FEDERAL UNIVERSITY OF AGRICULTURE
ABEOKUTA NIGERIA

89th INAUGURAL LECTURE

UNRAVELLING THE COUPLED HEAT AND WATER FLOW PHENOMENON: MY NON-INVASIVE VOYAGE INTO THE SUBSURFACE DOMAINS

by

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College of Physical Sciences
Federal University of Agriculture, Abeokuta, Nigeria

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FUNAAB INAUGURAL LECTURE SERIES

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The Vice Chancellor, Sir,

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Members of the University Senate,

All Academic and Non-teaching Staff,

All Special Guests and Friends of the University,

Members of my Family and Friends,

Gentlemen of the Press,

Distinguished Ladies and Gentlemen,

Great FUNAABITES

PREAMBLE

Mr Vice Chancellor, Sir, I stand today to present my inaugural lecture as a Professor of Earth Physics in the Department of Physics, College of Physical Sciences in this fabulous Federal University of Agriculture, Abeokuta. I joined the services of this University in 1998 as an Assistant Lecturer, and I rose through the ranks to the enviable status of a Professor in 2013. Today by the grace of the Almighty God, I am a Professor at bar.
This inaugural lecture is the 2nd from the Department of Physics and the 7th from the College of Physical Sciences. The first from the Department of Physics, which happened to be the first also in the College of Physical Sciences, and the 56th in the University, titled "*The use of innocuous geophysical tools in discerning the bowel of the earth: a strategy for manpower development*", was delivered by Prof. Joseph A. Olowofela on 23rd May, 2018. Hence, in the College of Physical Sciences, this lecture is coming after those of Prof. Joseph A. Olowofela, Department of Physics; Prof. Catherine O. Eromosele, Prof. Akinola K. Akinlabi, Prof. Enoch O. Dare of the Department of Chemistry; and Prof. Adio T. Akinwale, Prof. Adesina S. Sodiya of the Department of Computer Science.

This Inaugural Lecture presents a momentous platform to share, before the distinguished members of the University community and the general public, the opportunities I have had in research, innovation, collaborations, and academic mentoring within the last three decades, including 10 post-professorial years. It is indeed a great privilege to present the 89th Inaugural Lecture of this awesome University titled - **Unravelling the coupled heat and water flow phenomenon: my non-invasive voyage into the subsurface domains**. A simplified version of the topic would have been 'navigating the bowels of the earth to understand the flow systems with minimal physical contacts. Mr. Vice Chancellor, Sir, permit me to do a quick introduction of the governing principles, summarise my scholarly contributions and human developmental efforts, and offer some short-term and long-term recommendations. I humbly request this distinguished audience to please sit back, relax, and join me on this observatory cruise!

1.0 INTRODUCTION

My research in the past three decades has been around the complex interactions between two physical quantities which are constantly changing forms, magnitudes and directions in the subsurface domains. Heat and water fluxes are two quantities which are very helpful to nature but they also have their other sides of being unfriendly. According to the inspired cannons, God destroyed the then world, in the days of Noah, with water and later said that He will no longer use water but heat to finally destroy the earth, then something must be special about these two unique phenemena.

Heat transfer is the transport of thermal energy between physical systems due to a temperature gradient. Heat moves through *conduction, convection or radiation* mechanisms. *Conduction* is driven by a temperature difference in stationary solids or liquids through collisions between neigbouring atoms or molecules. C*onvection* occurs in a fluid through random molecular motion when heated fluid rises and sinks as it cools leading to continuous heat transfer. R*adiation* is a form of electromagnetic waves from a non-zero temperature surface to another at different temperature with no intervening medium. An important parameter is the heat flux which is a flow of heat energy per unit of area and per unit of time.

Groundwater flow, on the other hand, is driven by hydraulic gradient, hence its velocity is a function of the hydraulic gradient and the hydraulic conductivity *(Cheremisinoff,1997)*. Groundwater flows in cracks, cavities, and fractures of rocks as well as pores of sediments, and within high permeability and high hydraulic conductivity domains constituting the aquifer (*Mulligan and Charette, 2008*).

Groundwater usually moves with groundheat, hence the integrated movement of the duo is referred to as coupled flow in which heat

and water flow in and through the three-phase system. The heat may be latent and/or sensible, and water may be liquid and/or vapor. We have expanded the frontiers of knowledge about this unique couple, yet investigations continue on the interactions between them. The two are usually referred to as a couple because, though distinct in terms of properties and characteristics, both are most times fused together. Having studied this inanimate couple for some time, I have come to the conclusion that human couples have a lot to continue to learn from their unique attributes, and permit me to share some of them:
i). Water is visible while the heat is not but can be felt;
ii). Heat can sometimes be at some degrees of hotness while water shares part of it, absorbs it and brings down the temperature;
iii). The pair sometimes move in separate directions but many times move in same directions iv). Water is very moody, anomalous, and temperamental thereby changing forms very easily from solids to liquids and vapour while heat remains unmoved, unadaptable and inflexible,
v.) Both are very complementary to each other, water serves as a carrier to heat, thereby enhancing its movement and reach.

1.1 Interior of the Earth

Earth scientists do not have any way to explore the earth's interior directly but have found non-invasive ways through the mechanical, electrical, magnetic, gravity, and seismic properties of the earth in order to understand the complex interactions within the earth subsurface system (Knight *et al.*, 2010). We infer its structure by measuring how *seismic waves* travel through the interior.
The earth's crust is constantly subjected to forces (stress) that push, pull, or twist it. In response, the materials of the earth undergo strain, also known as deformation, as a result of the sudden release of energy in the earth. The energy moves outward from its source in the form of seismic waves which cause the earth's surface to shake or quake. Hence, earthquakes are caused by sudden slippage of sections of the crust along faults, magma movement in the crust,

volcanic eruptions, and abrupt reduction in the volume of minerals in a subducting plate as they adjust to higher pressures in the mantle. Most earthquakes occur in the earth's crust while a smaller number occur in the uppermost mantle (to about 700 km deep) where subduction takes place (Knight *et al.*, 2010).

When an earthquake occurs, some of the energy released go into heat within the earth, some are expended in breaking and permanently deforming the rocks and minerals along the fault, while the rest is radiated from the focus of the earthquake in the form of seismic waves. Seismic waves fall into two general categories: body waves {primary (P) and secondary (S)}, which travel through the interior of the earth, and surface waves {Raleigh (combined effect of the P and S waves) and Love}, which travel only at the earth's surface. *P-waves,* or *longitudinal waves*, can travel through both liquids and solids unlike *S-waves, or transverse waves,* which travel only through solids, as liquids do not possess shear strength. In addition, the speed of seismic waves depends on the elasto-mechanical properties of the earth materials. Therefore, we can use the pattern of waves measured by seismometers during earthquakes to deduce the interior structure of the earth, hence, our main interests are the P and the S waves.

From the analysis of the properties, it has been determined that the earth consists of several layers (Figure 1).

1.1.1 The Lithosphere

The lithosphere consists of the crust and the upper mantle. The Crust can be divided into two different types - continental and oceanic. Both types “float” on the denser mantle. Continental crust is about 25-90 km thick and divided into tectonic plates. These plates move slowly, by a few centimetres, each year over the more fluid mantle. The tectonic plates make up distinct regions of the earth's surface such as continents. Oceanic crust, which is much thinner than continental crust at only 6-11km thick, is where new crust is formed. This can happen by two plates moving apart and magma from the asthenosphere coming up and cooling to form new seafloor.

1.1.2 The Asthenosphere

The Asthenosphere is more fluid, with a plastic-like texture, than the rigid Lithosphere above it. This is due to the increased temperature and pressure that rocks experience as they descend into the Asthenosphere from the Lithosphere, making them molten. The molten nature of the Asthenosphere makes it possible for plate tectonics to happen. If the plates were not able to shift on the semi-liquid region, then new mountains would not form. Mountains are formed when two plates converge, or flow towards each other, and possibly even cause asthenospheric material to flow up through vents thereby causing a volcano. Asthenospheric material can also escape to the surface when plates move away from each other, or diverge. The Asthenosphere is the supplier of new materials to the Lithosphere and replaces the lithospheric material as it is cycled through.

1.1.3 The Mantle

We move from the Asthenosphere into the Upper Mantle through the Mohorovicic discontinuity, or Moho. The Upper Mantle is fairly plastic, relative to the layers above it. Not much is known about the seismic activity of the Lower Mantle, but scientists assume that it is relatively consistent. Since the mantle is molten, flowing freely, it has convections similar to those that occur when boiling water on a stove. The magma heats as it gets closer to the Core and rises closer to the Asthenosphere, cooling as it gets closer and falling again to be re-heated and rising again, continuously cycling.

1.1.4 The Core

The Core is something that scientists can only make hypothesis about because it is so deep in the earth that no instrument could make it that far down, even if it was long enough. The temperatures and pressure are so extreme that anything would be destroyed before any data was accumulated (*Fowler, 1996*). What we do know is that there are two parts, an Outer Core and an Inner Core.

The Outer Core is liquid flowing and molten iron alloy, at extremely high temperatures. The Inner Core is thought to be solid iron, and has been thought to be pure iron for many years until recently.

