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Hydrogeophysical and Hydrogeochemical Characterization of Volcanic Aquifers in northwest Ethiopia

PhD Thesis

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1. INTRODUCTION

Groundwater not only supplies fresh drinking water for humanity but also helps to sustain life. It accounts for more than 50% of the global freshwater supply and 43% of all water used for irrigation. Groundwater stored in pore spaces, fractures, cracks, and weathered parts of rocks constitutes the largest freshwater supply share for all living things. The distinguishing characteristics of groundwater, such as its reduced susceptibility to pollution and climate change as well as its continuous supply respective to the seasonal fluctuation of rain, makes it preferable over surface water. With surface water emerging as increasingly unreliable due to climate change and anthropogenic pollution, comprehension of the groundwater system has become crucially essential.

Volcanic aquifers are vital and sometimes the only groundwater source in many regions. The plateau land of the highlands and large igneous provinces in central and northwest Ethiopia are covered by volcanic rocks that have been used as a reservoir of volcanic aquifers. These aquifers are sources of various cross-boundary rivers, including the Blue Nile River, which is among the longest rivers in the world. Ethiopia's groundwater, dominantly obtained from volcanic aquifers, supplies more than 90% of the freshwater for domestic and industrial applications. However, its exploration and accessibility have been challenging due to the complicated nature of volcanism that occurred during the Oligocene–Miocene to recent Quaternary geological times. The volcanic cover of most Ethiopian landmass forming highlands and rift basins form complex reliefs due to the Oligocene–Miocene volcanism and the late exogenic process. As a result, it formed the Ethiopian highlands with a volcanic massif of flood and shield volcano basalts ranging from 0.5 to 3 km thickness that formed spectacular trap topography of 1,500 m to 4,500 m altitude flanking the main Ethiopian rift.

Moreover, the Ethiopian terrain is imprinted by volcanism, uplifting, and rifting in which the uplifting accelerates erosional processes. The uplifted terrain of Ethiopia has been undergoing erosion at a rate between 0.029 and 0.185 mm/yr for nearly 30 million years (Pik et al., 2003). These processes produced highly rugged terrain, fragmented plateau, deep gorges, and canyons, as well as mountain peaks for a long geologic time.

The investigation area is situated in the northwestern Ethiopian highlands in the southern part of the Lake Tana basin. The Lake Tana basin was formed due to a junction of three grabens that was later contradicted as a caldera. The area's volcanic terrain possesses a variety of landforms similar to other plateau lands of Ethiopia, with momentous importance to groundwater occurrence and movement.

The occurrence of groundwater and its accessibility as freshwater resources impacted Ethiopian history and culture. Ethiopia's easily accessible groundwater areas, especially springs, have been the centers of ancient and modern civilizations. The volcanic aquifers in northwestern Ethiopia, surrounding the town of Dangila, have focused on numerous water-related sectors for the past four decades. Multiple sectors have conducted numerous plans to alleviate the scarcity of drinking water over the past 47 years (1973-2020). However, the explorations and management of the groundwater face challenge with numinous borehole failure and low yield of springs and shallow wells.

The efforts to alleviate the scarcity of drinking freshwater supply, including recently conducted smallscale irrigations, were accompanied by several borehole failures. To illustrate, among the 24 deep boreholes (depth > 58 m) which were found in the study area and surrounding Dangila town, only four have an initial groundwater yield of 18–30 L/s, and the groundwater yield from each spring as well as shallow wells did not exceed 1 L/s. However, the water-centered development was comprehended as the access argument for the growth and poverty purge in Ethiopia. Groundwater resource development is integrated with economic development and land use planning, and hence, it has become a source of domestic water for the growing urban population and rural areas. The future development of urban settlement in Ethiopia is highly dependent on the potential of aquifers to meet the ever-increasing demand from the populations' growth and industries. Besides, its importunacy for irrigational use is significant due to the possibility of controlling the resources allowing efficient and flexible infield application that increases yield.

Moreover, the increase in population with time, yield reduction in several boreholes, the minimal amount of water from shallow aquifers, increased investor's demand to establish water bolting companies, increased smallscale irrigation practiced by the people necessitates detailed investigations and characterizations of the aquifer system of the area using a multidisciplinary investigation approach.

