Barcelona. Retrieved from: http://2010.foss4g.org/presentations_show.php?id=3374

Akıncı H., Sesli, F.A., and Doğan, S. (2012). Implementation of a web services-based SDI to control and manage private ownership rights on coastal areas. *Ocean and Coastal Management 67 (2012)*, pp. 54-62.

Alam, A., Khan, L., Thuraisingham, B.(2011). Geospatial Resource Description Framework (GRDF) and security constructs. *Computer Standards and Interfaces, 33* (2011), pp. 35–41. doi:10.1016/j.csi.2010.01.002

Alexander, N., and Ravada, S. (2006, April). RDF object type and reification in the database. In *Data Engineering, 2006. ICDE'06. Proceedings of the 22nd International Conference on* (pp. 93-93). IEEE.

Apache Software Foundation (2013a). *Getting started with Apache Jena*. Retrieved from: http://jena.apache.org/getting_started/index.html.

Apache Software Foundation (2013b). *ARQ-A SPARQL Processor for Jena*. Retrieved from: http://jena.apache.org/documentation/query/index.html

Apache Software Foundation (2013c). *ARQ-Querying Remote SPARQL Service*. Retrieved from: http://jena.apache.org/documentation/query/sparql-remote.html

Apanovich, Z., and Marchuk, A. (2013). Experiments on Using LOD Cloud Datasets to Enrich the Content of a Scientific Knowledge Base. In *Knowledge Engineering and the Semantic Web* (pp. 1-14). Berlin Heidelberg: Springer.

Archer, P., Smith, K., and Perego, A. (Eds.). (2009). *Protocol for Web Description Resources (POWDER): Description Resources*. W3C Recommendation 1September 2009. W3C. Retrieved from: http://www.w3.org/TR/powder-dr/

Arenas, M., Alexandre, B., Prud'hommeaux, E., Sequeda, J. (2012). *A Direct Mapping of Relational Data to RDF*. W3C Recommendation 27 September 2012. W3C. Retrieved from: http://www.w3.org/TR/rdb-direct-mapping/

Ashton, K. (2009). That ‘internet of things’ thing. *RFiD Journal*, *22*, pp. 97-114.

Anselin, L. (2012). From SpaceStat to CyberGIS twenty years of spatial data analysis software. *International Regional Science Review, 35*(2), pp. 131-157.

Auer, S., Demter, J., Martin, M., and Lehmann, J. (2012). LODStats–an extensible framework for high-performance dataset analytics. In *Knowledge Engineering and Knowledge Management* (pp. 353-362). Berlin Heidelberg: Springer.

Auer,T., MacEachren, A.M., McCabe, C., Pezanowski, S., and Stryker, M. (2011). HerbariaViz: A web-based client–server interface for mapping and exploring flora observationdata. *Ecological Informatics 6*(2), pp.93-110.

Ballatore, A., Bertolotto, M., and Wilson, D. C. (2013). Grounding linked open data in WordNet: The case of the OSM semantic network. In *Web and Wireless Geographical Information Systems* (pp. 1-15). Berlin Heidelberg: Springer.

Banerjee, D., Dürst, M.J., McKenna, M., Addison, P., XenCraft, T.T., Trumble, M.,… Noji, K. (Eds.). (2004). *Web services internationalization usage scenarios*. W3C Working Group Note 30 July 2004. W3C. Retrieved from: http://www.w3.org/TR/ws-i18n-scenarios/

Bastin, L., Buchanan, G., Beresford, A., Pekel, J. F., and Dubois, G. (2013). Open source mapping and services for Web-based land-cover validation. *Ecological Informatics*, *14* (2013), pp. 9-16.

Baumann, P. (2010). *OGC® WCS 2.0 Interface Standard – Core* (OGC 09-110r3),Version 2.0.0. OpenGIS® Interface Standard. Open Geospatial Consortium (OGC) Inc.

Bechhofer, S., *et al.* (2013). Why linked data is not enough for scientists. *Future Generation Computer Systems*, *29*(2), pp. 599-611.

Beckett, D., and Broekstra, J. (Eds.). (2013). *SPARQL Query Results XML Format.* Second Edition. W3C Recommendation Recommendation 21 March 2013. W3C. Retrieved from: http://www.w3.org/TR/rdf-sparql-XMLres

Berners-Lee, T. (2006). *Linked data.* Design issues (Personal View). W3C. Retrieved from: http://www.w3.org/DesignIssues/LinkedData.html

Berruetta, D., and Phipps, J. (Eds.) (2008). *Best practice recipe for publishing RDF vocabularies.* W3C Working Group Note 28 August 2008. W3C. Retrieved from: http://www.w3.org/TR/swbp-vocab-pub/

Birgoren, M. and Gumusay, U. (2010). Serving map with OGC standards by network. In A.M.Brovelli., S. Dragicevic .,S. Li ., and B.Veenendaal (Eds). *ISPRS archives*, *XXXVIII 4/W13*, 2010. International Society for Photogrammetry and Remote Sensing.

Bizer, C., Heath, T., and Berners-Lee, T. (2009). Linked data: The story so far. *International Journal on Semantic Web and Information Systems*, *5*(2009), pp.1-22.

Bizer, C., Heath, T., Idehen, K., and Berners-Lee, T. (2008). Linked data on the Web (LDOW2008). *17th international conference on World Wide Web*, International World Wide Web Conference Committee, pp. 1265-1266.

Bizer, C., Jentzsch, A., and Cyganiak, R. (2011). *State of the LOD cloud, 2011*. Retrieved from: http://wifo5-03.informatik.uni-mannheim.de/lodcloud/state/

Blower, J.D., Gemmell, A.L., Griffiths, G.H., Haines, K., Santokhee, A., and Yang, X. (2013). A Web Map Service implementation for the visualization of multidimensional gridded environmental data. *Environmental Modelling and Software, 47* (2013), 218-224

Booth, D., Haas, H., McCabe F., Newcomer, E., Champion, M., Ferris, C., and Orchard, D., (Eds.). (2004). *Web Services Architecture*. W3C Working Group Note 11 February 2004. W3C. Retrieved from: http://www.w3.org/TR/ws-arch/

Bornea, M. A., Dolby, J., Kementsietsidis, A., Srinivas, K., Dantressangle, P., Udrea, O., and Bhattacharjee, B. (2013, June). Building an efficient RDF store over a relational database. In *Proceedings of the 2013 international conference on Management of data* (pp. 121-132). ACM.

Breitman, K.K., Casanova, A.M., and Truszkowski, W. (2010). *Semantic Web: Concepts, Technologies and Applications*. NASA Monographs in Systems and Software Engineering. London: Springer.

Brisaboa, N.R., Luaces, M.R., Places, Á. R., and Seco, D. (2010). Exploiting geographic references of documents in a geographical information retrieval system using an ontology-based index. *Geoinformatica, 14*(3), pp. 307–331.

Calì, A., Calvanese, D., De Giacomo, G., and Lenzerini, M. (2013). Data integration under integrity constraints. In *Seminal Contributions to Information Systems Engineering* (pp. 335-352). Berlin Heidelberg: Springer.

Caquard, S. (2013). Cartography I Mapping narrative cartography. *Progress in Human Geography, 37*(1), pp. 135-144. Doi: 10.1177/0309132511423796

Carroll, J. J., Dickinson, I., Dollin, C., Reynolds, D., Seaborne, A., and Wilkinson, K. (2004, May). Jena: implementing the semantic web recommendations. In *Proceedings of the 13th international World Wide Web conference on Alternate track papers and posters* (pp. 74-83). ACM.

Cartwright, W. (2009). Cartography and Cartographic Communication. In W. Cartwright, G. Gartner, L. Meng and P. M. Peterson (Eds.), *Cartography and Art*. *Lecture Notes in Geoinformation and Cartography*. Berlin Heidelberg: Springer.

Cartwright, W., Gartner, G., and Lehn, A. (2009). Maps and mapping in the eyes of artists and cartographers – experiences from the international symposium on cartography and art. In W. Cartwright, G. Gartner, L. Meng and P. M. Peterson (Eds.), *Cartography and Art. Lecture Notes in Geoinformation and Cartography* (p. 66). Berlin, Heidelberg: Springer.

Castano, S., and De Antonellis, V. (1998). A framework for expressing semantic relationships between multiple information systems for cooperation. *Information Systems, 23(3)*, pp. 253-277.

Castronova, A. M., Goodall, J.L., and Elag, M.M. (2013). Models as web services using the Open Geospatial Consortium (OGC) Web Processing Service (WPS) standard. *Environmental Modelling and Software, 41*(0), pp. 72-83.