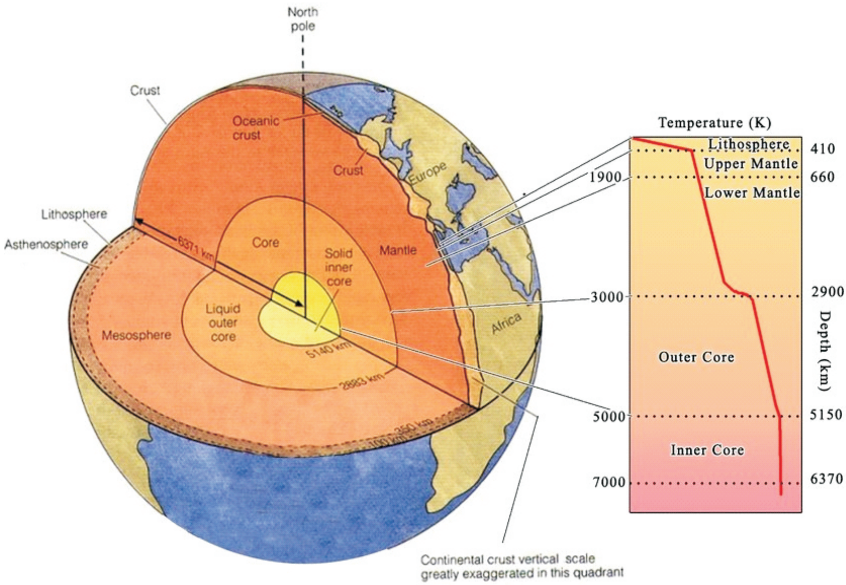

Fig. 1: Structure of the Earth Interior (*Fowler, 1996*)

Geothermal energy is a clean and sustainable source of energy beneath the surface of about 3982°C, super-hot gas and molten are constantly being replenished.

1.2 Geothermal Energy Potentials

Geothermal energy is generated from the earth's crust and is transported through cracks and fractures in the host rocks and its natural fluids at temperatures above the ambient level. The rate of heat flow in the crust is estimated to be 59 mWm^{-2}. In mature continental cratons, the geothermal gradient can be as low as 10°C

km^{-1}. However, in active volcanic areas, it can exceed 100°C km^{-1}. A typical geothermal gradient of 25°C km^{-1} gives a conductive heat flux of 60 mWm^{-2} for electricity generation. Considering the Nigerian basement complex, the estimated geothermal gradient of Borno and Sokoto States, both located in the Northern region, are 1.1 to 5.9°C/100m with a heat flow of 8.9 to 117.8 mWm^{-2} and 0.9 to 7.6°C/100m with a geothermal heat flow of 52.11 to 130.28mWm^{-2}, respectively. In addition, in Anambra State, eastern Nigeria, the estimated geothermal gradient is 2.5 to 4.9°C/100m with a heat flow of 64.4 to 97.3 mWm^{-2}. Geothermal energy has the potential to improve Nigeria's current poor energy dynamic. Enhanced Geothermal System would exploit heat energy that is trapped in the subsurface host rock by creating an open system of connected fractures along which water can flow down the injection wells and get heated through contact with the rocks. This is then recovered to the surface in production wells to form a closed loop. The idea is an extrapolation that emulates a hydrothermal circulation system – which produces electricity that can be applied commercially (*Fowler, 1996*).

1.3 The Paradox

The most common belief is that the centre of the earth is a place for afterlife. Ancient Greeks called it the *underworld*, some Hebrews named it as *Sheol* while some religious scholars refer to it as *hell*. Hell is usually referred to as somewhere below. As a matter of fact, phrases like "descended into", "went down into", "thrust down into", "great depths", "from beneath", "lower parts of the earth" are not uncommon in the inspired scriptures to illustrate hell. There is strong convergence of opinions that Sheol or hell is an extremely hot place, located somewhere down beneath, and burns continuously with brimstone (an old name for sulphur). Where then is the paradox? On the one hand, the subsurface domain is attributed with hellish things, on the other hand, it remains the single biggest repository of natural resources, as designed by God for the wealth of the Nations. This is the paradox, and this is where it becomes interesting. The basis for this is clear, we (including our creations and inventions) all come from it and must all return back into it after expiration, and all these remains undergo different transformations to finally end up as underground resources.

2.0 MY CONTRIBUTIONS TO KNOWLEDGE

For the purpose of brevity and clarity, I will be discussing my contributions in five areas: 1. Coupled heat and water transfer; 2. Physical properties of earth materials; 3. Contaminant transfer within the surface; 4. Prospecting for desirable resources within the subsurface, and 5**. Forensic Investigation of the Subsurface.**

2.1 Coupled Heat and Water Transfer

The transfer of heat and mass is coupled because the movement of one substance affects the movement of the other. For example, the movement of water in the ground affects the movement of heat in the ground, and both are governed by either the temperature gradient or the moisture gradient. The study is of great importance in various fields such as hydrogeology, geothermal energy, building physics, oil recovery, and environmental engineering.

The study of underground coupled heat and water transfer is complex and requires the use of mathematical models to describe the behaviour of the system. These models are used to predict the behaviour of the system under different conditions and to optimize the design of systems that utilize coupled heat and mass transfer.

Hence, our first attempt was to develop a numerical algorithm to simulate the simultaneous transfer of heat and mass in porous media. The governing physics was based on the fact that moisture can be transferred in the gas phase, following evaporation-diffusion-condensation paths, because of the temperature dependence of the *water vapour saturation pressure* (D_{TV}) and, in the liquid phase, through the temperature dependence of the *interfacial tension* (D_{TL}).

In our work we considered a mathematical model that linearized the vapour-giving term exchanged at the boundaries in terms of temperature and moisture content. A generic algorithm was introduced that simultaneously solves the governing equations for each time step. The upper surface was assumed to be exposed to the atmospheric variables while the other surfaces of the ground were considered adiabatic and impermeable. We, however, disregarded (i) convection and radiation heat transfer in the pores, and (ii) the sensible heat transfer by the liquid and vapour phases. To ensure numerical stability, linearized set of equations were obtained by using the finite-volume method and the MultiTriDiagonal-Matrix Algorithm (MTDMA) to describe the physical phenomena of heat and water transfer. A simulation code was finally developed based on the coupled heat and moisture transfer phenomenological model of Philip and De Vries (1957) and de Vries (1957). The code was found to be unconditionally stable, fast and robust {Akinyemi and Mendes (2007), Akinyemi *et al*. (2007a), Akinyemi and Mendes (2008a, 2008b)}.

2.1.1 Experimental validation at the near surface

We needed to first subject the algorithm to near-surface flow before numerically experimenting other depths. This set out to compare field experimental results of measured volumetric water content and temperature at two depths close to the surface with the developed numerical model. The validations were made under different boundary conditions to verify the robustness of the numerical code.

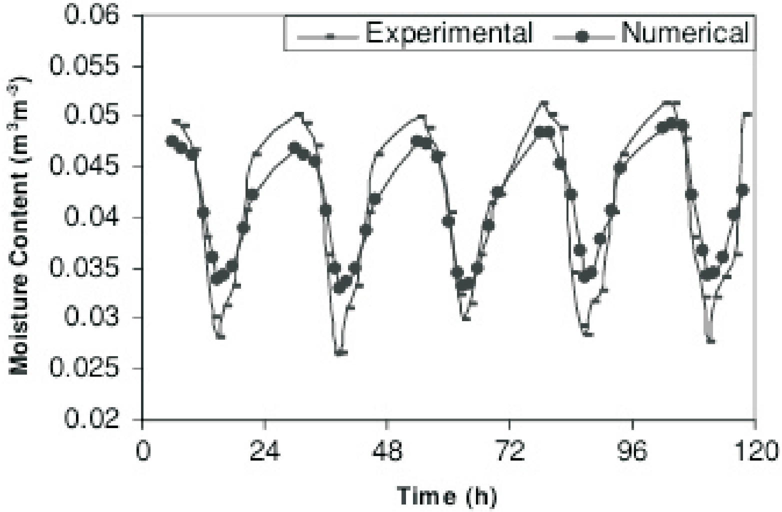

Fig. 2: Measured versus predicted water content

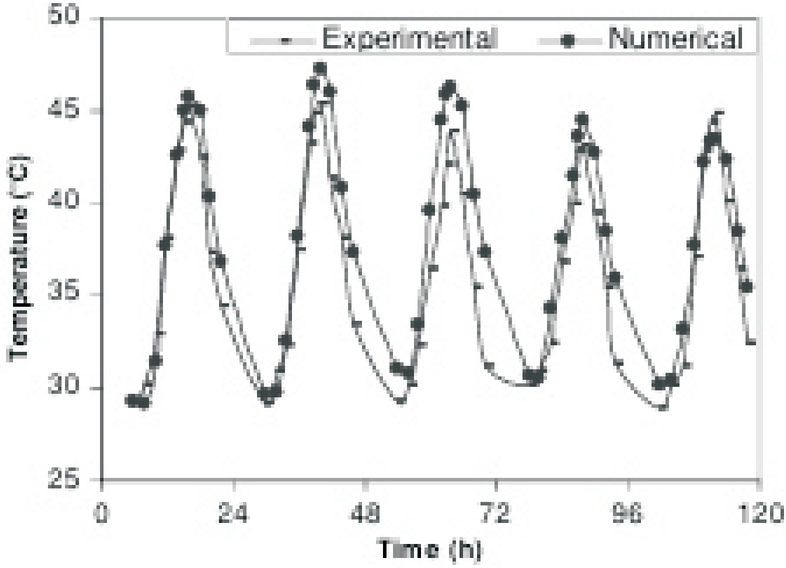

Fig.3: Measured versus predicted temperatures (Akinyemi and Mendes, 2008b)

Experimental measurements were compared with predicted numerical values and the model performance improved as daily variation in atmospheric variables decreased (Figures 2 and 3), suggesting that the model can be used to build a reliable water evolution and temperature data base especially given a mild weather {Akinyemi and Mendes (2007), Akinyemi et al. (2007a), Akinyemi and Mendes (2008b)}.

