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**HANOI UNIVERSITY OF SCIENCE**

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# APPLICATION OF GEOPHYSICAL EXPLORATION METHODS FOR GROUNDWATER INVESTIGATION IN LAOS

Major: Physics of The Earth

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DOCTORAL THESIS ABSTRACT IN PHYSICS

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# INTRODUCTION

Groundwater is an essential source of fresh water in many regions of the world. Groundwater is an important source for irrigation, industries and for both eating, drinking water and domestic use. A growing number of countries in Southeast Asia have encountered serious groundwater quantity and quality issues such as declining groundwater tables, subsidence, groundwater quality, and overexploitation leading to unsustainable management of groundwater resources. In Laos in general and in the central parts of Laos in particular, groundwater usage has been increasing; therefore, demand for groundwater is constantly raising. However, there is still a lack of information on groundwater, monitoring and evaluation activities regarding groundwater quantity and quality have not yet been carried out to any significant degree in this region. For example, a drilling project in the 1990s in Vientiane Province was implemented by the Japan International Cooperation Agency (JICA) for domestic supply in rural areas. Unfortunately, 60% of the 118 deep drilled wells were unusable due to poor water quality, such as high salinity. In addition, more than 100 boreholes were drilled in the Outhomphone district, with a success rate of 50-60%, and approximately 50 boreholes were selected for production wells. Meanwhile, dug wells are unsafe sources of drinking water due to biological contamination and usually dry out during the dry season. Moreover, the use of surface water sources for eating and drinking can result in outbreaks of water-borne diseases because they may easily be contaminated with domestic waste from farm animals.

The combination of resistivity and induced polarization techniques can delineation fresh and saline water and high groundwater potential zones, while seismic methods have been applied for identifying water table, thickness of aquifers and groundwater potential in the selected study areas. However, due to the main limitation of the magnetic resonance sounding (MRS) method is electromagnetic interference (EM), the noise can be caused by magnetic storms, thunderstorms, etc., and we don't have MRS equipment that is very expensive, due to the main limitation of the vertical electrical sounding (VES) technique cannot be taken into account the horizontal variation in the subsurface earth resistivity, thus the these methods were not selected in this thesis work.

The application of geophysical methods for groundwater investigation has been effective in many parts of the world. Therefore, it is necessary to conduct geophysical exploration to localize the locations of freshwater and saltwater areas to plan future well drilling in some study areas in Laos. Thus, we chose the thesis entitled "Application of Geophysical Exploration Methods for Groundwater Investigation in Laos". Three selected study areas in Central Laos are Vientiane, Khammouane and Savannakhet Provinces.

**The objectives of the thesis**

- To apply geophysical methods to find groundwater in three research areas: defining water table, depth and thickness of aquifers; delineating freshwater aquifers and saline aquifers.

- To determine groundwater quality directly from geophysical parameters and water samples from different wells in the first selected area.

- To provide the groundwater information in three research areas to assist water resource managers in the development of groundwater exploration and use plans.

**The mission of the thesis**

- To research and conduct an integrated analysis of achievements of domestic and foreign scientists related to the application of geophysical methods for groundwater investigation in Laos.

- To learn and study the application of multi-electrode electrical exploration, improved multi-electrode electrical exploration (both resistivity and induced polarization), and refractive seismic methods for groundwater investigation in Laos.

- To apply the above methods for groundwater investigation in three areas of Laos.

- To drill and check the results obtained by the application of geophysical methods in the survey areas and determine groundwater quality in the first selected area.

- To report the groundwater information in the three research areas to the Department of Water Resources, Ministry of Natural Resources and Environment, Lao PDR for managers in planning exploitation and the use of groundwater resources.

**New results of the thesis**

- Using the multi-electrode electrical exploration and refractive seismic methods simultaneously, especially the first use of the improved multi-electrode electrical exploration for groundwater investigation in Laos has increased the accuracy of the research results.

- Providing new geophysical results at three research areas such as depth of groundwater tables or aquifers, the thickness of aquifers, and groundwater quality in the first selected area. These results can assist water resource managers in the development of groundwater exploration and use plans.

**Scientific and practical significance**

- The simultaneous use of the multi-electrode electrical exploration and the seismic refraction methods, especially for the first time using the improved multi-electrode electrical exploration method (both resistivity and induced polarization) to survey groundwater in Laos have complemented each other and increased the accuracy of research results while the field time is faster, the implementation cost is less.

- The results of the thesis will be a useful reference for future researchers who are interested in the field of groundwater exploration and evaluation in the 3 studied areas. At the same time, the results of this study will contribute directly to the managers in the planning, exploitation, and use of water resources in the 3 studied areas.

# CHAPTER 1
# AN OVERVIEW OF GROUNDWATER RESEARCH USING GEOPHYSICAL METHODS

Geophysical methods apply the principles of physics to the investigation of the earth's subsurface structures. Geophysical data processing and interpretation can identify subsurface characterization for groundwater sources, environmental problems, and understand the influence of subsurface geological conditions as shown in many geophysical investigations.