Chen, H., Yu, T., and Chen, J. Y. (2013). Semantic web meets integrative biology: a survey. *Briefings in Bioinformatics, 14*(1), pp. 109-125.

Chong, E. I., Das, S., Eadon, G., and Srinivasan, J. (2005, August). An efficient SQL-based RDF querying scheme. In *Proceedings of the 31st international conference on Very large data bases* (pp. 1216-1227). VLDB Endowment.

Coetzee, S. (2009). *An analysis of a data grid approach for spatial data infrastructures*. PhD research, University of Pretoria, Pretoria, South Africa.

Coetzee, S., Harvey, F., Iwaniak, A., and Cooper, A. (2013, August). *Sharing and coordinating SDIs in the age of crowdsourcing and mobile technologies.* In 26th International Cartographic Conference, Dresden, Germany. International Cartographic Association.

Colomo-Palacios, R., Stantchev, V., and Rodríguez-González, A. (2014). Special issue on exploiting semantic technologies with particularization on linked data over grid and cloud architectures. *Future Generation Computer Systems*, *32*(2014), pp.260-262.

Connolly, D. (Ed.) (2007). *Gleaning Resource Descriptions from Dialects of Languages (GRDDL).* W3C Recommendation 11 September 2007. W3C. Retrieved from: http://www.w3.org/TR/grddl/

Cooper, A. K., Rapant, P., Hjelmager, J., Laurent, D., Iwaniak, A., Coetzee, S., ... and Düren, U. (2011,July). *Extending the formal model of a spatial data infrastructure to include volunteered geographical information*. In 25th International Cartographic Conference (ICC), Paris, France: International Cartographic Association (ICA). Retrieved from http://researchspace.csir.co.za/dspace/handle/10204/5212

Cooper, A. K., Moellering, H., Hjelmager, J., Rapant, P., Delgado, T., Laurent, D., ... and Rajabifard, A. (2013). A spatial data infrastructure model from the computational viewpoint. *International Journal of Geographical Information Science*, *27*(6), pp. 1133-1151.

Cooper, A. K., Coetzee, S., Rapant, P., Laurent, D., Danko, D. M., Iwaniak, A., ... and Düren, U. (2014). Exploring the impact of a spatial data infrastructure on value-added resellers and vice versa. In M. Buchroithner, N. Prechtel, and D. Burghardt (Eds.).*Cartography from Pole to Pole* (pp. 395-404). Berlin Heidelberg: Springer.

Crampton, J.W. (2009). Cartography: maps 2.0. *Progress in Human Geography*, *33*(1), pp. 91–100.

Crampton, J. W. (2010). *Mapping: a Critical Introduction to Cartography and GIS*. West Sussex: Wiley-Blackwell.

Curry, E., O'Donnell J., Edward Corry, E., Hasan, S., Keane, M., O'Riain, S. (2013). Linking building data in the cloud: Integrating cross-domain building data using linked data. *Advanced Engineering Informatics, 27*(2), pp. 206-219.

Cyganiak, R. and Jentzsch, A. (2011). *The Linking Open Cloud Diagram*. Retrieved from: http://lod-cloud.net/state/#domains

Dadzie, A. S., and Rowe, M. (2011). Approaches to visualising linked data: A survey. *Semantic Web*, *2*(2), pp. 89-124.

Das, S., Sundara, S., and Cyganiak, R. (2012). *R2RML: RDB to RDF mapping language*. W3C Recommendation September 2012. W3C. Retrieved from: http://www.w3.org/TR/r2rml/

de la Beaujardiere, J. (2006). *OpenGIS® Web Map Service Implementation Specification* (OGC® 06-042), Version 1.3.0. OpenGIS® Implementation Specification. Open Geospatial Consortium Inc.

de Longueville, B. (2010). Community-based geoportals: The next generation? Concepts and methods for the geospatial Web 2.0. *Computers, Environment and Urban Systems*, *34*(4), pp. 299-308,

de Mendonça, A. L. and Delazari, L. S. (2012). Remote evaluation of the execution of spatial analysis tasks with interactive web maps: A functional and quantitative approach. *The Cartographic Journal*, *72*, pp. 7-20.

Díaz, L., Bröring, A., McInerney, D., Libertá, G., and Foerster, T. (2013). Publishing sensor observations into Geospatial Information Infrastructures: A use case in fire danger assessment. *Environmental Modelling and Software*, *48(2013)*, pp. 65-80.

Dobbins, C., Merabti, M., Fergus, P., Llewellyn-Jones, D., and Bouhafs, F. (2013). Exploiting linked data to create rich human digital memories. *Computer Communications,36*(15–16), pp. 1639-1656.

Dodge, M., Kitchin, R., and Perkins, C. (2009). Thinking about maps. In M. Dodge, R. Kitchin, and C. Perkins, (Eds.). *Rethinking Maps* (pp 1-25). London and New York: Routledge.

Durbha, S.S., King, R.L., Shah, V.P., and Youman, N.H. (2009). A framework for semantic reconciliation of disparate earth observation thematic data. *Computers and Geosciences, 35* (2009), pp. 761–773.

Eddy, B. G., and Taylor, D. R. F. (2005). Exploring the concept of cybercartography using the holonic tenets of integral theory. *Modern Cartography Series,4, pp. 35-60*.

Eidgenössische Technische Hochschule Zürich (ETH), Institute of Cartography (2009). *QGIS mapserver*. Retrieved from: http://karlinapp.ethz.ch/qgis_wms/index.html

Ermilov, I., Martin, M., Lehmann, J., and Auer, S. (2013). Linked Open Data Statistics: Collection and Exploitation. In *Knowledge Engineering and the Semantic Web* (pp. 242-249). Berlin Heidelberg: Springer.

European Environment Agency (EEA), 2014. Semantic data service. Available from: http://semantic.eea.europa.eu/

Evangelidis, K., Ntouros, K., Makridis,S., Papatheodorou, C. (2014). Geospatial services in the Cloud. *Computers and Geosciences 63*(0), pp. 116-122.

Fan, M., Fan, H., Chen N., Chen, Z., and Du, W. (2013). Active on-demand service method proven on event-driven architecture for geospatial data retrieval. *Computers and Geosciences, 56*(0), pp. 1-11.

Farnaghi, M., and Mansourian, A. (2013). Disaster planning using automated composition of semantic OGC web services: A case study in sheltering. *Computers, Environment and Urban Systems 41* (2013), pp. 204–218.

Fensel, D. (Ed). (2011). *Foundations for the Web of Information and Services*. Berlin Heidelberg: Springer.

Field K. (2012). ‘Mapping the London 2012 Olympics’, *The Cartographic Journal,49,* pp. 281- 296.
Friedman, M., Levy, A. Y., and Millstein, T. D. (1999). Navigational plans for data integration.

AAAI/IAAI, 1999, 67-73.

Fritz, S., McCallum, I., Schill, C., Perger, C., See, L., Schepaschenko, D., ... and Obersteiner, M. (2012). Geo-Wiki: An online platform for improving global land cover. *Environmental Modelling and Software, 31*(2012), pp.110-123.

Galiotou, E. and Fragkou, P. (2013). Applying Linked Data Technologies to Greek Open Government Data: A Case Study. *Procedia - Social and Behavioral Sciences, 73*(2013), pp. 479-486.

GeoServer (2012). *GeoServer User Manual* (Release 2.1.4). Retrieved from: http://docs.GeoServer.org/stable/en/user/

Gkatzoflias, D., Mellios, G., and Samaras, Z. (2013). Development of a geospatial web service application for emissions inventory spatial allocation proven on open source software tools. *Computers and Geosciences*, 52, 21-33.

Goodchild, M. F., Guo, H., Annoni, A., Bian, L., de Bie, K., Campbell, F., ... and Woodgate, P. (2012). Next-generation digital earth. *Proceedings of the National Academy of Sciences, 109*(28), pp.11088-11094.

Granell, C., Fernández, O.B., and Díaz, L. (2014). Geospatial information infrastructures to address spatial needs in health: Collaboration, challenges and opportunities. *Future Generation Computer Systems, 31*(2014), pp. 213-222.

Granell, C., Schade, S., and Hobona, G. (2010). Linked Data: Connecting Spatial Data Infrastructures. *Geospatial Web Services: Advances in Information Interoperability*, 189.

Giuliani, G., Ray, N., and Lehmann, A. (2011). Grid-enabled Spatial Data Infrastructure for environmental sciences: Challenges and opportunities. *Future generation computer systems, 27*(3), pp. 292-303.

Halevy, A., Rajaraman, A., and Ordille, J. (2006, September). *Data integration: the teenage years*. In Proceedings of the 32nd international conference on Very large data bases (pp. 9-16). VLDB Endowment.

