UNIVERSIDADE DE ÉVORA

ESCOLA DE CIÊNCIAS E TECNOLOGIA

DEPARTAMENTO DE GEOCIÊNCIAS

Identification of groundwater patterns based on remote sensing. Case study: fractured hard rock aquifers in Wako Kungo, Angola

Irina Liudimila de Ferro Miranda Miguel

Orientação | António Alberto Chambel Gonçalves Pedro
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Mestrado em Engenharia Geológica

Dissertação

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INDEX

UNIVERSIDADE DE ÉVORA

INDEX–FIGURES

INDEX–TABLES

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Identification of groundwater patterns based on remote sensing. Case study: fractured hard rock aquifer in Wako Kungo, Angola

Abstract

Groundwater is considered the major portion of the world´s freshwater resources.

Groundwater in Angola is utilised for several urban centres on the coast and in the arid southern provinces and is a major source for rural supply.

The main objective of the present work was to process and analyse optical and radar images that cover the study area and combine them in a GIS to identify groundwater patterns in fractured hard rock aquifers and sedimentary basins in the valleys.

Field observations and the geological data allowed to distinguish two main aquifer types in the study are: one detritic and other fractured that is the object of this study.

The results from the study show that, integration and interpretation of different thematic layers such as lineament, drainage, vegetation index and on field data is useful to predict the recharge and discharge areas.

Concerning to water quality, hydrogeochemistry analysis shows that, to the physical-chemical parameters analysed, groundwater in the study area can be evaluated as good quality water.

Keywords: Angola, groundwater, hard rock, remote sensing (RS), geographic information systems (SIG).

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Identificação de padrões de água subterrânea com base em detecção remota. Estudo de caso: aquíferos em rochas duras fracturadas no Wako Kungo, Angola

Resumo

A água subterrânea é considerada a maior porção dos recursos de água doce do mundo.
A água subterrânea é utilizada em vários centros urbanos das províncias do litoral de Angola e nas províncias áridas do Sul é uma das principais fontes de abastecimento nas zonas rurais.
O presente trabalho tem como objetivo principal processar e analisar imagens ópticas e de radar que cobrem a área de estudo e combiná-las em um SIG para identificar padrões de águas subterrâneas em aquíferos fracturados e bacias sedimentares nos vales.
As observações de campo e os dados geológicos permitiram distinguir dois principais tipos de aquíferos na área de estudo, um de tipo detrítico e outro fracturado, que é o objecto deste estudo.
Os resultados mostram que a integração e interpretação de diferentes camadas temáticas tais como lineamentos, drenagem, índice de vegetação e dados de campo, é útil para prever áreas de recarga e descarga.
No que diz respeito à qualidade da água, o estudo hidrogeoquímico mostrou que para os parâmetros físico-químicos analisados, as águas subterrâneas da área de estudo podem ser avaliadas como águas de boa qualidade.

Palavras-chave: águas subterrâneas, rochas duras, detecção remota (RS), sistemas de informação geográfica (SIG), Angola.

1. INTRODUCTION

Water is one of the most precious natural resources of the earth and it is of utmost importance in every facet of human life (Chaudhary *et al.* 1996). Although water is the more dynamic renewable natural resource, it´s availability with good quality and proper quantity in appropriate time and space is of significant importance.

Groundwater is a term used to denote all the waters found in the saturated zone under the ground surface.

Salt water (mainly in oceans) represents about 97.2% of the global water resources with only 2.8% available as fresh water. Groundwater accounts for between 93% (Shiklomanov 1992) to 98% (USGS/Nace 1967 and USGS/Pamphlet 1984) of all freshwater in the planet. Surface water represents between 2 and 7% of freshwater. The problem is not only to locate groundwater, as it is often imagined, but often to find water at such a depth, in such quantities, and of such quality that can be economically utilised. Aquifers are not just a source of water supply, but also a vast storage facility providing great management flexibility at relatively affordable costs.

In developing countries like Angola water resources management has become a challenging problem. Thus, techniques that enable immediate data generation for supporting decision making at low cost are required.

The lack of information on land cover and land use has a huge impact on the water resources management, since it may hamper the collection, treatment and distribution of water for human consumption.

Angola is endowed with substantial surface water resources, with all the major rivers (apart from the Zaire and Chiluango of Cabinda) originating within the country. The majority of rivers rise in the mountainous coastal ridge, with those flowing into the Atlantic being relatively short and those flowing east and north forming longer systems (Kubango and Kuando). Groundwater is used for several urban centres on the coast and in the arid southern provinces and is a major source for rural supply. Additionally, small groundwater based systems have recently been developed to assist in the water supply shortfall in growing peri-urban areas.

A large portion of the country is underlain by hard rock, including the study area.

Groundwater in hard rock aquifers is essentially confined to fractured and/or weathered horizons. Therefore, groundwater is an important source of water supply in the study area and comes mainly from hand-dug wells, boreholes and springs.

Groundwater prospection is controlled by many factors such as geology, geomorphology, drainage, slope, depth of weathering, presence of fractures, surface water bodies, canals and irrigated fields, amongst others (Abdelkareem and El-Baz 2014).

The use of Earth Observation (EO) data for identification of groundwater patterns is very promising due to the current lack of information on the territory, the large extension of the country and to difficulties on field data gathering.

Therefore, the integration of geologic and hydrogeological surveys with remote sensing data and geographic information systems (GIS) can contribute efficiently to this study.

One of the largest land use changes with major impact on groundwater resources is the conversion from forest/woodlands to agricultural land. Here, two things can happen, either agriculture uses surface water, and leaking from irrigation will be a form of artificial groundwater recharge, or agriculture uses groundwater and some depletion on groundwater storage can happen.

Since updated quantitative information on Angola's water resources is lacking, the development of a methodology for identification of groundwater patterns, which integrates multi-source and EO data and in-situ observations, is required for a sustainable water resources management.

1.1. Objectives

The main objective of the present work is to process and analyse optical and radar images that cover the study area and combine them in a GIS to identify groundwater patterns in fractured hard rock aquifers and sedimentary basins in the valleys, namely fractures, fracture density, and discharge areas in fractured rocks, limits of sedimentary basins, and rivers, as discharge linear structures in sedimentary rocks.

At the same time, field work and data gathering about water points (drilled wells, traditional wells, springs and even rivers) allow to bring new information about groundwater levels and chemistry.

The work also aims to:

- Investigate and predict the groundwater recharge and discharge areas;
- Propose the best locations of groundwater potential for abstraction based on multiple criteria;
- Produce thematic maps to supply the lack of information related to water resources in the study area, namely fracture density, drainage density, and distribution of vegetation maps;
- To identify groundwater levels and quality.

1.2. Material and methods

1.2.1. Satellite data

In view of the hydrogeological objectives of the study, satellite image such as SPOT-5 and Sentinel-1 were selected as acquired in the dry season, to evidence features (stream, vegetation) related to the occurrence of water and to avoid overshadowing by too much vegetation. Both satellite data available for this study are listed in Table 1.

Table 1. Sentinel-1 and SPOT-5 acquisition dates. The data in bold corresponds to Sentinel-1 acquisition dates and the data in non-bold corresponds to SPOT-5 acquisition dates.

Acquisition Date	DOY	Acquisition Date	DOY
26 March	**85**	**30 June**	**181**
10 April (*)	100	4 July	185
15 April (*)	105	9 July	190
19 April	**109**	14 July	195
30 April	120	19 July	200
5 May	125	**24 July (+)**	**205**
10 May	130	29 July (*)	210
13 May	**133**	8 August	220
15 May	135	13 August	225
20 May	140	**17 August (+)**	**229**
25 May	145	18 August	230
4 June	155	23 August (*)	235
6 June (+)	**157**	28 August	240
9 June	160	**29 August**	**241**
14 June	165	2 September (*)	245
19 June	170	7 September	250
24 June	175	12 September	255
29 June	180	**4 October**	**277**

(*) not used due to the presence of a significant cloud cover
(+) lack of the Northern part of the image

1.2.1.1. Radar data

Sentinel-1

All Sentinel-1 C-band SAR images were made available in Interferometric Wide Swath (IW) mode with a dual polarization scheme (VV+VH). These images were distributed as Level-1 products, as Single Look Complex (SLC), except for the first two acquisition dates, and Ground Range Detected (GRD) for all dates.

Ground resolution of the GRD images is 10 m. Level-1 GRD products were used in this study.

All images were acquired in ascending mode with incidence angles ranging from 38°.87 to 39°.26.

Level-1 GRD products consist of pre-processed SAR data that has been detected, multi-looked and projected to ground range using the Earth ellipsoid model WGS84. Besides these corrections, in GRD products the thermal noise was removed using the open source software Sentinel Application Platform (SNAP), to improve the quality of the detected image. In these images pixel values represent detected magnitude while phase information is lost. The resulting product has approximately square resolution pixels and square pixel spacing with reduced speckle at a cost of reduced geometric resolution. For the IW GRD products, multi-looking is performed on each burst individually. All bursts in all sub-swaths are then seamlessly merged to form a single, contiguous, ground range, detected intensity image per polarization channel (https://sentinel.esa.int/web/sentinel/missions/sentinel-1/data-products).

SRTM

SRTM is a joint project of NASA and the National Geospatial-Intelligence Agency (NGA). SRTM data was distributed in two levels: SRTM1 with data sampled at one arc-second intervals in latitude and longitude, and SRTM3 sampled at three arc-seconds. Three arc-second data are generated by three averaging of the one arc-second samples. One arc-second at the equator corresponds to roughly 30 m in horizontal extent. For this study the SRTM3 were used. Its data are of 90 m horizontal resolution and are available from the Global Land Cover facility (https://www2.jpl.nasa.gov/srtm/).

The SRTM digital elevation model (DEM) was used in extracting of stream networks. This was done using a hydrology module of Spatial Analyst package of the ArcGIS in subsequent steps including filling sinks, flow direction, flow accumulation, and stream delineation steps to extract the stream network (El Basstawesy *et al.* 2010; Abdelkareem *et al.* 2012; Abdalla 2012 in Abdelkareem and El-Baz 2014).

1.2.1.2. Optical image

SPOT-5

SPOT-5 images were taken in the framework of the SPOT-5 Take 5 programme of ESA, which were distributed both at Level-1C (orthorectified, Top of Atmosphere- TOA-reflectance) and Level-2A (orthorectified, Bottom of Atmosphere-BOA-reflectance's), in 10 m spatial resolution such as the Sentinel-2 products. In analogy to the previous SPOT-4 Take-5 experiment, on 2 May 2015, SPOT-5 was placed in a 5 days cycle orbit, acquiring data over 150 selected sites every 5 days under constant angles. This SPOT-5 Take-5 time series were made available by ESA and CNES (https://earth.esa.int/web/guest/missions/3rd-party-missions/current-missions/spot-5) to the scientific community to support the development of time series analysis in preparation for the exploitation of the Sentinel-2 mission.

In this study SPOT-5 level-2A images were used.

1.3. Methodology

Integrations of Synthetic Aperture Radar (SAR) from Sentinel-1 and SRTM data were used in the present study using ArcGIS software package. A flowchart with all steps adopted in this study is given in Figure 1.

The SPOT-5 image was used to generate an NDVI image and vegetation map. Lineaments were delineated by visual interpretation of false color composite, which was fused with the Sentinel (VH+VV bands) to enhance the interpretation. Drainage network was automatically extracted from SRTM DEM data, and was used to validate the active (ephemeral) streams. Geological map, vegetation map, hydrochemical characterization and field observations (including well locations and water table) were used to complement satellite image analysis and interpretation and predict the best locations for groundwater infiltration, accumulation and discharge.

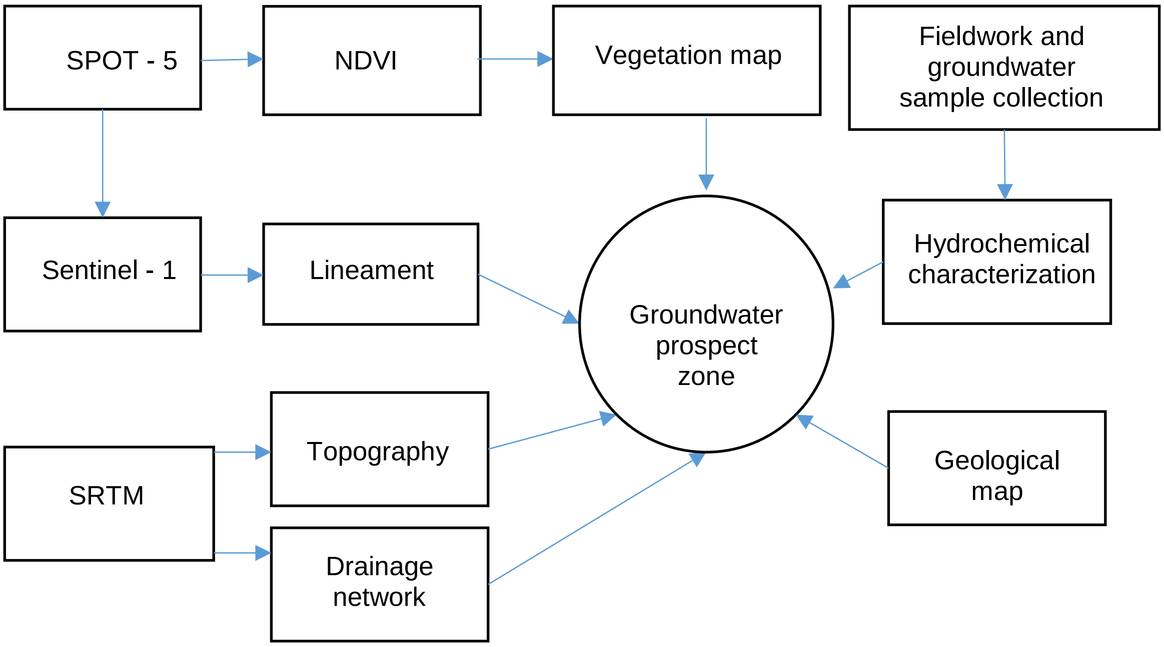


Figure 1. Methodology flowchart for identifying groundwater prospect zones

1.3.1. Pre-processing of images

Sentinel-1A Level-1 GRD products were used in this study due to their improved quality. The first step of the images processing consisted in applying precise orbit files followed by the thermal noise removal. Then, since typical SAR data processing does not include radiometric corrections and because significant radiometric bias remains, it was necessary to radiometrically correct the images. Moreover, radiometric correction is also required when comparing images acquired from the same sensor, but at different times, as in this case. Radiometric calibration was applied using Equation 1 (MDA 2011 in Navarro *et al.* 2016):

$$\sigma^0{}_i = \frac{(DN_i^2 + b)}{A_i} \qquad (1)$$

where A_i is the gamma calibration vector (*i*), *b* is a constant offset and DN_i^2 is the intensity. Level-1 products provide four calibration look-up tables (LUTs) to produce $\beta^0{}_i$, $\sigma^0{}_i$ and γ_i or a digital number (DN). The LUTs apply a range-dependent gain, including the absolute calibration constant. Independently of the selected LUT (in this case, $\sigma^0{}_i$ was chosen), for any pixel *i* that falls between points in the LUT, the A_i value is found by bilinear interpolation.

Finally, a terrain correction was also applied to the images because, due to the topographical variations of a scene and the tilt of the satellite sensor, distances can be distorted in SAR images. The range Doppler orthorectification method was used to geolocate all of the SAR images using available orbit state vector information in the metadata, radar timing annotations and reference DEM data. NASA's Shuttle Radar Topography Mission (SRTM) DEM sampling at 3 arc-seconds was adopted.

Level-2A SPOT-5 images were used in this study due to its improved pre-processing level. Therefore, no further pre-processing steps were required for these images.

1.3.2. Normalized difference vegetation index (NVDI)

NDVI is based on the difference in reflectance in the near-infrared (NIR) and red bands of the electromagnetic spectrum (EMS). Its valid results fall between -1 and +1. The higher values indicate more green vegetation (Figure 2).

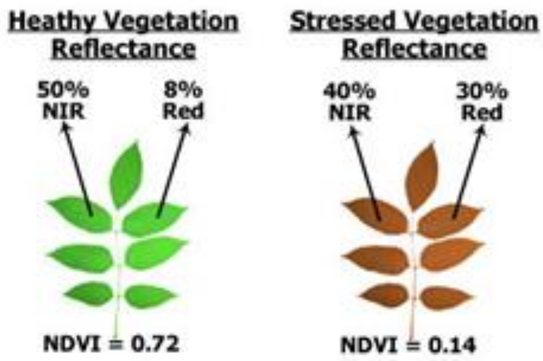


Figure 2. Differences in NDVI based on plant health status (https://earthobservatory.nasa.gov/.../measuring_vegetation_2.php).

The NDVI equation is (Equation 2):

$$\text{NDVI} = \frac{(\text{NIR - Red})}{(\text{NIR + Red})} \quad (2)$$

In this study SPOT-5 bands B2 (Red) and B3 (NIR) were used to compute a NDVI image (Figure 41).

1.3.3. Fusion of optical and radar images

Image fusion is a process that integrates images from different data sources to reveal more information that can be separately derived from any of them alone (Abdelkareem and El-Baz 2014). Data fusion was done by applying layer stacking to VV and VH bands with SPOT, to improve visual interpretation of morphotectonic features and drainage systems.

1.3.4. Field work

Ground truth information was collected in the field. Field work has been done from 26th July, 2016 to 29th July, 2016. The main purpose of the fieldwork was to find and monitor water points and record them using GPS. At the same time geomorphologic and lithologic characteristics were observed and noted. The field work also allowed to measure some chemical-physical parameters of the water and to collect samples that were later sent to the laboratory.

2. GEOGRAPHIC SETTING

Wako Kungo town (11°25’ 33” S, 15° 06’ 10” E) is located in Cela municipality in the South-Kwanza province (Figure 3) and is located on a plateau zone above 1200 masl.

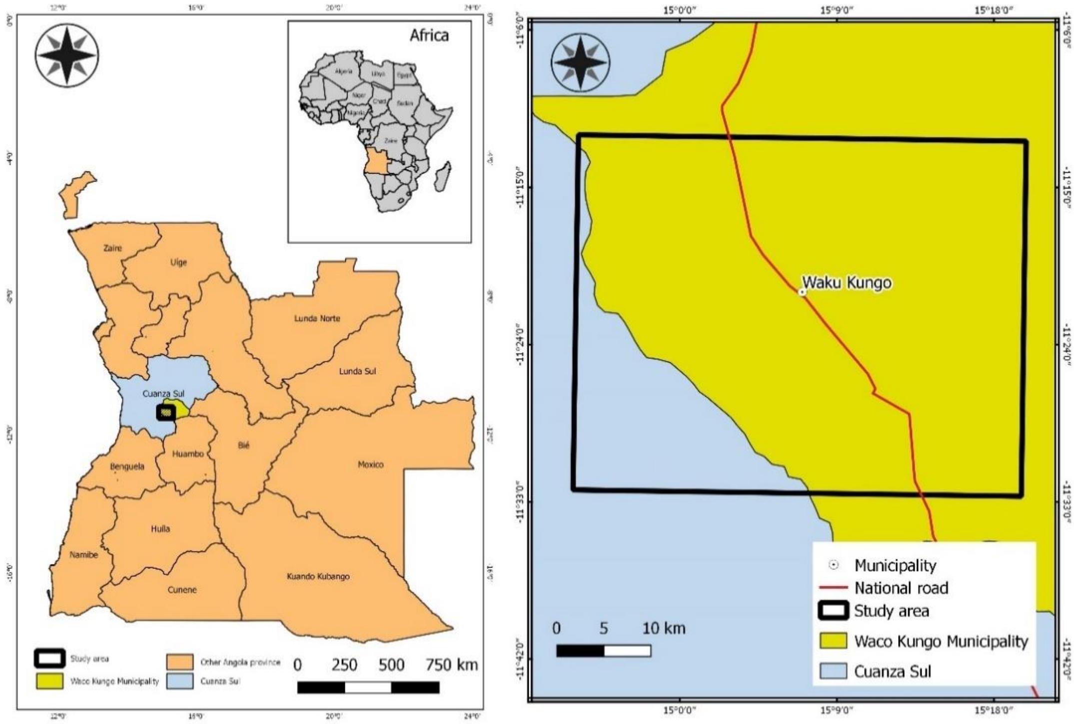


Figure 3. Regional context of the study area (hatch lines rectangle) with the location of Wako Kungo municipality.

The municipality of Cela has a dense hydrographic network, bordered by River Nhia in the north and the River Queve in the south. There is also the River Cussói, which plays an important role in the settlement of the region, being connected to the first settlements. A large number of streams, with appreciable flow during the months of the rainy season, complete the availability of surface water in the region.

2.1. Physical Geographic setting

2.1.1.Geomorphology

Angola belongs to the "African Interior Plateau", also called "High Plain", "Planalto Antigo", or "planation surface IV". It is bordered in the west by high mountains and the Great Escarpment, overlooking the step-like coastal plateaus (I-III) zone.

Towards the east, the African Interior Plateau is depressed and forms the Kalahari Basin. Incision of valleys started during the Cretaceous and further deepening took place following the Miocene tectonical upheaval. One of the most characterizing elements of African geomorphology are the different planation surfaces. These pediplains, nowadays plateaus, represent the final stage of individual cycles of erosion and are separated from each other by escarpments.

According to Monteiro Marques 1968, the study area is located in a vast depression zone crossed in the direction N-S by a series of granite porphyry hills whose slopes can incline more than 20% with predominance of concave shape (Figure 4 and Figure 5). This depression is surrounded, to the west and south, by extensive mountain ranges made up of eruptive and some metamorphic rocks.

The mountainous relief reaches 2100m of altitude.

The erosive processes that act mainly on the slopes are those of pediplanation.

According to Jessen's geomorphological sketch (Feio 1964), the area of the Wako Kungo is located on surface II and that author dates it from the end of the Cretaceous to the beginning of the Eocene, but an exhaustive study conducted in Wako Kungo and surroundings areas by Monteiro Marques and Sanches Furtado (1967), determined that in this region the surface II of Jessen belongs to the mid Tertiary.

The study area is divided into four natural zones.

- The first consists of the interfluvial surfaces, located between the Queve and Cussói rivers, on which some mountain-islands are present. The altitude of these surfaces is around 1300 m;
- The reliefs formed by granite porphyry hills that composes the second zone and rise hundreds of meters above the interfluvial surfaces. In these hills the predominant concave forms of the slopes and shield foothills partially fossilized by the alluviums of the Cussói (Monteiro Marques and Sanches Furtado 1967) stand out;
- The third zone is composed by the low Cussói. This depression lies in the contact between granite porphyries and medium to fine grain granites. In this zone it is possible to observe the existence of a conglomerate shield on the eastern edge of the depression,

at the foot of the granite hills. There are also foothill shield surfaces at the base of the porphyry hills that extend beneath the Cussói alluvium.

- Finally, the fourth zone, carved from medium to fine grain granite, stretches eastward from the lower Cussói to the Nhia (affluent of the Longa). This area is characterized by irregular topography alternating with small levelled areas, where some mountain-islands stand. This relief is rejuvenated by a relatively young hydrographic network, commanded by SE-NW faults and steering fractures, of which the Nhia is the most important example (Monteiro Marques and Sanches Furtado 1967).

