Development of an Interactive WebGIS Platform for the Visualization of Hydrogeological Information, Bandung Basin, Indonesia

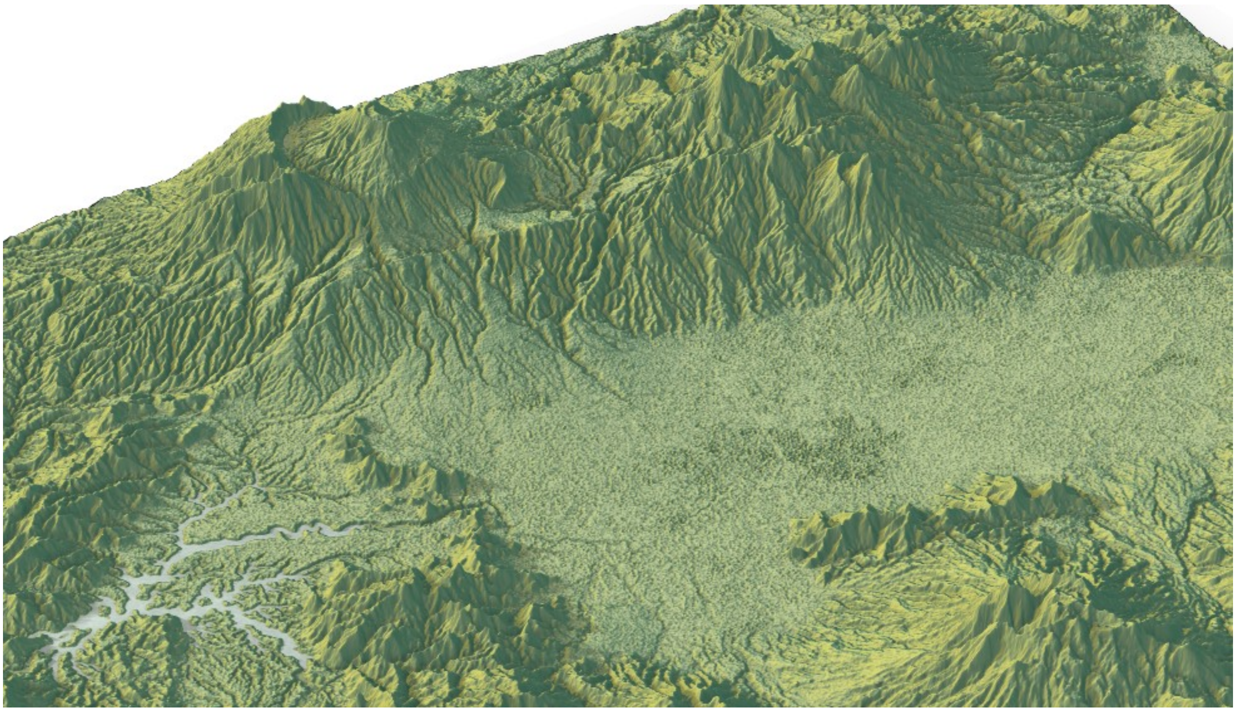
TECHNISCHE UNIVERSITÄT DARMSTADT

Master Thesis of

Muhammad Malik Ar Rahiem, Matr.-Nr.: 2321114

Institut für Angewandte Geowissenschaften

Darmstadt, March 2020



Digital Elevation Model of Bandung Basin Rendered with Rayshader Package

Declaration of Authorship

Hereby I certify, Muhammad Malik Ar Rahiem (Matrikel No. 2321114) that the complete work of this master thesis

"**Development of an Interactive WebGIS Platform for the Visualization of a Hydrogeological Information, Bandung Basin, Indonesia**"

was done by myself and only by using the referenced literature and the described methods. This thesis was not submitted in identical or similar form to another examination authority and it was not published before.

Bandung, March 23rd 2020

Place, date Signature

First supervisor: Professor Christoph Schüth

Second supervisor: Dr. Rouwen Lehné

Abstract

Excessive groundwater extraction is a major threat to the sustainability of groundwater management in Bandung Basin, Indonesia. Therefore, it is crucial for Bandung Basin to strengthen its groundwater management system, for example by developing more precise aquifers geometry model and real time extraction monitoring system. The challenge in developing aquifers geometry model is the lack of available well data. Of more than 2000 wells data that registered in the government, very less of that number are possible to be extracted because the data are scattered in several department. Moreover, well-archived dataset is only available in print. This is the main reason why developing a WebGIS platform for the visualization of hydrogeological information of Bandung Basin, matters.

This application compiles available well-data in Bandung Basin from several sources; government, publications, and thesis. The data are digitised and visualised in a WebGIS platform developed using open-source language R and utilising tens of packages available in R environment. There are three main functions of this application, namely: 1) Maps visualisation, 2) Well profiles visualisation, and 3) Cross-section visualisation. There are 189 wells and 4 maps available to explore. These maps are: geological map, hydrogeological map, groundwater basin map, and groundwater zonation map. In the well profiles and cross section visualisation, 3 information can be obtained: lithology, resistivity, and well screen placement.

This application is meant to democratise subsurface data in Bandung Basin to encourage open data so that further research, especially on groundwater management can be taken place. This is also an effort to promote open science. The data that is being used in this application are provided for public in online repositories Github and so does the script code. This application of subsurface visualisation is expected to encourage open data, open science, and later further research on subsurface model development, especially on more transparent groundwater management.

The apps can be accessed from https://malikarrahiem.shinyapps.io/BandungBasin/

The repository can be accessed from https://github.com/malikarrahiem/thesismalik

Keyword: groundwater, application, open data, visualisation

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1 Introduction

The Bandung Basin, is an intramontanne basin, which is home to around 8 million people and is the second largest metropolitan in Indonesia, after the Greater Jakarta metropolitan area that surrounds the Indonesian capital, Jakarta.. The basin located in the Province of West Java and consists of 4 districts / cities, namely; Bandung City, Cimahi City, Bandung Regency and West Bandung Regency.

Mankind has lived in this basin for milennias. The Pawon Man, a fossil found in the western part of the Bandung Basin, is at least 6000 years old, based on carbon dating (Yondri 2005). Ancient humans have long lived in the Bandung Basin, especially in areas of> 700 meters above sea level, mainly related to the existence of ancient lakes at the bottom of the basin formed at the end of the Pleistocene until the lake deposits were dried about 12 thousand years ago (Dam 1997).

Currently clean water demand in Bandung Basin, both for citizens consumption and industrial needs, are obtained from groundwater extraction. Local people usually uses shallow groundwater with a depth of less than 30 meters, while industries usually use deep groundwater with a depth of more than 100 meters.

Excessive groundwater pumping has lead to serious land subsidence issue, which in average reach -8 cm per year, and can be up to -16.9 cm per year in certain region in certain periods of time (Gumilar et al. 2015). The basin is also faced with the challenge of illegal groundwater extraction which fasten the groundwater depletion. Therefore, it is crucial for Bandung Basin to strengthen its groundwater management system, for example by developing the aquifers geometry and real time extraction monitoring system. One way to do that is to tidy up the well drilling database.

Well data should be abundant in Bandung Basin. The first deep well drilling was recorded in 1893. At that time groundwater was used to secure an annual water supply (Braadbaart and Braadbaart 1997). Since then, permits for groundwater exploitation have continued to be granted, until in 2004 there were 2,200 deep well permits in the Bandung Basin (Wangsaatmaja, Sutadian, and Prasetiati 2006). The real number is certain to be much greater because there are so many unregistered wells.

The deep well permit data should be a very potential database for subsurface reconstruction, especially to find out the aquifer layers in the Bandung Basin. But this is not the reality. The subsurface reconstruction of the Bandung Basin has not yet utilized this vast database.

As of September 2019, there have been several studies that discuss the conditions of subsurface geometry in the Bandung Basin. Recent research on subsurface geometry was published by Hidayat et al. (Hidayat et al. 2017) that used 27 drilling points, 20 geoelectric points, and 9 well log points. In addition, Sunarwan (Sunarwan et al. 2014) in his dissertation divided the hydrostratigraphic unit and made a diagram of the subsurface fence of the Bandung Basin using 96 well log data.

A decade ago Hutasoit (Hutasoit 2009) modeled hydrogeological subsurface geometry in the Bandung Basin using 253 well log data. In the 1990s, Dam et al (Dam and Suparan 1992; Suparan and Dam 1992) conducted quarternary geological research in the Bandung Basin and produced a quarternary geological map that described subsurface conditions, especially at shallow depths (<30 meters). The most comprehensive research on subsurface hydrogeological conditions in the Bandung Basin was published by Iwaco and Waseco in 1990 (IWACO 1990).

The main problem in the existing subsurface geometry models in the Bandung Basin is that none of these models can be reproduced easily because the data used to develop the model is not publicly available. Existing data is still scattered in each researcher, institutions, and stored in a conventional paper-based form. In the digital age, this data needs to be digitized so that it can be used for other research. Unfortunately in the case of drilling log data of the Bandung Basin, this has not been done.

In this study, drilling data and geological maps in the Bandung Basin obtained from previous publications data that can be accessed and data from the Department of Energy and Mineral Resources, West Java, Province are compiled, digitized, and displayed on a WebGIS platform. This platform is an online-based platform that allows people connected to the internet to interact with geological and hydrogeological data in the Bandung Basin.

Through this application, it is expected that an initial step in developing the Bandung Basin subsurface database can be carried out, so that data is more inclusive and accessible to everyone. Ease of access to data will encourage further research, especially on the development of more reproducible hydrogeological model.

This study is the first in Indonesia, where hydrogeological data is displayed as an application and can be accessed interactively.

1.1 Problem Statement

1. There is already a lot of subsurface data of the Bandung Basin, but it cannot / is difficult to access

2. There is no platform yet to access subsurface data from the Bandung Basin

3. Interesting data visualization needs to be developed so that the information is better perceived by public

1.2 Research Objectives

In general, the aim of this research is to develop an online application that allows users to view, access, and interact with subsurface hydrogeological data in the Bandung Basin. This application is intended as a form of documentation and educational facilities for the subsurface data of the Bandung Basin. The outputs of this study are the application of well points and cross sections of Bandung Basin which can be accessed interactively. The outcome is that students, researchers, or stakeholders might be able to use the platform for their own purpose.

1.3 Approach and Outline

1.4 Study Area

The study area is in the Bandung-Soreang Groundwater Basin (GWB), West Java Province, Indonesia. This basin is located about 150 km southeast from the Capital of the Republic of Indonesia, Jakarta, at around 7 ° S and 107 ° -108 ° East, with an area of ± 1702 km^2. CAT Bandung-Soreang covers 4 regencies/cities, namely Bandung City, Bandung Regency, Cimahi City, and West Bandung Regency (Figure-1).

The selection of area studies based on the Groundwater Basin is based on Law No. 17 of 2019 concerning Water Resources. Where the groundwater management of an area is based on the Groundwater Basin, which is an area that is bounded by hydrogeological boundaries, where all hydrogeological events, such as recharge, discharge, and release of groundwater take place.

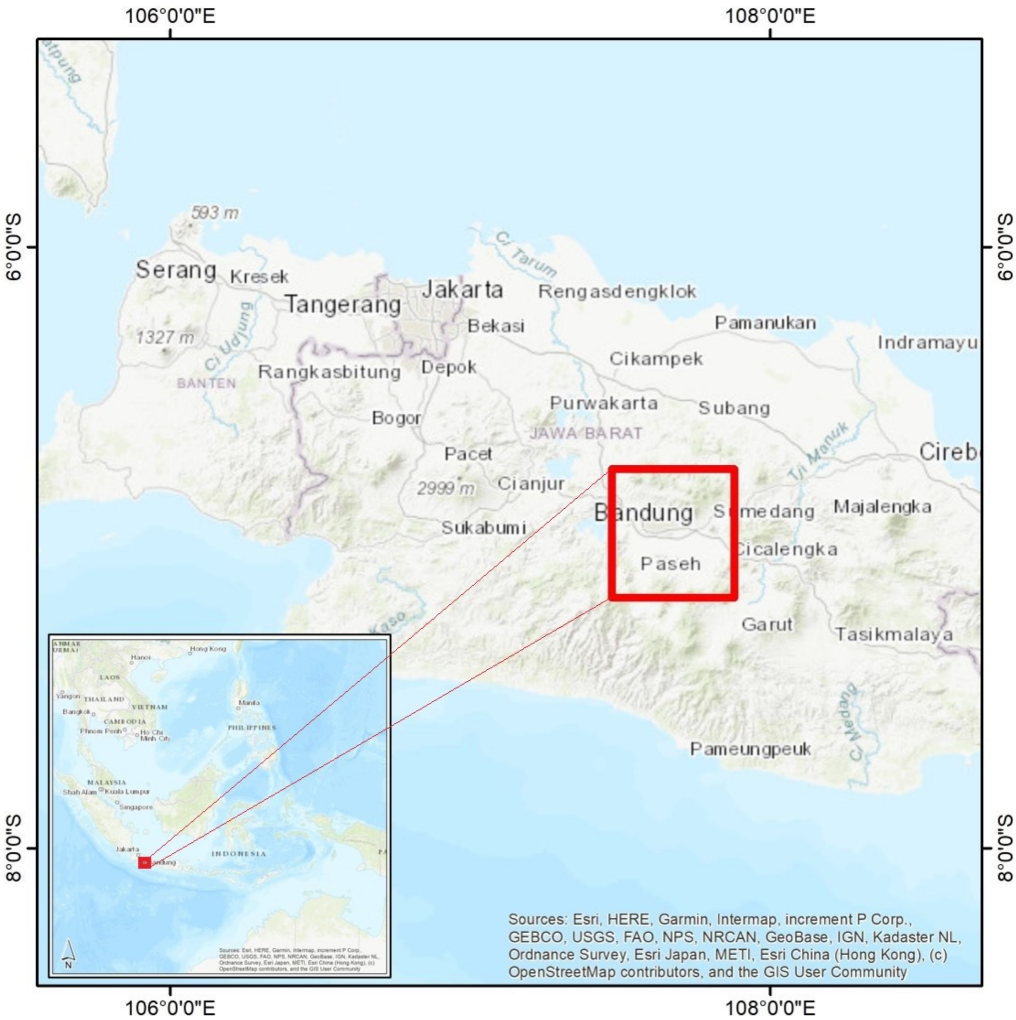

Figure 1 Study area located in Bandung Basin, an intramontanne basin at West Java Province, Indonesia

2 Literature Review

2.1 Geology of Bandung Basin

The Bandung Basin region has long attracted the attention of geologists. Franz Wilhelm Junghuhn, a naturalist from Germany, was the first person to map the geology of Java in 1855, including the Bandung Basin (Junghuhn 1855). He divided the Bandung Basin geology into 4 rock groups; Lake sediments, volcanic rocks, intrusive rocks, and older tertiary sedimentary rocks.