2.1.2 *Experimental validation at depths*

We realised that heat transfer and moisture movement in porous media are closely related and play a central role in hydrology, atmospheric sciences, geophysics, and environmental physics. In particular, the hydrological and physical characteristics of the media and the atmospheric variables subject to the prevailing climatic conditions are strongly decisive factors. The ground surface layer is of great influence and an increasingly important interest in the subsurface environment is the detailed knowledge of the hydrological and thermal regime, and the factors controlling them. We then buried water flux and heat flux sensors underground at varying depths (Figure 4) and began measurements after attaining some form of equilibrium.

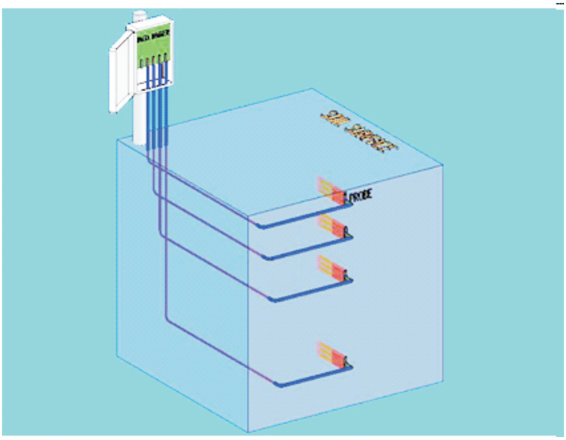

Fig. 4: Measurements in Depths (Akinyemi and Mendes, 2008)

The mean water content ± standard deviation over the entire period of investigation was 0.27 ± 7.235, 0.25 ± 3.499, 0.17 ± 4.728 and 0.16 ± 11.732 m^3m^{-3}, while the mean temperature ± standard deviation was 17.8 ± 2.687, 17.5 ± 2.046, 17.4 ± 1.666 and 17.4 ± 1.248 °C, respectively, at the measured depths. We compared the simulated data with the measured data and we obtained a good agreement {Akinyemi and Mendes (2007), Akinyemi *et al*. (2007a), Akinyemi and Mendes, 2008b)}.

2.1.3 Ground temperature and water distribution in four continents

After some rigorous testing of the algorithm through field measurements, we went further to do remote application of the code. We applied the MTDMA model to describe coupled heat and water transfer in the ground for the four selected cities with strikingly different climates of *Curitiba*, Brazil (-25.52 °N, -49.17 °E), *Johannesburg*, South Africa (-26.13 °N, 28.23 °E), *Singapore*, Singapore (1.37 °N, 103.98 °E) and *Seattle*, United States of America (47.45 °N, -122.3 °E). *Curitiba* which is the coldest in Southern subtropical Brazil, being located on a plateau (900 m), is said to have four distinct seasons and sometimes uniquely having all the four on some days. With a height of 1753 m, Johannesburg is the largest city located in the eastern plateau area of South Africa which enjoys dry and sunny climate. Singapore Island, on the other hand, is a lowland with a gently undulating central plateau terrain which is warm and humid all year round with only slight variations in temperature, relative humidity, direct and diffuse radiation. Seattle is a Pacific Northwestern city of the United States which has a mild temperate marine climate where the temperatures are moderated by the sea and protected from winds and storms by the mountains. The hourly Typical Meteorological Year (TMY2) weather files which provide ambient temperature, relative humidity, direct and diffuse solar radiation wind speed and direction among other data were used for the simulation purposes.

In order to analyze the simultaneous heat and moisture transfer, ground property data for the target ground were necessary for the simulation processes. However, property data obtained by Oliveira *et al.* (1993) were used in the study for all the cities because it was one of the commonest available. Considering the temperature range for the simulations, the properties were very moderately temperature dependent so that the transport coefficients [λ (thermal conductivity), $D_{\theta L}$ (moisture content gradient liquid-phase transfer coefficient), D_{TL} (temperature gradient liquid-phase transfer coefficient) $D_{\theta V}$ (moisture content gradient vapour-phase transfer coefficient) D_{TV} (temperature gradient vapour-phase transfer coefficient)] were considered as a function of water content only.

Hence a 5 m depth was simulated in all cases using a time step of 10 min and a 2-year warm-up period which was later converted to hourly data for daily comparison and thus hourly profiles of moisture and temperature was generated from January to December across the depths. At the topmost layer in January, daily average soil temperature was highest in Singapore and lowest in Seattle while the daily average soil moisture content was highest in Singapore and lowest in Johannesburg. In July, the daily average temperature was highest in Singapore and lowest in Curitiba while the daily average moisture was highest in Curitiba and lowest in Johannesburg {Akinyemi and Mendes (2007), Akinyemi *et al*. (2007a), Akinyemi and Mendes (2008a)}.

2.1.4 *Factoring precipitation effects into the model and discountenancing the temperature gradient in the moisture conservation equation*

In most of our previous investigations (2007 – 2012), rain was not implemented and where it was, the problem of convergence was encountered. In 2012, however, an attempt to get better results was made by decoupling the moisture transport from the heat transport and by including the gravity effect and the rain as boundary conditions. The Philip and de Vries model was solved using the

TriDiagonal Matrix Algorithm (Mendes *et al.* (2002), Mendes and Philippi (2004)) included in the Power Domus software which simultaneously solved the mass and energy conservation equations for performing simulations, avoiding numerical instability problems and allowing the use of large time steps.

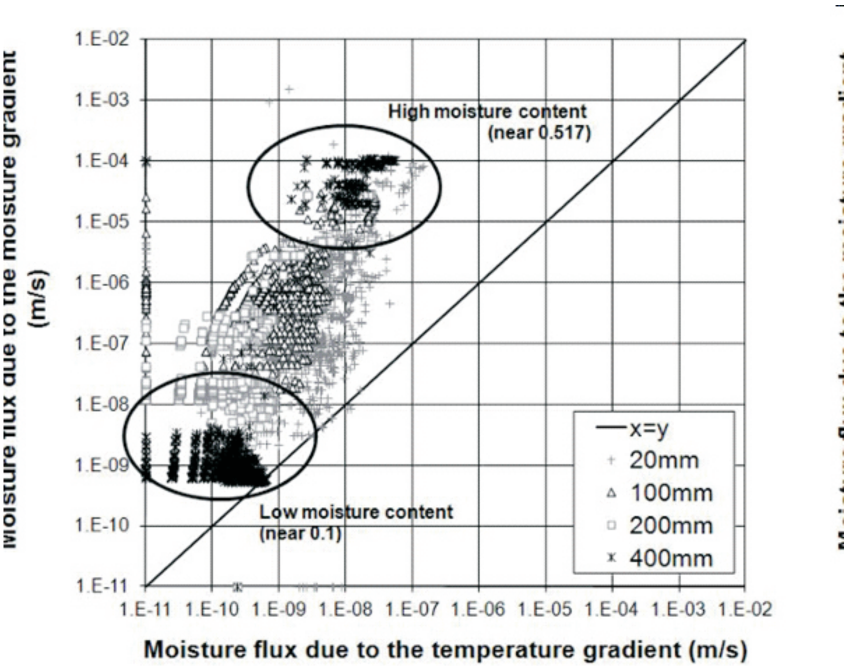

Fig. 5: Moisture flux due to moisture gradient versus moisture flux due to Temperature Gradient (Mendes *et al*., 2002)

2.1.5 Comparison between temperature and moisture content gradients effects on the moisture flow

An evaluation of the relative importance of the temperature gradient on the moisture distribution was carried out by comparing the moisture flux due to the moisture gradient $D\theta(\partial\theta/\partial y)$ and the moisture flux due to the temperature gradient $D_T(\partial T/\partial y.)$ The was effectively done using the measured values of both temperature and moisture content and the mass transport coefficients associated with a moisture content and a temperature gradient. Fron Figure 5, it was found out that:

1. the moisture gradient driven flow is predominantly higher than the temperature gradient driven flow, and
2. there is a factor of 1000 to 10,000 when high moisture content is reached (rain episodes) and a factor of 1 to 10 when low moisture occurs.

As a consequence, the Philip and de Vries model was discretized considering the temperature gradient negligible so that only the moisture transfer can be considered in the model. There was, however, the need to correctly initialize the ground moisture and to adjust the ground properties, particularly in the funicular region in order to easily impose moisture content or flux at the domain boundaries.