Figure 4. Different panoramas of granite porphyry hills of the study area

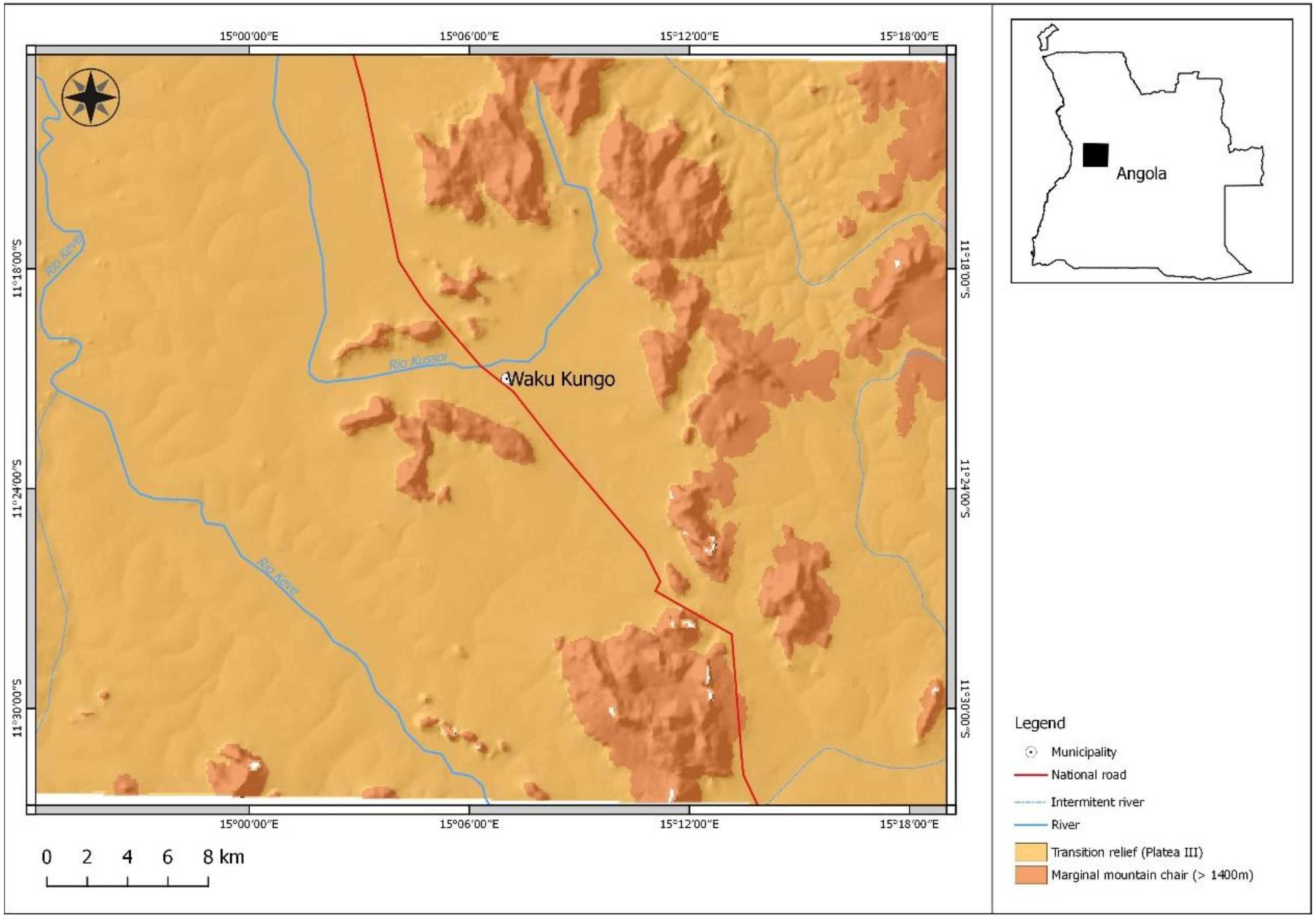


Figure 5. Geomorphology map of study area.

2.1.2.Climate

The IPCC (2007) defines climate as “the average weather in terms of the mean and its variability over a certain time-span and a certain area”.

Climate characterizes weather conditions based on climate elements such as temperature, atmospheric pressure, precipitation, wind, humidity, among others, in a certain area, considering and analysing the average values for a long period of time (Sousa 2014). The World Meteorological Organization establish 30 years as a normal length of time used for statistical climate characterization.

The struggle for independence and armed conflict that lasted more than 30 years caused irreparable material damage to the in situ observation network. The existing climatic data set for the Wako Kungo region refer to the period 1962-1982, with several gaps not only in the available material but also due to the closing of the Cela weather station. Nowadays, there are two active meteorological stations in the study area, one belonging to the Institute of Agronomic Research (IIA) and another installed by the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) in 2012 and whose data can be freely accessed.

The region of study has an average annual precipitation of 1270 mm. The rainy season starts in October and runs through April, with average monthly rainfall ranging from 101 mm (February) to 230 mm (November). At the transition period from wet to dry (May) the average rainfall is 27 mm. In the dry season (June and July) also called Cacimbo, precipitation is near nill. At the transition from dry to wet period (September) the precipitation is 64 mm. The average annual temperature is 21°C. The hottest period is the rainy season. The average annual thermal amplitude is about 4°C.

According to Barros Aguiar (1962) the different climate classifications, referring to the Wako Kungo region are:

Martonne's classification: super-humid climate (exorbitant flow);

Köppen´s classification: climate type C (mesothermic-temperate-humid climate), subtype w (with dry winter), being in the transition from Cwa to Cwb because the average air temperature, in September and October, is equal to 22˚C;

Thornthwaite´s classification: it is a type B climate, B'2wa ', that is, humid mesothermic climate with moderate water deficiency in winter.

2.1.3.Soils and soil use

The region is dominated by ferralitic soils, associated with para-ferralitic soils which show up in hilly places, especially on the foothills. These are soils derived from pre-Cambrian granite, granodiorites and quartz-diorites. In the lowlands where the rivers start to meander there is a tendency for the formation of organic soils. The climate conditions combined with the fertile soils make the region suitable for agriculture (Figure 6). The main crops in the rainy season are maize, rice, some vegetables and pastures, with dairy farming as the main activity.

Figure 6. A) Ferralitic soil in the study area; Different crop types: B) Bean, C) Soybean; D) Pasture in the study area.

3. GEOLOGIC SETTING

3.1. Regional geology

Wako Kungo region it is a folded band that belongs to the Quipungo mobile Belt, of Eburneana age.

The foliation and/or orientation of the rocks affected or generated during the genesis of this moving belt reflect the orientation of the folded band (Silva 2005).

The Quipungo mobile Belt consists of two folded bands: Quipungo and Cela Cariango that contributed to the rejuvenation of pre-existing rocks and provided the development of the largest period of granitogenesis in Angola, through the genesis of migmatites, gneisses and granites.

Many exposures of metasedimentary, metavulcano-sedimentary and metavolcanics rocks are located in this belt. These rocks often constitute true islands, usually in syncline structures, overlapping the granite-migmatitic substrate, preserved from destruction by further erosion.

The Wako Kungo rocks belong to the Quibala Group. In the Cariango-Quibala-Lussusso region this group was subdivided, from the base to the top, by Utende formation (metasiltites, metagreywackes, often migmatized, and subordinate metaconglomerates), Cariango formation (quartzites and metasandstones, with non-frequent intercalations of metagreywackes and phyllites), Quissongo formation (itabirites), Serra of Banga formation (granitoid or quartz-feldspathic metaporphyries, metadacites, metarhyolites, metagreywackes and other metasediments alternating with metadacites) (Silva and Fernandes, 1978, in Silva, 2005).

The Eburnean regional granite that emerges in the Wako Kungo region had its origin in the remobilization, sometimes incomplete, by granitization and anatexy of quartz-feldspathic metaporphyries and metavolcanic rocks, from dioritic to granitic composition, between other pre-existing rocks. Therefore, inside, there are still relics of plagioclases, considered of high temperature, typical of these last hypoabyssal and extrusive rocks, in many and expressive spots.

The Wako and Quitemo (Cariango) granites, both porphyroblastic biotitic, also without Eburnean kinematics and related to the Quibala granites, which provided conventional Rb/Sr ages in total rock of 1926 ± 62 Ma and 1904 ± 146 Ma, respectively (Silva and Kawashita 1978 in Silva 2005).

3.2. Geology of the study area

The zone of study is mainly composed by eruptive (granitic) rocks and sedimentary (laterites and alluviums) formations.

According to the geological map of Angola at 1:1,000,000, the age of the eruptive formations is Pre-Cambrian, but more modern than the nesting gneisses (Base Complex). On what concerns the sedimentary formations they are dated from the Middle Tertiary to the Quaternary (Figure 7).

3.2.1.Pre-Cambrian

The granitoid rocks of the study area are divided into three main groups: porphyritic granites, medium to fine grain granites and granite porphyries. The delimitation of these three petrographic types is difficult, because in some cases it passes almost insensibly from one type to the other and in others, as with the porphyries, a vast depressive area covered mainly by alluviums separates them from the granites. At one or the other site the granites show signs of dynamometamorphism.

3.2.1.1. Porphyry granite

This spot is formed by meso-melanocratic porphyroid granites, essentially consisting of quartz, feldspars and biotite. The predominance of plagioclase over potassium feldspar and abundance of hornblende in some samples leads to types similar to granodiorites (Monteiro Marques and Sanches Furtado 1967).

3.2.1.1.1. Medium- to fine-grained granites

Leucocrate to leuco-mesocrate granites show in some samples indications of marked gnaissization. The fundamental components are the same as those of previous rocks, but biotite is in some cases very poorly represented.

3.2.1.1.2. Granite porphyry

They are mesocratic rocks, sometimes meso-melanocratics, in which phenocrysts of feldspars (mainly plagioclases) and more rarely (or in certain samples even absent) of quartz, biotite and hornblende are observed, in the middle of a microgranular paste.

From the mineralogical point of view (Monteiro Marques and Sanches Furtado 1967) certain differences between the rocks of the three groups and even within them are noted. Medium to fine grain granites are very poor in ferromagnesian minerals, but, in turn, porphyritic granites and porphyries, in addition to biotite, present in remarkable amounts, appears frequently with hornblende, often in amounts close to those of biotite

Therefore, it can be concluded that the rocks in the study zone, despite having great textual differences, have similar chemical composition.

3.2.2.Quaternary

Undifferentiated quaternary deposits are wind, proluvial-alluvial, and deluvio-eluvial deposits.

In the Wako Kungo locality, the sedimentary rocks that represent these deposits are alluviums and laterites (ferruginous shields).

3.2.2.1. Alluviums

Essentially there is a shale-sandy formation covering the depression areas of the study area. The thickness of the alluvium is variable, being able to reach in some places between 15 and 20 m, as it happens in the areas of Macedo de Cavaleiros and of Pena.

By their characteristics, these rocks compose the main reservoir for groundwater.

3.2.2.2. Laterites

The ferruginous cuirasses of the Wako Kungo zone are well described in Monteiro Marques (1968). According to the author, these formations have, in general, a thickness ranging from 2 to 6 m. They can present two main aspects: some are formed by vesicular or vacuolar material with matured elements, linked by clay-quartz cement; others show, in the middle of clay-quartz-ferruginous cement, many well-rolled and flat quartz stones with diameters ranging from 3 to 10 cm.

The minerals that form the shields are, essentially, kaolinite, goethite and quartz, the latter one being much more represented in the conglomeratic shields. Other minerals were also identified, but in very small quantities, such as gibbsite and sometimes micaceous minerals. Hematite is also present in some samples of the conglomeratic shields.

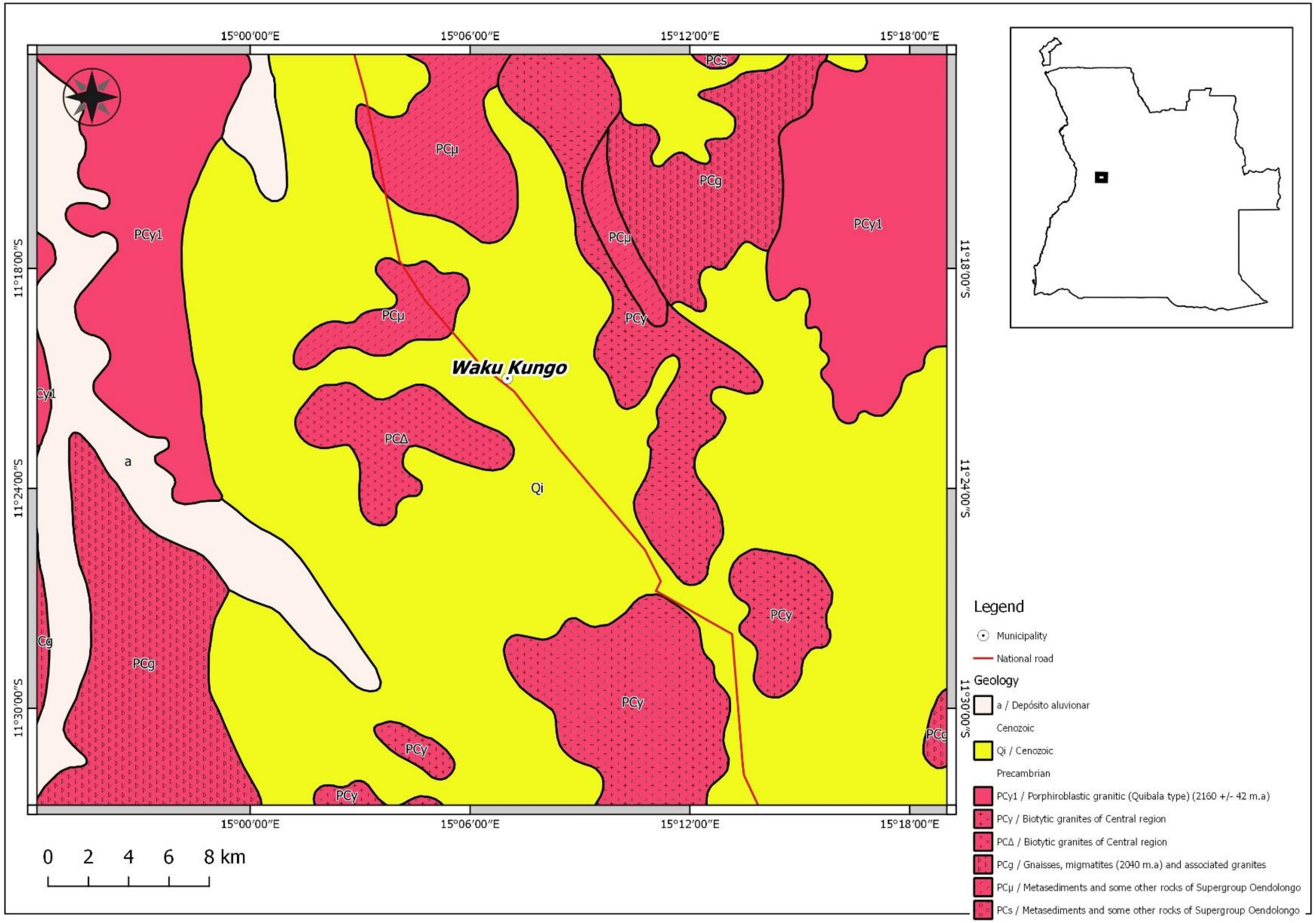


Figure 7. Surface geology map of the study area.

4. HIDROGEOLOGY IN HARD ROCK

Hard rock terrains comprise a great variety of igneous and metamorphic rocks. But from the hydrological point of view they are rather homogeneous in two respects:

- They have virtually no primary porosity as do sandstones and other sedimentary rocks;
- They have a secondary porosity due to fracturing and weathering, which permits the flow and storage of groundwater.

For some years, hydrogeologists have been using a general term for all these igneous and metamorphic rocks. They call them “hard rocks”. The most common hard rocks are gneisses and granites.

Krásný (1996) and Rubbert *et al.* (2006) in Chambel (2014) demonstrate that hard rocks have three to four layers of interest for hydrogeology. According to Chambel (2014), Krásný (1996) describes three layers that represent the geological environment of a hard rock aquifer (Figure 8):

- Upper weathered bedrock
- Middle fissured bedrock
- Unweathered bedrock

Thus, the productivity of a well is dependent on:

- The groundwater levels
- The thickness of the two first layers
- The resulting weathering characteristics of the upper two layers: the presence of clay materials can make the layers impermeable and unproductive, whereas a granular composition can be beneficial both for infiltration and storage
- Number, length, dip, fracture intersection, dilation, and composition and filling of the fractures in the second and third layers.

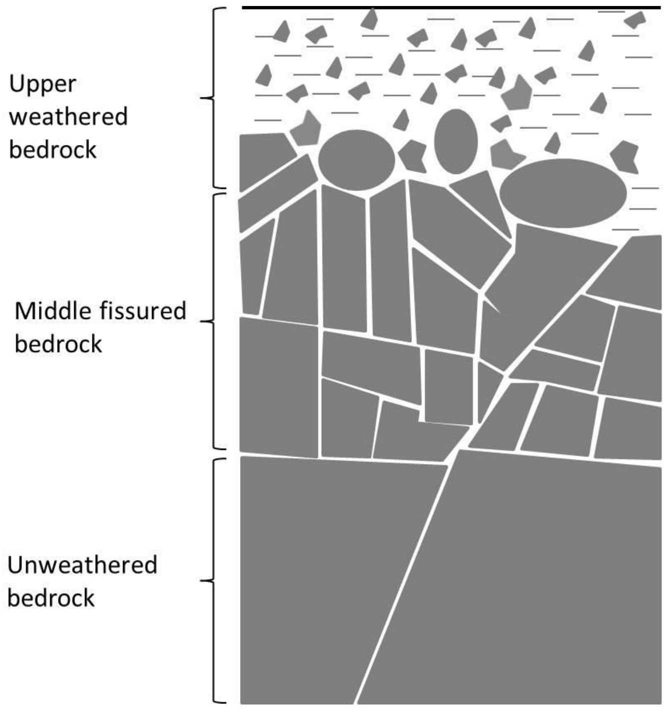


Figure 8. Schematic profile of a hard rock environment, with the three characteristic vertical zones (according Krásný 1996, in Chambel 2014).

If the first layer has a low clay content and a high porosity and the second layer is represented by the same kind of weathering materials as the matrix between boulders or rock fragments, a 10 m thick saturated zone is of interest for prospecting, for water supply to small rural communities. If the thickness exceeds 20 m, it is having the potential to be used for irrigation. One characteristic of this kind of aquifer is the potential to overexploit in dry periods, as this can induce a higher rate of infiltration, when much of the infiltration capacity is controlled by a piezometric level near the soil surface (Figure 9).

This rapid replenishment of the aquifer is much more effective if the weathered layer is porous, and less effective when fine-grained particles are present or the fractured layer is close to the surface (Chambel 2014).

According to this author, the kind of rocks that can adapt to these circumstances are varied, but the most acid rocks (granites and similar rocks) are those whose weathering layer has a good granular porous media in the upper layer. The hardest of the metamorphic rocks offer the best potential for recharge (i.e., quartzites or greywackes), and the clay rocks (e.g. shales) produce clay-rich weathered layers. The depth of the weathered layer in basic rocks is normally deeper than in acid rocks, and the deeper weathered layer can form excellent aquifers in semi-arid areas beneath superficial clayey layers, with water accumulating in the fissured bedrock (Chambel 2014).

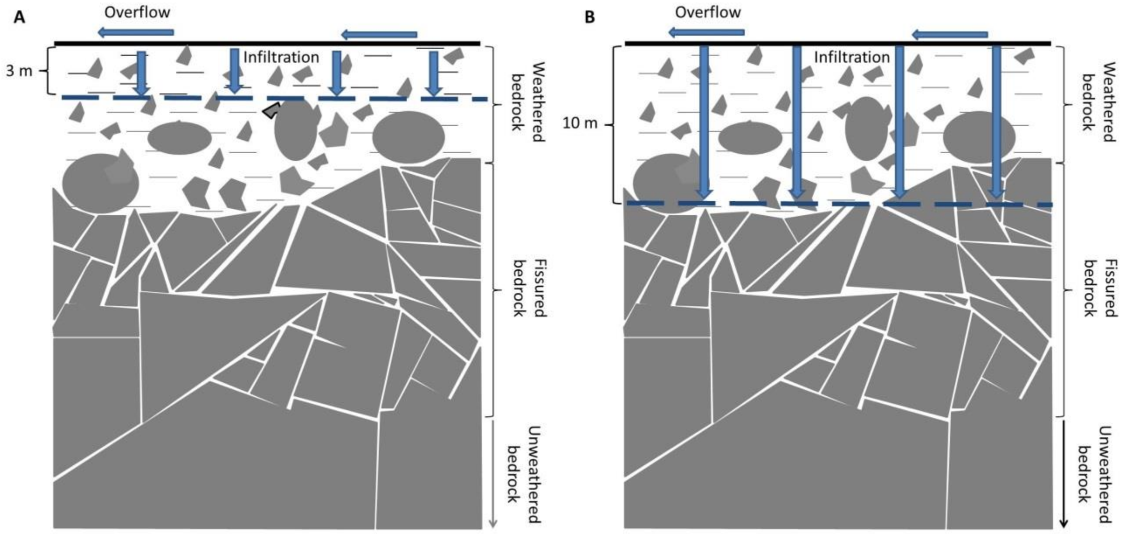


Figure 9. Explanation on how groundwater level can affect the recharge capacity of a shallow aquifer in hard rocks. In case A, in natural conditions, the overflow can occur after the replenishment of the first 3 m of unsaturated zone with water; in case B, the overexploitation permits a much higher recharge, by filling the 10m length space between the artificial water level and the surface, before overflow happens (Chambel 2014).

Direct observation of the fractured zone can be problematic, as it is normally covered by the weathered zone. When direct observation is not possible, the best way to get more information on the fracture zone is through the application of geophysics.

The fractures can be interconnected or not at all interconnected. And if the fractures are interconnected the chance of striking water is much higher when inclined fractures are present (Figure 10).