Seismic refraction method (SRT) is commonly applied to delineate the subsurface earth, the depth to water table, basement structures in engineering and construction sites. This method has been extensively used for a variety of purposes in various geological information in many countries around the world to map structural geology, including groundwater studies. Nevertheless, this method is frequently used for subsurface detection and depth to water table with high accuracy.

The multi-electrode electrical exploration was developed over the last two decades. In this measurement, automatic acquisition systems and new inversion algorithms for Electrical Resistivity Tomography (ERT) have been applied to resolve the complex subsurface geology. The ERT is growing and being applied in groundwater investigations. The Advanced Multi-Electrode Electrical Sounding (AMES) methods were studied and developed. They named exactly the Improved Multi-Electrode Electrical Exploration (IMEE) methods (using both resistivity and induced polarization) by using the (2D) improved multi-electrode arrays (abbreviated as MC array). These new development methods have high scientific reliability, really usefulness, and scientific and practical significance. Many geophysical methods and software have been developed to delineate subsurface structures at high precision and accuracy, including groundwater exploration. A combination of ERT and SRT methods is the most widely applied for determining reliable subsurface structures as well as finding groundwater sources.

**Conclusion of chapter 1**

- Several geophysical methods were used to target groundwater potential zones. The purpose of geophysical exploration is to identify aquifers or locate potential groundwater for water exploitation.

- The obtained results of geophysical methods from previously published studies on groundwater finding in Vientiane province, Laos indicate ambiguity in low resistivity values can either consider as higher clay content or higher water content. This includes the main limitation of the Vertical Electrical Sounding method in which the horizontal variation in subsurface resistivity cannot be taken into account, whereas the main limitation of the Magnetic Resonance Sounding method is electromagnetic interference, noise that can be caused by magnetic storms. Meanwhile, the application of geophysical methods to search for groundwater remains limited to two study areas in Khammouane and Savannakhet provinces, central Laos.

- To overcome the above limitations, three main geophysical methods: 2D ERT, SRT, and especially the IMEE methods were chosen to use on groundwater finding in central Laos in this thesis work.

- One thing to keep in mind is how to ground the electrode when using the electrical exploration method, if the electrode is not grounded well, the results may not be obtained or the results may not be accurate. Choosing the grounding method of the electrodes while applying the Improved Multi-Electrode Electrical Exploration method has been noted in the research work.

# CHAPTER 2: GEOPHYSICAL EXPLORATION METHODS APPLIED TO SURVEY GROUNDWATER IN THE RESEARCH AREAS

## 2.1. Basic resistivity theory

The earth's resistivity largely depends on different rock types, such as igneous, metamorphic, and sedimentary rocks, as well as the amount of liquid or water contained in cracks or voids in the pores. In general, sedimentary rocks have lower resistance than igneous and metamorphic rocks because there is more porous and water content in sedimentary rocks. Usually, earth resistivity depends on porosity and clay content, the resistivity of the clay layer is lower than that of the sand layer. The earth's resistivity is a function of porosity, permeability, water saturation, and the concentration of dissolved solids in pore liquid within the subsurface materials (Table 2.1)

Table 2.1. Resistivity of various earth materials

| Materials | Resistivity (Ohm.m) |
|---|---|
| Top soil | 1-300 |
| Clay and silt | 1-2000 |
| Clay sand | 30-215 |
| Clay | 1-100 |
| Gravel | 100-5000 |

| | |
|---|---|
| Sand | 60-1000 |
| Sandstone | 8- 4000 |
| Shale | 20-2000 |
| Sand and gravel with fresh water | 15-600 |
| Groundwater | 10-800 |
| Fresh groundwater | 20-160 |
| Sediments with salt water | <10 |
| Salt water | 0.2 |

## 2.2. Basic induced polarization theory

Induced polarization was performed to further clarify the distinction between groundwater and clay. The induced polarization measurements in the time domain involve the observation of the voltage decay between the two potential electrodes and were observed after the current had been turned off. The changeability of various materials is different (Table 2.2)

Table 2.2. The chargeability of earth materials

| Materials | Chargeability (ms) |
|---|---|
| Aquifers | 0 |
| Alluvium | 1-4 |
| Sandstone | 3-12 |
| Limestone | <1 |
| Gravel | 3-9 |
| Quartzite | 5-12 |
| Gneiss | 6-30 |
| Shale | 50-100 |

## 2.3. Traditional Electrical Exploration Methods

The electrical resistivity survey aims to measure the resistivity distribution in the subsurface layers by conducting measurements along the ground surface. This measurement is conducted by the injected current into the earth's subsurface through the two current electrodes and measures the potential difference at the other two potential electrodes on the ground surface. The apparent resistivity can be calculated by the ratio between the measured potential difference and the input current, and multiplying by a geometric factor (coefficient of array) for the specific array. In this thesis work, the Wenner electrode array (Figure 2. 3) was used for 2D resistivity data acquisition manually and automatically with the ABEM Terrameter SAS 1000 for 49 electrodes system.