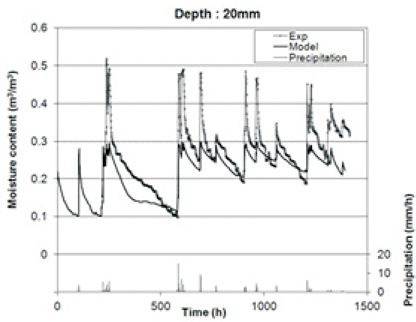

Fig. 6: Moisture content variation with time (20)

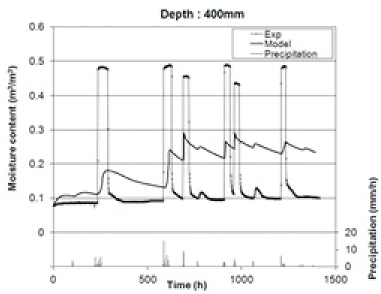

Fig. 7: Moisture content variation with time (400)

Results of predicted ground moisture evolution using the decoupled Philip and de Vries model compared fairly well with values obtained from experiment, especially at the topmost layers (Figures 6 and 7). Both experiment and numerical models were very sensitive to the rain episodes and were reduced and delayed according to the profoundness, which suggests that the studied ground was quite heterogeneous regarding its characteristics. At that point again, we saw the profound need to consider heterogeneity and hysteresis in the numerical model, which can play an important role in the prediction of heat and moisture transfer through unsaturated porous soils (Mendes, Abadie, and Akinyemi, 2012).

2.1.6 Estimation of ground water content using water balance and regression approach

Near-surface water content (NSWC) is a variable in space and time that significantly affect physical processes. The complex interactions between the atmosphere and the surface as well as between the surface and underground, which results in exchange of energy and moisture at quantities varying with time, make it difficult to estimate the NSWC. The traditional techniques of measuring NSWC give point data that does not represent the spatial profile. In this work, attempt was made to estimate the NSWC of an area in Abeokuta using water balance and regression approach. The study was carried out at Akole, Oke-Ata, Abeokuta, Nigeria.

NSWC were measured hourly at depths 2, 50, 100, 150, and 200 cm between 1 January 2014 and 31 December 2014 using Decagon EM50 data logger. Daily air temperature, solar radiation, relative humidity, and precipitation data for the location were obtained from the Nigerian Metrological Agency. Water balance approach combines empirically only the air temperature and precipitation readings to estimate NSWC. Regression approach employed the knowledge of water content at the surface or near the surface layer to estimate NSWC at other depths. Models were tested by Nash-Sutcliffe (NS) efficiency and coefficient of determination (R^2) estimated NSWC using water balance approach was in good agreement with measured data at depths of 2, 50, 100, and 200 cm with R^2 of 0.9091, 0.9166, 0.8540, and 0.7139, respectively.

The NSWC estimated with regression approach was reasonably close to observed values at depths of 50, 100, 150, and 200 cm with R^2 of 0.9881, 0.8567, 0.6418, and 0.6278 while the NS were 0.6394, ?0.8132, ?3.5785, and 0.3642, respectively. The NS value of 0.6394 shows that the model performed creditably well at the depth of 50 cm only. The high and consistently positive values of NS efficiency revealed that water balance approach was better than the regression approach in estimating NSWC (Alabi *et al*., 2018).

2.2 Physical Properties of Earth Materials

Earth materials are the media through which heat and mass move underground, hence the different earth layers exhibit different reactions, based on their properties, when such movements occur. Thermal conductivity is the ability of the material to conduct heat while permeability is a measure of the ability of a material to allow water to pass. In addition, when a stress is applied to earth materials, they experience a change in dimension, volume, or shape, which is called strain. The magnitude of the strain in response to the applied stress is related to various elastic constants, including Young's modulus, shear modulus, bulk modulus, and Poisson's ratio. Confining pressure increases the elasticity, strength, and ductility of rocks, while internal pore-fluid pressure reduces the effective stress acting on the sample, thus reducing the strength and ductility. The electrical properties of earth materials are defined by their electrical conductivity and their dielectric constant. Electrical conductivity is a bulk property of material describing how well electric current is allowed to flow through as governed by Ohm's Law. Resistance will change if the measurement geometry or volume of material changes. The electrical conductivity of Earth's materials depends on the rock type, porosity, connectivity of pores, nature of the fluid, and metallic content of the solid matrix. Hence, mechanical properties (density, porosity, permeability); thermal properties (conductivity, diffusivity, thermal inertia); electrical properties (conductivity, apparent resistivity), elastic properties (bulk modulus, Poisson ratio), and petrophysical properties (p-wave and s-wave), have been studied for the various earth materials.

2.2.1 Contact Resistance Problem in Earth Materials

The constant underestimation of thermal properties of earth materials has been traced to the presence of thermal contact resistance, the exact magnitude of which was difficult to estimate especially under field conditions. This continued to be an area of persistent uncertainty for a long time. Advancement in technology led to the recommendation of thermal heat sink compounds with conductivity greater than 4 W/mK to reduce contact resistance errors. The situation, however, remained unclear between air-dry and saturated conditions. Hence, values of thermal conductivity (k) of glass beads, quartz sand, stone dust and clay were determined using a thermal probe with and without heat sink compounds (arctic silver grease (ASG) and white grease (WG)) at different water contents, bulk densities and particle sizes. The heat sink compounds (HSC) increased k at air-dry condition, thereby reducing the thermal contact resistance (TCR), but reduced values of k when water was added. The increase in values of k was higher with application of high-conductivity ASG than low-conductivity WG. The maximum percentage increase in k with application of ASG was 25, 118, 22 and 25 % in glass bead, quartz sand, stone dust and clay, as compared with increase of 10, 22, 23 and 22 % respectively for WG. The increase in k for 1 mm samples exceeded the increase in 2 mm samples. At water saturation, application of HCS on the probe did not change the values of k suggesting almost a non-existent TCR at such conditions {Akinyemi and Sauer (2007), Akinyemi et al. (2007b)}.

2.2.2 Electrical resistivity and permeability of limestone deposits in Ewekoro formation, South Western Nigeria

Physical parameters of limestone in Ewekoro formation, south-western Nigeria were determined via direct laboratory method. The permeability and bulk density values obtained range from 1.47 to 7.99 ms^{-1} and 1.26 to 1.90gcm^{-3} respectively. The resistivity values of the limestone samples collected from the study site were obtained by laboratory direct method and the result revealed that the resistivity values fall within 6 and 171 kΩm. These values correlate favourably with the results obtained from electrical resistivity method of geophysical prospecting of the study area. The two approaches showed a good degree of correlation in the resistivity value of the limestone and their varying qualities. This research work further showed the occurrence of vast deposit of limestone, which can be of economic importance in mining and for industrial purposes (Olurin *et al.,* 2012).

2.2.3 Density and porosity of rock samples

Knowledge of densities of rocks is essential in petrological and geological studies, interpretation of gravity anomalies and groundwater exploration. Fifty samples were collected from across the Local Governments in Ogun State and dry bulk density, saturated density, porosity and particle density were determined. Results showed that Ewekoro shale has the lowest mean density of 1.35 gcm^{-3} while Ibese limestone has the highest mean density of 3.9 gcm^{-3}. Porosity ranges from 0.030 to 0.640 with the granite in Odeda having the highest porosity and the shale in Ewekoro having the lowest porosity. Mean porosity for all the rocks samples in the seven Local Government Areas was 0.34. Test of significance revealed that there is significant relationship in the values of density of rock samples within the State (Akinyemi *et al.*, 2012b).

2.2.4 Permeability of riverbed sediments

Laboratory investigations involving riverbed sediments from Abeokuta, southwestern Nigeria, were carried out to investigate permeability which could potentially have useful and practical applications in many areas of geosciences and building technologies. Different dimensions of packed tubes were inclined at varying angles of tilt starting from horizontal flow. Samples were processed to ensure uniform grain sizes and porosity was determined volumetrically. Hydraulic conductivity was measured using the constant head method, which allows water to move through the soil under a steady-state condition while the volume of water flowing through the samples is measured over a period of time. Packed tubes were inclined at varying angles and pressure determined at predetermined positions along the tube using a digital pressure manometer. Discharge capacity increased with inclination angle, with the exception of horizontal flow, while the maximum discharge capacities increased with the lengths and diameters of tubes. Comparing the volume rate of flow with angles of flow at different tube dimensions revealed unique convergence points at which the discharge capacity and angles of inclination remained constant for all the samples. The points of intersection, however, varied with flow channel dimensions. The discharge capacity convergence point ranged from 0.3×10^{-9} to 0.5×10^{-9} m^3s^{-1}, while the angle of tilt convergence point ranged from 2.1° to 6.0°. Convergence angle of tilt and the convergence discharge capacity increased as the tube length increased from 0.25 to 2.0 m for channel diameters of 1.5 and 2.0 cm (Akinyemi *et al.*, 2012e).

2.2.5 Experimental investigation of factors affecting compressional and shear wave velocities in shale and limestone of sedimentary basin in southern nigeria

Compressional (Vp) and shear (Vs) wave velocities measurements were taken out on fluid-saturated shale and limestone obtained from the Ewekoro quarry of Southern Nigeria sedimentary basin at constant differential pressure of 50 MPa with porosities ranging from 0.32 to 0.53% and 0.01 to 0.35 for limestone and shale, respectively, while the volume of clay content C ranges from 0 to 60% and 0 to 40% for limestone and shale, respectively. Correlation coefficient for the velocities of clean samples and those with clay minerals ranged from 0.972 to 1.000 and 0.971 to 1.000, respectively, with limestone having the lesser for both. A very small amount of clay, about 0.21% and 0.23%, reduced the elastic modulus of limestone and shale, respectively. For water-saturated shaly samples, Vs was more sensitive to porosity and clay content than Vp. Consequently, velocity ratios (Vp/Vs) also showed a reasonable degree of correlations with clay content and porosity. For both limestone and shale studied, porosity is the most important parameter in reducing velocities followed by clay content due to the softening of its matrix. This study established that wave velocities are functions of porosity and clay content of porous shale and limestone of Ewekoro formations (Abatan *et al*., 2016).