In 1896, after the eruption of Mount Krakatau in 1883, the geologist of the Dutch Colonial Government, R.M. Verbeek maps the geology of Java. Around the Bandung Basin, Verbeek divides the lithology of this area into at least 5 rock groups; lake deposits, volcanic deposits, andesite intrusions, young tertiary sedimentary rocks, and limestone sedimentary rocks.

A more detailed mapping with a scale of 1: 100,000 was carried out by Dutch geologist, R.W. van Bemmelen and J. Szemian in 1934 (Bemmelen and Szemian 1934). On this more systematic geological map, van Bemmelen and Szemian divided lithology in the Bandung Basin into two types of formations, namely sedimentary formations and volcanic formations. In sediment deposits there are lake and river deposits, volcanic deposits (*gebergtepuin*), Breccia and Pliocene aged Tuffs, Cilanang Layers (tuffs and limestone). In volcanic formation deposits, van Bemmelen and Szemian divide into young volcanic deposits, Mount Dano tuff layers and Tangkuban Perahu Volcano (Period B), Lava Basalt Flow, Tangkuban Perahu deposits (Period A), Andesite Intrusion, and Dasit Intrusion.

On this map, interesting geological features are well mapped. Alluvial fan deposits are now a major part of the city of Bandung today. Lembang fault which divides the plains of Bandung and the plains of Lembang. Also a north-south cross section sketch showing the lithologic-lithological stratigraphic relationship in the Bandung Basin.

The next geological map was published in 1973 by the Indonesian Geology Directorate. There are not many changes from the previous geological map by van Bemmelen and Szemian, only there is a more detailed mapping of the Mount Tangkuban Perahu deposit (Silitonga 1973).

In 1981, Hartono and Koesomadinata mapped the geology of the Bandung area in a lithostratigraphic manner with stratigraphic units in the form of formation (Koesoemadinata and Hartono 1981). Through this classification, Hartono and Koesoemadinata divided the Bandung Basin geology into 5 formations. At the top is the recent river deposit unit. Next is the Cikidang Formation in the form of basal lava, then the Kosambi Formation which is an alternation of volcanic claystone, volcanic siltstone, and volcanic sandstone, then Cibeureum Formation which is a recurrence of tuff-breccia sequences. Below it, erosionally bounded is the

Cikapundung Formation with volcanic conglomerate lithology, volcanic breccia, and andesite lava. The stratigraphy of Bandung Basin according to Koesoemadinata and Hartono can be seen on table-1 below:

Table 1 Bandung Basin Lithostratigraphy (Koesoemadinata and Hartono 1981)

Age	Stratigraphical Unit	Thickness (m)	Explanation
Holocene	Alluvial deposits	5	Loose and unconsolidated clay to boulder size sediments
	Erosional Surface		
	Cikidang Fm	0-65	Column structured basaltic lava, volcanic conglomerates, coarse-tuff with parallel bedding with volcanic breccia. Mostly brownish in color
	Kosambi Fm	0-80	Volcanic clay, volcanic silt and volcanic sand, contain remnant of plants, sometimes parallel and cross lamination occurs
Late Pleistocene	Cibeureum Fm	0-180	Recurrence of tuff-breccia, scoria fragment, basaltic-andesitic, and pumice stone
	Erosional Surface		
Early Pleistocene	Cikapundung Fm.	0-150	Volcanic conglomerates, volcanic breccia, tuf and andesitic lava. Can be distinguished by its bright coloured and its andesite-pyroxene fragment.

The maps published hereinafter are thematic maps. The Quaternary Deposition Lithology Distribution is mapped by Suparan and M.A.C. Dam in 1992 (Dam and Suparan 1992). On this map, Suparan and Dam map Bandung lake and alluvial fan deposits. In general, young sediments in Bandung can be divided into several facies, namely: Alluvium Fan Sediment, Bandung Fan Sediments, Bandung Fan Sediments Mixed Facies, Floodplains Sediments, Lake Sediments, Lake Fan Sediments, Sand Facies Sediments, River Flow Sediments, Sediments Lake Peat Faces, and Intrusion Rocks.

A year later in 1993, Dam, Suhirman, and Toloczyki through cooperation between the Directorate of Geology and Environmental Planning and German Geological Agency, *Bundesanstalt für Geowissenschaften und*

Rohstoffe (BGR), published the Geological Map of Bandung Basin for the purpose of Land Use and Regional Planning (Dam, Suhirman, and Toloczyki 1993). In this most recent map, the Bandung Basin geology is divided into 9 age groups; Tertiary-Oligocene in the form of limestone; Middle Tertiary-Miocene in the form of Sandstone, marl, claystone, limestone, breccias; Upper Tertiary-Miocene in the form of rocky tuffaan breccias, tuffaceous sandstones; Upper Tertiary-Miocene to Pliocene in the form of Andesite, Basal, and Dacite; Tertiary-Pliocene in the form of volcanoes, sandstones, irreducible conglomerates; Quaternary - Upper Pliocene to Lower Pleistocene in the form of irreducible volcanoes; Quaternary - Lower to Middle Pleistocene in the form of irreducible volcanoes and volcanic neck; Quaternary - Upper Pleistocene in the form of sandy tuffs, alluvial fan deposits and clastic volcanic rocks, irreducible volcanic yields, and lava flows; and Quaternary - Holocene deposits of alluvial and colluvial deposits, fluvial sand deposits and lake deposits (**Figure-2**).

Generally, the geology of Bandung Basin can be drawn as conceptual model below (**Figure-2**):

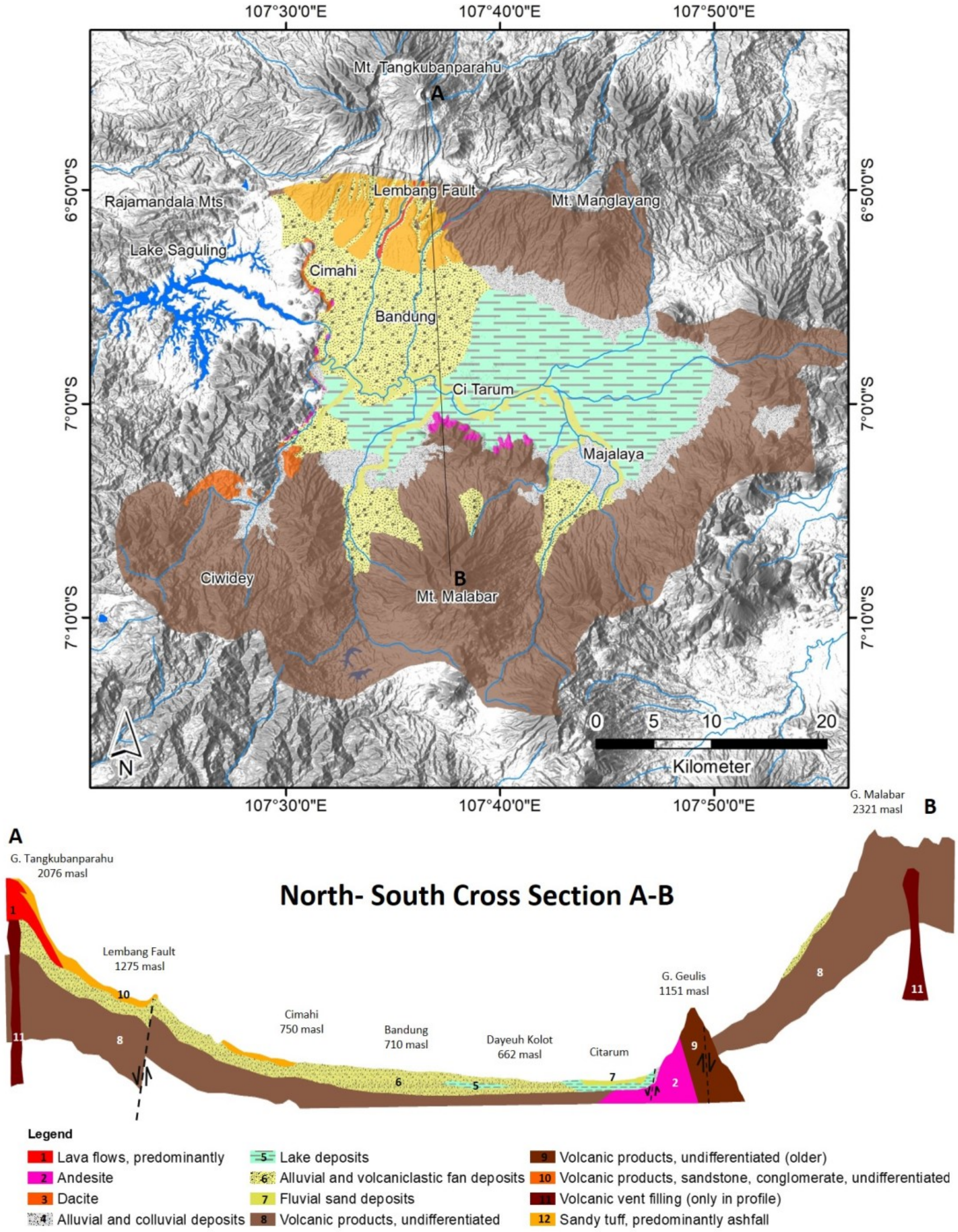

Figure 2 Geological Map of Bandung-Soreang Groundwater Basin (Dam, Suhirman, and Toloczyki 1993)

2.2 Hydrogeology of Bandung-Soreang Groundwater Basin

2.2.1 Historiography of Hydrogeological Study in Bandung Basin

The history of hydrogeological mapping in Indonesia was started in 1972 by cooperation with the BGR, through a project of German Hydrogeological Advisory Group (CTA-40). The project produced hydrogeological map scale of 1:250.000, focused on Java Island.

In the 1970s, the city government of Bandung and its surroundings had begun to look for sources of water other than surface water to meet the needs of the citizens. Population growth is quite high, coupled with several symptoms that indicating surface water degradation such as; loss or decrease in spring discharge and river pollution due to solid waste and industrial chemical waste (Hudoro 1991). In 1976, Pulawski and Obro, from consultants Nielsen & Rauschenberger and Cowiconsult from Denmark, published the results of an investigation of groundwater potential in Bandung. At that time only around 100 wells were drilled in Bandung and its surroundings (Pulawski and Øbro 1976).

Pulawski and Obro's results show that the foot slope bordering the Bandung plain is an area that contains abundant water resources. While deeper into the ground there are two types of aquifers in the Bandung Basin, namely confined aquifers and unconfined aquifers. The confned aquifer shows the artesian nature, where the static water level exceeds the surface elevation (Pulawski and Øbro 1976).

Following up on the results of this study, in the 1980s the government drilled 19 deep bore wells. In addition, the private sector also began to drill wells to meet its water needs (Hudoro 1991). In this decade the Directorate of Environmental Geology published a 1: 250,000 sheet of Indonesian Hydrogeology Map in Bandung (Soetrisno 1983).

In the late 1980s and early 1990s, Iwaco-Waseco published research on hydrological studies in Bandung. From the results of this study it is known that groundwater levels in aquifers in the city of Bandung have decreased at an alarming rate due to intensive exploitation of water sources (DAM 1994).

The awareness that groundwater must be protected and its use must be regulated in the years has existed since the 1980s. But research on this subject only began to develop in the 1990s. The Indonesian Directorate of Environmental Geology in collaboration with the BGR conducted research on efforts to conserve and regulate the use of natural resources for spatial planning in the Bandung Basin. A paper on environmental geology as a guide to the use of land use and spatial planning in the Bandung Basin was published in 1993 (Suhari and Siebenhüner 1993). Along with this paper a geo-information map of 1: 100,000 was also published which contained information on geological resources (including groundwater, minerals and rocks) and natural disasters.

2.2.2 Hydrogeological Characteristics

According to the hydrogeological map of Bandung, the area of Bandung and its surroundings has moderate to high aquifer productivity, groundwater scarce areas are found locally in the south and hilltop areas. The high productivity aquifer area is located in the city of Bandung to Cimahi, the aquifer lithology is composed by the Cibeureum Formation. Other plains have moderate productivity, aquifer lithology is composed of the Kosambi Formation and the Cibeureum Formation. Aquifers with productivity are also being found in the foothills, originating from the Cikapundung Formation and young volcanic deposits (Soetrisno 1983). Hydrogeological map of Bandung-Soreang GWB can be seen on the Figure-3 below:

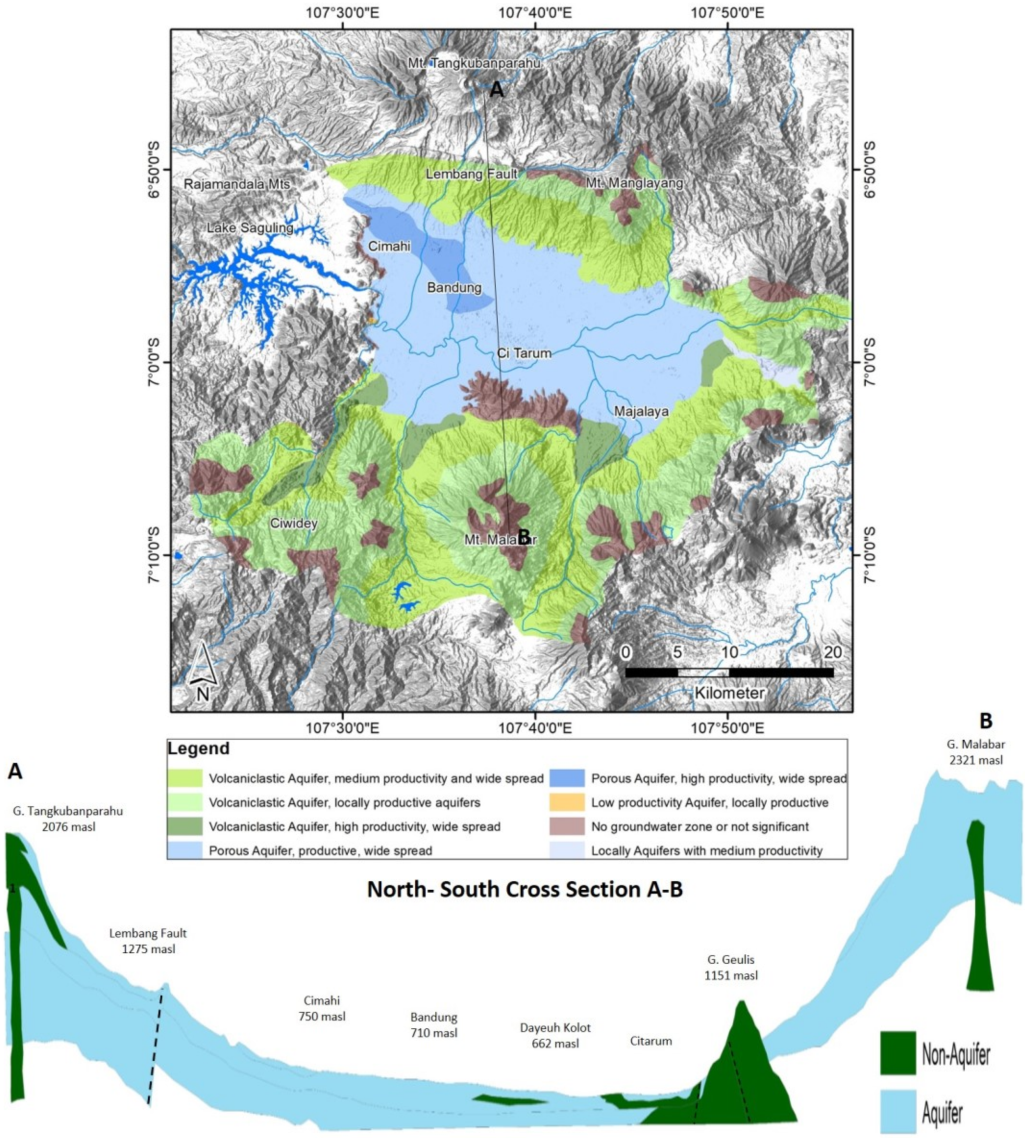

Figure 3 Hydrogeological Map of Bandung-Soreang Groundwater Basin and North-South Cross Section. A modification from (Soetrisno 1983; Dam, Suhirman, and Toloczyki 1993)

In Bandung, the Cibeureum Formation is the main aquifer, the Kosambi Formation is the aquitar, while the Cikapundung Formation is the deep aquifer (Hutasoit 2009). The Cibeureum Formation, especially in the alluvial fan section, is the main aquifer. This formation consists mainly of intercallation of breccias and tuffs with low consolidation rates and some basal lava layers, with Late Pleistocene - Holocene age. Breccias in this formation are volcanic breccias composed by scales fragments of igneous basaltic-andesite rocks and pumice.

The main valleys which incising the high altitude slopes in the Bandung Basin generally produce alluvial fan deposits that make good aquifers. Based on geological maps (Dam and Suparan 1992), these alluvial fan groups are mainly sourced from Tangkuban Perahu Mountain, Malabar Mountain, Gunung Wayang Complex in the south, and small fans from the mountains around the Bandung Basin. The lithology encountered in the volcanic fan consists of volcanic breccias, tuffs and sand, which are also the main aquifers. According to Hutasoit, the hydraulic conductivity in this aquifer ranges from $1x10^{-5}$ to $4 x10^{-5}$ m/s or around 1-3.5 m/day (Hutasoit 2009).

The middle part of the Bandung Basin is filled with soft sediment consisting of claystone, siltstone and sandstone that is not compacted. Koesoemadinata and Hartono named this group Kosambi Formation (Koesoemadinata and Hartono 1981). This formation has an interfingering relationship with the upper Cibeureum Formation. Based on its lithological properties, this formation acts as an aquitar in the study area and has hydraulic conductivity between $2x10^{-7}$ to $8 x10^{-7}$ m/sec or around 0.017 - 0.070 m/day (Hutasoit 2009).

The Cikapundung Formation is the oldest rock unit exposed in the study area (Koesoemadinata and Hartono 1981) and consists of conglomerates and compact breccia, tuff, and andesite lava. This formation can be distinguished from the Cibeureum Formation through the compactness of the formation lithology. According to Harnandi, this rock belongs to the deep aquifer with a semi-depressed to depressed nature (Harnandi and Herawan 2009).

In short, aquifer potential in Bandung Basin according to its geology can be simplified into Table-3 below:

Table 2 Lithological comparison from time to time and its potential to become an aquifer. Formation with red box are considered to be aquifer

Lithostratigraphy According to Previous Geologist						
Age		Verbeek (1896)	Van Bemmelen and Szemian (1934)		Hartono and Koesoemadinata (1981)	Dam, Suhirman, and Toloczyki (1993)
Holocene		Lake deposits	Alluvial and coluvial deposits Lake deposits	Tuff Layer of Gunung Dano Basaltic lava Tuff Tangkuban parahu	Alluvial Deposits Cikidang Fm. Kosambi Fm	Alluvial and coluvial deposits Fluvial sand deposits Lake deposits
Pleistocene	Upper	Volcanic deposits		Older volcanic		Sandy tuff Alluvial and volcaniclastic fan deposits
	Middle				Cibeureum Fm Cikapundung Fm	Undifferentiated volcanic products
	Lower	Intrusion				Volcanic vent
Pliocene	Upper		Pliocene Breccia	Andesite		Undifferentiated volcanic products
	Middle			Dacite		
	Lower	Older sedimentary rock				Subvolcanic
Miocene						Pumiceous tuff breccia

2.3 Shiny-Based WebGIS

Many regions in the world have published geological information through the WebGIS platform. Some examples include, but not limited to:

- Brandenburg (http://www.geo.brandenburg.de/Brandenburg_3D/client/portal/index.html),
- Hessen (http://geologie.hessen.de/mapapps/resources/apps/geologie/index.html?lang=en),
- Arizona (http://data.azgs.az.gov/geologic-map-of-arizona/#) **(Figure-4)**

This interactive information makes it very easy for people to see and to learn about the geology of the area. However, for many people, making a platform like this seems complicated and out of reach. This is caused by people's perceptions about web-related matters that seem difficult, full of programming, coding, and mostly technical obstacles.

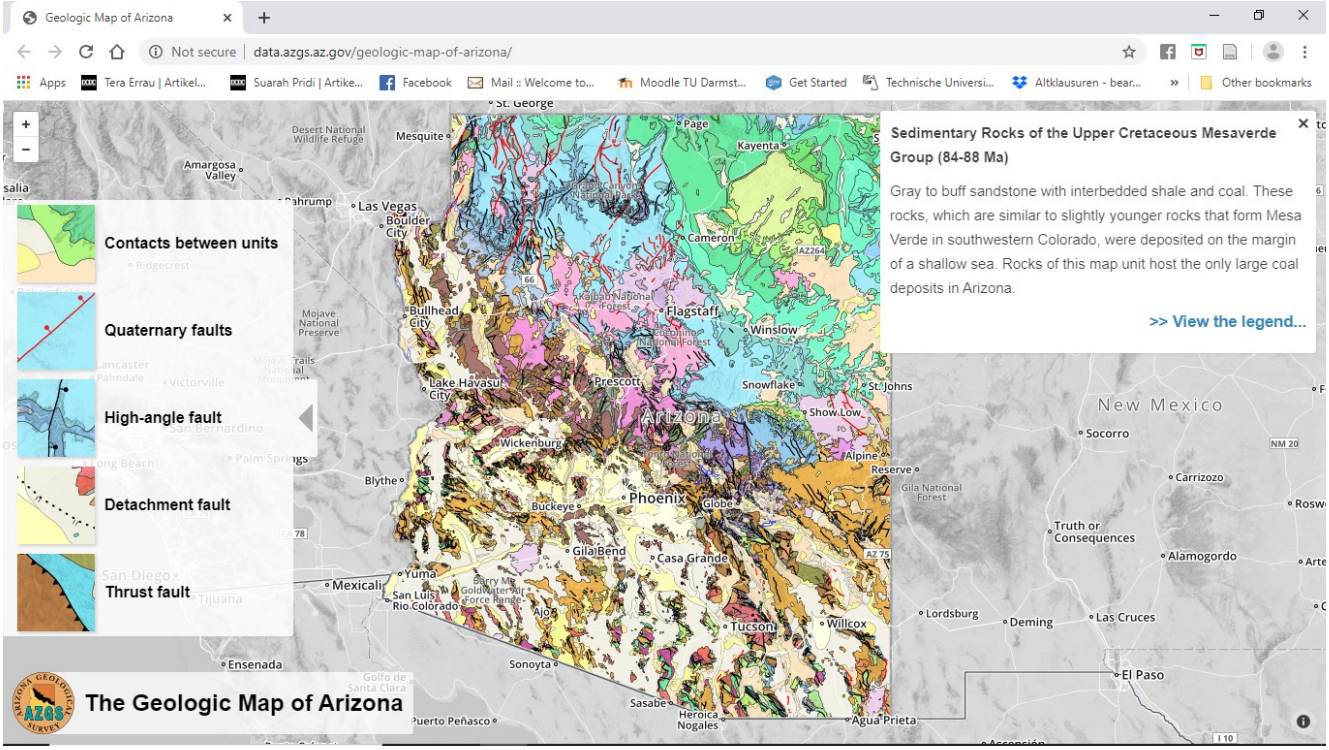

Figure 4 Interactive WebGIS of Geological Map of Arizona that can offers and explanation about lithology of geological formation whenever cursor is directed to any area (Arizona Geological Survey 2013)

Meanwhile, there are now many facilities available for everyone to publish their own webGIS. Mainstream devices such as ArcGIS are already connected to ArcGIS online, whose appearance and procedure greatly facilitates the publication of webGIS. Other devices that are open like QGIS are not much different.

Even more programming-based devices exist and are easy to learn. Leaflets are Javascript libraries that are open-source and can be used to create interactive maps that are mobile-friendly. The geological map of Arizona's above is an example of map developed with Leaflet's. To do it yourself, there are already so many tutorials for beginners who want to try to make each interactive map.

In this study an interactive map was developed using the R programming language and utilizing packages that have been developed in this language. R is the language and environment for computational statistics and graphics (R Core Team 2019). R is part of the GNU project similar to the S language previously developed by John Chambers et al from Bell Laboratories. R enables data processing and storage, graphical visualization of analytical data, with language that is not too complicated, and easily understood by programming beginners.

Because it is open-source, R develops very democratically, where the tools and packages that are available are the result of community development and people competing to share work, share input, share procedures for the use of packages developed by each R-Packages developers

The advantage of developing interactive maps using programming is the ease of customization. Other devices such as ArcGIS and QGIS are more rigid and makes it to be difficult to customise.

3 Methodology

The development of the Hydrogeology Information System of Bandung Basin with R goes through several stages, namely; database development, which includes well data and map data; R script development, which includes development of function for well profiles and cross section making; developing leaflet maps; reactivity development; user interface development; and finishing applications. In general, the description of the development of this application can be seen in the following flowchart (Figure-5):

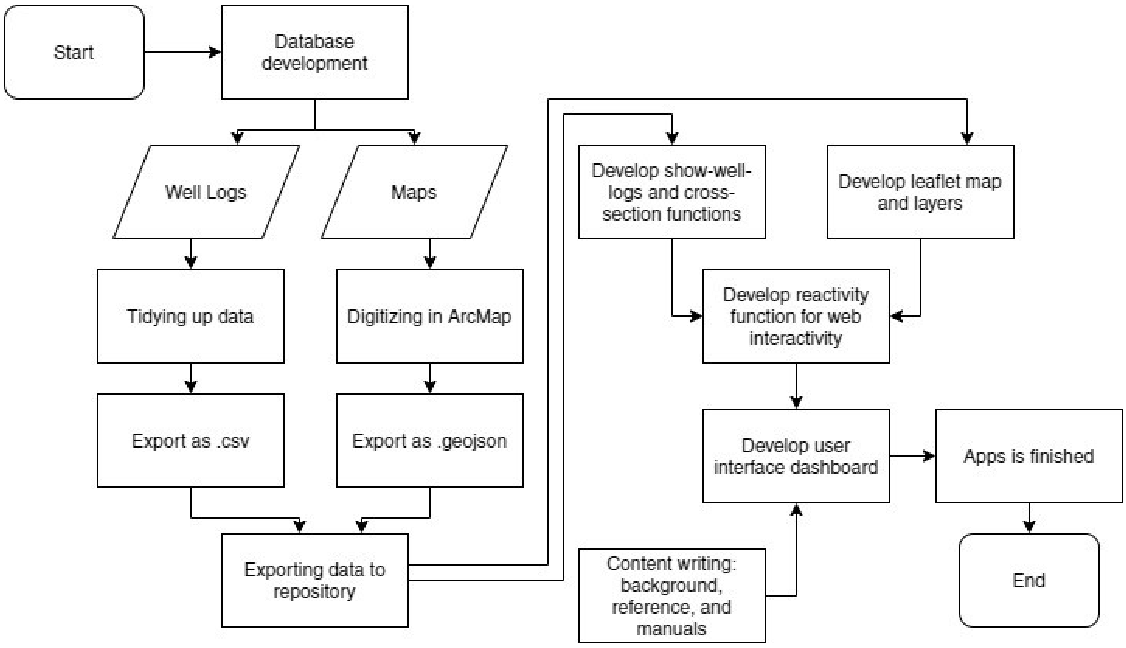

Figure 5 Flowchart of application development

3.1 Database Development

The database developed in this application includes well logs data and maps data.

3.1.1 Well Logs

Compiling and managing the database for the development of this application is the most time-consuming effort. The collected data consist of published data, data in publications, and especially hard-copy data which must be digitized and formatted in an R-Friendly structure table or extension. Although an inventory of water drilling data has been carried out for a long time by the Department of Energy and Mineral Resources of West Java Province, in reality this data is spread across the official department and is not so easy to obtain. In the end the data collected is the data in the following Table-3:

Table 3 Well data obtained from several sources

Data Code	Amount	Sources
P	86	Ph.D thesis of Bambang Sunarwan (Sunarwan et al. 2014)
PL	73	Drilling logs of IWACO-WASECO (IWACO 1990)
ESDM	23	Dinas ESDM Provinsi Jawa Barat, Inventarisation of 2017-2018
DH&MT	5	Geotechnical drilling logs Adrin Tohari, Geoteknologi LIPI (Tohari, Sari, and Syahbana 2016; Tohari, Soebowo, and Wibawa 2015)
DPDR	2	Drilling logs M.A.C. Dam (DAM 1994; Dam 1997)
Total	189	

In R, especially in manipulating data using dplyr package (Wickham et al. 2019), it is very important to have tidy data. Tidy data is an alternative name for a statistical model data matrix. According to Hadley Wickham, tidy data is data arranged so that each variable is a column and each observation is a row (Wickham et al. 2019).

The well data in Bandung Basin are arranged to be tidy data. The final form is in the form of columns and rows as follows Table-5:

Table 4 Example of well logs data that has been tidy up. Each variable is a column and each observation is a row

Code	Z	Lon	Lat	Depth	TopElev	BotElev	SP	R	KodeLito	Screen	Akifer
P1	697	107.617	-6.9227	1	697	696			TanahPenutup		FALSE
P1	697	107.617	-6.9227	2	696	695			TanahPenutup		FALSE
P1	697	107.617	-6.9227	3	695	694			TanahPenutup		FALSE
P1	697	107.617	-6.9227	4	694	693			TanahPenutup		FALSE
P1	697	107.617	-6.9227	5	693	692			TanahPenutup		FALSE
P1	697	107.617	-6.9227	6	692	691			TanahPenutup		FALSE
P1	697	107.617	-6.9227	7	691	690			TanahPenutup		FALSE
P1	697	107.617	-6.9229	8	690	689			TanahPenutup		FALSE

Each meter of data is represented by one row of values with consideration, so that the smallest unit of well in this database is 1 meter. This figure was chosen with the consideration that the reported geophysical logs has 1-meter resolution. Therefore, it is used as the smallest resolution.

This measurement method has a disadvantage in the form of very large data. Of the total 189 wells, 27,615 rows produced data with 2.6 Megabytes of data.

3.1.2 Maps

The geological map data used is the Bandung Basin Geological Map scale 1:100.000, which was published by the Directorate of Geology and Environmental Planning of the Indonesian Republic in 1993 (Dam, Suhirman, and Toloczyki 1993). This map was chosen because it has covered the Bandung Basin in its entirely. While in the existing geological map system, the Bandung Basin is at the corner of 4 geological maps.

The hydrological map data used is the 1: 250,000 scale Indonesian Hydrogeology Map sheet Bandung published in 1983 (Soetrisno 1983). Groundwater basin data was obtained from the Department of Energy and Mineral Resources of West Java Province in 2019. This Groundwater Basin Map is based on the Minister of Energy and Mineral Resources Regulation No. 02 of 2017 concerning the Groundwater Basin in Indonesia. Data on the groundwater extraction status was obtained from the Department of Energy and Mineral Resources of West Java Province in 2019.

These maps are digitized and saved in the .geojson format and then displayed in the Longitude - Latitude projection with the 1984 WGS datum. The .geojson format was chosen because this format is friendly to network-based applications. Unlike the .shp format that is commonly used, the .geojson format only has one file, while the .shp format consists of several files. The number of additional files in the .shp format data makes it difficult to retrieve data from the repository.

3.1.3 Repository

The data that has been tidied and digitized is then stored in an online repository, so that the data can be accessed by everyone. This is also to facilitate data retrieval from shiny servers so that data can be opened from anywhere. The repository used is the github repository, which is the most common repository used by developers. In this repository the data stored is well data, geological map data, hydrogeological map data, groundwater extraction status maps, and groundwater basin maps. The data in the github repository can be called directly from the R-Studio application. To access the repository please visit the link below:

https://github.com/malikarrahiem/thesismalik

3.2 R-Scripting

3.2.1 Developing User Interface Dashboard

The Hydrogeology Information System of Bandung Basin was developed using the R programming language using the Shiny package (Chang et al. 2017). Shiny makes it easy for application developers to create interactive online applications. With shiny, anyone can create and host the application, or embed it in an R Markdown document, or create a dashboard. Shiny combines the ease of computing using the R language and the interactivity of modern internet sites. Most interestingly, Shiny-based applications are easy to develop and do not require advanced web-development skills.

In general, shiny is divided into two parts, namely the User-Interface (UI) section and the Server section. In the UI, the developer designs the appearance of the application. In the server section, the developer manages how the application works. What would happen when user click any button, change any inputs. This is called the reactive function.

In developing the user interface, there is a shinydashboard package (Chang and Borges Ribeiro 2018), which is a package that allows application developers to design a professional-looking dashboard.

3.2.2 Developing Interactive Map with Leaflet

Leaflet packages (Cheng, Karambelkar, and Xie 2019) are used to display spatial data. Using this package, we can create leaflet maps that can be rendered into HTML pages, whether from R Markdown, Shiny, or other applications.

In the leaflet map, we can arrange the basic map that is available for free. In this application, the basemap used is the World Street Map basemap which was provided by Esri. Then we can determine the work area with the fitBounds function. Then you can determine the location that is first seen when the first application opens and the zoom level.

Next is to display polygons, polyline, and points from the data that we have. Polygon, polyline, and point data are opened using the geojsonio (Chamberlain and Teucher 2019). Projection system setup and projection transformation using the Rgdal package (Bivand, Keitt, and Rowlingson 2019). Each element that we have can be grouped into groups so that we can choose which layer we want to display. Finally, we can add a scalebar and measure bar to measure distances.

3.2.3 Develop Reactive Function to Plot Well Profiles and Cross Sections

In this application, after the well data is plotted into the map, the application user can find out how the subsurface conditions are at that point. In shiny systems this is possible with a reactive programming. Reactive programming is an elegant and powerful programming paradigm. The key idea of reactive programming is to set the visualization dependency, so that if the input changes, all related outputs will be automatically updated. This makes the flow of thinking of the application simpler, although from the point of view of the developer, at first the application can be quite confusing (Wickham 2020).

The way of thinking of the reactive function to plot the well is as follows:

When the application user clicks on a point, then shiny will temporarily save the well code that was clicked. Furthermore, using the **%in%** function in the dplyr package (Wickham et al. 2019), this function allows us to select the well code that is in the database.

After the well code has been selected, R will filter the database and only select rows with the appropriate well code of the choice. Next is data visualization using ggplot2 (Wickham 2016, 2). Ggplot2 is a system for creating graphics based on the Grammar of Graphics. The application developer provides the data, then tells ggplot2 how the variables will be plotted through aesthetics and the type of plot to be used. In this application, there are 4 variables to be plotted, namely well casing, lithology log, resistivity log, and well screen placement.

The entire plot uses the same x-axis and y-axis. The x-axis is the height value, the y-axis is resistivity. Then this axis is flipped. This is because the line plot does not show satisfactory results if the x-axis used is resistivity and the y-axis the height value.

The well casing is plotted using geom_rect, which is the language ggplot2 to make a square. The parameters that must be entered are xmin, xmax, ymin, and ymax. Xmin is set to Bottom Elevation, while Xmax is set to Top Elevation. Ymin is set to 0, ymax is set to 50. Furthermore, the screen also uses geom_rect. Xmin is set to Bottom Elevation, Xmax is set to Top Elevation. Ymin is set to -5, ymax is set to 55, fill = Screen. Furthermore, Lito Code also uses geom_rect, with xmin = BotElev, xmax = TopElev, ymin = 0, ymax = 50. Finally, for resistivity plots use geom_line with x = TopElev and y = resistivity values.

The legend for the lithology and screen plot is defined in advance so that we will get the same color even though the plot changes. This is to prevent the plot from using the default color of ggplot2.

Furthermore, to plot several wells at once, the steps that are passed are quite different. The flow of thought is as follows:

1. We need to make imaginary cross-sections that passes through observation points.
2. Saving the points passed as a column
3. Make the cross-section function
4. Make an if-condition with a radio button to allow the cross section to be displayed

In addition to the predetermined cross section, there is one feature that allows user to determine the cross section themselves. In this feature the user can choose which points will be displayed. In principle the same as the process of making the previous cross section. The difference is, we do not save the points at the beginning, but choose them later. To do this, we use the mapedit package (Appelhans, Russell, and Busetto 2019). Mapedit is a package in R that allows users to interactively edit and select geospatial data. Using mapedit allows the user to temporarily save points that are clicked manually, then later to plot them into a cross section using the PlotPenampang function. Unfortunately, due to the incompatibility between Mapedit-Mapview with Shiny, this feature cannot be displayed in the application.

The following table-6 summarises the packages used to develop the Bandung Basin subsurface visualization application:

Table 5 R-packages that use to develop Bandung Basin Well Database Application

Package Type	Package Name
Data manipulation tools	dplyr (Wickham et al. 2019), tidyverse (Wickham 2017)
Data visualization tools	ggplot2 (Wickham 2016)
Spatial analysis tools	leaflet (Cheng, Karambelkar, and Xie 2019), mapview (Appelhans et al. 2019), mapedit (Appelhans, Russell, and Busetto 2019), sp (Pebesma and Bivand 2005; Bivand, Pebesma, and Gomez-Rubio 2013), rgdal (Bivand, Keitt, and Rowlingson 2019), sf (Pebesma 2018), geojsonio (Chamberlain and Teucher 2019)
Web Application Framework	shiny (Chang et al. 2017), shinydashboard (Chang and Borges Ribeiro 2018)

3.3 Online-Visualization

This application is hosted by Shinyapps.io, a R-Studio service that allows shiny users to share their shiny applications online without the need to set up a standalone server. You can learn more about Shiny and building Shiny apps at www.shiny.rstudio.com. To learn more about Shiny Server go to http://www.rstudio.com/products/shiny/shiny-server/.

To see the application that I developed, please visit the site directly below:

https://malikarrahiem.shinyapps.io/BandungBasin/

When opening the application, please wait as it takes a while to load due to server capacity.

All the related script needed for this apps to be worked is in Appendix 1-4 below.

4 Result

To better experience the result of this master thesis, it is strongly suggested to open the application directly from laptop or computer, through https://malikarrahiem.shinyapps.io/BandungBasin/.

This apps is available for public and can be accessed anytime. However, some limitation occurs as this apps are hosted on the free shinyapps.io. The limitation is that this apps are only allowed to be active for 25 active hours. Active ours are hours of the application are not idle. It is capped per account per month to protect the service from exceptional resource consumer.

The apps userinterface consist only of three main units; the title, dashboard, and the main panel. The apps consist of several function as shown in the Figure-6 below:

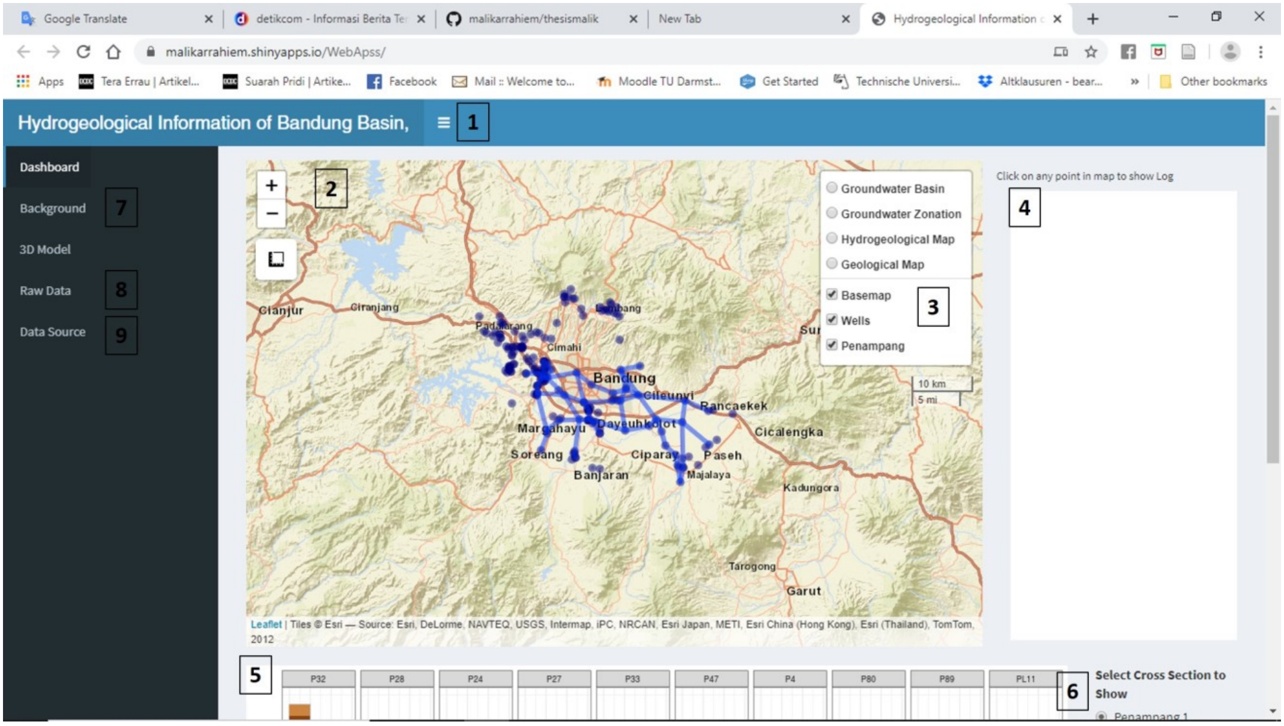

Figure 6 How the user interface of this apps looks like

Number 1 is the title of the apps. It is also accompanied with an icon, a three strips that can be used to hide the dashboard on the left side, so that the main panel be expanded. Number 2 is the main panel, which consist of 4 main parts. These are the maps, well log profile, cross section of the wells, and radio button for selector. Number 3 is the panel to show well profiles of selected well. Number 4 is the panel to show cross section of several well profiles. The option to select profiles (no 5) is in the right side of this panel, which are a radio button selector. There are several cross sections to be selected.

The left side of the dashboard is a list of additional information related to this application. The background is a naration behind the background of this application. Raw Data is filtered data of the wells, so that any user can download it for their own purpose. Data source is the reference of this application and the dataset sources.

4.1 Leaflet Map

The map are equiped with three function: zooming tools in the top left of the map, below it lies the measuring bar tool. In the top right of the map lies the layer control which are consist of two types of layer. Upper box, which called baseGroups consist of 4 layers; Groundwater Basin, Groundwater Zonation, Hydrogeological Map, and Geological Map. Of all this map, only one are allowed to be selected at once to avoid stacking of the maps. The lower box, which called ovarlayGroups consist of three layers; Basemap, wells, and penampang (cross section). This layers can all be selected at once. It is necessary to inform that layer stacking system in leaflet is based on which layer selected last. So the last layer selected will be to topmost layer.

If the user select on the Groundwater Basin Layer, then the layer will appear. Whenever the user direct their cursor to the area inside the Groundwater Basin, then the name of the basin will appear. Figure-7 show the example when Groundwater Basin layer is selected and directed to GWB Bandung-Soreang.

The same applies as Groundwater Zonation Layer. When this layer is clicked, then the map will appear and the layer name will pop when the area is touched by the cursor. As can be seen in the **Figure-8**, the cursor was directed to the green area in the southern mountain of Bandung Basin. This map is the recharge area of the aquifers in Bandung Basin. It is unfortunate that in leaflet, it is not possible (at least for now) to show multiple legend at once. The result is messy if multiple legend are shown. Therefore, the information is shown as pop-up message.

In case of Groundwater Zonation, green color means recharge area, blue color means safe area for extracting water, yellow is vulnerable area for extracting water, and red is degraded area. This system are based on the regulation of West Java Governor number 31 year 2006 (Hutasoit 2009).

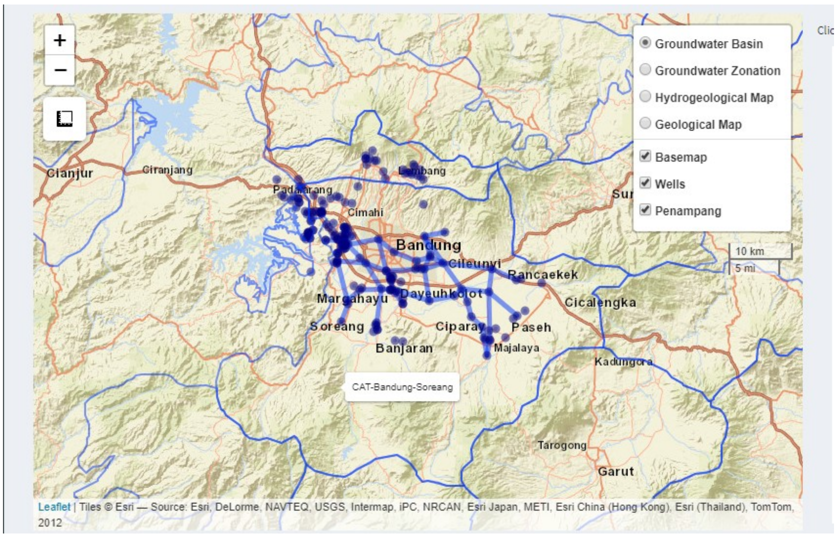

Figure 7 Groundwater Basin layer appear as the user click on the radio button

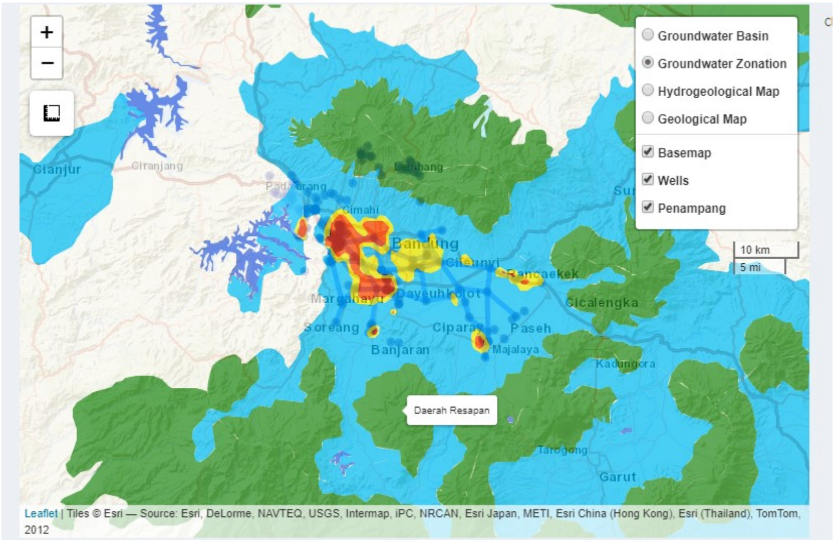

Figure 8 Groundwater Zonation layer appear as the user click on the radio button and direct to the green area

Hydrogeological map are shown in Figure-9 below. The map was based on Soetrisno's Hydrogeological Map of Bandung scale 1:250.000 (Soetrisno 1983) which are clipped into the polygon of GWB Bandung-Soreang. In this map, the color legend are;

Darkgreen: "Porous and fractured aquifer, high productivity, widespread" ,

Forestgreen: "Porous and fractured aquifer, medium productivity, widespread",

Palegreen: "Porous and fractured aquifer, locally productive",

Dodgerblue: "Porous aquifer, high productivity, widespread",

Dodgerblue4: "Porous aquifer, productive, widespread",

Turquoise: "Porous aquifer, locally aquifer with medium productivity", Chocolate4: "Insignifincant groundwater zone"

Geological map are shown in Figure-10 below. The map was based on Dam's Geological Map of Bandung scale 1:100.000 (Dam, Suhirman, and Toloczyki 1993). In this map, the color legend are:

Red= "Lava flows, predominantly",

Violetred4 = "Andesite

Red3= "Dacite"

Gray72= "Alluvial and colluvial deposits"

Lightblue= "Lake deposits"

Khaki1 = "Alluvial and volcaniclastic fan deposits"

Yellow= "Fluvial sand deposits"

Salmon4= "Volcanic products, undifferentiated",

Saddlebrown= "Volcanic products, undifferentiated (older)"

Orangered ="Volcanic products, sandstone, conglomerate, undifferentiated"

Tan1= "Sandy tuff, predominantly ashfall"

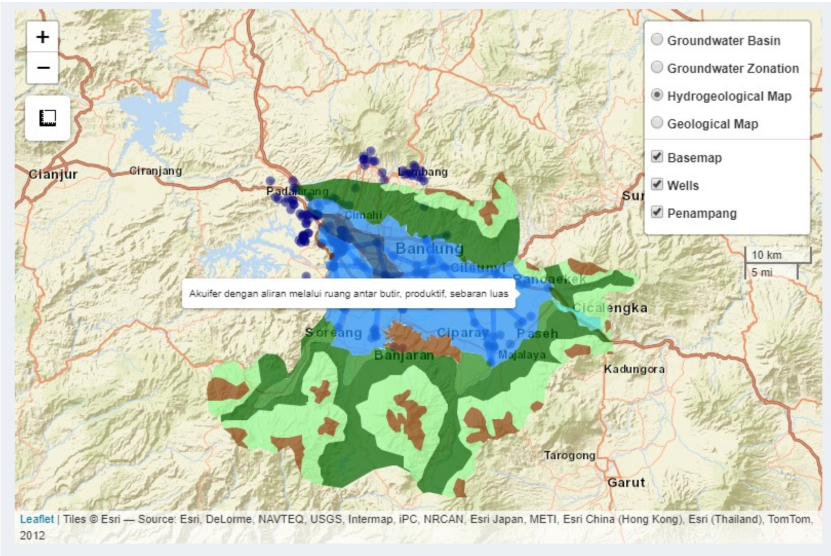

Figure 9 Hydrogeological Map layer appear as the user click on the radio button and direct to the blue area

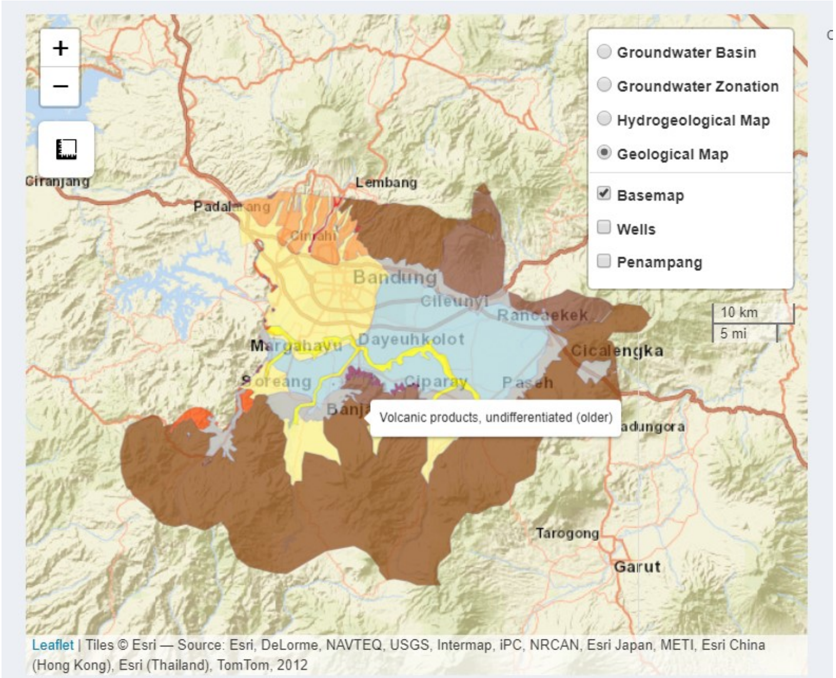

Figure 10 Geological Map layer appear as the user click on the radio button and direct to the orange area

4.2 Plotting Well Profile

Now when user click the wells radio button, it will bring wells layer to the top. Afterwards, the user can click to any wells they desired to see its log profiles, as can be seen on Figure-11 below:

Well profiles consist of lithological information, resistivity logs, and casing placement. There are 8 groups of lithology used in this application, namely: *Andesit (*Andesite), *Breksi (*Breccia), *Kerikil (*Gravel), *Lava (*Lava), *Pasir (*Sand), *TanahPenutup (*Top Soil), and *Tufa (*Tuff). It is worth to note that most of the drilling logs are made for groundwater drilling purpose, so the description of the rocks is confusing, not uniform, and most of the time inconsistent. Actually there could be more category if each description are made a class. For example the group Sand is not only sand. It can also clayey sand, or silty sand, or gravelly sand. It is whenever sand is the main component of the lithology, then sand become the group. It is also applies to another categories.

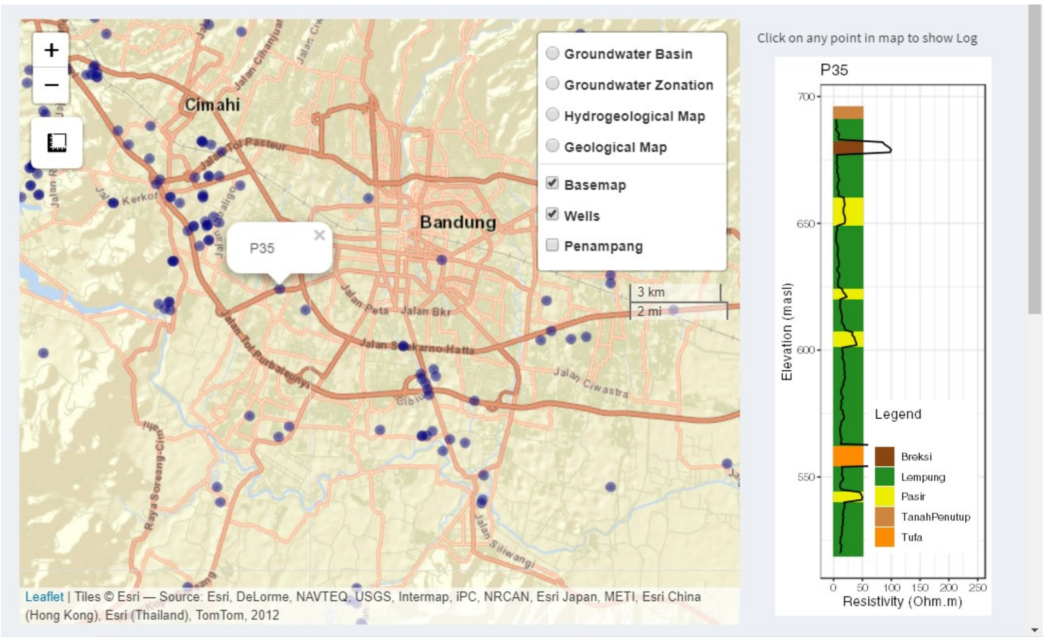

Figure 11 User interface of well profiles plotter function

Each well contains different information. Some of them contain full informations; lithology, resistivity, and well screen. Some other only contain one or two informations. Well screen information are plotted as a rectangle, a little bit wider as the lithological rectangle, and placed behind the lithological layer. The example of these well plot can be seen on Figure-12 below:

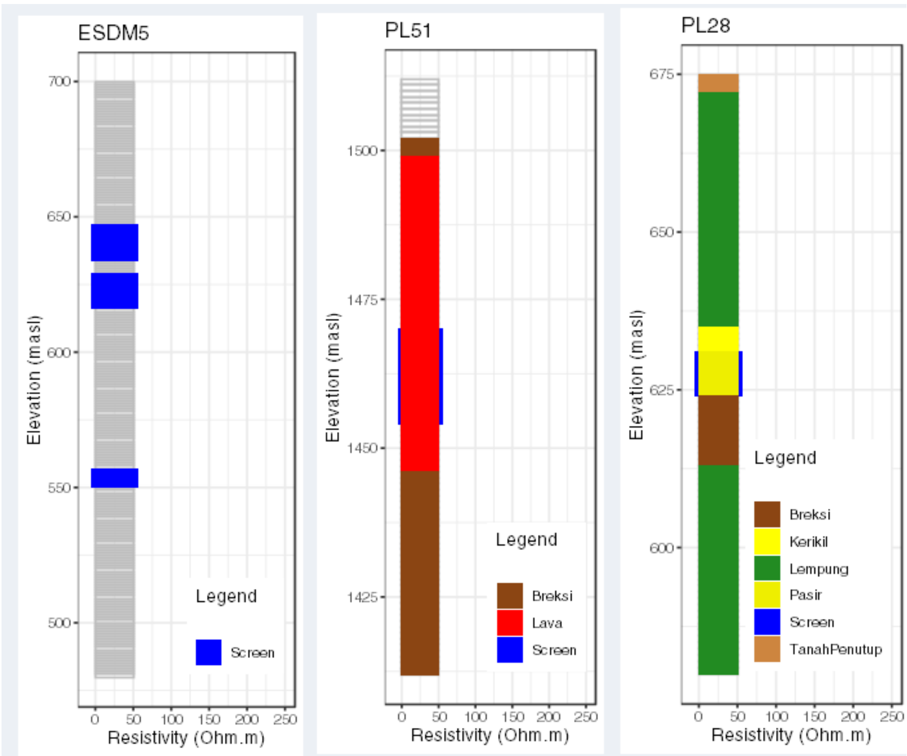

Figure 12 Example of well profiles which contain different information

4.3 Plotting Predefined Well Cross-Section

As geologist prefer wider information (2D and when possible 3D), mostly as a cross section, a cross section generator is provided when the user scroll-down the apps. There are 9 predefined cross sections. Each consist of minimum 5 and maximum 10 wells each. Six cross sections are North-South cross section (*Penampang* 1 to *Penampang* 6), and 3 cross sections are West-East cross section (*Penampang* BT1 – *Penampang* BT2), **Penampang* means Cross Section in Indonesian Language (**Figure-13)**.

List of defined cross-section

Penampang 1 <- c("P32","P28", "P24", "P27", "P33", "P47", "P4", "P80", "P89", "PL11")

Penampang 2 <- c("PL68", "ESDM1", "P91", "P16", "P35", "P48", "P73", "P36", "P92")

Penampang 3 <- c("P30", "P93", "PL18", "PL19", "PL20", "PL21", "P62", "P61", "P14")

Penampang 4 <- c("ESDM13", "P10", "P51", "P95", "P90","DPDR_1")

Penampang 5 <- c("P10", "P49", "DHBLA", "MT03", "DH02", "ESDM9", "PL5", "PL6", "ESDM11")

Penampang 6 <- c("P87", "DPDR_2", "P9", "ESDM10", "ESDM11")

Penampang BT_1 <- c("P4", "P48", "P93", "P63", "P43", "P90", "P49", "P87", "P21")

Penampang BT_2 <- c("P41", "P67","P71", "ESDM5", "P16", "P30", "P1", "P38", "P95", "P49")

Penampang BT_3 <- c("P80", "PL16", "P73", "P62", "PL27", "DPDR_1", "DH01", "DHBLA", "DPDR_2", "PL2")

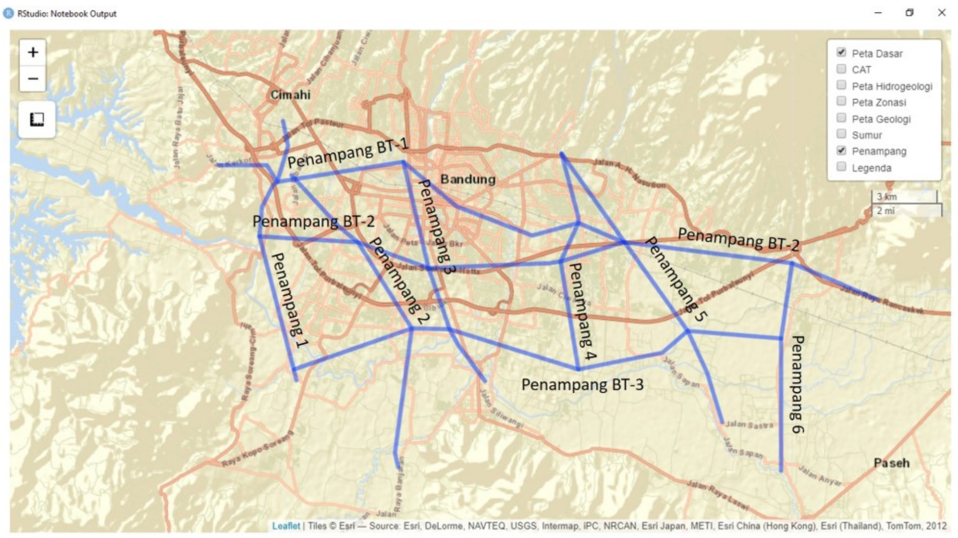

Figure 13 Available cross sections shows when the Penampang button is clicked

The right side of the cross section window is the list of possible cross sections to show, which are displayed as radio button. Using this option, user can select which cross section they would like to see. The information contained in these well profiles are the same as in the previous sub-chapter, only it shows as facet. The limitation of this cross section is up to 10 wells. If it reach more than 10 wells, it will give two rows.

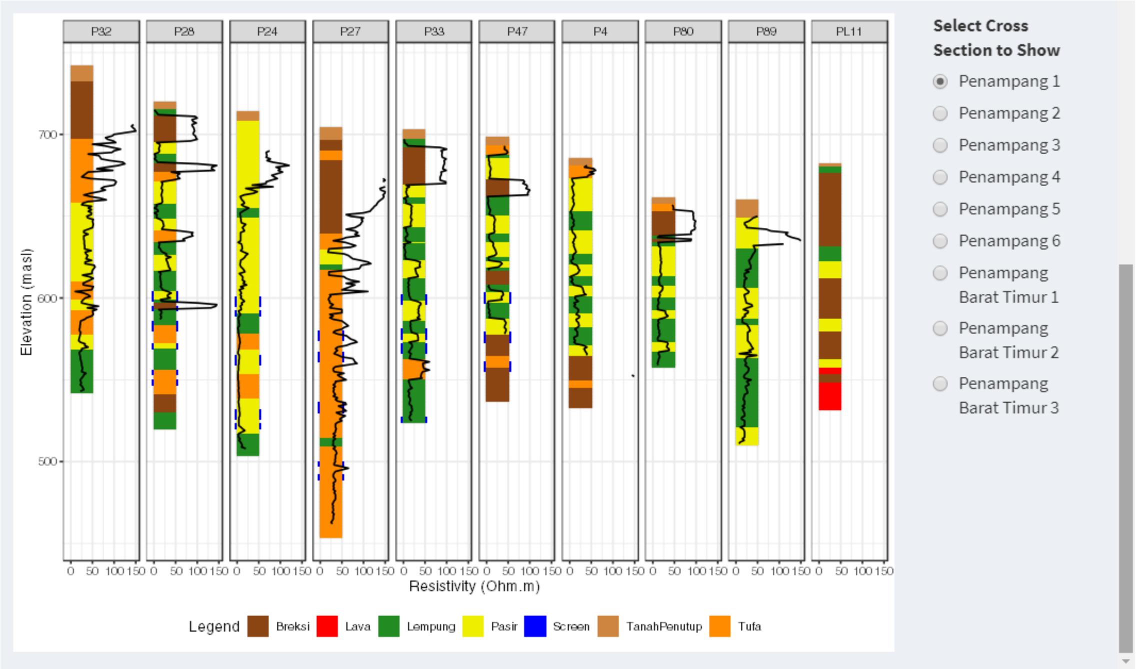

Figure 14 Multiple wells displayed as cross sections and could be intrepreted later

4.4 Background Page

This page contains the background behind the development of this application. It is mostly the summary of introduction chapter in this thesis.

4.5 Raw Data

This page contains the raw data of selected wells in the well profile function. In this page, 25 rows of data are shown as default, but it could be changed. It is also possible to download the file as CSV and save it at your device.

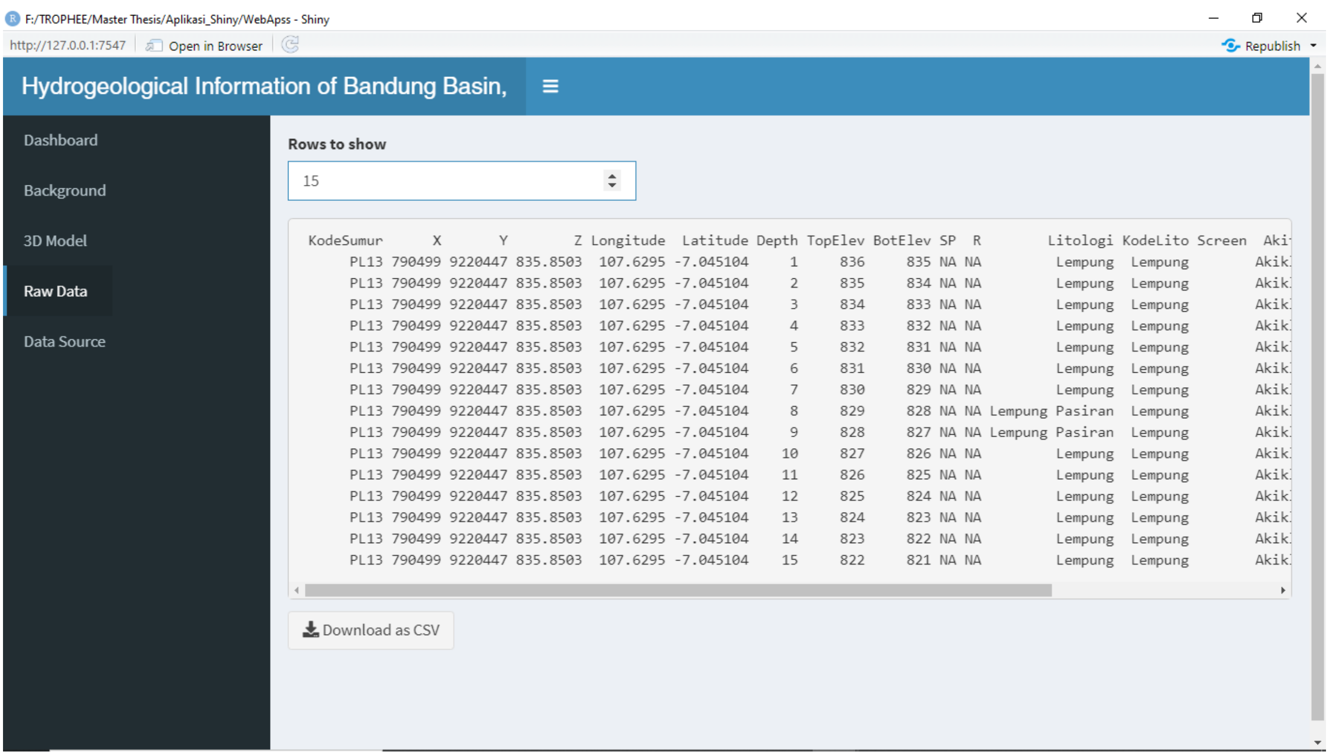

Figure 15 Raw data of the well selected in the leaflet map. It can be downloaded by clicking the button Download as CSV

4.6 Data Source Page

This page contains the source of data used in this apps and the reference used to write the thesis.

4.7 Plotting Well Cross-Section (User Defined)

This is the function that is not yet available in the apps due to the incompatibility between the packages behind this function. The function can be used to plot a well cross section that pass through any points that are selected by user. User can select any points, afterward save it and shows it as a cross section. Similar to the function of Predefined Well Cross-Section, but in this case, the points are user-defined.

The display would be a map with well points (**Figure-16**). Afterward user can click at any points and click done. Next the cross section will be shown (**Figure-17**).

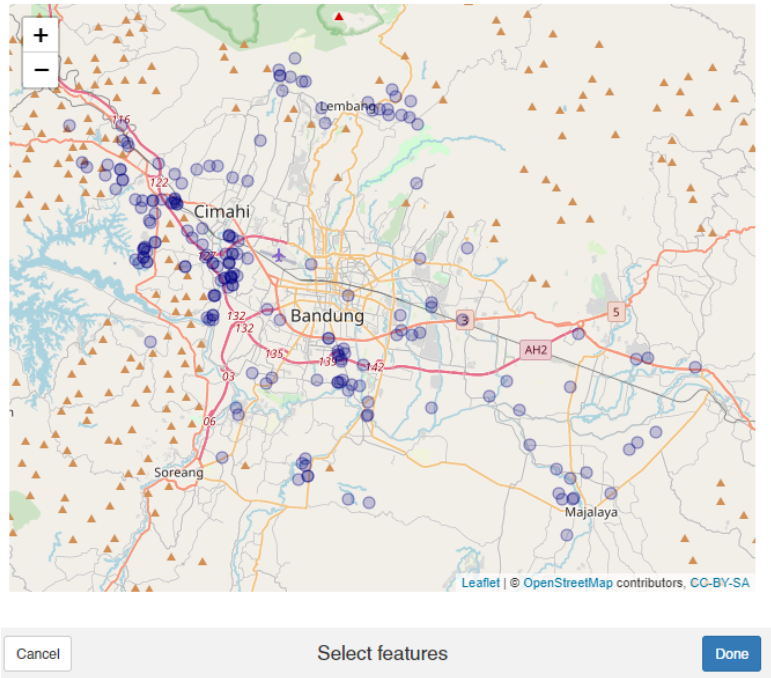

Figure 16 Display of User Defined Well Cross-Section

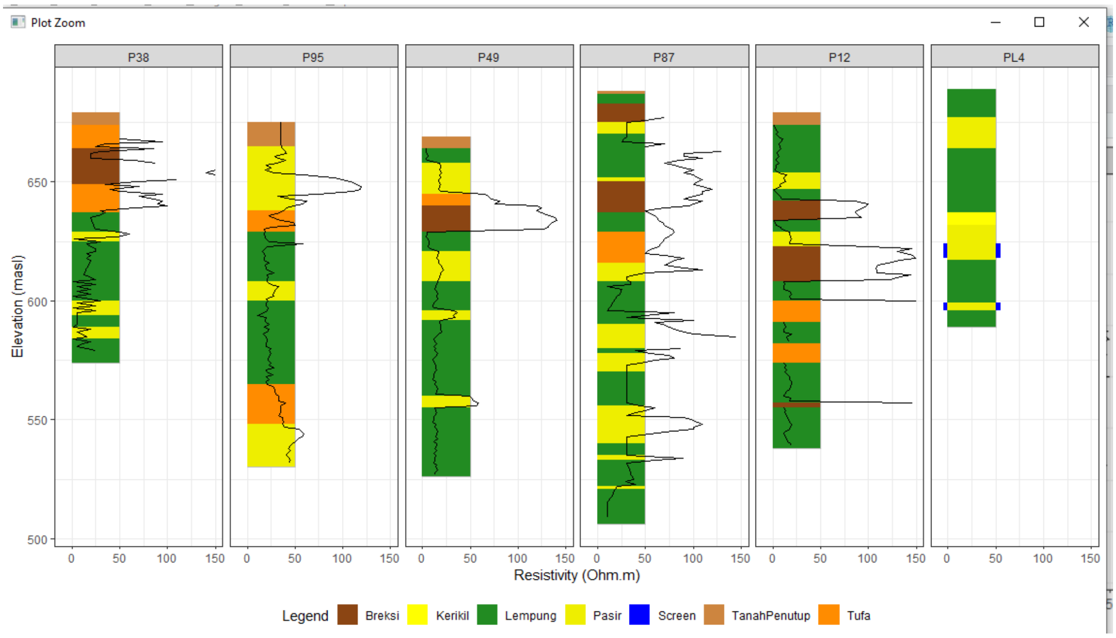

Figure 17 Cross section as the result of User-Defined Well Cross-Section

This function is available in the repository as:

https://raw.githubusercontent.com/malikarrahiem/thesismalik/master/selectMap_shiny.R

5 Discussion and Recommendation

Open data is part of a broad global movement that is not only advancing science and scientific communication but also transforming modern society and how decisions are made (Huston, Edge, and Bernier 2019). Open data is beneficial to accelerate science development, especially in developing country like Indonesia. Many times, if not most of the times, any scientist in Indonesia are faced with a thick barrier names lack-of-data. While this seems true, but the truth is that the country has more data than it seems to be.

It was stated in the beginning, that there should be more than 2000 wells profile available for Bandung Basin and surrounding. The government mandated that all deep groundwater extractor licensee have to report their extraction plan, along with its well profile. However, due to the dynamics in the responsible department regarding groundwater, the data become scattered. So there has to be a movement to open the data, in this thesis is one effort to do that.

Bandung Basin is in a major threat of groundwater depletion. It has been realized since decades that in Bandung, excessive pumping of groundwater might leads to land subsidence (Hudoro 1991). Subsidence rate in Bandung Basin is in average -8 cm per year and can reach to about -16.9 cm per year in a certain location and time period (Gumilar et al. 2015). The most suspected culprit is excessive groundwater pumping (Gumilar et al. 2015; Ge et al. 2014; Abidin et al. 2013).

Figure-18 below shows the depletion of groundwater in several industrial wells in Bandung Basin.

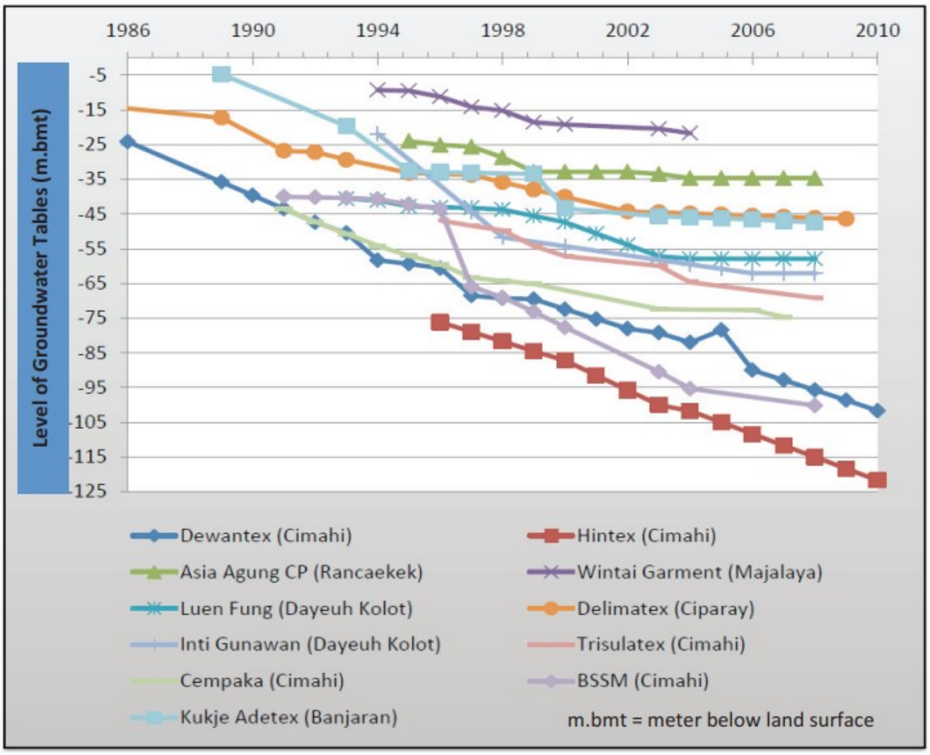

Figure 18 **Decrease of groundwater table at several factory wells in Bandung basin (Courtesy of Indonesian Geological Agency) (Gumilar et al. 2015)**

In order to restore the balance in groundwater extraction, dramatic effort has to be taken. Aquifer geometry has to be modeled precisely, and therefore well-logs information is really needed. After precise geometry has been modeled, the extraction of groundwater has to be measured digitally and be send telemetrically so that real time information regarding water table is acquired and can be plotted subsequently.

Currently, the Geological Survey of Indonesia has already developed a web-based telemetric information system of the groundwater monitoring wells network (Asghaf and Purnomo 2017). However, the system is not open for public. In the near future, information related to groundwater has to be open, because of the threat that lies on excessive pumping of groundwater. Research has shown that open data is one effort in accountability to fight against corruption (Hulstijn, Darusalam, and Janssen 2017). It is very possible that there are more wells extracting water from the aquifers than the registered wells in the government database. With transparency, the degradation of groundwater in Bandung Basin can be handled together, hand by hand government, scientist, and concerned citizens.

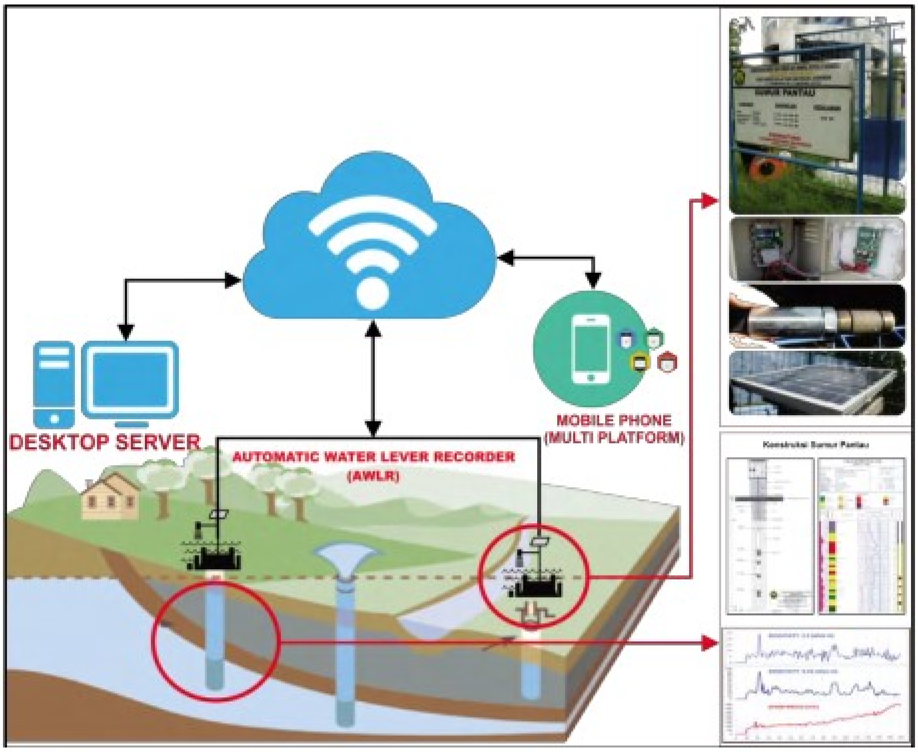

Figure 19 web-based telemetric information system of the groundwater monitoring wells network being developed by Indonesian Geological Survey

Currently there are 189 wells saved in this application. Of course this is very small number compared to 2200 wells reported by (Wangsaatmaja, Sutadian, and Prasetiati 2006) in the year 2004. Opening current data are hoped to encourage the willingness of data owner to share their data.

6 Conclusion and Outlook

The application Hydrogeology Information System of Bandung Basin which are available in https://malikarrahiem.shinyapps.io/BandungBasin/ is an effort to democratise the management of subsurface information in Bandung Basin, which are facing the catastrophic threat of land subsidence and groundwater scarcity. To obtain that purpose, people should be able to access the information easily, in this case through online platform.

In this application, well data from several sources are obtained, digitised, and visualised in the form of web-GIS platform so that people can interact with subsurface data of Bandung Basin in an interactive way. The code, which are written in R, an open, free, and easy to practice programming software, are publicly available. It means that interested peer can review, give comment, or give an advice on how this apps should develop. Not only that, due to the openness of the code, anyone that interested in developing similar application can copy and modify it easily.

This web aplication to inform subsurface information is expected to encourage further research on subsurface model development, not only in Bandung Basin, but also anywhere in the world, where data accessibility is a big problem.

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Appendix 1

```
#Packages dependencies
# If you want to open this apps in your own system, it is required that you
#install the packages used in this apps. In doing so, all you need to do is
#to run all the line in this page.

requiredpackages <- c("ggplot2", "tidyverse",
                "dplyr", "leaflet", "shiny",
                "shinydashboard", "geojsonio", "rgdal",
                "htmlwidgets")

lapply(requiredpackages, install.packages,
    character.only = TRUE) ## download the required packages

lapply(requiredpackages, library,
    character.only = TRUE) ## load the required packages
```

Appendix 2

```
#The function that was used in the application
#The main function is to plot the wells. In this function,
#the data that is being input is well code, it can be one well, or more
#The format of the data is x = c(P1, ...)

PlotSumur <- function (x){
  p <- FilterSumur(x) #the name of the function is made in Indonesian Language
  PlotGrafik(p)
}
#There are two more function needed to plot the graph. It is to filter the
#data according to the name of selected well/wells, and to make the plot
#1. FilterSumur Function. In this function, several variable that is needed
#can be selected. For example longitude, latitude, well-code, depth, lithocode
#next, we will arrange the well according to its selected order, not its alphabet

FilterSumur <- function(x){
  p <- Logs %>%
    dplyr::select(KodeSumur, TopElev, BotElev, Litologi, KodeLito, R, Screen) %>%
    filter(KodeSumur %in% x) %>%
    mutate(KodeSumur=factor(KodeSumur, levels = x)) %>%
    arrange(KodeSumur)
  return(p)
}

#2. Plotgrafik Function. This function is plot the lithology as a rectangle,
#fill the color according to the KodeLito, and plot the depth accordingly
#Beside of that, the resistivity log are plotted as line. Afterward,
#the graph has to be flip, because geom_line make a line from smaller to bigger
#x number

PlotGrafik <- function(x){
  WS <- x %>%
    dplyr::select(KodeSumur, TopElev, BotElev, Screen) %>%
    filter(Screen == "Screen")
```

```
if(dim(WS)[1] == 0) {
 ggplot()+
  geom_rect(data = x,
       mapping = aes(xmin=BotElev, xmax=TopElev,
             ymin=0, ymax= 50,
             colour="grey",
             weight = 0.2,
             fill=NA))+
  scale_color_manual(values=c('grey'),
           guide=FALSE)+
  geom_rect(data = x,
       mapping = aes(xmin=BotElev, xmax=TopElev,
             ymin=0, ymax= 50, fill= KodeLito))+
  facet_wrap(~KodeSumur, ncol = 10)+
  geom_line(data= x, mapping = aes(x= TopElev, y= R))+
  theme_bw()+
  coord_flip()+
  scale_y_continuous(, limits=c(-10,150))+
  scale_fill_manual(values = Warna)+
  labs(x = "Elevation (masl)" , y = "Resistivity (Ohm.m)", fill = "Legend")+
  theme(legend.position = "bottom")+
  guides(fill = guide_legend(nrow = 1))

} else {
 ggplot()+
  geom_rect(data = x,
       mapping = aes(xmin=BotElev, xmax=TopElev,
             ymin=0, ymax= 50,
             colour="grey",
             weight = 0.2,
             fill=NA))+
  scale_color_manual(values=c('grey'),
           guide=FALSE)+
  geom_rect(data = WS,
       mapping = aes(xmin=BotElev, xmax=TopElev,
```

```
                    ymin=-5, ymax= 55, fill= Screen))+
    geom_rect(data = x,
           mapping = aes(xmin=BotElev, xmax=TopElev,
                    ymin=0, ymax= 50, fill= KodeLito))+
    facet_wrap(~KodeSumur, ncol = 10)+
    geom_line(data= x, mapping = aes(x= TopElev, y= R))+
    theme_bw()+
    coord_flip()+
    scale_y_continuous(, limits=c(-10,150))+
    scale_fill_manual(values = Warna)+
    labs(x = "Elevation (masl)" , y = "Resistivity (Ohm.m)", fill = "Legend")+
    theme(legend.position = "bottom")+
    guides(fill = guide_legend(nrow = 1))
 }
 }

PlotSumur <- function (x){
 p <- FilterSumur(x)
 PlotGrafik(p)
}

## An example of the PlotSumur Function
# just fill any well code that you are willing to plot in the rows R <- ...
#, R are made as factor so that the wells are arrange according to our
#need, not according to its alphabet order



#This is the list of cross section defined in the beginning:
#note that it is also possible to have your own cross section
Q1 <- c("P32","P28", "P24", "P27", "P33", "P47", "P4", "P80", "P89", "PL11")
Q2 <- c("PL68", "ESDM1", "P91", "P16", "P35", "P48", "P73", "P36", "P92")
Q3 <- c("P30", "P93", "PL18", "PL19", "PL20", "PL21", "P62", "P61", "P14")
Q4 <- c("ESDM13", "P10", "P51", "P95", "P90","DPDR_1")
Q5 <- c("P10", "P49", "DHBLA", "MT03", "DH02", "ESDM9", "PL5", "PL6", "ESDM11")
Q6 <- c("P87", "DPDR_2", "P9", "ESDM10", "ESDM11")
QBT_1 <- c("P4", "P48", "P93", "P63", "P43", "P90", "P49", "P87", "P21")
```

```
QBT_2 <- c("P41", "P67","P71", "ESDM5", "P16", "P30", "P1", "P38", "P95", "P49")
QBT_3 <- c("P80", "PL16", "P73", "P62", "PL27", "DPDR_1", "DH01", "DHBLA", "DPDR_2", "PL2")
PlotSumur(Q4)

#Plot Cross Section in the map function. In this function, the data are filtered
#to select only the top layer (depth=1).

TitikSumur <- Logs %>%
  select(KodeSumur, Longitude, Latitude, TopElev, Depth) %>%
  filter(Depth==1)

GarisPenampang <- function(x){
  p <- TitikSumur %>%
    filter(KodeSumur %in% x) %>%
    mutate(KodeSumur=factor(KodeSumur, levels = x)) %>%
    arrange(KodeSumur)
  return(p)
}

PQ1 <- GarisPenampang(Q1)
PQ2 <- GarisPenampang(Q2)
PQ3 <- GarisPenampang(Q3)
PQ4 <- GarisPenampang(Q4)
PQ5 <- GarisPenampang(Q5)
PQ6 <- GarisPenampang(Q6)
PQBT_1 <- GarisPenampang(QBT_1)
PQBT_2 <- GarisPenampang(QBT_2)
PQBT_3 <- GarisPenampang(QBT_3)

leaflet(data = TitikSumur) %>%
  addTiles() %>% setView(lng = 107.6, lat = -6.9, zoom=11) %>%
  addCircleMarkers(~Longitude, ~Latitude, radius= 5, label = ~KodeSumur, clusterOptions = markerClusterOptions()) %>%
  addPolylines(data = PQ1, ~Longitude, ~Latitude, weight= 2, label ="Penampang 1") %>%
  addPolylines(data = PQ2, ~Longitude, ~Latitude, weight= 2, label ="Penampang 2") %>%
  addPolylines(data = PQ3, ~Longitude, ~Latitude, weight= 2, label ="Penampang 3") %>%
```

```
addPolylines(data = PQ4, ~Longitude, ~Latitude, weight= 2, label ="Penampang 4") %>%
addPolylines(data = PQ5, ~Longitude, ~Latitude, weight= 2, label ="Penampang 5") %>%
addPolylines(data = PQ6, ~Longitude, ~Latitude, weight= 2, label ="Penampang 6") %>%
addPolylines(data = PQBT_1, ~Longitude, ~Latitude, weight= 2, label ="Penampang Barat Timur 1") %>%
addPolylines(data = PQBT_2, ~Longitude, ~Latitude, weight= 2, label ="Penampang Barat Timur 2")

#This function was developed by me (Muhamamad Malik Ar Rahiem) and my wife
# (Tifany Aprillia)
```

Appendix 3

```
#Color Legend
#Geological Map Legend
GeolMap_col <- colorFactor(palette = c("red","violetred4", "red3", "gray72",
                        "lightblue","khaki1", "yellow", "salmon4",
                        "saddlebrown", "orangered", "tan1"),
                levels = c("Lava flows, predominantly","Andesite", "dacite",
                        "Alluvial and colluvial deposits", "Lake deposits",
                        "Alluvial and volcaniclastic fan deposits",
                        "Fluvial sand deposits", "Volcanic products, undifferentiated",
                        "Volcanic products, undifferentiated (older)",
                        "Volcanic products, sandstone, conglomerate, undifferentiated",
                        "Sandy tuff, predominantly ashfall"))

#Hydrogeological Map Legend
HydroMap_col <- colorFactor(palette = c("Porous and fractured aquifer, high productivity, widespread" = "darkgreen",
                        "Porous and fractured aquifer, medium productivity, widespread"= "forestgreen",
                        "Porous and fractured aquifer, locally productive" = "palegreen",
                        "Porous aquifer, high productivity, widespread" = "dodgerblue",
                        "Porous aquifer, productive, widespread" = "dodgerblue4",
                        "Porous aquifer, locally aquifer with medium productivity" = "turquoise",
                        "Insignifincant groundwater zone" = "chocolate4"), domain = HydroMap$Aquifer_en)

#Groundwater Zonation Map Legend
GWZMap_col <- colorFactor(palette = c("Bukan Cekungan" = "grey99",
                       "Daerah Resapan" = "forestgreen",
                       "Waduk/Danau" = "royalblue",
                       "Zona Aman" = "deepskyblue",
                       "Zona Kritis" = "orangered",
                       "Zona Rawan" ="yellow2",
                       "Zona Rusak" = "red3"),
               domain = GWZMap$KONDISI)

#Cross Section Map Legend
```

```
Warna <- c("Andesit" = "red4", "TanahPenutup" = "peru",
        "Tufa" = "darkorange", "Pasir" = "yellow2",
        "Lempung" = "forestgreen", "Screen" = "blue",
        "Breksi" = "chocolate4", "Kerikil" = "yellow",
        "Lava" = "red1")
```

Appendix 4

```
## app.R ##
library(ggplot2)
library(tidyverse)
library(dplyr)
library(leaflet)
library(shiny)
library(shinydashboard)
library(geojsonio)
library(rgdal)
library(htmlwidgets)



#selecting data
#Well Log data saved in repository
url<-
"https://raw.githubusercontent.com/malikarrahiem/thesismalik/master/Complete_Logs.csv?token=AMDKGM
XFOOP6CAQ4JJ2OJXS6ODU6A"
Logs <- read.csv(url, header = TRUE)

# retriving geojson data from github
url1 <- "https://raw.githubusercontent.com/malikarrahiem/thesismalik/master/EnvGeoMap_longlat.json"
url2 <- "https://raw.githubusercontent.com/malikarrahiem/thesismalik/master/Hidrogeologi_longlat.json"
url3 <- "https://raw.githubusercontent.com/malikarrahiem/thesismalik/master/cat-jabar-
kepmen_longlat.json"
url4 <- "https://raw.githubusercontent.com/malikarrahiem/thesismalik/master/zonasi_longlat.json"

GeolMap <- readOGR(dsn=url1)
HydroMap <- readOGR(dsn=url2)
GWBMap <- readOGR(dsn=url3)
GWZMap <- readOGR(dsn=url4)

#design the user interface
ui <- dashboardPage(
  dashboardHeader(
    title = "Hydrogeological Information of Bandung Basin, Indonesia",
```

```
  titleWidth = 450
 ),
 dashboardSidebar(
  sidebarMenu(style = "position: fixed; overflow: visible;",
  menuItem("Dashboard", tabName = "dashboard"),
  menuItem("Background", tabName = "Background"),
  menuItem("3D Model", tabName = "3D Model"),
  menuItem("Raw Data", tabName = "rawdata"),
  menuItem("Data Source", tabName = "Data Source")
 )),
 dashboardBody(
  tabItems(
   tabItem(
    tabName = "dashboard",
       fluidPage(
        fluidRow(
         column(9, leafletOutput("shinymap", height = "520px")),
         h6("Click on any point in map to show Log"),
         column(3, plotOutput("plot", height = "480px"))),
         br(),
        fluidRow(
         column(10, plotOutput("test", height = "500px")),
         column(2, radioButtons("var",
              label = "Select Cross Section to Show",
              choices = list("Penampang 1",
                     "Penampang 2",
                     "Penampang 3",
                     "Penampang 4",
                     "Penampang 5",
                     "Penampang 6",
                     "Penampang Barat Timur 1",
                     "Penampang Barat Timur 2",
                     "Penampang Barat Timur 3"),
                    selected = "Penampang 1"))
                )
           )
```

```
          ),
    tabItem(tabName = "Background",
         fluidRow(
          column(12,
          includeMarkdown("Background.Rmd")))),
    tabItem("rawdata",
         numericInput("maxrows", "Rows to show", 25),
         verbatimTextOutput("rawtable"),
         downloadButton("downloadCsv", "Download as CSV")),
    tabItem(tabName = "Data Source",
         fluidRow(
          column(12,
              includeMarkdown("Data_Source.Rmd"))))
  )))

#managing the back-end
server <- function(input, output) {

 ## showing leaflet map
 output$shinymap <- renderLeaflet({
  leaflet() %>%
    addProviderTiles(providers$Esri.WorldStreetMap,
              group = "Basemap") %>%
    fitBounds(lng1 = 107.35, lat1 = -6.75,
          lng2 = 107.9, lat2 = -7.2)%>%
    setView(lng=107.65, lat = -6.95,
         zoom=10) %>%
    addPolygons(data= GWBMap,
           stroke = TRUE,
           weight = 2,
           label = GWBMap$NAMA_CEK,
           fillOpacity = 0,
           group = "Groundwater Basin") %>%
    addPolygons(data= GWZMap,
           stroke = TRUE,
           weight = 0,
```

```
            label = GWZMap$KONDISI,
            fillColor= ~GWZMap_col(GWZMap$KONDISI),
            fillOpacity = 0.7,
            group = "Groundwater Zonation",
            opacity = 1) %>%
addPolygons(data= HydroMap,
            stroke = TRUE,
            weight = 0,
            label = HydroMap$Aquifer,
            fillColor= ~HydroMap_col(HydroMap$Aquifer),
            fillOpacity = 0.7,
            group = "Hydrogeological Map",
            opacity = 1) %>%
addPolygons(data= GeolMap,
            stroke = TRUE,
            weight = 0.1,
            label = GeolMap$Legend,
            fillColor= ~GeolMap_col(GeolMap$Legend),
            fillOpacity = 0.7,
            group = "Geological Map",
            opacity = 1) %>%
addCircleMarkers(data = Logs, #adding well points
               ~Longitude, ~Latitude,
               layerId = ~KodeSumur,
               popup = ~KodeSumur,
               radius = 2,
               weight= 5,
               stroke = TRUE,
               label = ~KodeSumur,
               color = 'navy',
               group = "Wells") %>%
addPolylines(data = PQ1, ~Longitude, ~Latitude, #adding cross sectional lines
             label ="Penampang 1", group = "Penampang") %>%
addPolylines(data = PQ2, ~Longitude, ~Latitude,
             label ="Penampang 2", group = "Penampang") %>%
addPolylines(data = PQ3, ~Longitude, ~Latitude,
```

```
            label ="Penampang 3", group = "Penampang") %>%
    addPolylines(data = PQ4, ~Longitude, ~Latitude,
            label ="Penampang 4", group = "Penampang") %>%
    addPolylines(data = PQ5, ~Longitude, ~Latitude,
            label ="Penampang 5", group = "Penampang") %>%
    addPolylines(data = PQ6, ~Longitude, ~Latitude,
            label ="Penampang 6", group = "Penampang") %>%
    addPolylines(data = PQBT_1, ~Longitude, ~Latitude,
            label ="Penampang Barat Timur 1", group = "Penampang") %>%
    addPolylines(data = PQBT_2, ~Longitude, ~Latitude,
            label ="Penampang Barat Timur 2", group = "Penampang") %>%
    addPolylines(data = PQBT_3, ~Longitude, ~Latitude,
            label ="Penampang Barat Timur 3", group = "Penampang") %>%
    addLayersControl(
     baseGroups = c('Groundwater Basin',
             'Groundwater Zonation',
             'Hydrogeological Map',
             'Geological Map'),
     overlayGroups = c('Basemap',
              'Wells',
              'Penampang'),
     options = layersControlOptions(collapsed = FALSE),
     position = 'topright')%>% #Activating layer control
    hideGroup('Geological Map') %>%
    hideGroup('Groundwater Basin') %>%
    hideGroup('Groundwater Zonation') %>%
    addScaleBar(position = 'topright') %>%
    addMeasure(
     primaryLengthUnit = "kilometers",
     primaryAreaUnit = "hectares",
     position = 'topleft')
})

# mengeklik sumur di peta dan menampilkan profil log sumur
WellCode <- reactive({
  print(input$shinymap_marker_click)
```

```
  KodeSumur <- input$shinymap_marker_click$id
  print(KodeSumur)})

ggplot_data <- reactive({
  print(input$shinymap_marker_click)
  KodeSumur <- input$shinymap_marker_click$id
  print(KodeSumur)

  data <- Logs[Logs$KodeSumur %in% KodeSumur,]
  print(data)
  data})

output$plot <- renderPlot({
  if(nrow(ggplot_data()) == 0)
    return(NULL)

  ggplot()+
    geom_rect(data = ggplot_data(),
          mapping = aes(xmin=BotElev, xmax=TopElev,
                    ymin=0, ymax= 50,
                    colour="grey",
                    weight = 0.2,
                    fill=NA))+
    scale_color_manual(values=c('grey'),
                 guide=FALSE)+
    geom_rect(data = ggplot_data(),
          mapping = aes(xmin=BotElev, xmax=TopElev,
                    ymin=-5, ymax= 55,
                    fill= Screen
          ))+
    geom_rect(data = ggplot_data(),
          mapping = aes(xmin=BotElev, xmax=TopElev,
                    ymin=0, ymax= 50,
                    fill= KodeLito))+
    geom_line(data= ggplot_data(),
          mapping = aes(x= TopElev, y= R))+
```

```
    scale_fill_manual(values = Warna)+
    theme_bw()+
    coord_flip()+
    scale_y_continuous(, limits=c(-10,250))+
    ggtitle(WellCode() )+
    labs(x = "Elevation (masl)" , y = "Resistivity (Ohm.m)", fill = "Legend")+
    theme(legend.justification = c("right", "bottom"),
        legend.position = c(.95, .05))
  })

  #Plotting the cross section from available database

  output$test <- renderPlot({
    if (input$var == "Penampang 1"){
      PlotSumur(Q1)}
    else if(input$var == "Penampang 2")
    {PlotSumur(Q2)}
    else if(input$var == "Penampang 3")
    {PlotSumur(Q3)}
    else if(input$var == "Penampang 4")
    {PlotSumur(Q4)}
    else if(input$var == "Penampang 5")
    {PlotSumur(Q5)}
    else if(input$var == "Penampang 6")
    {PlotSumur(Q6)}
    else if(input$var == "Penampang Barat Timur 1")
    {PlotSumur(QBT_1)}
    else if(input$var == "Penampang Barat Timur 2")
    {PlotSumur(QBT_2)}
    else if(input$var == "Penampang Barat Timur 3")
    {PlotSumur(QBT_3)}
  })

#Download the data as CSV
  output$downloadCsv <- downloadHandler(
    filename = "cranlog.csv",
```

```
    content = function(file) {
      write.csv(pkgData(), file)
    },
    contentType = "text/csv"
  )

  output$rawtable <- renderPrint({
    orig <- options(width = 1000)
    print(head(ggplot_data(), input$maxrows), row.names = FALSE)
    options(orig)
  })
}

shinyApp(ui, server)
```