ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of GeographyVol 55, No 1 (2023): 41-50
DOI: 10.22146/ijg.56539 website: https://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

RESEARCH ARTICLE

Determination of Groundwater Flow Pattern in the basement complex terrain of Ado-Ekiti, Southwestern Nigeria

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Received : 2020-06-01
Revised: 2020-07-26
Accepted: 2023-01-23

Keywords: dumpsite; flow direction; groundwater head; leachates; water table

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Abstract. Hydrostatic level sampling, geo-referencing and Geographic Information System were employed to delineate the major groundwater recharge / discharge zones, the groundwater flow direction and the groundwater divides in Ado-Ekiti metropolis with the objective of groundwater resource protection. Static water level measurements were made from 108 hand – dug wells evenly distributed on a regional basis. The latitudes, longitudes and elevations above mean sea level of the well points were measured using the Global Positioning System. A mean value of 5.84 ± 2.35 m above mean sea level was observed for the depths to the static water level with a mean value of 408.27 ± 46.06 m above mean sea level for the groundwater head. The contour maps obtained enabled the delineation of the major groundwater recharge / discharge zones, the groundwater flow direction and the groundwater divides with the regional tendency of the underground flow approximately lying along the Northwest – Southeast direction and groundwater divides along the South – Eastern/ South – Western axes of the Central portion. Strict environmental ethics must be enforced around the groundwater recharge / discharge zones and flow directions in order to avoid groundwater contamination.

1. Introduction

The water needs of the residents of the ancient city of Ado-Ekiti, Southwestern Nigeria, are mainly met by tapping groundwater from hand-dug wells often susceptible to surface pollutants (Oyedele, 2009; Dada *et al.*, 2911; Awopetu & Baruwa, 2017). The top of the water surface in the saturated part of an aquifer, the water table, varies in depth according to local topography and prevailing climate. It may be deep or shallow and may rise or fall depending on such factors. The water table may fall as a consequence of an extended period of dry weather. On the other hand, heavy rains may cause the water table to rise. The depth is generally established by a long term balance between recharge and seasonal climatic fluctuations (Oseji *et al.*, 2009; Taiwo *et al.*, 2011). Water is exclusively a basic need for living things and a source of life for humans (Zahra & Putranto, 2021; Daramola *et al.*, 2022).

Most local groundwater supplies in Ado-Ekiti comes from an unconfined aquifer made up of loose soil materials such as sands, gravels, and floodplain deposits with varying clay content and degree of saturation. Unconfined aquifers or water table aquifers are often shallow and frequently overlie one or more confined aquifers. Being the uppermost aquifer, they are recharged through permeable soils and subsurface materials above the aquifer. Inherently, groundwater could be prone to contamination from anthropogenic activities. Groundwater pollution is anticipatory in most developing countries as a result of increased anthropogenic activities apart from possible natural pollutants (Talabi and Kayode, 2019; Bon *et al.*, 2021). Often, hydrochemical processes, nature of the aquifer media and high precipitation will influence the interplay (Oyedele *et al.*, 2019; Popoola *et al.*, 2020; Lachassagne *et al.*, 2021). Human activities often trigger surface pollution and gradually affect the subsurface, including groundwater (Zahra & Putranto, 2021).

Talabi (2016) reported on the Hydrochemistry and Sanitary Risk Assessment of Domestic Hand-Dug Wells in some parts of the study area, Ado Ekiti. The study cautioned on the risk of contamination. High concentrations of NO^{3-} and Cl^- as well as presence of *Escherichia coli* (*E. coli*) in the water indicated pollution from anthropogenic sources related to human and animal wastes. Deductions from Oyedele *et al.* (2019) revealed the imprints of natural weathering, ion-exchange processes and anthropogenic activities on the groundwater quality in the study area. Šrajbek *et al.* (2022) traced the degradation of groundwater quality globally to incessant and intensive anthropogenic sources particularly with the growth of the human population. The study underlined the need for groundwater protection.

The overall dependence on groundwater as the common water source in Ado Ekiti for both domestic and drinking purposes mandates its protection especially from contamination induced by soil particles eroded during heavy downpours on which water-impairing substances like nitrates and phosphates are washed into the wells (Tinuola & Owolabi, 2007; Taiwo *et al.*, 2011; Nowbuth *et al.*, 2012). Access to safe drinking water for every individual regardless of the economic and social status is one of the main objectives of the World Health Organization (WHO). Large portions of the populace in developing countries die annually as a result of water-borne diseases such as cholera, typhoid, hepatitis, diarrhea, etc (WHO, 2008).

Sustainable groundwater management must emphasize prevention of contamination. The contaminant load introduced into the soil-rock-groundwater system will spread within the system with the availability of a transport mechanism. Hendrayana *et al.* (2021) emphasized the need to protect groundwater resources. The study made apt recommendations for groundwater management including environmentally sound groundwater use. It is noted that remediation is often very expensive and perhaps impractical. Prevention of contamination is hence critical in effective groundwater management (Adekeye & Ishaku, 2004; Gbadebo *et al.*, 2010; Ishaku *et al.*, 2015). Indiscriminate solid waste disposal, effluent management and similar challenges in Ado Ekiti metropolis account for the need to study the groundwater flow pattern to forestall regional groundwater pollution since contaminants generally move in the direction of groundwater flow (Ige & Adetunji, 2014; Talabi & Kayode, 2019; Bon *et al.*, 2021). Prediction of the movement of contaminants through the local groundwater system could then be made.

Analysis of groundwater flow system connecting recharge and discharge areas is vital in land-use planning and management. It is imperative to know the direction of groundwater flow and ensure that land use activities in the recharge area will not constitute any threat to the quality of groundwater (Oborie & Nwankwoala, 2017; Zahra & Putranto, 2021). The total driving mechanism of groundwater flow as embodied in Darcy's Law is well documented in literature. It is established that a hydraulic gradient must exist for groundwater to flow (Amah & Agbebia, 2015; Bon *et al.*, 2021; Lachassagne *et al.*, 2021).

