Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 16

The Nkhata Bay Lakeshore Catchment

Ministry of Water and Sanitation

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Contents

Acronyms and Abbreviations

BAWI	BAWI Consultants Lilongwe Malawi
BGS	British Geological Survey
BH	Borehole
BY	Billion Years
$^\circ$C	Degree Celsius
CAPS	Convergence Ahead of Pressure Surges
DCCMS	Department of Climate change and Meteorological Services
EC	Electrical Conductivity
FB	Fractured Basement
ITCZ	Intertropical Convergence Zone
l/s	Litres per second
Km^2	Square Kilometre
Km^3	Cubic Kilometre
m	metre
m^2	Square metre
MASDAP	Malawi Spatial Data Portal
masl	Metres above sea level
mbgl	Metres below ground level
MBS	Malawi Bureau of Standards
m/d	Metre/day
m^2/d	Square metres per day
m^3/s	Cubic metre per second
m/d	Metres per day
mm	Millimetre
mm/d	Millimetre per day
MoWS	Ministry of Water and Sanitation (current)
MoAIWD	Ministry of Agriculture, Irrigation and Water Development (pre-2022)
MS	Malawi Standard
MY	Million Years
N-S	North- south
SWS	Sustainble Water Solutions Ltd Scotland
SW-NE	Southwest-Northeast
pMC	Percent modern carbon
QA	Quaternary Alluvium
UNICEF	UNICEF
UoS	University of Strathclyde
WB	Weathered Basement
WRA	Water Resource Area
WRU	Water Resource Unit
µs/cm	Micro Siemens per centimetre

Review of Malawi Hydrogeology

Groundwater in Water Resource Area 16 is interpreted within the same context as presented in the Hydrogeology and Water Quality Atlas Bulletin publication. A general description of the Hydrogeology of Malawi and its various units is provided here to remind the reader of the complexity of groundwater in Malawi and its nomenclature. The various basement geologic units have variable mineralogy, chemistry, and structural history that may be locally important for water quality parameters such as Fluoride, Arsenic and geochemical evolution. Therefore, translation of geologic units to potential hydrostratigraphic units was based on the 1:250,000-scale Geological Map of Malawi compiled by the Geological Survey Department of Malawi (Canon, 1978). Geological units were grouped into three main aquifer groups for simplicity.

These groups are assigned here as the national Aquifer Identifications consisting of 1) Consolidated Sedimentary units, 2) Unconsolidated Sedimentary Units overlying Weathered Basement, and 3) Weathered Basement overlying Fractured Basement (**Table 1**). Consolidated sedimentary rocks of the Karoo Supergroup (Permian – Triassic) comprise the Consolidated Sedimentary Aquifers in Malawi (**Figure 1a**). Karoo sedimentary rocks possess dual porosities (primary and secondary porosities) although cementation has significantly reduced primary porosity in those units.

Throughout Malawi, localised fluvial aquifers and sedimentary units in the Lake Malawi Basin are ubiquitous (**Figure 1b**). Colluvium has been deposited across much of Malawi on top of weathered basement slopes, escarpments and plains (**Figure 1b**). The unconsolidated sediment aquifer type represent all sedimentary deposits of Quaternary age deposited via fluvial, colluvial, alluvial, and lacustrine processes. Most sediments were either deposited in rift valley or off-rift valley basins, along lakeshores or in main river channels.

Table 1. Redefined Aquifer groups in Malawi with short descriptions.

Aquifer Group	Description
Consolidated Sedimentary Units (**Figure 1a**)	Consolidated sedimentary rocks of various compositions including sandstones, marls, limestones, siltstones, shales, and conglomerates. Groundwater is transmitted via fissures, fractures, joints, and intergranular pore spaces.
Unconsolidated Sedimentary Units overlying Weathered Basement (**Figure 1b**)	All unconsolidated sediments including sands, gravels, lacustrine sediments, colluvium, alluvium, and fluvial sediments. Groundwater is transmitted via intergranular pore spaces. Name indicates that all sediments are generally deposited onto weathered basement aquifers at variable sediment depths.
Weathered Basement overlying Fractured Basement (**Figure 1c**)	Weathered basement overlying fractured basement at variable depths. Groundwater is stored and transmitted via intergranular pore spaces in the weathered zone, and mainly transmitted via fractures, fissures and joints in the fractured zone.