2.2.6 Estimation of thermal inertia of abeokuta, ogun state, southwestern nigeria

Thermal inertia (I) is an important parameter in the Earth's thermal study. There is no doubt that correct and up-to-date knowledge of thermal inertia, particularly as it is affected by the land use/cover, will provide good and useful information to agriculturists and environmental scientists. In this work, thermal inertia of Abeokuta city of Ogun State, southwestern Nigeria, was determined. Map of the study area was gridded using 2-min resolution which gave 5 × 5 sampling points from where core samples were collected. Bulk density, thermal conductivity, and heat capacity of the samples were determined. The pattern of variation of the city view of I (in the order of $\times 10^{3} Jm^{-2} s^{-1/2} K^{-1}$) showed that the main urban built-up part of the study area, Abeokuta South, had the highest Imean, 0.76160 with standard deviation of 0.032547 and standard error of 0.01455541. The trend also varied along each sampling latitudinal line. It ranges between 0.509 and 0.756 on latitude $7°1^{2/}$, 0.557 and 0.768 on latitude 7° 12, 0.642 and 0.782 on latitude $7° 10^{/}$, 0.7 and 0.794 on latitude $7° 08^{/}$, and between 0.642 and 0.728 on latitude $7° 06^{/}$. Hence, we have estimated thermal inertia of Abeokuta using the thermophysical properties of the study area. Thermal inertia tends to gradually decrease with distance from the city centre (Abeokuta South). This result is promising in future consideration of urban ground heat energy conversion to other forms of energy (Kuforiji *et al*., 2017).

2.2.7 Temporal variation of ground surface temperature in an experimental field in Abeokuta, South-Western, Nigeria

Variation of temperature in the ground with time and depth from the surface is a natural phenomenon which affects most physical and chemical properties of soil. Records of soil temperature were obtained at five depths (2, 50, 100, 150, and 200 cm) below the surface of the earth at Akole, Abeokuta, between 1 January 2014 and 31 December 2014. The soil temperature varied from 27.75 °C at depth 200 cm to 29.9 °C at 2 cm. The diurnal temperature range for depths between 2 and 200 cm during the dry season was higher (about 18 °C) than that during the rainy season (about 12 °C).

The temporal variation of ground temperature from the surface at different depths was analyzed by Fourier technique, and thermal diffusivity was computed using amplitude and phase angles of the first three harmonics of the annual thermal wave. The coefficients of soil temperature obtained by Fourier analysis depict the impartial description of the variation with depth of the soil temperature waves. Among the three harmonics calculated, the first harmonic described soil temperature variation to 95.07% while the first two harmonics described the variation to 98.72%.

Further harmonics contribute insignificantly to the improvement of the variation. The annual damping depths of the study area calculated from the phase angle and amplitude angle and directly from daily average soil temperatures were 217.39, 227.27, and 217.90 cm, respectively. In the same vein, thermal diffusivity of the study area was found to be 5.1463×10^{-7}, 4.708×10^{-7}, and 4.7305×10^{-7} m2/s, respectively. The annual amplitude, the mean wavelength, and the phase displacement at the surface were 2.68 cm, 14.0 m, and 31.38 days, respectively (Alabi et al., 2017).

2.2.8 *Wave Velocity Variation with Temperature: Influential Properties of Temperature Coefficient of Selected Rocks*

The intrinsic compressional and shear wave's velocities of rocks decrease with increasing temperature. An important parameter that quantifies the temperature effect on rocks' wave velocities is the temperature coefficient (V/T), which is the gradient of the linear relationship between the wave velocity and temperature. This study investigated properties affecting the temperature coefficient of selected lithology in Ogun State Southwestern Nigeria. The samples were heated and the compressional velocities were measured at a constant pressure of 0.01 GPa and 50 °C intervals from 50 to 300 °C. The result showed that both elastic modulus and density varied directly with the absolute compressional temperature coefficient, Vp/T while porosity had an inverse variation. The elastic modulus, density, and porosity exhibited a notable effect on the temperature coefficient with their respective correlation coefficient as 0.98495, 0.97594 and 0.93787. Clay content, which also exhibited an inverse variation with the temperature coefficient, had a correlation coefficient of -0.44668. For both the same and different rock types, elastic modulus is the most important property that controls the temperature coefficient (Kuforiji *et al.*, 2021).

2.2.9 Interrelatedness of geotechnical and petrophysical properties

Geophysical investigations involving electrical resistivity and seismic refraction surveys were carried out on traverses connecting previously geotechnically sampled points in the vicinities of buildings pre-identified to be exhibiting foundation failures in Lagos.

Resistivity profile lines were conducted with the aid of PASI 16GL-N resistivity meter using Wenner and Schlumberger arrays to obtain 2D and 1D models, respectively. Seismic profiling was done with a 24-channel ABEM Terralock Mark 6 seismogram using 5 kg sledge hammer as energy source based on the split-spread configuration.

The refraction survey was carried out using 4.5-Hz geophones on 30 traverses to develop s-wave velocity models. CT 130 Pundit 200 UPV instrument containing two p-wave 54 kHz transducers and two s-wave 40 kHz transducers was deployed to measure the compressive and shear wave velocities (Vp and Vs) of the samples. Spatial maps were then developed for all the measured parameters in the whole of Lagos State (Figures 8 and 9).

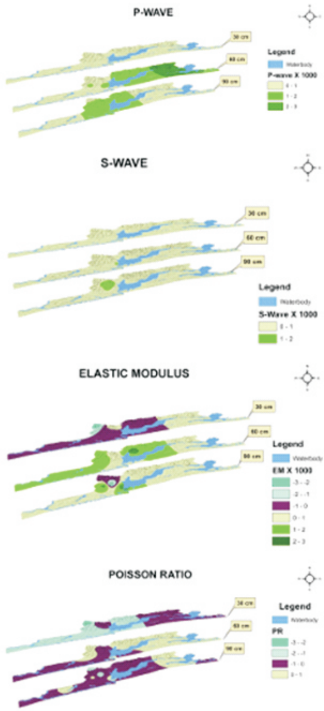

Fig. 8: Spatial Map of Petrophysical Parameters in Lagos

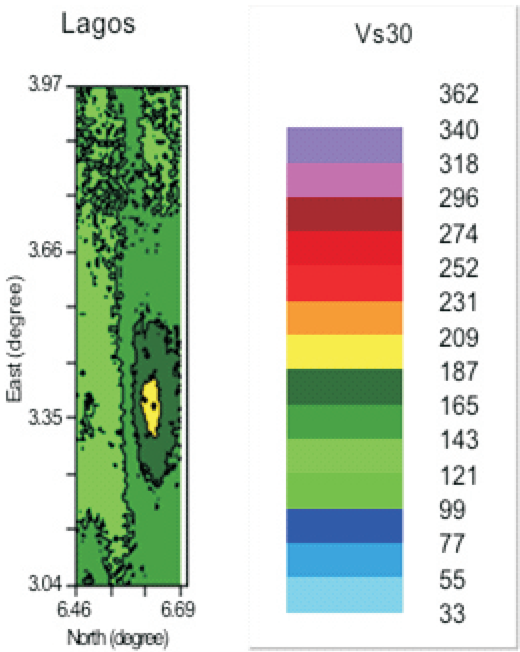

Fig. 9: Spatial Map of V_s30 in Lagos

Field-based topsoil (V_s1m) shear wave velocity was extracted for Ikorodu, Ebute Meta, Ikeja, Lagos Island, and Ifako Ijaye for the purpose of comparing with corresponding laboratory-based values. In similar vein, topsoil electrical resistivity was extracted for the same locations with corresponding inferred lithology for the purpose of comparison and validation. Degree of correlation of V_p/V_s with porosity (Φ), sand fraction (S), clay fraction (C), unconfined compressive strength (U), and California bearing ratio (*R*) followed order Φ > S > C, and U > R. Trend correlation of shear velocity showed good agreement ($R^2 = 0.992$) between laboratory-based and field-based data though an amplification factor of 4.13 separates the corresponding values. Lithology determined from soil analysis showed good agreement with that inferred from the electrical resistivity, and trend correlation of shear velocity showed good agreement ($R^2 = 0.992$) between field and laboratory observations (Akinyemi, 2022).

2.3 Contaminant Transfers within the Subsurface

Contaminants in groundwater can move in different ways depending on the type of contaminant and the characteristics of the aquifer. The movement of contaminants in groundwater is influenced by two primary mechanisms of advection and dispersion.

Advection is the movement of contaminants with the flow of groundwater, while dispersion is the spreading of contaminants due to the mixing of groundwater. The rate of contaminant movement in groundwater is dependent on several factors, including the hydraulic conductivity of the aquifer, the concentration of the contaminant, and the distance from the source of the contaminant. Groundwater contamination can have serious environmental and health consequences. It is important to monitor and manage groundwater resources to prevent contamination and protect public health.