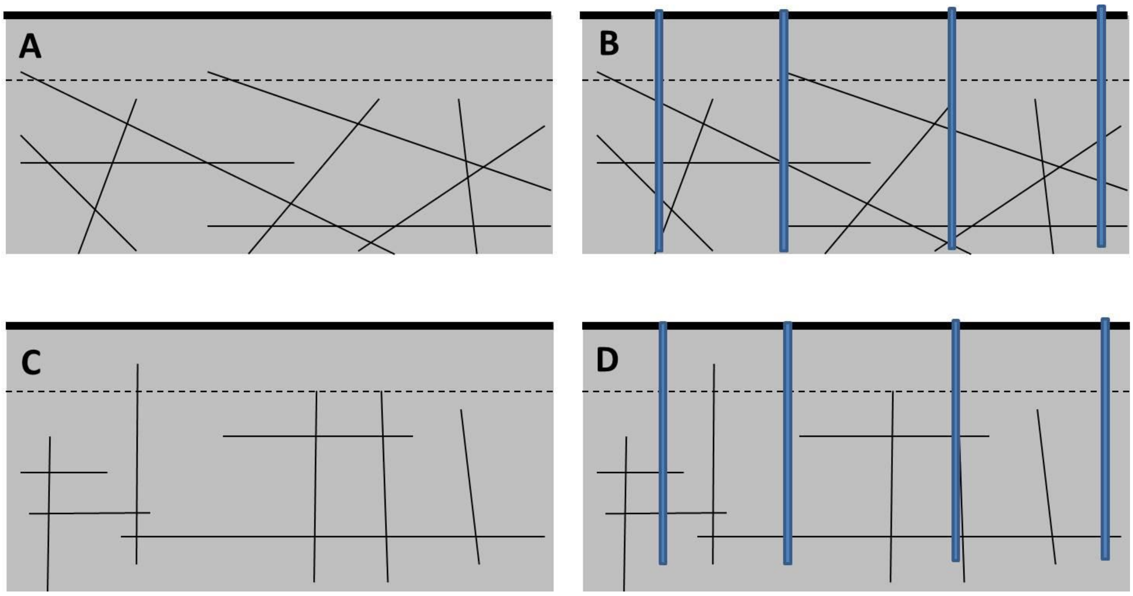


Figure 10.Example of two possible fracture patterns where fractures are all connected with each other (on top a tilted fracture network, down a vertical and horizontal fracture pattern). At right it can be seen that a set of wells will always be successful in both patterns (Chambel 2014).

4.1. Groundwater status in Angola

It was in 1942 that Angolan hydrogeology took its first steps, with the creation of the Geology and Mines Services, whose functions include the study, research and development of groundwater and its exploitation by boreholes (United Nations 1989). The existing bodies were strengthened in 1963 in order to solve the increasingly acute problems of supplying water to rural dwellers. This resulted in the preparation of a “co-ordination plan for the provision of water in the grazing regions of Southern Angola” in association with the Applied Geology Service of the Office of Geological Services and Mines, the institution responsible for carrying out hydrogeological prospecting, while the drilling crew, likewise part of the Mines Service is responsible for the well drilling.

The prospecting and drilling for groundwater have been carried out for the most part in the formations of the Precambrian crystalline basement rocks (gabbro and granites) and also in the Cretaceous sediments, the Kalahari formations and other Cenozoic sediments, and in the recent alluviums.

By preference, operations begin by the analysis of the geologic information and by a photogeological study, with the locations chosen close to watercourses or the geological accidents which traverse them. A large number of geophysical studies are also carried out (electrical and microseismic prospecting). The most favourable zones in the basement rock, with respect to water-bearing properties, are: the quartz veins and basic rocks, the contact zones between crystalline rocks of differing texture and composition, the zones of contact between the eruptive and the metamorphic schists, shales, etc., and the metamorphic rocks with quartz fractured veins.

A large number of borehole have yields between 1 and 7 m^3/h. Some have higher yields: up to 30 m^3/h at Catuiti in fractured and tectonized gabbros. A structural study has shown that the size of the yield bears a direct relationship to the tectonic directions (direction of the fractures). For example, for a N-E/S-W fracture’s direction, the yield is under 3 m^3/h; for a E-W/N-W/S-E direction, it is 8,5 m^3/h, and for a N-S direction is over 8,5 m^3/h.

Since Independence (1975), the Applied Geology Service has acquired the status of a state company – “Hidromina”, under responsibility of the Ministry of Industry.

Until 1983 Hidromina had about 15 drilling rigs, only a few of which were operating.

Only limited research has been conducted concerning groundwater and no national resource estimates have been completed. However, based on the presently identified potential and the limited level of existing development, it is safe to assume that only a very small portion of the national groundwater resources are being used (GCBP 2002).

4.2. Hydrogeological setting

The hydrogeology of the study zone is not well known. The field observations and the geological data allowed to distinguish two main aquifer types: one detritic (constituted by alluviums and sands with laterites) and other fractured (constituted by granites, metamorphic and metasedimentary rocks), which are the object of this study (Figure 11).

4.2.1.Hard rock aquifer systems

The Precambrian shields are among the oldest parts of the Earth’s crust. They contain hard rocks of different age, grade of metamorphism and structure. Many orogenic movements have affected the shields. Faulting processes have had different influences on the rocks due to the difference in strength of the individual rock types. These differences can easily be seen in the field.

The hard rocks in the study area are underlying the undifferentiated quaternary deposits and, where exposed, are covered by dense vegetation. In the lack of detailed and precise geological maps, and due to the extent of the study area, satellite data and GIS techniques were required to identify the recharge and discharge areas.

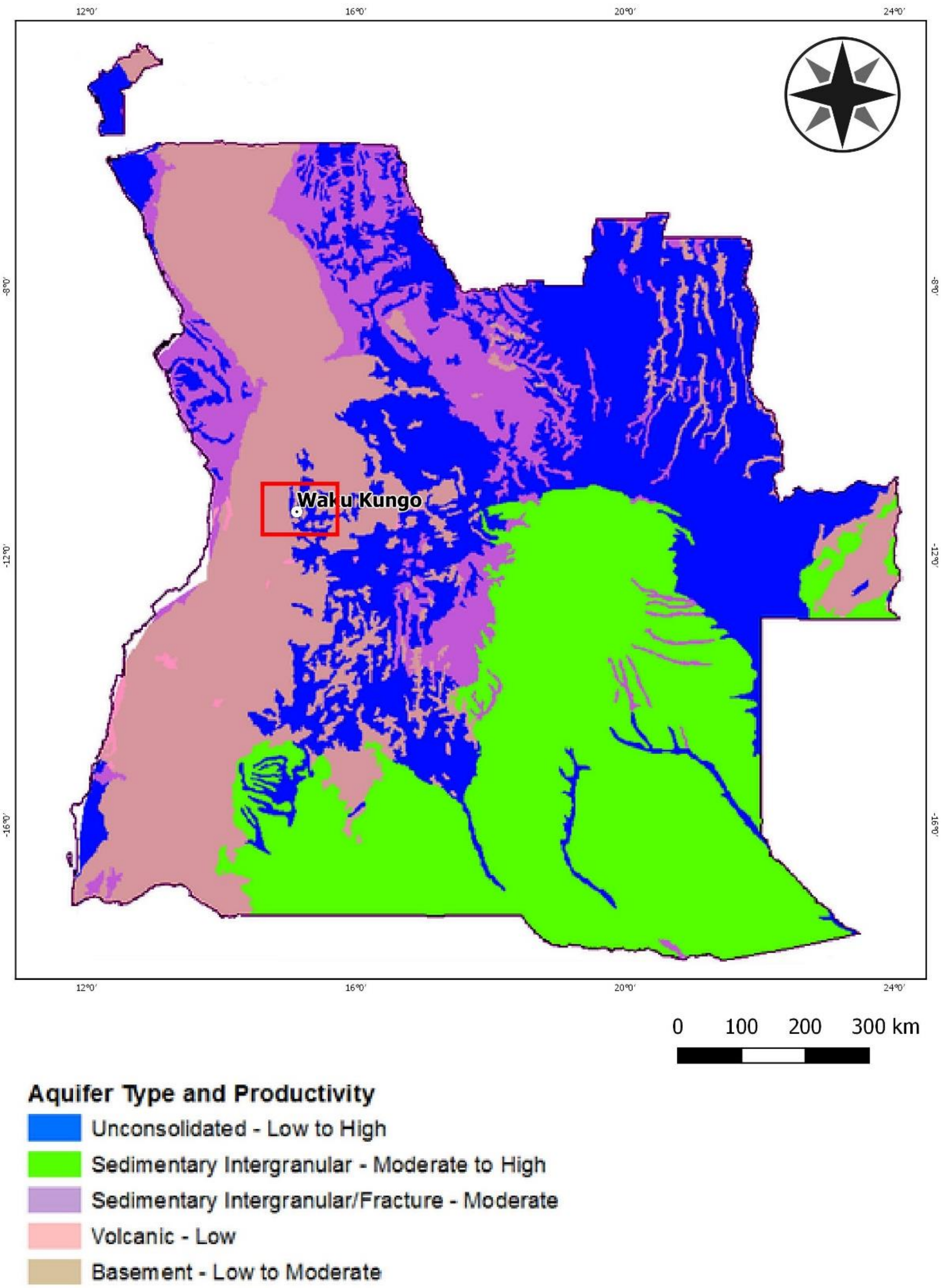


Figure 11 Regional context of aquifer type and productivity in the study area (hatch lines rectangle).

Petrological characteristics of the main hard rocks in the aquifer system were described in Chapter 3. The yields of the wells are normally of the order of 3 to 30 m^3/h (United Nations

Educational Scientific and Cultural Organization 1984)). In this study, the water flow of two springs was monitored. Spring W-16 had a discharge of 3.6 m^3/h on day 27 and spring W-29 had a discharge of 10 m^3/h on day 28. Other indications of productivity were informed by the owners of the wells and the information is that wells can supply between 1.5 and 10 m^3/h in 5 wells, with exception of one (the sixth one) that has 40 m^3/h.

On the one hand the relative recharge to groundwater in fractures takes place by direct infiltration from rainfall (wet season), on the other hand, recharge occurs chiefly by infiltration from streams where streams cross or closely follow open fracture lineaments (Figure 12).

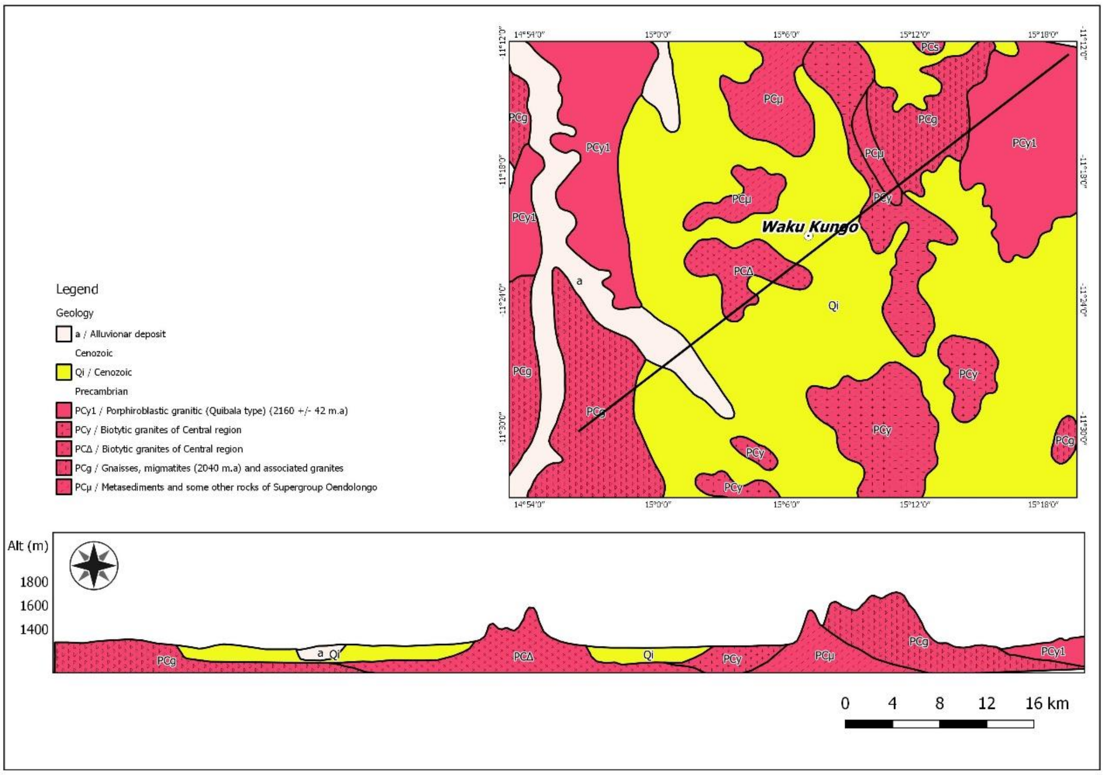


Figure 12. Hydrogeological profile of study area.

4.2.2.Sedimentary rocks

The sedimentary rocks in Wako Kungo region are composed by porous unconsolidated and consolidated rocks. In these kind of rocks, porosity is given by the space between the rocks grains and groundwater is stored in these open porous spaces. Rocks and sediments near the surface are under less pressure than those at significant depth and therefore tend to have more open space. For this reason, and because it’s expensive to drill deep wells, most of the groundwater that is accessed by individual users in the study area is within the first 50 m of the surface. Just a few farmers get groundwater from deeper levels.

Sedimentary rock formations are exposed over approximately 70% of the earth's land surface. These sedimentary formations are typically hundreds to thousands of meters thick, and they are underlain by the igneous and metamorphic rocks that make up the rest of the crust (Earle 2006) (Figure 13).

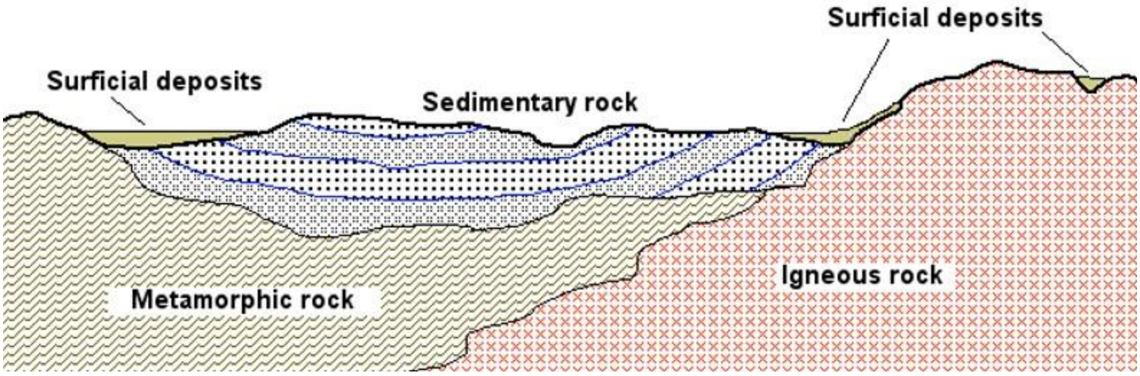


Figure 13. Example of sedimentary rocks over igneous and metamorphic rocks (Earle 2006).

Sedimentary rocks are formed close to the surface of the earth at relatively low temperatures and pressures. Clastic sedimentary rocks are formed by weathered and transported fragments of other rocks and minerals, in this case, by the decomposition of the igneous rocks present in the area. Depending on the degree of sorting and rounding of those fragments, and the extent to which they are cemented together, clastic sedimentary rock can be quite porous. Some clastic sedimentary rocks are also relatively soft and weak, and are easily susceptible to fracturing. Most sedimentary rocks also have some bedding features that can enhance porosity (Earle 2006).

In the study area, the sedimentary formations include undifferentiated quaternary deposits such as alluviums and laterites (ferruginous shields). They are "unconsolidated" because they have not been around long enough, and have not been buried deep enough to have become lithified. In the area of Waco Kungo, these sediments will just be a few tens of meters deep and the impressive outcrops of igneous rocks are seen everywhere.

Both consolidated and unconsolidated sedimentary rocks are important as aquifers (Figure 14), and are the most important origins of groundwater in the region, once they tend to have the highest porosities and permeabilities in the region.

In the study area surficial deposits more than a few metres thick are very important sources of groundwater, partly because they tend to have quite high porosities and permeabilities, and also because they are amenable for the development of shallow wells (Figure 15).

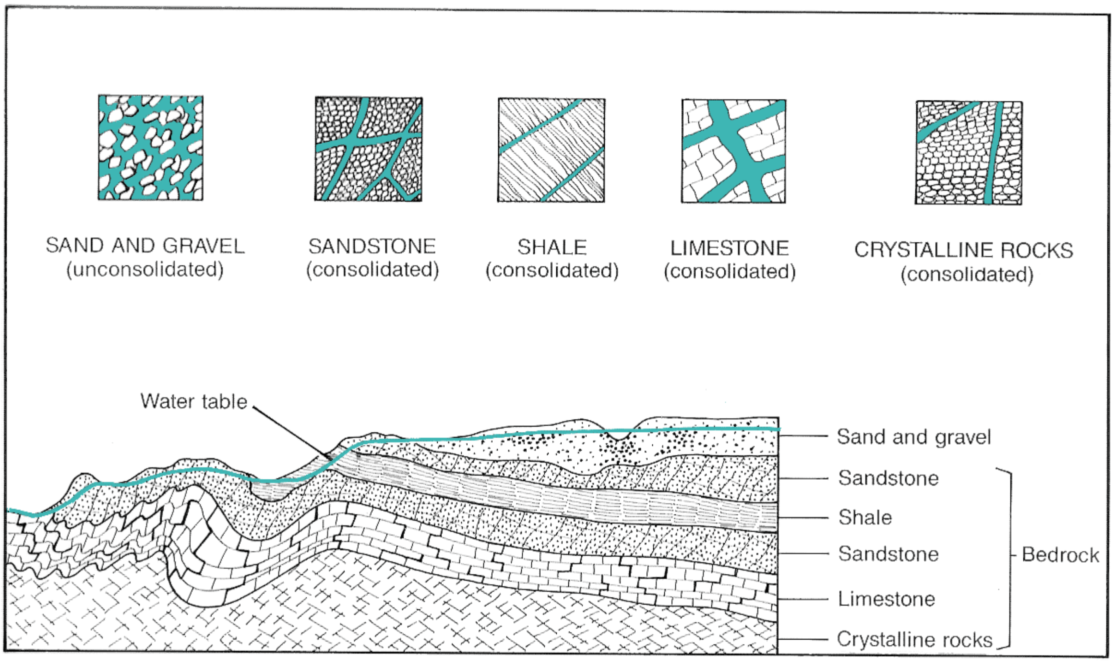


Figure 14. Aquifers can be composed of a variety of rock types with different water-bearing properties. Unconsolidated and consolidated sedimentary rocks are between the most productive in terms of groundwater abstraction rates (Water resources education network in: http://wren.palwv.org/pubs/primer.html).

Figure 15. Hand-dug wells in the study area.

4.3. Groundwater use

In Angola, most urban centres are supplied from surface water, but the provincial capitals of Malange, Benguela, Lubango and Namibe, as well as the urban centres of Tômbwa and Lobito rely on groundwater to a greater or lesser extent. In general, groundwater use is concentrated in southern and coastal areas where conditions are more arid and surface water is less available.

Additionally, groundwater is being increasingly developed for local systems to augment urban supply in the rapidly growing peri-urban areas, particularly Luanda (GCBP 2002).

Rural areas largely rely on groundwater, from boreholes, hand-dug wells and springs. In areas where existing water supply systems are no longer working or have not been developed, surface water is more widely used.

Another major use of groundwater is for livestock in the southern provinces. Water supply for livestock watering is co-ordinated by the Ministry of Agriculture, and groundwater is supplied through wells equipped with either manual or powered submersible pumps. In a 1973 survey there were 943 boreholes and 319 wells supporting such systems. The present number is not available, but based on recent figures available from Cunene Province, where 125 out of 607 systems are working, the current number of operable systems is likely to be less than in 1973. However, individual farmers and ranchers also commonly construct boreholes and wells in these southern areas (GCBP 2002).

In the study area, groundwater is essentially used for agriculture and livestock, and only a small percentage is used for public supply.

4.4. Groundwater management and monitoring

Presently, the National Directorate for Water (DNA) is responsible for the water supply and water resources management.

In 2002 there was no formal institution responsible for data collection related to groundwater. However, since 1996, DNA have carried out annual field surveys of the operational status of water supply systems, including boreholes and hand-dug wells, to assess the status of water supply coverage. During these field campaigns, the collected data includes the location of boreholes and hand-dug wells; the number of users of each borehole or well; the borehole/well depth, the phreatic water level; the type and mark of pump; the name of a responsible person; and the maintenance record over the previous year. This field information is kept in paper form in the DNA archive for future use, and used to compile annual reports summarizing the total number of water point sources by province and a summary of their operational status. In 2002 there were records of over 3600 groundwater points in all country (GCBP 2002), which is clearly a short number for such a big country. This means that probably a huge number of wells are not registered.

5. USE OF REMOTE SENSING AND GIS IN HYDROGEOLOGY

The concept of using modern techniques like Remote Sensing (RS) and Geographical Information System (GIS) in groundwater assessment is comparatively new.

Remote sensing, in general terms is defined as collecting and interpreting information about a target without physical contact with the object (Sabins 1986 in Kovalevsky *et al.* 2004). The observations are usually made from aircrafts or satellites. The term 'remote sensing' is commonly restricted to methods that employ electromagnetic energy (light, heat, radar waves) as a means of measuring the characteristics of the earth's surface. Moreover, the gravity field of the Earth is also measured for groundwater studies, but the spatial resolution of this method (in the range of 100 km) is not suitable for our study. Some of the most commonly used RS products are aerial photographs and satellite images (Kovalevsky *et al.* 2004).

A geographical information system (GIS) is a computer system for capturing, storing, checking, integrating, manipulating, analysing and displaying data related to positions on the Earth's surface. It is thus a way of linking databases with maps, to display information, perform spatial analyses or develop and apply spatial models (WHO 2017).

5.1. Physical fundamentals of remote sensing

5.1.1. Electromagnetic radiation

Electromagnetic radiation is a wave phenomenon propagating with the speed of light, which is 3.10^8 m/sec.

For waves the velocity (c), wavelength (λ) and frequency (f) are related by the equation (Equation 3):

$$c = \lambda \cdot f \qquad (3)$$

The different classes of EM radiation, such as X rays, UV, visible light, infrared, radar and radiowaves are based on the wavelength or frequency. Figure 16 gives an indication of the nomenclature of different wavelength ranges.

5.1.2. Interactions with matter

Figure 17 schematically depicts the interaction mechanisms between electromagnetic radiation and matter. When the radiation encounters matter it is called the incident radiation. The following interactions can take place: reflection, scattering, transmission, absorption and emission. The interaction between EM radiation and matter is usually a combination of the basic interaction phenomena described above. What is important is that all interactions vary as a function of the wavelength. Some of these interactions are recorded by a remote sensing system and the characteristics of the matter may be interpreted. By far the most important properties recorded are the reflection characteristics.