Weathered metamorphic and igneous rocks overlying fractured rock regardless of age comprise the basement aquifers in Malawi (**Figure 1c**). It should be recognised the Fractured basement only transmits water locally and depends on storage in the overlain weathered zone of saprolite (known as the weathered basement aquifer), except where basement rock forms steep topographical highs (mountains/plutons/rift escarpments). Groundwater flow regimes are highly variable in fractured basement aquifers as there is no primary porosity and secondary porosity is dominant. Weathered basement aquifers behave similarly to unconsolidated sediments hydrogeologically, but generally possess lower hydraulic conductivities and storage except locally where highly fractured and weathered. Weathered basement aquifers are generally hydraulically connected to the underlying fractured zones. The weathered zone can provide significant groundwater storage and often recharge the underlying fractured bedrock.

To facilitate detailed IWRM review of aquifer units, water tables, geologic units, land use, topography and rivers, water quality and borehole yield data, there are a series of Annexes provided with this atlas that provides detailed evaluation at Water Resources Area (WRA) level and detailed maps at Water Resource Unit (WRU) across all of Malawi. All lithological units, including those too small to view on a map were assigned a unique GIS code (not published) for groundwater management purposes. A common example in Malawi are small carbonate occurrences (usually marble) which are too small to be regarded as karst aquifers. Those occurrences are generally within the basement rock matrices and thus included as basement rock.

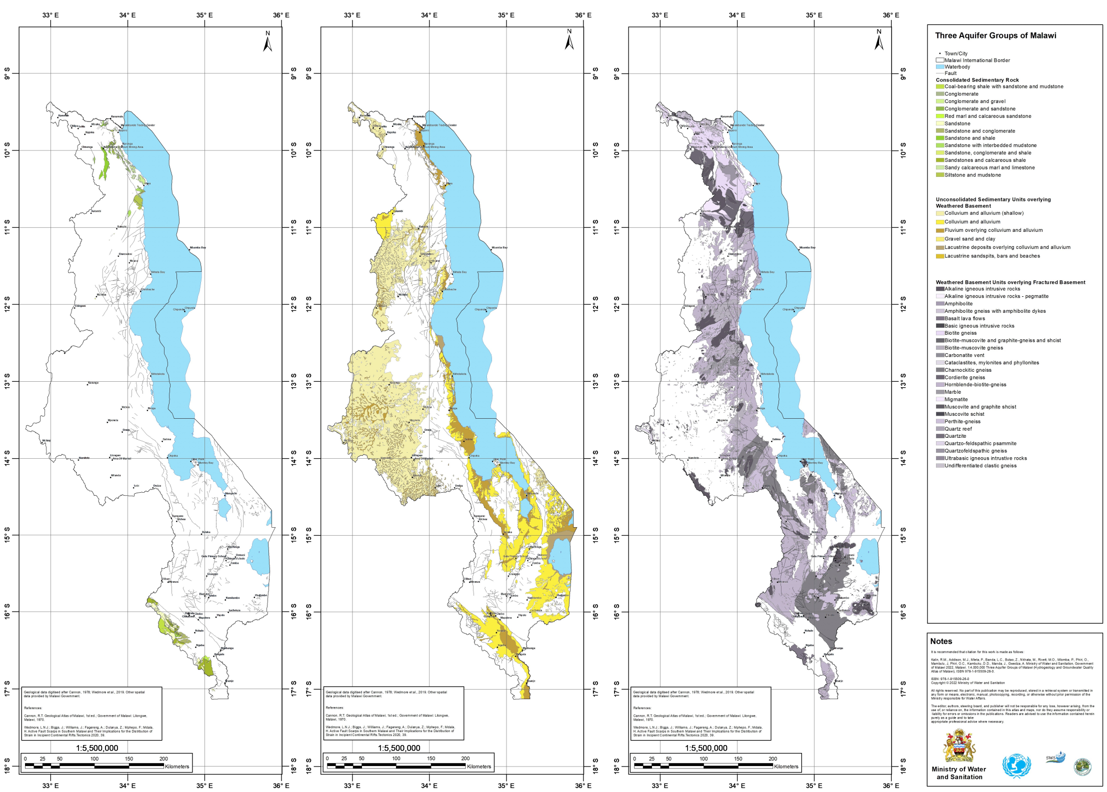

Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure shows weathered basement (including saprolite) units overlying fractured basement that are highly variable as water bearing units. [Available as Map at A0 size]