2.3.1 *Numerical models in groundwater flow*

The movement of sediments in aquifers was studied in order to explain the migration and fate of contaminants in groundwater. Firstly, a numerical model to describe the migration and fate of contaminants in groundwater was developed. Secondly, a numerical model was then developed to explain the effects of sediment size and depth on the movement of groundwater in an open channel bend system which is a condition in which liquid flows with a free space subject to atmospheric pressure. Thirdly, empirical equations were derived for determination of flow directions of shallow aquifers. The sensitivity analysis revealed that the performance of the models was dependent on some critical physical parameters{Akinyemi *et al*. (2003, 2008d), Awokola ***et al***. (2014), Olowofela and Akinyemi (2001)}.

2.3.2 Stability Analysis of Numerical Schemes in Seismic Imaging

Seismic images are affected by amplitude and phase fluctuations of waves travelling through heterogeneous media. As such waves move through elastic medium they suffer from attenuation of seismic energy, the attenuation rate being the sum of the redistribution of seismic energy and the conversion of seismic energy into heat. A finite difference scheme is produced when partial derivatives in the partial differential equation(s) governing a physical phenomenon like the propagation of seismic waves through real media are replaced by a finite difference approximation. Stability of a numerical scheme like that of finite difference scheme in the solution of partial differential equations is crucial for correctness and validity and it means that the error caused by small perturbation in the numerical solution remains bound. Hence, the stability analyses were carried out using the amplitude and phase portrait (Olowofela *et al*., 2015, 2017a).

2.4 Prospecting for Desirable Resources within the Subsurface

Geophysics relies on the principles of Physics to study the earth through the measurements, collection and analysis of physical properties at or near the ground surface (Tables 1 and 2). It involves the use of electrical, seismic, gravity, magnetic, and electromagnetic methods towards:

a. delineation and exploration of physical resources, including aquifers, within the earth subsurface system;
b. determination of underground contaminant pathways and salinization routes for ground water protection;
c. characterization of heat transfer within the earth **systems;**

d. identification and mapping of geological structures and subsurface lithology;
e. characterization of leachate spread from landfill and buried waste dumps including chemical and nuclear wastes;
f. landslides, ground subsidence, earthquake, and earth tremor studies, and
g. general environmental safety.

Table 1: Applications of Geophysical Methods (*Fowler, 1996*)

Method	Measured parameter	"Operative" physical property	Application
Gravity	Spatial variations in the strength of the gravitational field of the Earth	Density	Fossil fuels Bulk mineral deposits Construction
Magnetic	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility and remanence	Fossil fuels Metalliferous mineral deposits Construction
Seismic	Travel times of reflected/refracted seismic waves	Seismic velocity (and density)	Fossil fuels Bulk mineral deposits Construction
Electromagnetic (SeaBed Logging)	Response to electromagnetic radiation	Electric conductivity/resistivity and inductance	Fossil fuels Metalliferous mineral deposits
Electrical -Resistivity -Self potential	 Earth resistance Electrical potentials	 Electrical conductivity Electrical conductivity	Widely used
Radar	Travel times of reflected radar pulses	Dielectric constant	Environmental Construction

Table 2: Geophysical Techniques for Mining Investigations (*Fowler, 1996*)

Geophysical Techniques for Mining Investigations			
Method	Sensitive To...	Typical Applications	Advantages
Seismic Refraction	Changes in strata type (soil, weathered rock, rock), rock quality (jointed, weathered), elastic properties	Rock interface, overburden mapping, rock quality, degree of weathering/ jointing, faults, fracture mapping	Excellent method for rippability assessment, stratigraphy.
Resistivity Imaging/ Electrical Resistivity	Moisture content variations, conductivity, water table, porosity, chargeability	Sulphides, some oxides, mapping of geological structures, groundwater, engineering & environment	Excellent method for ore body mapping, and water table mapping.
Induced Polarization	Polarisability/ chargeability	Sulphides, some oxides, particularly disseminated ores like porphyry copper deposits, ground water & environmental problems	Excellent method for mineral exploration in case of disseminated ores.
Gravity Surveys	Changes in density of the material	Mapping of ore bodies having significant difference in density compared to host material	Excellent tool for chromite, manganese, barytes etc. Also used for buried channels, folds, faults etc.
Magnetic Surveys	Difference in magnetic properties of the material	Mapping of ore bodies based on magnetite content in ore	Excellent tool for iron ore mapping
Seismic Reflection	Difference in acoustic impedance (velocity x density)	Detects interfaces, maps faults/ fractures/ water lenses/ shear zones along tunnel routes	Excellent tool for coal bed mapping
Ground Penetrating Radar	Change in dielectric properties	Detection of buried pipes and cables, with exact location and depth. Also used for inspection of concrete structures.	Avoids costly mistakes (foundation over pipe)/ accidents/ damage to utilities

2.4.1 Mapping of saline water intrusion in coastal environments

Rainwater has a lower specific gravity than saltwater, hence it stays afloat on top of the saltwater. Moreover, because of weight, it will gradually depress the surface of the saltwater, creating a convex lens-shaped region of fresh-water. Saltwater intrusion can naturally occur in coastal aquifer in two ways:

a) owing to the hydraulic connection between groundwater and seawater, and because saline water is denser than freshwater and has a higher water pressure, it can push inland beneath the freshwater, and

b) can move on-land when sea level rises and storms surge.

The seasonal variation of saltwater intrusion in coastal areas was studied using an integrated approach of electrical resistivity tomography (ERT) and groundwater physicochemical analysis. The ERT survey was completed with 22 profiles using dipole–dipole array method covering seven major communities east of Lagos. The field survey was carried out between August 2016 and March 2017 with a minimum electrode spacing of 2.5 m. The inverted model generally revealed a resistivity range of 1.0 – 100,000 ? m delineated through a depth range of 37 – 197 m. The model obtained for Imakun-omi, Irokun, Isekun, and Ode-Omi revealed significant impact of saltwater intrusion from nearby lagoon, sea, or creeks indicated as low-resistivity structures generally below 20 ? m. The intrusion became more pronounced during the dry season due to decrease in groundwater level associated with low precipitation and possibly aggravated by high rate of groundwater extraction. Groundwater physicochemical analysis obtained in the study area supported the ERT survey which indicated the aquifer contamination status of the communities {Fasunwon *et al*. (2005), Badmus *et al*. (2021)}.

2.4.2 Depth to basement characterization

The digitized aeromagnetic data for some parts of the sedimentary basin and basement complex in the Southwestern Nigeria was used to conduct structural analysis and investigate a relationship between basement and intra–sedimentary structures present in the area. The aim was to investigate the location of the magnetic anomalies within the subsurface in form of variation in the observed magnetic field from the differences in the magnetic properties of the underlying rocks or some other sources. Hence, we determined the basement depth, basement morphology, relief and the structural features associated with the subsurface. The magnetic intensity distributions and depths to magnetic sources were generated across the Southwestern Nigeria with a view to estimating burial depth and the thickness of the low susceptibility superficial material overlying the magnetite crystalline rocks {Fasunwon *et al*. (2007), Olowofela *et al*. (2012), Ganiyu *et al*. (2013), Olowofela *et al*. (2013), Badmus *et al*. (2013a), Olurin *et al*. 2015a,b)}.

2.4.3 *Iimaging and mapping underground contaminants spread from landfill sites*

Originating from medical imaging to image organs of interest, Electrical Impedance Tomography (EIT) is a non-invasive tomography technique to exploit the differences in the passive electrical properties of targeted object and generate tomographic images (Metheral, 1998). The Electrical Impedance Tomography involves the injection of current into a body using circular electrode arrangements or configuration patterns to image the internals of the medium under investigation. The technique allows the generation of two or three-dimensional images of electrical conductivity for a given profile or volume of ground known as electrical images or tomograms, and we then applied it to landfill sites due to its sensitivity to high electrical contrasts as caused by changes in material types, fluid saturation and ion concentration levels since most waste fluids are highly conductive due to their elevated ion concentrations. Investigation was carried out on the Abule Egba (21-ha established in 1982 in Agbado-Oke-Odo LCDA), Solous-1 (7-ha in Alimosho LG), and Solous-2 (4-ha in Alimosho LG) dumpsites in Lagos State. The dumpsites were all surrounded by residential, commercial and industrial buildings. In some cases we found out that the leachate contaminant plumes had migrated about 50 to 100m away from the base of the dumpsite {Olowofela *et al*. (2012a,b), Folarin *et al*. (2023)}

2.4.4 Mineral exploration

Data acquisition was carried out along Oyan river bank with a total of twenty-three (23) Vertical Electrical Soundings (VES). This location was divided into two zones: VES 01 to 09 and VES 10 to 23. Rock samples hosting specks of tantalite, tourmaline and beryl were collected from the artisan pits within the study area and taken for geochemical analysis in the laboratory. The result of geochemical analyses revealed the quality of the solid minerals in terms of mineral compositions (major, trace and rare earth elements) while geophysical field measurement revealed the resistivity values, vertical and lateral distributions and depth of the solid minerals. The range of electrical resistivity values of these solid minerals as revealed by laboratory measurement is 19.4 - 31.1? m while that of the host rock is 10.0 – 100.0 ? m as obtained from field measurements. Specks of tantalite, tourmaline and beryl were suspected to be sparsely distributed in other VES locations except at VES02 and 09, where vast deposits were suspected. Two litho-facies changes were observed and this revealed the economic values of these solid minerals. Black tourmalines, beryl and tantalite samples collected as specks within the study area were of low quality while pink tourmaline is of moderate quality on the basis of the chemical constituents contained {Akinyemi *et al*. (2012a), Badmus *et al*. (2013b)}.