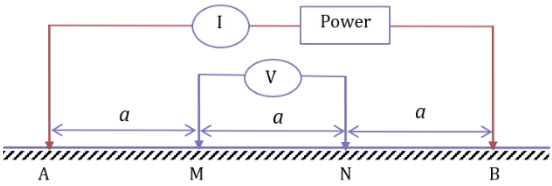


Figure 2.3. The Wenner electrode array

The electrical resistivity tomography is one of geophysical methods, that can be applied to image subsurface structures from tens of meters to several hundred meters in depth with still maintain higher resolution conventional methods, e.g. vertical electrical sounding. In this thesis work, the Wenner electrode array was selected for data acquisition, thus potential electrode spacing increases as current electrode spacing increases, which fewer sensitive voltmeters are required. Whereas, limitations of this method are basically to the depth of penetration of the technique is limited by the maximum electrical power that can be conducted into the ground and by the difficulties of laying out long lengths of electrical cable. Moreover, the topography and the influence of near-surface resistivity variations have an impact on the measurement results that need to be properly addressed.

## 2.4. Improved Multi-electrode Electrical Exploration Methods

The Improved Multi-Electrode Electrical Exploration (IMEE) methods have been proposed on the basis of the integration and development of Improved Electrical Sounding (IES) methods, the traditional Multi-Electrode Electrical Exploration (MEE) method and the Improved Multi-Electrode Electrical Sounding (IMES) method. In this thesis work, the IMEE methods were used for 2D resistivity and polarization data acquisition with the SuperSting R8 for 56 electrodes system.

The IMEE methods are more advantageous than the previous methods, the most prominent of which are: i) Build an (2D) improved multi-electrode arrays (abbreviated as MC array) to ensure easy 2D measurements; ii) The field data collection is fast and there is no data redundancy; iii) Data processing can use available software or a combination of its own program and available software depending on the research purpose; iv) Just using a certain array to collect data in the field, through processing and analysis by simple algebraic formulas, data of other corresponding arrays can be obtained (including the improved Petrovski parameter with degree higher resolution). The limitations of this method are: This method has 02 options for data processing and analysis. With option 1 will have more accurate results with horizontal objects. As for option 2, there will be more accurate results with inclined or vertical surfaces. However, it has not been studied to be able to process and analyze the parameter $\rho_{pm}^{ct}$ with EarthImager 2D software, so when the results are presented, they are not as expected.

## 2.5. Basic theories of seismic refraction

The seismic technique is based on a seismic wave's propagation in the subsurface which depends on the velocity variation in a different medium, but it is applicable in cases where velocity varies smoothly as a function of depth. The factors affecting seismic velocity depend on their various compositions, textures (i.e., grain shape and degree of sorting), porosities, and contained pore fluids, rocks differ in their elastic moduli and densities (Table 2.3).

Table 2.3. The P-wave velocity of earth materials

| Materials | P-wave velocity (m/s) |
|---|---|
| Air | 332 |
| Water | 1400-1600 |
| Sandstone and shale | 2000-4500 |
| Limestone | 2000-6000 |
| Sand and gravel | 500-1500 |
| Shale | 2000-4500 |
| Alluvium | 500-2000 |
| Sand (dry) | 200-1000 |
| Sand (Saturated) | 1500- 2000 |
| Clay | 1000- 2500 |

The advantages of the seismic refraction method are refraction observations generally employ fewer source and receiver locations and are thus relatively cheap to acquire. Meanwhile, because such a small portion of the recorded ground motion is used, developing models and interpretations is no more difficult than other geophysical surveys. While limitations of the seismic refraction method are refraction seismic only works if the speed at which motions propagate through the Earth increases with depth. Refraction seismic observations are generally interpreted in terms of layers with the same velocities.

**Conclusion of chapter 2**

- The geophysical methods could provide the relevant geological information as the first concerns the aquifer geometry and the second concerns the parameters describing the groundwater quantity, including identifying fresh and saline groundwater by physical properties of earth subsurface such as electrical resistivity or electrical conductivity and density of the earth subsurface.

- The designing of electrical and seismic refraction surveying like electrode arrays and geophone spacing were chosen during data acquisition is important in obtaining precise results based on the main objective of the research work.

- The simultaneous use of the multi-electrode electrical exploration and seismic refraction methods, especially for the first time using the improved multi-electrode electrical exploration method (both resistivity and induced polarization) to survey groundwater in Laos have complemented each other and increased the accuracy of research results.

# CHAPTER 3: GROUNDWATER SURVEY RESULTS IN CENTRAL LAOS

## 3.1. Geological characteristics of the research areas

The three study areas were selected in the central part of Laos named Vientiane, Khammouane, and Savannakhet Basins. The first study area is located in Vientiane Province whereas the second and third study areas are located in Savannakhet and Khammouane Provinces respectively. The three Basins were considered as a northwest extension of the Sakon Nakhon basin of the Khorat Plateau, Thailand (Figure 3.1). The PhuPhan range separates Khorat Plateau into two basins, namely the Khorat basin in the south covering an area of about 36,000 square kilometers, and the Sakon Nakhon basin in the north covering an area of about 21,000 square kilometers.