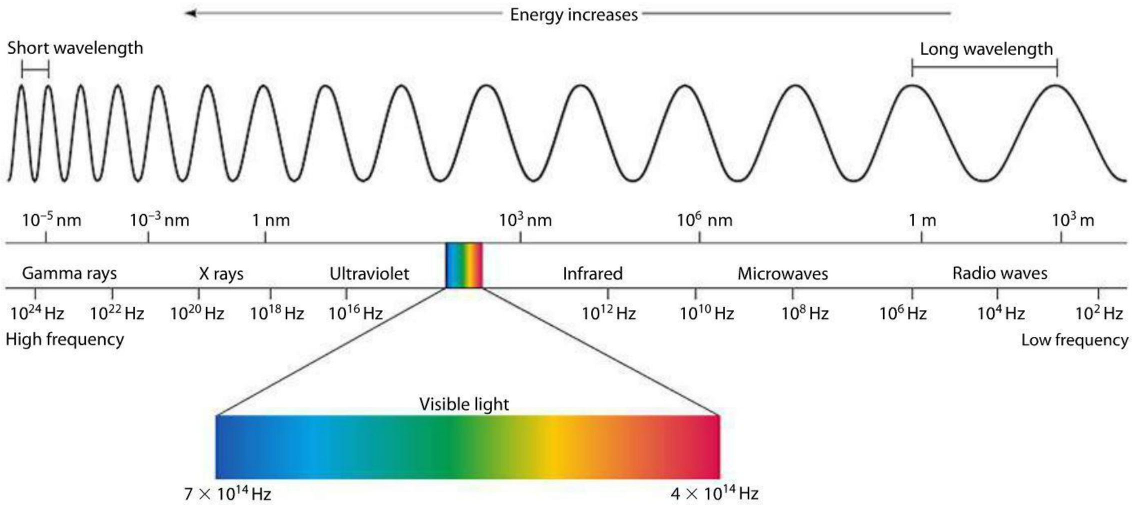


Figure 16. The electromagnetic spectrum (https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html)

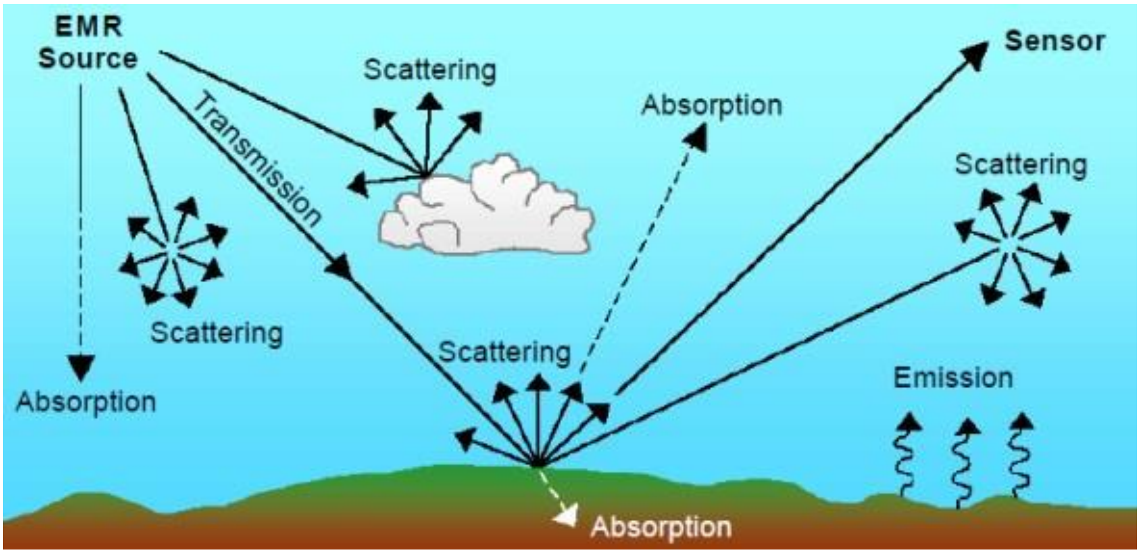


Figure 17. Interaction between EM radiation and matter (Daneshgar 2015).

As remote sensors cannot detect groundwater directly, the presence of groundwater is inferred from different surface features derived from satellite imagery such as geology, landforms, soils, land use/ land cover, surface water bodies, etc., which act as indicators of groundwater existence (Todd and Mays 2005; Jha and Peiffer 2006 in Chowdhury *et al.* 2009).

5.2. Geographical information systems

Geographical information systems, has been a fast-developing technology in spatial information processing. An overlap exists with pure image processing and many software packages offer both image processing and GIS capabilities. GIS can enter, store, retrieve, process and display spatial information in the form of maps or images (satellite, aerial photographs) including a database which is linked to the mapping units (Meijerink *et al.* 1987). On map three elementary entities can be distinguished: points, lines or segments and surfaces or polygons. Points may represent villages, wells, met stations, lines may represent roads, rivers, faults, whereas polygons may represent countries, districts, soil classes, geological formations, or any other mappable units. Information on the points, lines, polygons are called attributes and are stored in a database.

One record in the database contains the information on a geographical entity (point, line, and polygon). The attributes stored in the database can be the number of lanes, quality, type, etc. of a road, the discharge, water quality, etc. of a river, the names, population, number of schools, etc. in towns and villages, the population of a district, etc., soil data like permeability, thickness, salinity, etc.

The two main data structures to store spatial information are vector and raster data structures (Figure 18).

The raster data structure used in a GIS is also used to store satellite images. Many models (groundwater, surface water, erosion, crop yield) use a raster as their main data structure, and Digital Elevation Models (DEM) can also be represented in a raster data structure. A cell of a raster based GIS representing a certain soil, may also represent a pixel with a certain digital number (DN) from a satellite image, or represent a cell in a groundwater model for which the phreatic level can be calculated. The only condition is that the raster should represent the same area on the ground and the raster dimensions and cell sizes must be equal in all cases. All spatial data can be integrated in a GIS by their thematic map units, remotely sensed images, administrative boundaries, topography, demographical data, towns, roads, wells, rivers, interpolated data from rainfall or groundwater levels, the simulated water levels, or river discharges.

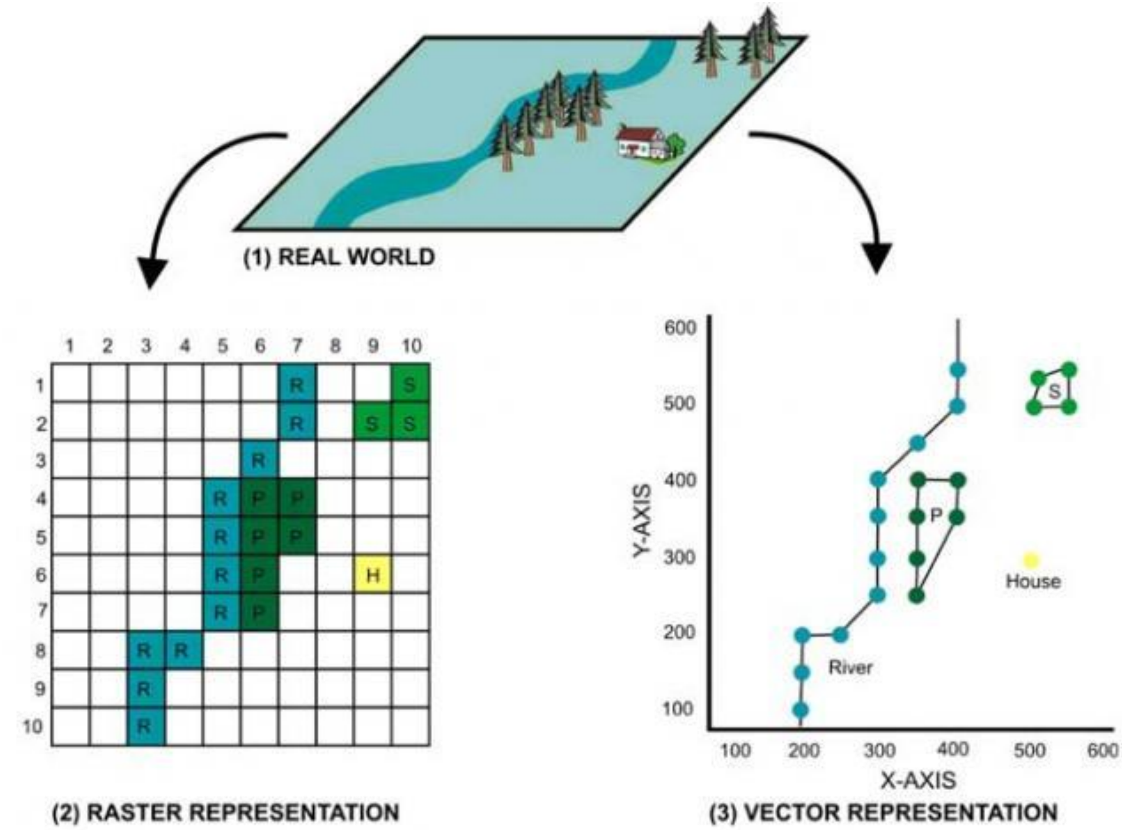


Figure 18. Raster and vector data structures (gisgeography.com).

GIS has the ability of processing the information, which may reveal certain relationships, and visualizing different types of information simultaneously. In contrast, remote sensing (RS) technology, with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time, has emerged as a very useful tool for the assessment, monitoring and management of groundwater resources (Engman and Gurney 1991, Jha *et al.* 2007).

Moreover, geographic information systems (GIS) have emerged as powerful tools for handling spatial data and decision-making in several areas including engineering and environmental fields. Since the delineation of groundwater prospect zones involve a large volume of multidisciplinary data, an integrated application of RS and GIS techniques has become a valuable tool.

The hydrogeologic interpretation of satellite data has been shown to be a valuable survey tool in areas of the world where little geologic and cartographic information exist or is not accurate, as well as in inaccessible regions of the world (Engman and Gurney 1991).

Remote sensing and GIS have been widely used for the preparation of different types of thematic layers and integrating them for the different purposes (Saraf and Choudhury 1998). Integration of these two techniques has proved to be an efficient tool in groundwater potential and several other studies and have been conducted in various parts of the world (Raj and Sinha 1989, Baldev *et al.* 1991, Gustafsson 1993, Shahid *et al.* 2000, Taylor *et al.* 2013, Abdelkareem and El-Baz 2014)

6. HYDROGEOCHEMISTRY

Hydrogeochemistry is defined as the study of the chemical characteristics of ground and surface waters as related to areal and regional geology (Dictionary of Earth Science 2002). In the field of hydrogeochemical studies, hydrochemistry is a scientific approach used to understand the hydrogeochemical process evolution of water quality, to examine human impacts against natural conditions and take a look at how the protection and management of water resources can be achieved (Prasanna *et al.* 2011).

6.1. Hydrogeological inventory and water points characterization

The hydrogeological field study was based on the inventory of water points in the region, mainly based on drilled wells, hand dug wells and springs, to better understand the behaviour and characteristics of water in fractured rocks. One sample was also collected in a river, in order to know if the characteristics of the river water was similar to the regional groundwater.

The inventory was performed from 26th July, 2016 to 29th July, 2016, using also physical-chemical field analysis equipment, and the following parameters were systematically measured at each point:

- temperature
- electrical conductivity

At the same time other data was recorded, related with location of wells, elevation, lithologies representing the water points' location, hydrostatic levels, water flow and physical data of the water points, such as depth, diameter, grouting type and its greater or lesser protection against surface contamination (Annex I).

From this study a sampling map was created (Figure 19). Taking into account the spatial distribution and representativeness, some water samples were later collected for physical-chemical laboratory analyses. From this screening, it resulted in a total of 14 samples distributed in the following order of priority and representativeness: springs, dug wells, drilled wells and rivers (Figure 20). Pictures of all the points were groundwater was collected for laboratory chemical analysis are shown in Annex II.

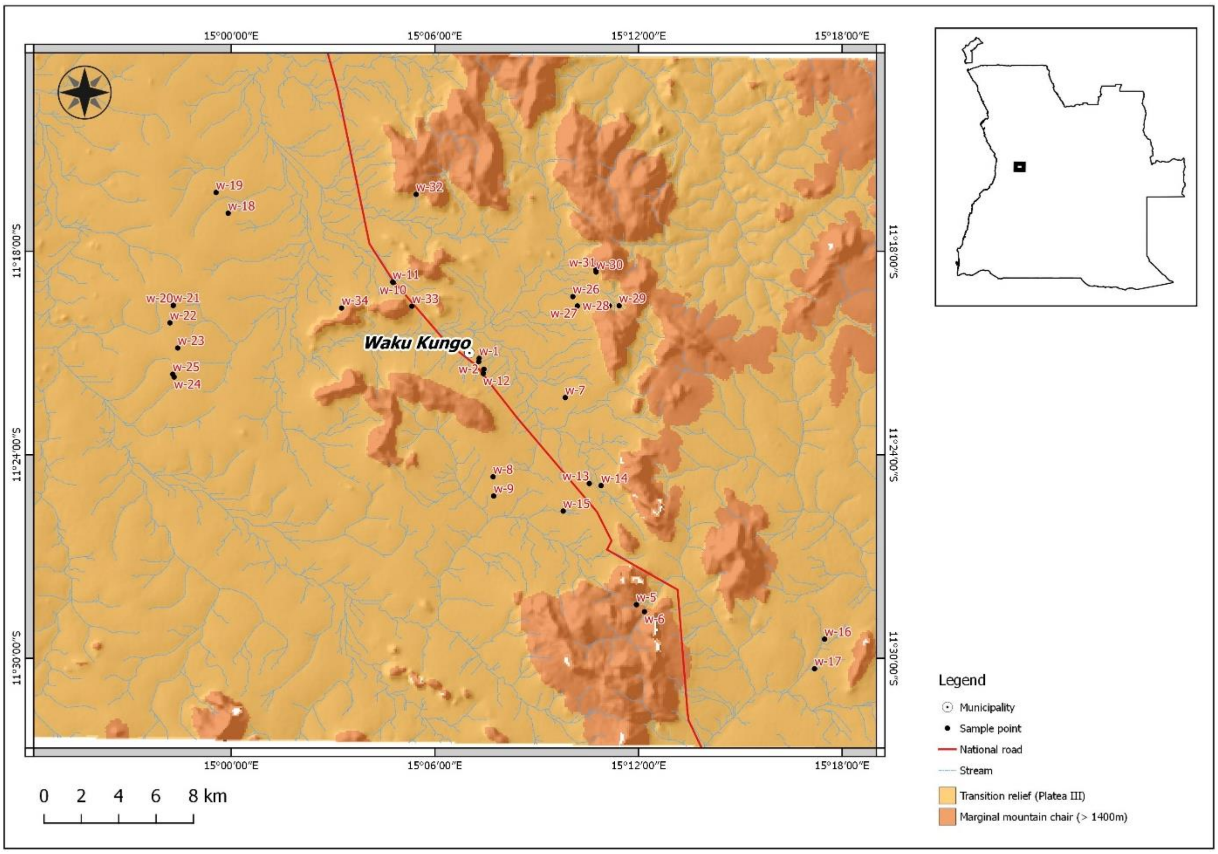


Figure 19. Location and water point's distribution.

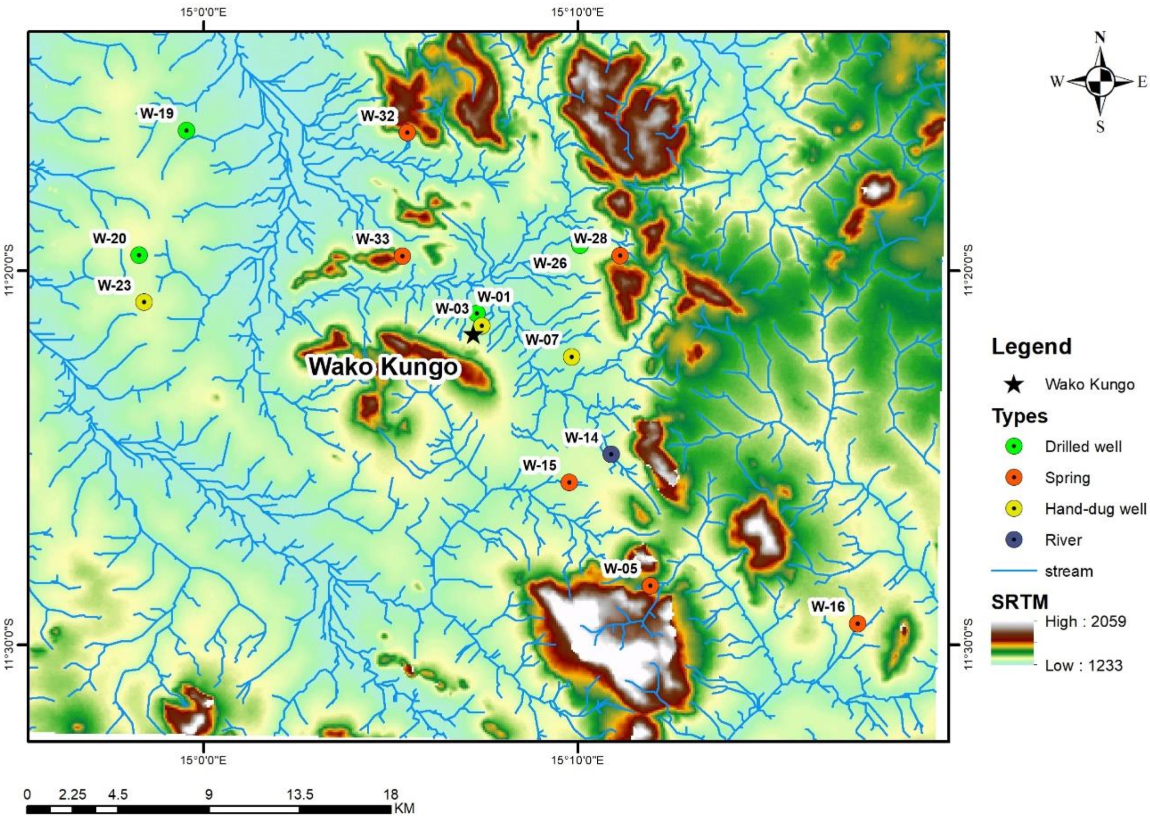


Figure 20. Sampled points in the study area.

6.2. Water hydrochemical characterization

To access the water chemistry, a representative water sample collection was done after the on-spot measurements. Sampling points for water quality investigation were selected based on geomorphology, geological formation and spatial representation. About 34 water points were monitored, and 14 water point samples were collected for physic-chemical laboratory analyses.

The water samples were collected using acid-washed polyethylene plastic bottles of 500 ml and acidified with nitric acid for cation and anion analysis. Samples bottles were tightly capped, labelled and preserved in the refrigerator. A detailed description is summarized in Table 2, the location and distribution can be seen in the Figure 20.

The following methods were used to determine the physic-chemical water parameters:

- Temperature (in place): WTW digital thermometer;
- Electrical conductivity: WTW digital conductivity meter.
- Other parameters such as pH, alkalinity, total hardness, TDS, calcium, magnesium, chlorides and others, were measured in laboratory in accordance with Presidential Decree 261/11 of October 6 of the Angolan Law, whose analytical methods are well described in Annex II.

Table 2. Description of the type of water points for sample collection

Type of water points					
	Drilled well	Spring	Hand-dug well	River	Total
Sample point	10	12	11	1	34
Sample collected	4	6	3	1	14

6.3. Critical analysis of the analytical results

The samples collected were sent to two reference laboratories in Angola and results are found in Annex III. From the obtained results it was observed that:

- from different resources only 45 per cent of results from water quality data fulfilled the acceptable requirement for classification;
- some essential parameters for water classification, such as anions, were not measured due to lack of reagents;
- others did not present acceptable values for classification due to the limits of quantification defined by the respective analytical methods;

- from the major essential elements for water classification, it was only possible to obtain the cation results (Ca^{2+}, Mg^{2+}, Na^{+}).

To fill some deficiencies, a database that integrates the results obtained in the two laboratories was created, to classify the referred samples (Table 3). Represented in this table are also the laboratory results that are under the detection limits, which were not considered in our analysis.

Table 3. Hydrogeochemical analysis summary result.

Station ID	Alkalinity (mg/l)	HCO_3 (mg/l)	Ca (mg/l)	EC (µS/cm)	Total hardness (mg/l)	Fe (mg/l)	Mg (mg/l)	NO_3 (mg/l)	pH	K (mg/l)	TDS (mg/l)	Si (mg/l)	Na (mg/l)
W-01	88.0	108.0	4.0	197.0	78.0	0.2	3.5	8.0	7.0	3.1	126.0	0.8	8.7
W-03	10.0	-	0.8	115.0	<17.99(LQ)	0.3	0.1	20.0	3.7	1.0	74.0	0.4	4.5
W-05	<5(LQ)	-	0.7	71.0	<17.99(LQ)	2.5	0.1	18.0	3.9	1.2	46.0	0.3	1.2
W-07	<5(LQ)	-	1.6	123.0	<17.99(LQ)	0.2	0.2	17.0	3.6	0.8	79.0	0.3	0.7
W-14	<5(LQ)	-	<0.01	37.0	<17.99(LQ)	0.1	<0.01	9.0	4.3	0.8	24.0	0.3	0.6
W-15	<5(LQ)	-	1.3	92.0	<17.99(LQ)	0.2	0.4	17.0	3.8	1.7	59.0	0.3	0.5
W-16	<5(LQ)	-	1.3	44.0	<17.99(LQ)	0.1	1.1	14.0	4.5	0.4	28.0	0.3	1.2
W-19	51.0	62.0	2.8	148.0	52.0	0.1	1.6	16.0	6.3	4.0	95.0	0.6	8.8
W-20	18.0	22.0	1.0	86.0	<17.99(LQ)	0.2	0.6	13.0	6.2	4.6	55.0	0.5	6.1
W-23	<5(LQ)	-	4.0	77.0	<17.99(LQ)	0.1	0.4	14.0	4.0	1.4	49.0	0.4	1.2
W-26	<5(LQ)	-	1.3	104.0	<17.99(LQ)	0.1	0.2	13.0	6.1	1.8	67.0	0.5	10.9
W-28	<5(LQ)	-	0.04	47.0	<17.99(LQ)	0.1	<0.01	16.0	5.7	1.0	30.0	0.3	4.5
W-32	9.0	11.0	1.2	57.0	<17.99(LQ)	0.1	0.2	13.0	6.3	0.8	37.0	0.3	6.0
W-33	<5(LQ)	-	0.9	77.0	<17.99(LQ)	0.1	0.2	20.0	4.2	1.0	49.0	0.3	3.9

Notes:
The results expressed in the form <X are below the limit of quantification (LQ) of referred test method and the results presented in the form (-) were not obtained.
Sample collected from spring (w-5, w-15, w-16, w-28, w-32, w-33); drilled well (w-1, w-19, w-20, w-26); hand-dug well (w-3, w-7, w-23) and river (w-14).
The samples printed in orange are from hard rocks and samples printed in yellow are from sedimentary rocks.

6.4. Hydrochemical facies

The concept of hydrochemical facies was developed in order to understand and identify the water composition in different classes.

Among the classification methods that uses as fundamental basis the main cationic and anionic constituents present in groundwater; whose best represent the hydrochemical typology of the waters of a region continue to be the classic diagrams of Piper and Stiff (Chambel 1999).

The first one has the advantage of being able to show the total number of samples in a single diagram, obtaining an overview that allows analysing the general quality of these waters. Each chemical analysis is represented by three points, one for the cations, another for the anions, and a third for the cation/anion pairs.

In the case of the Stiff diagrams, each water sample corresponds to a polygon that expresses the relation between the main ions and the total mineralization.

However, and because in this study the chemical analysis was not complete, in the present study water types is given using just a ternary diagram.