Šrajbek *et al.* (2022) developed a groundwater flow model in the study of groundwater Nitrate Pollution Sources for a Contaminated Wellfield. The work entailed a simulation of nitrate pollution propagation by advection and dispersion processes. The simulation results demarcated the anthropogenic point sources and the influence area of the wellfield. Oborie and Nwankwoala (2017) generated a water table contour map of Yenegoa metropolis with respect to the variation in static water level from which the major and minor flow directions were delineated. The main forces affecting groundwater movement were attributed to gravity and external pressure due to pumping.

Contamination of shallow wells with fecal matter presents a grave public health threat in developing countries, where large numbers of households rely on shallow groundwater for domestic utilization. Efforts are made in this paper to map the groundwater convergent/divergent zones and direction of groundwater flow/flow pattern using fundamental hydrostatic measurements. The research work is driven by the increased concern for the quality of groundwater in a typical hard rock terrain.

2. Methods

Ado-Ekiti, Fig. 1, is located within latitude 7° 33' and 7° 42' N and longitude 5° 11' and 5° 20' E, Southwest, Nigeria. The topography of the area is fairly rugged due to the presence of crystalline basement rocks like charnockite and quartzite ridges which rise abruptly above the surrounding country rocks (Fig. 2). The occurrence of groundwater in the Basement Complex terrain is localized and confined to weathered/fractured zones. The area is drained by River Ireje, Elemi, Omisanjana and Awedele Stream (Ebisemiju, 1993; Ige & Adetunji, 2014).

Numerical models of groundwater flow are now common techniques used for water resource management. Determination of the direction of groundwater flow has been accomplished using the steady-state finite difference model (MODFLOW software). However, effective simulations require many data and a comprehensive explanation of the flow arrangement (Bon *et al.*, 2021; Pande *et al.*, 2022; Šrajbek *et al.*, 2022). Application of geoelectric sounding results in areas where there is little or no well from where hydrogeologic measurements could be made, has been deployed to determine groundwater flow direction.

Conducting geolectric measurements on a regional basis is admittedly not cost effective. Interpretation of data demands expertise to avoid ambiguities (Olorunfemi *et al.*, 1999; Adeyemo *et al.*, 2014; Arsène *et al.*, 2018). The method of determining the direction of groundwater movement by measuring the elevation of groundwater at multiple locations over the aerial extent of an aquifer has been widely acknowledged (Hendrayana *et al.* (2021). Unlike other methods, hydrostatic measurements offer *in-situ* data in groundwater investigations. This methodology has been adopted for this work (Messene, 2017; Oborie & Nwankwoala, 2017; Bon *et al.*, 2021).

The study commenced with a reconnaissance survey. Existing base maps (topographical and geological maps) of the study area were examined. It also entailed studying the drainage pattern and groundwater utility distributions within the area. In the course of obtaining permit, interviews were conducted with residents to secure copious and first - hand information. The information gathered was subsequently used to prepare the fieldwork layout map.

The research outline entailed hydrostatic level sampling, geo - referencing and application of GIS to prepare thematic maps upon which interpretations were based. The static water level measurements were made from 108 hand - dug wells evenly distributed within the study area on a regional basis (Fig. 3). The average sampling distance between successive well points was 500 m. This was however constrained by accessibility. The depths to the static water level were measured using steel band tape. Global Positioning System was employed to measure the latitudes, longitudes and elevations above mean sea level at the well locations. The acquired hydrostatic levels were used to obtain the groundwater head values, which were plotted to generate the groundwater head contour map for the study area using GIS facilities (Fadahunsi, 2010; Singh *et al.*, 2013; Messene, 2017).

The resulting hydrologic maps paved way for the interpretation of the groundwater flow pattern of aquifer regimes, as expressed by the water table elevations contour (groundwater head values or the hydraulic head). The groundwater divergent/convergent zones (or groundwater recharge/discharge zones) and direction of groundwater flow were delineated from the distribution pattern (Dai *et al.*, 2001; Oseji *et al.*, 2009; Oborie & Nwankwoala, 2017). The flow chart of the methodology is presented in Figure 4.

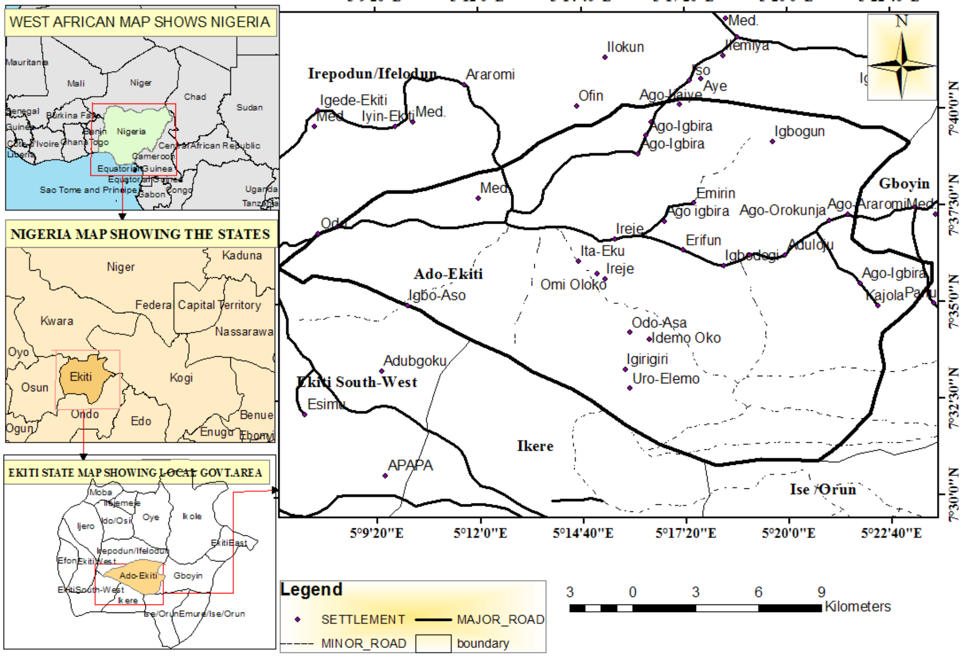

Figure 1. Location map of Ado-Ekiti - the study area (adapted from google map)