Hall, G. B., Chipeniuk, R., Feick, R. D., Leahy, M. G., and Deparday, V. (2010). Community-based production of geographic information using open source software and Web 2.0. *International Journal of Geographical Information Science, 24*(5), pp. 761-781.

Han, W., Yang, Z., Di, L., and Mueller, R. (2012). CropScape: A Web service based application for exploring and disseminating US conterminous geospatial cropland data products for decision support. *Computers and Electronics in Agriculture*, *84*(2012), pp. 111-123.

Hartig, O., and Langegger, A. (2010). Database perspective on consuming linked data on the Web. *Datenbank Spektrum*, *10*(2), pp. 57–66.

Hartig, O., Mühleisen, H., and Freytag, J-C. (2009, June). Linked data for building a map of researchers. In *Proceedings of 5th Workshop on Scripting and Development for the Semantic Web (SFSW) at the 6th European Semantic Web Conference*, Heraklion, Greece.

Harvey, F., Iwaniak, A., Coetzee, S., and Cooper, A. K. (2012). SDI past, present and future: a review and status assessment. In A. Rajabifard, J. Crompvoets, M. Kalantari and B. Kok (Eds.). *Spatially Enabling Government, Industry and Citizens: Research and Development Perspectives* (pp.23-38). GSDI Association.

Hausenblas, M. (2009). Exploiting Linked Data to Build Web Applications. *IEEE Internet Computing*, *13*(4), pp.68-73.

Hausenblas, M. (2011). Utilising Linked Open Data in Applications. In *Proceedings of Web Intelligence Mining and Semantics*, *WIMS 2011*, ACM 2011, May 25–27, Sogndal, Norway.

Heath, T. (2008). How Will We Interact with the Web of Data? *IEEE Internet Computing*, *12*(5), pp. 88-91.

Heath, T., and Bizer, C. (2011). Linked data: Evolving the web into a global data space. *Synresearch lectures on the semantic web: theory and technology*, *1*(1), pp.1-136.

Herzog, A. (2003). Developing cartographic applets for the Internet. In Peterson, M. P. (Ed.) *Maps and the Internet* (pp. 117-130). Oxford: Elsevier.

Hjelmager, J., Moellering, H., Delgado, T., Cooper, A.K., Rajabifard, A., Rapant, P., …and Martynenko, A. (2008). An initial formal model for spatial data infrastructures. *International Journal of Geographical Information Science*, *22*(11), pp. 1295–1309.

Holmes, C., Doyle, A., and Wilson, M. (2005). Towards a Free and Open source Spatial Data Infrastructure. *Proceedings of the Faraohs to Geoinformatics FIG Working Week 2005 and GSDI, 8.*

Iosifescu-Enescu, I., Hugentobler, M., and Hurni L. (2010).Web cartography with open standards – a solution to cartographic challenges of environmental management. *Environmental Modelling and Software, 25* (9), pp. 988–999.

ISO 3166-1, *Codes for the representation of names of countries and their subdivisions – Part 1: Country codes*. International Organisation for Standardisation (ISO), Geneva, Switzerland

ISO 19109:2005, *Geographic information - Rules for application schema*. International Organization for Standardization (ISO), Geneva, Switzerland

ISO 19125-1:2004, *Geographic information – Simple Feature access, Part 1: Common architecture*. International Organisation for Standardisation (ISO), Geneva, Switzerland

ISO 19128:2005 *Geographic information --Web Map Server Interface*. International Organisation for Standardisation (ISO), Geneva, Switzerland

Janowicz, K. (2012). Observation-Driven Geo-Ontology Engineering. *Transactions in GIS 16*(3), pp. 351–374.

Janowicz, K., Bröring, A. Stasch, C., Schade,S.,Everding T. and Llaves, A. (2013). A RESTful proxy and data model for linked sensor data, *International Journal of Digital Earth*, (6):3, 233-254, DOI: 10.1080/17538947.2011.614698

Janowicz, K., Schade, S., Bröring, A., Keßler, C., Maué, P., and Stasch, C. (2010). Semantic enablement for spatial data infrastructures. *Transactions in GIS*, *14*(2), pp.111-129.

Jones, J., Kuhn, W., Keßler, C., and Scheider, S. (2014). Making the web of data available by web feature services. In *Connecting a Digital Europe Through Location and Place* (pp. 341-361). Springer International Publishing.

Jupp, S., Malone, J., Bolleman, J., Brandizi, M., Davies, M., Garcia, L., ... and Jenkinson, A. M. (2014). The EBI RDF platform: linked open data for the life sciences. *Bioinformatics*, btt765.

Kaivosoja, J., Jackenkroll, M., Linkolehto, R., Weis, M., and Gerhards, R. (2014). Automatic control of farming operations proven on spatial web services. *Computers and Electronics in Agriculture 100* (2014), pp. 110–115.

Kaoudi, Z., and Koubarakis, M. (2013). Distributed RDFS Reasoning Over Structured Overlay Networks. *Journal on Data Semantics*, *2*(4), pp. 189-227.

Kolas, D. (2008). A Benchmark for Spatial Semantic Web Systems. In *International Workshop on Scalable Semantic Web Knowledge Base Systems*.

Kolas, D., and Self, T. (2007). Spatially-augmented knowledgebase. In *The Semantic Web* (pp. 792-801). Berlin Heidelberg: Springer.

König, M., Dirnbeket, J. and Stankovski, V. (2013). Architecture of an open knowledge base for sustainable buildings proven on Linked Data technologies. *Automation in Construction, 35*(0), pp. 542-550.

Keivanloo, I. and Rilling J. (2014). Software trustworthiness 2.0—A semantic web enabled global source code analysis approach. *Journal of Systems and Software*, *89*(0), pp. 33-50.

Kraak, M. J. (2001a). Settings and needs for Web cartography. In Kraak, M. J. and Brown, A. (Eds.). *Web cartography*. *Developments and prospects* (pp. 2-7). London and New York: Taylor and Francis.

Kraak, M. J. (2001b). Trends in cartography, In Kraak, M. J. and Brown, A. (Eds.). *Web cartography*. *Developments and prospects* (pp. 9-19). London, New York: Taylor andFrancis.

Krygier, J. (2003). Geographic information literacy and the WWW, In Peterson, M. P. (Ed.). *Maps and the Internet* (pp. 17-33). Oxford: Elsevier.

Kwakye, M. M. (2011). *A Practical Approach to Merging Multidimensional Data Models* (Master dissertation). University of Ottawa.

Lenzerini, M. (2002, June). *Data integration: A theoretical perspective*. In Proceedings of the twenty-first ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems (pp. 233-246). ACM.

Lieberman, J., Singh, R., and Goad, C. (2007a). *W3C Geospatial Vocabulary*. W3C Incubator Group Report 23October 2007. Retrieved from: http://www.w3.org/2005/Incubator/geo/XGR-geo

Lieberman, J., Singh, R., and Goad, C. (2007b). *W3C Geospatial Ontologies*. W3C Incubator Group Report 23 October 2007. W3C. Retrieved from: http://www.w3.org/2005/Incubator/geo/XGR-geo-ont

Lopez-Pellicer, F.J, Renterı´a-Agualimpia, W., Be´jar, R., Muro-Medrano, P.R., and Zarazaga-Soria, F.J. (2011). Availability of the OGC geoprocessing standard: March 2011 reality check. *Computersand Geosciences* (2011), doi:10.1016/j.cageo.2011.10.023

Lopez, V., Ungerb, C., Cimiano, P., and Motta, E. (2013). Evaluating question answering over linked data. *Web Semantics: Science, Services and Agents on the World Wide Web, 21*(0), pp. 3-13.

Lund, K., Eggen, A., Hadzic, D., Hafsoe, T., and Johnsen, F.T. (2007). Using web services to realize service oriented architecture in military communication networks. *IEEE Communications Magazine 45* (10), pp. 47-53.

Lupp, M. (2007). *Styled Layer Descriptor Profile of the Web Map Service Implementation Specification*(OGC® 05-078r4). Version1.1.0. OGC Implementation Specification. Open Geospatial Consortium Inc.

MacEachren A. M. (1979). The evolution of thematic cartography/a research methodology and historical review. *The Canadian Cartographer* (16)1,pp. 17-33.

Maguire, D. J., and Longley, P.A. (2005). The emergence of geoportals and its role in spatial data infrastructures. *Computers, Environment and Urban Systems*, 29(1), pp. 3-14.

Manola, F., and Miller, E. (Eds.). (2004). *RDF Primer*. W3C Recommendation 10 February 2004. W3C. Retrieved from: http://www.w3c.org/TR/rdf-primer/

Mattern, F., and Floerkemeier, C. (2010). From the Internet of Computers to the Internet of Things. In *From active data management to event-based systems and more* (pp. 242-259). Springer Berlin Heidelberg.