Ternary diagrams are commonly used to determine the relationship between the concentrations of three different parameters in multiple samples. Like the Piper and Stiff, the ternary diagram displays relative concentrations of each parameter with respect to the sum of the concentrations of each parameter. Each vertex of the Ternary plot represents a relative concentration of 100% for the parameter at the respective vertex, while the base represents a relative concentration of 0% for the parameter plotted at the opposite vertex.

In general, the water samples can be classified as sodium, with a calcic tendency.

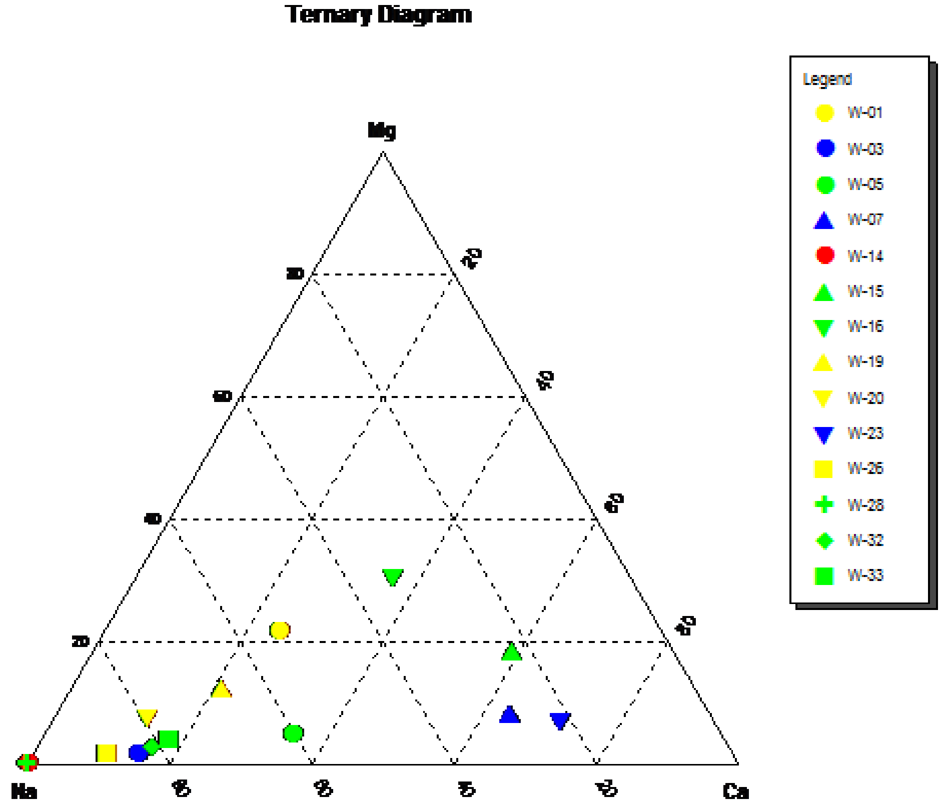


Figure 21. Water type classification of water points using Ternary diagram.
Legend: Blue-springs; Green-hand-dug well; Yellow-borehole; Red-river.

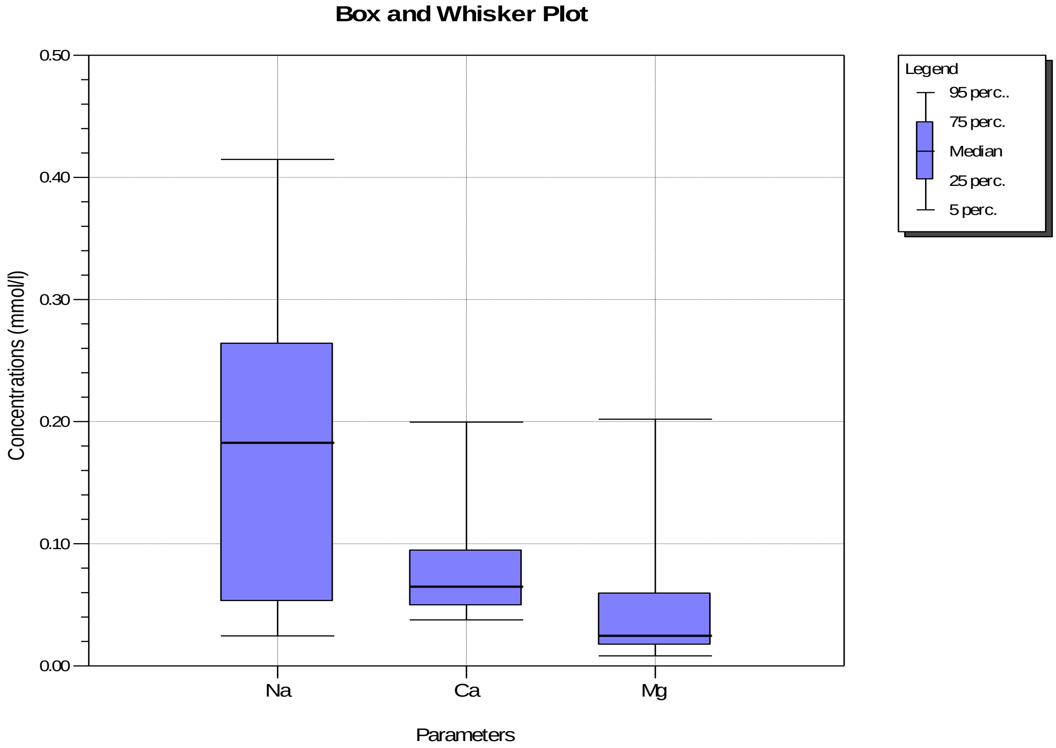
6.5. Statistical analysis

The main statistical data on the several physical-chemical parameters analysed can be seen in Table 5, based on the 14 physic-chemical laboratories analyses performed.

The number of samples analysed is not the same for all parameters, since in some cases, it was not possible, either because of an analytical error or simply due to the low limits of quantification defined by the laboratories that carried out the analysis. The total hardness, alkalinity and bicarbonate anion are examples of the first case, in turn the chlorides and sulphates fall into the second case.

It is verified that the median values are generally lower than the average values, and this tendency is observed especially in the case of electrical conductivity. This means that for this parameter there are points with extremely high values. Thus, the median has the particularity of smoothing the anomalous effects caused by extreme values and better projecting the reality of a set of values.

The box and whisker plot (Figure 22) represents, schematically, the ranges of variation, maximum and minimum, the 1st and 3rd quartiles, and the value of the median relative to the analysed cations for the 14 water samples.



.Figure 22. Box diagrams for sodium, calcium and magnesium.

For calcium and magnesium, the median and 3rd quartile values are relatively close. In terms of amplitude of values, sodium presents value higher than the parameters already mentioned, with a maximum of 10.9 mg/l.

The groundwater mineralisation of the hard rock and sedimentary aquifers is very low in both of them, as it can be seen in Table 4.

Table 4. Statistics for Ca, Na and pH parameters for hard rocks (6 samples) and sedimentary rocks (3 samples) in the study area.

	Hard rock				Sedimentary rock			
	EC	**pH**	**Ca**	**Na**	**EC**	**pH**	**Ca**	**Na**
Average	63.4	4.9	0.9	3.2	105	3.8	2.1	2.1
Median	57	4.5	1.2	3.9	115	3.7	1.6	1.2

Even so, a slight difference can be noted:

- The Electrical Conductivity (EC) in the hard rocks is half of the one in the sedimentary rocks
- pH is acid in both of them, but lower in the sedimentary aquifer;
- Calcium content is slightly lower in the hard rock aquifers than in the sedimentary aquifers;
- Sodium content is higher in the hard rock aquifers than in the sedimentary ones.

The low values of total mineralisation, reflected in the low values of EC, show that the groundwater cycle is short and quick in this area and probably the mineralogical composition of both sedimentary and igneous rocks is strongly stable and resistant to weathering. Granites have normally the most resistant mineralogical composition (quartz, feldspar and micas) of all the igneous rocks. The sedimentary rocks are probably also mainly quartz sand, which is also highly resistant to weathering. The higher levels of sodium in the hard rocks can be originated in some Na-plagioclase still present in the granites and the higher level of calcium in the sedimentary rocks can be justified by some calcium shells incorporated in the sediments (snails for example). At the same time, the lower level of calcium in the hard rocks shows that the Ca-plagioclase is probably not present in the igneous rocks. The low level of pH shows the acidic composition of groundwater. With this chemical power to attack the minerals and the low levels of ions in the water, it is shown that the minerals are highly resistant to weathering and/or the water contact time with the rock is short.

Table 5. Statistical parameters of the hydrochemical variables of the points sampled.

Parameters	Alkalinity	HCO_3	Ca	Cl	Cond.	Total hardness	Fe	Mg	Mn	NO_3	pH	K	TDS	Si	SO_4	Na
Nº Samples	6	4	14	0	14	2	14	14	0	14	14	14	14	14	0	14
Unit	mg/l	mg/l	mg/l	mg/l	µS/cm	mg/l	mg/l	mg/l	mg/l	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l
Average	33.7	50.8	1.5		91.1	65.0	0.3	0.6		14.9	5.0	1.7	58.4	0.4		4.2
Variance	787.6	1452.7	1.5		1806.4	169.0	0.4	0.8		12.0	1.4	1.5	740.4	0.0		11.4
Standard deviation	28.1	38.1	1.2		42.5	13.0	0.6	0.9		3.5	1.2	1.2	27.2	0.1		3.4
Minimum	9.0	11.0	0.0		37.0	52.0	0.1	0.0		8.0	3.6	0.4	24.0	0.3		0.5
1º quartile	12.0	19.3	0.9		60.5	58.5	0.1	0.2		13.0	3.9	0.9	39.3	0.3		1.2
Median	22.0	42.0	1.2		81.5	65.0	0.1	0.2		15.0	4.4	1.1	52.0	0.3		4.2
3º quartile	44.8	73.5	1.5		112.3	71.5	0.2	0.5		17.0	6.2	1.8	72.3	0.5		6.1
Maximum	88.0	108.0	4.0		197.0	78.0	2.5	3.5		20.0	7.0	4.6	126.0	0.8		10.9

6.1. Distribution of hydrochemical variables

The classes of values for the representation of each parameter were stipulated taking into account the recommended maximum values (VMR) and / or admitted (VMA) by Decree-Law no. 261/2011 of October 6, annex I of the Angolan law, which establishes the "water quality regime for human consumption".

The punctual distribution of each of the physical-chemical parameters analysed is presented below, and it can be seen that all the detected values are much lower than the upper limits recommended by law.

6.1.1. Temperature

Temperature is an important factor affecting the solubility of salts and gases, the speed of chemical reactions and the biochemical processes that accompany the variations of the concentration for minerals and organic substances, the development of microorganisms, etc. (Custodio and Llamas 1983).

Groundwater has a very low temperature and generally corresponds to the annual mean atmospheric temperature of the site, and is also a function of the depth and the geothermal gradient (Custodio and Llamas 1983).

In Wako Kungo municipality the average annual temperature is about 21°C, ranging between 22°C in wet season and 18°C in dry season (Russo *et al.* 2011).

In the study area, the natural values of temperatures are all below the maximum value allowed by the Dec.-Law in force, that is 25°C. The minimum value recorded was 15˚C and the maximum was 23˚C, but part of these temperatures was clearly affected by the air temperature at the moment, once the water for example in dug wells reflects pretty much the air temperature and even some solar direct incidence on the water inside the well.

6.1.2. pH

According to Chambel (1999), the hydrogen ion concentration $[H^+]$ is a very important value. It is, however, a very small value, so it is defined as (Equation 4):

$$\mathbf{pH = -log\,[H^+]} \qquad (4)$$

The pH value of the water is an index of its acidity or alkalinity and results from the acid/base interactions of its mineral or organic constituents, being determined mainly by the correlations between the concentrations of free CO_2 and the carbonate and bicarbonate ions.

Most groundwater has a pH between 6.5 and 8, and, in a wider band, between 5.5 and 8.5 (Custodio and Llamas 1983). In exceptional cases it can vary between 3 and 11.

According to Chambel (1999), the pH increases by 8%/°C by raising the temperature and therefore has to be given as a function of a certain temperature, in this case 20°C.

The study area presents acidic pH values, probably due to the silicic composition of the granitoids. Figure 23 shows that only one sample has a neutral pH.

So, for this parameter the water can be considered good.

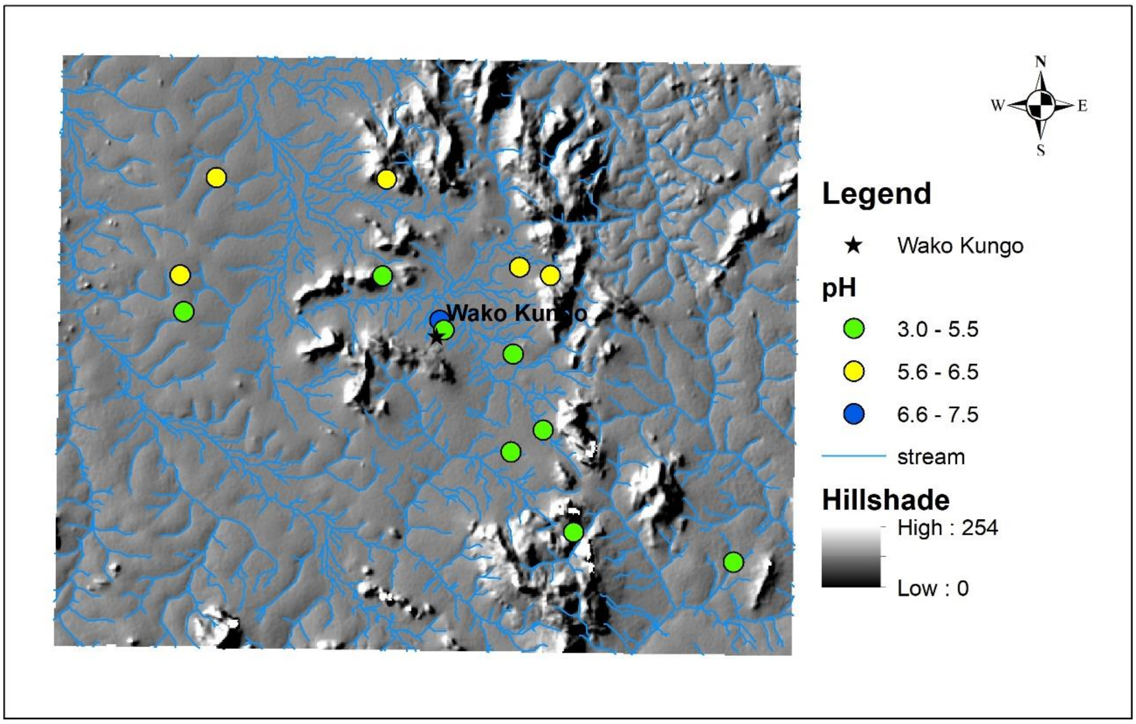


Figure 23. pH distribution values on groundwater in the study area.

6.1.3. Electrical conductivity

The electrical conductivity of a natural water is related to the total concentration of ions present and their nature. Its value is used as an evaluation index of the global mineralization of water and is measured, in this case, in μS/cm (Chambel 1999).

The conductivity increases with temperature, making it necessary to consider a reference temperature (Custodio and Llamas 1983), in this case it was 20˚C.

Figure 24 clearly illustrates that the waters of the study area shows very low mineralization, with maximum value in the order of 197 μS/cm, well below the recommended maximum value (VMR = 400 μS/cm).

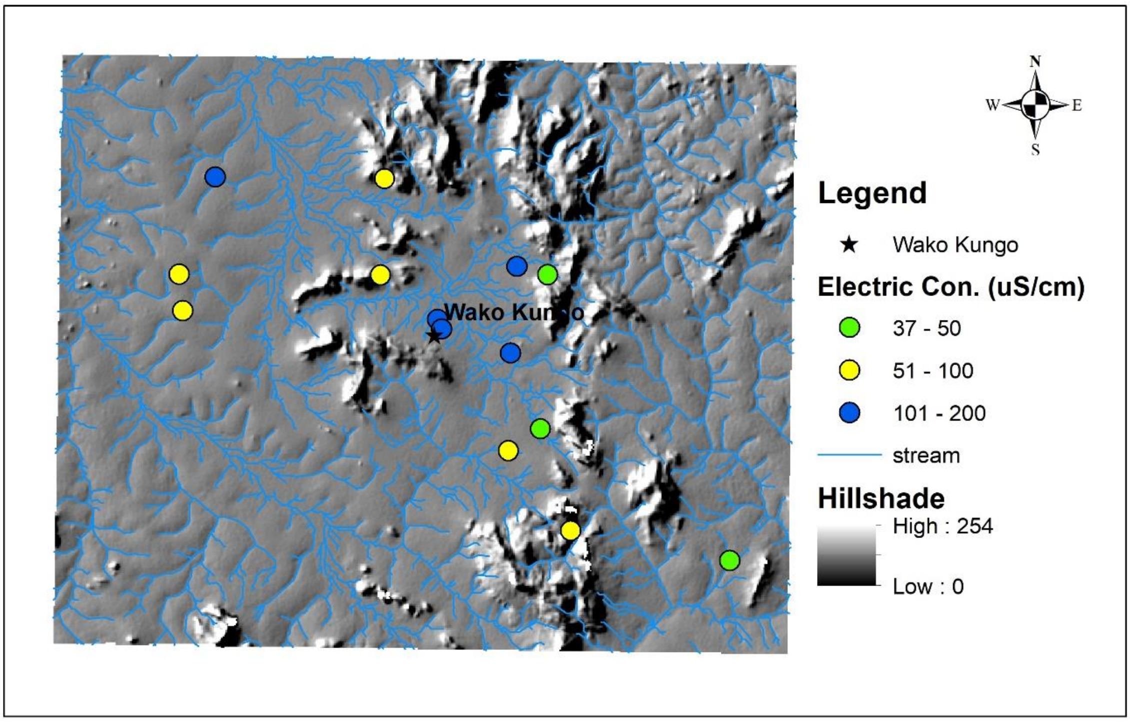


Figure 24. Electrical conductivity distribution values on groundwater in the study area.

6.1.4.Sodium

Sodium has very high solubility and is very difficult to precipitate. It is easily affected by the exchange of bases. It is usually associated with Cl^- ion, although this does not always happen (Custodio and Llamas 1983).

The distribution chart of the sodium values (Figure 25) shows the highest values in the centre and a sample in the northwest. Even so, it is observed that the waters of the region present values of sodium below the VMR (20 mg/l).

Waters with high concentrations of sodium in the soil can reduce the permeability, damaging the plants. They are especially harmful when Ca and Mg concentrations are low (Chambel 1999).

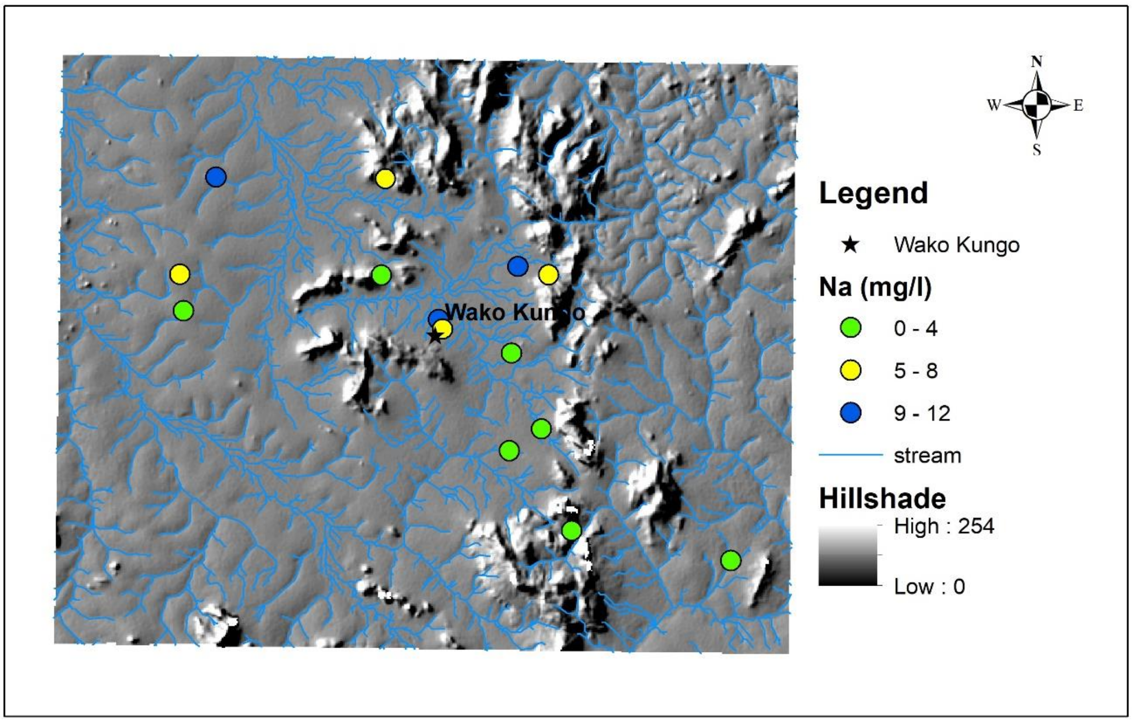


Figure 25. Sodium values distribution on groundwater in the study area.

6.1.5.Calcium

The salts are moderately to highly soluble (Custodio and Llamas 1983). It is very easy to precipitate as $CaCO_3$ and its chemistry is closely associated with that of HCO_3^- and CO_3^{-2} ions in many natural waters, and can precipitate or dissolve easily by changing the pH or partial pressure of CO_2.

Normal concentrations in freshwater vary between 10 and 250 ppm, reaching 600 ppm in waters in contact with gypsum (Custodio and Llamas 1983).

In the study area, calcium presents values much lower than the VMR (100 mg/l) (Figure 26). There is no limit value for the VMA in the Dec.-Law.

The greatest inconvenience of excess calcium is associated with increased hardness and scale production, which is not the case with local waters.