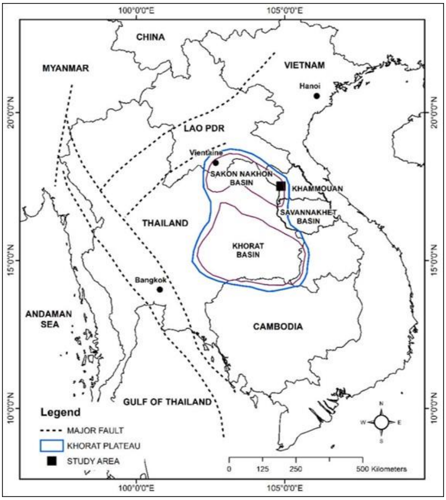


Figure 3. 1. Map of the Khorat and the SakonNakon basins on the Khorat Plateau, Thailand

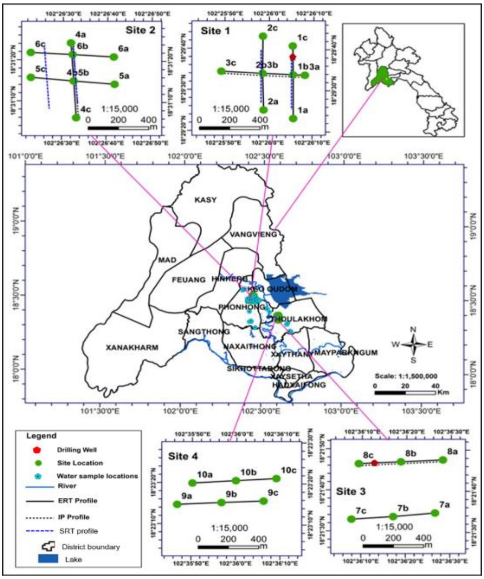


Figure. 3.4. Map of geophysical survey profiles in Vientiane Province

## 3.2. Network of survey profiles and used geophysical methods

*3.2.1. Vientiane Province*

Ten resistivity and three induced polarization profiles were conducted at the four sites using the IMEE methods with the MC array with 10 m electrode spacing and profile lengths of 550 m (Figure 3.4). Four seismic profiles were conducted on selected resistivity profiles at two sites (Figure 3.4). Additionally, two boreholes were drilled for verification comparison with geophysical results at Phonhong and Thoulakhom sites.

The seismic profile length of 440 m, with geophone interval of 5m, 8 spreads for each profile. The shot points are produced by striking a 5kg sledgehammer into a steel plate at 7 shots per spread (Figure. 3.7).

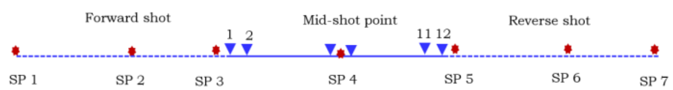


Figure. 3.7. A typical seismic refraction data acquisition layout and location of shot points for seismic refraction survey profile.

3.2.2. Savannakhet Province

The five ERT profiles were conducted in the Outhomphone district of Savannakhet province, in which there are 4 profiles were oriented in the NE - SW directions, whereas another profile left was oriented in the NW - SE directions, the maximum length of a profile of 480m. The Wenner electrode array was selected to conduct with an electrode spacing of a=10 up to 160 m. The two seismic refraction profiles were conducted on overlies on two selected ERT profiles (2 and 4) in the study area (Figure 3.9), seismic profile length of 330 m, a geophone interval of 5m, 6 spreads for each profile. Two boreholes were drilled at the study area for verification comparison with the results of these geophysical methods.

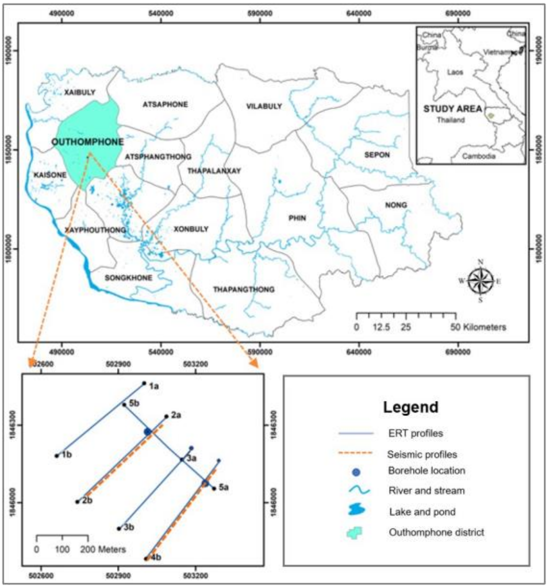


Figure. 3.9. Map of the ERT and SRT profiles in Savannakhet Province

3.2.3. Khammouane Province

The four ERT profiles were conducted in the Thakhek district, in which there are 3 profiles were oriented in the W - E direction, another profile was oriented in the N - S direction, the maximum length of a profile of 480 m (Figure 3.10). The Wenner electrode array was selected with an electrode spacing of a=10 up to 160 m. The three seismic refraction profiles were conducted on overlies on three selected ERT profiles (1, 2 and 4) in the study area (Figure 3.10).