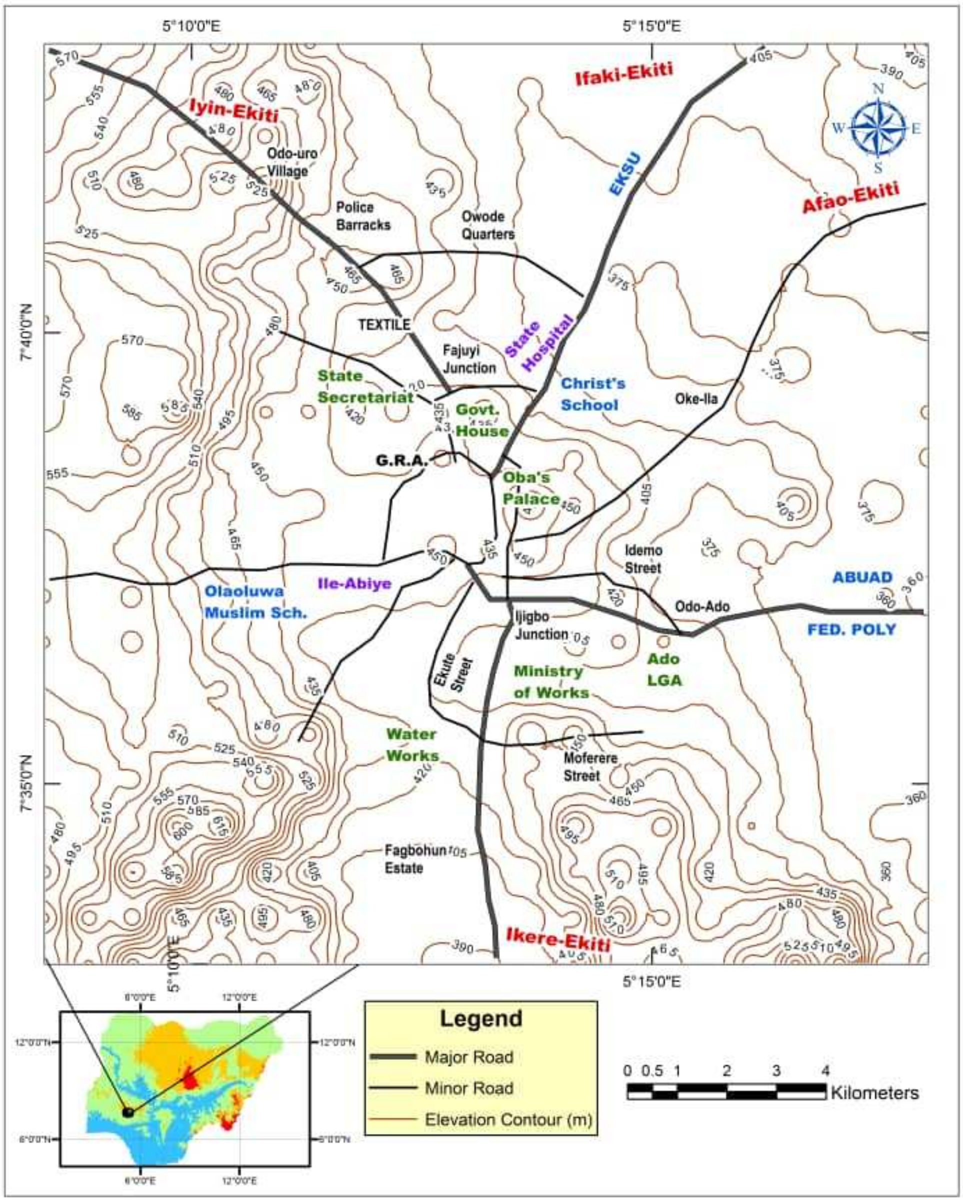

Figure 2. Topographical map of Ado-Ekiti (adapted from Oyedele, 2019)