2.4.5 *Lithological profiling and groundwater vulnerability*
The Ibese and Ewekoro groundwater systems were sampled to determine the pollutions vulnerability arising from limestone mining and cement producing industrial activities. The pollutants were particulate matter depositions and the total volatile organic compounds in the air, the activity concentrations of the naturally occurring radioactive materials in the soils, and the heavy metal concentrations in the soils and water. The lithology consisted of strata of less permeable materials, intercalated with sand/lime stone in some parts (Table 3), with resistivity, depth to top, and thickness of the layer ranging from 3.66 to 90.7 ? m, 0 to 26 m, and 0.5 m to infinity and 13.4 to 47.5 ? m, 0 to 0.5 m, and 0.5 m to infinity, respectively.

Table 3: Protective Layer Descriptions in Ewekoro and Ibese Communities

Community	VES number	Protective layer	Resistivity (Ωm)	Layer position	Layer thickness (m)	Depth to layer (m)
Ibese group						
Afami	VES1	Clay	28.3, 21.5	1st, 3rd	1.41, infinity	1.41, 3.96
	VES2	Clay	60.9, 21.3	2nd, 4th	0.9, infinity	0.5, 3.95
Ajibawo	VES1	Clay	70.1	3rd	Infinity	1.89
	VES2	Clay	76.4	3rd	Infinity	6.53
Abule oke	VES1	Clay	90.7, 46.9	1st, 3rd	0.5, 3.2	0, 1.1
	VES2	Clay	74.5	2nd	5.28	1.9
Balogun	VES1	Clay	40.8, 33.2, 10.6	1st, 2nd, 4th	0.8, 1.59, infinity	0, 0.8, 10
	VES2	Clay	33.9, 32.9	2nd, 4th	1.39, infinity	0.5, 26
Ibese	VES1	Shale	6.52, 3.66	2nd, 3rd	5.8, 20	1.89, 7.69
	VES2	Shale	11.6, 4.01, 7.43	2nd, 3rd, 4th	3.56, 5.27, infinity	1.65, 5.21, 10.48
Ewekoro group						
Lapeleke	VES1	Clay	28.4	2nd	2.25	0.5
	VES2	Clay	29.4	2nd	2.7	0.5
Akinbo	VES1	Clay/shale	47.5, 37.6, 13.6	1st, 2nd, 3rd	0.5, 2.89, infinity	0, 0.5, 3.39
	VES2	Clay/shale	46.4, 38.5, 13.8	1st, 2nd, 3rd	0.5, 2.77, infinity	0, 0.5, 3.27
Ewekoro	VES1	Clay	25	1st	1.44	0
	VES2	Clay	32.7	1st	1.44	0
Itori	VES1	Clay	15	1st	2.37	0
	VES2	Clay	13.4	1st	2.67	0
Elebute	VES1	Clay	28.4	2nd	2.15	0.5
	VES2	Clay	30.4	2nd	2.9	0.5

The ground water vulnerability was estimated using the modified overlay–index method based on the assumptions and nature of the investigated site. Owing to the size of the investigated sites, in addition to physical observations, net recharge, aquifer media, topography, impact of vadoze zone media, and hydraulic conductivity of the aquifer were assumed to largely uniform around the two groups of communities. The thickness of clay was used to substitute for the soil media, while the depth to infinity top was used to substitute for the depth to the water table. Hence, the modified drastic index (mDRi) was computed and categorized into classes A (1 to 11), B (12 to 20), and C (21 to 30). The Balogun community was categorized as class A vulnerability index; the Afami, Ajibawo, Ibese, Akinbo, and Ewekoro communities as class B; and the Abule-Oke, Lapeleke, Itori, and Elebute communities as class C, where C > B > A with regard to vulnerability concerns. The mDRi values were generally low, but given that only two out of the seven DRASTIC components were factored while others were assumed to be uniform, classes B and C, which reflected higher pollution indices, showed more vulnerability concerns, and this will provide useful information towards environmental management and mitigation purposes {**Olowofela *et al*. (2017), Akinyemi *et al*. (2022), Akinyemi *et al*. (2023a)**}.

2.5 Forensic Investigation of the Surface

A land mine is an explosive device concealed under or camouflaged on the ground, and designed to destroy or disable enemy targets, ranging from combatants to vehicles and tanks, as they pass near or over it. Such a device is typically detonated automatically by way of pressure when a target steps on it or drives over it, although other detonation mechanisms are also sometimes used. They usually contain little amount of metal to evade metal detectors. This forensic science includes study, search, localisation, and mapping of buried objects or elements beneath the soil or the water using geophysics tools for legal purposes**.** The objects include weapons, energetic materials (TNT, RDX, HMX), cash, human beings, jewelleries, graves, bones, archaeological materials etc. Thermal imagers exist now but they are unaffordable because of cost.

2.5.1 *Improvised thermography for sensing buried objects*

Metals, wood, plastics, and graphite of different dimensions (12cm × 12cm × 0.5cm and 12cm × 12cm × 3cm) were buried at depths ranging from 1 to 50 cm. Temperature was measured directly above each of the materials, somewhere else without buried objects but at the same depths, and at the surface. There was a remarkable phase shift which increased with burial depth. A change in burial depth of steel from 1 to 10 cm caused the maximum positive peak to shift from 46.5 to 38.0°C and a change in burial depth from 40 to 50 cm caused the maximum peak to shift from 30.0 to 29.0°C. The burial depth of the buried objects has effect on the amplitude of the temperature at the surface and thus its thermal signature. It was also observed that the thickness of the buried objects has a significant effect on its thermal signature (Figures 10 and 11). The experiment was carried out under different environmental conditions best performance was obtained in less humid areas (Olowofela *et al*., 2010a, 2010b).

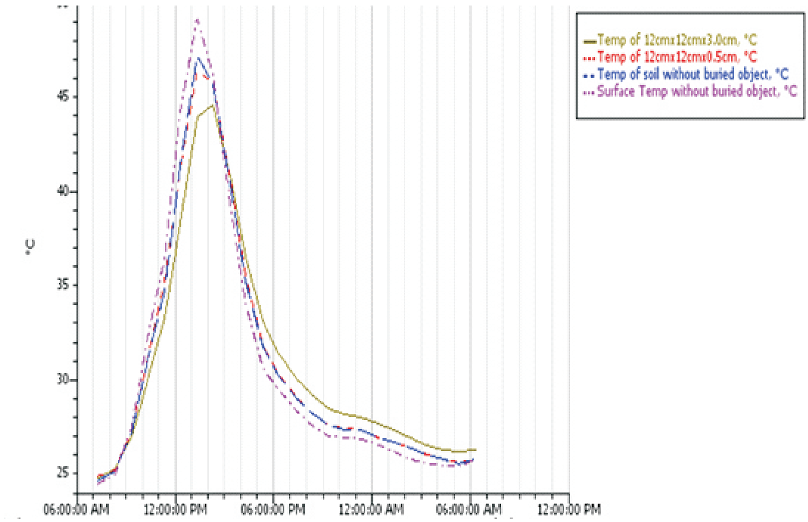

Fig. 10: Thermography of Buried Steel at 1cm

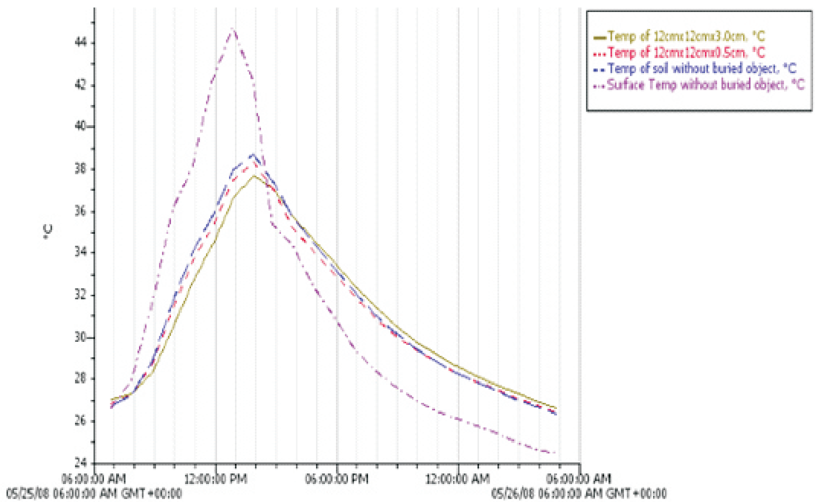

Fig. 11: Thermography Fingerprints of Buried Steel at 10 cm

2.5.2 Sensing buried metallic objects in porous media using attenuation coefficients

Ground Penetrating Radar (GPR) uses the technique of sending electromagnetic waves into the earth and records the energy that is reflected back from materials located under. They are almost inexistent in this part of the world because of their cost, and they work best in smooth areas with constant elevation. Hence, experiments were carried out to improvise a GPR to determine the Q-factor of electromagnetic signals passing through sediments with buried objects while Lissajous figures generated at different frequencies were analysed to assess the impacts of the objects with a view to determining their Q-factor fingerprints (Figure 12). Q-factor is the attenuation characteristic or fractional loss of energy per cycle expressed as a function of change in amplitude of the signal after passing through a medium. Study showed that buried objects have distinct and unique attenuation characteristics almost irrespective of the porosity of the surrounding medium (Akinyemi *et al.*, 2013b).