The seismic profile length of 352 m, with a geophone interval of 4m, and consisting of 8 spreads for each seismic profile, including two boreholes were drilled at the study area to match the results of these geophysical methods.

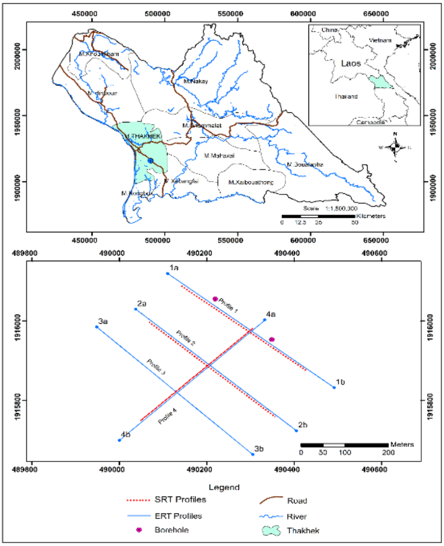


Figure 3.10. Map of the ERI and SRT profiles in Khammouane Province

## 3.3. Results and Discussions

### 3.3.1. Vientiane Province

✓ *For IMEE methods*

The results obtained on ten resistivity and three induced polarization profiles from IMEE methods showed that a moderate resistivity region of 18 to 80 Ohm.m and a low chargeability region of 0 to 21 ms found at depth from 22 to 70 m and extended downward in a deeper depth at profile 1 and some zones at profile 2 is considered as possible groundwater or good quality aquifers in these study sites. Here is an example of the obtained results with resistivity regions of 18 to 80 Ohm.m at depth of 22 to 70 m and extended downward in a deeper depth at profile 1 and some zones at profile 2, indicating possibly suitable areas for groundwater extraction (Figure 3.12a) that correlated well with the previous studies on groundwater zones range from 22 m to 70 m in the Vientiane region and which respond well with the water table at around 22 m depth at borehole VBH-1, profile 1 (Figure 3.12b) at site 1.

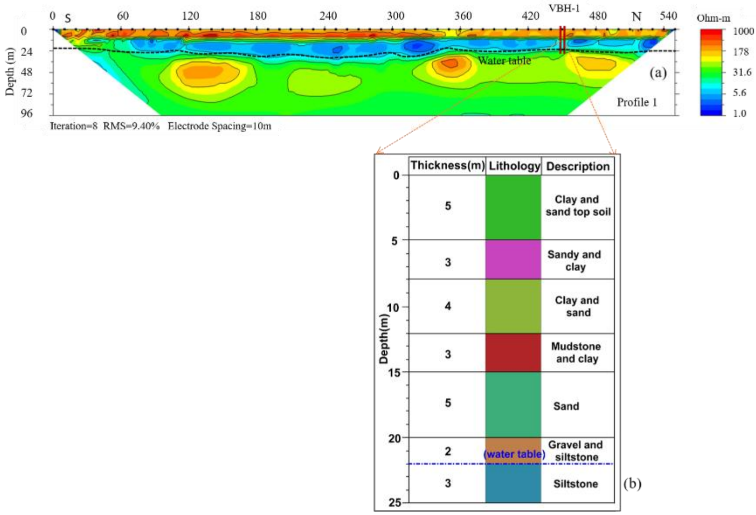


Figure 3.12. (a). 2D Resistivity cross sections under profiles 1 at site1; (b). Vertical geological section under borehole VBH-1 at 450 m on profile 1

The results of Total dissolved solids (TDS), Electrical conductivity (EC) and pH of water samples from different existing and new wells in Vientiane province, revealed mean values lower than the contamination thresholds, confirming that the water is suitable for eating and drinking without causing health risks (Figure 3.19 and 3.20).

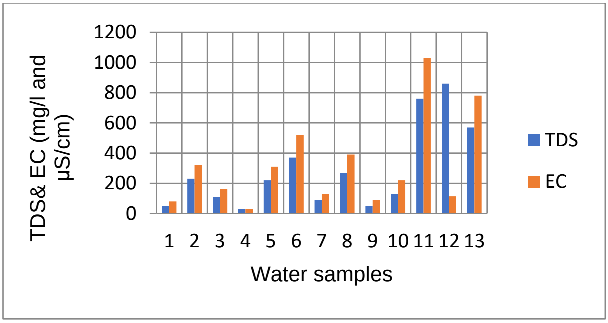


Figure 3.19. Distribution of physical properties (TDS and EC) from 13 water samples in existing shallow wells