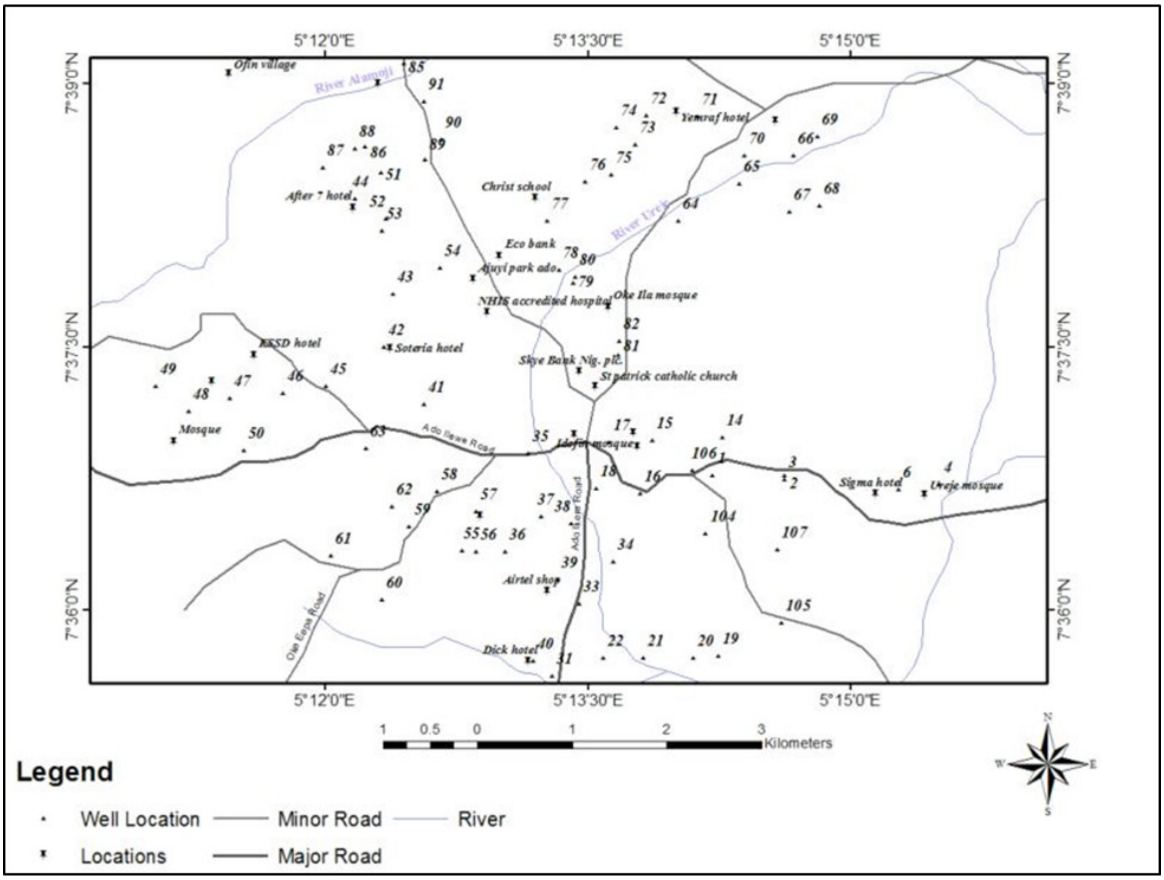

Figure 3. Map of the study area showing the well points

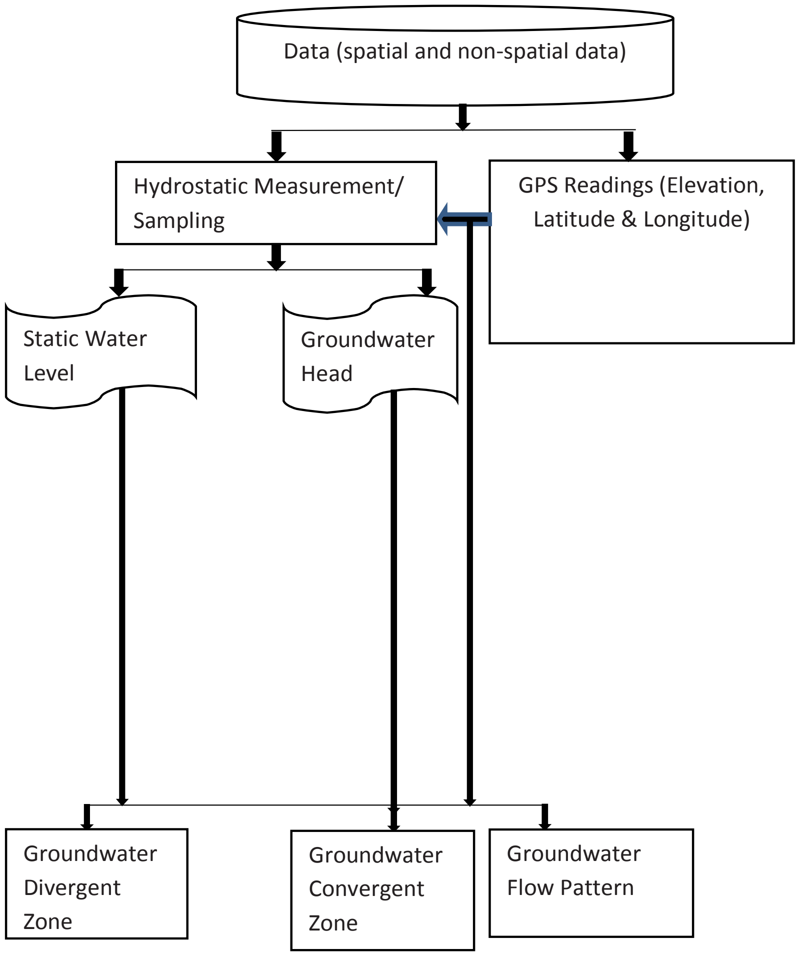

Figure 4. The processing flow chart

3. Results and Discussion

The depths to the static water level, Fig. 5, within Ado-Ekiti metropolis varied widely with a maximum value of 13.12 m and a mean value of 5.84 ± 2.35 m above mean sea level. The groundwater head had a maximum value of 460.40 m with a mean value of 408.27 ± 46.06 m above mean sea level (Fig. 6). Figs. 7 and 8 show the static water level map and the groundwater head map of the study area, respectively. The maps were produced to show the variations in depths to the water surface in the various hand-dug wells in the area and the groundwater head. The contour pattern is characterized by isolated closures typical of discontinuous basement aquifer system. The static water level is relatively deep in northwestern, southwestern, central parts and the eastern flanks of the metropolis and mainly shallow within the northwest, central and southern parts. Super-positioning of the maps shows that zones of high groundwater head values correspond with zones of low static water level values while zones of high/ deep static water level values correspond with low groundwater head values (Olorunfemi *et al*., 1999; Oseji *et al*., 2009; Oborie & Nwankwoala, 2017).