Maué P., Michels, H., and Roth, M. (2012). Injecting semantic annotations into (geospatial) web service descriptions. *Semantic Web (3)*,pp. 385-395.

McGuinness, D. L., and van Harmelen, F. (Eds.). (2004). *OWL Web Ontology Language Overview*. W3C Recommendation 10 February 2004. W3C. Retrieved from: http://www.w3.org/TR/2004/REC-owl-features-20040210/

Mildorf, T. et. al (2014). Open Data Platform for Data Integration,Visualisation and Map Design Bandrova, T. et al. (eds.), *Thematic Cartography for the Society*, Lecture Notes in Geoinformation and Cartography. Switzerland: Springer. DOI: 10.1007/978-3-319-08180-9_1,

Miles, A. and Bechhofer S. (Eds.). (2009). *SKOS Simple Knowledge Organisation System Reference*. W3C Recommendation 18 August 2009. W3C. Retrieved from: http://www.w3.org/TR/skos-reference/

Müller, M. (2006). *Symbology Encoding Implementation Specification* (OGC 05-077r4). Version: 1.1.0 (revision 4). OpenGIS® Implementation Specification. Open Geospatial Consortium Inc.

Nečaský, M., Klímek, J., Mynarz, J., Knap, T., Svátek,V., and Stárka, J. (2014). Linked data support for filing public contracts. *Computers in Industry* (2014).

Nebert, D. (2004). *Developing spatial data infrastructures: The SDI Cookbook*. Retrieved from: http://www.gsdi.org/docs2004/Cookbook/cookbookV2.0.pdf

Neumann, T., and Weikum, G. (2010). The RDF-3X engine for scalable management of RDF data. *The VLDB Journal*, *19*(1), pp. 91-113.

O'Donnell, J., Corry, E., Hasan S., Keane, M., and Curry, E. (2013). Building performance optimization using cross-domain scenario modeling, linked data, and complex event processing. *Building and Environment, 62*(0), pp. 102-111.

Organisation for the Advancement of Structured Information Standards (OASIS) (2004). *The UDDI Technical White Paper*. Retrieved from: https://www.oasis-open.org/committees/uddi-spec/doc/spec/v3/uddi-v3.0.2-20041019.htm.

Open Geospatial Consortium (OGC) (2011). *OGC Reference Model* (OGC 08-062r7), version 2.1. OpenGIS Educational/Informative document. Retrieved from: http://www.opengis.net/doc/orm/2.1 .

Open Geospatial Consortium (OGC) (2012a). *Implementation statistics*. Retrieved from: http://www.opengeospatial.org/resource/products/stats

Open Geospatial Consortium (OGC) (2012b). *All registered products*. Retrieved from: http://www.opengeospatial.org/resource/products

Open Geospatial Consortium (OGC) (2012c). *Implementations by specifications*. Retrieved from: http://www.opengeospatial.org/resource/products/byspecs

Open Geospatial Consortium (OGC) (2014a). *OGC standards and supporting documents*. Retrieved from: http://www.opengeospatial.org/standards

Open Geospatial Consortium (OGC) (2014b). *Implementation statistics*. Retrieved from: http://www.opengeospatial.org/resource/products/stats

Open Knowledge Foundation (2014). *CKAN, the world's leading open source data portal platform*. Retrieved from: http://ckan.org/

Ormeling, F. (2011). Cartography and geoinformation in the 20th and 21st centuries. *Meta–Carto–Semiotics, Journal for Theoretical Cartography*, *4* (2011).

Owusu-Banahene, W., and Coetzee, S. (2012, October). *An evaluation of the suitability of open source web map servers for setting up a geospatial thematic web map service*. GISSA Ukubuzana 2012, Ekurhuleni, South Africa.

Owusu-Banahene, W., and Coetzee, S. (2013). *Integrating linked open data into open source web mapping*. 26th International Cartographic Conference (ICC). Dresden. International Cartographic Associat. (ICA). Retrieved from: http://icaci.org/files/documents/ICC_proceedings/ICC2013/_extendedAbstract/37_proceeding.pdf

Owusu-Banahene, W., and Coetzee, S. (2014). Challenges to Exploiting Linked Data in Cartographic Web Services. Submitted.

Owusu-Banahene, W., Mensah, F., Coetzee, S., Cooper, A. K., Rautenbach, V., Sinvula, K. M., ... and Hippondoka, M. (2013). A Description of Spatial Data Infrastructure Stakeholders in Ghana Using the ICA Model. In H. Onsrud and A. Rajabifard (Eds.). *Spatial Enablement in Support of Economic Development and Poverty Reduction*: *Research, Development and Education Perspectives*, (pp. 63 – 84). GSDI Association.

Papazoglou, M.P. (2008). *Web Services: Principles and Technology* (pp.8, pp. 22-23). Essex: Pearson.

Peng, Z-R., and Tsou (2003). *Internet GIS: distributed geographic information services for the internet and wireless networks* (pp. 196-197). New Jersey: John Wiley and Sons.

Perry, M., and Herring, J. (Eds.). (2012). *OGC GeoSPARQL - A Geographic Query Language for RDF Data* (OGC 11-052r4, 1.0.). OGC® Candidate Implementation Standard, 2. Open Geospatial Consortium Inc.

Peterson, M.P. (2005). Pervasive public map displays. In Taylor D.R.F.(Ed.). *Cybercartography: Theory and practice* (pp 349-371). Amsterdam, San Diego, Oxford, London: Elsevier.

Pohorec, S., Zorman, M., and Kokol, P. (2013). Analysis of approaches to structured data on the web. *Computer Standards and Interfaces*, *36*(1), pp. 256-262.

Prud'hommeaux, E., and Buil-Aranda, C. (2013). *SPARQL 1.1 Federated Query*. W3C Recommendation20130321. W3C. Retrieved from : http://www.w3.org/TR/sparql11-federated-query/

Prud'hommeaux, E, and Seaborne, A. (2008). *SPARQL Query Language for RDF*. W3C Recommendation 20080115. W3C. Retrieved from: http://www.w3.org/TR/rdf-sparql-query/20080115

QGIS. (2013). *QGIS API documentation*. Retrieved from: http://qgis.org/api/2.0/index.html

Rafoss T., Sælid K., Sletten A., Fredrik G. L., and Engravslia L. (2010). Open geospatial technology standards and their potential in plant pest risk management—GPS-enabled mobile phones utilising open geospatial technology standards Web Feature Service Transactions support the fighting of fire blight in Norway. *Computers and Electronics in Agriculture 74*(2), pp. 336-340.

Rajabifard, A., Binns, A., Masser, I., and Williamson, I. (2006). The role of sub-national government and the private sector in future spatial data infrastructures.*International Journal of Geographical Information Science*, *20*(7), 727-741.

Ramsey, P. (2006). uDig desktop application framework. In *Presentation at FOSS4G2006 conference*, Lausanne, Switzerland. Retrieved from: http://2006.foss4g.org/contributionDisplay74db.html?contribId=132andsessionId=44andconfId=1

Ramsey, P. (2007). The state of open source GIS. In *Presentation at FOSS4G 2007 conference,*Vancouver, BC, Canada. Retrieved from: http://refractions.net/expertise/whitepapers/

Rautenbach, V. and Coetzee, S. (2013, August). *Books for SDI Education and Training in South Africa*. In 26th International Cartographic Conference, Dresden, Germany. International Cartographic Association (ICA).

Rautenbach, V., Coetzee, S., and Iwaniak, A. (2013). Orchestrating OGC web services to produce thematic maps in a spatial information infrastructure. *Computers, Environment and Urban Systems*, *37* (2013), pp.107-120.

Rhea, S., Geels, D., Roscoe, T., and Kubiatowicz, J. (2004, June). Handling churn in a DHT. In *Proceedings of the USENIX Annual Technical Conference*(pp. 127-140).

Richmond, E. R., and Keller, P. (2003). Internet cartography and official tourism destination Web sites. In Peterson, M. P.(Ed.). *Maps and the Internet* (pp.77-96). Oxford: Elsevier.

Rohloff, K., Dean, M., Emmons, I., Ryder, D., and Sumner, J. (2007, January). An evaluation of triple-store technologies for large data stores. In *On the Move to Meaningful*

Internet Systems 2007: OTM 2007 Workshops (pp. 1105-1114). Berlin Heidelberg: Springer.

Sae-Tang, A., and Ertz, O. (2007). Towards web services dedicated to thematic mapping. *OSGeo Journal*, *3*(1).