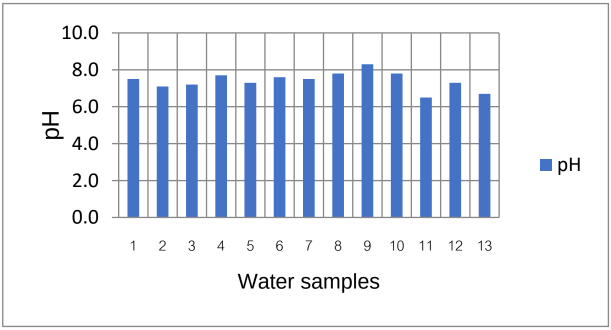


Figure 3.20. Distribution of physical properties (pH) from 13 water samples in existing shallow wells

✓ *For seismic refraction method*

The results of seismic refraction on 4 profiles found the depth of the main aquifer ranges from 20 to 25 m which responds well to the results of MRS and VES in the Vientiane basin, including the study area in the Phonhong districts. In addition, drilling found the water table at a depth of 20-22 m in the Phonhong district. Below is an example comparing the results of seismic refraction method and borehole VBH-1 at profile 1 (Figure 3.25).

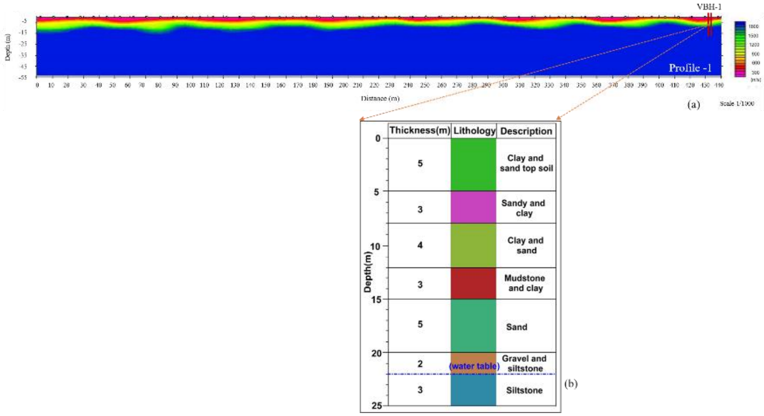


Figure 3.25. (a) Seismic velocity model under profile 1 at site1; (b) Vertical geological section of borehole VBH-1 at 440 m on profile 1

### 3.3.2. Savannakhet Province

The results obtained on 5 resistivity and 2 seismic refraction profiles showed that the moderate resistivity regions from 15 to 60 Ohm.m and seismic velocity vary from 1200 to 1800 m/s respectively found at the depth of 16 to 80m, which is considered as possible groundwater aquifers. Here is an example of the obtained results from the borehole SBH-1 and SBH-2 showed the water table at about 16 m depth for borehole SBH-1 and 20 m depth for borehole SBH-2 (Figure 3.30c and 3.31c), which respond well to electrical resistivity and seismic refraction results (Figure 3.30a, b and 3.31a, b) were identified for groundwater zones.

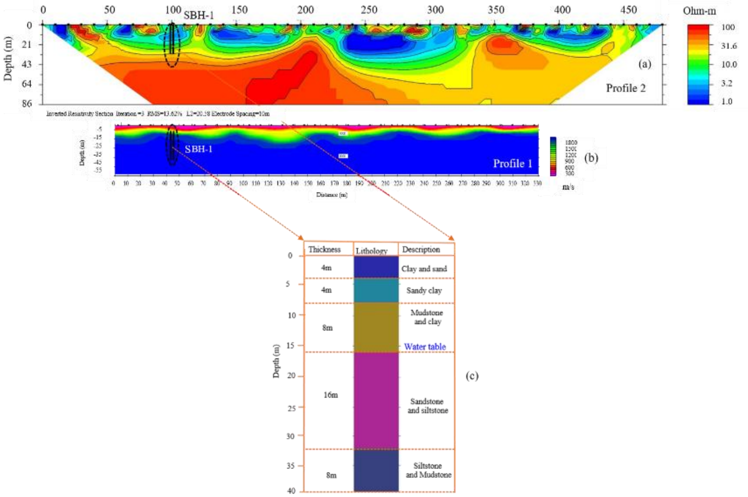


Figure 3.30. (a) 2D geoelectric cross section at profile 2; (b) The seismic velocity model at profile 1; (c) Vertical geological section of borehole SBH-1 at 100 m along ERT profile 2 and 45 m along SRT profile 1.