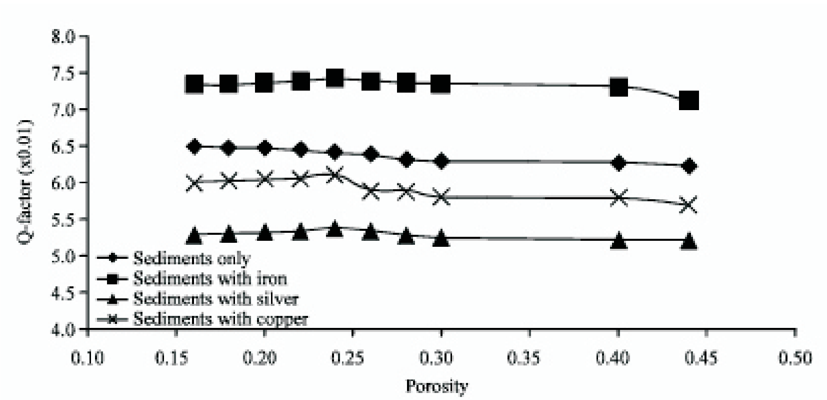

Fig. 12: Q-Factor Fingerprints of Buried Metals

2.6 Other Major Contributions

Apart from the contributions earlier discussed, there are other significant achievements in terms of models, methods, and manpower development.

2.6.1 A new heat flux plate

Accurate measurement of heat flux is essential to optimize structural and process design and improve understanding of energy transfer in natural systems. Hence, a new perforated heat flux measuring device was developed by a team in France and evaluated in Nigeria and USA through collaborative experiments {S*auer et al. (2008a, 2008b)}. The plate was designed to reduce heat flow distortions for environmental applications.*

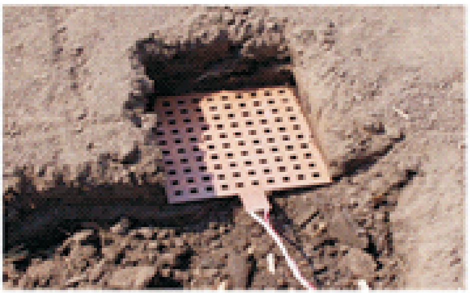

Figure 13 A New Thermal Properties Analyzer

In modelling the thermal behaviour of materials, accurate determination of thermal properties is quite imperative. However, thermal properties analyzers are usually very expensive and unaffordable. Hence, a simple and inexpensive thermal properties analyzer was achieved in collaboration with a team in Nigeria and Canada {Fasunwon *et al*. (2008a)}.

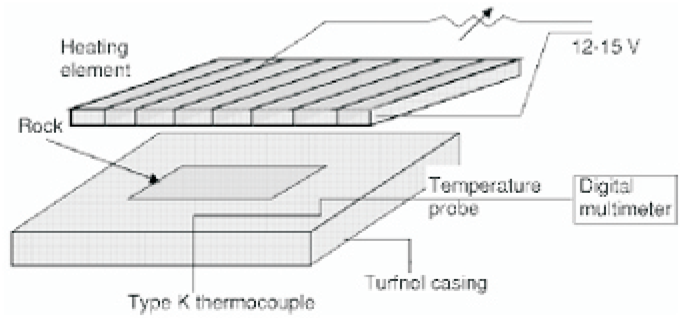

Figure 14 A New Modified Thermal Block

Thermal properties are usually the key parameters governing heat transfer through earth materials. Thermal block was previously conceptualized in the earth science community but later discontinued due to accuracy concerns. Hence, arising from the collaborative efforts between our Nigerian research team and a USA-based research team, the thermal block concept was revisited and modified to address the accuracy concerns {Akinyemi *et al*. (2011 2012a, 2012f, 2013a)}.

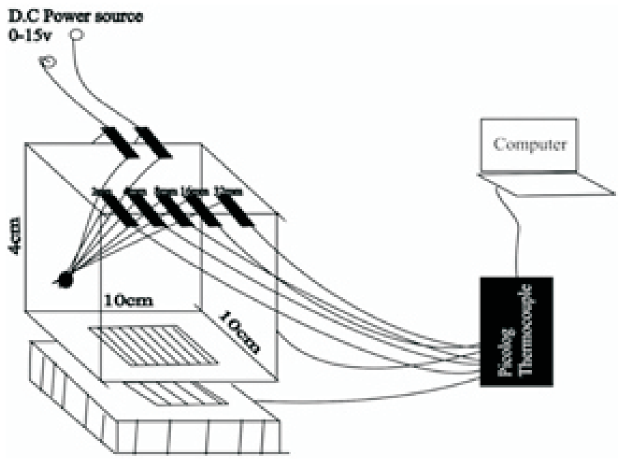

Figure 15 A New Modified Thermal Block

2.6.2 *A new method for determining the aggregate pollution index*

There was a very scanty information in the literature, prior to now, on the aggregate pollution index as an indicator to describe the overall effects of pollutants in the different media. Hence, our team developed a novel method to aggregate groundwater, surface water, soil, and air pollutions to serve as basis for environmental comparison between geographical locations {Akinyemi *et al*. (2023b)}.

2.7 Human Resources Development

I have supervised nine PhDs to completion. They include: Onifade, O., Abatan, A., Alabi, A., Kuforiji, I., Adeyeye, J., Badmus, O., Dami-Adekunle, A., Ogundeji, T., and G. Odimgbe.

I have equally supervised eight M.Sc to completion and several undergraduates.

Additionally, I have co-supervised other PhDs and M.Sc to completion including Prof. R. Bello, Prof. O. Ogungbe, Dr. O. Olurin, Dr. F. Akinboro, and Dr. O. Ajani.

3.0 CONCLUSIONS

Finding easier ways to unravel the complex interactions within the bowels of the earth is increasingly becoming important, not just because of the enormous resources lying beneath, but also because of the threats of contamination, as well as the danger of human clandestine activities. A major concern is getting the right mix of expertise and available resources to continue to carry out non-invasive studies. In the course of my non-invasive voyage into the subsurface domains, I have had the rare privilege of working with some of the best minds, either as mentors or collaborators. I have worked in some top-notch laboratories but there are some of my collaborators that I have never met face-to-face even after many years of close collaborations. The implication is that the whole research community does not need to relocate before collaborating.

As part of the strategic contribution to the development of manpower that will continue to expand the knowledge frontiers in the critical areas, I have had the opportunities of working with very reliable mentees in the Universities, Polytechnics, Military, and other relevant private institutions. Knowledge of the quantity of heat and water fluxes within the subsurface has always been of primary importance to a large chain of stakeholders operating in the earth space. Earth science is a vast area that requires constant monitoring of activities through very expensive large observation systems, hence, a multidisciplinary approach, through harnessing the power of simulation and field experiments, will be a viable alternative. Hence, my research has focused on developing new numerical models that can easily and accurately describe the complex dynamics of the coupled movements within the subsurface. In addition, new methods and new measuring devices that are simple, affordable and easy-to-use have been developed for the purposes of earth observations.

Finally, the earth system is one critical entity through which all other research areas within the field of science revolve, hence, there must continue to be decisive and deliberate efforts, from policy makers and researchers, to ensure its survival. The earth may not need us to survive, but we surely do need the earth to survive. Therefore, let us do our part and let God do what only He can do.

4.0 RECOMMENDATIONS

a. Multidisciplinary research groups need to be constituted from economics to mathematics, from physics to animal physiology, from mechatronics to plant breeding. That is the way to go now even as a nation.

b. Solution room (ideation room) should be encouraged where people from different backgrounds (including students) meet to constructively interrogate research ideas with a view to come up with practicable solutions.

c. We will continue to appreciate the Tertiary Education Trust

Fund for coming up with Institutional-Based Research funds, with a maximum of 2M, and the National Research Fund, with a maximum of 50M. However, there may be the need to consider special funding for multidisciplinary projects to the tune of 500M (400,000.00 USD) with a bid to frontally address some high-magnitude national challenges.

d. The College of Earth Sciences, where all related disciplines can be warehoused, in the Federal University of Agriculture Abeokuta is overdue. There is the need to consider this as a matter of priority.
e. It has become absolutely necessary for targeted funding of exploitation of geothermal energy potentials in Nigeria as a viable energy alternative.
f. Exploration of underground natural resources in Nigeria needs to be better coordinated with more robust frameworks and appropriate legal instruments.
g. The military needs to collaborate with researchers from both military-and non-military institutions to help in addressing subsurface forensic detections.
h. There is the need for the government to abolish indiscriminate and unprofessional siting of refuse dumps and encourage properly sited landfill sites.

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'This is my story, this is my song, praising my Saviour, all the day long, this is my story, this is my song, praising my Saviour, all the day long'

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