Closed contour curves of minimum static water level / maximum groundwater head in the flow domain is a hydrologic characteristic indicating presence of sinks or discharge zones. Closed contour curves of maximum static water level / minimum groundwater head in the flow domain is indicative of the presence of sources or groundwater recharge zones at that portion. Recharge is promoted by natural vegetation cover, flat topography, permeable soils, a deep water table and the absence of confining beds. Zones of high groundwater head values which are zones of low static water level translate to crests / high rise. They are thus groundwater radiating zones or groundwater divergent zones. Areas of high static water level or deep static water level values are characterized by low groundwater head. The zones are diagnostic of troughs which are groundwater collecting centres or groundwater convergent zones (Olorunfemi *et al*., 1999; Amah & Agbebia, 2015; Messene, 2017).

The groundwater head map, Fig. 8, shows that the groundwater flows away from the low water table zones (high groundwater head/ hydraulic head zones) towards the high water table zones (low groundwater head/ hydraulic head zones) into the collecting or convergent centres. The observations and results agree with the works of Oseji *et al*. (2009), Oborie and Nwankwoala (2017) and Messene (2017) which affirmed that groundwater flows in the direction determined by the slope of the water table essentially from high hydraulic head to low hydraulic head. The flow is thus from regions of increasing head to that of decreasing head.