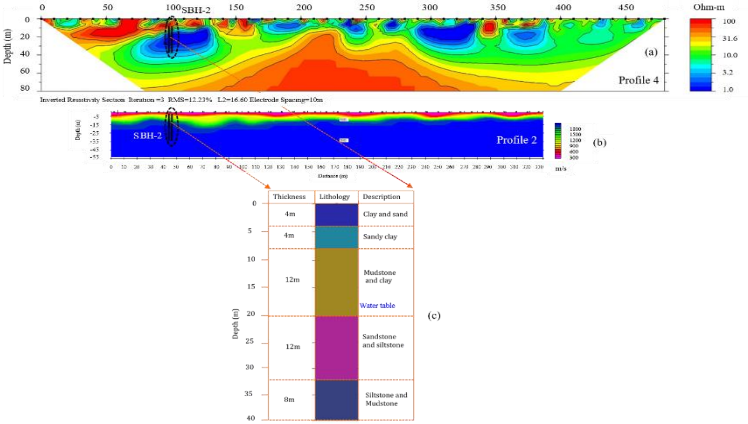


Figure 3.31. (a) 2D geoelectric cross section at profile 4; (b) The seismic velocity models at profile 2; (c) Vertical geological section of borehole SBH-2 at 100 m along ERT profile 4 and 45 m along SRT profile 2.

3.3.3. Khammouane Province

The results obtained on 4 ERT and 2 SRT profiles showed moderate resistivity and seismic velocity regions of 18.8 to 71 Ohm.m and 1220 to 2140 m/s found at 12 to 30 m depth are considered as possible groundwater aquifers. Here is an example of the obtained results from both boreholes indicated the water table at around 12 m depth for borehole KBH-1 and 15 m depth for borehole KBH-2 (Figure 3.36c, d), which respond well with resistivity and seismic results (Figure 3.36a, b) are identified for groundwater zones.

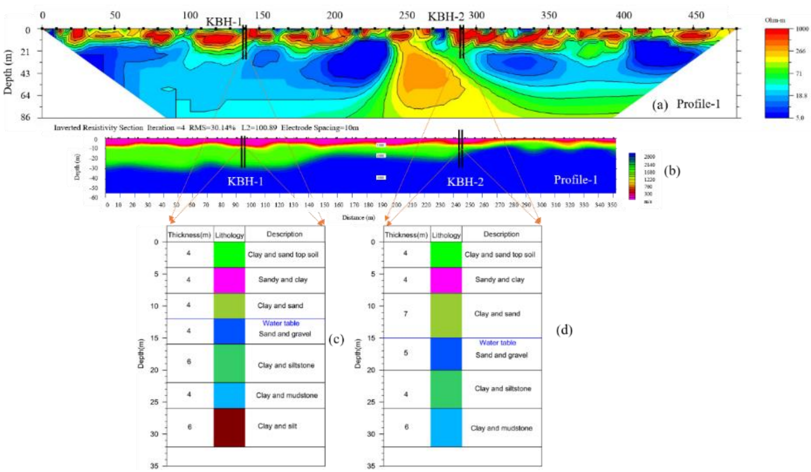


Figure 3.36. (a) 2D ERT cross-section at profile 1; (b) The SRT cross-section at profile 1; (c) Vertical geological cross-section of borehole KBH-1 at 140 m at ERT profile 1 and 96 m at SRT profile 1; (d) Vertical geological cross-section of borehole KBH-2 at 290 m at ERT profile 1 and 246 m at SRT profile 1.

## Conclusion of chapter 3

The three selected geophysical methods were carried out in different study areas. In Vientiane province: ten resistivity and three induced polarization profiles were conducted at four sites using the IMEE methods with the MC array with 10 m electrode spacing and profile lengths of 550 m; Four seismic profiles were conducted at two sites in Phonhong district, with the profile length of 440 m. While the five 2D ERT profiles and the two SRT profiles were conducted in the Outhomphone district of Savannakhet province with a maximum length of a profile of 480m and 330 m respectively. The four ERT and the three seismic refraction profiles were conducted in Thakhek district, Khammouane province with a maximum length of a profile of 480 m and 352 m respectively. In addition, two boreholes were drilled to compare with the geophysical results in the three different research areas above.

- The study area 1 in Vientiane province: the results obtained from IMEE methods indicated that a moderate resistivity region of 18 to 80 Ohm.m and low chargeability region of 0 to 21 ms found at depths from 22 to 70 m and extended downward in a deeper depth at profile 1 and some zones at profile 2 is considered as possible groundwater or good quality of aquifers. The results of IMEE methods were well correlated with the water level at a depth of 22 m of the borehole in the Phonhong district. While results from seismic refraction method found that water table at depth from 20 to 25 m. The results of TDS, EC and pH values indicated that the water is suitable for eating and drinking without causing health risks.

- The study area 2 in Savannakhet province: the results obtained from ERT and SRT methods showed that the moderate resistivity regions vary from 15 to 60 Ohm.m and seismic velocities ranging from 1200 to 1800 m/s found at a depth of 16 to 80m, is considered as possible groundwater aquifers. These results also agree well with information obtained from two boreholes in the district, where samples are at depths of 16 to 20 m.

- The study area 3 in Khammouane province: the obtained results showed the moderate resistivity regions of 18.8 to 71 Ohm.m and seismic velocity vary from 1220 to 2140 m/s found at 12 to 30 m depth are considered as possible groundwater aquifers. These results correlate well with those obtained from boreholes which show the groundwater level at a depth of about 12 m for borehole KBH-1 and a depth of 15 m for borehole KBH-2.