Sagar, B.D. (2010). Visualization of Spatiotemporal Behavior of Discrete Maps by Generation of Recursive Median Elements. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *32*(2), pp.378-384. IEEE Computer Society.

Sahoo, S. S., Halb, W., Hellmann, S., Idehen, K., Thibodeau Jr, T., Auer, S., ... and Ezzat, A. (2009). *A survey of current approaches for mapping of relational databases to rdf*. W3C RDB2RDF Incubator Group Report.

Schmachtenberg, M., Bizer C.,, and Paulheim H. (2014, October). *Adoption of the Linked Data Best Practices in Different Topical Domains*. In 13th International Semantic Web Conference, Trentino, Italy.

Schmachtenberg, M., Bizer C., Bizer, C., Jentzsch, A. and Cyganiak,R. (2014). Linking Open Data cloud diagram. Retrieved from:

Schmidt, M., and Weiser, P. (2012). Web Mapping Services: Development and Trends. In M. P. Peterson (Ed). *Online maps with APIs and web services* (pp. 13-21). Lecture Notes in Geoinformation and Cartography. Berlin Heidelberg: Springer.

Scianna, A. (2013). Experimental studies for the definition of 3D geospatial web services. *Applied Geomatics*, *5*(1), pp. 59-71.

Seaborne, A. (Ed.). (2013a) *SPARQL 1.1 Query Results JSON Format*. W3C Recommendation 21 March 2013. W3C. Retrieved from: http://www.w3.org/TR/sparql/11-results-json.

Seaborne, A. (Ed.). (2013b). *SPARQL 1.1 Query Results CSV and TSV Formats*. W3C Recommendation 21 March 2013. Retrieved from: http://www.w3.org/TR/sparql/11-results-json.

Shanming, W., and Jianjing, S. (2008, December). Ontology-based framework for geospatial web services. In *Information Science and Engineering, 2008. ISISE'08. International Symposium on* (Vol. 2, pp. 107-110). IEEE.

Sinvula, K. M., and Coetzee, S. (2012). Exploring the potential suitability of an SDI model in context of the National Spatial Data Infrastructure (NSDI) of Namibia.

Sinvula, K. M., Coetzee, S., Cooper, A. K., Nangolo, E., Owusu-Banahene, W., Rautenbach, V., and Hipondoka, M. (2014). A Contextual ICA Stakeholder Model Approach for the Namibian Spatial Data Infrastructure (NamSDI). In M. Buchroithner, N. Prechtel, and D. Burghardt (Eds.). *Cartography from Pole to Pole* (pp. 381-394). Berlin Heidelberg: Springer.

Slocum, T. A., McMaster, R. B., Kessler, F. C., and Howard, H. H. (2010). *Thematic Cartography and Geovisualisation.* Upper Saddle, NJ : Pearson Prentice Hall.

Spanos, D. E., Stavrou, P., and Mitrou, N. (2012). Bringing relational databases into the semantic web: A survey. *Semantic Web*, *3*(2), pp. 169-209.

Speckmann, B., and Verbeek, K. (2010). Necklace Maps. *IEEE Transactions on Visualization and Computer Graphics*, *16*(6), pp.881-889. doi: 10.1109/TVCG.2010.180

Stadler, C., Lehmann, J., Höffner, K., and Auer, S. (2012). Linkedgeodata: A core for a web of spatial open data. *Semantic Web*, *3*(4), pp. 333-354.

Steiniger, S., and Hunter, A. J. (2012). Free and open source GIS software for building a spatial data infrastructure. In *Geospatial free and open source software in the 21st century* (pp. 247-261). Berlin Heidelberg: Springer.

Steiniger, S., and Hunter, A. J. (2013). The 2012 free and open source GIS software map–A guide to facilitate research, development, and adoption. *Computers, Environment and Urban Systems*, *39*(2013), pp. 136-150.

Steve, H., and Seaborne, A. (2013). *SPARQL 1.1 Query Language*. W3C Recommendation 21 March 2013. W3C. Retrieved from: http://www.w3.org/TR/sparql11-query/

Stevens, J. (2015). *Bivariate Choropleth Maps: A How-to Guide.* Retrieved from: http://www.joshuastevens.net/cartography/make-a-bivariate-choropleth-map/

Stigmar, H., and Harrie, L. (2011). Evaluation of analytical measures of map legibility, *The Cartographic Journal*, *48*, pp. 41-53.

Sun, X., Shen, S., Leptoukh, G. G., Wang, P., Di, L., and Lu, M. (2012). Development of a web-based visualization platform for climate research using google earth. *Computers and Geosciences*, *47*(2012), pp.160-168.

Tait, G. M. (2005). Implementing geoportals: applications of distributed GIS. *Computers, Environment and Urban Systems*, *29*(1), pp. 33-47.

Taylor, D. R. F. (2005). The theory and practice of cybercartography: An introduction. In Taylor, D. R. F. (Ed.), *Cybercartography: Theory and practice* (1-13). Amsterdam, San Diego, Oxford, London: Elsevier.

The MapServer Team (2012). *MapServer, open source web mapping platform* (Release 6.0.3). Retrieved from: http://mapserver.org/about.html

Tian, Y., and Huang, M. (2012). Enhance discovery and retrieval of geospatial data using SOA and Semantic Web technologies. *Expert Systems with Applications 39*(16), pp. 12522-12535.

Tyner, J. A. (2010). *Principles of map design*. New York : The Guilford Press.

United Kingdom (UK) Government Open Data (2014). Available from: http://data.gov.uk/

United States (US) Government Open Data (2014). Available from: https://www.data.gov/

University of Minnesota (UMN). (2013). *Welcome to MapServer*. Retrieved from: http://mapserver.org/about.html

Villa, P., Molina,R., Gomarasca,M. A. and Roccatagliata E., (2012). Harmonisation requirements and capabilities towards a European spatial data infrastructure (ESDI): the HUMBOLDT protected areas scenario. International Journal of Digital Earth,5(5),pp 417-438

W3C (World Wide Web Consortium) (2007a). *Web Services Description Language (WSDL) 2.0.* Retrieved from: http://www.w3.org/TR/2007/REC-wsdl20-adjuncts-20070626/#_http_binding_default_rule_method .

W3C (World Wide Web Consortium) (2007b). *Simple Object Access Protocol (SOAP) Specifications*. Retrieved from: http://www.w3.org/TR/soap/.

W3C (World Wide Web Consortium) OWL Working Group (2012). *OWL 2 Web Ontology Language* . Second Edition. W3C Recommendation 11 December 2012. W3C. Retrieved from: http://www.w3.org/TR/owl-overview/

W3C (World Wide Web Consortium) 2013a. SPARQL 1.1 Federated Query. W3C Recommendation 21 March 2013. Available from: http://www.w3.org/TR/2013/REC-sparql11-federated-query-20130321/

W3C (World Wide Web Consortium) 2013b. SPARQL 1.1 Overview. W3C Recommendation 21 March 2013. Available from: http://www.w3.org/TR/2013/REC-sparql11-overview-20130321/

W3C (World Wide Web Consortium) 2013c. SPARQL 1.1 Query Language.W3C Recommendation 21 March 2013. Available from: http://www.w3.org/TR/2013/REC-sparql11-query-20130321/

W3C (World Wide Web Consortium) 2013d. SPARQL Query Results XML Format (Second Edition). W3C Recommendation 21 March 2013. Available from: http://www.w3.org/TR/2013/REC-rdf-sparql-XMLres-20130321/

W3C (World Wide Web Consortium) 2013e. SPARQL 1.1 Query Results CSV and TSV Formats. W3C Recommendation 21 March 2013. Available from: http://www.w3.org/TR/2013/REC-sparql11-results-csv-tsv-20130321/.

W3C (World Wide Web Consortium) 2013f. W3C SWEO Linking Open Data community project. Available from: http://www.w3.org/wiki/SweoIG/TaskForces/CommunityProjects/LinkingOpenData

W3C (World Wide Web Consortium) 2014a. RDF 1.1 Concepts and Abstract Syntax. W3C Recommendation 25 February 2014. Available from: http://www.w3.org/TR/rdf11-concepts/

W3C (World Wide Web Consortium) 2014b. Resource Description Framework (RDF): Concepts and Abstract Syntax. W3C Recommendation 10 February 2004. Available from: http://www.w3.org/TR/2004/REC-rdf-concepts-20040210/#section-data-model

Villata, S., Costabello, L., Delaforge, N., and Gandon, F. (2013). A Social Semantic Web Access Control Model. *Journal on Data Semantics*, *2*(1), pp.21-36.

Van Hage, W. R., Wielemaker, J., and Schreiber, G. (2010). The space package: Tight integration between space and semantics. *Transactions in GIS*, *14*(2), pp. 131-146.