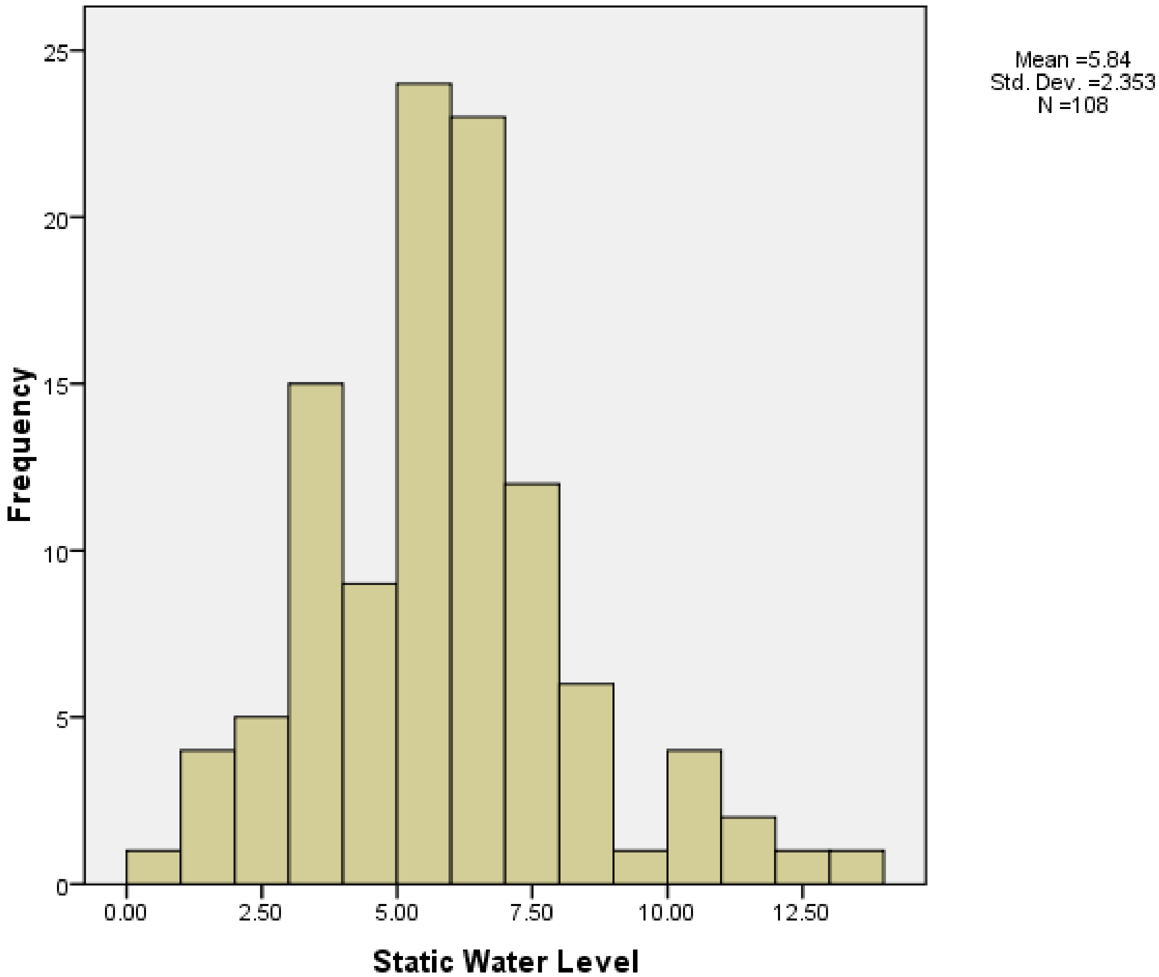

Figure 5. Frequency distribution of static water level

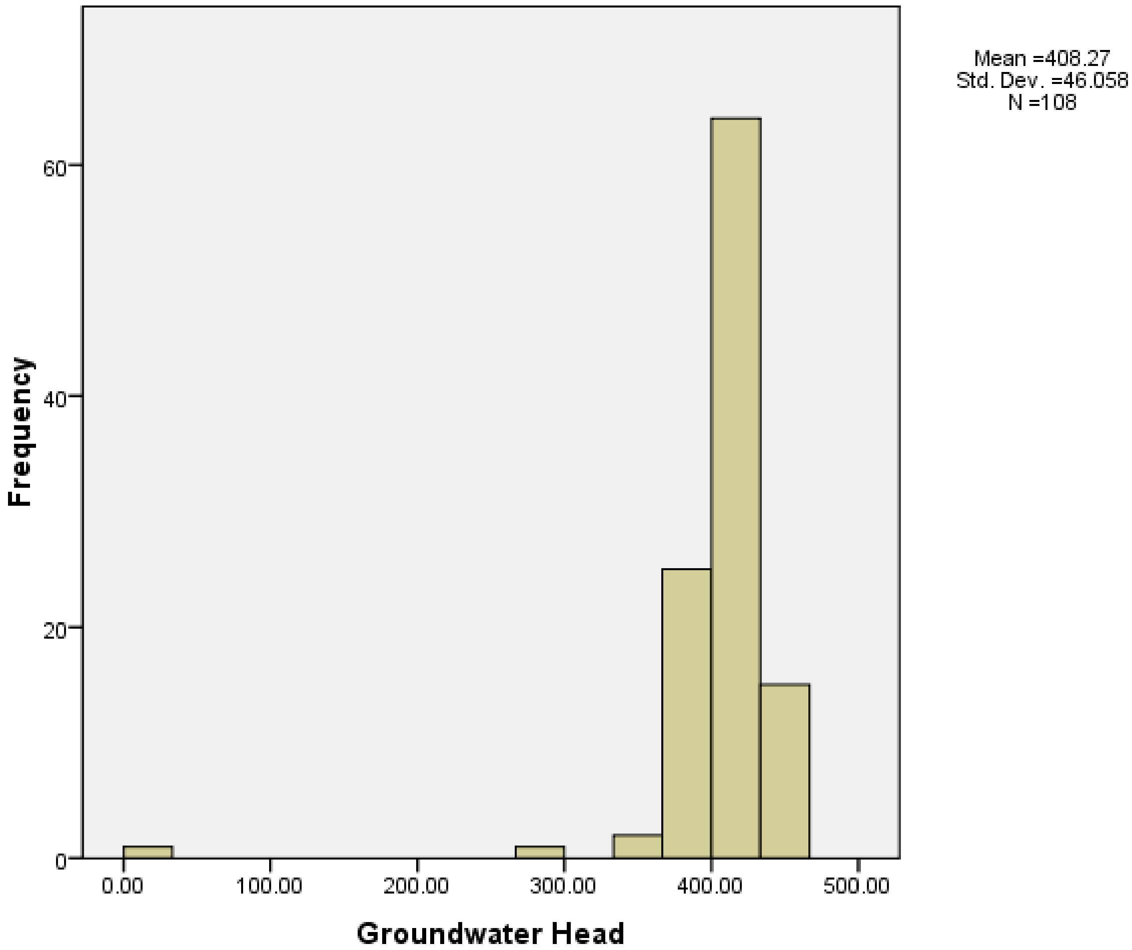

Figure 6. Frequency distribution of groundwater head

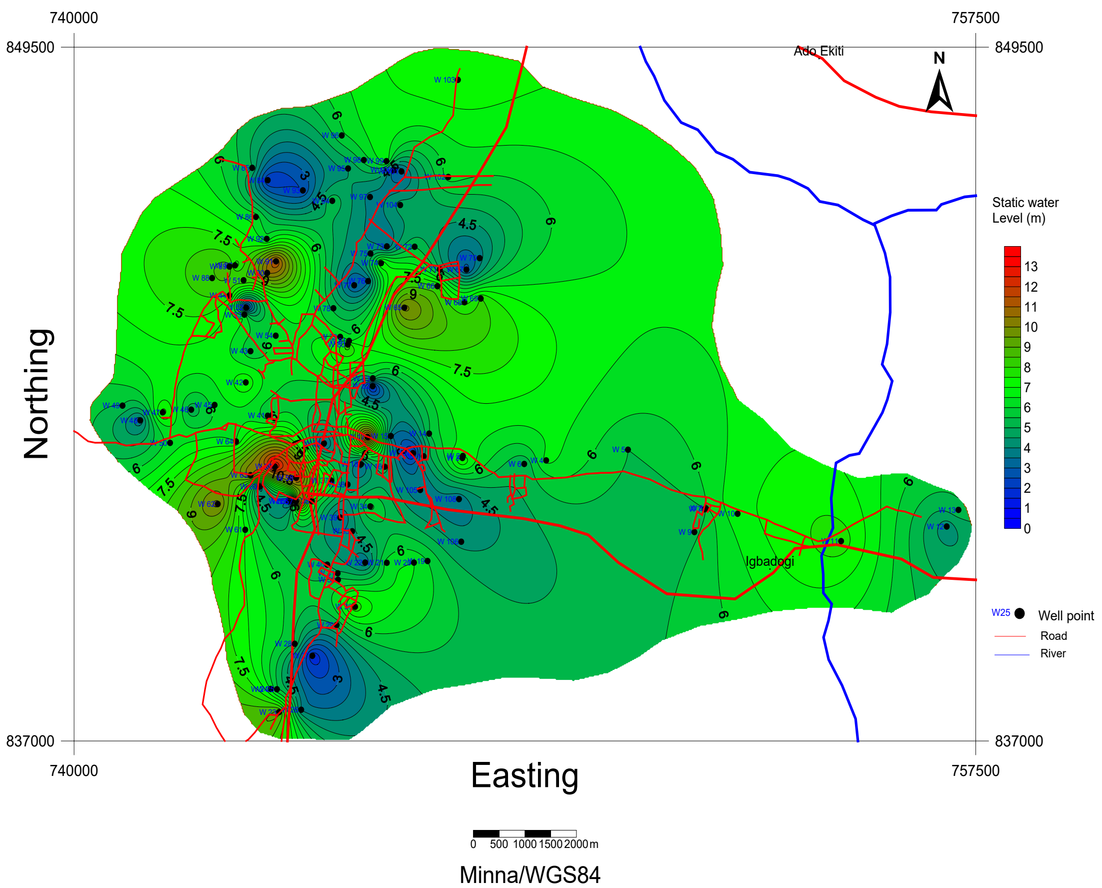

Figure 7. Static water level map of Ado-Ekiti

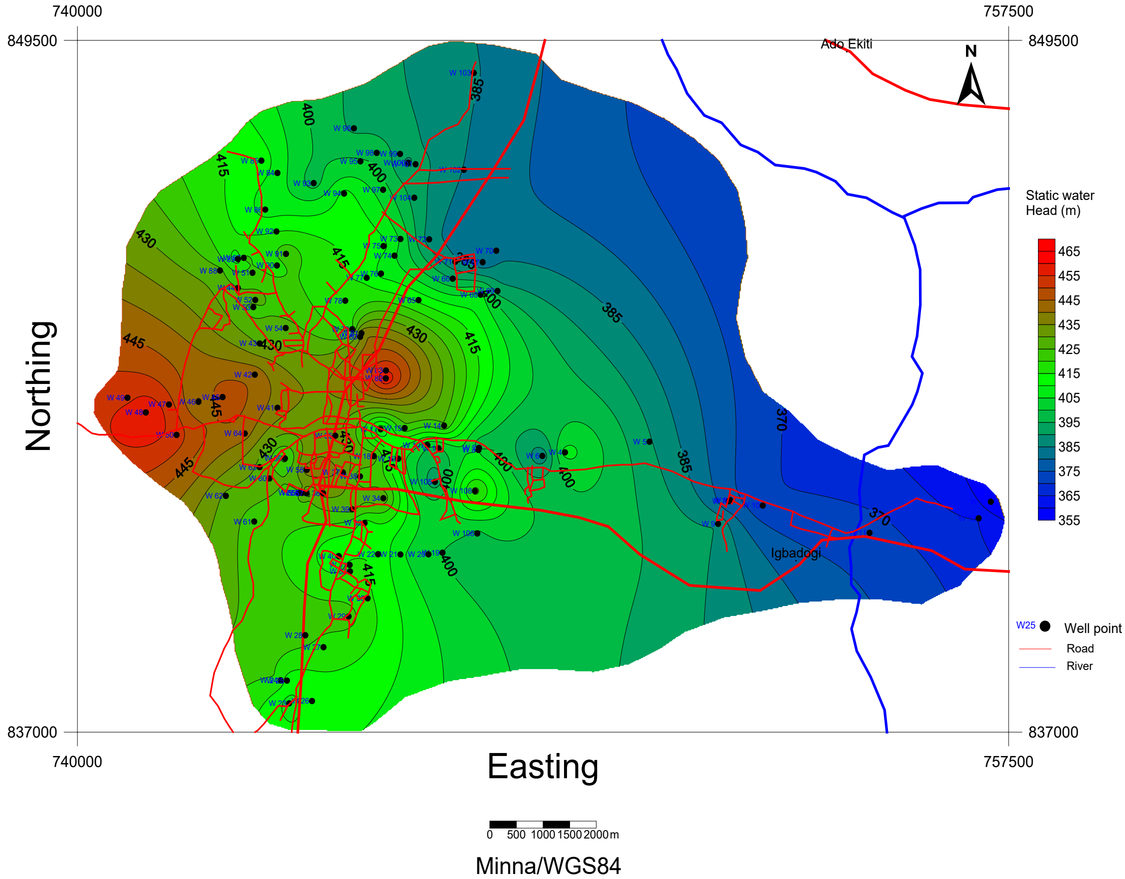

Figure 8. Groundwater head map of Ado-Ekiti

Ado-Ekiti enjoys a mean annual total rainfall of 1367 mm with a low coefficient of variation of about 10% (Ebisemiju, 1993; Bankole, 2010; Oyedele, 2019). This high annual rainfall favours significant recharge of the basement aquifers through surface precipitation. Daramola *et al.*, (2022) observed that the Shiroro dam downstream of the Kaduna Watershed, North Central Nigeria is principally recharged by groundwater and surface runoff.

It is evident that the main groundwater flow direction in the study area lies along the northwest – southeast direction. Occurrence of local sinks or discharge zones between the central and south – eastern portions of the study area and similar occurrence lying approximately southwest between the high groundwater head portions of the western flank and the central parts of the metropolis are indicative of groundwater divides and sub domains. A groundwater divide indicates distinct groundwater flow regions within an aquifer. Groundwater divides often occur where aquifers are shallow and strongly influenced by surface water flow. The groundwater divide is indicated on groundwater head contour map by a curve in horizontal plane, which separates the flow domain into sub domains, such that all groundwater from a sub domain drains out through a separated outlet such as spring, river, stream, etc (Olorunfemi *et al.*, 1999, Buddermeier & Schloss, 2000; Messene, 2017)

Groundwater flow direction is presented as vector grids, with arrows showing the flow pattern from higher elevation to lower elevation areas (Fig. 9). The map with the vector notion allows visual assessment of the groundwater flow pattern; as a function of combined elevation (relief or topography) and groundwater head (water-table elevation). It reveals the major groundwater flow direction as well as the major recharge and discharge zones delineated in the study area. Often, the divergence and convergence of vector flow lines is an indicator of the recharge and discharge areas, respectively (Messene, 2017). It is observed that the regional tendency of the underground flow is towards River Ogbese. Within this regional tendency approximately along the northwest – southeast direction are local variations. Local variations to the regional flow are observed along the south – eastern / south – western axes of the central portion. The variations are traceable to directional changes of groundwater flow associated with the occurrence of superficial clay layers or local geology. Fashae *et al.* (2014) noted that the occurrence and movement of groundwater in a crystalline terrain depend on the degree of weathering and extent of fracturing of the bedrock rocks.