## CONCLUSIONS AND RECOMMENDATIONS

### CONCLUSIONS

1. A combination of Electrical Resistivity Tomography, Improved Multi-electrode Electrical Exploration and Seismic Refraction Tomography methods has been chosen to search for groundwater potential zones in the three research areas of central Laos. The results obtained from the geophysical methods were compared to the results of boreholes drilled along geophysical profiles. In addition, the TDS, EC, and pH values are also analyzed from water samples in different existing and new wells in the first survey area.

- The obtained results from IMEE methods in Vientiane province indicated that a moderate resistivity region of 18 to 80 Ohm.m and low chargeability region of 0 to 21 ms found at depths from 22 to 70 m and extended downward in a deeper depth at profile 1 and some zones at profile 2 is considered as possible groundwater or good quality of aquifers. The results of IMEE methods were well correlated with the water level at a depth of 22 m of the borehole in the Phonhong district. While results from seismic refraction method found that water table at depth from 20 to 25 m. In addition, the TDS, EC, and pH analysis from water samples in different wells in the survey area confirm that water is suitable for eating and drinking without causing health risks.

- The results of ERT and SRT methods in Savannakhet province showed that the moderate resistivity region of 15 to 60 Ohm.m and the seismic velocity of 1200 to 1800 m/s at a depth of 16 to 80 m was considered as possible groundwater aquifers, which correlates well with the water table obtained from the first and second boreholes at depths of 16 m and 20 m respectively.

- The results of ERT and SRT methods in Khammouane Province found that moderate resistivity values of 18.8 to 71 Ohm.m and the seismic velocity of 1220 to 2140 m/s at a depth of 12 to 30 m are considered as possible groundwater aquifers, which correlates well with the water table obtained from the boreholes at depths of 12 m and 15 m respectively.

Regarding to the recrent obtained electricity results indicated, it can be delineated fresh water zones and other zones based on their electrical properties contrast. On the basic of resistivity values range from 20-160 Ohm.m and very low chargeability 0 ms is considered as fresh groundwater or good aquifers. These results are consistent with the TDS, EC and pH results from water samples in existing wells and new borehole.

The obtained results of the three studied areas indicated that water tables or depth to aquifers are slightly different from each other, which found water tables at 20 to 22 m in Vientiane province, whereas found water tables at 16 to 20 m and 12 to 15 m in Savannakhet and Khammouane provinces respectively.

2. The research results indicated that the combination of the geophysical exploration methods such as the Improved Multi-electrode Electrical Exploration (both electrical resistivity and induced polarization)/2D Electrical Resistivity Tomography and Seismic Refraction methods to search for groundwater is feasible

and efficient in the three research sites of central Laos. There are a few geophysical profiles were conducted in the three study areas due to limitation on budget and time. Therefore, the obtained geophysical results, including results from water samples analysis of TSD, EC and pH parameter for groundwater studies in this thesis work to assess the quality and availability of groundwater at specific locations of the 3 selected study areas.

The results of induced polarization and seismic refraction methods can reduce ambiguity in resistivity data analysis, which can distinguish between clay content or saturated water earth subsurface. The combination of resistivity and induced polarization methods can identify fresh and saltwater groundwater and high groundwater zones in these areas. While seismic refraction method to identify water tables or aquifers. The obtained results indicated that these geophysical methods can provide new and higher resolution results in the three research areas of central Laos. The results demonstrated the benefits of using these geophysical methods to find groundwater zones in the research areas and they can be used for other areas with similar geology formations in further research work.

**RECOMMENDATIONS**

The results of this thesis need to be reported to the Department of Water Resources, Ministry of Natural Resources and Environment, Lao PDR. The results should be used as a useful reference for researchers who are interested in groundwater exploration. At the same time, these results will attract directly for managers in planning exploitation and the use of groundwater resources as well as use these results will be useful for a public awareness strategy to promote safe and sustainable use of groundwater in the future in Laos.

## LIST OF SCIENTIFIC WORKS OF THE AUTHOR RELATED TO THE THESIS

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2. **Viengthong Xayavong**, Vu Duc Minh, Nguyen Anh Duong, Vu Minh Tuan, (2020), "Seismic Refraction Exploration for Groundwater Potential Evaluations: A Case Study of Vientiane Province, Laos", *VNU Journal of Science: Earth and Environmental Sciences*, 36(4), pp. 90-101, DOI: https://doi.org/10.25073/2588-1094/vnuees.4651.

3. **Viengthong Xayavong**, Minh Duc Vu, Duong Anh Nguyen, Tuan Minh Vu, Chung Anh Do, (2021), "Application of the electrical resistivity tomography and seismic refraction methods for groundwater investigation in Savannakhet province, Laos", *Proceedings of the 7th Academic Conference on Natural Science of ASEAN Countries (CASEAN –7),* Ha Noi.

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