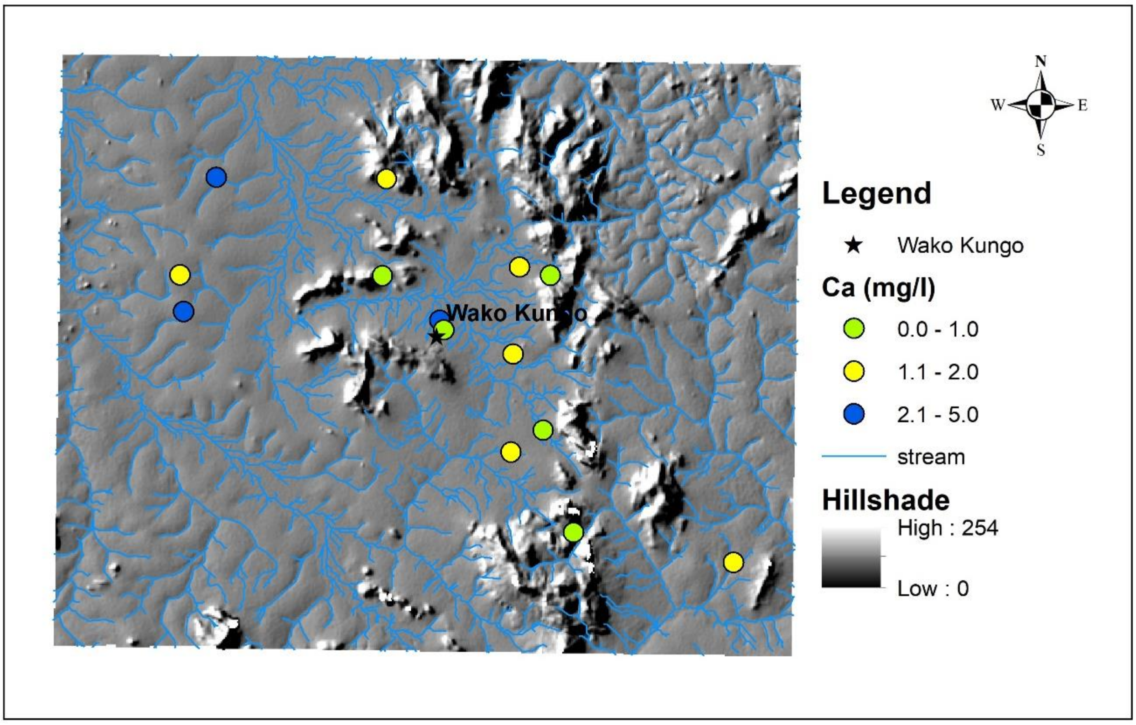


Figure 26. Calcium values distribution on groundwater in the study area.

6.1.6.Magnesium

Magnesium presents properties similar to those of calcium ion, but is more soluble and more difficult to precipitate (Custodio and Llamas 1983). Concentrations in fresh water range from 1 to 100 ppm, and can reach several thousand ppm in saline or brine waters.

Magnesium is originated by the solubilization of the minerals of the crossed lithologies and by industrial contamination. This cation, in terms of human metabolism, acts as a constituent element of the bone tissue and as an activator of abundant enzyme systems (ERHSA 2001).

Figure 27 represents the distribution of the magnesium values. It can be observed that its spatial distribution is very homogeneous, with the exception of one value in the extreme southeast and another two in the centre and extreme southwest of the area.

According to the Decree-Law, for this parameter, the VMR is 30 mg/l and the VMA is 50 mg/l, according to the samples analysed, the groundwater of the work zone, have much lower magnesium than the VMR.

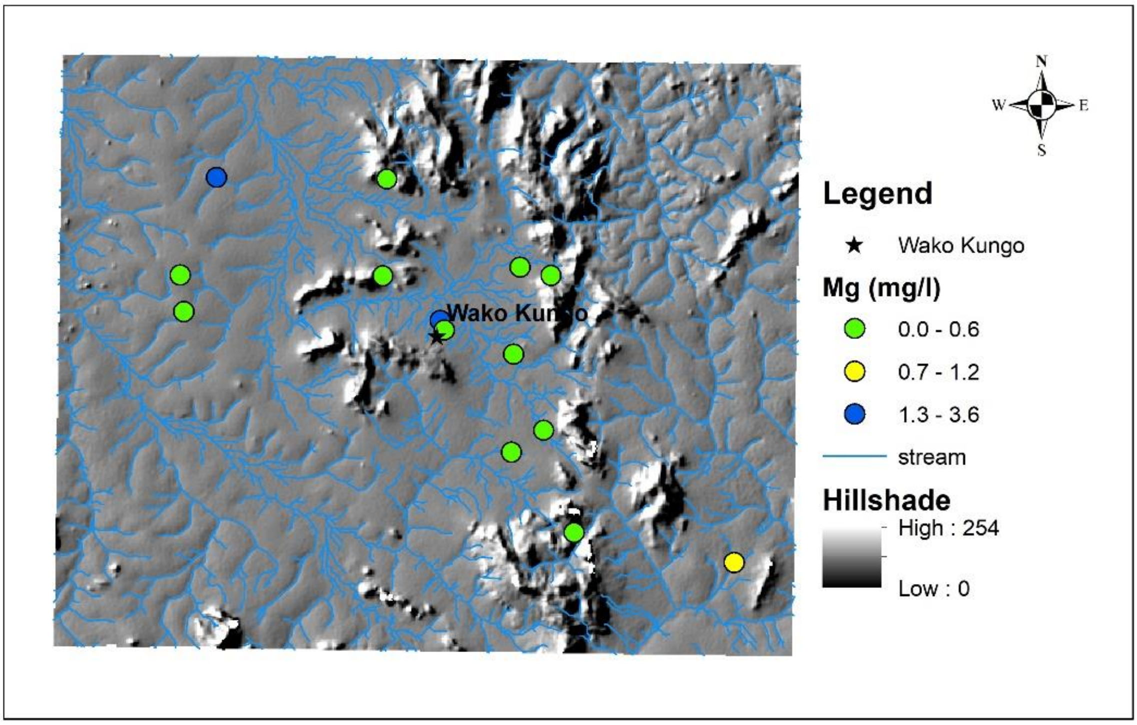


Figure 27. Magnesium values distribution on groundwater in the study area.

6.1.7. Potassium

Potassium is a chemical element abundant in the earth's crust, but occurs in small quantities in groundwater, since it is easily fixed by clays and intensively consumed by plants. This cation originates mainly from the following minerals: potassic feldspar, mica, muscovite and biotite, which are not very resistant to weathering.

The potassium distribution pattern does not present a regular trend in the study area (Figure 28).

In Decree-Law, it is defined for potassium that the VMR is 10 mg/l and the VMA is 12 mg/l. It is observed that, in general, the samples present values below the VMR.

At the usual concentrations it presents no problems and is a vital element for plants (Custodio and Llamas 1983).

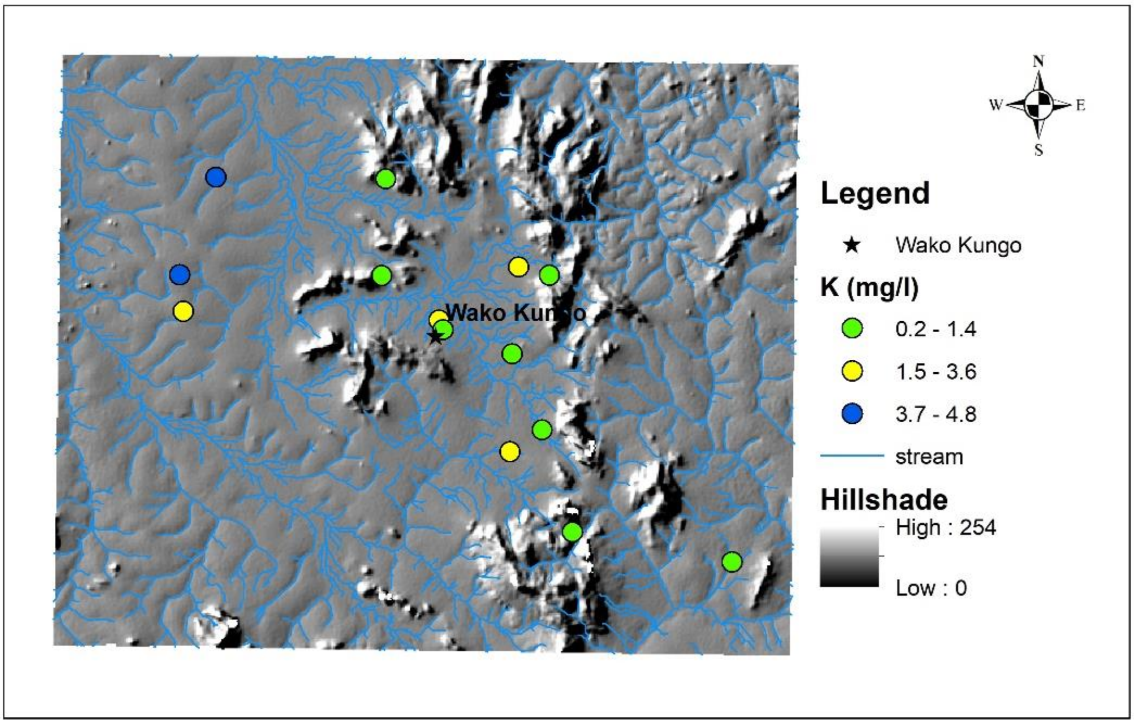


Figure 28. Potassium values distribution on groundwater in the study area.

6.1.8.Nitrates

Nitrates are normally produced in the soil by bacteria that synthesize them either by fixing atmospheric nitrogen or by decomposing organic matter of plant or animal origin (Appelo and Postma 1993, Déoux and Déoux 1996 in Chambel 1999).

The presence of nitrates in soil and water only became, however, a problem, after the Second World War, with the intensive use of nitrogen fertilizers to increase the yield of agricultural production, while intensifying animal farming, namely in stable, producing huge quantities of sludge and other wastes (Déoux and Déoux 1996 in Chambel 1999). This is an increasingly significant problem and represents one of the most important future threats to groundwater-based supplies (Appelo and Postma 1993 in Chambel 1999).

In terms of behaviour, this ion is relatively stable, but it can be fixed in soil or reduced to N_2, NH_4^+ and, exceptionally, NO_2^- in reducing environments (ERHSA 2001).

The concentration of this ion in the water can cause methemoglobinemia in latent, that is, the blue disease (Guerreiro 2014).

The distribution of the nitrates analysed in the water samples collected in the field (Figure 29) shows that, although all the values are below the VMR (25mg/l), there are more than half of them that are now higher than 10 mg/l, showing clearly an influence of agriculture and/or cattle breeding on water quality.

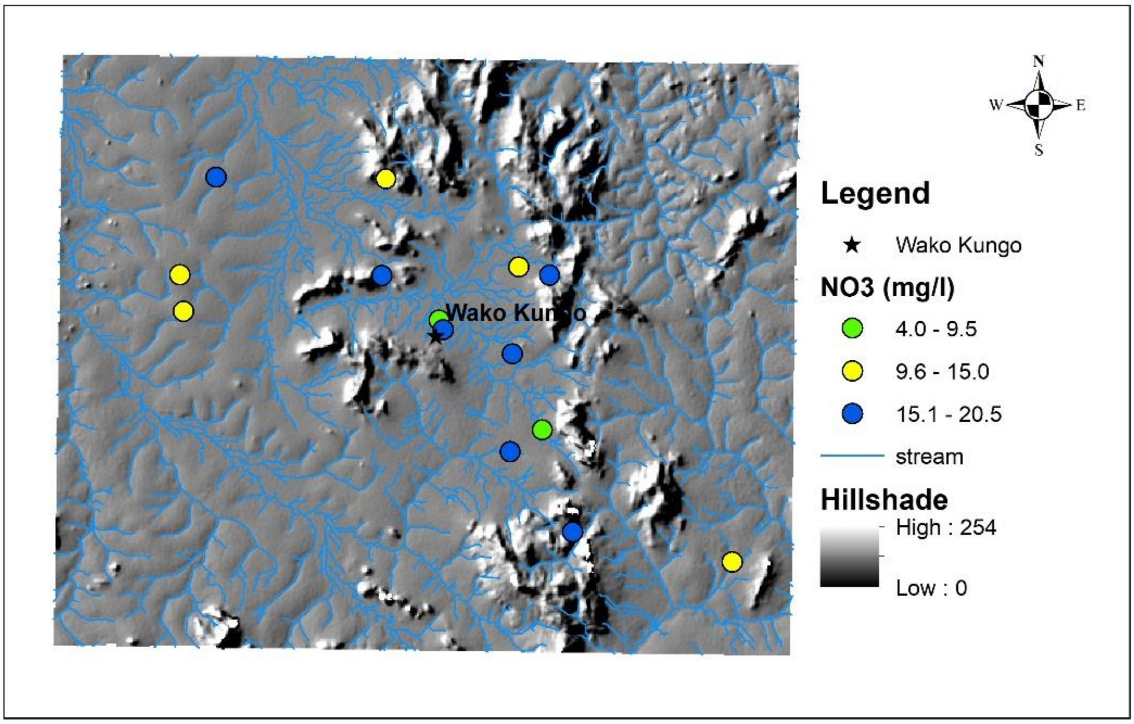


Figure 29. Nitrates values distribution on groundwater in the study area.

6.1.9. Silica

The hydrochemistry of silica is not yet fully understood, but it is believed that most of the silica is in the form of partly dissolved and partly colloidal SiO_4H_4, and only a small part is ionized ($SiO_4H_3^-$) at normal pH values (Custodio and Llamas 1983).

Quartz is very sparingly soluble, but amorphous silica is a lot more soluble.

Silica values in groundwater are in the approximate range of 5 to 85 mg/l, with the mean being 17 mg/l (Langmuir 1997 in Chambel 1999). It is a compound considered essential to human metabolism, not representing adverse physiological effects (Guerreiro 2014).

In the study area, the silica values had an average of close to 0.4 mg/l and the median was close to 0.3 mg/l. The highest values are less than 1 mg/l, thus much below the global mean levels (Figure 30).

There is no limit to the content of silica in the legislation.

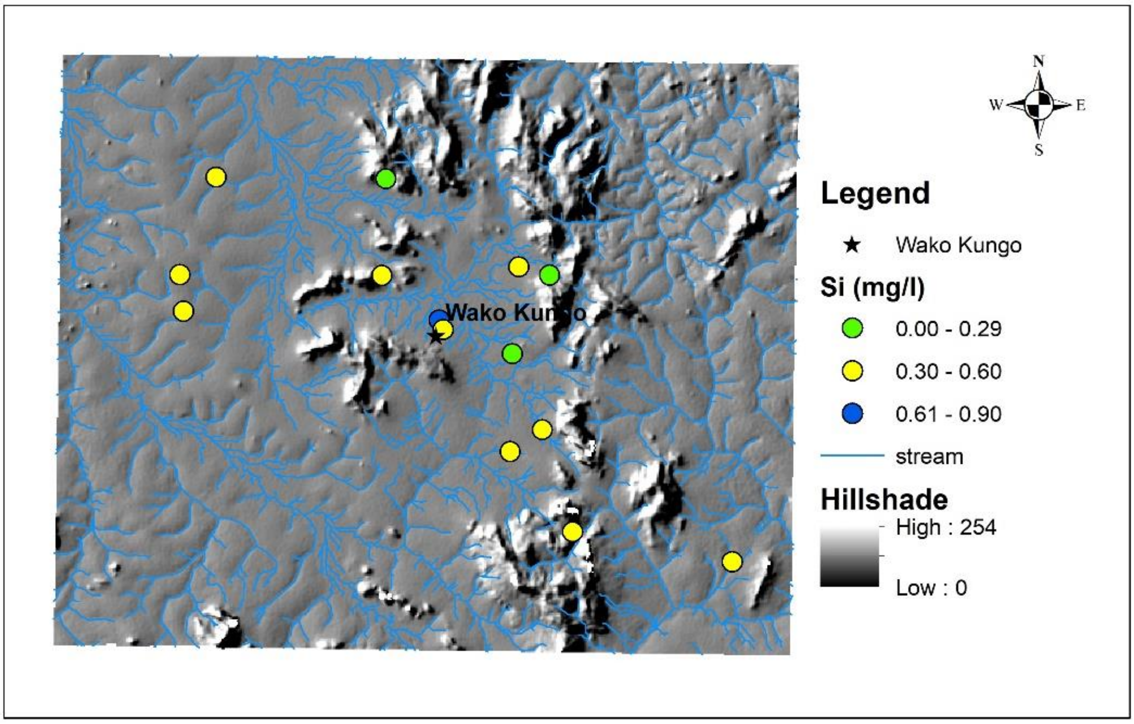


Figure 30. Silica values distribution on groundwater in the study area.

6.1.10. Iron

Iron is a cation which presence in groundwater is normally due to the dissolution of the iron from minerals of the lithologies crossed by groundwater, namely the iron-bearing mafic minerals.

The presence of high concentration of this parameter in the water can cause problems of appearance of color in the water, but does not represent sanitary risks if the water is ingested.

According to the Decree-Law, for iron, the VMR is 0.1 mg/l and the VMA is 0.3 mg/l.

The analysis of the distribution of the iron values (Figure 31) shows that the waters of the sampled points, in general, have relatively high values, which would be expected in a region constituted essentially by granitoids.

It can be observed that, for the groundwater of the study area, about 86% present values between the VMR and the VMA. Only one sample (W-19) presented an iron value below the VMR (0.1 mg/l), while another sample (W-05) presented a highest value than the VMA (0.3 mg/l).

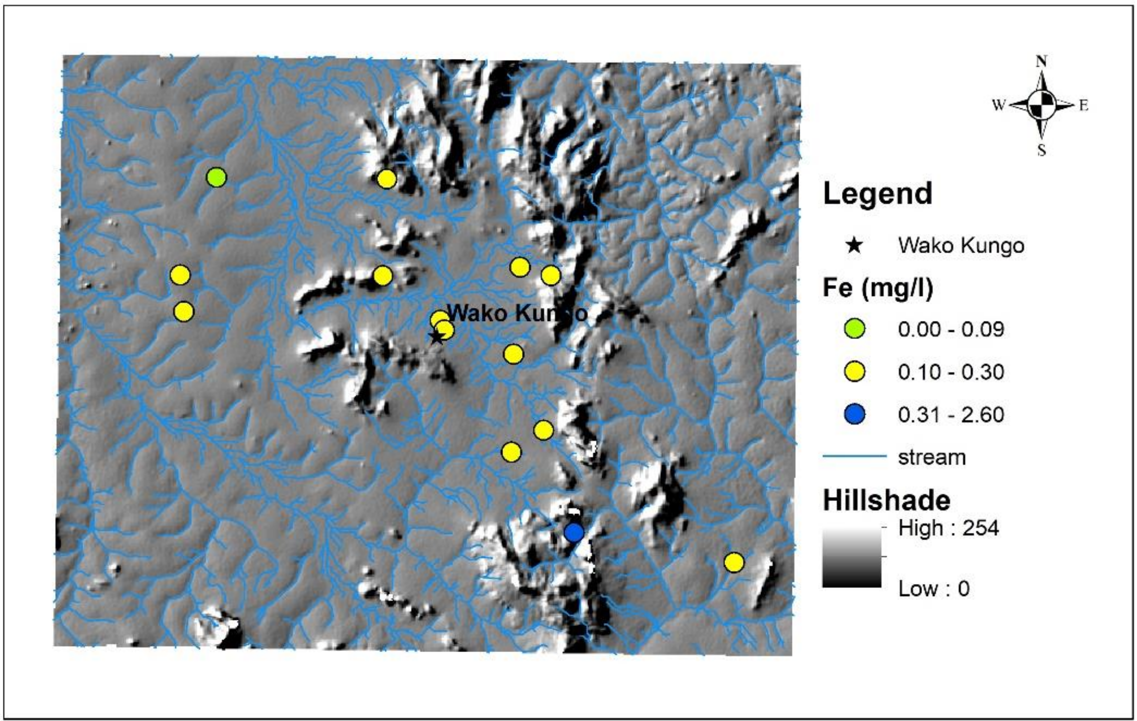


Figure 31. Iron values distribution on groundwater in the study area.

6.2. Water-rock equilibrium

The composition of groundwater is a function of numerous chemical and biogeochemical processes, from those occurring in the atmosphere and influencing the composition of the infiltration waters, to those occurring in the soil, and in the saturated and intermediate zones (Chambel 1999).

One of the most important processes results from the interaction between water and rock, with occurrence of mineral dissolution and precipitation phenomena, adsorption and ion exchange phenomena, and the results of interaction between the various dissolved species, often conditioned by the action of microorganisms, as in the case of oxidation-reduction phenomena (Almeida 1991 in Chambel 1999).

The evaluation of the equilibrium state of an aqueous solution in relation to a given set of reactions is a complex process involving, among other steps, the calculation of the thermodynamic activities of all dissolved species, including ion pairs and complexes (Appelo and Postma 1993, Langmuir 1997 in Chambel 1999), so there is a need for adequate calculation programs (Almeida 1991 in Chambel 1999).

The Giggenbach Triangle (K-Mg-Na Triangle) representation provides a visual aid to determine the water-rock equilibrium and allows you to verify the extent to which water-rock equilibrium has been attained (Giggenbach 1988).

The triangle is comprised of three zones:

- Immature equilibrated waters (at the base);
- Partially equilibrated waters (in the middle);
- Fully equilibrated waters (along the curve).

According to this triangle all the water samples fall under the category of immature water (Figure 32). This reflects the low dwell time of groundwater observed in the ternary diagram.

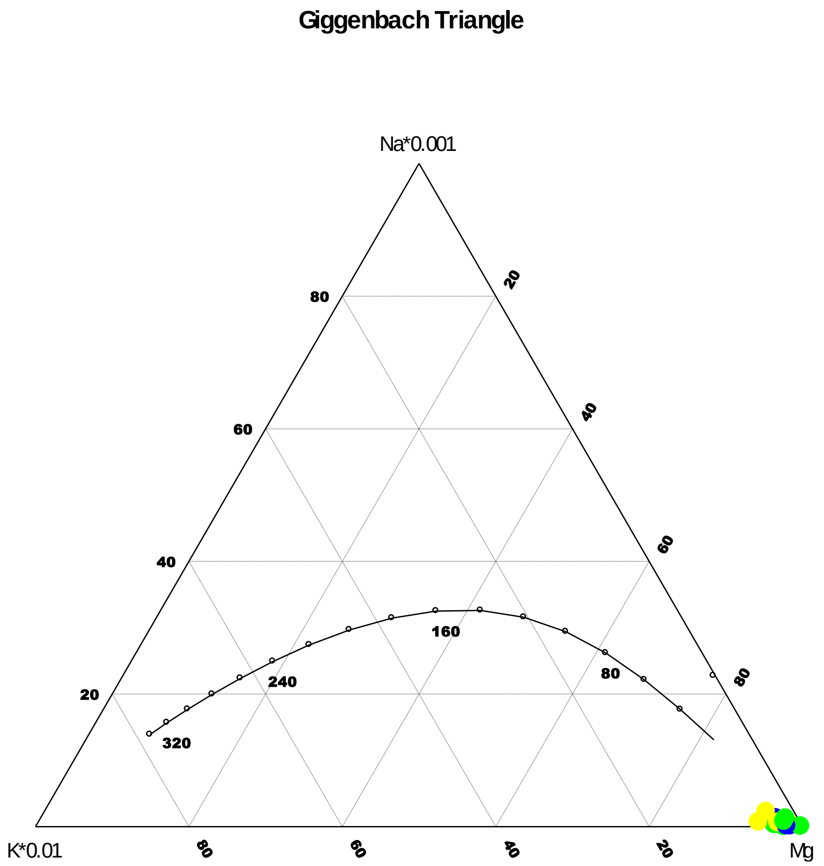


Figure 32. Triangle showing maturity of the water samples, Giggenbach (1988).

6.3. Water quality for Irrigation

Water quality for irrigation refers to its suitability for agricultural use. The estimation of concentration and composition of dissolved constituents in water plays an important role in ascertaining its quality for irrigation. Quality of water is an important consideration in any appraisal of salinity or alkalinity conditions in an irrigated area.

Wilcox (1995) classified groundwater for irrigation purposes based on per cent sodium and electrical conductivity. Eaton (1950) recommended the concentration of residual sodium carbonate to determine the suitability of water for irrigation purposes. The US Salinity Laboratory of the Department of Agriculture adopted certain techniques based on which the suitability of water for agriculture is explained.