Vavliakis, K. N., Grollios, T. K., and Mitkas, P. A. (2013). RDOTE–Publishing Relational Databases into the Semantic Web. *Journal of Systems and Software*, *86*(1), pp. 89-99.

Vidal, J. C., Lama, M., Otero-García, E., and Bugarín, A. (2014). Graph-based semantic annotation for enriching educational content with linked data. *Knowledge-Based Systems*, *55*(2014), pp. 29-42.

Von Hagen, C. (2007). Towards a spatial data infrastructure for Somalia using open source standards, *Journal of Spatial Science*, 52(1), pp. 157-169.

Vretanos P.A. (2010). *OpenGIS Web Feature Service 2.0 Interface Standard* (OGC 09-025r1 and ISO/DIS 19142), Version 2.0.0. OpenGIS Implementation Standard. Open Geospatial Consortium Inc.

Wang, S., Anselin, L., Bhaduri, B., Crosby, C., Goodchild, M. F., Liu, Y., and Nyerges, T. L. (2013). CyberGIS software: a synthetic review and integration roadmap. *International Journal of Geographical Information Science*, *27*(11), pp.2122-2145.

Walker Johnson, G., Gaylord, A. G., Franco, J. C., Cody, R. P., Brady, J. J., Manley, W., ... and Tweedie, C. E. (2011). Development of the Arctic Research Mapping Application (ARMAP): interoperability challenges and solutions. *Computers and Geosciences*, *37*(11), pp. 1735-1742.

Weiss, C., Karras, P., and Bernstein, A. (2008). Hexastore: sextuple indexing for semantic web data management. *Proceedings of the VLDB Endowment*, *1*(1), pp. 1008-1019.

Wiegand, N., Kolas, D., and Berg-Cross, G. (2010). Intersecting semantic web and geospatial technologies, *Transactions in GIS, 14*, pp. 93–95.

Yang, C., Chen, N., and Di, L. (2012). RESTFul based heterogeneous Geoprocessing workflow interoperation for Sensor Web Service. *Computers and Geosciences*, *47*(2012), pp. 102-110.

Yang, P., Cao, Y. and Evans, J. (2007). WMS Performance and Client Design Principles. *Journal of GIScience and Remote Sensing*, 44(4), pp. 320-333.

Yu, S., and Spaccapietra, S. (2010). A knowledge infrastructure for intelligent query answering in location-based services. *Geoinformatica, 14(3), pp.* 14:379–404.

Yue, P., Di, L., Wei, Y., and Han, W. (2013). Intelligent services for discovery of complex geospatial features from remote sensing imagery. *ISPRS Journal of Photogrammetry and Remote Sensing 83(2013),* pp. 151-164.

Yue, P., Gong, J., Di, L., He, L., and Wei, Y. (2011). Integrating semantic web technologies and geospatial catalog services for geospatial information discovery and processing in cyberinfrastructure. *Geoinformatica*, *15*(2), 273-303.

Zaslavsky, A., Perera, C., and Georgakopoulos, D. (2013). Sensing as a service and big data. *arXiv preprint arXiv:1301.0159*.

Zaslavsky, I. (2003). Online cartography with XML. In Peterson, M. P. (Ed.). *Maps and the Internet* (pp. 171-196). Oxford: Elsevier.

Zhao, P., Foerster, T., and Yue, P. (2012). The geoprocessing web. *Computers and Geosciences 47* (10), pp. 3–12.

Zhao, J., Miles, A., Klyne, G., and Shotton, D. (2009). Linked data and provenance in biological data webs. *Briefings in bioinformatics*, *10*(2), pp. 139-152.

Zhao, T., Zhang, C., Wei, M., and Peng, Z. R. (2008). Ontology-based geospatial data query and integration. In *Geographic Information Science* (pp. 370-392). Berlin Heidelberg : Springer.

Appendix A. Implementation of GTWS-1

A.1 SPARQL Query 1

SPARQL query to *retrieve all names population and population density per square kilometer of all landlocked countries in the world.*

```
PREFIX type: <http://dbpedia.org/class/yago/>
PREFIX prop: <http://dbpedia.org/property/>
SELECT ?country_name ?population ?populationDensity
WHERE {
?country a type:LandlockedCountries; rdfs:label?country_name ;
prop:populationEstimate?population;prop:populationDensityKm
?populationDensity.
FILTER (langMatches(lang(?country_name), "EN")).
}
```