Climate of the area

The study area, including Dangila town and its surrounding areas, has a mean annual rainfall of 1640 mm, 91% of which falls between May and October. Conversely, the average annual precipitation across the whole country of Ethiopia is 817 mm/yr. The rainfall amount is the highest in the area in question than the average rainfall of Ethiopia, as it is situated in the northwestern plateau land of the country. Furthermore, the area's climate is moist subtropical (locally called *Woyna Dega*) with a median annual daily maximum temperature of 25 °C and minimum of 9 °C, with one primary rainy season, occurring between June and September. The mean annual temperature of Ethiopia varies from over 25 °C in the hot lowlands to less than 7 °C–12 °C in the high-altitude plateau.

Aim and objectives of the study

This research aims to characterize the hydrogeological system of the northwest Ethiopian volcanic aquifers by incorporating multidisciplinary data sets. The study characterizes the hydrogeological framework the groundwater quality for drinking and irrigation applications. Further effort is exerted to identify the controlling factors for groundwater flow and storage and outline conceptual models for future sustainable groundwater management. It mainly utilizes information of various deep and shallow wells, hydrochemistry, and stable water isotopic data, as well as nearsurface geophysical survey results to characterize and infer valuable parameters of the complex geological settings of volcanic aquifers.

Subsequently, the research aims to acquire a comprehensive picture and understanding of volcanic aquifers systems, infer hydraulic parameters, and map the potential drilling sites for future groundwater abstraction. To this end, the following objectives are demarcated:

i) To assess the hydrogeological framework, map potential groundwater sites, and demarcate the groundwater storage and flow controlling factors.

ii) To evaluate the groundwater quality for drinking and irrigation and assess its hydrogeochemical evolution.

iii) To determine groundwater's residence time, recharge sources, discharge areas, and surface water-groundwater interaction.

iv) To estimate the variations in hydraulic conductivity and transmissivity of the volcanic aquifers.

v) To assess the recent new geophysical technologies that can be implemented in groundwater studies.

vi) To develop a hydrogeological conceptual model from the combined results of multidisciplinary investigation approaches that will help understand and manage the area's groundwater resources in the future.

This work uses multidisciplinary investigation approaches to characterize the complex geological aquifers as a research concept and apply laboratory and field survey-based methodologies. The distinct investigational and methodological approaches are first interpreted individually and then integrated to utilize the data for the final conceptual hydrogeological model construction.

2. MATERIALS AND METHODS

Both multidisciplinary data sources and interpretation approaches were employed to achieve the desired goal as well as objectives and characterize volcanic aquifers. The data was mainly gathered from the field surveys and laboratory analysis in addition to limit causes from previous researches and open data sources. The overall progress of the research followed a stepwise/hierarchal procedure for data collection and interpretation of results, which can be summarized into three categories—preliminary/reconnaissance, intermediate/detailed investigations, and final/hydrogeological conceptual model development (Fig.1). Each step, in turn, comprised distinct data sets that can be categorized as geological, hydrogeological, and geophysical. Finally, based on the results, a conceptual hydrogeological model was constructed that can assist in managing the volcanic aquifer of the area.