The sodium in irrigation waters is usually denoted as per cent sodium and can be determined using the following equation (Equation 5):

$$\textbf{\% Na} = (Na^{+1}) \times 100 / (Ca^{2+} + Mg^{2+} + Na^{+1} + K^{+1}) \qquad (5)$$

Where the quantities of Ca^{2+}, Mg^{2+} Na^{+} and K^{+} are expressed in milliequivalents per litre (meq/l).

The classification of groundwater samples with respect to per cent sodium is shown in Table 6. It is observed that related with per cent sodium all samples are excellent.

Table 6. Sodium percent water class

Sodium %	Water Class
< 20	Excellent
20 - 40	Good
40 - 60	Permissible
60 - 80	Doubtful
> 80	Unsuitable

The US Salinity Laboratory Staff (USSLS 1954) classified groundwater on the basis of electrical conductivity and sodium adsorption ratio (SAR) (Table 7).

Table 7. Groundwater classification for irrigation based on EC, SAR.

Quality of Water	Electrical Conductivity(µS/cm)	Sodium Adsorption Ratio (SAR)
Excellent	< 250	< 10
Good	250 - 750	10-18
Doubtful	750 - 2250	18 - 26
Unsuitable	> 2250	> 26

Sodium Adsorption Ratio (SAR) is an important parameter for determining the suitability of groundwater for irrigation because it is a measure of alkali/sodium hazard to crops. SAR is computed as (Equation 6):

$$SAR = \frac{Na^{+}}{\left\{\frac{Ca^{2-} + Mg^{2+}}{2}\right\}^{1/2}} \qquad (6)$$

Where all ionic concentrations are expressed in milliequivalents per litre (meq/l).

Irrigation waters were classified based on SAR (WHO 2011). Based on the classification, all analysed samples fall in excellent water category, shown in Figure 33. It´s noted that only 5 samples are shown in the diagram. The reason is that the diagram axis of electrical conductivity begins at 100 μS/cm, while 9 out of the 14 samples have less than this value.

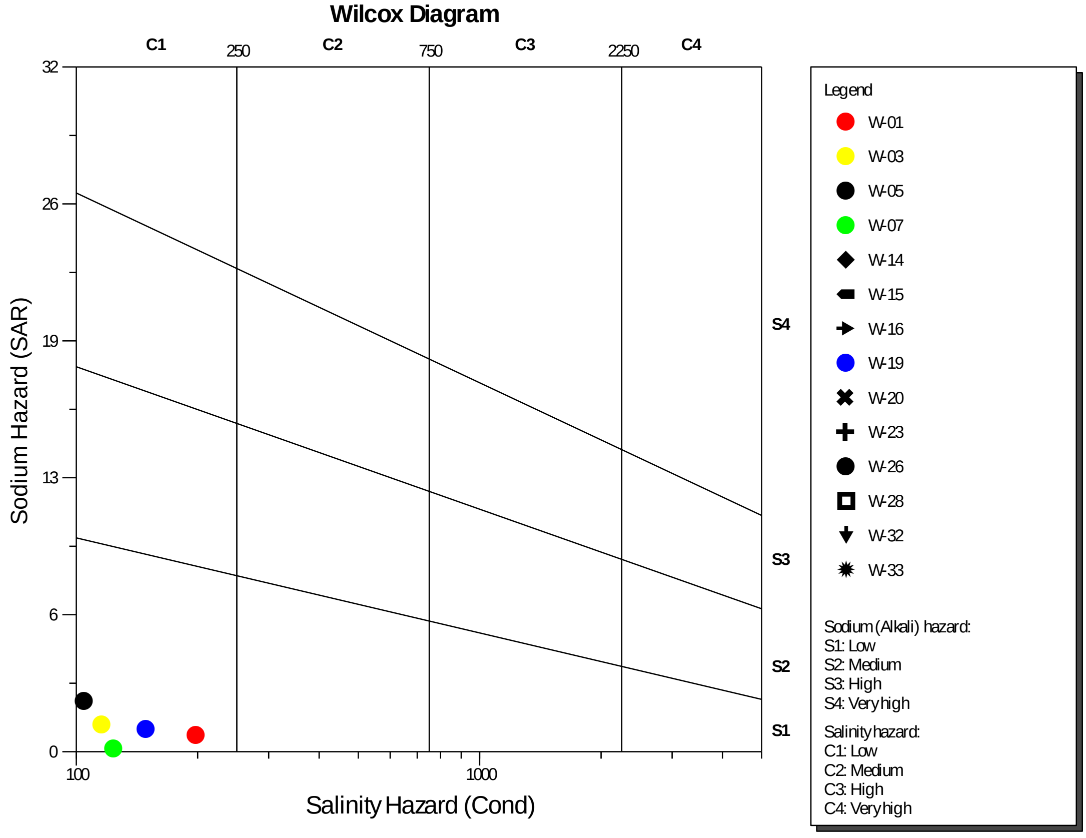


Figure 33. Rating of water samples in relation to salinity and sodium hazard (USSLS 1954).

7. ANALYSIS OF OPTICAL AND RADAR IMAGES

7.1. Drainage

Drainage is source for groundwater recharge. Drainage pattern map of the study area has been drawn with the help of SRTM DEM data updated from (http: glcf.umiacs.umd.edu/index.shtml). The Figure 34 shows the drainage map of the study area.

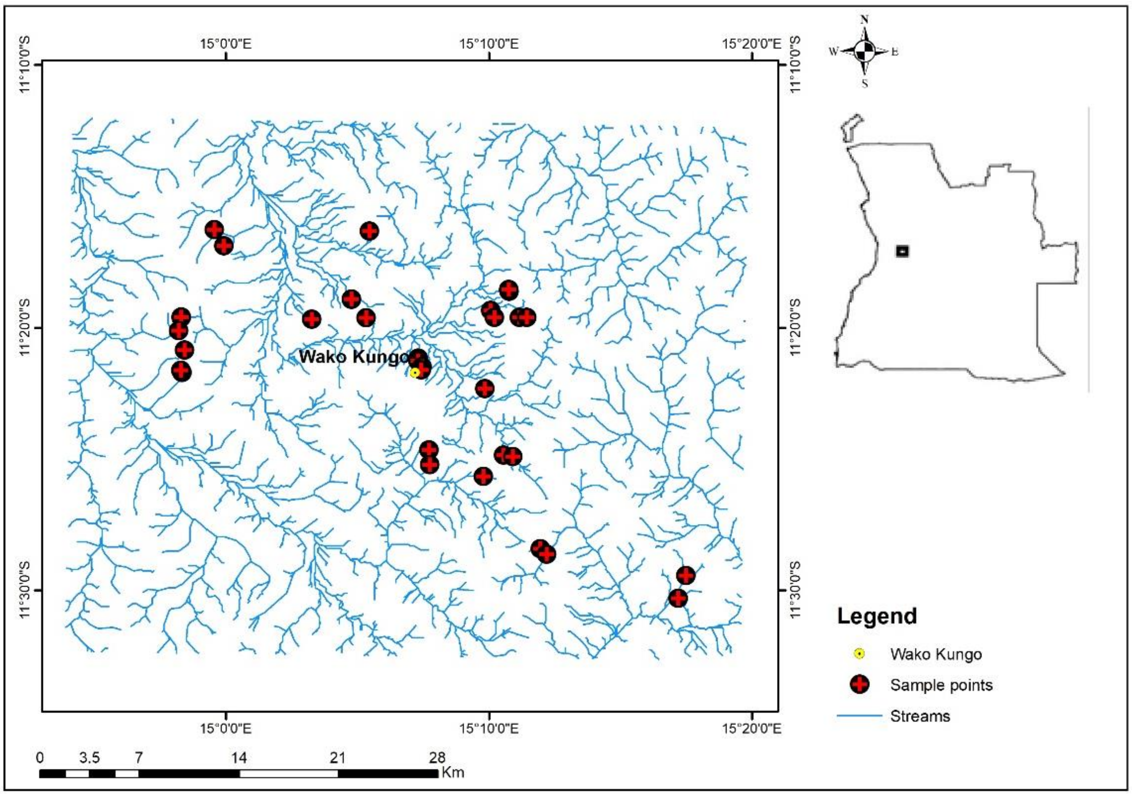


Figure 34. Drainage map of the study area.

The drainage analysis of the study area revealed that mainly dendritic type of drainage pattern presents which indicates that drainage of the study is geomorphologically and structurally controlled.

Usually, drainage patterns are said to be reflections of surface and subsurface formations while drainage density is proportional to surface run-off due to the fact that more the drainage density, the higher the runoff (Talabi and Tijani 2011).

Hence, the drainage density characterizes the runoff in an area as the volume of relative water that was unable to penetrate into the subsurface. In addition, drainage density does give indications of clogging of stream/river channels which in turn will depend on the degree of fracturing and nature and degree of weathering of the surface and subsurface lithologic units.

Low drainage density therefore enhances the chance of recharge and contributes positively to groundwater availability if other groundwater occurrence conditions are favourable (Nayak *et al.* 2017).

The lowland part of the study area that are characterized mainly by diverse rock units (porphyritic granite, fine-medium grained granite, granite gneiss and migmatite) presents low density an indication of favourable condition for vertical infiltration of runoff from surrounding hills and thus enhancing groundwater occurrence.

The drainage density map presented in Figure 35 reflects the infiltration characteristics with high drainage density indicating low-infiltration and the low drainage density high infiltration respectively. Since the drainage density can indirectly indicate the groundwater potential of an area due to its relation to surface runoff and permeability (Jasrotia *et al.* 2016), in the present study it was considered as one of the indicators of groundwater occurrence.

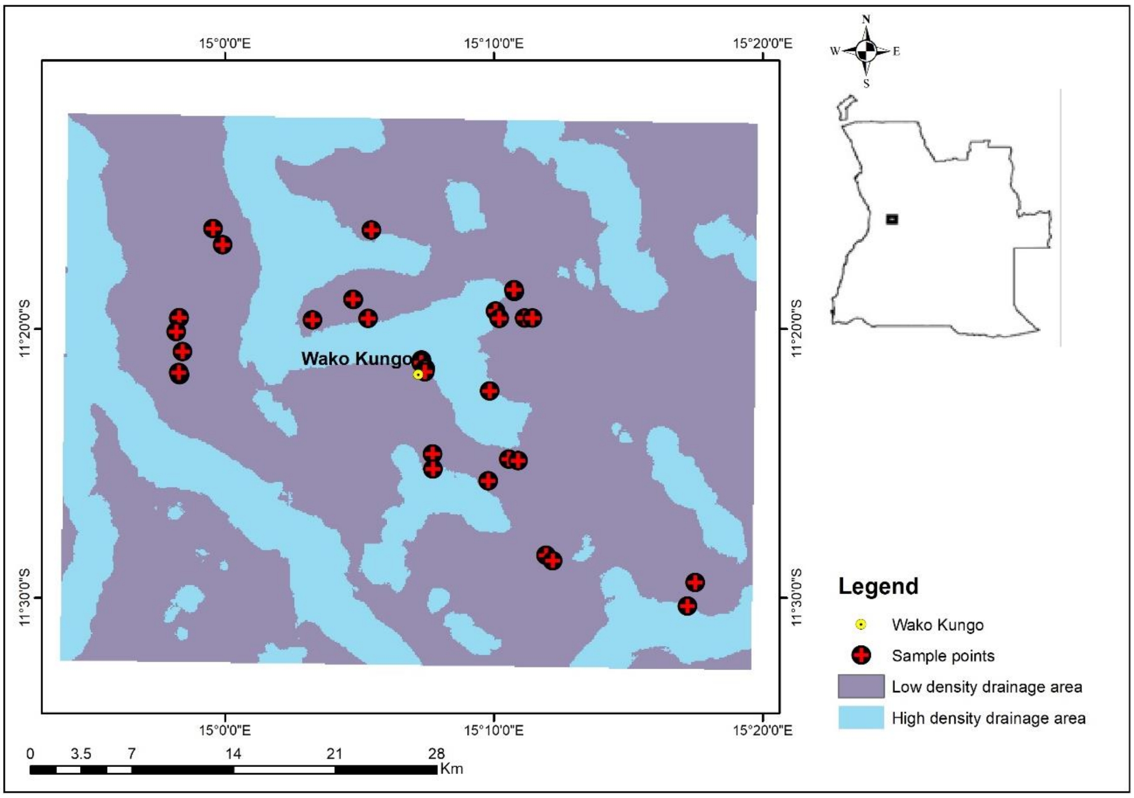


Figure 35. Drainage density map of the study area.

This observation signifies that groundwater occurrence in the lowland part of the study area is not only controlled by rock formations but other factors like topography and weathering as products from the surrounding hills pile up to form overburden thickness aquifer while during igneous rocks intrusion fractures favourable for vertical infiltration were developed and thus additionally support groundwater occurrence.

7.2. Lineaments

Lineaments are the linear, rectilinear, curvilinear features of tectonic origin observed in satellite data. These lineaments normally show tonal, textural, soil tonal, relief, drainage and vegetation linearity and curvilinearities in satellite data (Sukumar *et al.* 2014).

The reason for the lineament formation is due to the tectonic activities, which generally reflect the surface manifestation of underground fractures. Lineaments represent the zones of faulting and fracturing resulting in increased secondary porosity and permeability (Magesh *et al.* 2012). The increased secondary porosity and permeability gives rise to the high infiltration rate of water in the ground due to which the area having good number of lineament serves as a good site for groundwater availability. The study was interested in topographically negative lineaments, which may represent joints, faults and, probably, shear zones. In order derive the geomorphologic context of the terrain, the DEM data was subjected to produce the hillshade relief image for the study area (Figure 36).

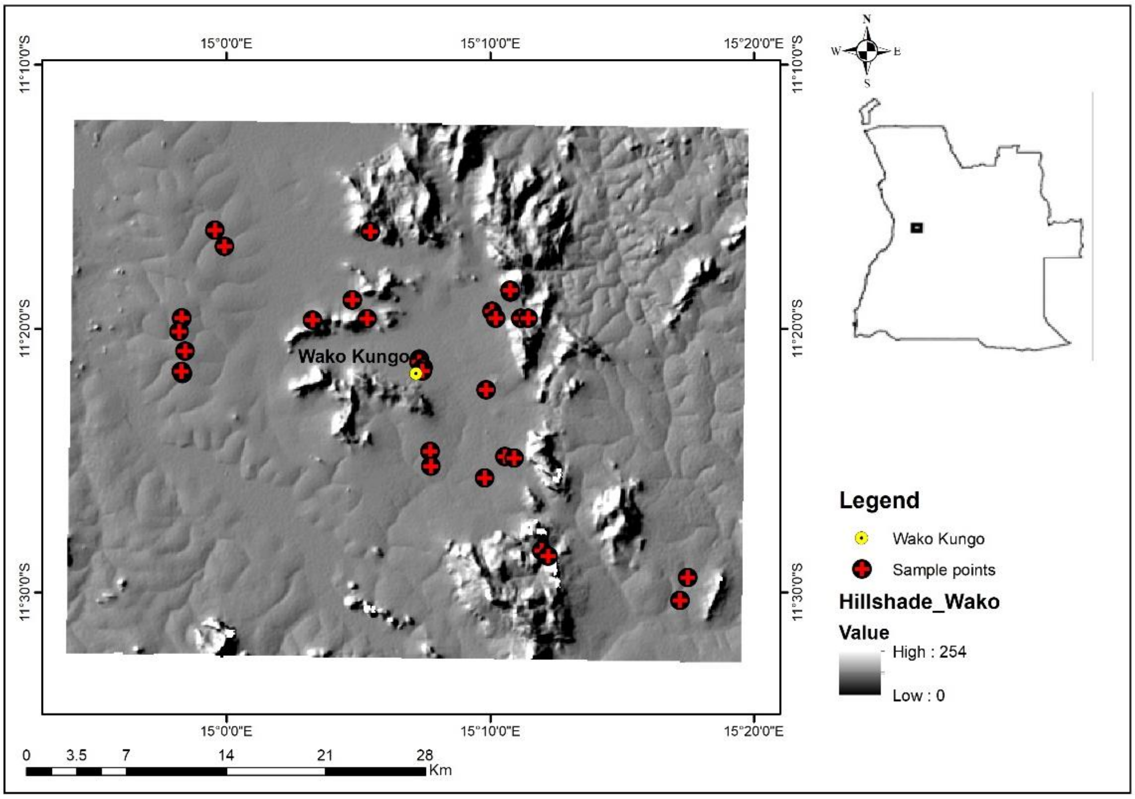


Figure 36. Hillshade image obtained from SRTM DEM data.

Identification of the lineaments in the study area was based on the anomalies associated with features like straight drainage courses, vegetation patterns, topography, etc. Bands combination of 3 (Near infrared), 2 (Red band) and 1 (Green band) were fused together to generate a false colour composite image (321) (Figure 37) for linear geological features enhancement in ArcMap 10.4.1 window interface.

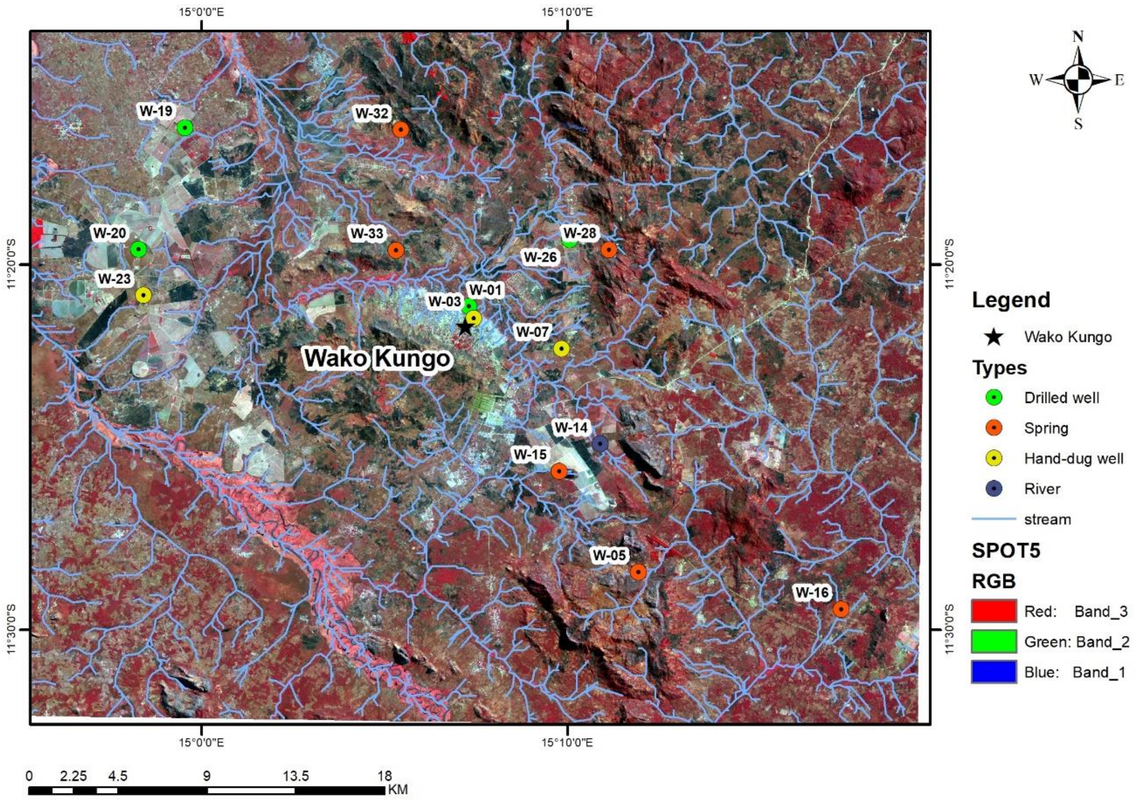


Figure 37. False colour composite image used for lineament visual interpretation.

The non-geological lineaments such as path, roads, power cables and field boundaries in the study area were eliminated using the hillshade map (Mogaji *et al.* 2011).

The study area is crisscrossed by major and minor lineaments and is shown in Figure 38.

The aim of the lineament interpretation was to digitize accurately all linear features that could represent a lineament of tectonic origin.

The mapped structural lineaments were analysed using lineament density (LD) parameter which result analyses are presented as lineament density map (Figure 39).

According to Edet *et al.* (1998) in Mogaji *et al.* (2011), the zones of relatively high lineament density are identified as zones of high degree of rock fracturing, which are prerequisite for groundwater conduit development in an area.

The result from the present study shows that RS technique is capable of extracting lineament trends in an inaccessible hilly terrain. The analysis indicated that the area has numerous long and short lineaments whose structural trends are mainly NW-SE and NNW-SSE directions and, secondarily, some NE-SW directions (Figure 40), which are also the main directions of the regional structures in basement complexes of Angola.

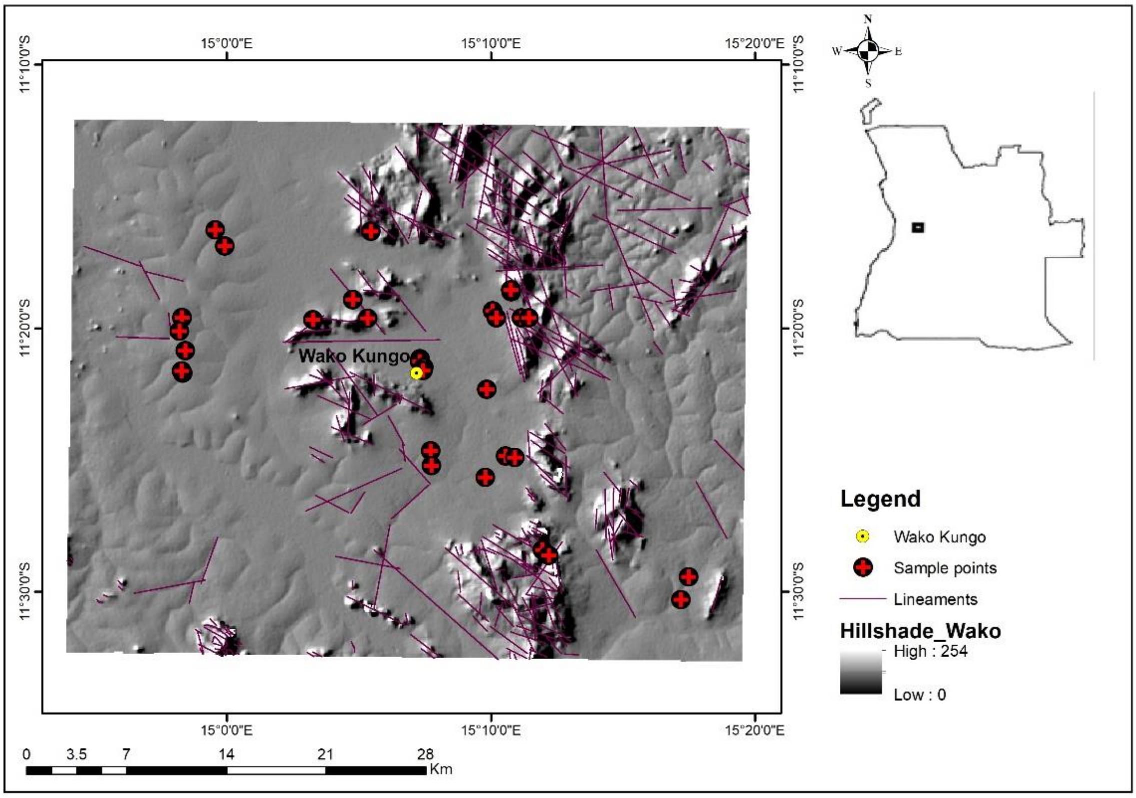


Figure 38. Lineament map of the study area.