A.2 Response to SPARQL Query 1 in RDF/XML

```
<rdf:RDF xmlns:res="http://www.w3.org/2005/sparql-results#"
xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#">
<rdf:Description rdf:nodeID="rset">
<rdf:type rdf:resource="http://www.w3.org/2005/sparql-
results#ResultSet" />
    <res:resultVariable>country_name</res:resultVariable>
    <res:resultVariable>population</res:resultVariable>
    <res:resultVariable>populationDensity</res:resultVariable>
    <res:solution rdf:nodeID="r0">
      <res:binding
rdf:nodeID="r0c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Luxembourg</res:value></res:binding>
      <res:binding
rdf:nodeID="r0c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">509074</res:value></
res:binding>
      <res:binding
rdf:nodeID="r0c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">194</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r1">
```

```
      <res:binding
rdf:nodeID="r1c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Switzerland</res:value></res:binding>
      <res:binding
rdf:nodeID="r1c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">7952600</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r1c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">188</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r2">
      <res:binding
rdf:nodeID="r2c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Tajikistan</res:value></res:binding>
      <res:binding
rdf:nodeID="r2c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">7616000</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r2c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">49</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r3">
      <res:binding
rdf:nodeID="r3c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Swaziland</res:value></res:binding>
      <res:binding
rdf:nodeID="r3c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">1185000</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r3c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">68</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r4">
      <res:binding
rdf:nodeID="r4c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Azerbaijan</res:value></res:binding>
      <res:binding
rdf:nodeID="r4c1"><res:variable>population</res:variable><res:value
```

```
datatype="http://www.w3.org/2001/XMLSchema#int">9165000</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r4c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">106</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r5">
      <res:binding
rdf:nodeID="r5c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">San Marino</res:value></res:binding>
      <res:binding
rdf:nodeID="r5c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">31887</res:value></r
es:binding>
      <res:binding
rdf:nodeID="r5c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">501</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r6">
      <res:binding
rdf:nodeID="r6c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Kazakhstan</res:value></res:binding>
      <res:binding
rdf:nodeID="r6c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">16600000</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r6c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">6</res:value></res:b
inding>
    </res:solution>
    <res:solution rdf:nodeID="r7">
      <res:binding
rdf:nodeID="r7c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Uzbekistan</res:value></res:binding>
      <res:binding
rdf:nodeID="r7c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">29559100</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r7c2"><res:variable>populationDensity</res:variable><res
:value
```

```
datatype="http://www.w3.org/2001/XMLSchema#int">61</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r8">
      <res:binding
rdf:nodeID="r8c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Kyrgyzstan</res:value></res:binding>
      <res:binding
rdf:nodeID="r8c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">5550239</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r8c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">27</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r9">
      <res:binding
rdf:nodeID="r9c0"><res:variable>country_name</res:variable><res:valu
e xml:lang="en">Slovakia</res:value></res:binding>
      <res:binding
rdf:nodeID="r9c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">5445324</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r9c2"><res:variable>populationDensity</res:variable><res
:value
datatype="http://www.w3.org/2001/XMLSchema#int">111</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r10">
      <res:binding
rdf:nodeID="r10c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Hungary</res:value></res:binding>
      <res:binding
rdf:nodeID="r10c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">10014324</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r10c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">107</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r11">
```

```
   <res:binding
rdf:nodeID="r11c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Austria</res:value></res:binding>
   <res:binding
rdf:nodeID="r11c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">8414638</res:value><
/res:binding>
   <res:binding
rdf:nodeID="r11c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">1003</res:value></re
s:binding>
  </res:solution>
  <res:solution rdf:nodeID="r12">
   <res:binding
rdf:nodeID="r12c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Armenia</res:value></res:binding>
   <res:binding
rdf:nodeID="r12c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">3262200</res:value><
/res:binding>
   <res:binding
rdf:nodeID="r12c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">108</res:value></res
:binding>
  </res:solution>
  <res:solution rdf:nodeID="r13">
   <res:binding
rdf:nodeID="r13c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Afghanistan</res:value></res:binding>
   <res:binding
rdf:nodeID="r13c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">29835392</res:value>
</res:binding>
   <res:binding
rdf:nodeID="r13c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">44</res:value></res:
binding>
  </res:solution>
  <res:solution rdf:nodeID="r14">
   <res:binding
rdf:nodeID="r14c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Botswana</res:value></res:binding>
   <res:binding
rdf:nodeID="r14c1"><res:variable>population</res:variable><res:value
```

```
datatype="http://www.w3.org/2001/XMLSchema#int">2029307</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r14c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">3</res:value></res:b
inding>
    </res:solution>
    <res:solution rdf:nodeID="r15">
      <res:binding
rdf:nodeID="r15c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Burundi</res:value></res:binding>
      <res:binding
rdf:nodeID="r15c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">10216190</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r15c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">367</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r16">
      <res:binding
rdf:nodeID="r16c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Ethiopia</res:value></res:binding>
      <res:binding
rdf:nodeID="r16c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">82101998</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r16c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">74</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r17">
      <res:binding
rdf:nodeID="r17c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Moldova</res:value></res:binding>
      <res:binding
rdf:nodeID="r17c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">3559500</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r17c2"><res:variable>populationDensity</res:variable><re
s:value
```

```
datatype="http://www.w3.org/2001/XMLSchema#int">122</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r18">
      <res:binding
rdf:nodeID="r18c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Zimbabwe</res:value></res:binding>
      <res:binding
rdf:nodeID="r18c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">12521000</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r18c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">26</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r19">
      <res:binding
rdf:nodeID="r19c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Lesotho</res:value></res:binding>
      <res:binding
rdf:nodeID="r19c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">2067000</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r19c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">68</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r20">
      <res:binding
rdf:nodeID="r20c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Andorra</res:value></res:binding>
      <res:binding
rdf:nodeID="r20c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">84082</res:value></r
es:binding>
      <res:binding
rdf:nodeID="r20c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">180</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r21">
```

```
      <res:binding
rdf:nodeID="r21c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Liechtenstein</res:value></res:binding>
      <res:binding
rdf:nodeID="r21c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">36010</res:value></r
es:binding>
      <res:binding
rdf:nodeID="r21c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">224</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r22">
      <res:binding
rdf:nodeID="r22c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Vatican City</res:value></res:binding>
      <res:binding
rdf:nodeID="r22c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">832</res:value></res
:binding>
      <res:binding
rdf:nodeID="r22c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">1877</res:value></re
s:binding>
    </res:solution>
    <res:solution rdf:nodeID="r23">
      <res:binding
rdf:nodeID="r23c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Burkina Faso</res:value></res:binding>
      <res:binding
rdf:nodeID="r23c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">15730977</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r23c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">57</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r24">
      <res:binding
rdf:nodeID="r24c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Nepal</res:value></res:binding>
      <res:binding
rdf:nodeID="r24c1"><res:variable>population</res:variable><res:value
```

```
datatype="http://www.w3.org/2001/XMLSchema#int">29331000</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r24c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">199</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r25">
      <res:binding
rdf:nodeID="r25c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Laos</res:value></res:binding>
      <res:binding
rdf:nodeID="r25c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">6500000</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r25c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">27</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r26">
      <res:binding
rdf:nodeID="r26c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Niger</res:value></res:binding>
      <res:binding
rdf:nodeID="r26c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">15730754</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r26c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">12</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r27">
      <res:binding
rdf:nodeID="r27c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Turkmenistan</res:value></res:binding>
      <res:binding
rdf:nodeID="r27c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">5110000</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r27c2"><res:variable>populationDensity</res:variable><re
s:value
```

```
datatype="http://www.w3.org/2001/XMLSchema#int">11</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r28">
      <res:binding
rdf:nodeID="r28c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Bhutan</res:value></res:binding>
      <res:binding
rdf:nodeID="r28c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">708427</res:value></
res:binding>
      <res:binding
rdf:nodeID="r28c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">18</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r29">
      <res:binding
rdf:nodeID="r29c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Rwanda</res:value></res:binding>
      <res:binding
rdf:nodeID="r29c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">11689696</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r29c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">420</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r30">
      <res:binding
rdf:nodeID="r30c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Zambia</res:value></res:binding>
      <res:binding
rdf:nodeID="r30c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">12935000</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r30c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">17</res:value></res:
binding>
    </res:solution>
    <res:solution rdf:nodeID="r31">
```

```
      <res:binding
rdf:nodeID="r31c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Malawi</res:value></res:binding>
      <res:binding
rdf:nodeID="r31c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">14901000</res:value>
</res:binding>
      <res:binding
rdf:nodeID="r31c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">129</res:value></res
:binding>
    </res:solution>
    <res:solution rdf:nodeID="r32">
      <res:binding
rdf:nodeID="r32c0"><res:variable>country_name</res:variable><res:val
ue xml:lang="en">Serbia</res:value></res:binding>
      <res:binding
rdf:nodeID="r32c1"><res:variable>population</res:variable><res:value
datatype="http://www.w3.org/2001/XMLSchema#int">7120666</res:value><
/res:binding>
      <res:binding
rdf:nodeID="r32c2"><res:variable>populationDensity</res:variable><re
s:value
datatype="http://www.w3.org/2001/XMLSchema#int">919</res:value></res
:binding>
    </res:solution>
  </rdf:Description>
</rdf:RDF>
```

A.3 Response to SPARQL Query 1 in CSV Format

```
Country_name,population,populationDensity
Ethiopia,82101998,74
Afghanistan,29835392,44
Uzbekistan,29559100,61
Nepal,29331000,199
Kazakhstan,16600000,6
Burkina Faso,15730977,57
Niger,15730754,12
Malawi,14901000,129
Zambia,12935000,17
Zimbabwe,12521000,26
Rwanda,11689696,420
Burundi,10216190,367
Hungary,10014324,107
Azerbaijan,9165000,106
Austria,8414638,1003
```

```
Switzerland,7952600,188
Tajikistan,7616000,49
Serbia,7120666,919
Laos,6500000,27
Kyrgyzstan,5550239,27
Slovakia,5445324,111
Turkmenistan,5110000,11
Moldova,3559500,122
Armenia,3262200,108
Lesotho,2067000,68
Botswana,2029307,3
Swaziland,1185000,68
Bhutan,708427,18
Luxembourg,509074,194
Andorra,84082,180
Liechtenstein,36010,224
San Marino,31887,501
Vatican City,832,1877
```

A.4 SQL Script for Implementing the *Integrator* in GTWS-1

```
-- Creating Table: "LandLocked"
CREATE TABLE "LandLocked"
   (
   country_rdfslabel character varying(40),
     "prop_populationEstimate" bigint,
     "prop_populationDensityKm" integer
   )
   WITH (
     OIDS=FALSE
   );
ALTER TABLE "LandLocked"
     OWNER TO postgres;
--Loading SPARQL query results (saved as csv file) into PostgreSQL -
--table
   copy "LandLocked" from 'D:\\lod.csv'
   WITH DELIMITER ',' ENCODING 'Latin1';
--Creating a new relation from the join of existing tables DROP
TABLE  public."WorldCountries_LandLocked" ;
   CREATE TABLE public."WorldCountries_LandLocked"  AS
   SELECT
     "World_Countries".gid,
     "World_Countries".country_name,
     "World_Countries".geom,
     "LandLocked".country_rdfslabel,
     "LandLocked"."prop_populationEstimate",
     "LandLocked"."prop_populationDensityKm"
```

```
   FROM
     public."World_Countries"
   LEFT OUTER JOIN public."LandLocked" ON
("World_Countries".country_name="LandLocked".country_rdfslabel);
```

A.5 SLD Codes for Generating Choropleth Map Showing Landlocked and Non-Landlocked Countries

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<StyledLayerDescriptor
version="1.0.0"xmlns="http://www.opengis.net/sld"
xmlns:ogc="http://www.opengis.net/ogc"
xmlns:xlink="http://www.w3.org/1999/xlink"
xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:gml="http://www.opengis.net/gml"
xsi:schemaLocation="http://www.opengis.net/sld
http://schemas.opengis.net/sld/1.0.0/StyledLayerDescriptor.xsd">
     <NamedLayer>
       <Name>landlocked_nonlandlocked</Name>
       <UserStyle>
         <Name> landlocked_nonlandlocked </Name>
         <Title>Landlocked and non-landlocked countries in the
                World</Title>
         <Abstract>A filter that filters landlocked and non-
         landlocked countries</Abstract>
         <FeatureTypeStyle>
          <Rule>
             <ogc:Filter>
               <ogc:PropertyIsNull>
                <ogc:PropertyName>prop_populationDensityKm
                </ogc:PropertyName>
                     </ogc:PropertyIsNull>
             </ogc:Filter>
             <PolygonSymbolizer>
                <Fill>
                 <!-- CssParameters allowed are fill (the color) and
                  fill-opacity -->
                 <CssParameter name="fill">#FC8D59</CssParameter>
                 <CssParameter name="fill-opacity">1</CssParameter>
                </Fill>
             </PolygonSymbolizer>
              </Rule>
             <Rule>
             <Title>&gt; 0</Title>
             <!-- like a linesymbolizer but with a fill too -->
             <ogc:Filter>
```