The hydrostatic maps could be used to solve problems associated with groundwater flow such as groundwater contamination or groundwater quality degradation (Buddermeier & Schloss, 2000; Braga *et al.*, 2006; Nowbuth *et al.*, 2012). The maps thus serve as inputs into the database for groundwater management studies in the study area. Proper management is required to maintain the sustainable function of groundwater (Hendrayana *et al.* 2021; Zahra & Putranto, 2021).

Ige and Adetunji (2014) examined the relationship of some socio-economic factors and household sanitation in Ado-Ekiti. An indifferent status was observed for the general attitude of the residents towards household sanitation and waste disposal. The study of Zahra and Putranto (2021) suggests that specific attention should be paid to land management in areas with a high level of pollution resistance and vulnerability.

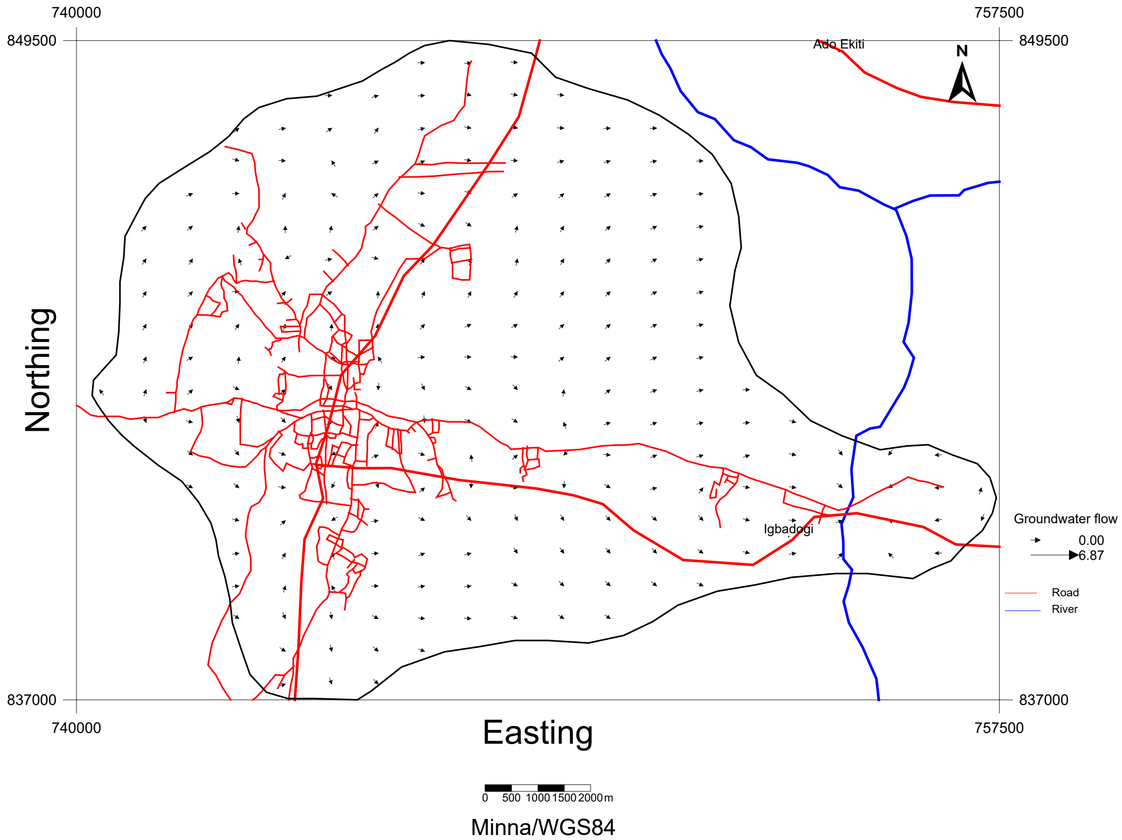

Figure 9. Groundwater flow direction map of Ado-Ekiti

Environmental considerations demand that the groundwater divergent/convergent zones and the flow domains are devoid of environmentally unfriendly activities including location of landfill, dunghills and waste disposal sites to prevent leachate from reaching the water table and the aquifer zone with the attendant consequences of groundwater contamination.

Contaminant plumes generally flow along the same path as the groundwater. It is necessary to install monitoring wells along the groundwater flow directions and the groundwater divides such that water samples from these wells are subjected to regular comprehensive water quality analysis to ensure overall protection of groundwater resources (Nowbuth *et al.*, 2012; Messene, 2017; Zahra & Putranto, 2021).

4. Conclusion

The study has identified the regional groundwater flow direction, the groundwater divides and the major groundwater recharge / discharge zones in Ado-Ekiti. The analysis of hydrostatic level measurements has enabled the delineation of the major groundwater recharge / discharge zones, groundwater flow direction and groundwater divides with the regional tendency of the underground flow approximately lying along the northwest – southeast direction and groundwater divides along the south – eastern / south – western axes of the central portion of the metropolis. Mapping land area that recharges the wells, streams, rivers, public water supply or dam in the metropolis would aid general town planning and control of municipal landuse activities along the axes that could pose threats to the quality of groundwater resources. In many cases, groundwater flow governs hydrochemical conditions and transport of contaminants. The knowledge of groundwater flow direction, flow patterns, groundwater recharge and discharge is essential for effective management of groundwater resources. It provides vital information for sustainable groundwater development, management and protection.

Acknowledgment

The authors appreciate the comments and useful suggestions of the Chief Editor and the anonymous reviewers.

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