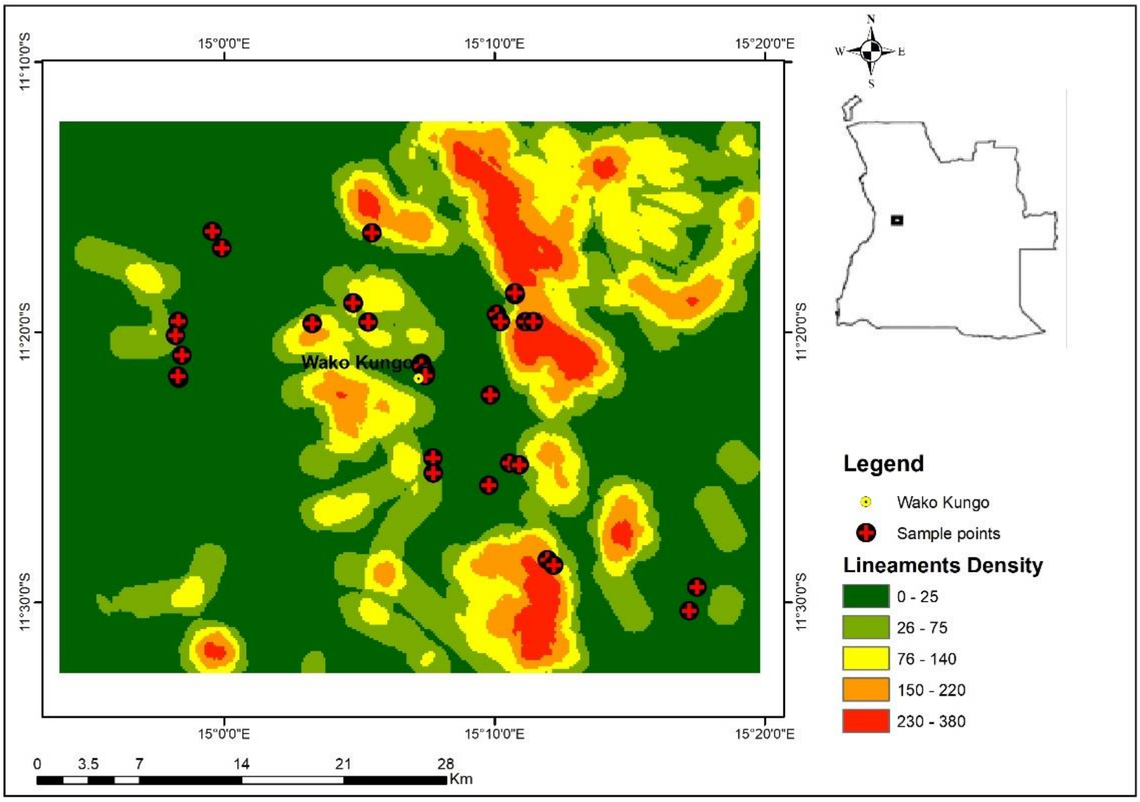


Figure 39. Lineament density map of the study area.

The tectonic capture process reveals active fault and fracture systems that probably act as medium for the surface water infiltration to recharge the underlying aquifers, during wet season.

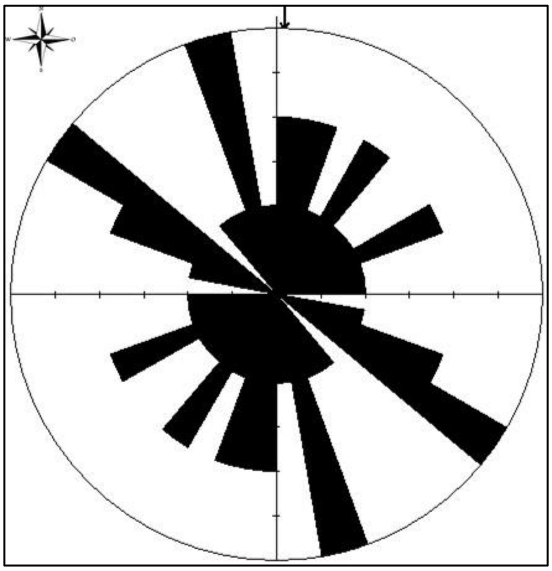


Figure 40. Rose diagram of the lineament orientation in the study area.

7.3. Normalized Difference Vegetation Index (NDVI)

One of the most widely used indicators for vegetation monitoring is the Normalized Difference Vegetation Index (NDVI).

NDVI is an index based on spectral reflectance of the ground surface feature.

The NDVI method has been used to identify and map geologic linear features (lineaments) in hard-rock terrains based on tone, color and textural identifying pattern (Mogaji *et al.* 2011). Boyer and McQueen (1964) in Mogaji et al. (2011) established the usefulness of NDVI in detecting fractures and faults which can be associated with the occurrence of vegetation alignment.

NDVI values range from –1 to +1. Because of the high reflectance in the NIR portion of the electromagnetic spectrum, healthy vegetation is represented by high NDVI values between 0.05 and 1.

Conversely, non-vegetated surfaces (such as water bodies) yield a negative NDVI value. Bare soil areas have NDVI values which are closest to 0 due to the high reflectance in both the visible and NIR portions of the electromagnetic spectrum.

In this study, the NDVI value was calculated from SPOT 5 image and ranges from -1 to 1 (Figure 41).

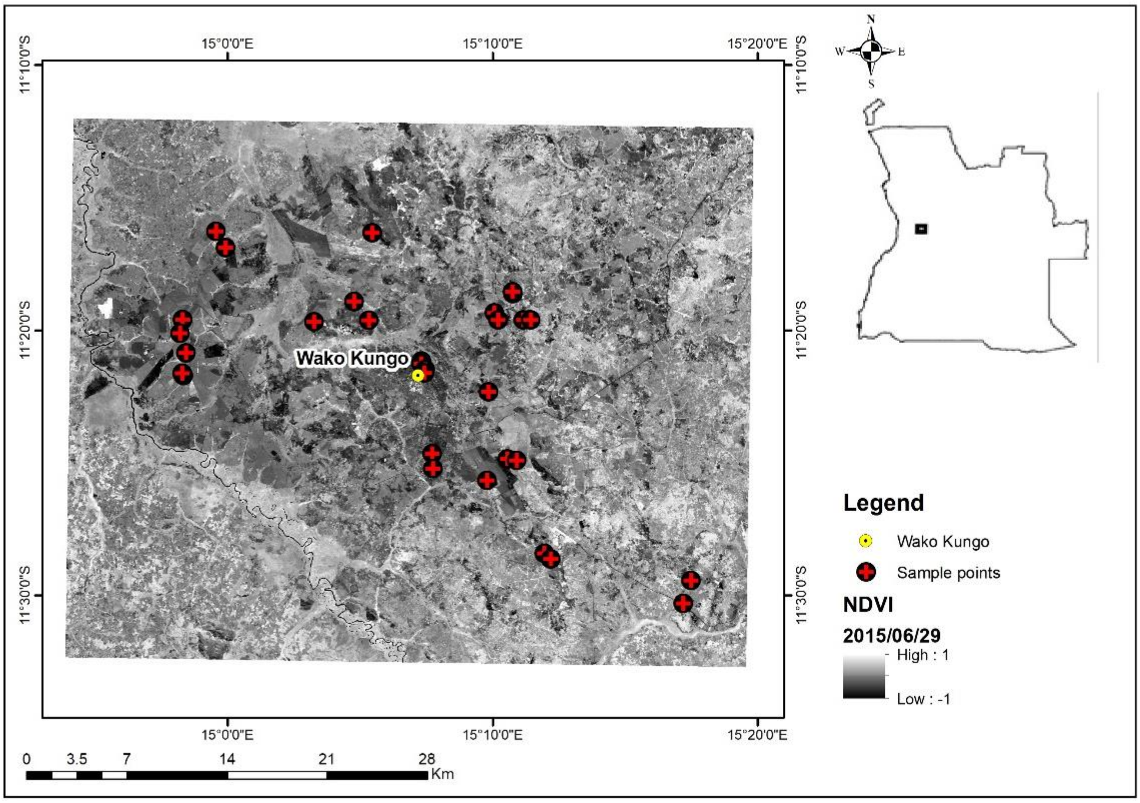


Figure 41. NDVI map of the study area.

A further break down of the NDVI values shows that healthy vegetation was assigned with values of 0.5 to 1 in the region, while unhealthy vegetation, bare soil and other features have values ranging from -1 to 0.4. The mountain foothills have higher NDVI values, and correspond to the forested areas in the mountains. The lower values of NDVI were found in the rivers and wetland regions of the study area.

The vegetated areas were mapped applying the raster calculator, a tool from Spatial analyst, using 0.5 as threshold value on NDVI image. In this study a vegetation index was used to identify lineaments with higher groundwater potential by distinguishing unvegetated from vegetated areas with high lineament densities.

Lineaments digitised along the fractures show the concentration of lineaments with high groundwater potential on NDVI (Figure 42) for infiltration or groundwater flow. This allowed to enhance dry season vegetation and shows clearly the relation between vegetated areas and the high density of lineaments (Figure 43).

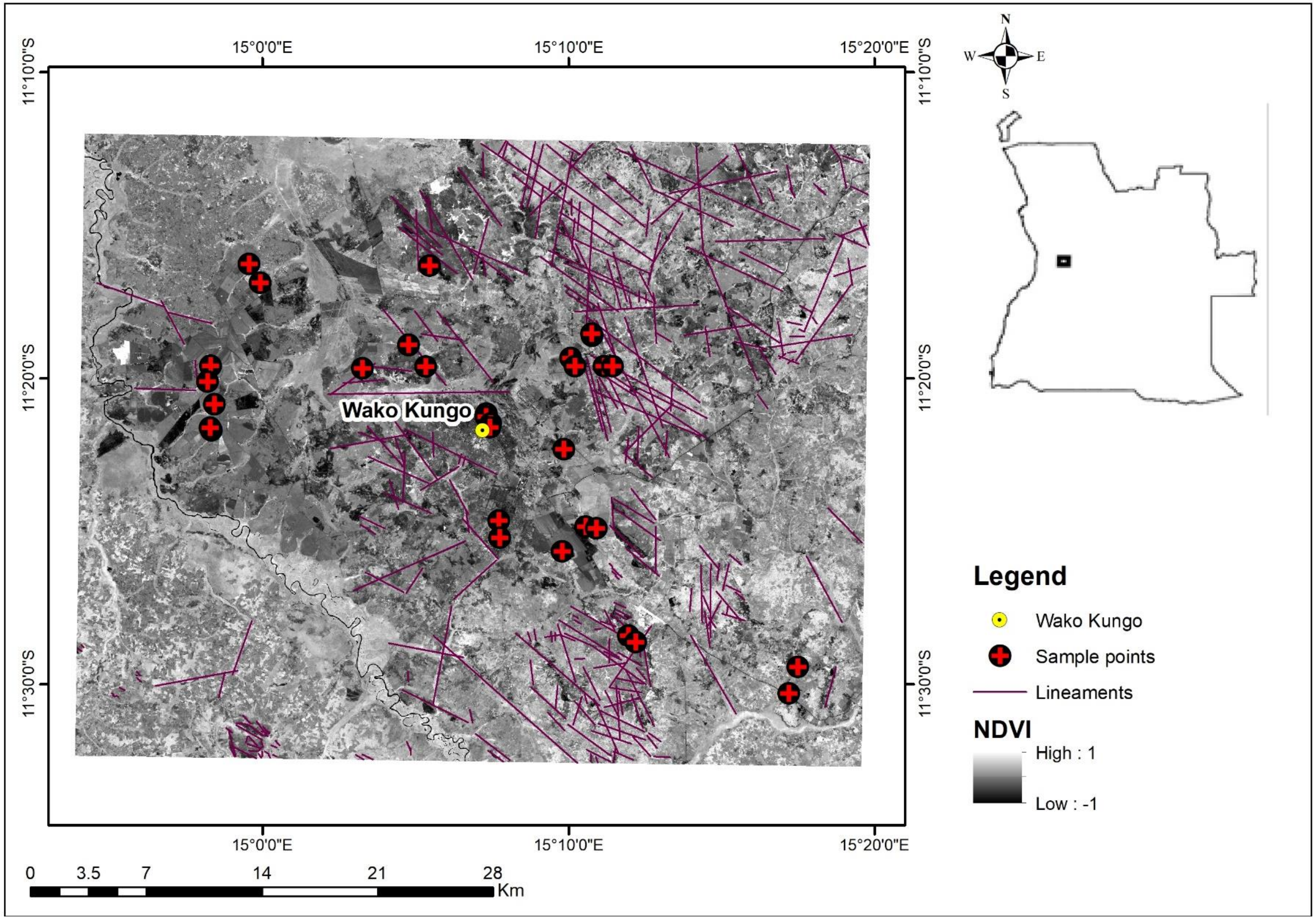


Figure 42. NDVI map overlaid by the lineaments of the study area.

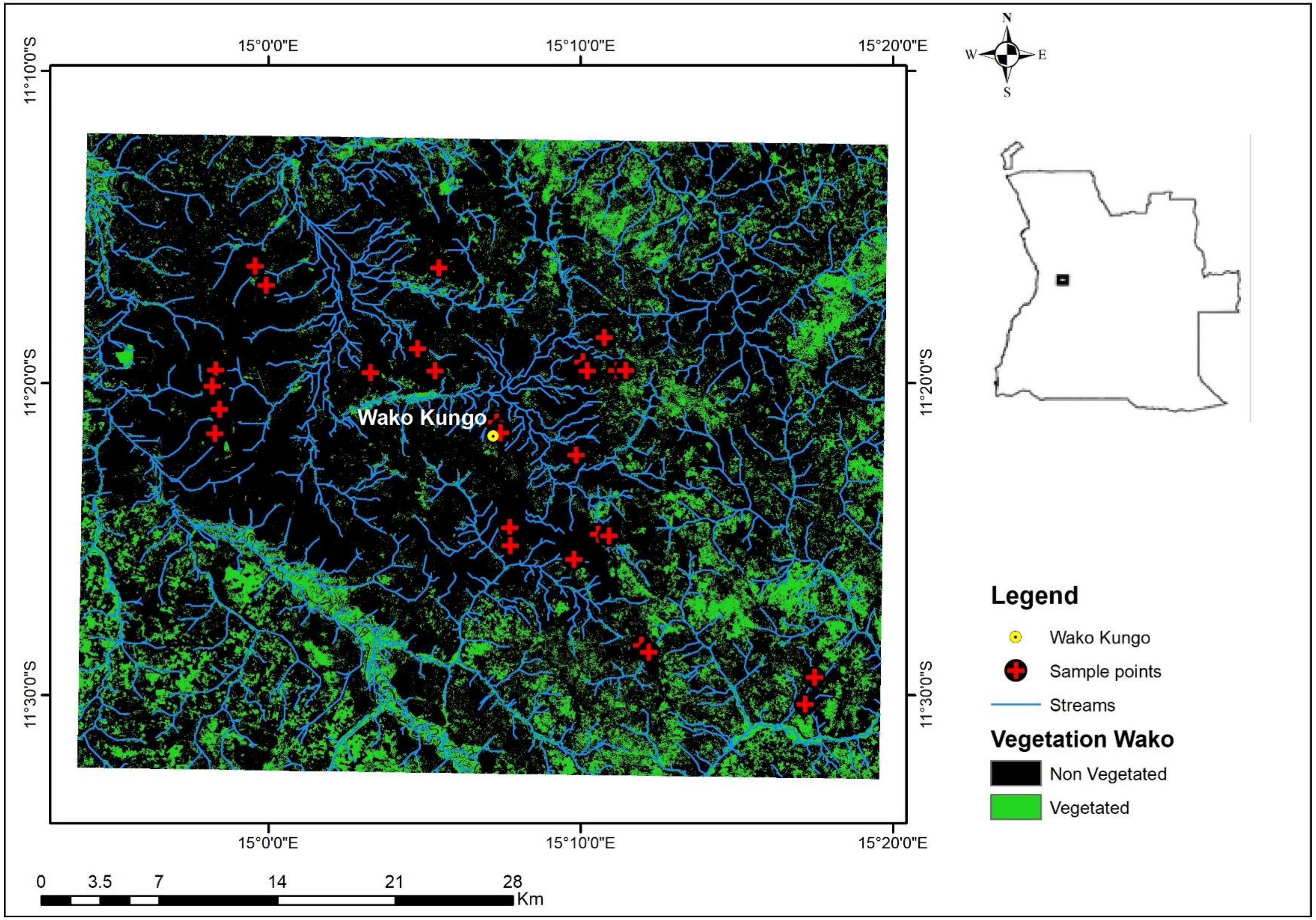


Figure 43. Vegetation map of the study area.

8. GROUNDWATER RECHARGE AND DISCHARGE AREAS

Based on the analysis of the physical-chemical groundwater parameters (chapter 6.5), on the interpretation of the lineaments density map (Figure 39), and on the vegetation map of Figure 43, and integrating all the other analysis performed on the terrain and other maps, the resulting interpretation about the infiltration and discharge groundwater zones is shown in Figure 44.

As expected in these types of rocks and in this type of geomorphological environment, the infiltration occurs mainly in the highest areas (here formed by granitic outcrops), migrating then to the lower areas, here represented by the sedimentary rocks. Along the borders of the granitic outcrops there are clear signs of direct discharge from the igneous rocks, namely many foothill springs. Here the water coming from the higher areas discharge from the granitic outcrops to the sedimentary basins.

In the sedimentary basins, rivers are the main discharge groundwater linear structures. Some infiltration will also occur in the lower sedimentary areas, in this case with much short link between the recharge and the discharge areas in the rivers.

Chemistry also shows that, as expected, the contact time of groundwater with the rock is longer in the sedimentary formations, where the infiltrated water from the granitic areas are discharging, showing the link between the two hydrogeological environments.

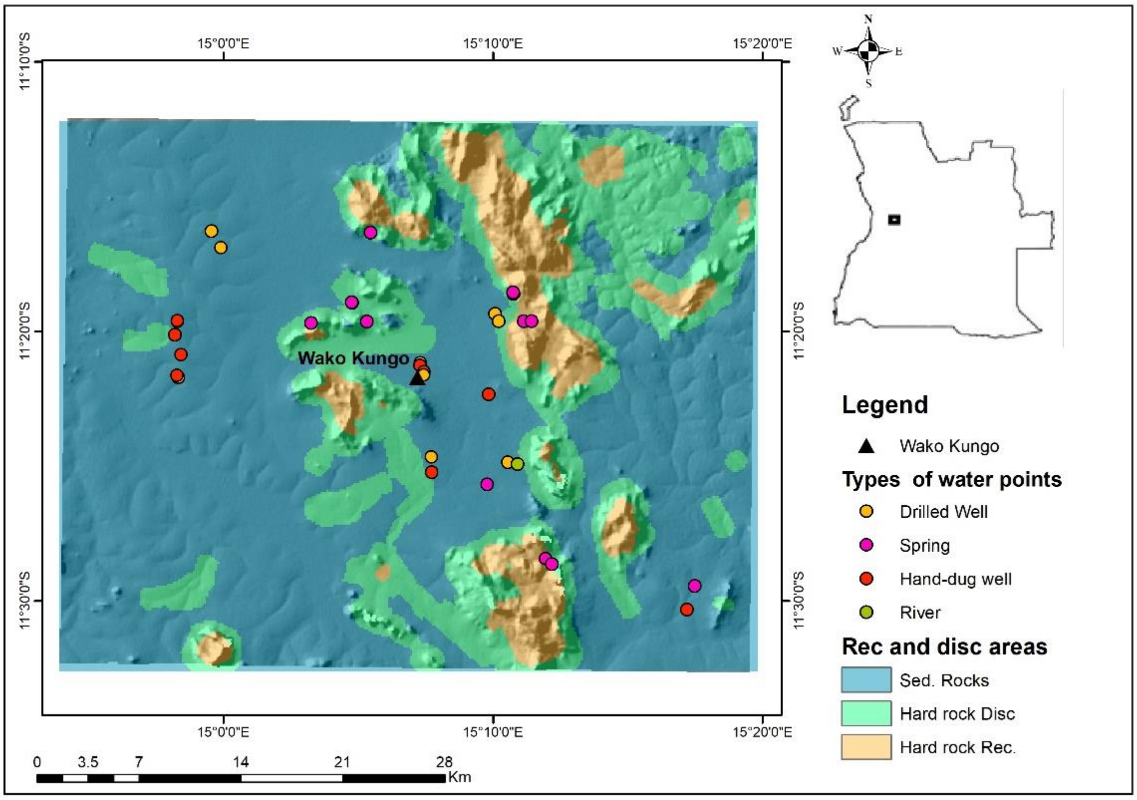


Figure 44. Map of groundwater recharge and discharge areas in the study area. Hard rock recharge occurs in the higher areas, discharge from hard rocks occur on the borders of the outcrops and the main discharge on the sedimentay rocks is the river network.

9. FINAL REMARKS

With the increasing demand of water, mapping of groundwater resources has been increased over the years. From the previously mentioned studies related to the use of remote sensing and GIS in groundwater mapping, it could be concluded that groundwater mapping is one of the main tools for efficient and controlled development of groundwater resources.

In this study, groundwater patterns have been identified based on satellite imageries, DEM and on field data.

All data were integrated using remote sensing and geographic information system techniques, to prepare different thematic layers such as drainage, drainage density, lineament density and NDVI maps.

The results from the study show that maps of lineament, drainage, vegetation index and on field data are useful to predict the recharge and discharge areas.

The results suggested that the high lineament intersection and density should be combined with detailed structural elements to better reveal points of groundwater recharge and discharge.

Interpretation of Spot -5 image combined with high-resolution Sentinel-1 radar scenes shows that NW-SE and NNW-SSE lineament directions present best yield on groundwater prospecting.

A lineament density map was correlated with the collected well and spring locations in Wako Kungo and shows that highly productive wells can be located along the intersection areas of faults, near active streams and springs. The fracture pattern and the position of springs in hard rocks are clearly linked to tectonic activities.

The zones of high lineament intersection density at higher altitudes are clearly areas of high potential for infiltration and the zones of high lineament intersection density at lower altitudes are feasible zones for groundwater prospecting in the study area, and hence, it is suggested that these zones be combed with detailed geophysical mapping for quantitative evaluation of the groundwater potential of the study area.

Concerning to water quality, hydrogeochemistry analysis shows that, for the physical-chemical parameters analysed, groundwater in the study area can be evaluated as good low mineralized quality water.

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