```
            <ogc:PropertyIsGreaterThan>
              <ogc:PropertyName>prop_populationDensityKm
              </ogc:PropertyName>
             <ogc:Literal>0</ogc:Literal>
            </ogc:PropertyIsGreaterThan>
          </ogc:Filter>
          <PolygonSymbolizer>
             <Fill>
                <!-- CssParameters allowed are fill (the color)
              and fill-opacity -->
                <CssParameter name="fill">#91CF60</CssParameter>
                <CssParameter name="fill-
              opacity">0.7</CssParameter>
             </Fill>
          </PolygonSymbolizer>
        </Rule>
         </FeatureTypeStyle>
    </UserStyle>
 </NamedLayer>
</StyledLayerDescriptor>
```

A.6 SLD Codes for Generating the Proportional Symbols Map Showing Nominal GDP Per Capita of Countries

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<StyledLayerDescriptor version="1.0.0"
    xsi:schemaLocation="http://www.opengis.net/sld
StyledLayerDescriptor.xsd"
    xmlns="http://www.opengis.net/sld"
    xmlns:ogc="http://www.opengis.net/ogc"
    xmlns:xlink="http://www.w3.org/1999/xlink"
    xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance">
  <NamedLayer>
    <Name>World Countries Nominal GDPPerCapita</Name>
    <UserStyle>
      <Title>World Countries Nominal GDPPerCapita</Title>
      <FeatureTypeStyle>
               <Rule>
          <Name>Less Than 5000</Name>
          <Title>1 to 5000</Title>
       <ogc:Filter>
         <ogc:And>
           <ogc:PropertyIsGreaterThanOrEqualTo>
              <ogc:PropertyName>GDPPerCapita_Nominal
              </ogc:PropertyName>
             <ogc:Literal>1</ogc:Literal>
```

```
      </ogc:PropertyIsGreaterThanOrEqualTo>
      <ogc:PropertyIsLessThan>
        <ogc:PropertyName>GDPPerCapita_Nominal
        </ogc:PropertyName>
        <ogc:Literal>5000</ogc:Literal>
      </ogc:PropertyIsLessThan>
    </ogc:And>
  </ogc:Filter>
  <PointSymbolizer>
    <Graphic>
      <Mark>
        <WellKnownName>circle</WellKnownName>
        <Fill>
          <CssParameter name="fill">#0033CC</CssParameter>
        </Fill>
      </Mark>
      <Size>1</Size>
    </Graphic>
  </PointSymbolizer>
</Rule>
<Rule>
  <Name>5000 to 25000</Name>
  <Title>5000 to 25000</Title>
  <ogc:Filter>
    <ogc:And>
      <ogc:PropertyIsGreaterThanOrEqualTo>
        <ogc:PropertyName>GDPPerCapita_Nominal
        </ogc:PropertyName>
        <ogc:Literal>5000</ogc:Literal>
      </ogc:PropertyIsGreaterThanOrEqualTo>
      <ogc:PropertyIsLessThan>
        <ogc:PropertyName>GDPPerCapita_Nominal
        </ogc:PropertyName>
        <ogc:Literal>25000</ogc:Literal>
      </ogc:PropertyIsLessThan>
    </ogc:And>
  </ogc:Filter>
  <PointSymbolizer>
    <Graphic>
      <Mark>
        <WellKnownName>circle</WellKnownName>
        <Fill>
          <CssParameter name="fill">#0033CC</CssParameter>
        </Fill>
      </Mark>
      <Size>5</Size>
    </Graphic>
  </PointSymbolizer>
```

```
     </Rule>
 <Rule>
       <Name>25000 to 50000</Name>
       <Title>25000 to 50000</Title>
       <ogc:Filter>
         <ogc:And>
           <ogc:PropertyIsGreaterThanOrEqualTo>
             <ogc:PropertyName>GDPPerCapita_Nominal
                   </ogc:PropertyName>
             <ogc:Literal>25000</ogc:Literal>
           </ogc:PropertyIsGreaterThanOrEqualTo>
           <ogc:PropertyIsLessThan>
             <ogc:PropertyName>GDPPerCapita_Nominal
           </ogc:PropertyName>
             <ogc:Literal>50000</ogc:Literal>
           </ogc:PropertyIsLessThan>
         </ogc:And>
       </ogc:Filter>
       <PointSymbolizer>
         <Graphic>
           <Mark>
             <WellKnownName>circle</WellKnownName>
             <Fill>
               <CssParameter name="fill">#0033CC</CssParameter>
             </Fill>
           </Mark>
           <Size>10</Size>
         </Graphic>
       </PointSymbolizer>
     </Rule>
<Rule>
       <Name>50000 to 100000</Name>
       <Title>50000 to 10000</Title>
       <ogc:Filter>
         <ogc:And>
           <ogc:PropertyIsGreaterThanOrEqualTo>
             <ogc:PropertyName>GDPPerCapita_Nominal
             </ogc:PropertyName>
             <ogc:Literal>50000</ogc:Literal>
           </ogc:PropertyIsGreaterThanOrEqualTo>
           <ogc:PropertyIsLessThan>
             <ogc:PropertyName>GDPPerCapita_Nominal
             </ogc:PropertyName>
             <ogc:Literal>100000</ogc:Literal>
           </ogc:PropertyIsLessThan>
         </ogc:And>
       </ogc:Filter>
       <PointSymbolizer>
```

```
            <Graphic>
              <Mark>
                <WellKnownName>circle</WellKnownName>
                <Fill>
                  <CssParameter name="fill">#0033CC</CssParameter>
                </Fill>
              </Mark>
              <Size>20</Size>
            </Graphic>
          </PointSymbolizer>
        </Rule>
        <Rule>
          <Name>Above 100000</Name>
          <Title>Greater than 100000</Title>
          <ogc:Filter>
            <ogc:PropertyIsGreaterThanOrEqualTo>
                <ogc:PropertyName>GDPPerCapita_Nominal
                </ogc:PropertyName>
              <ogc:Literal>100000</ogc:Literal>
            </ogc:PropertyIsGreaterThanOrEqualTo>
          </ogc:Filter>
          <PointSymbolizer>
            <Graphic>
              <Mark>
                <WellKnownName>circle</WellKnownName>
                <Fill>
                  <CssParameter name="fill">#0033CC</CssParameter>
                </Fill>
              </Mark>
              <Size>25</Size>
            </Graphic>
          </PointSymbolizer>
        </Rule>
      </FeatureTypeStyle>
    </UserStyle>
  </NamedLayer>
</StyledLayerDescriptor>
```

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

Appendix B. Publications from this Research

B.1 Refereed Journal Publications

Owusu-Banahene, W., and Coetzee, S. (2014). *Three integration styles for combining attributes from the linked open data cloud with geospatial data for web thematic mapping . Submitted*.

B.2 Refereed Conference Proceedings

Owusu-Banahene, W., and Coetzee, S. (2012, October). *An evaluation of the suitability of open source web map servers for setting up a geospatial thematic web map service*. GISSA Ukubuzana 2012, Ekurhuleni, South Africa.

Owusu-Banahene, W., and Coetzee, S. (2013). *Integrating linked open data into open source web mapping.* 26th International Cartographic Conference (ICC). Dresden. International Cartographic Associat. (ICA). Retrieved from: http://icaci.org/files/documents/ICC_proceedings/ICC2013/_extendedAbstract/37_proceeding.pdf

B.3 Book Chapters

Owusu-Banahene, W., Mensah, F., Coetzee, S., Cooper, A. K., Rautenbach, V., Sinvula, K. M., ... and Hippondoka, M. (2013). A Description of Spatial Data Infrastructure Stakeholders in Ghana Using the ICA Model. In H. Onsrud and A. Rajabifard (Eds.). *Spatial Enablement in Support of Economic Development and Poverty Reduction*: *Research, Development and Education Perspectives*, (pp. 63 – 84). GSDI Association.

Sinvula, K. M., Coetzee, S., Cooper, A. K., Nangolo, E., **Owusu-Banahene, W.,** Rautenbach, V., and Hipondoka, M. (2014). A Contextual ICA Stakeholder Model Approach for the Namibian Spatial Data Infrastructure (NamSDI). In M. Buchroithner, N. Prechtel, and D. Burghardt (Eds.). *Cartography from Pole to Pole* (pp. 381-394). Berlin Heidelberg: Springer.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences