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FURTHER DEVELOPMENT OF THE WATER INFORMATION SYSTEM IN THE MUNICIPALITY OF TECOLUCA, EL SALVADOR

Master thesis

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submitted by:

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Abstract

This master's thesis aimed to enhance the existing water information system (WIS) of the municipality of Tecoluca, El Salvador. The local WIS was transformed into a web-based system, based on open source software. Non-geo and geospatial water-related data is now publicly accessible to both authorities and the interested people (population, planners).

It was checked whether the WIS worked properly, existing data was updated, and further data has been generated. The data was then unified (data format, IDs, layer names, data types ...) and related to each other. A database was designed taking into account the available data. The data was inserted into a PostgreSQL database with PostGIS extension.

The existing WIS was further developed, by selecting suitable web-GIS capable components, installing them on the municipal server and setting them up. Subsequently a browser application has been programmed, which provides access to the geographic data of the water information system. The browser application is now a service provided by the municipality and can be accessed on the homepage of the municipality.

Trainings on the usage of the WIS were conducted, as to ensure that the system is used in the future. In addition, a manual was composed, which – in detail – explains the components of the WIS and provides tutorials on how to work with the system.

Kurzfassung

Diese Masterarbeit setzte sich zum Ziel, das bestehende Wasserinformationssystem (WIS) der Gemeinde Tecoluca (El Salvador) zu verbessern. Auf open source Software basierend wurde das lokale WIS zu einem webbasierten System erweitert. Sachdaten und georeferenzierte wasserbezogene Daten sind nun für Behörden und interessierte Personen öffentlich zugänglich (Bevölkerung, Planer).

Es wurde geprüft, ob das bestehende WIS einwandfrei funktionierte, vorhandene Daten wurden aktualisiert und weitere Daten erzeugt. Des Weiteren wurden die Daten vereinheitlicht (Datenformat, IDs, Layer, Datentypen ...) und in Beziehung zueinander gesetzt. Eine Datenbank wurde entworfen, basierend auf den verfügbaren Daten. Die aufbereiteten Daten wurden in eine PostgreSQL Datenbank mit PostGIS Erweiterung eingegeben.

Das bestehende WIS wurde, durch Auswahl geeigneter Web-GIS fähiger Komponenten, weiterentwickelt, auf dem kommunalen Server installiert und eingerichtet. Anschließend wurde eine Browser Applikation programmiert, die den Zugriff auf die geografischen Daten des Wasserinformationssystems ermöglicht. Die Browser Applikation ist jetzt als Dienstleistung der Gemeinde auf deren Homepage verfügbar.

Es wurden Schulungen zur Nutzung des WIS durchgeführt, um sicherzustellen, dass das System auch in Zukunft benutzt wird. Des Weiteren wurde ein Handbuch erstellt, das, im Detail, die Komponenten des WIS erläutert und Anleitungen zur Funktionsweise des Systems bereitstellt.

Layout scheme

In this master's thesis, a lot of abbreviations, technical terms and proper names are introduced. In order to facilitate the reading, a layout scheme was developed and terms were highlighted consistently throughout the thesis.

Type	**Description**	**Examples**
Tables, layers and proper table/layer names	Non-geo and geographic data is stored in database tables. If only geographic data is meant, tables can also be layers (e.g. in GeoServer and QGIS). Proper names of tables and layers are also highlighted.	***Layer*** ***table*** ***table/layer water_source***
Column and proper column names	Tables and layers consist of columns, which must be named.	<u>*column*</u> <u>*id_water_source*</u>
Database	Terms associated with database design.	**entity** **primary key** **relation**
SQL commands	SQL commands enable database manipulations.	INSERT UPDATE DELETE
Data formats	Various technologies (GIS, GNSS) require different data formats for storing or transferring data.	**CSV** **GPX** **WKT**
Data and geometry types	Data types concerning databases and geometry types used in GIS are highlighted.	<u>integer</u> <u>multi linestring</u>
Users	Users of database or GeoServer.	*postgres*
Proper names other than tables/layers or columns	Additional proper names mostly regarding to setting up the database and GeoServer were introduced.	<u>**GIS_TECOLUCA_SV**</u> <u>**websig**</u>
Programmes, web services, programming or markup languages	A lot of different programmes, web services and programming and markup languages were used.	*OpenStreetMap* *PostgreSQL* *SLD*

Abbreviations

ANDA	Administración Nacional de Acueductos y Alcantarillados National Administration for Water and Sanitation Services
CFU	Colony Forming Units
CMS	Content Management System
CNR	Centro Nacional de Registros National Registry Center
CRS	Coordinate Reference System
CSS	Cascading Style Sheet
CSV	Comma-separated Values
DBMS	Database Management System
DIGESTYC	Dirección General de Estadística y Censos General Directorate for Statistics and Census
EHPM	Encuesta de Hogares de Propósitos Múltiples Survey of Households regarding multiple Sectors
EPSG	European Petroleum Survey Group Geodesy
ERM	Entity Relationship Model
GIS	Geographic Information System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPX	GPS Exchange Format
HTML	Hypertext Markup Language
LAN	Local Area Network
MARN	Ministerio de Medio Ambiente y Recursos Naturales Ministry of the Environment and Natural Resources
MINSAL	Ministerio de Salud Ministry of Health
OGC	Open Geospatial Consortium
OSM	OpenStreetMap
POI	Point of Interest
QGIS	Quantum GIS
SDK	Software Development Kit
SLD	Style Layer Decriptor
SQL	Structured Query Language
SRID	Spatial Reference Identifier
UCA	Universidad Centroamericana José Simeón Cañas Centralamerican University José Simeón Cañas
UML	Unified Modeling Language
VPS	Virtual Private Server
WFS	Web Feature Service
WKB	Well-Known Binary Format
WKT	Well-Known Text Format
WIS	Water Information System
WMS	Web Map Service

1. Introduction

Salvador is a small but densely populated country in Central America. The population density reaches 304 people/km² (DIGESTYC, 2015). The municipality of Tecoluca reflects this development in its settlement structure: there are over a 100 communities scattered in the municipality, many of which can be characterized as rural. This results in uncoordinated construction of catchments of springs, drilled wells and water tanks, some of which are in poor condition and sometimes not well administered.

Tecoluca suffers from questionable drinking water quality. When measuring in the field it could be seen that both wells and spring tappings were in bad condition and lacked of regular maintenance. Water quality samples show that the water of most of the water resources is indeed not suitable for drinking without proper treatment. The overall bad condition of the water distribution system is probably contributing to the problem. Water treatment, such as chlorination, is rarely applied. The untreated water consumption can lead to serious diseases (WHO, 2011).

Locals reported that the yield of wells and springs has declined in the past years. However, because of the lack of data this cannot be verified. It is likely that the impact of climate has hit El Salvador already. Hence the need of implementing monitoring programs to have reliable data is indispensable.

INTERSOL, an Austrian based NGO, has developed projects to improve the livelihood in the region since 2000 (INTERSOL, 2016). In 2015 two students of the University of Natural Resources and Life Sciences, Vienna conducted their master's theses in Tecoluca in cooperation with INTERSOL and the municipality of Tecoluca. Their goal was to implement a Geographic Information System (GIS), which provides information of the water parameters in geospatial context.

A GIS is a useful tool for better water management as it enables authorities to make decisions based on actually available data. It is possible to geographically illustrate the existing water resources and link this data with technical data, such as water quality, water quantity and many more. A possible scenario: Determine the location of possible future water resource catchments by analyzing data of the GIS.

An open GIS can provide information of public interest. The population, planners or people with special interest in the region can use the information and the following questions can be addressed: Where is the next water resource? What are the quality parameters and do they comply with laws and standards?

This master's thesis relies on the collected data and the already existing GIS of the previous work. During a 4 months stay the practical part of the project was conducted with the help of the municipality of Tecoluca and the Universidad Centroamericana José Simeón Cañas (UCA). The water information system has been enhanced and more data was collected and implemented into the GIS.

2. Objectives

2.1 Main objective

The overall goal of this master's thesis is the enhancement of the existing GIS based water information system at the municipal office in order to improve the management of the water resources in Tecoluca. The existing GIS was to be converted into a web-GIS, which enables the public to access certain information about the water resources online. The web-GIS should further be secure, capable of handling multiple parties, and most importantly it should only use open source and/or free (non-commercial) software. It should facilitate remote data access for different parties.

At the beginning of the process the following questions were asked:

- How can a web-based GIS system be implemented?
- Which software can be used that fulfils the mentioned requirements?

Further steps included creation of data (e.g. measuring of water quality parameters at water source sites), maintaining the existing water information system, analyzing the data and storing it. It was important to assure that the water information system is actually being used after the departure of the author which was achieved by trainings in the usage of the web-GIS.

The water information system should also have the ability to be extended, thus making it a "municipal information system", which can be fed also with other information about the municipality, such as waste management or regional planning.

2.2 Specific objectives

The fieldwork of the master's thesis was divided into three specific objectives:

- Improvement of data base.
- Further development of the existing water information system.
- Improvement of usability of the water information system.

3. Fundamentals

3.1 Basics of Tecoluca

3.1.1 General information

Location

Tecoluca is a municipality in the Central American country El Salvador (see Figure 1). The only neighboring countries are Guatemala and Honduras.

Figure 1: El Salvador and Tecoluca (Universidad de El Salvador, 2015).

Tecoluca is situated in the department of San Vicente. It is surrounded by two main cities: San Vicente, capital of the department of San Vicente and Zacatecoluca, capital of the department of La Paz. The river Lempa forms the natural boundary to the east and the Pacific Ocean to the south (see Figure 2). Tecoluca covers an area of 284.65 km², making it the fifth biggest municipality of El Salvador (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

Figure 2: Tecoluca, its surrounding municipalities and river Lempa (Universidad de El Salvador, 2015).

Demography and settlement structure

As of 2014 the population of El Salvador approximately reached 6.4 million people. Considering the small size of the country (approx. 21,000 km^2), the population density is very high. On average 304 people inhabit one square kilometer of El Salvador (DIGESTYC, 2015). The population density of El Salvador outreaches its neighboring countries significantly (UNICEF, 2014).

The department of San Vicente in which the municipality of Tecoluca is located, provides more space for its inhabitants. Table 1 shows that only 178,216 people inhabit the department of San Vicente resulting in a population density of 151 people/km^2 (DIGESTYC, 2015). The number of urban and rural population is almost balanced. 49.3% live in urban areas (UNICEF, 2014).

Approximately 30,000 people live in the municipality of Tecoluca (see Table 1). According to the most recent census only around 3,000 people or 10% (see Figure 3) live in the urban zone of Tecoluca town (MINSAL, 2015a). The municipality can be characterized as rural. There are slightly more women (51%) than men (see Figure 3). This applies to both, the rural communities and Tecoluca town.

Table 1: Summary of population, size and population density on different scales. (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002; MINSAL, 2015a; DIGESTYC, 2015)

	Population	**Size**	**Population density**
	persons	km²	persons/km²
El Salvador	6,401,415	21,040.79	304
San Vicente	178,216	1,184.02	151
Tecoluca	29,550	284.65	104

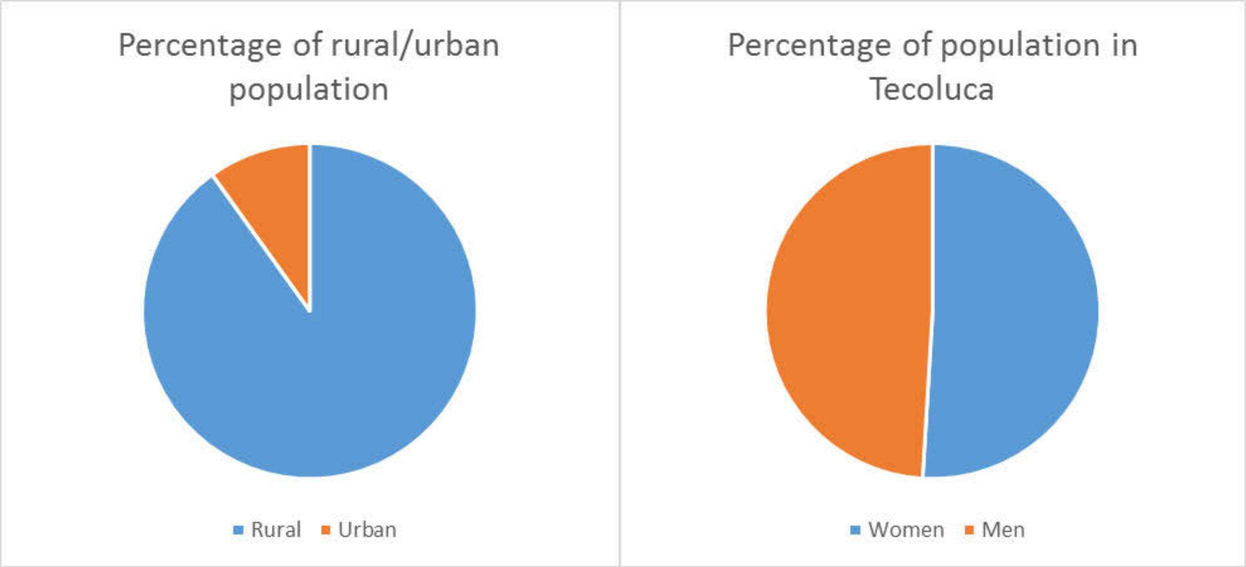

Figure 3: Demographics: Percentage of rural and urban population in Tecoluca and percentage of population in Tecoluca (MINSAL, 2015a).

Figure 4 shows the municipal area of Tecoluca. The size of the points correspond to the population size of the respective communities. There are over a 100 communities in Tecoluca, most of which have less than 250 inhabitants. The biggest communities are in the northern part along the asphalted road that connects the two main cities San Vicente and Zacatecoluca (see also Figure 2). In the statistics these points are regarded as the urban areas within the municipality Tecoluca. There is a high density of small to middle sized communities from west to east in the middle part of Tecoluca along the asphalted road (the so-called Litoral). Smaller communities are only reachable by non-asphalted roads. There are also communities which are not actually within the borders of the municipality but they are administered by the local government.

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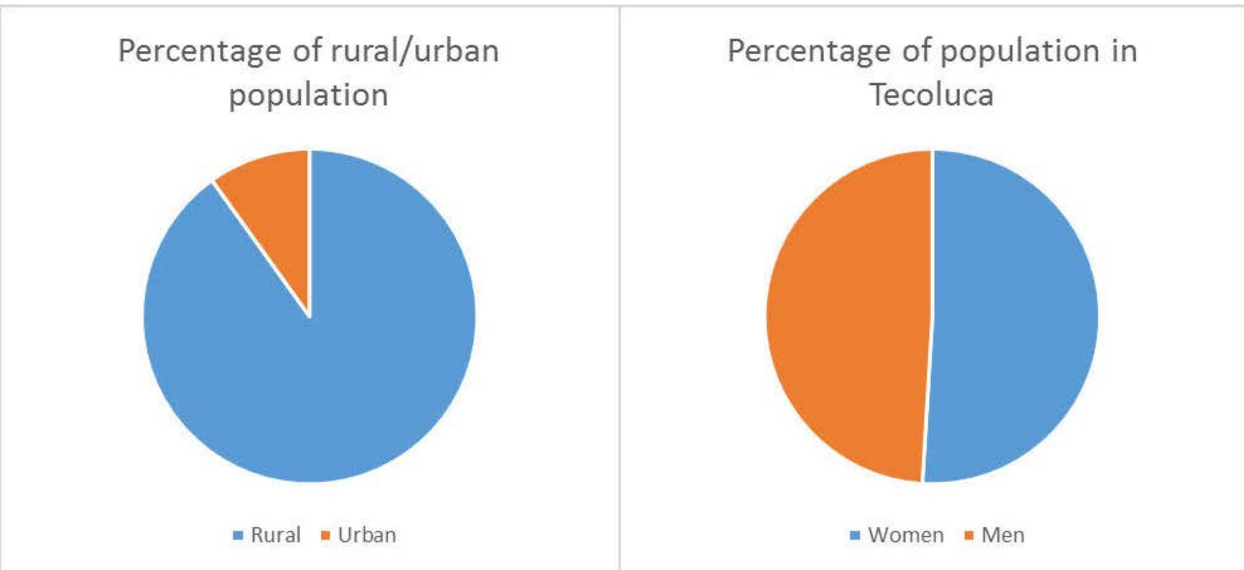

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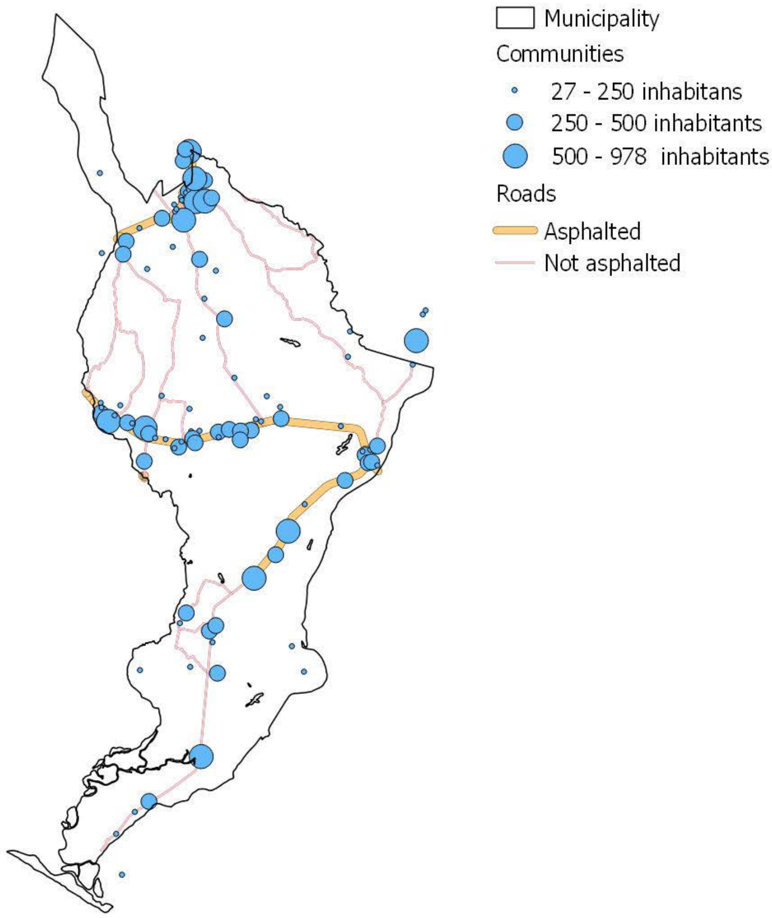

Figure 4: Shape of Tecoluca, roads and its communities (CNR, 2015; MINSAL, 2015b).

Parameters of development: alphabetization and economy

The alphabetization rate of the department of San Vicente is below country average. 12.8% are illiterate. The unemployment rate is the highest in El Salvador. 9.5% of the inhabitants are unemployed. On a national scale it can be stated that unemployment is higher among men than among women and that there is a slightly better employment rate in cities. 16 to 24 year olds are suffering from unemployment the most (DIGESTYC, 2015).

Table 2 shows that the department of San Vicente is poorer than average El Salvador. The most basic basket of commodities is calculated each month by the DIGESTYC. It includes basic food supply so that an urban family of 3.73 or a rural family 4.26 family members is still able to maintain a sufficient diet. Families with a monthly income below 46.8 USD per capita in urban agglomerations or 29.4 USD per capita in rural areas are regarded as extremely poor (DIGESTYC, 2013a). This applies to approximately 10% of the inhabitants in San Vicente (see Table 2).

The enhanced basket of commodities is also calculated by the DIGESTYC. Families which have more money at hand than the extremely poor but less than the sum of the enhanced basket of commodities, are considered as relatively poor. This applies to a quarter of the inhabitants in the department of San Vicente (see Table 2), thus a total of 35% of the population is either extremely or relatively poor (DIGESTYC, 2013a).

Table 2: Extreme and relative poverty in El Salvador and the department of San Vicente (DIGESTYC, 2013a).

	Extreme poverty	Relative poverty
	%	%
El Salvador	7.1	22.5
San Vicente	10.2	25.4

The most important business sectors in El Salvador are (DIGESTYC, 2015):

- Trading, hotels and restaurants (31%).
- Agriculture, livestock breeding, hunting and silviculture (18%).
- Manufacturing industry (15%).

The development plan of Tecoluca states that agricultural resources are crucial to local economy. Notably the cultivation of sugar cane and – in the past – cotton (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

In 2015 the Salvadorian GDP accounted for 25.85 billion USD (World Bank, 2016). The country depends heavily on money transfers from family members working abroad. In 2015 Salvadorians received 4.4 billion USD. In 2014 remittances claimed 16.8% of the GDP, which was only surpassed by Haiti and Honduras in Latin America and the Caribbean (World Bank Group, 2016). In the department of San Vicente each person received on average 41.19 USD monthly (DIGESTYC, 2013b).

Land use

Figure 5 shows the land use pattern of the municipality of Tecoluca. Few urban areas can be spotted. Besides the urban center Tecoluca (see also Figure 4), there are some urban agglomerations around the road Litoral and along the river Lempa (San Nicolas Lempa). Some parts in the southern and northern parts are forests, though most of Tecoluca is somehow cultivated. There is annually cultivation, such as basic crop, mixed cultivation and permanent cultivation, most notably sugar cane. Mangroves in the south are protected areas.

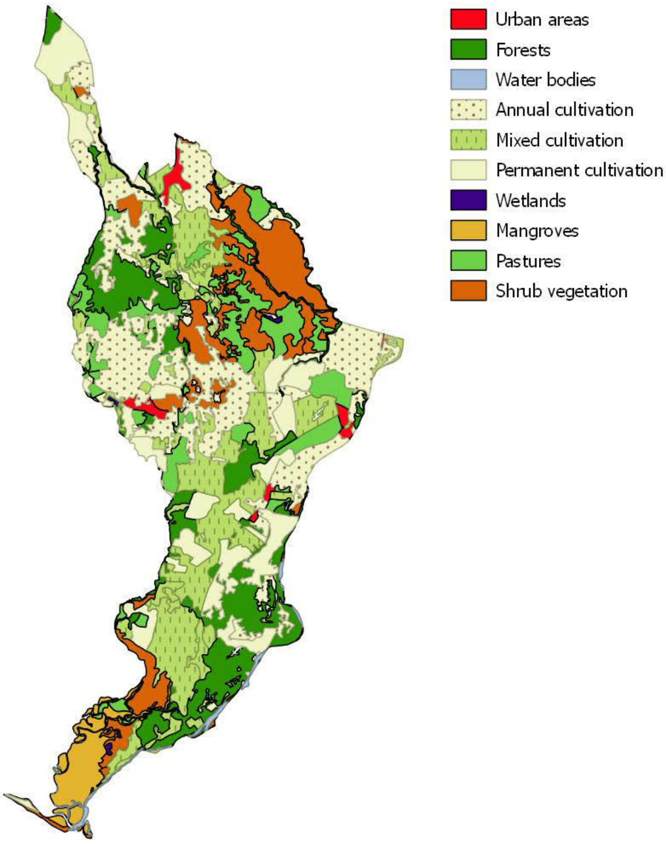

Figure 5: Land use of the municipality in Tecoluca (Universidad de El Salvador, 2015).

3.1.2 Water sources

Topography and geology

The topography of Tecoluca is dominated by the volcano San Vicente in the northern part of the municipality and by the Pacific Ocean to the south. The contour lines in Figure 6 illustrate that the northern part is both the steepest and topographically highest part in the municipality with 2150 m above sea level being the highest point. The further south the flatter the surface becomes, resulting in a flat southern part without any substantial elevations.

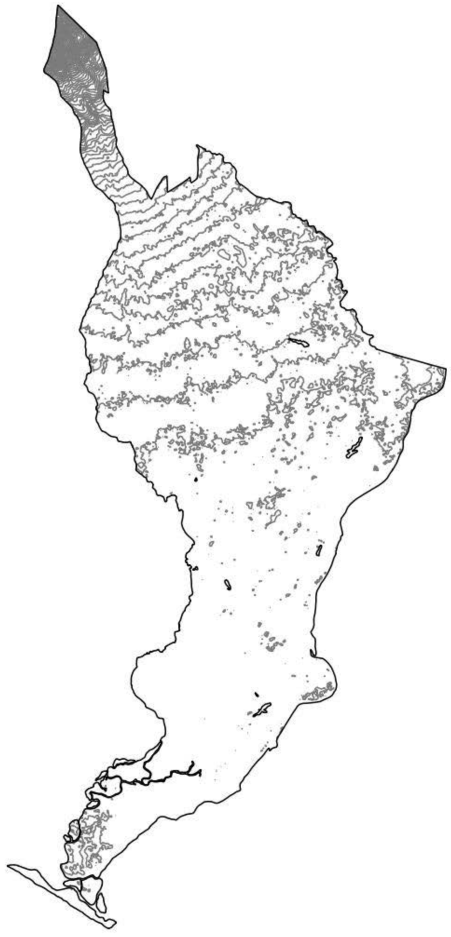

Figure 6: Contour lines (25 m) (Universidad de El Salvador, 2015).

The northern part of Tecoluca mainly consists of volcanic rocks and sediments. Epiclastic materials, former lava streams, effusive andesite and basalt and pyroclastic acid rocks can be found (see Figure 7). The volcano did not have any known eruptions but it is seismic active (MARN, 2016b). The southern part of Tecoluca is dominated by alluvial sediments, which the river Lempa has accumulated.

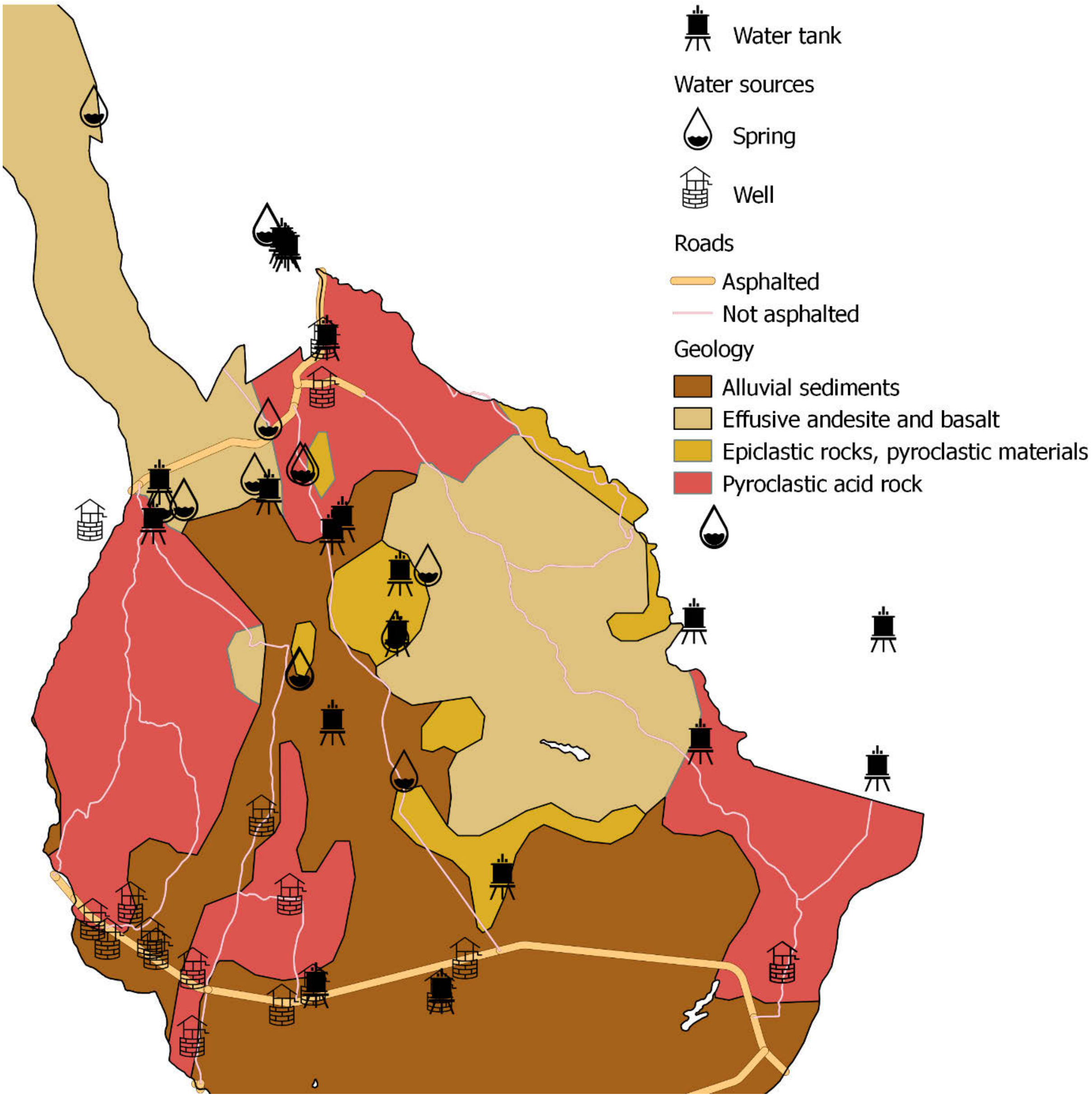

Figure 7: Geology and water sources of Tecoluca (Schaidreiter, 2015; CNR, 2015).

Hydrology and precipitation

The municipality of Tecoluca has a variety of rivers and canyons. The biggest rivers (besides the river Lempa) are: San Jacinto o Los Achiotes, Guajoyo o La Bolsa and San Antonio y El Socorro. Furthermore, there are two catchment areas that are within the boundaries of Tecoluca: river Lempa and lagoon of Jaltepeque (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

There are a few aquifers in Tecoluca, which can be either of quaternary material of high permeability (infiltration rate of approximately 50%) or alluvial sediments. The former are major groundwater recharge zones, located at the flanks of the volcano San Vicente. Aquifers of alluvial sediments form the banks of river Lempa and the slope toe of the volcano (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

The groundwater sources are abundant with the ground water table being only shallow south of the Litoral (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002). E.g. the drilled well of Santa Theresa (also called Trinidad), which supplies approximately 700 families, is 82 m deep and the water table is currently at a depth of 35 m.

North of the Litoral there is also sufficient groundwater but it is located at greater depths (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002). Many villages surrounded by hilly or mountainous terrain are supplied by spring tappings, which leads to the conclusion that it is likely that there are several near-surface aquifers, too.

The climate of El Salvador is characterized as tropical, divided into two seasons: dry and rainy season. The rainy season begins in May and ends in November and can produce intense precipitation events, which can lead to floods (UNICEF, 2014). The volcano San Vicente presents a natural barrier which forces airstreams to rise, therefore, producing rain. Thus also the municipal area of Tecoluca is separated into the wetter north and the drier south.

Figure 8 shows the average monthly precipitation in mm of two locations in the municipality of Tecoluca. Santa Cruz Porrillo lies around the Litoral with the precipitation maxima in June and September and a total rainfall of 1,763 mm. The same applies to Tehuacan but the total rainfall is 2,003 mm, probably because Tehuacan lies topographically higher than Santa Cruz Porrillo. The data suggests that, the lowest annual rainfall occurs in the south (~1,700 mm), while the wettest annual rainfall can be located in the northernmost point around the summit of volcano San Vicente (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

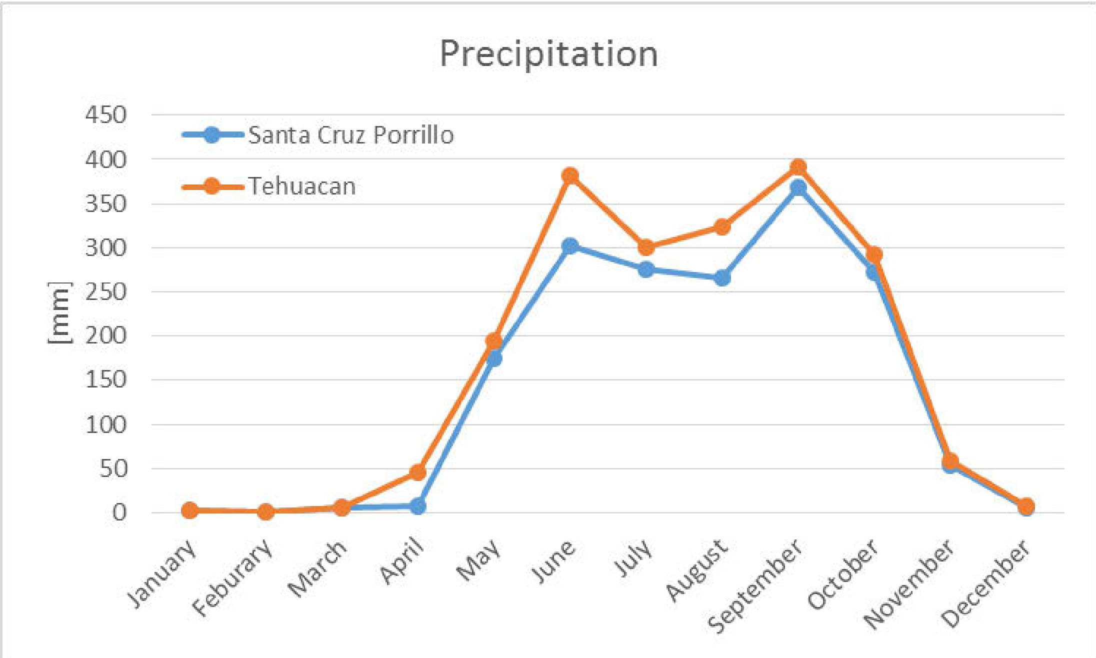

Figure 8: Average monthly precipitation in Santa Cruz Porrillo and Tehuacan (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

The annual potential evapotranspiration amounts to 1,800 mm in heights between 400-1,200 m most likely because of the elevated temperatures in the southern flatlands. The average precipitation rate of this area is only 1,600 – 1,800 mm. This could mean that the potential evapotranspiration might be higher than the precipitation in some areas (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

Water supply

The water supply systems that were geospatially captured in the GIS use spring tappings and drilled wells, which in two cases are also hand-pump wells. Some communities use only one water source, while others use multiple. Either the water is transported from the source to a water tank by gravity lines or in the case of drilled wells: directly pumped into a water tank by a pump. However, there are water sources which are directly connected with the consumers, most notably the drilled well of Santa Theresa and the spring tapping of the ecotourism park Tehuacan. Most of the systems provide the option of chlorinating the water, though rarely applied.

In Figure 7 it can be seen that there tend to be more spring tappings in the north, while the middle part around the Litoral road is exclusively supplied by drilled wells. The data collected by Schaidreiter (2015), indicates that in the southern part there are currently only two drilled wells in operation: Taura and Isla Montecristo.

Presently there are several approaches to manage the water sources in the municipality of Tecoluca:

- Community based approach.
- National water supply.
- Individual responsibilities of families.

A community or an association of communities is responsible for constructing and manging the water supply systems (spring tappings or drilled wells). There is a water board that consists of several members, which is, amongst other things, in control of the water price policy. This is by far the most common type of management approach and is the preferred way of providing water in rural Tecoluca.

Tecoluca town and a few communities around the Litoral are supplied by the national water association ANDA. They drilled two wells which now supply Tecoluca town and Tecoluca San Romero, and one well at the countryside, which supplies 12 communities around the Litoral. The new facility at the Litoral, called Noventa Dos, uses state of the art technology.

If neither the community nor the national water association is able to provide water, it is the responsibility of each and every family to obtain water, though most of Tecoluca is already part of community operated water supply systems.

It can be said with certainty that 4 communities in the municipality of Tecoluca are not supplied by any public water supply (MINSAL, 2015a):

- Arcos de San Lorenzo – 42 families.
- El Paraíso – 7 families.
- La Suisa – 12 families.
- Salamanca – 62 families.

Information on the kind of water supply of 21 other communities is still incomplete. It is likely that in a few of these communities the community operated water systems cannot provide area-covering water supply to all its residents. These communities lacking public water supply have to use other means of obtaining water.

Table 3 provides a brief overview of the number of water sources in Tecoluca, indicating that there are a total of 45 water sources – with some exceptions – being used. There are currently 27 water tanks either in use or being constructed at the moment (Schaidreiter, 2015).

Table 3: Number of water sources per type according to Schaidreiter (2015), adapted by the author.

Water source	No.
Spring tapping	24
Wells	21
Sum	45

Standards of drinking water

The most recent drinking water Salvadorian standard was issued in 2008 (República de El Salvador en la America Central, 2008). The standard provided a basis in order to be able to select the water parameters which are subject to the regulations in El Salvador. Thus these water parameters were incorporated into the water information system. Table 4 lists the type of parameters and some common water quality parameters.

Table 4: Salvadorian drinking water quality standard: parameters and their critical values (República de El Salvador en la America Central, 2008).

Type of parameter	Common water quality parameters	Critical max. value	Unit
Microbiological	Coliform bacteria	0	CFU
	E. coli	0	CFU
Organoleptic	Taste	Not rejectable	-
	Odor	Not rejectable	
Physical-chemical	pH	8.5	pH
	Turbidity	5	NTU
	Residual chlorine	1.1	mg/l
Non-desired substances	Nitrate	45	
	Iron	0.3	
	Manganese	0.1	
Toxic substances	Chrome	0.05	
	Mercury	0.001	
	Arsenic	0.01	

The standard also regulates the amount and frequency of sampling. Basically there are “minimal”, “normal” and “complete” samples. A complete sample consists of all 35 parameters listed in the standard, while minimal sampling only incorporates 5 parameters. The frequency of sampling depends on the size of the population. E.g. population sizes smaller than 25.000 (such as Tecoluca town) require one minimal sample per month, one normal sample biweekly and a complete sample only once per year. Microbiological parameters, such as the amount of E. coli or coliform bacteria colony forming units (CFU), have to be determined always (República de El Salvador en la America Central, 2008).

3.1.3 Waste water

Statistics suggest that 97% of the waste water in El Salvador is not treated at all, thus simply being discharged into the water bodies of El Salvador. There are, however, 16 waste water treatment plants, located in and around the capital of El Salvador, San Salvador (Biber, 2016).

Access to improved sanitation (i.e. hygienic separation of excreta and human contact) in El Salvador is not equally distributed. There is a gap between urban and rural sanitation. 82% have access to improved sanitation in the cities, while only 60% in rural areas. Nevertheless an overall coverage of 75% in El Salvador fulfils the Millennium Development Goals of the United Nations (Biber, 2016).

According to a survey carried out by Biber (2016) the sanitation situation of Tecoluca is only basic. Greywater is generally discharged untreated onto the streets, from where it then discharges to the next water body. Only few communities use basic treatment facilities, such as infiltration pits. In rural areas excreta are generally collected in latrines (mostly compost but also dry and pit latrines), while the population of Tecoluca town uses cistern flush toilets, which are connected to a pit. In villages without latrines it is still common to practice open defecation (Biber, 2016).

3.2 Web based GIS technologies

A web-GIS is a Geographic Information System application that can be accessed via intra- or internet. It can potentially offer information to many people with different interests in the planning region. The only software required is any modern Web-Browser (with *JavaScript* functionality), thus making the web-GIS not restricted to specific operating systems. Web-GIS applications can help to avoid high costs for acquiring licences for common GIS applications (CCGIS GbR and terrestris GbR, 2004).

A web-GIS creates at least one dynamic map that is pannable and/or zoomable and, depending on the available information, can be used to select and combine ***layers*** to gain further information. Web-GIS software has to be installed on a publicly available server in order to provide GIS functionalities (CCGIS GbR and terrestris GbR, 2004).

3.2.1 Overview

Figure 9 depicts a simple web-GIS flow. The user requests geospatial information via a browser application, firstly by communicating with the web server over the HTTP protocol. The web server redirects the request to a geographically enabled server, which is able to process the given parameters by the user (***layer***, style, coordinate boundaries…), and as a result sends back a map in the desired **format** (image or vector file). The web server sends the map via the HTTP protocol to the user who will then be able to see the dynamically produced map (CCGIS GbR and terrestris GbR, 2004). The geodata is stored in a geospatially enabled database, such as *PostgreSQL* (see also 3.2.4).

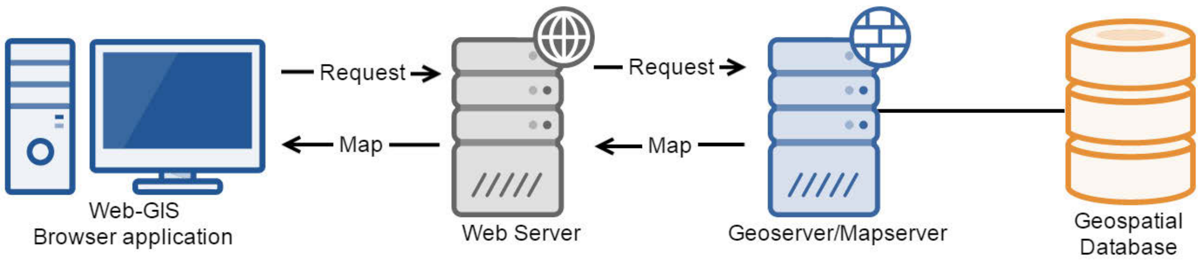

Figure 9: Web-GIS scheme according to CCGIS GbR and terrestris GbR (2004).

Nowadays web-GIS technologies offer versatile applicability and are used widespread. The use of web-GIS in El Salvador is still limited though. However, there are projects, such as the geoportal of MINSAL, which indicates information in association with health (e.g. location of hospitals or health care community centers) and statistics of diseases like number of dengue cases or HIV diagnoses per municipality (MINSAL, 2016). VIGEA is a web-GIS of the ministry of the environment and natural sources, which provides information on conservation areas, water bodies or meteorological weather stations to name but a few (MARN, 2016a).

3.2.2 OGC standards and file formats

The Open Geospatial Consortium (OGC) was formed in the early 1990s in order to establish GIS standards. Before that, every GIS company used their own formats and distinct ways of exchanging GIS data (Reed et al., 2015). Nowadays the OGC has implemented a lot of standards which are widely used for web-GIS purposes (Open Geospatial Consortium, 2016):

- *Web Map Service* (*WMS*)
- *Web Coverage Service* (*WCS*)
- *Web Feature Service* (*WFS*)

Web Map Services yield maps dynamically consisting of geospatial data. These maps are usually rendered using image formats, such as GIF, PNG and JPEG or vector-based formats as for example SVG. A basic *WMS* has to support at least two types of requests: *GetCapabilities* and *GetMap*. To initiate a request certain parameters need to be specified, such as the version of the *WMS* or the type of request, while others are optional. The *WMS* supports the HTTP GET method of the HTTP protocol, meaning that the parameters of requests are handled via URL (Beaujardiere, 2006).

The user requests information about the service-level metadata via the *GetCapabilities* function (see Figure 10). The *WMS* responds by sending a **XML** file to a *WMS*-compatible GIS software or – in the thesis' case – browser application in order to know what the *WMS* is able to do. The document contains data about the *WMS* in general, such as contact data or keywords lists, and information on the data ***layers*** and their styles the *WMS* has to offer. The geospatial information is structured in ***layers*** as in normal GIS. Various other properties (name, title, coordinate system) of each and every ***layer*** are defined in the document (Beaujardiere, 2006).

Once the user software knows the capabilities of the system, a *GetMap* request can be sent to the server which will yield either a map or a service exception. There are several parameters that can be defined to satisfy the *GetMap* request, e.g. ***layers***, size, height, **format** or coordinate system (Beaujardiere, 2006).

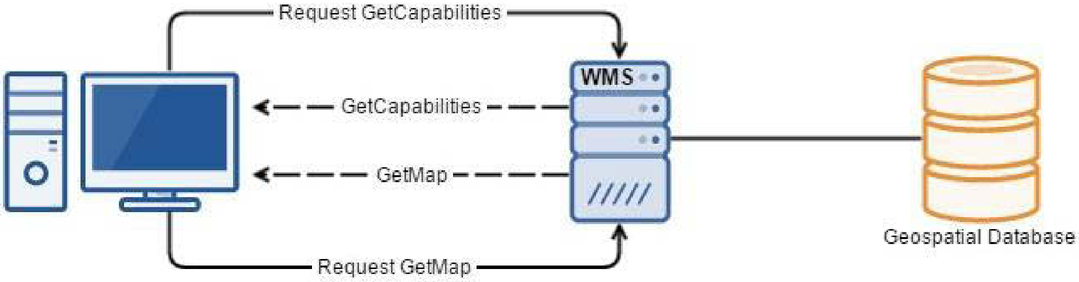

Figure 10: Schematic overview of OGC standard *Web Map Service* (*WMS*).

In Figure 11 a *WMS GetMap* request is depicted, showing that a graphical picture (=the map) of the requested ***layer*** (***geology***), with certain width and height, projected on the WGS84 ellipsoid will be produced.

```
http://localhost:8080/geoserver/websig/wms?service=WMS&version=1.1.0&r
equest=GetMap&layers=websig:geologia&styles=&bbox=-88.86,13.24,-
88.68,13.61&width=374&height=768&srs=EPSG:4326&format=image%2Fjpeg
```

Figure 11: *WMS GetMap* request.

While the *WMS* delivers only a static map image as a result of certain requested parameters, *WCS* and *WFS* allow working with either multi-dimensional coverage data of varying space-time or features (Panagiotis, 2005; Baumann, 2012). The procedure is basically the same as for *WMS*: first a *GetCapabilities* request is sent to the server and after responding, there are certain operations available depending on the type of service.

The *WCS* core covers *GetCapabilities*, DescribeCoverage and GetCoverage operations making it possible to request coverage data (Baumann, 2012). A basic *WFS* supports *GetCapabilities*, *GetFeatureType* and *GetFeature* operations, which would be considered as a read-only access to features. In addition, there is the Transaction operation available, which enables the user to alter the requested features permanently on the server (Panagiotis, 2005).

File formats – WKT and WKB

Web-GIS geo data is mostly stored in databases, thus the need for standardized file formats is important to assure the functionality of all components. The OGC implemented two standard file formats:

- **WKT – Well-Known Text**.
- **WKB – Well-Known Binary**.

The **Well-Known Text** is a human readable representation of geographic objects (Herring, 2011). In a GIS real life objects are abstracted to a certain level in order to represent them. The most basic geometry types which the **WKT** handles are points, linestrings and polygons.

Table 5 shows examples of these geometries. The first example represents a point with the x and y coordinates 10 and 10, the linestring is a sequence of points, while the polygon is a closed sequence of points. However, there exist other geometry types, for instance multi linestrings, polygons or geometry collection, which provide the option to store geo objects of different geometry types.

Table 5: **WKT** representation of geometry type (Herring, 2011).

Geometry type	WKT representation
Point	Point (10 10)
Linestring	LineString (10 10, 20 20, 30 40)
Polygon	Polygon ((10 10, 10 20, 20 20, 20 15, 10 10))

The **WKT format** was recently updated by the OGC extending the **format** to incorporate information about the coordinate reference system as well and is now called **WKT** CRS (Lott, 2015).

The **Well-Known Binary format** represent "geometric objects as a contiguous stream of bytes" (Herring, 2011). It is used to store geographic entities in *PostgreSQL* databases with *PostGIS* extension. The **WKB** representation of the point with the coordinates 10 and 10 in the WGS84 coordinate reference system would be:

```
0101000020E6100000000000000000244000000000000002440.
```

3.2.3 CRS and Tiles

There are two types of coordinate reference systems that have to be distinguished: unprojected and projected coordinate systems. The former system (see Figure 12) uses angles in degrees relative to defined points (also known as latitude and longitude) to describe the location of geo objects on the earth's surface (Westra, 2010). E.g. Tecoluca is located at 13.538° north of the equator (latitude) and -88.781° west of the prime meridian at Greenwich (longitude).

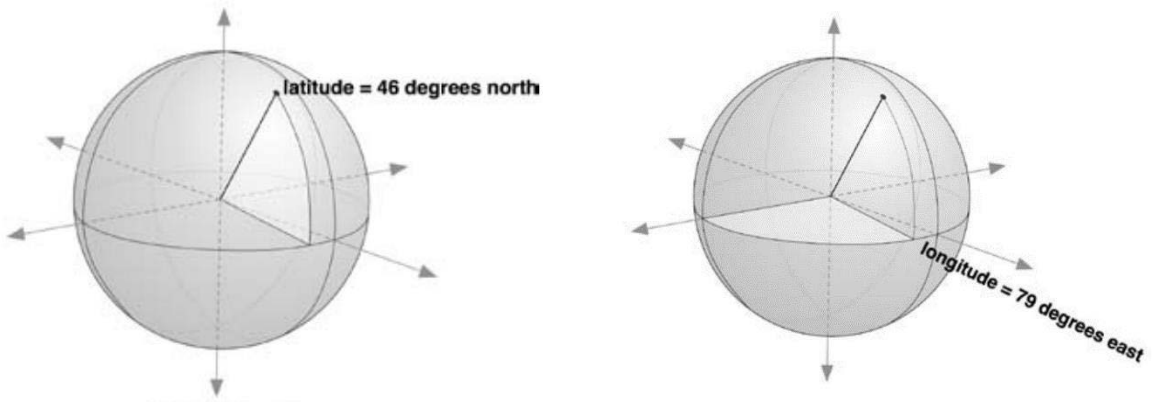

Figure 12: Unprojected coordinate systems: latitude and longitude (Westra, 2010).

Projected coordinate systems are two-dimensional representation of the location of geo objects on the earth's surface. By projecting the earth's surface onto a Cartesian plane it is easier to perform distance calculations between two points. There exist a sizeable number of different projection methods because it is mathematically impossible to project the 3D earth onto a 2D plane without some kind of distortion (Westra, 2010).

The most important type of projection for use in GIS is the cylindrical projection (see Figure 13), which can amongst others yield the Mercator projection (Westra, 2010). Well known web-GIS applications, such as *Google* maps or *Bing,* use this projection because the shape of its represented features does not alter anywhere on the projected 2D plane, though the size gets distorted the further away from the equator the projected area is located. That is why in a map with a cylindrical projection it seems that Greenland is as big as Africa. The cylindrical Mercator projection provides constant orientation, i.e. that north is always perpendicular up (Kaseorg, 2016; Schwartz, 2016).

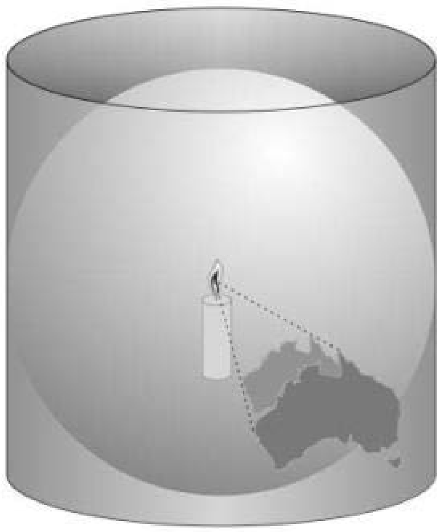

Figure 13: Cylindrical projection of the earth onto a 2D plane (Westra, 2010).

The OGC defined a standard way of representing coordinate reference systems (CRS). The WGS84 CRS has the following parameters (Butler et al., 2016a):

```
GEOGCS["WGS 84",
    DATUM["WGS_1984",
       SPHEROID["WGS 84",6378137,298.257223563,
           AUTHORITY["EPSG","7030"]],
       AUTHORITY["EPSG","6326"]],
    PRIMEM["Greenwich",0,
        AUTHORITY["EPSG","8901"]],
    UNIT["degree",0.01745329251994328,
        AUTHORITY["EPSG","9122"]],
    AUTHORITY["EPSG","4326"]]
```

At the beginning of the 21st century the nowadays popular *Web Map Services Google* and *Bing* introduced a technique to provide fast access to their data by pre-generating the map. The world map is a big image that is divided into so called tiles (see Figure 14), which are stored on the server, and – if requested – can be provided to users very fast (Quinn and Dutton, 2014).

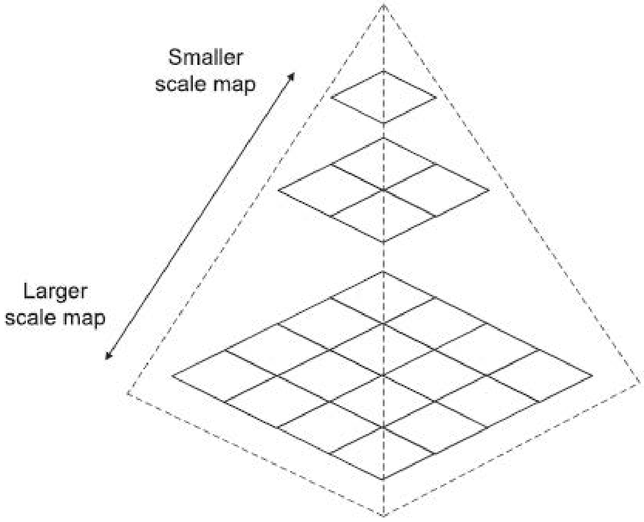

Figure 14: Tiles in web maps (Quinn and Dutton, 2014).

At the smallest scale the world map only consists of 512 tiles, while a larger scale at e.g. zoom level 16 (corresponding approximately to a scale of 1:9000) requires roughly 17 million images (Schwartz, 2016).

Web Map Services provide simple access to aesthetic and scalable map contents but lack certain features that normal GIS would have, like e.g. the possibility to change ***layer*** orders or symbols. *Google*, *Bing* or *OpenStreetMap* services serve as the foundation of web-GIS, by providing so called ***base layers***. Other information can be added, such as additional ***layers***, which are also called overlays and tools e.g. for distance measuring (Quinn and Dutton, 2014).

3.2.4 Databases and SQL

Databases are collections of structured data which is logically related. A database management system (*DBMS*) is an interface or program that provides all features for administering such data (Jarosch, 2010).

Nowadays a multitude of database systems exist, either open source (*PostgreSQL*, SQLite) or commercially distributed (IBM DB2, Oracle). They can be used for manifold purposes, from small scale internet applications to data ware house applications, which can handle an enormous amount of data (Dittrich, 2013).

Database management systems can be administered by the standardized Structured Query Language (*SQL*). It allows to access data stored in databases and perform queries, such as INSERT, UPDATE, DELETE, JOIN data, and many more operations (Dittrich, 2013; Jarosch, 2010).

PostgreSQL was the first open source database on the market (Dittrich, 2013). It is still being actively developed, platform independent (Windows, Mac, Linux) and highly reliable concerning data integrity, making it a powerful tool to manage data. *PostgreSQL* databases are able to store geographic objects by optionally installing the *PostGIS* extension (The PostgreSQL Global Development Group, 2016a). Thus *PostgreSQL* databases are suitable solutions for web-GIS.

3.2.5 Database design

In order to design a database and applications relying on the database it is necessary to transform semantic knowledge that local experts have garnered over the years into syntactic structures of databases and applications. This is mostly achieved by verbal communication, either by meetings or by the creation of a functional design document. The biggest impediment to this process are the barriers of natural language, which by nature is inexact (Jarosch, 2010).

According to Jarosch (2010) the following steps are required to identify possibilities to structure data:

- Describe part of the real world that is to be modelled: e.g. technical language of economists.
- Find possibilities of structuring data which allow to describe part of the reality: **Entity relationship model** (**ERM**) or Unified Modeling Language (UML).
- Find possibilities to describe data structures of actual DBMS: hierarchical model, network model or **relational model**.

ERMs are used to create conceptual data models, which help to structure data. The following steps are compulsory developing an **ERM** (Jarosch, 2010):

- Classifying **entity** and **entities** types. **Entity types** are defined as classes, which hold all **entities**. "**Entities** are people, objects or non-material things" (Jarosch, 2010). The reality consist of many **entities**, which produce data in the real world.
- Reducing **attributes** of **entities**. **Attributes** describe features of **entities**. As **entities** can potentially have a lot of **attributes**, it is necessary to reduce the amount to core **attributes**.
- Determining **identifying attributes**. As classes (=**entity types**) are mathematical sets, whose elements (=**entities**) have to be distinguished uniquely, it is necessary to determine **identifying attributes**, which can be either unique or be represented by a combination of **attributes**. **Describing attributes** provide further information about the **entities** and cannot be used to identify them.
- Description of **relationships** between **entity types**. A **relationship** determines the **relation** between two **entities**.

Figure 15 identifies the main elements of an **ERM**. The boxes in the model world are **entity types**, consisting of various **attributes**, one of which must be an **identifying attribute**. The **entity types** can have different **relationship** types (dual or recursive). **Entities** are objects of the real world, e.g. a particular person (e.g. Ms. Powers), while belonging to the **entity type** person in the model world at the same time. **Attribute** values are real world characteristics of objects (e.g. age, address). Real world **entities** are able to pursue **relation** between other real world **entities** (Jarosch, 2010).

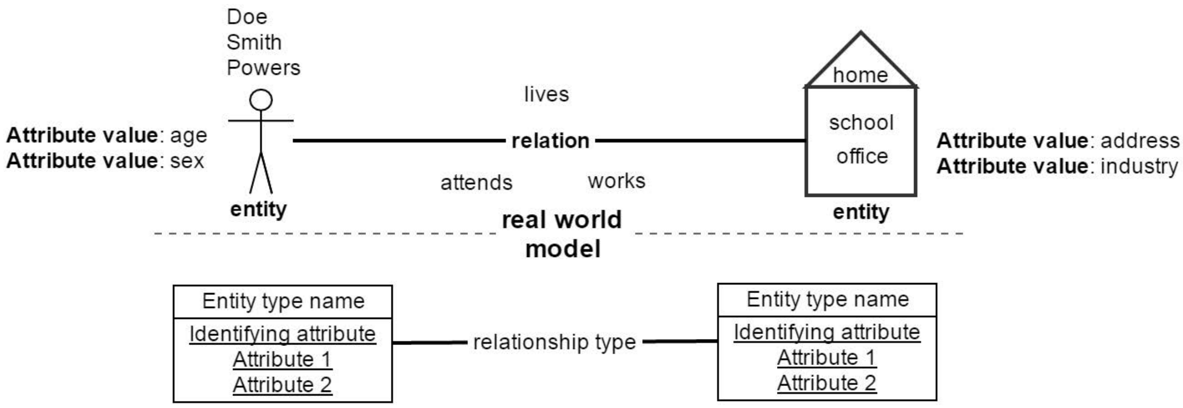

Figure 15: Elements of an **entity relationship model**. Real world and model, according to Jarosch (2010).

The commonly used **relational database model** stores each **entity type** at the beginning without any predefined **constraints** or **relations** to other **entity types**. **Entity types** can then be related with each other, and queries can be directed in both ways. A major advantage of this database model is that its content can be represented as ***tables***. The **ERM** as part of the conceptual data model is to be transformed into a logical data schema (Jarosch, 2010).

The key of a ***table*** is an **attribute** (or a combination of **attributes**) which allows to uniquely identify every row of a ***table***. The key(s) should have consistent naming and must have a value. In the case of several keys a **primary key** is to be elected, whose main purpose is to access rows of the ***table***. In order to establish **relations** between **entity types** it is necessary to place the **primary key** of ***table A*** as a **foreign key** into ***table B***. The **primary keys** of ***table C, D*** … can also be placed into ***table A***. E.g.: The **relation** "schools are part of community" means that the ***table school*** stores the **primary key** of the ***table community*** as **foreign key** (Jarosch, 2010).

Table 6 depicts the concept of **primary keys** and **foreign keys**. Each photo in the ***table photo***, and each photographer in the ***table photographer*** has an assigned number (=**primary key**), which makes it possible to determine each photo or photographer uniquely. In order to relate ***tables,*** in this case it is necessary to put the **primary key** of the ***table photographer*** into the ***table photo*** (=**foreign key**), providing information on which photo was taken by which photographer. Mr. Doe e.g. took the photo with the *fid* 1, while Ms. Powers took a photo with the *fid* 3.

If the **foreign key** *fid* of the ***table photo*** was stored in ***table photographer***, it would create redundant data because if a photographer took more than one picture, it would store the *pid* and name of the photographer with every taken picture (Dittrich, 2013).

Table 6: **Primary key** and **foreign keys**, according to Dittrich (2013).

photographer			photo		
pid	**name**		**fid**	**camera**	**pid**
23	Doe		1	Canon	23
45	Smith		2	Canon	45
12	Powers		3	Nikon	12

According to (Dittrich, 2013) there are four important **relationship** types:

- **One-to-many relationship**: see Table 6 and Figure 16. One **entity** (photographer) can be in a **relationship** with many photos: one photographer can take various photos.

- **Many-to-one relationship**: would be vice versa. In this case it does not make sense though: Many **entities** (photographers) can relate to one photo: One picture can be taken by various photographers but a photographer is not allowed to take more than one picture in this notation. There is always the option though that an **entity** cannot participate in the **relationship** (=the photographer must not take a picture).
- **One-to-one relationship**: One **entity** can have a **relationship** with exactly on photo. Photographers can take one picture or one picture is taken by exactly one photographer.
- **Many-to-many relationship**: Many **entities** can participate in a **relationship** with many photos. Various photographers can take various photos or various photo can be taken by various photographers.

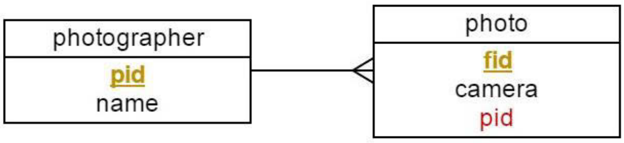

Figure 16: **Entity relationship model**: **One-to-many relationship**: one photographer can take many photos, according to Dittrich (2013).

Tables are commonly connected with each other using the SQL operator JOIN, thus visualizing the **relations**. There are various types of JOINS, such as natural, inner, outer, left or right. VIEWS are **relations** derived from base **relations** (***tables***), which have several functions (Schicker, 2014):

- Data privacy: users are only able to see data that should be seen
- Clarity: users only see relevant data
- Readability: the data is prepared for easy comprehension

3.2.6 MapServer and GeoServer

MapServer and *GeoServer* are able to manage geographic information and interact with the Webserver. They provide tools which make it possible to see maps in the browser without the need of a GIS software. There are two important geographically capable servers: *MapServer* and *GeoServer*. Both basically provide the same features: it is possible to view, publish and edit geospatial data via the OGC service standards (see also chapter 3.2.2).

The *GeoServer* project was founded in 2001 and nowadays supports many different input and output formats (see Figure 17). It is open source, published under the GNU General Public License, written in Java, therefore, running on any operating system. *GeoServer* complies fully with several OGC standards, such as *WCS*, *WFS* and *WMS* (see also 3.2.2 and Figure 17) (Geoserver, 2014). It is worthwhile noting that *GeoServer* supports *PostGIS* databases (i.e. *PostgreSQL* databases with *PostGIS* extension, see 3.2.4).

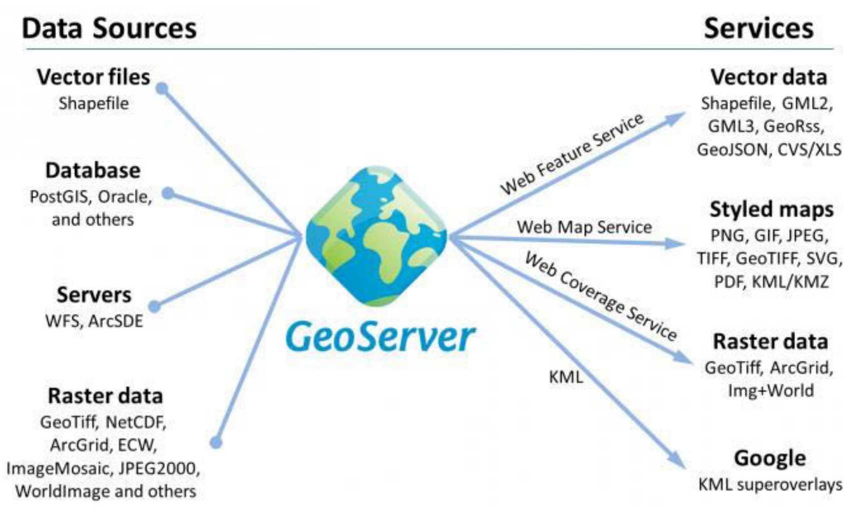

Figure 17: Overview of *GeoServers'* input and output **formats** and their respective services (eAtlas, 2016).

3.2.7 OpenLayers

OpenLayers is a JavaScript library that enables developers to create web map applications, which can be used within the Browser. It is able to implement maps of different sources by using either raster (*OpenStreetMap*, *WMS*) or vector (GML, KML, *WFS*) ***layers*** and it conforms to the OGC standards (*WMS*, *WFS* …). Various tools which facilitate the navigation of maps (zoom, scales, and distance measurement tools) are easily added (Perez, 2012).

3.2.8 Global Navigation Satellite System

The Global Navigation Satellite System (GNSS) is a satellite-based positioning system that allows to determine positions on land and sea by communicating with artificial satellites, assuming that their positions are always known at every moment orbiting the earth. Nowadays GNSS comprise of the American Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS). GPS-receivers are able to calculate its position based upon the received satellite signals, usually expressed as latitude and longitude. GPS uses the World Geodetic System 1984 (WGS84) as its reference system (see also 3.2.3) (Hofmann-Wellenhof et al., 2008).

4. Materials and Methods

This chapter describes the approach to achieve the main objectives of this thesis: improve the data base, further develop the water information system (WIS) and increase its usability. It is described how the WIS was adapted and set up to be a web-based GIS. The first steps mainly involved data check, update, collection and unification while the second part consisted of the setup of the water information system. At the end of the practical field work it is described how trainings in the usage of the WIS have been conducted.

The following steps have been performed:

- General tasks
  - Test functionality of existing GIS
  - Check and update data
  - Unify and prepare data for database insertion
- Improvement of data base.
  - Measurement of water quality and quantity parameters.
  - Measurement of coordinates of geo objects.
  - Generation of information by analyzing existing data.
  - Interviewing local experts to gain further explanatory information.
  - Further development of the existing water information system.
    - Conception and creation of the database for storing data.
    - Insertion and check of collected data.
    - Selection and installation of Web-based components for the water information system.
    - Programing a browser application, which facilitates online access to GIS data.
    - Installing components on a server of municipal office in Tecoluca.
- Improvement of usability of the water information system.
  - Creation of a manual for the usage of the web-GIS.
  - Trainings in the usage of the web-GIS.

4.1 Further development of water information system in Tecoluca

The WIS by Schaidreiter (2016) was further developed, requiring several steps. At the beginning it was paramount to check whether the existing GIS was suitable to the needs of a web-GIS, thus the following tasks have been carried out:

- Test functionality of the existing GIS
- Check if available data is uniform (*IDs*, ***table names***, …) and – if necessary – update data
- Acquire more data

After having assured that the data is uniform, it was decided to insert all the data into a geospatially enabled database. Consequently the next goal was to first design a database, which is able to incorporate all of the provided information, and secondly implement the data into the database. The following steps have been carried out:

- Design the database
- Implement the local GIS data into the database
- Check the database

Once the data has been entered correctly into the database the conception of the WIS has been elaborated, determining the necessary components. The following components have been installed and/or set up:

- *GeoServer*
- *OpenGeo Suite*
- *OpenGeo* component: *Boundless SDK*
- Browser application
- Server

4.1.1 Testing functionality, check and update data

The existing GIS which was installed and set up by Schaidreiter (2016), was implemented into an open source desktop GIS application called Quantum GIS (*QGIS*) (Schaidreiter, 2016). It was checked whether the data is displayed as expected or if any errors occurred. At the same time the uniformity of the existing data was checked by using various tools of *QGIS* and looking at the attribute table. Further possible data acquisitions were contemplated. All the work was achieved using *QGIS* 2.12.0 (Lyon).

Name schema

It was further checked, whether the data ***tables*** were suitable for storing the existing data into a database. As it turned out, the ***table*** layouts of the respective ***layers*** were not uniform, mainly because of the different origins of the geoinformation. The information was procured by different sources, while some information was created by Schaidreiter (Schaidreiter, 2016). The concept of having a stringent nomenclature was crucial to facilitate the process of implementing the data into the database (see also chapter 4.1.3).

Thus one of the first steps was to uniform the ***table*** layouts, by coming up with a consistent name schema, which allows to rename the ***layers*** and *columns* of each ***layer***. It was decided that the names should be lowercase and singular. *IDs* should have the prefix *id* followed by the ***layer name***, e.g. *id_geology* is the first *column* of the ***layer geology***. Underline characters are allowed and are useful to clarify the *column* as much as possible, e.g. the ***layer*** named ***type_treatment*** contains information of the water treatment types. Where not applied, it was necessary to add *IDs* to the ***table*** layout.

Further data manipulation

Some ***layers*** encountered accuracy issues, as they did not coincide well because of their different origins, while others contained topological errors. Geoprocessing tools and sometimes workarounds had to be applied to solve these issues. In some cases it was not possible to solve the accuracy problems without having additional geoinformation, thus certain inaccuracy has to be accepted.

Further the data types of each *column* of each ***layer*** were revised, and where necessary changed. It is advisable to use integer as data type for *IDs* or whole-numbers, e.g. number of water tanks, and numeric data types for decimal numbers, otherwise GIS operations which require numbers will not work properly or even at all. In some cases *columns* were designed as string data types instead of numeric data types (integer or numeric), so this was changed as well.

The ***layers'*** coordinate reference systems were unified – if necessary – by reprojecting them to the WGS84 reference system. *QGIS* supports 'on the fly' CRS transformation, so unifying each ***layer*** would not be necessary, though the browser application requires all of the ***layers*** to be part of the same CRS.

If necessary the already existing GIS ***layers*** were further edited. This could range from adding or deleting <u>*columns*</u>, merging information, clipping features to reprojecting ***layers***.

Only ***layers*** that deemed important to a water information system were included into the database. The extent of the ***layers*** was limited to the municipality of Tecoluca. Future extension of the WIS should consider the ***table*** layout (name schema) of the already implemented ***tables***.

Thus the ***layers*** were prepared for the implementation into the web-GIS. A thorough list of each ***layer*** and its manipulation is available in the appendix (see chapter 9.2).

In order to achieve this, a variety of functionalities, tools and plugins within *QGIS* were used:

- *QGIS* functionalities:
    - Field calculator
    - "On the fly" CRS transformation
    - Reprojection of ***layers***
    - Creation of objects (digitize)
- Vector tools
    - Geometry tools
        - Multipart to singleparts…
        - Singleparts to multipart…
    - Geoprocessing tools
        - *Dissolve*
        - *Clip*
    - Data management tools
        - Join attributes by location
    - Topology checker
- Raster tools
    - Extraction: Contour
- Plugins
    - DB Manager
    - GPS Tools
    - Join multiple lines
    - MMQGIS
    - *OpenLayers* Plugin
    - *Spit*
    - Table Manager

4.1.2 Improvement of data base

New data was acquired by several means:

- Measurement of water quality and quantity parameters of spring tappings and drilled wells and, if not available, their coordinates
- Generation of information by analyzing existing data
- Interview local experts to gain further explanatory information
- Further data generation by measurement of coordinates: **waypoints** and **tracks**

Measurement of water quality and quantity parameters

In the first part of the field work it was important to get acquainted with the area and its water sources. While doing so the following parameters have been measured:

- Water temperature
- pH value

- Electrical conductivity
- Delivery of spring tappings or water tanks
- Coordinates of water sources and water tanks (if not already available)
- General data: year of construction, constructor…

Before the available GIS data was implemented into the database the newly acquired data was temporarily entered in a MS Excel spreadsheet because the ***table*** layouts to be used in the web-GIS were not yet defined at that time.

Generation of information by analyzing existing data

The census data provided by (MINSAL, 2015a) was split into demographic data (***table census***) on the one hand and information on water treatment and supply (***table type_treatment*** and ***type_supply***) on the other hand (see Table 7). This seemed like a more logical approach to grouping information, than elaborated in the provided census file.

The ***table water_sample*** is able to store every possible measured parameter with its respective unit and timestamp, including both water quality and quantity parameters (see Table 7). Generally all water quality parameters mentioned by the Salvadorian standard for drinking water (2008) are included. In addition, several other parameters were added because they were measured by some laboratories.

- Copper
- Chloride
- Electrical conductivity
- Sodium
- Alkalinity
- Calcium

Some communities provided the author with the laboratory results of water quality samples, which were inserted into the ***table water_sample***, while other measurements were conducted by the author (see above).

Table 7: List of generated information stored in ***tables***.

Table	Description
census	Demographic information, such as total population or male/female population by community.
type_treatment	Kind of water treatment by families and community.
type_supply	Kind of water supply by families and community.
water_sample	Measurements of water quality parameters: 35 parameters (Salvadorian standard), water quantity: delivery and further parameters.
person	List of persons and their telephone number working at the town hall of Tecoluca.
contact_person_water	List of persons responsible for water resources sites.
working_division	Working divions of town hall. Assigned to each person from tables person.
function	Working functions of town hall. Assigned to each person from tables person.

The ***table contact_person_water*** includes name and telephone number of the person(s) responsible of each water source. Having this information facilitates the communication between the municipal administration and the communities. This information was already partly available but needed to be updated in a lot of cases.

The ***table person*** incorporates persons associated with the municipal administration, including employees of the municipality of Tecoluca, volunteers and other people involved in the water system (such as laboratory staff handling water samples). Their working division and functions are mentioned in the ***table working_division*** and ***function*** and relate to the ***table person***.

Further explanatory information

Interviews have been conducted with members of the water committee or employees of the town hall, facilitating further explanatory information. ***Tables*** were generated by relating existing data to other existing data and – where applicable – extended by local knowledge:

- **Relations** of the water supply system between communities, water sources and water tanks, (further information on these **relations** can be found in chapter 4.1.3).
- **Relations** of the water contact person and his or her responsible water source.
- **Relations** between geographic objects (roads, mountains) and their affiliation to a geographic location (department, municipality).

Measurement of coordinates: waypoints and tracks

The coordinates of points of interests (**POI**) were measured with a GNSS-enabled device (Garmin eTrex 20). This GNSS receiver supports a function which averages many coordinate samples, which – in theory – should increase the accuracy of the positioning. The result is stored in a **XML** file on the device, as a **GPX** file, which can be easily imported into *QGIS* for further manipulation.

As the GNSS device determines its position every few moments, it is able to record the trajectory of the user, also known as **tracks.** This function was used to survey the urban center of Tecoluca in a very basic way, which then again can be imported into *QGIS*. The **tracks** were also used to improve the freely available, open source *OpenStreetMap* (*OSM*) of Tecoluca town and countryside (OpenStreetMap community, 2016a).

It was checked whether the urban center of Tecoluca was correctly depicted in *OpenStreetMap*. It turned out that most of the streets were digitized but the street names were missing, as were **POI**, such as the church or the town hall of Tecoluca. Every point of particular interest to the city was captured as a **waypoint**, while every single street was recorded as a **track** by using the GNSS-enable receiver.

The results were digitized by using the open source editor JOSM by *OpenStreetMap* (OpenStreetMap community, 2016b). Missing streets and their names and **POI** were added and it is now possible to find Tecoluca on *OpenStreetMap* by searching Tecoluca in the search box (OpenStreetMap contributors, 2016). The hyperlink to the map section of Tecoluca is also available in the reference section of this thesis. The contribution to OSM is depicted in Figure 18.

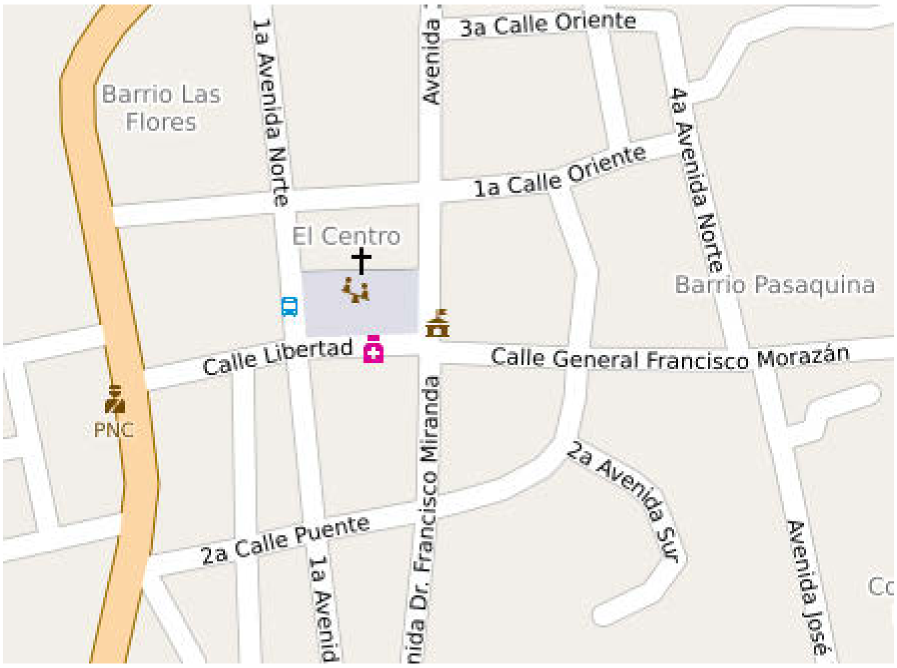

Figure 18: Tecoluca map section: a contribution to *OSM* (OpenStreetMap contributors, 2016).

4.1.3 Database design

It was necessary to understand the water supply system of the municipality of Tecoluca by getting acquainted with the region first. GIS data represents information about the geographic location and its properties, so it seemed to be a good idea to visit several spring tappings and wells to get a comprehensive overview of the environment of Tecoluca. Thus the first weeks of the field study took place outdoors, determining water quality and quantity parameters, verifying available information of the existing GIS. Informal interviews with people associated with the water board of the community were also conducted.

It has to be stated that the water supply system of Tecoluca is very basic concerning the infrastructure. It was hard to get an overview of the situation because as of 2016 there exist 116 communities in Tecoluca (Schaidreiter, 2015), 45 water sources and 27 water tanks. It cannot be taken for granted, however that the provided numbers capture every element in Tecoluca. With the help of the local population it was possible to gather information on the **relations** between water sources, water tanks and communities, making it possible to answer the following questions:

- Water sources and water tanks: Which water sources (one or multiple spring tappings or wells) are connected to which water tank(s)?
- Water sources and communities: Which water sources (one or multiple) supply which community (one or multiple)?
- Water tanks and communities: Which water tanks (one or multiple) supply which community (one or multiple)?

Figure 19 systematically shows various options of how drinking water supply schemes work in Tecoluca. In general almost every scenario is possible. The simplest system that has been captured can be found at Parque Tehuacan: a spring directly supplies the consumers via one pipe, without the option of storing water in a tank. More sophisticated water supply systems can have multiple water sources, supplying multiple water tanks and communities. In order to design a database according to the above mentioned, it was necessary to model the **relationships** as **many-to-many relationships** (see chapter 3.2.5).

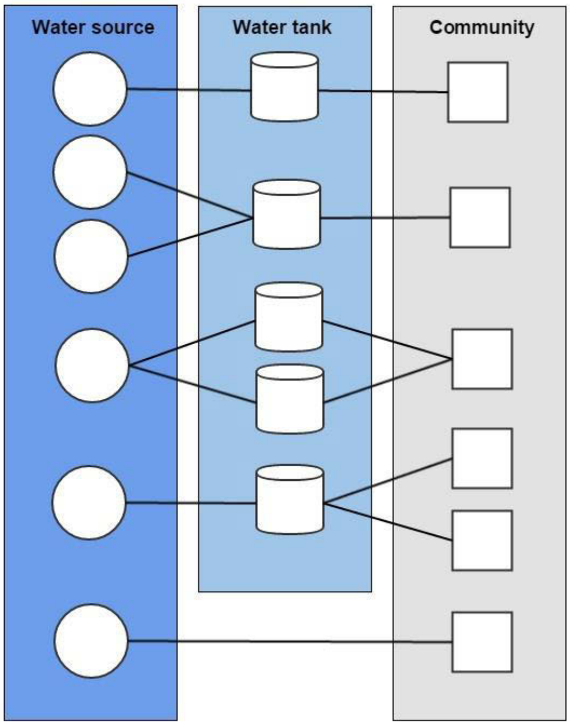

Figure 19: Various options of drinking water supply systematically depicted.

Facing this challenge concerning the water supply situation the database was designed with the help of two local students who study Informatics at the UCA in San Salvador. An **entity relationship model** was created, graphically depicting every **relation** of every ***table*** of the database (Ramos and Recinos, 2016). After that it was necessary to define the data types of each *column* of each ***table*** of the database, thus transferring the **ERM** to a **relational model**. Once the data types and ***tables*** are defined, it is possible to create the database. The students provided the ***table definitions*** of the database written in SQL.

Table 8 gives an overview of the data types used in the database. Serial data types are applied to every ***table*** of the database in order to identify it uniquely, functioning as a **primary key**. Numbers are either represented as integer or as numeric for decimal numbers, such as areas or lengths, while strings are modelled as character varying. The length of the field can be adjusted to the purpose, preventing from misusing the field.

Table 8: Used data types of database (Ramos and Recinos, 2016; The PostgreSQL Global Development Group, 2016b).

Data type	Description	Example
serial	Incrementing numbers	Create unique identifier column (id)
integer	Whole numbers	Year of construction of water tank
numeric	Large numbers of digits (decimal number)	Capacity of water tank
character varying(n)	String with up to n characters	Constructor of water tank
timestamp without time zone	Time format: YYY-MM-DD hh:mm:ss	Date and time of water sampling
geometry	PostGIS geometry types	School (point), road(MultiLinestring), municipality (MultiPolygon)

Selected *PostGIS* geometry types in the database are points, multi linestrings, polygons and multi polygons. Timestamp without time zone are applied to identify date and time of measurements of water sources. The information of the exact hour is necessary for the future possibility to extend the system to real time measurements, which would be able to store data – if necessary – every second.

Figure 20 shows parts of relevant elements of the WIS and their interrelations. A **many-to-many relationships** can be modelled by connecting two ***tables*** with a third in between. E.g. the ***tables community*** and ***water_tank*** require **many-to-many relationships** (as stated above), therefore, they are connected by a third ***table*** called ***community_x_water_tank***. The **primary keys** of the ***tables*** (id_community, id_water_source) are combined in the third ***table***, so either way one community can partake in many **relationships** with the ***table*** in between and one water tank can be part of many **relationships** with said ***table***.

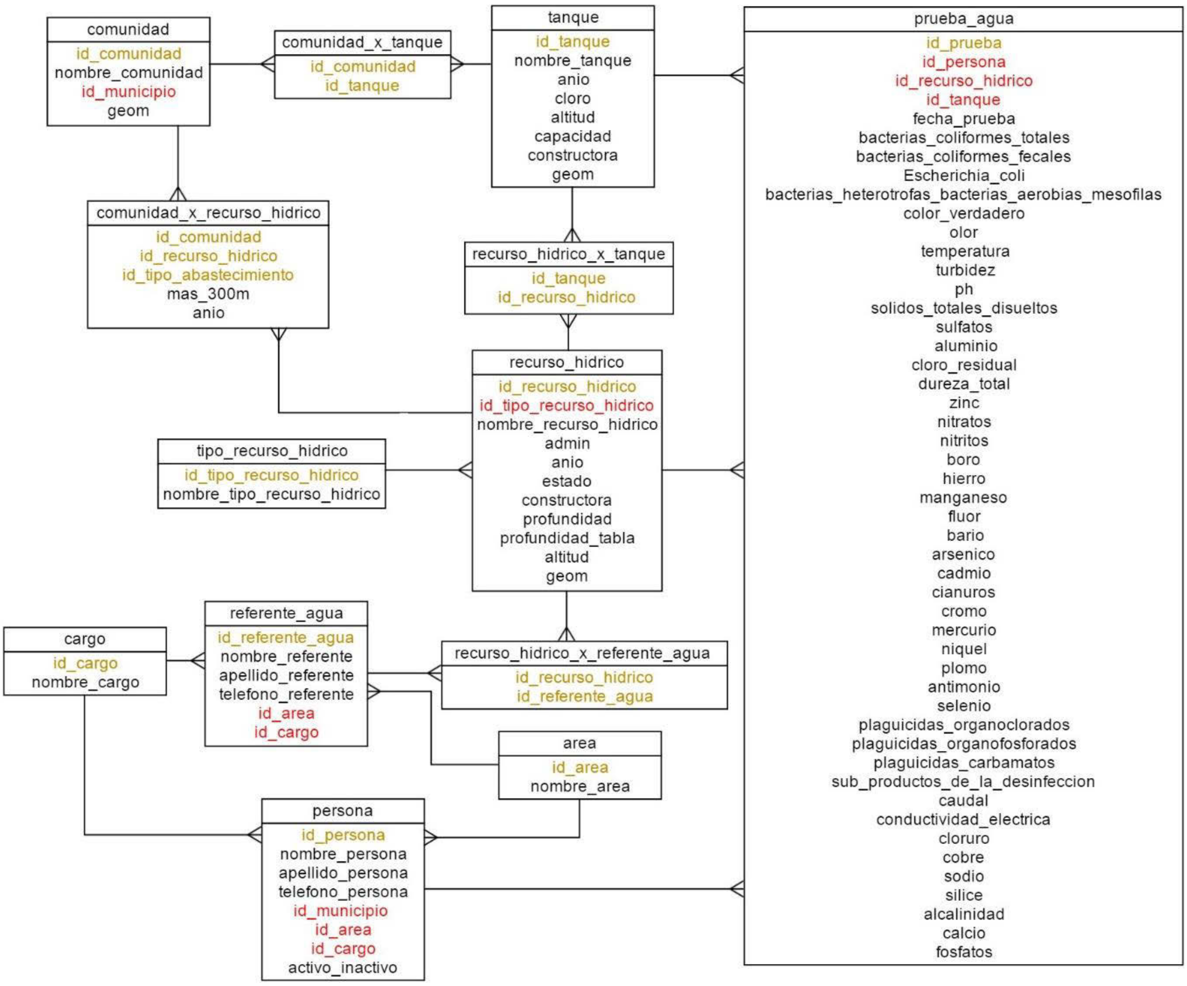

Figure 20: Part of the **entity relationship model** concerning water sources and water sampling (Ramos and Recinos, 2016).

The long ***table*** at the right side of Figure 20 contains information about water samples and has many affiliations to other ***tables***: a person (who is part of the ***table person***) has to take the sample of either a water source or a water tank. All of these **relations** are modelled as **one-to-many**, indicating that one person and one water source or water tank can participate in many **relationships** with water samples (i.e. a person can take various samples, a water source or water tank can have many samples taken from it). The entire **ERM** can be examined in the appendix (see chapter 9.3).

4.1.4 Set up database and implementation of local GIS data

The implementation of the unified GIS data was first undertaken in a local environment, thus the database software was installed on a local computer, as was the *PostGIS* extension of the database. The installation comes with an open source database management tool called *pgAdmin*, which serves as an interface for database operations. A database (*PostgreSQL* 9.4) was created with the following parameters:

- Database name: ***GIS_TECOLUCA_SV***.
- Port: 5433.
- Owner: *postgres*.
- Schemas: ***public***, ***geo***, ***interno***, ***prueba***.
- Extensions: *adminpack*, *PostGIS*, *plpgsql*.

After setting up the database the ***table definitions*** of the local students were restored onto a clean database, which provided information on the *column*, data types, **primary** and **foreign keys**, **entities** and **relations** but not yet any data. In the beginning all the ***tables*** were moved from the ***public*** schema to another schema called ***geo*** because otherwise when the database is backed up and restored into the ***public*** schema, there would occur a lot of errors (Ramsey, 2010), as it happened when restoring the ***table definition*** into the newly installed database for the first time. After this procedure it was possible to backup and restore the database without any errors. The advantage is that – once the database is fed – all the information of the database can be stored in one SQL file, which makes backing up and restoring the whole water information system very easy.

The implemented data can be distinguished between spatial and non-spatial data. The former are existing GIS data which is stored as **ESRI shapefile format** (**SHP**) though this **format** cannot store *column* names containing more than 10 characters. This was an impediment to the implementation process, as many *column* name titles are longer than 10 characters, while *PostgreSQL* databases do not have such restrictions. Non-spatial data is stored in files as **comma-separated values** (**CSV**), which can be edited by MS Excel.

Spatial data was entered by using the graphical interface of the command line program *shp2pgsql* on Windows, which is part of the *PostgreSQL* installation, and – when troubles occurred – the *Spit* plugin of *QGIS*. These are convenient ways to insert spatial data, as the *geometry column geom*, which stores the geographic location of objects using the **WKB format**, is added to the ***tables*** and the application assigns the geometry type (point, linestring …) to the ***tables*** automatically. Because of the prior mentioned limitations the file was inserted, the *column* titles had to be renamed and – where necessary – data types adjusted, so that they match with the **ERM** and the existing ***table definitions***. The order of the *column* titles of the **ESRI shapefile** has to match exactly the ***table definitions***, otherwise errors would occur or data is falsely written to the ***tables***. This was achieved by creating the right order with the plugin Table Manager of *QGIS*.

Once the *column* names matched, it was possible to first insert the ***layer*** into the database by using either *shp2pgsql* or the *Spit* plugin and then merge the empty ***table definition*** of the database with the inserted ***table*** containing the data by using the SQL command UNION. Figure 21 shows the SQL command which merges the ***table community*** with the existing ***table definition*** of community provided by the students.

```
INSERT INTO geo.comunidad
SELECT
FROM public.comunidades
UNION
SELECT
FROM geo.comunidad
```

Figure 21: Merging data table from schema ***public*** with ***table definition*** of schema ***geo***.

In some cases it was necessary to delete the existing *geometry column* of the ***table definitions*** and add it again (see Figure 22) because the order of the ***table definitions*** was wrong or certain parameters had to be changed (e.g. multi polygon instead of polygon).

```
SELECT AddGeometryColumn
('geo','rio_tecoluca','geom',4326,'MultiLineString',2);
```

Figure 22: Adding a *geometry column* (*geom)* – *PostGIS* extension.

Non-spatial data was inserted by using the SQL command COPY (see Figure 23). In most cases further alterations were not necessary.

```
COPY geo.rio_tecoluca_x_municipio FROM
'/Tablas/rio_tecoluca_x_municipio.csv' DELIMITER ';' CSV HEADER
ENCODING 'LATIN1';
```

Figure 23: Inserting relational ***tables*** by using the SQL command COPY.

Figure 24 shows a ***table*** called ***ngo*** storing the name of the object and geographic information.

id_ong [PK] serial	nombre_ong character varying(25)	geom geometry(Point,4326)
1	Cordes	0101000020E61000006696I
2	Aprainores	0101000020E6100000BC28I

Figure 24: Inserted data into ***table ngo***, with *ID*, *name of NGO* and *geometry column* (**WKB format**).

4.1.5 Checking database and creating views

During the implementation process the database gave hints whether **constraints** (**primary key**, **foreign key** rules) were violated making implementations impossible because the *PostgreSQL* database would stop the data from being inserted (e.g. missing **foreign keys** produce an error). The data ***tables*** had to have exactly the same order and data types as the ***table definitions***, which can be regarded as a first check whether the data was implemented well.

After having successfully implemented over 50 ***tables*** containing spatial and non-spatial data, the integrity of the database was checked by using the SQL command JOIN. It was checked whether the **relations** between 2 or more data ***tables*** were correct. Especially ***tables*** which contain information about water sources, tanks, communities, demographics and their **relations** were checked thoroughly. If mismatches had occurred, it would have been clear that the data was falsely implemented. Figure 25 shows the result of a SQL JOIN producing the name of the NGO and the community name as an output, which then can be checked.

id_ong integer	nombre_ong character varying(25)	id_comunidad integer	nombre_comunidad character varying(50)
1	Cordes	91	El Playon
2	Aprainores	54	San Carlos Lempa

Figure 25: Joining the ***table ngo*** with the ***table community*** via the relational ***table ngo_x_community***.

In order to increase the usability of the database the next step was to create VIEWS which join data of various ***tables*** throughout the database to visualize their relations. Figure 26 depicts a VIEW accessing information of several ***tables*** in the background.

id_comunidad integer	nombre_comunidad character varying(50)	id_recurso_hidrico integer	nombre_recurso_hidrico character varying(254)
1	Barrio Las Flores	20	Tecoluca Ciudad
38	Barrio Nuevo	31	Barrio Nuevo
2	Barrio San José Pasaquina	20	Tecoluca Ciudad
5	Barrio Santa Tecla	20	Tecoluca Ciudad
89	Betania 1	17	Marcial Gavidia 3
89	Betania 1	37	Marcial Gavidia 1
89	Betania 1	38	Marcial Gavidia 2

Figure 26: VIEW of communities and their water sources.

The following common VIEWS have been created:

- Communities and census.
- Communities, type of water supply and walking distance to water sources.
- Communities and water treatment.
- Communities and their water sources.
- Communities and their water tanks.
- Water sources and water tanks.
- Water sources and water resource type.
- Responsible person of water source and which water source.
- Water quantity, responsible person/laboratory and water source/tank.
- Microbiological water quality, responsible person/laboratory and water source/tank.
- Common water quality parameters, responsible person/laboratory and water source/tank.
- All water parameter (quality and quantity), responsible person/laboratory and water source/tank.
- Employees of Tecoluca, with telephone number and their section and function.

There are several water parameter VIEWS because the ***table water_sample*** incorporates a lot of parameters, which are not always of particular interest, and can make consultations rather confusing. Some laboratories measured parameters which do not comply with the Salvadorian standard, thus a common parameter VIEW has been generated, most importantly containing information on the electrical conductivity (though not part of the 2008 Salvadorian standard). The water quantity VIEW, only relates the delivery of springs with their respective sources or tanks, which is particular useful for analyzing temporal fluctuations.

The microbiological water quality VIEW automatically generates a *column* that indicates whether the water is potable or not. As long as the CFU equals zero the water can be considered as potable from a microbiological perspective, complying also with the Salvadorian norm (2008) (República de El Salvador en la America Central, 2008).

4.1.6 GeoServer

GeoServer was installed as part of the Boundless *OpenGeo Suite* application (see chapter 4.1.7). The software can be managed via a web administration interface through which all the following settings are adjusted. *GeoServer* needs to be set up as *WMS* in order for the web application to work and the data source (=database) has to be determined. In addition, *GeoServer* was set up as *WFS*, which facilitates e.g. *QGIS* to access vector data of the database. The following storage parameters have been applied:

- Workspace: ***websig***.
- Store: ***websig_bd***.
- Layers: all the incorporated ***layers*** of the database.
- Styles: generation of different styles for each ***layer***.

Within the workspace a store has been created (***websig***) connecting *GeoServer* with the *PostgreSQL* database. The database credentials and some general connection parameters were provided. It was then possible to publish point, line and polygon ***layers*** in *GeoServer* by using the implemented *WMS* standard. In the publish menu of the ***layers***, the extent of the ***layers*** have mostly been calculated automatically – in some cases though they had to be entered manually. All of the implemented ***layers*** of the database, which contain spatial data, have been published via *GeoServer*.

In the ***layer*** preview section, published ***layers*** can be viewed in many formats:

- As *WMS*: Image output. Formats: E.g., GIF, JPEG, *OpenLayers*.
- As *WFS*: Text and data output. Formats: E.g., **CSV**, **GeoJSON**, **ESRI Shapefile**.

For convenience and information gain some non-spatial ***tables*** were merged with spatial ***layers*** by using SQL VIEWS. Such as:

- Water sources and water source type.
- Community, census data, water sources and water tank.

These ***layers*** not only contain information on their geographic location but also additional information, which was fetched from other related ***tables*** of the database.

GeoServer layer styles

GeoServer uses the very capable **XML**-based markup language Style Layer Descriptor (*SLD*) to visualize geospatial data (Geoserver, 2016a). In *QGIS* the ***layer*** style can be created according to the needs and then saved as a *SLD* file. The *SLD* cookbook also provided ideas, explanations and examples of a lot of styles (Geoserver, 2016b).

Geoserver ships several preconfigured ***layer*** styles for different geometry types (points, lines, polygons). For almost each ***layer*** a *SLD* file has been created with proper settings. In some cases it was only necessary to change the appearance settings, while in other cases, rules had to be applied to conditionally render different ***layer*** stylings according to the represented features.

The following methods have been used to create ***layer*** styles:

- Use preconfigured styles in *GeoServer*, adjust minimal settings, such as feature color (hexadecimal code) or stroke width, and apply ***layer*** styles to respective ***layers***.
- Create ***layer*** style in *QGIS*, export *SLD* file and import into *GeoServer*.
- Use ***layer*** style templates created by the *SLD* cookbook of the *GeoServer* documentation and change them to needs (Geoserver, 2016b).

The ***layer community*** consists of community and census data. The size of the points (=communities) is divided into three classes (small, medium, large). The filter function of the *SLD* language has been applied, allowing to specify the threshold values for depicting features. For each of the three classes rules have been defined at different zoom levels, being able to tweak the appearance exactly to the need (see Figure 27).

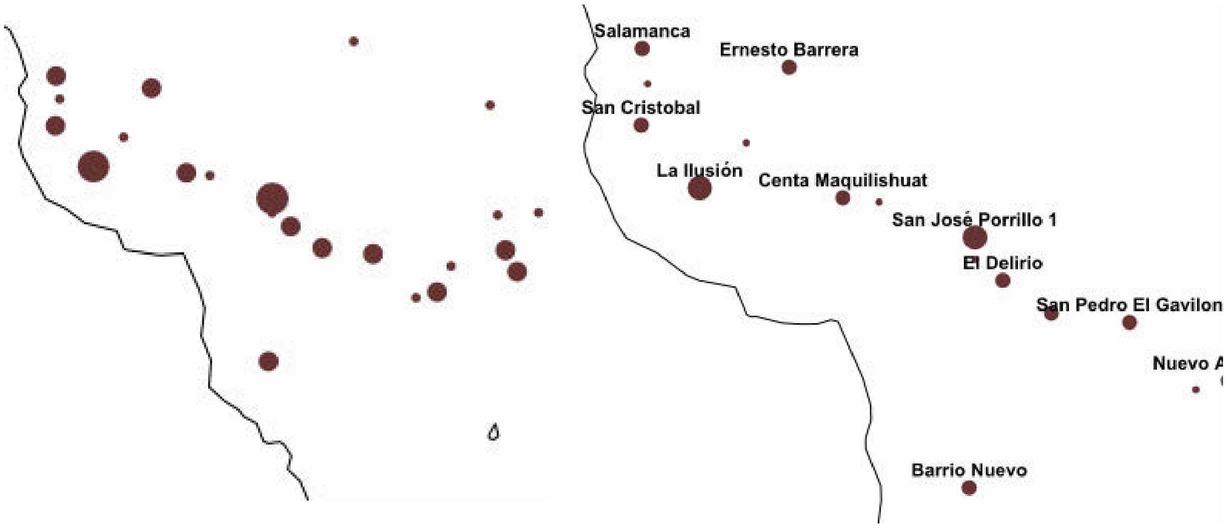

Figure 27: Rule based ***layer*** style: conditionally rendered community size depending on size of population, at certain zoom level additionally labels render.

GeoServer security

As *GeoServer* will be exposed to the World Wide Web, it has to actively handle web request from anybody all over the world and, therefore, should be well protected against possible adversaries. The following general security precautions have been undertaken:

- Passwords are encrypted before writing them to a text file within the data directory of *GeoServer*.
- The URL parameters are also encrypted.

There are four user types/roles:

- Admin
- Editing user
- Viewing user
- Anonymous user

Naturally admins are able to adjust any setting of their *GeoServer* instance. They can apply changes to each and every setting of every setting section (data, services, settings, tile caching, and security). They are fully capable of using all the *WMS* and *WFS* features, including transaction, which allows manipulating feature data via e.g. *WFS* capable applications, such as *QGIS*. The admin is responsible for the creation of the users and for setting the passwords of other users.

However, there exists a root account, which is always active, and cannot be deleted. The reason is because of the "highly configurable nature of *GeoServer*" (Boundless OpenGeo Suite, 2016c) which could result in total malfunction of the server. Even if the administrator locked himself out, *GeoServer* can be repaired via root access.

Editing users are granted full access to the data settings section of *GeoServer*, including options to create workspaces, stores, ***layers***, ***layer*** groups, styles and to import data. It is thus possible to publish ***layers*** and style them. They have all the rights to access the *WFS*, excluding transaction requests and they have full access to the *WMS* functionalities (*GetCapabilities*, *GetMap*).

Viewing users are only allowed to preview ***layers*** from the workspace ***<u>websig</u>*** in the *GeoServer* web interface. As for the web services (*WMS*, *WFS*), viewing users have the same rights as editing users but only for the publicly available workspace ***<u>websig</u>***.

Anonymous users are allowed to view the workspace ***<u>websig</u>*** but only by having access to *WMS* functionalities. They can neither create, edit, analyze nor retrieve data by other means (import data, *WFS*). Table 9 summarizes the *GeoServer* settings depicting the users of the WIS, their roles and access to data and web services.

Table 9: *GeoServer* users, their roles and access to data section (create, edit, delete data) and web services.

<table>
<tr><th>User</th><th>Role</th><th>Data access</th><th>WFS</th><th>WMS</th></tr>
<tr><td>Raquel Medina</td><td>Admin</td><td rowspan="3">full</td><td>yes (transaction)</td><td rowspan="7">yes</td></tr>
<tr><td>Herberth Sanabria</td><td rowspan="2">Editing user</td><td rowspan="5">yes</td></tr>
<tr><td>Edin Hernández</td></tr>
<tr><td>BOKU</td><td rowspan="3">Viewing user</td><td rowspan="4">preview public workspace</td></tr>
<tr><td>Intersol</td></tr>
<tr><td>UCA</td></tr>
<tr><td>Anonymous user</td><td>Anonymous user</td><td>no</td></tr>
</table>

GeoServer performance – tile caching

GeoServer uses GeoWebCache in order to increase the performance of the web-GIS (see chapter 3.2.3). In the ***layer*** settings menu of *GeoServer* there is a tile caching option. For every ***layer*** it was assured that tile caching was active and tiles were created, using both JPEG and PNG image formats.

GeoServer Backup

The data directory of *GeoServer* was backed up several times in the process, saving all adjustments concerning general settings (name, contact information), data section (workspaces, stores, ***layers*** and styles), specific settings (web service settings) and security settings. In the case of malfunction, server failures or misconfiguration it is fairly easy to restore all the settings again, simply by substituting the data directory of the newly installed *GeoServer* instance with the already configured settings.

4.1.7 OpenGeo Suite

OpenGeo Suite is a geospatial platform that allows managing geo data and facilitates the development of web maps significantly. It uses open standards (OGC), consists of open source software, supports various database technologies and runs on every platform. It can be used for free and is actively developed. A multitude of software packages can be used, thus making it very interoperable (Boundless OpenGeo Suite, 2016b). In the case of the master's thesis the following components have been used – as part of the *OpenGeo Suite*:

- *PostGIS* extension for *PostgreSQL* databases
- *GeoServer*
- GeoWebCache
- *OpenLayers*
- *Boundless SDK* – GXP Template

QGIS is not part of the *OpenGeo Suite* per se but the *OpenGeo* team puts a lot of effort into integrating *QGIS* with *OpenGeo Suite* as much as possible. A lot of plugins are being developed extending the functionalities of *QGIS*. The *GeoServer* Explorer plugin for *QGIS* allows to upload

QGIS projects (including all the ***layers*** and styles) to a *GeoServer* instance (Boundless OpenGeo Suite, 2016d).

There are several options to develop a web map with *OpenGeo*. The Composer and *GeoExplorer* application of *OpenGeo Suite* are WYSIWYG editors for creating web maps. There exists a plugin (Web App Builder for *QGIS*) that allows publishing ***layers*** from *QGIS* directly to web maps (Boundless OpenGeo Suite, 2016d). The Boundless Software Development Kit (SDK) allows building complete web applications by providing editable templates. There are two templates available: GXP template and *OpenLayers* templates.

4.1.8 Browser application

The web-GIS application was developed by using *OpenGeo's Boundless SDK*, which allows working in a productive manner. The development of the web map was carried out using the GXP template as a base, which can be created easily (see Figure 28) by using the command line program suite-sdk (as part of the *OpenGeo Suite*). The application can be run and debugged by the implemented server of *Boundless SDK* and runs via localhost on port 9080 (http://localhost:9080/application_name).

```
suite-sdk create \application_name gxp
suite-sdk debug \application_name
```

Figure 28: Create and debug GXP template browser application.

After the creation of the template it is stored in several directories, which contain stylesheets (*CSS*), JavaScript toolkits and frameworks (Ext JS, GeoExt), the *OpenLayers* library, GXP-specific plugins and widgets, and an index *HTML* file, which includes all necessary source codes to run the application successfully.

The Ext JS framework facilitates the development of JavaScript applications by providing interface widgets, such as panels, trees and grids. GeoExt combines *OpenLayers* functionalities with Ext widgets for geospatial purposes (Boundless OpenGeo Suite, 2012).

The basic template

The basic GXP template is composed of two panels. In the left panel there is a simple **layer** tree consisting of two ***layer*** groups: overlays and ***base layers***, with *OpenStreetMap* (as a ***base layer***) already implemented. The main panel is the viewer in which the geospatial information can be examined, by combining a **base *layer*** and overlay(s). The control buttons can be placed in the viewer, the left (tree) bar or the context menu of the ***layer*** tree. Several GXP plugins are already preconfigured:

- LayerTree
- Zoom
- ZoomToExtent
- NavigationHistory
- AddLayers
- RemoveLayers

The plugins for adding and removing ***layers*** (AddLayers, RemoveLayers) have been removed because this function can be substituted by checking and unchecking the ***layers*** to the needs of the user.

General settings and layers

The development of the web application was undertaken in a configuration file, which is stored in the source directory of the template. The so called app.js file is written in JavaScript, which itself has several dependencies, such as other JavaScript code for GXP plugins or widgets. It is then loaded into the index.html in the root directory of the application.

The app.js file handles configurations concerning the panels of the application, plugins, ***layer*** sources and published ***layers***. In the configuration file the projection is set to a projected coordinate system in this case called EPSG:900913. It is also known as EPSG:7483 or EPSG:3857 (from now on referred to as EPSG:3857), which is the nomenclature preferred by *QGIS,* and is used by common web map applications, such as *Google* and *OSM* (Butler et al., 2016b). The coordinates which are specified in EPSG:3857 are provided to center the shape of Tecoluca (see Figure 29). The default zoom level (11) allows to view the whole municipality of Tecoluca when loading the application. The locale has been changed to Spanish, so that the ***layer*** menus and tools are depicted in the local language.

```
id: "mymap",
title: "Sistema de Información de Agua ",
projection: "EPSG:900913",
center: [-9885000, 1509000],
zoom: 11
```

Figure 29: General settings concerning the map item of the configuration file.

By default *WMS* are implemented as a ***layer*** source. After specifying *GeoServer's* workspace, ***layer names*** and several other optional parameters (title, **layer** group …), the geodata provided by the *GeoServer's WMS* are loaded into the viewer (see Figure 30). This has been done for all the published *GeoServer* ***layers***. ***Base layers*** are *OpenStreetMap* (preconfigured) and *Google* satellite images for additional information.

```
source: "local",
name: "websig:geologia",
title: "Geología",
group: "medio_ambiente",
visibility: false
```

Figure 30: Adding ***layer geology*** of the workspace ***websig*** via *WMS* to the browser application configuration file.

Customizing application appearance

The GXP template was extended by a legend and a foot panel. The legend panel hosts the GXP legend plugin and was placed on the right side of the viewer, making it possible to see the active ***layers*** and their legend items.

The foot panel consists of a copyright claim, help and login button to the *GeoServer* web interface. This was achieved by inserting *HTML* code into the items section of the configuration file. Basic *HTML* tags were used to insert hyperlinks, images, while styles were implemented via *CSS* commands. When clicking the help button a window opens, which briefly explains the use of the web-GIS. A small chunk of JavaScript code was inserted into the index file in order for the help window to open, using the JavaScript function window.open (see Figure 31).

```
items: {
id: "foot",
xtype: "panel",
html: "<p style=\"font-size: 11px; font-family: Tahoma;
position:absolute; right:9px\">La página fue diseñada por la <a
href=\"http://www.alcaldiadetecoluca.gob.sv/\">Alcaldía de
Tecoluca</a> 2016 - <a href=\"mailto:
alcaldia.tecoluca@yahoo.es?Subject=Web-SIG Tecoluca\" target=\"_top\">
Contacto</a> - <a href=\"ayuda.htm\" onclick=\"return
ayuda('ayuda.htm')\">Ayuda</a> - <a href=\"/geoserver/web/\"
target=\"_parent\">Login</a>"
      }
```

Figure 31: Foot panel with copyright and contact information.

The left container has been modified so that it contains two panels. The upper panel hosts the logo of Tecoluca and – when clicked – redirects to the homepage of the town hall of Tecoluca, while the lower one features the ***layer*** tree.

Plugins and widgets

The following plugins have been implemented additionally:

- Legend
- *WMSGetFeatureInfo*
- ZoomToLayerExtent
- Measure
- GoogleSource

The only additionally implemented widget was a scale, both numerical and visual.

Packaging and deploying the application

By packaging the application a web archive (WAR) file was created by using the *Boundless SDK* command line program (see Figure 32). This is necessary to "concatenate and compress" only JavaScript resources which are to be implemented into the application (Boundless OpenGeo Suite, 2016a).

```
suite-sdk package \application_name
```

Figure 32: Creating a WAR file by packaging the application.

The WAR file must be stored in the webapps folder of the *OpenGeo's* embedded webserver jetty. It is automatically being unpacked in the process and can be reached locally by calling http://localhost:8080/appname in the web browser.

4.1.9 Setting up the server

The development of all the components of the web-GIS were undertaken locally so far. The overall goal of course is the implementation of the web-GIS into the World Wide Web. During the process it was discussed with the members of the town hall how to actually deploy the web-GIS into the web. A major prerequisite was that the server is able to handle geospatial requests, i.e. must be able to run a *GeoServer* instance and/or set up and run *OpenGeo Suite*.

Several solution came up:

- Hosting solution: Virtual private servers (VPS).

- *GeoServer* or *OpenGeo* hosting.
- Set up components on the server of the town hall.

The hosting options require a monthly payment, which over the years can be significant. The most convenient solution was to set up all the required components on the server of the town hall, which is locally reachable in the office, and was used for the sole purpose of local IP management (DHCP server). The operating system of the server is Windows Server. The following components were installed and set up:

- *PostgreSQL* with *PostGIS* extension.
- *OpenGeo Suite* which includes *GeoServer* and *GeoWebCache*.

The local database and all its information on the computer of the author was backed up. After having installed *PostgreSQL* and the *PostGIS* extension on the server, a new database was created and the backed up data was restored without any errors.

The *GeoServer's* data directory of the server was replaced with the respective *GeoServer* data directory, which include general settings, ***layer*** data, styles, workspaces and stores of the local computer of the author. Once the *GeoServer* instance was restarted all the configuration was set up properly.

At this stage it was possible to access the server within the local area network (LAN) by calling the server internal IP address. The internal port on which *OpenGeo* runs was changed from 8080 to 80, by tweaking the file start.ini of the jetty servlet within the *OpenGeo* jetty directory (Boundless\OpenGeo\jetty). Normally the port 80 is used by standard web servers. As the server of the town hall does not serve as a web server though it was possible to change the port without producing any conflicts.

The final task was to make sure that the web-GIS is actually reachable from everywhere. The person responsible for IT of the town hall of Tecoluca acquired a public IP address, exposing the server to the World Wide Web. After reconfiguring the firewall settings to allow connections from and to the server on port 80, it was possible to access the WIS from everywhere in the world.

At the same time it was assured that the web application of the WIS was promoted, so that interested people can use it, thus embedding it into the homepage of the town hall. A logo was created by the head of the communications department of the town hall Manuel Gutiérrez (see Figure 33). It was placed in the left panel and – upon clicking it – redirects to the web application.

Figure 33: Logo of the water information system of the municipality of Tecoluca (Gutiérrez, 2016).

4.2 Training in the usage of the water information system

After the successful implementation of the WIS on the server of the town hall, it was paramount to record the features and functionalities of the system and provide trainings to the future users.

4.2.1 Composing a manual

A manual has been composed on the usage of the WIS, which was then printed, and officially handed out to the town hall. It consists of three parts:

- Installation and maintenance
- Database and *GeoServer*
- GPS, coordinates and *QGIS*

The manual is written in a manner that even non technophile computer users are able to follow the instructions. The first part depicts the installation and setup process of the whole WIS, should the server – for whatever reason – fail (hard drive failure, misconfiguration of the server, change of hardware …). The second chapter describes the handling of the database and some basic theoretical information (***tables*** and their **relations**) and how to add ***layers*** to a *GeoServer* instance. The third chapter is divided into three subchapters.

- GPS and coordinates: How to measure coordinates (**waypoints** and **tracks**) with the GNSS-enable device (Garmin eTrex 20) and what is important to avoid in order to increase the accuracy of coordinate measurement and theoretical background on coordinate systems.
- *QGIS*: How to add coordinates to *QGIS*, some basic GIS functionalities (attribute tables, ***layer*** styles) and most importantly, adding measured coordinates to existing ***layers***.
- Database and *QGIS*: How to work with geospatial databases (*PostgreSQL*) in *QGIS* (BD Manager).

4.2.2 Training in the usage of the WIS

Trainings in the usage of the WIS were organized with the future admin and editing users of the WIS (see Table 9), volunteers and other interested people. The computers of the communal house which were provided by USAID offered excellent computers on which the application were installed. The trainings not only consisted of practical exercises of computer programs but also of theoretical background. The contents of the course are reflected in the manual.

Several theoretical key concepts were taught:

- What is a GIS? What are common geometry types?
- What is GPS? How is it possible to determine the position on the earth's surface?
- What are Coordinate Reference Systems?
- Geospatial databases: What are ***tables*** and **relations**?

After each theoretical input the participants were giving a task, which was explained and solved with the help of the instructor. After having finished the task together, an extra task was assigned, which were to be solved by the participants themselves.

5. Results and discussion

5.1 Water information system

The WIS consists of different components, each of which allow to access non-geo and geospatial data. The user is able to use the following application to connect to the WIS:

- Web-GIS browser application to view geospatial data.
- Database containing non-geo and geospatial data.
- *QGIS* for creating, inserting and analyzing geospatial data.
- *GeoServer* direct access.

Access data via the browser application

Figure 34 depicts the WIS scheme. A (mobile, stationary) device can access the browser application by sending a HTTP request to the web server. The web server cannot handle geographic requests, thus it redirects the request to *GeoServer*. *GeoServer's* workspace and stores are set up to connect with the *PostgreSQL* database, which itself is extended with the *PostGIS* extension. All non-geo and geospatial data is stored in the database. The database delivers the requested information to *GeoServer*, which conveys the desired information to the web server in the desired output **format** (*WMS*, *WFS*). The web server responds the request of the user by sending the data in the appropriate file **format**.

Access data from the database directly

The user is able to directly access the database (see Figure 34) by using database tools, such as *pgAdmin* or *DbVisualizer*. Entering the database this way is potentially harmful, as the user has full access to the database, thus not only being able to edit the data at will but to create schemata, new databases or potentially delete everything. Only the admin has access to the database directly via the user *postgres* and the respective password.

Access data via QGIS

Users are able to access geospatial data via *QGIS*, either by using *WMS* or *WFS*. *QGIS* directly communicates with *GeoServer*, avoiding the need to communicate with a web server (see Figure 34). The *WMS* only provides the user with images (raster data), which on one hand has the advantage that the ***layer*** styles, which were applied on the *GeoServer* level, are loaded but on the other hand cannot be further examined because it is not possible to access the attribute table. The *WFS* functionality of *QGIS* provides vector files, which allows to view the attribute table for further examining, however, the style needs to be adjusted manually via the properties menu of *QGIS*.

Access data via GeoServer (web interface)

Users can also connect to *GeoServer* directly by calling the *GeoServer's* web interface. Even anonymous users are allowed to preview ***layers*** on a *WMS* basis. They can choose from a multitude of formats to export the desired ***layers***.

Access data via GeoServer (URL)

Users can retrieve *WMS GetMap* requests, as in Figure 11, determining many parameters, so that the requested map satisfies the needs of the person.

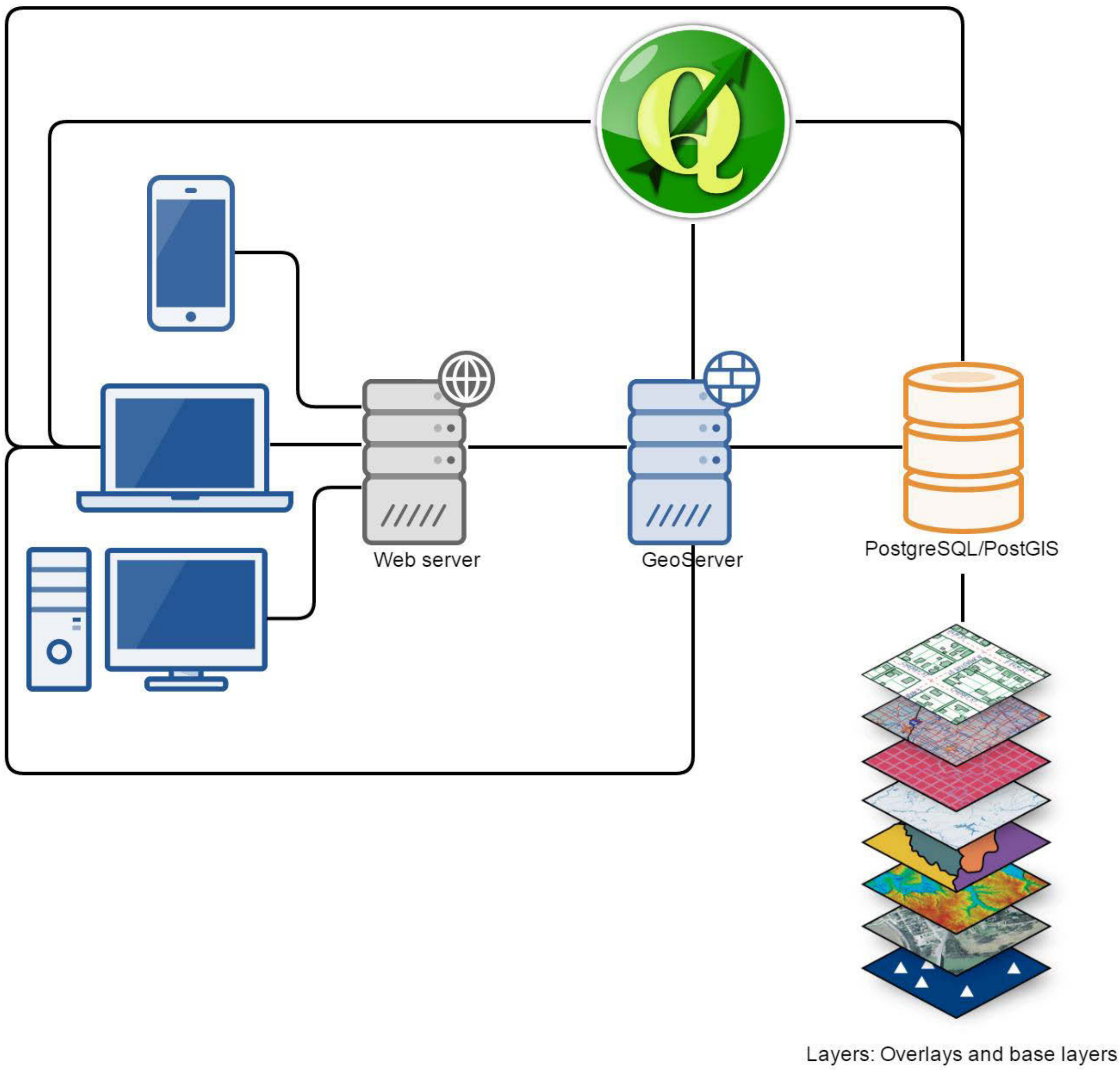

Figure 34: WIS scheme of the municipality of Tecoluca (IGIC, 2016).

Access interfaces via web browser

Table 10 depicts various interfaces, which can be accessed by typing the IP address into the web browser. In most cases the user will be an outsider who needs to call the public IP address of the server in order to be able to connect to the services. People working at the town hall, who have physical access to their LAN, can also connect by using the internal IP address, while only people having direct access to the server may use the internal IP address of the computer. The following IP addresses – depending on location – provide access to the services of the WIS:

```
http://216.184.100.195/
http://192.168.10.6/
http://localhost/
```

Combining the IP address with Table 10 provides access to the *OpenGeo* dashboard, which can be seen as the visual front-end of the *OpenGeo Suite*. The dashboard offers a variety of documentations and provides links to the *GeoServer* and *GeoWebCache* interface. *OpenGeo's GeoExplorer* can also be accessed, which enables the user to quickly generate web maps.

Table 10: Various options of connecting to web-GIS with a modern browser.

Hyperlink	Destination
http://ip-address/	OpenGeo's Dashboard
http://ip-address/sig_tecoluca/	Browser application
http://ip-address/geoserver/web/	GeoServer web interface

5.1.1 Web-GIS browser application

The app can be called by typing the following URL into a modern JavaScript enabled web browser:

```
http://216.184.100.195/sig_tecoluca
http://192.168.10.6 /sig_tecoluca
```

The web-GIS browser application provides the following features:

- Geospatial information organized in ***layer*** trees in proper lower left panel.
- View geospatial data in main panel.
- View legend items in right panel.
- Logo of the municipality in the upper left panel, with hyperlink to town hall's homepage.
- Zoom features: Zoom in/out, zoom to extent, zoom to layer extent, and zoom to previous/next extent.
- Measurement tools: Determine length and area of geospatial objects.
- Retrieval of feature information: View **attributes** of selected feature.
- Provision of ***base layers***: *OpenStreetMap* and *Google* satellite.

The browser application can be used by the interested public to examine the geographic data of the water sources in the municipality of Tecoluca. By combining ***layer*** overlays with ***base layers*** it is possible to interpret or analyze the data to a certain degree.

The tools of the web application can be selected in the toolbar located in the upper part of the main panel (see Figure 35).

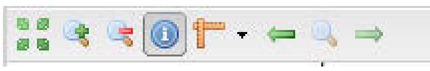

Figure 35: Toolbar of the browser application: zoom features, retrieval of ***layers'*** **attributes** and measurement tools.

The ***layers*** are thematically organized in groups (see Figure 36):

- Drinking water
- Water resources
- Infrastructure
- Locations of local importance
- Relief
- Environment
- Administrative borders
- ***Base layers***

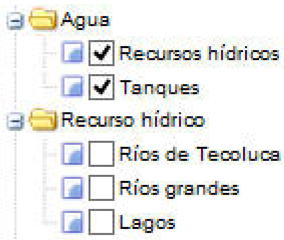

Figure 36: Layer tree: ***layer*** groups and ***layers***.

The legend items are depicted in the right panel of the browser application, depending on the selected ***layer*** overlays (see Figure 37).

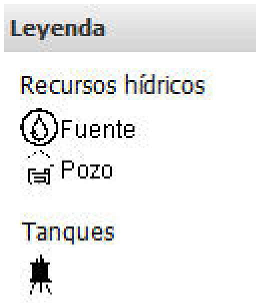

Figure 37: Legend items: water sources and water tanks. The legend items are displayed when checked in the ***layer*** tree bar.

The *OpenLayers* function *WMSGetFeatureInfo* provides information of a selected feature upon clicking on it. A popup opens and lists attribute name and their respective values in a grid. If more than one feature is selected because of ***layer*** overlays, it is possible to select which feature to view (see Figure 38).

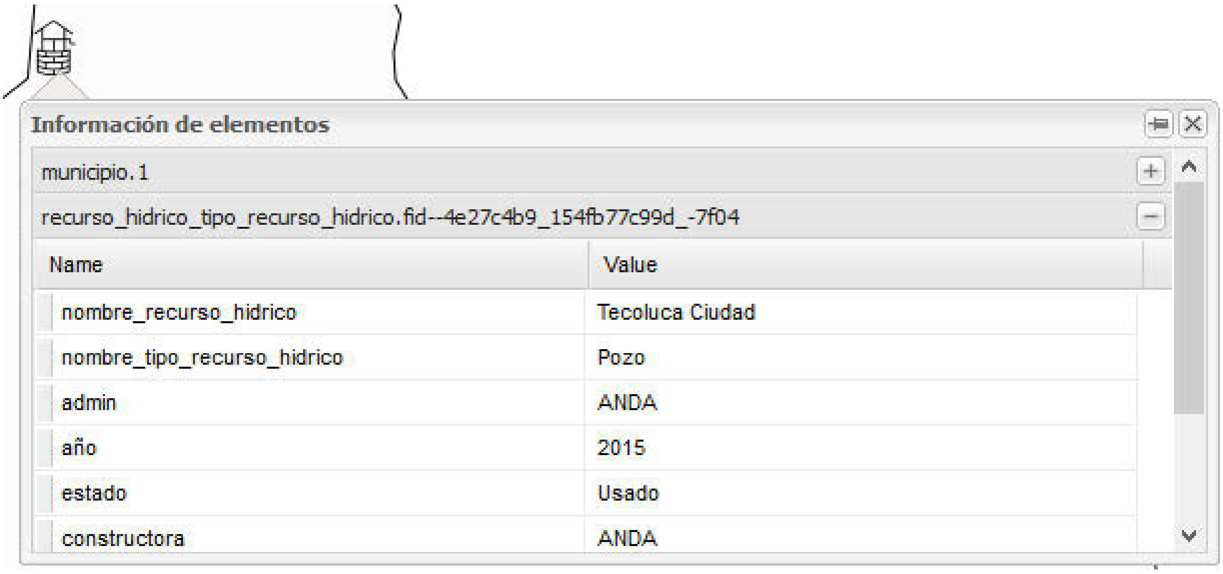

Figure 38: Feature information of water source (name, water source type, administration, year, state, and constructor) and the ***layer municipality***, which is overlain by the ***layer water source***. In this case the well of Tecoluca town.

The measurement tool provides the functionality for determining length (meters and feet) and area (square meters and square feet) (see Figure 39 and Figure 40).

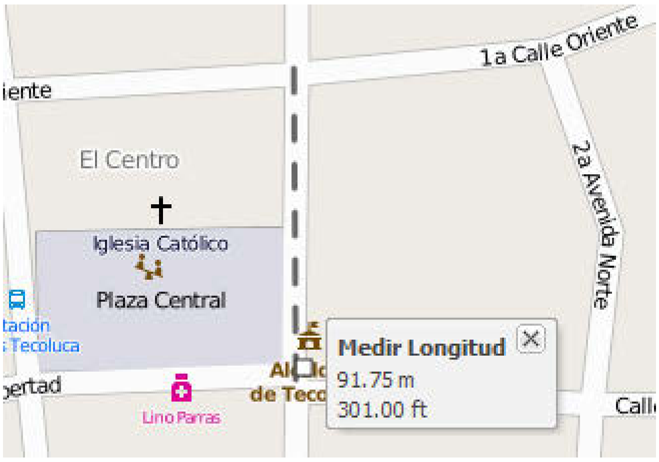

Figure 39: Measuring the distance between the town hall and the next intersecting street.

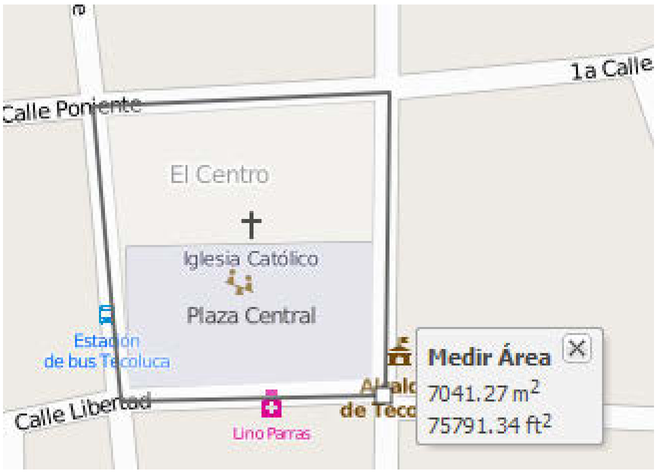

Figure 40: Measuring the area of the main plaza of Tecoluca.

As discussed in chapter 4.1.8 a scale was implemented (see Figure 41).

Figure 41: GXP widget: scale.

5.1.2 Database

The database named ***GIS_TECOLUCA_SV*** currently consists of 4 schemata, 52 ***tables*** (non-geo and geospatial information) and 13 VIEWS. Direct access to the database is useful when working with non-geo data, such as water quality parameters.

One of the biggest advantages of having all the data in one location is that backups are really easy because information of the database can be stored in one SQL file, containing all the parameters, ***table definitions***, **constraints** and data, thus restoring a database in another environment is just a matter of minutes.

At the moment data can only be accessed by *pgAdmin* or SQL commands, making it possible to draw conclusions on different water parameters on a temporal scale. The data can be exported to **CSV** and further analysed in e.g. MS Excel. The following paragraphs show exemplary analyses.

Exemplary analyses

Table 11 shows the results of the measurement of the delivery of the spring tapping "El Milgaro", which – despite observations of the local population – seems to not have declined in the recent past. Though because of lack of data the information cannot be used for further conclusions.

Table 11: Delivery of spring tapping "El Milagro" on three occasions, filtered by spring tapping and timestamp.

nombre_recurso_hidrico character varying(254)	nombre_persona character varying(50)	apellido_persona character varying(50)	fecha_prueba timestamp without time zone	caudal numeric
El Milagro	Verena	Schaidreiter	2015-04-17 09:00:00	0.84
El Milagro	Marion	Liemberger	2016-04-11 09:00:00	0.82
El Milagro	Marion	Liemberger	2016-06-15 15:30:00	0.84

Table 12 summarizes the CFU of the microbiological parameters "total coliform bacteria" and "E. coli" of the drilled well "Trinidad" of chlorinated (parameter "residual chlorine" in mg/l) and untreated water from 2008 to 2015. Naturally, there is a link between the presence of chlorine and bacteria. In one case, however – in 2012 – it seems that the water was so contaminated that even though it had been chlorinated, there was still bacteria left. The untreated water exceeded 100 coliform bacteria and *E.Coli* colonies. Generally, it can be said that it is not advisable to drink untreated water at this water source site, even though it may sometimes not be contaminated at all, because at other occasions the probability of contamination seems to be very high.

Table 12: Microbiological parameters of the drilled well "Trinidad" over the years.

nombre_recurso_hidrico character varying(254)	fecha_prueba timestamp without time zone	bacterias_coliformes_totales numeric	escherichia_coli numeric	cloro_residual numeric
Trinidad	2008-02-18 14:45:00	0	0	0
Trinidad	2012-06-19 10:30:00	15	9	0.1
Trinidad	2012-06-19 11:00:00	100	100	0
Trinidad	2013-06-06 15:30:00	0	0	0.3
Trinidad	2013-06-06 15:40:00	0	0	0
Trinidad	2013-09-25 15:40:00	0	0	2.1
Trinidad	2013-09-25 15:55:00	0	0	0.4
Trinidad	2014-05-13 09:47:00	7	0	0
Trinidad	2014-05-13 10:12:00	0	0	0.3
Trinidad	2015-01-19 09:35:00	6	0	0
Trinidad	2015-01-19 09:40:00	0	0	0.5
Trinidad	2015-10-01 10:15:00	0	0	0.2
Trinidad	2015-10-01 10:40:00	2	0	0

5.1.3 QGIS

The following *QGIS* functionalities allow to access the WIS:

- *WMS* via *GeoServer*.
- *WFS* via *GeoServer*.
- ***Tables*** via *PostgreSQL* database

Figure 42 shows the dialog box with some of the available ***layers*** of the web-GIS, which can be added to *QGIS*, viewed and further analyzed. The name of the ***layer*** consist of the workspace name (***websig***) and the ***layer name*** (e.g. ***canton***), the title of the ***layer*** and a brief description of its content. *WFS* ***layers*** can be added to *QGIS* almost the same way.

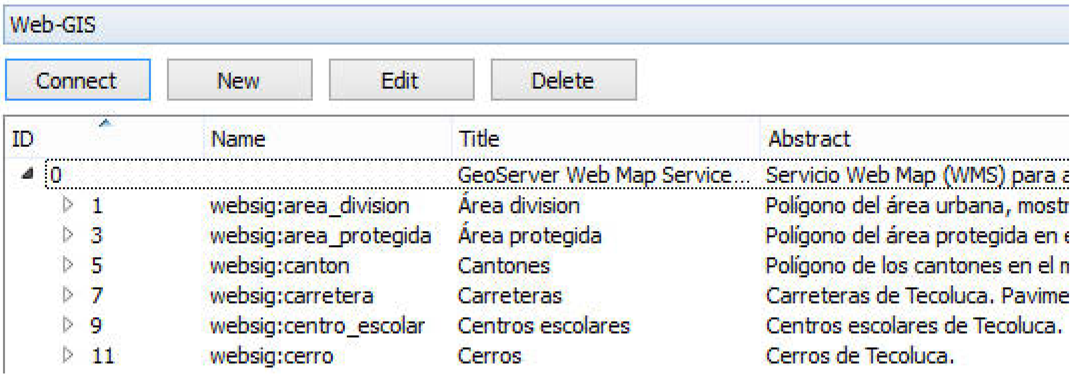

Figure 42: Accessing ***layers*** via *WMS* in *QGIS*.

It is possible to add ***layers*** by connecting to the database directly. The ***layers*** are grouped by schemata (in this case ***geo***) in which all of the ***tables*** can be seen. The name of the *geometry column* (*geom*), the geometry type (point, polygon …) and the **SRID** give further information on the ***table*** (see Figure 43).

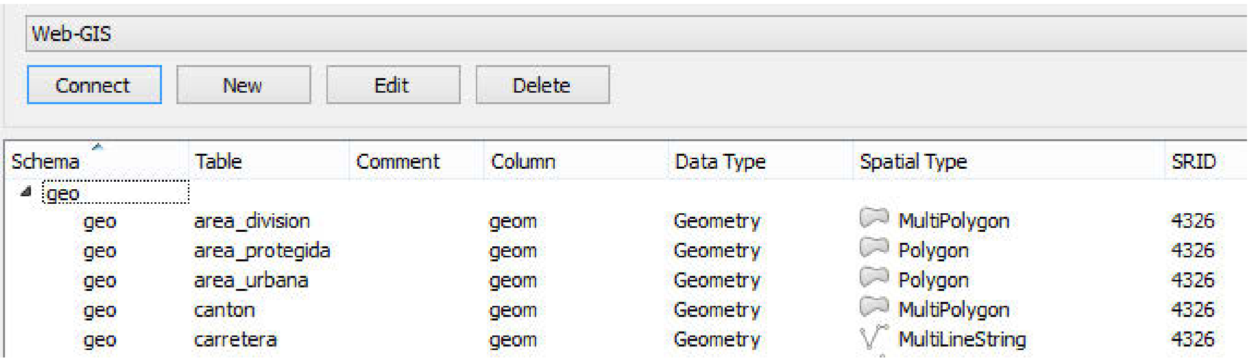

Figure 43: Direct access to *PostGIS* tables in *QGIS*.

5.1.4 GeoServer

Users of Table 9 are able to log into the web interface, each of which having different rights. Anonymous users cannot log into the system – while viewing users can – but neither of them are able to use further features of the web interface but to preview the ***layers***. Editing users have access to the data section (see Figure 44), being able to edit the subsections to their needs.

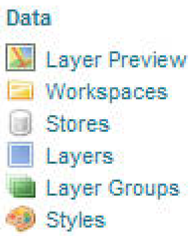

Figure 44: Data section of the *GeoServer* web interface.

Users – depending on their access authorization – are also able to query *GeoServer* web services via URL. Anonymous users can use requests concerning *WMS* (see Figure 45), while viewing users (and users with higher rights) are able to perform *WFS* requests, too (see Figure 46).

```
http://216.184.100.195/geoserver/websig/wms?service=WMS&version=1.1.0&requ
est=GetMap&layers=websig:tanque&styles=&bbox=-88.86,13.24,-
88.68,13.61&width=373&height=768&srs=EPSG:4326&format=image%2Fjpeg
```

Figure 45: Calling the ***layer water_tank*** as JPEG image via *WMS GetMap* request.

```
http://216.184.100.195/geoserver/wfs?service=wfs&version=2.0.0&request=Get
Feature&typeNames=websig:tanque&outputFormat=csv
```

Figure 46: Downloading the ***layer water_tank*** as **CSV** file via *WFS GetFeature* request.

5.2 Problems and challenges

Water related data and data accuracy

For now there are only basic **relations** on water issues (e.g. which water source is supplying which community). Aforesaid **relations** are not even complete.

The data provided in the WIS is partly inaccurate, especially geoinformation which was provided by different data sources. E.g. the course of the river does not correspond to the ***layer municipality***, while the ***layer protected_area*** (green area) was made fit by redrawing the polygons (see Figure 47). It was contemplated to georeference every inaccurate ***layer*** to the ***layer municipality*** but this approach was quickly disregarded, as this would possible worsen the accuracy.

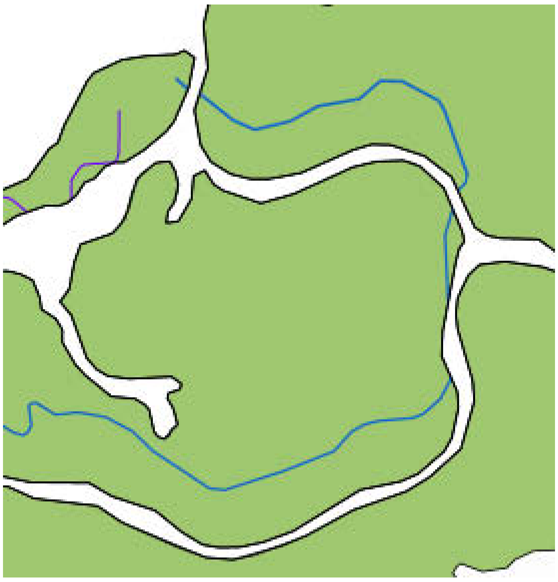

Figure 47: Data inaccuracy: ***layer river_tecoluca*** does not correspond with ***layer municipality*** (black outline).

Coordinates measurement and CRS projections

Coordinates which were measured by the author with a GNSS-enabled device are also subject to inaccuracy because of the nature of the measurement of satellite global positioning and the lack of further technologies (e.g. DGPS), which could have improved the accuracy of the measured objects. It can be assumed that the measured coordinates of the Standard Positioning Service (SPS) – based on a 95% probability level and a measurement interval of 24 hours averaged over all points – deviate up to 13 meters horizontally and 22 meters vertically from their actual position, while other studies show that horizontal and vertical errors are below 50 meters for a probability level of 99.99% (Hofmann-Wellenhof et al., 2008). As the WIS is currently not used as a base for technical projects which rely on more precise data, the inaccuracy can be accepted. Water sources and tanks which are located within a 10 meter radius are hard to distinguish, in the majority of the cases though the water sources and tanks can be assigned without any problems. If the WIS will – in future – however, be extended to e.g. provide the position of water meters, more accurate data would be appreciated, otherwise they would be hard to find, therefore, rendering the geoinformation useless.

The coordinates were measured in the WGS84 CRS, which store geo objects' position as latitude and longitude. In order to be able to use ***base layers***, such as *OSM* or *Google*, it was indispensable to project the coordinates onto the same CRS: a Pseudo Mercator projection (EPSG:3857). The projection though is not designed to measure distances or areas, as the distortion grows the further away from the equator, resulting in larger values (ArcGIS Server Development Team, 2010).

Browser application

The web application is only usable with JavaScript enabled modern browsers, installed on either portable or desktop computers. A mobile version is not available, thus accessing the web application with mobile phones is still possible but rather difficult to use.

The web application offers limited tools. It is not possible to:

- Create features
- Determine coordinates
- Print extent of the map

The measurement tool of the web application can only be used as a rough estimation of the distance (see above why). If the distance is to be measured, it is advisable to reproject the coordinates into a local CRS, e.g. in *QGIS*.

Database

At the moment handling the database requires both good computer skills and knowledge on databases (theoretical background, SQL …). The database is administered with the tool *pgAdmin*, which can at first make the easiest operations, seem hard and cumbersome. Non-spatial data can only be exported as user *postgres*, who is the administrator of the database, thus being able to potentially harm the database at the same time (unlike *GeoServer* users, who are subject to rights restrictions). Therefore, only experienced users should log into the database and perform operations (maintenance, backups …).

Two problems arise:

- Adding features to existing database ***tables*** is a challenging operation for non-experienced computer users.
- Extending the database (=WIS) with further ***tables definitions*** (e.g. water meters, pipes …) requires knowledge in the concept of databases: **constraints** and **relations** between the **entities** of database objects. Though setting up ***tables*** which do not have **constraints** (**primary keys** …) or **relations** to other **entities**, would work just the same, in **relation** to representing geoinformation. Further information, such as **relations** (e.g. which water meters belong to which house/community/person), cannot be conveyed.

6. Conclusion and outlook

6.1 Fulfilment of objectives

Main objective: Development of a web-based GIS

The existing GIS was transformed into a web-based GIS, based on open source software, and facilitates remote access to different parties. It was assured to provide a secure system. It is now possible for the concerned public to gather information on the water resources of Tecoluca. It can be stated that the provided results fulfil the main objective of this master's thesis "enhancement of the existing water information system". The three sub objectives are to be evaluated separately.

Specific objective 1: Improvement of data base

One big issue was establishing a coherent structure of the existing data in a way which enables future users to get acquainted with the system quickly. Whether using the database or the browser application, the data is always stored the same way (consistent name scheme and uniformity of data).

This master's thesis relied greatly on existing data, which had been collected by Schaidreiter (2016). A lot of non-water related information was available (community, health center, school ***layers***, etc.). Generally the existing data was checked, updated and edited. It was focused on relating data (especially water-related data) with each other, which itself is of value. In fact there was so much data that not all of it was taken into account.

Data on water quality and quantity is scarcely available, which make long-term (e.g. statistical) analyses next to impossible. Results of water samples of water source sites in Tecoluca are valuable information, which were hard to gather, but would potentially enhance the data base significantly. Some water-related ***tables*** are missing technical data (year of construction, constructor), while others lack geometric information, simply because the coordinates have not been measured yet. The data is now uniformly stored in a database and related with each other, making it possible to potentially store a great amount of data.

Specific objective 2: Further development of the existing water information system

The existing WIS consisted of a desktop GIS (*QGIS*), which could only be run locally at the town hall office in Tecoluca (Schaidreiter, 2016). The WIS was extended by several web-GIS enabled components, making it possible to access the system anywhere in the world. The database can be extended by people who have working knowledge in databases and their design. This, however, is a rather difficult task.

Specific objective 3: Improvement of usability of the water information system: Trainings and manual

It was paramount to improve the usability of the existing GIS, so that the employees of the town hall would start using the system on their own. Conducting trainings and composing a manual on the usage of the WIS facilitated the process but it can be stated that the outcome of these measures were probably limited. The manual, however, can be used as a reference book, should there ever occur a user-related question.

6.2 Future objectives

The process of developing a GIS based water information system, which was started in 2015 by INTERSOL, the BOKU – University of Natural Resources and Life Science, the municipality of

Tecoluca and since 2016 also the Universidad Centroamericana José Simeón should continue, as there is still a lot to do. In the future, the development of the WIS should first and foremost focus on acquiring more data, which is not only confined to the actual ***tables*** of the database but to information not yet incorporated into the structure of the database. Naturally, this requires the WIS to be developed further, in two ways:

- Extension of database
- Improvement of components of the WIS

Town hall employees and the interested public should eventually start using the WIS, which can only be achieved, if the usability is increased further. Thus the future goals represent an extension of the objectives of this master's thesis.

6.2.1 Further improvement of data base

The process of extending the data base should continue. Data must be checked, extended and updated regularly in the future. It should also be taken care that the information of the database is as complete as possible with regards to the **attributes** of every single **entity** (e.g., age or depth of water tables of water sources …). Some water source sites are not incorporated into the system yet and still need to be added to the WIS.

As villagers of the respective water source sites often reported that the deliveries of water sources are decreasing, it seems to be desirable to acquire further data on water production on the one hand, but also on physical losses in the individual water schemes on the other hand. Monitoring devices at concerned water source sites may fulfil the need of more data, producing time series, which can be used for statistical analyses and extrapolation. Ideally the monitoring sites are connected with the WIS, so that all the data is incorporated into the database.

Results of water sample testing are useful information, which for now – in the majority of the cases – is not inserted into the database because these results are administered and stored locally by the water committees. It is recommended to retrieve copies of these results for the town hall office, where the data could be entered into the database.

6.2.2 Improvement of the existing water information system

For now the WIS only addresses few aspects of water-related issues. In the future it would be desirable to extend/restructure the database to the needs of the municipality:

- Extending existing ***tables*** with more **attributes** (e.g. additional information on water source sites)
- Creating more ***tables*** concerning
  - Sanitary engineering aspects (water meters, waste water treatment)
  - Other water management types (river basin management, rural water management).
  - Other environmental issues (landscape management, deforestation, climate change, waste management)
  - Administrative topics (e.g. as a base to manage water pricing for each consumer)

The components of the web-GIS should further be kept up-to-date and improved. Especially the browsers application lacks certain features, which could be incorporated in the future. The toolbar only provides basic functionalities, which could be improved. Particularly measuring distances and areas in the web application does not return satisfactory results because of the major distortion of the projection to be expected. A mobile-improved version of the web application would also be desirable, as it is likely that local people prefer entering the application on mobile devices.

6.2.3 Improvement of usability of the water information system

A major concern is that, at the moment, it is rather difficult to use the WIS in terms of adding information to the database, developing and maintaining the system. This is something that only advanced computer users are able to do.

In order to facilitate the administration of the WIS, it was intended to implement a Content Management System (CMS) in collaboration with the Informatics students of the local UCA. A CMS alleviates the processes of inserting, editing, exporting, filtering and deleting data of the database, avoiding the need to handle SQL commands. Average computer users would thus be able to apply changes to the database easily, without the need to know anything about databases.

During the time of the stay the CMS was already being developed by the students. It will be necessary to pursue the implementation of the CMS on the local server of the town hall further because it would contribute to the usability of the WIS immensely. It would probably encourage employees of the town hall to keep using the system.

7. Summary

In 2015 the long lasting relationship between the Austrian-based NGO INTERSOL and the municipality of Tecoluca, El Salvador has been intensified by sending out engineering students of the University of Natural Resources and Life Science, Vienna. The students helped to improve the water resource management of the municipality by implementing a Geographic Information System (GIS), which facilitates the management of water resources significantly. A GIS can be used by different stakeholders on different levels (international, national, local authorities, organizations, and people). It is commonly used for better decision making by the authorities, while also the interested public is able to gather information on different aspects.

This thesis was conducted during a 4 months stay in Tecoluca, El Salvador, in 2016 during which the work of the antecedent students has been continued. The overall objective of this thesis was the enhancement of the existing GIS, consisting mainly in the transformation of the current local GIS into a web-based GIS. The improvement means an augmentation in terms of accessibility, while the conventional functionalities of a GIS can still be used.

To be able to reach the main objective, the following sub-tasks had to be performed:

Improvement of data base

The existing data was revised, and where necessary updated or edited. The data was restructured as to provide a consistent name scheme. The unification of the data was of particular interest because one of the key tasks was the transmission of the data into a geographically enabled database (*PostgreSQL* with *PostGIS* extension).

Further data was on one hand generated by measuring coordinates, deemed important in a general context (streets or **POI** of Tecoluca) and coordinates valuable in the context of water management (water sources, tanks). On the other hand existing water-related data was correlated to each other, which increased the benefit of having such information.

Further development of the existing water information system

The existing water information system (based on *QGIS*) was enhanced by using the geospatial platform *OpenGeo Suite*, which itself consists of several well-known open-source components (*PostgreSQL* with *PostGIS*, *GeoServer* and *GeoWebCache*). These components were set up individually and eventually installed on the local server of the town hall of Tecoluca. In order to provide access to the web-based GIS to the interested public, a browser application was developed, which is accessible on the homepage of the town hall of Tecoluca.

Improvement of usability of the water information system

A manual was composed, providing small tutorials on each of the components of the GIS, printed and handed out to the town hall employees. Trainings in the usage of GIS were also conducted, which provided both becoming acquainted with the enhanced system and theoretical background information.

Enhancement of the water information system

The water information system provides geographical and technical data, which is stored in a database. The data can be accessed using the following options:

- Browser application
- Directly via the database
- *QGIS*
- *GeoServer*

Most of the geographical data can be accessed via the *Web Map Service* (*WMS*), which yields images. Advanced data access is only provided for users with more extensive rights. The data can then be examined, analysed, edited and deleted.

In the future it would be advisable to keep improving the enhanced GIS even further. Especially the development of a user-friendly interface would contribute to the usability of the web-based GIS significantly. There is also room for developing the water information system (WIS) and its components further. At the same time the data base should be extended, possibly even beyond water management issues towards a GIS on a more general level.

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9. Appendix

9.1 English - Spanish layer translation list

Table 13: Translation of ***layers*** incorporated into the water information system.

Table	Tabla
canton	canton
census	censo
community	comunidad
contact_person_water	referente_agua
contour_line_100	curva_de_nivel_100
contour_line_25	curva_de_nivel_25
function	cargo
geology	geologia
health_center	ucsf
hill	cerro
hydrogeology	hidrogeologia
lake	lago
land_use	uso_suelo
mountain	montana
municipality	municipio
ngo	ong
person	persona
protected_area	area_protegida
public_institution	lugar_publico
river_national	rio_grande
river_tecoluca	rio_tecoluca
road	carretera
school	centro_escolar
type_supply	tipo_abastecimiento
type_treatment	tipo_tratamiento
urban_area	area_urbana
urban_district	area_division
vegetation	vegetacion
water_sample	prueba_agua
water_source	recurso_hidrico
water_tank	tanque
working_division	area

9.2 List of layers and data manipulation

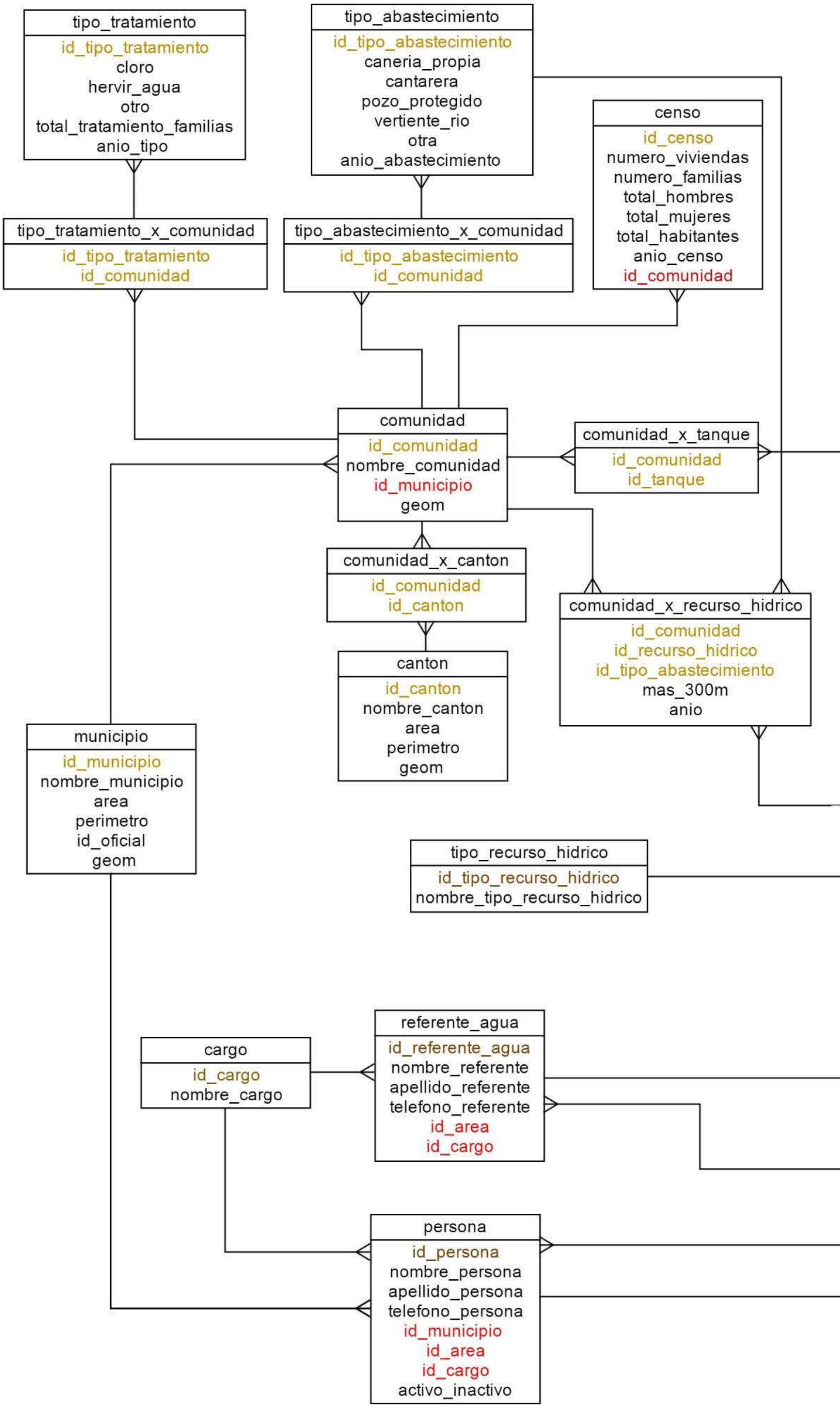
Table 14: List of manipulated ***layers*** incorporated into the web-GIS – part 1.

Category	Layer	Manipulation
Drinking water	water_source	Changed id name. Added new items. Deleted redundant information. Updated information if available.
	water_tank	See layer water source. Changed data type of ids to integer.
Hydrology	river_tecoluca	Unified table layout. Deleted unnecessary information. CRS changed to WGS84.
	river_national	Unified table layout. Deleted unnecessary information.
	lake	Unified table layout. Clipped lakes to boundaries of Tecoluca.
Infrastructure	road	Unified table layout. Added id column. Merged street segments with the same name. Calculated length of roads. Fixed topology errors (pseudo nodes).
Facilities	school	Unified table layout. Added id column.
	public_institution	Unified table layout. Added id column. Layer was separated from layer NGO.
	ngo	Unified table layout. Added id column. Layer was separated from layer public institution.
	health_center	Unified table layout. Added id column. Deleted unnecessary information. Clipped health centers to boundaries of Tecoluca.
Relief	mountain	See layer health center.
	hill	See layer health center.
	contour_line_100	Created contour lines with DEM. Clipped DEM to boundaries of Tecoluca.
	contour_line_25	See layer contour line - 100m.

Table 15: List of manipulated ***layers*** incorporated into the web-GIS – part 2.

Category	Layer	Manipulation
Environment	protected_area	Unified table layout. Added id column. Deleted unnecessary information. Redigitized polygons. Calculated area of new polygons.
	geology	Unified table layout. Deleted unnecessary information. Clipped geology to boundaries of Tecoluca. Calculated area and perimeter of polygons.
	hydrogeology	See layer geology.
	land_use	See layer geology.
	vegetation	See layer geology.
Administrative borders	community	Unified table layout.
	urban_area	Unified table layout. Added id column. Layer was separated from layer districts. Merged urban districts to one polygon. Calculated area of new polygon.
	urban_district	Unified table layout. Added id column. Layer was separated from layer urban districts.
	municipality	Unified table layout. Added id column. Deleted unnecessary columns. Deleted unnecessary municipalities.
	canton	Unified table layout. Added id column. Calculated area and perimeter.

9.3 Entity relationship model


tipo_tratamiento
id_tipo_tratamiento
cloro
hervir_agua
otro
total_tratamiento_familias
anio_tipo
tipo_abastecimiento
id_tipo_abastecimiento
caneria_propia
cantarera
pozo_protegido
vertiente_rio
otra
anio_abastecimiento
censo
id_censo
numero_viviendas
numero_familias
total_hombres
total_mujeres
total_habitantes
anio_censo
id_comunidad
tipo_tratamiento_x_comunidad
id_tipo_tratamiento
id_comunidad
tipo_abastecimiento_x_comunidad
id_tipo_abastecimiento
id_comunidad
comunidad
id_comunidad
nombre_comunidad
id_municipio
geom
comunidad_x_tanque
id_comunidad
id_tanque
comunidad_x_canton
id_comunidad
id_canton
comunidad_x_recurso_hidrico
id_comunidad
id_recurso_hidrico
id_tipo_abastecimiento
mas_300m
anio
canton
id_canton
nombre_canton
area
perimetro
geom
municipio
id_municipio
nombre_municipio
area
perimetro
id_oficial
geom
tipo_recurso_hidrico
id_tipo_recurso_hidrico
nombre_tipo_recurso_hidrico
referente_agua
id_referente_agua
nombre_referente
apellido_referente
telefono_referente
id_area
id_cargo
cargo
id_cargo
nombre_cargo
persona
id_persona
nombre_persona
apellido_persona
telefono_persona
id_municipio
id_area
id_cargo
activo_inactivo

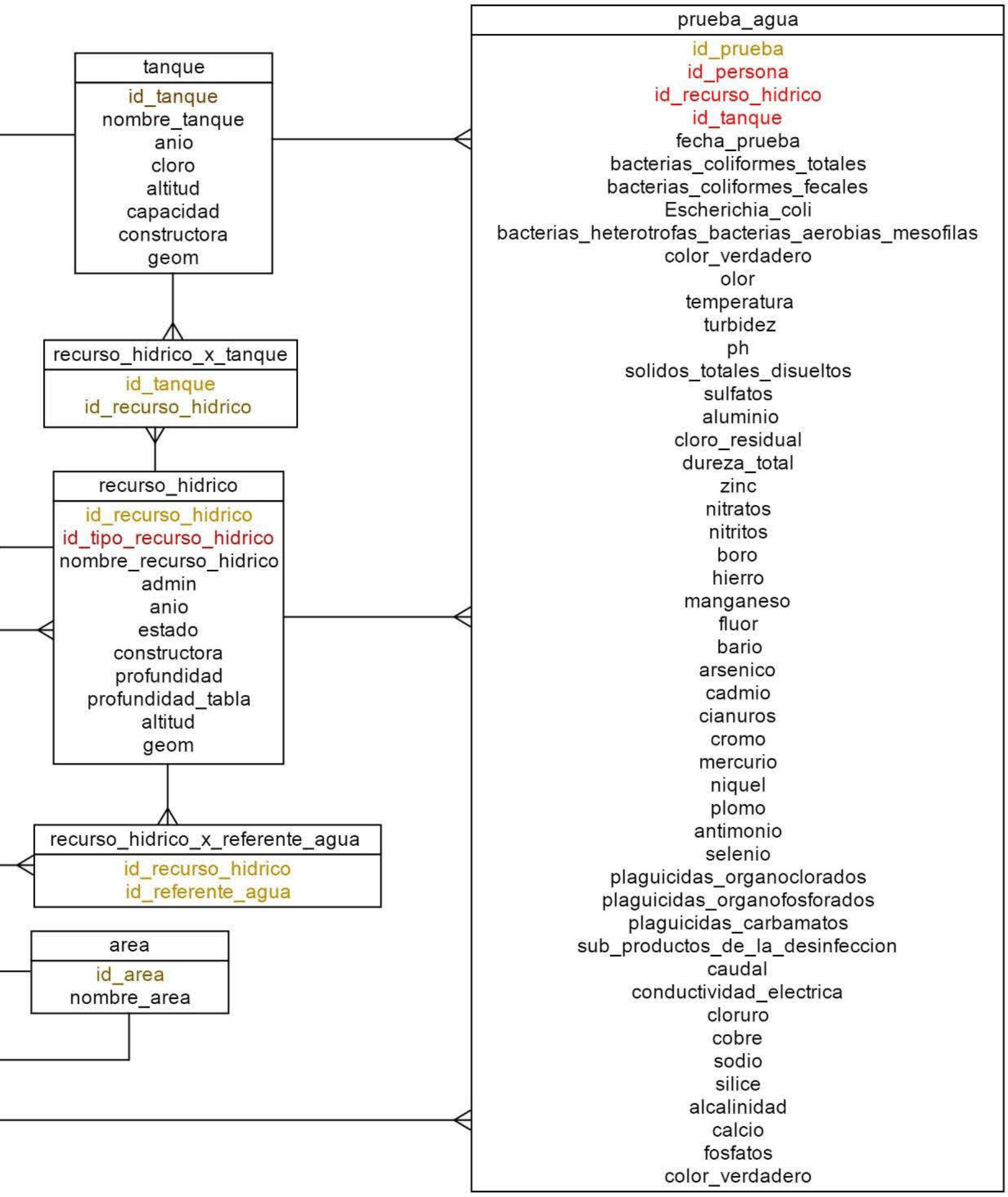


Figure 48: **Entity relationship model** of the water information system (Ramos and Recinos, 2016).

10. Curriculum Vitae

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Curriculum Vitae

Education

Since Oct. 2014 - Jan. 2017 — **Master's programme, Civil engineering and water management**, University of Natural Resources and Life Sciences, Vienna.
Specialisation: Sanitary engineering, Hydrobiology, GIS Applications.

Master's thesis, Title: Further development of the water information system in the municipality of Tecoluca, El Salvador, University of Natural Resources and Life Sciences, Vienna.
Carried out at the Institute of Sanitary Engineering and Water Pollution Control. Received scholarship of the University of Natural Resources and Life Sciences, Vienna.

Oct. 2010 - Sept. 2014 — **Bachelor's degree, Environmental engineering**, University of Natural Resources and Life Sciences, Vienna.
Bachelor's thesis: Untersuchung der Lawinensituation an der Schneealpe. Pass with distinction.

Mar 2008 - Apr. 2012 — **Bachelor's degree, Urban and regional planning**, Vienna University of Technology.
Bachelor's thesis: Stadtumbau in Rudolfsheim-Fünfhaus.

June 2006 — **Matura**, Lise Meitner Realgymnasium, Wien.

Experience

Feb. 2016 - June 2016 — Intern, **Town hall Tecoluca**, El Salvador, Central America.
Measurement of water quality parameters of different water source sites in rural El Salvador. Installation and set-up of components of a water information system in order to monitor various water quality parameters. Was condcuted in cooperation with the Austrian-based NGO INTERSOL, the University of Natural Resources and Life Sciences and the Universidad Centroamericana "José Simeón Cañas" . Work routine in Spanish language.

July - Aug. 2013 — Intern, Section hydropower, **Verbund HYDRO Power AG**.
Water ecology: technical documentation of ecological measures to improve fish stock of Austrian rivers

Oct. 2011 - Aug. 2015 — Audience services (occasionally), **Stadthalle Wien**.

Sept. 2007 - Feb. 2008 — Volunteer: Teacher (Full time), **Escuela Eliada**, Ecuador, South America.
Taught English and Informatics in various public primary schools in urban and peri-urban areas.

Jan. - Sept. 2007 — Civilian service, **ESRA Psychosocial Centre**, Vienna.
Support of holocaust survivors in their daily routines, and miscellaneous administrative tasks.

Sept. - Dec. 2006 — Catering (Full time), **Vienna International Airport**.

Languages

German — **Native language.**
English — **Fluent in spoken and written**
Spanish — **Advanced skills: Various work stays in Latin America.**
Russian — **Basic knowledge.**

Computer skills

MS Office — Excellent MS Word and Excel skills.
GIS — ArcGIS, ERDAS Imagine, QGIS, Web-GIS technologies.
Engineering — AutoCAD, EPANET, HEC-RAS, SWMM.
Statistics, Programming — Statistical tool: R, Python (programming language), designing homepages.

11. Affirmation

I certify that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Place, date, name surname, signature

Land use

Figure 5 shows the land use pattern of the municipality of Tecoluca. Few urban areas can be spotted. Besides the urban center Tecoluca (see also Figure 4), there are some urban agglomerations around the road Litoral and along the river Lempa (San Nicolas Lempa). Some parts in the southern and northern parts are forests, though most of Tecoluca is somehow cultivated. There is annually cultivation, such as basic crop, mixed cultivation and permanent cultivation, most notably sugar cane. Mangroves in the south are protected areas.

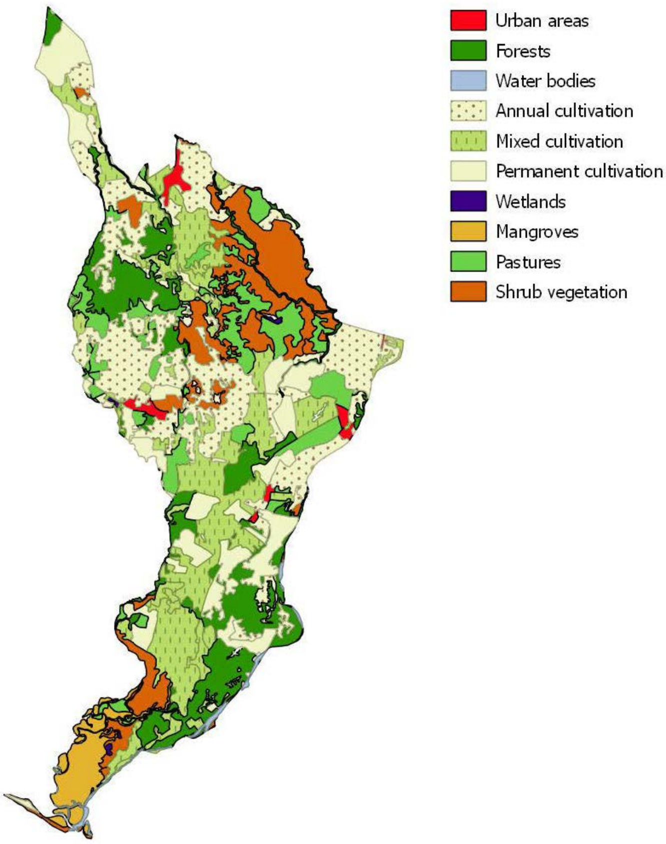

Figure 5: Land use of the municipality in Tecoluca (Universidad de El Salvador, 2015).

3.1.2 Water sources

Topography and geology

The topography of Tecoluca is dominated by the volcano San Vicente in the northern part of the municipality and by the Pacific Ocean to the south. The contour lines in Figure 6 illustrate that the northern part is both the steepest and topographically highest part in the municipality with 2150 m above sea level being the highest point. The further south the flatter the surface becomes, resulting in a flat southern part without any substantial elevations.

of Santa Theresa (also called Trinidad), which supplies approximately 700 families, is 82 m deep and the water table is currently at a depth of 35 m.

North of the Litoral there is also sufficient groundwater but it is located at greater depths (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002). Many villages surrounded by hilly or mountainous terrain are supplied by spring tappings, which leads to the conclusion that it is likely that there are several near-surface aquifers, too.

The climate of El Salvador is characterized as tropical, divided into two seasons: dry and rainy season. The rainy season begins in May and ends in November and can produce intense precipitation events, which can lead to floods (UNICEF, 2014). The volcano San Vicente presents a natural barrier which forces airstreams to rise, therefore, producing rain. Thus also the municipal area of Tecoluca is separated into the wetter north and the drier south.

Figure 8 shows the average monthly precipitation in mm of two locations in the municipality of Tecoluca. Santa Cruz Porrillo lies around the Litoral with the precipitation maxima in June and September and a total rainfall of 1,763 mm. The same applies to Tehuacan but the total rainfall is 2,003 mm, probably because Tehuacan lies topographically higher than Santa Cruz Porrillo. The data suggests that, the lowest annual rainfall occurs in the south (~1,700 mm), while the wettest annual rainfall can be located in the northernmost point around the summit of volcano San Vicente (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

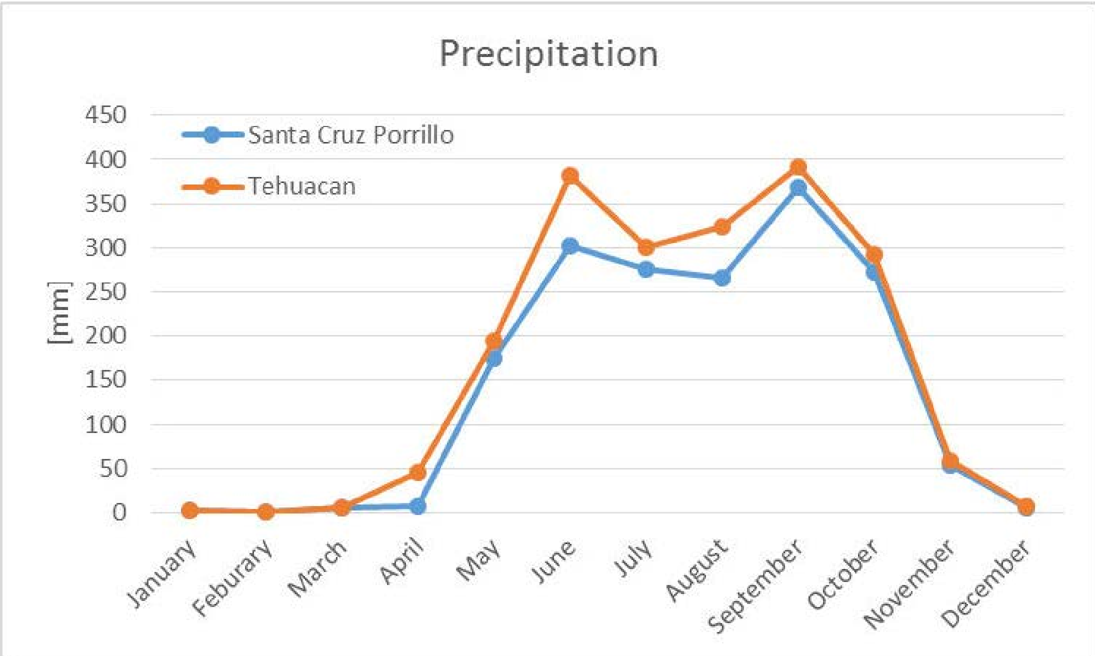

Figure 8: Average monthly precipitation in Santa Cruz Porrillo and Tehuacan (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

The annual potential evapotranspiration amounts to 1,800 mm in heights between 400-1,200 m most likely because of the elevated temperatures in the southern flatlands. The average precipitation rate of this area is only 1,600 – 1,800 mm. This could mean that the potential evapotranspiration might be higher than the precipitation in some areas (FUNDE and Alcaldía municipal de Tecoluca, presumably 2002).

Water supply

The water supply systems that were geospatially captured in the GIS use spring tappings and drilled wells, which in two cases are also hand-pump wells. Some communities use only one water source, while others use multiple. Either the water is transported from the source to a water tank

- *GeoServer* or *OpenGeo* hosting.
- Set up components on the server of the town hall.

The hosting options require a monthly payment, which over the years can be significant. The most convenient solution was to set up all the required components on the server of the town hall, which is locally reachable in the office, and was used for the sole purpose of local IP management (DHCP server). The operating system of the server is Windows Server. The following components were installed and set up:

- *PostgreSQL* with *PostGIS* extension.
- *OpenGeo Suite* which includes *GeoServer* and *GeoWebCache*.

The local database and all its information on the computer of the author was backed up. After having installed *PostgreSQL* and the *PostGIS* extension on the server, a new database was created and the backed up data was restored without any errors.

The *GeoServer's* data directory of the server was replaced with the respective *GeoServer* data directory, which include general settings, ***layer*** data, styles, workspaces and stores of the local computer of the author. Once the *GeoServer* instance was restarted all the configuration was set up properly.

At this stage it was possible to access the server within the local area network (LAN) by calling the server internal IP address. The internal port on which *OpenGeo* runs was changed from 8080 to 80, by tweaking the file start.ini of the jetty servlet within the *OpenGeo* jetty directory (Boundless\OpenGeo\jetty). Normally the port 80 is used by standard web servers. As the server of the town hall does not serve as a web server though it was possible to change the port without producing any conflicts.

The final task was to make sure that the web-GIS is actually reachable from everywhere. The person responsible for IT of the town hall of Tecoluca acquired a public IP address, exposing the server to the World Wide Web. After reconfiguring the firewall settings to allow connections from and to the server on port 80, it was possible to access the WIS from everywhere in the world.

At the same time it was assured that the web application of the WIS was promoted, so that interested people can use it, thus embedding it into the homepage of the town hall. A logo was created by the head of the communications department of the town hall Manuel Gutiérrez (see Figure 33). It was placed in the left panel and – upon clicking it – redirects to the web application.

Figure 33: Logo of the water information system of the municipality of Tecoluca (Gutiérrez, 2016).