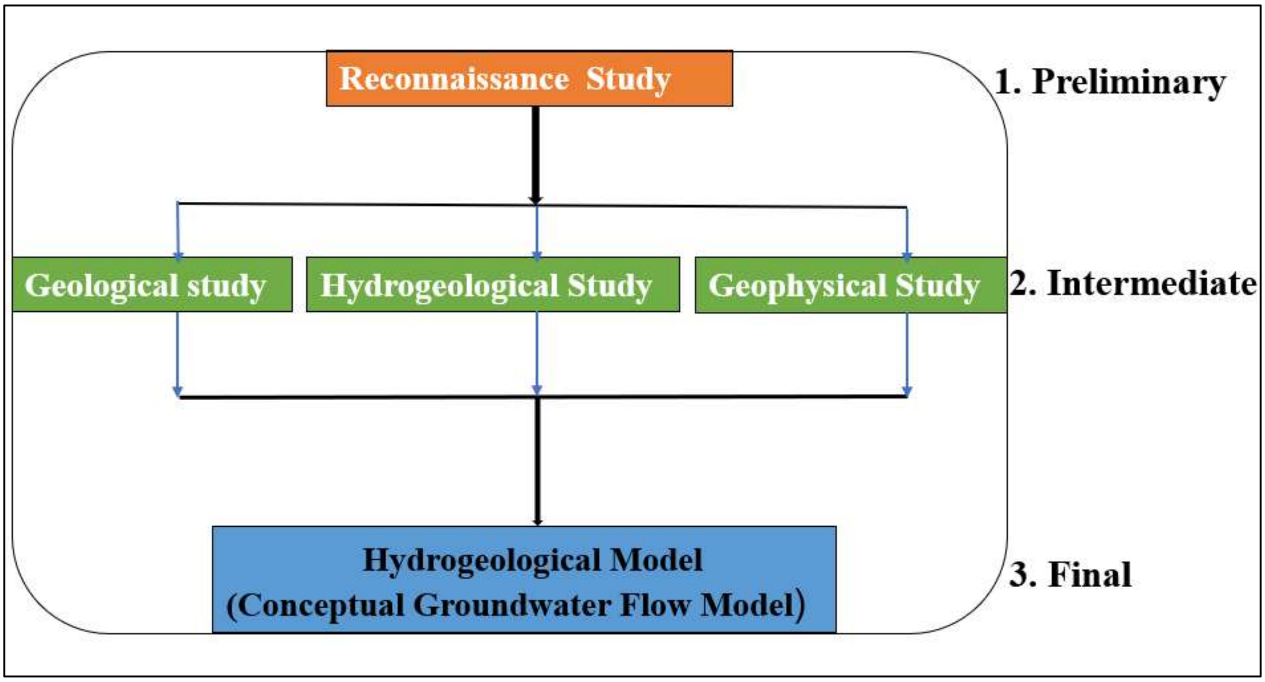

Fig.1 Stepwise/hierarchal methodological flow chart.

In the reconnaissance study, I defined the study area boundary, located water points, assessed the existing boreholes, hand-dug wells, springs, and rivers, and identified the geophysical survey areas. I reviewed the previously conducted research and gathered important information for the current study. It contains both prefield office work as well as short-duration field observations work. I framed and limited the scope of the study, including the required time and resources for detailed investigations. I determined the type and quantity of outputs required to achieve the desired goal and objectives. Besides, during the preliminary step of the research phase, I collected Landsat-7 satellite images from the USGS explorer, prepared a digital revelations model, and defined and outlined the detailed investigations of the areas. The reconnaissance study was followed by thorough investigations where I collected various field data, analyzed, and delivered the samples to laboratories for further analysis. The details of these data collection and analyses from different sources include geological, hydrogeological, and geophysical data sets.

During my fieldwork, I collected three rock outcrop samples of the area as a representative sample, took them to the Department of Mineralogy, Geochemistry, and Petrology of the University of Szeged, prepared a thin-section, and analyzed the mineralogical composition of the rocks in a microscopic scale using ore microscope. I collected the lithological logs of 24 deep boreholes (58–210 m depth) from the drilling companies as well as the water offices and analyzed them to produce geological cross-sections. I used the lithological data to identify the groundwater reservoir rock types and their characteristics to get priority information during geophysical survey result in data modeling. Besides, I used the borehole information as support during preparation of the geological map of the area.

Hydrochemical analysis

I collected 25 water samples from both deep and shallow aquifers (boreholes, shallow wells, and springs) during the dry season (February to April) in 2016–2017. The samples were taken to the Amhara waterworks supervision enterprise in Ethiopia for hydrochemical laboratory analysis. During water sampling, the three water physical parameters (pH/EC/TDS) were recorded using a multiparameter measuring instrument (Hanna HI 991, USA), which were repeated again in the laboratory together with the hydrochemical parameters. The deep and shallow groundwater measurements representing the area close to Dangila town in the upper Branti, Amen, and Kilti river catchments were analyzed in the laboratory for major cations of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), iron (Fe), manganese (Mn^{2+}), anions of bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), chlorine (Cl^{-}), nitrate (NO_3^{-}), fluoride (F^{-}), and boron (B). The analysis was conducted using the atomic absorption spectrometry (AAS) (novAA 400P, Germany), integrated with the ASPECT LS software for cations and the colorimetry instrument (Palintest photometer 7100, UK) for anions. Alternatively, the concentration of carbonate and bicarbonate measurements were also conducted using titration.

Water-stable isotope analysis

A total of 48 seasonal water samples were collected and taken to Institute for Nuclear Research, Debrecen, Hungary, for water-stable isotope analysis during autumn 2019 (September–October) and spring 2021 (April–March). Samples measuring 50 ml were retrieved individually from the deep aquifer (boreholes), shallow aquifer (spring and shallow wells), surface water (rivers), and rain for their ^{2}H & ^{18}O content analysis.

Vertical Electrical Sounding (VES) survey

I collected 16 VES data, mainly at the floodplain area close to Dangila town and toward the northwest of the Denegeshita kebele, during February–April of 2017 and 2020. The previously obtained 16 VES data around Dangila town supply deep borehole field were retrieved from Amhara Amhara Design And Supervision Works Enterprise. Therefore, a total of 32 VES data were collected, using the Lud company product ABEM SAS 4000 terametre, along transects and traversals to streams and expected structures. I used the Schlumberger electrode spread extending with current electrode separation (AB/2(m)) from 1.5 m (minimum) to 500–750 m (maximum) to investigate the groundwater potential extending from a maximum depth of 200–500 m. I filtered the 32 points of VES data, each with 19 to 20 recordings, and plotted them on a log-log paper to check the data adequacy, apply correction, and smooth the data for further processing. Furthermore, I prepared different maps, 2D sections, and 3D sliced maps from the results of 1D inverse modeling. Finally, I interpreted the VES data both qualitatively and quantitatively to understand the aquifer systems, delineate potential groundwater zones, and determine the resistivity of different subsurface layers.

Ground geomagnetic Survey

I conducted a geomantic survey along selected lines, using a GSM-19T proton precision magnetometer at a total of 718 discreet points along preselected traverses with station spacing of 50 m, 100 m, and occasionally 200 m, depending on the expected magnetic gradients and target structures. I gathered repeated readings at the base stations using a single magnetometer on the field every 1–2 hrs to monitor the diurnal variations. The manmade feature, including electricity, fences, and other metallic objects, have been cared to remove the unwanted signals from the magnetic substances, and the sensor positions have been leveled at every reading point depending on the direction of the survey. Time and space coordinates were retrieved from the handheld global positions system and recorded for the magnetic data corrections. After the diurnal and geomagnetic corrections have been applied, the remaining magnetic field variations caused exclusively by spatial variations in the magnetic properties of the subsurface rocks called magnetic anomalies were prepared in maps and profile plots. Resultantly, I inferred the different types of structures possibly used as a conduit and storage of groundwater flow.

The new geophysical technologies

I have reviewed the new geophysical technologies and their possibilities for hydrogeological problems from the worldwide open source data. The recent technology, using the fiber cables as a sensor, and data transmitter, using light waves as a carrier, is a modern technique that can detect both the static and dynamic characteristics of the aquifer. It is beneficial to local and regional scale studies with better accuracy than nearsurface or borehole geophysical techniques.

Pump test

I analyzed the data of the constant rate pumping tests of four selected boreholes using the Moench fracture flow model to estimate the aquifer hydraulic parameters. Conversely, I gathered the hydraulic parameters of representative shallow wells from previous research.

Shallow groundwater level data

I collected the shallow groundwater level data and the piezometer water level of the deep borehole after the main rainy seasons and utilized the data to infer the shallow groundwater flow directions in relation to the rivers.

Conceptual hydrogeological model development

The results and information obtained from the individual investigation approaches were utilized as input to develop the Dangila groundwater flow conceptual hydrogeological model. Moreover, I further conceptualized the groundwater flow, assuming a simplified groundwater flow system, and developed a flownet using Modflow. The flownet considers all the recharge and discharge area, intermediate, and the possibility of the regional groundwater flow by taking the surface topography from the area and using the Toth conceptual groundwater flow model in a small river catchment as the benchmark.

Conclusively, the research methodology I followed has three data sources of information: field-based data, laboratory-based data, and worldwide open sources information. I analyzed, modeled, and calculated various parameters to evaluate, characterize, and understand the volcanic aquifer of the area.

3. SUMMARY OF NEW SCIENTIFIC RESULTS

R1:- I found that rock weathering is the dominant mechanism that controls the groundwater chemistry of the study area more than the evaporation and precipitation processes.

I assessed controlling factors of the groundwater chemical composition relating its composition with the dominance sources using the Gibbs diagram. On the Gibbs diagram, three distinct zones were incorporated, namely, precipitation dominance, evaporation dominance, and rock weathering dominance. For such purposes, I used the weight ratio of major cations $Na^+/(Na^+ + Ca^{+2})$ and major anions $Cl^-/(Cl^- + HCO_3^-)$ on the x-axes and total salinity variation of the groundwater on the y-axes. The cation and anion diagrams indicated that rock weathering dominates as the controlling factor for groundwater chemistry and that the influence of evaporation on groundwater chemistry is minimal.

R2:- I discovered that the three rock-water interaction processes, like silicate weathering, cation exchange, and carbonation, are the main hydrogeochemical processes that control the evolution of groundwater.

To understand the main hydrogeochemical process, I analyzed the relationship between major cation and anions concentrations of the groundwater samples. I used the plot of $((Na^++K^+)-Cl^-)$ versus $((Ca^{+2} + Mg^{+2})-(HCO_3^- + SO_4^{-2}))$ that is used to study cation exchange in groundwater and obtained a negative correlation. The negative correlation value is neither precisely on the line 1:1 with slope −1 nor very close to −1, indicating a complete cation exchange. Even though there is a cation exchange of major cations, Ca^{+2} and Mg^{+2} by Na^+, a higher amount of Na^+ was released into the aquifer from weathering of Na^+ containing silicate minerals.

The plots of Na^+ versus Cl^- and Ca^{+2} versus HCO_3^- were utilized along the halite and calcite dissolution lines to examine the halite and calcite dissolution as possible sources of Na^+ and Ca^{+2} cations, respectively. It was concluded that halite dissolution is not the source of either sodium or chlorine, which increases the concentration of Na^+ from the shallow to the deep aquifer system. Similarly, the source of HCO_3^- is not CO_3^{-2} that results from calcite dissolution.

However, a plot of HCO_3^- versus the sum effect of Ca^{+2} and Mg^{+2} $(Ca^{+2} + Mg^{+2})$ showed a similar increase in bicarbonate values from the shallow aquifer to the deep aquifer system. It was determined that the primary source of bicarbonate ions in volcanic aquifers is attributed to soil carbon dioxide interacting with water to form carbonic acid. The plots of HCO_3^- versus $(Ca^{+2} + Mg^{+2})$, $((Na^+ + K^+)-Cl^-)$ versus $((Ca^{+2} + Mg^{+2}) - (HCO_3^- + SO_4^{-2}))$ were incorporated, and the results support the above findings. The results revealed that calcium and magnesium ions change from dominant to

subordinate in relation to total cations with increasing depth and as groundwater flows away from recharge sources.
Generally, groundwater associated with a recharge in the shallow aquifers is represented by water dominant in calcium, magnesium, and bicarbonates, with lesser amounts of sodium; as groundwater flows away from the source of recharge, the interaction between water and rock increases, resulting in an increment of sodium. In all cases, the rock-water interactions involve silicate weathering, cation exchange, and carbonation, which increases the concentration of sodium and bicarbonate ions with residences time, resulting in groundwater evolved to sodium-bicarbonate types.

R3: I found out that the area's groundwater system has five main hydrochemical facies; Ca-HCO_3, Ca-Mg-HCO_3, Ca-Na-HCO_3, Na-Ca-HCO_3, and Na-HCO_3 types. The Ca-HCO_3 groundwater type dominates the shallow, unconfined aquifer system, and the Na-HCO_3 type dominates the deep aquifer system.

I utilized the Piper trilinear diagram, placing the concentration of cation and anion values on the triangles. The corresponding values from the two triangles were projected on the diamond to determine the sources of the dissolved constituent salts in the groundwater. Total five different hydrochemical facies were found from the Piper trilinear diagram as Ca-HCO_3 and Ca-Mg-HCO_3 in shallow aquifers, in addition to Na-Ca-HCO_3, Ca-Na-HCO_3, and Na-HCO_3 in the deep aquifer system. The presence of Ca-HCO_3-Cl and Ca-Mg-HCO_3-Cl water facies in two shallow well water samples was apprehended as the influence of anthropogenic pollution on the shallow aquifer.
This type of water facies might be due to intermixing shallow and deep aquifers, where fractures connect them. The dominant water type in the shallow aquifer system is Ca-HCO_3, a typical water facies in shallow young groundwater and Na-Ca-HCO_3 and Na-HCO_3 are the dominant water facies in a relatively deep aquifer. Conversely, the intermixing of shallow and deep aquifer systems leads to Ca-Na-Mg-HCO_3 type of hydrochemical facies.

R4:- I evaluated and demonstrated the suitability of the volcanic aquifer systems water for drinking and irrigational uses.

The hydrochemistry data indicates that except for one shallow well sample with 12.5 mg/L of Cl and a few shallow and deep wells of high pH and Fe concentrations values, all physical and chemical water parameters are within the standards of drinking water limits set by the World Health Organization. The fluoride concentration is <0.82 mg/L, unlike the groundwater of Ethiopian rift volcanic rocks that cause health problems. Lower concentrations of sulfate and nitrate were also found in both aquifers systems. The high value of Cl^- at shallow aquifer systems is attributed to anthropogenic effects related to poor construction and mismanagements of the water schemes (hand-dug wells) in some rural villages. This marks that the area's groundwater is potable without considering the microbial water quality.

I analyzed the SAR values of samples from Na^{+}, Ca^{+2}, and Mg^{+2} ion concentrations using Suarez's equation. I used the concentrations of Na^{+}, Ca^{+2}, Mg^{+2}, and K^{+} to calculate the Na%, whereas I used HCO_3^{-}, CO_3^{2-}, Ca^{2+}, and Mg^{2+} to calcite the RSC based on the United States Salinity Laboratory Staff's equations. I found that the results of the SAR and RSC values from all groundwater schemes are of excellent quality and can be used for irrigation without any challenges. However, high Na% in the borehole samples restricts deep groundwater suitability for irrigation without adjustments and can result in sodic soils, which consequently reduces the crop yield.

R5:- I discovered that the depleted heavier isotope and high d-excess values in the deep aquifer system have different recharge sources and times than the modern recharged shallow aquifer and rivers. Furthermore, I noticed that the recharge of the deep aquifer system is mainly related to the late Holocene humid phase that retains moisture recycling in the atmosphere and is less affected by evaporation. However, the shallow aquifer system and the surface water are recharged from precipitations sources to the Atlantic Ocean, Congo forests transpiration, and possibly from local recycled moisture.

I collected seasonal groundwater, surface water, and rain sample for laboratory analysis of $\delta^{2}H$ and $\delta^{18}O$ contents. The laboratory analysis results demonstrated that there is a proportional increase in the less abundant heavier isotopes content during the dry season in comparison to the rain samples. Similar results were noticed in some rivers, shallow wells, and springs samples with the enrichment of heavier isotopes during the dry season and depleted heavier isotopes during the rainy season. The atmospheric temperature effect is observed in the dry season precipitation and direct evaporation in the rivers during the dry season.

The relationship between the elevations, used as a proxy for surface water flow and enrichment of heavier isotopes, is noticeable for the shallow aquifer system. The direct increase with topography or decrease to the directions of surface water flow is more recognizable for deuterium than for $\delta^{18}O$. However, the $\delta^{18}O$ increases with the surface water flow directions. This suggests that the deuterium content is more affected in the atmospheric phenomena, including moisture recycling than the surface and groundwater evaporation. However, the content of $\delta^{18}O$ is affected by both atmospheric moisture recycling, the surface and groundwater evaporation being more influenced by surface evaporation.

The depleted heavier isotope and high d-excess values in the deep aquifer indicate that the aquifer system is recharged from precipitations that retain moisture recycling in the atmosphere and is less affected by evaporation. Northwestern Ethiopian precipitation relates their precipitation sources to the Atlantic Ocean, Congo forests transpiration, and possibly from local recycled moisture and the deep aquifer recharge time to the late Holocene humid phase.

R6:- I revealed that the aquifer systems of the area are not continuous; instead, it is an intermittent or compartmentalized aquifer system dissected by several faults and fractures.

I conducted the nearsurface geomagnetic and VES geophysical surveys focusing on the floodplain topography lands. The geomatic survey results enabled me to delineate the buried structures (faults and fractures) that can have a possibility of being a conduit and storage of groundwater. These structures have an orientation of N-S, NW -SE, NE-SW, and E-W, similar to the orientation of the Lake Tana basin regional structures. I related the location of dry and productive boreholes, 24 boreholes with 60–210 m depth, to the location of these structures. I observed that most boreholes, both productive and dry, are located along these fracture lines, indicating that the presence of a fracture is not enough to have a productive borehole.

The analysis of the resistivity survey data and the borehole lithology enables me to locate the aquifer zones, depth, and spatial extent. Resultantly, I identified that the depth to the aquifer, the aquifer extent, and its distributions in the area are unpredictable and do not continue with depth or lateral extent. The most productive boreholes that supply fresh groundwater to the Dangila town (DTW1, DTW3, and DTW4) are located along with the NW-SE fractures with their productive aquifer layers situated at different depths. The two deep borehole drilling recommendations based on the PhD thesis research geophysical survey results in 3.5 L/s yields from a 210-m depth and >30L/s yield from 160-m-depth boreholes, respectively. The first borehole was located away from major fracture lines. In contrast, the area's second and most productive borehole is along the NE-SW fractures lines mapped by geomagnetic survey results.

Alternatively, numerous dry boreholes were also located along these fracture lines, indicating that the presence of the fracture is not enough for a borehole to be highly productive. The combined investigation results signified that the fractures with connections to highland recharge areas are utilized as a conduit and storage of groundwater at different depths. Most aquifers are concentrated along the fracture lines resulting in dry boreholes within <1 km of productive boreholes locations. Besides, the product boreholes' pump test data best fits the fracture models than the less product boreholes data. Therefore, the combined information of the field geophysical and the boreholes enables me to identify that the aquifer systems of the area are not continuous. Instead, it is an intermittent or compartmentalized aquifer system dissected by several faults and fractures.

R7:- I found the modern and comprehensive fiber optics technology as an auspicious and vigorous geophysical method to be applied at complex geological settings groundwater resources management.

I reviewed the worldwide field and laboratory experimental research results concerning the possibility of using the new technologies as a geophysical technique and applied them to earth resources explorations. I realized that different smallscale laboratories and field experiments that detect various physical parameters using the recent fiber optics sensing technologies could be analyzed and outlined as a new/modern and comprehensive branch of geophysics. The new fiber optic sensor prospecting detects temperature, pressure, acoustic, and strain in distributed systems as single or multiparameter simultaneously have excellent potential for hydrogeophysical applications.

The maximum sensitivity of fiber optic cables, the option to measure one or more physical parameters, the higher operating temperature, and the enhanced coatings for both protection and sensitivity are attractive for nearsurface and borehole geophysical surveys. It has a better capacity than the current geophysical techniques in sensing performance comprising sensing range, spatial resolution, and measurement parameters. It can be said that fiber optic technology is a revolutionary technological departure from traditional copper wires. The application of this technology in hydrogeophysics will result in a new paradigm. As we move forward in the Information Technology age, the movement of extreme amounts of data can potentially be held accountable on this new technology.

Besides, the technology is crucial for high-temperature geothermal wells in detecting mineral dissolution, changes in inflow from reservoir rocks to the well, and changes in borehole liquid density during drilling and production. Moreover, the development of computing and extensive data handling techniques will help one to interpret comprehensive data from long-distance fiber optic arrays. Among several big data handling techniques, artificial intelligence (Al) is a recent and beneficial method to enhance the performance of future distributed fiber optic geophysical sensing systems through big data generation, artificial neural networks, and deep learning. Therefore, the applications of the new technology in hydrogeological problems will assist in understanding various complex aquifers systems which had not been recognized using conventional geophysical techniques.

R8:-I have identified that the shallow groundwater flow and surface water-groundwater interactions vary along the flow paths.

The shallow groundwater level after the main rainy seasons was measured to utilize the data to denote groundwater flow directions and examine the continuum attempt. The field data and previous research on shallow aquifers indicate that both shallow aquifers and rivers have high interaction with the

rainfall. Walker et al. have estimated recharge of the shallow aquifer at 280–430 mm/yr or 17%–26% of mean annual precipitation using nine recharge estimation techniques. Comparably, Yenehun et al. estimated the average groundwater recharge value from 429 to 477 mm/yr based on four recharge estimation techniques being 28% of the total evapotranspiration.
The groundwater flow analysis enables me to identify the substantial recharge variability between the river and shallow groundwater along the shallow aquifer flow from the recharge to the discharge area. The highly topographic dependant flow nature of the shallow aquifer recharges the Kilti river at most places where the Kilti river recharges the shallow aquifer system around the flood plains. To illustrate, the groundwater flows away from the river around the Dengeshita and Wufta Daty localities, where the Kilti river recharges the shallow groundwater system.

Conversely, unlike the Kilti river, the Branti river recharges the groundwater system to the eastern side of the river. The groundwater recharges the river on the western side, where the shallow groundwater flows toward the river. However, the flow system might have changed at various locations during the dry seasons. A supportive result is that Walker et al. noticed a change in the shallow aquifer system's hydraulic conductivity: 2.3 m/d in the dry season and 9.7 m/d in the wet season.

R9:- I have conceptualized the catchment scale groundwater flow system of the area based on the multidisciplinary investigation approach. The groundwater flow is controlled by fractures/faults with the deeper aquifers found at depths extending up to 210 m below the surface are recharged from the upper unconfined aquifer through fractures. The conceptual model can be helpful for future groundwater management.

The multiple-investigations approach result from the volcanic aquifer of northwest Ethiopia enables me to identify that none of the present-day conceptual groundwater flow models can be adapted for groundwater management. Consequently, I developed a conceptual hydrogeological model called the Dangila model to fulfill the specific study area aquifer characteristics. In the Dangila model, the water flow is highly controlled by fractures/faults, and the deeper aquifers found at depths extending up to 210 m below the surface are recharged from the upper unconfined aquifer through fractures.
I made further assumptions on the groundwater flow being a continuous steady-state flow and developed groundwater flownet at a small river catchment scale using Toth's small river basin groundwater flow model as a benchmark. The Dangila and its surrounding area groundwater flownet comprise three types of groundwater flow system, local, intermediate, and regional, each with its own recharge and discharge areas. The local flow paths are relatively short, whereas the intermediate flow systems originate at recharge areas and discharge downgradient following topography and fracture

network. Intermediate flow systems encompass at least one local flow system. The regional flow systems originate at regional recharge areas and flow to distant discharge locations, with relatively long flow paths. The regional system often surrounds one or more local and intermediate flow systems.

Persuasively, my PhD research in the volcanic aquifer of northwestern Ethiopia plateau land was twofold. Firstly, it minimizes the water supply for drinking, irrigation, and industrial applications in the area due to the two-borehole drilling recommendation. A 3.5-L/s yield borehole is used by a water bottling private company, and >30-L/s yield borehole at Dengeshita rural Kebele is used as a fresh drinking water source as well as small scale backyard irrigation water by the rural dwellers. Secondly, it contributes detailed scientific knowledge to understand the complex volcanic aquifer nature of the area for future groundwater management.

4. SCIENTIFIC PUBLICATIONS

List of publications in Scopus and web of sciences indexed journals

1. **Fenta, M.**, Anteneh, Z. , Szanyi, J., & Walker, D. (2020). Hydrogeological framework of the volcanic aquifers and groundwater quality in Dangila Town and the surrounding area, Northwest Ethiopia. *Groundwater for Sustainable Development*, *11*, 1–13. https://doi.org/10.1016/j.gsd.2020.100408.

2. **Fenta, M.** , Anteneh, Z., Szanyi, J., & Walker, D. (2020). Hydrochemical data on groundwater quality for drinking and irrigation use around Dangila town, Northwest Ethiopia. *Data in Brief*, *31*, 1–11. https://doi.org/10.1016/j.dib.2020.105877.

3. **Fenta, M.,** Potter, D., & Szanyi, J. (2021). Fibre Optic Methods of Prospecting : a Comprehensive and Modern Branch of Geophysics. *Surveys in Geophysics*. 42, 551–584. https://doi.org/10.1007/s10712-021-09634-8.

4. Anteneh,Z.,Alemu,M.,Bawoke,G.,Kehali,A.,**Fenta,M.,&**Desta,M.(2022).Appraising potential groundwater zones using geospatial and multi-criteria decision analysis(MCDA) techniques in Andasa-Tul watershed, Upper Blue Nile Basin, Ethiopia. *Environmental Earth sciences, 81*(14). https://doi.org/10.1007/s12665-021-10083-0.

5. Ingle, K., **Fenta,M.,** Harada, K., Ingle, A., Ueda A. (2022). Wastewater treatment plants advantage to combat climate change and help sustainable water management. In the book 'Water Resource Management and Environmental Sustainability,' Edited Book (Springer Series): Advances in Geographical and Environmental Sciences, Series Ed by R.B. Singh. Chapter -3,Pp.

6. Ingle, K., Polikovsky, M., **Fenta**, M., Ingle, A., Golberg, A.(2022): Integrated multitrophic aquaculture approach with marine energy projects for management and restoration of coastal ecosystems of India. Ecological Engineering.

List of Conference Proceedings and Abstracts

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9. **Fenta, M.**, Lewi, E., Hail, T., Fisseha, S. (2019). High precision gravity assisted with a differential global positioning system (DGPS) and geomagnetic surveys for mapping groundwater reservoir potential in volcanic terranes of south Ethiopia. In: Geophysical Research: EGU General Assembly 2019. Vinea, Austria (conference Abstracts): 303, P1.

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