Nomenclature: Hydrogeology of Malawi

The hydrogeology of Malawi is complex. Some publications and maps in the past have highly generalised this complexity resulting in an over simplification of the interpretation of groundwater resources and short cuts in the methods and means of groundwater exploration, well design and drilling, and management. This atlas makes an attempt to conceptualise the hydrogeology of Malawi while revising the nomenclature and description of the main aquifer groups.

Weathered Basement overlying Fractured Basement

Weathered basement overlying fractured basement is ubiquitous across Malawi (**Figure 1d**) and will occur at variable depths. The areal distribution of these units will be topographically and geographically controlled, with defined "aquifers" being localised and non-contiguous. Groundwater is stored and transmitted via intergranular pore spaces in the weathered (most probable areas of high groundwater storage in the saprolite / saprock) zone, and also transmitted via fractures, fissures and joints in the fractured zone (most probable areas of highest hydraulic conductivity, K). The units may have limited storage, and the volume of groundwater available will be strongly dependant on the recharge catchment and interactions with surface water and rainfall-runoff at higher elevations. Therefore, detailed pump test analysis (sustainable yield determination) must be carried out for any large-scale abstractions combined with continuous monitoring of water levels and water quality (given possible geogenic sources and fast transport of groundwater contaminates e.g. e-coli from pit latrines).

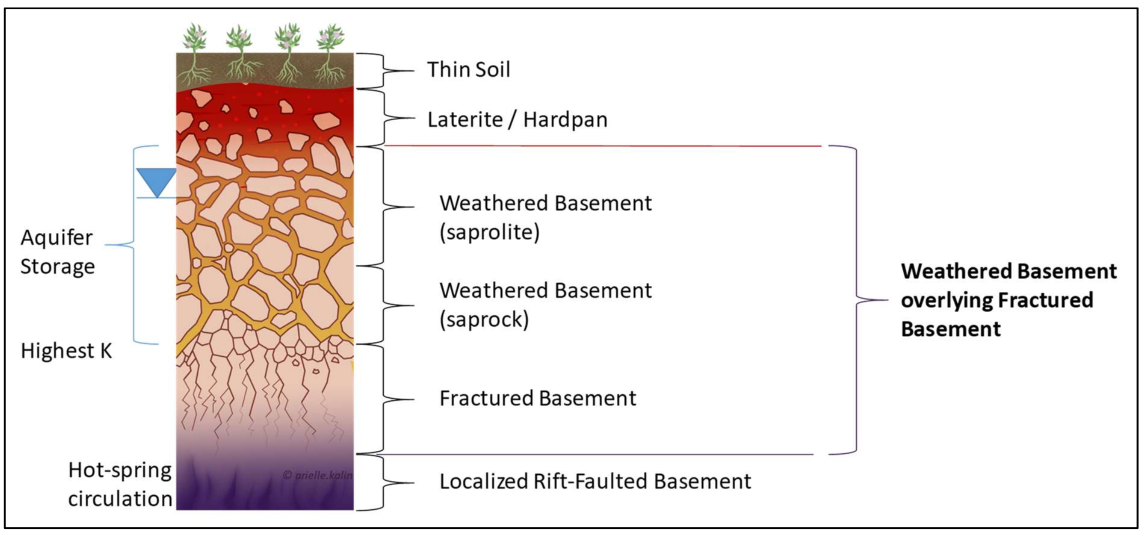

Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

Unconsolidated Colluvial and Alluvial Sedimentary Units overlying Weathered Basement

This sub-group of Unconsolidated Sedimentary Units overlying Weathered Basement (**Figure 1e**) is dominated by colluvium and alluvium. In these units groundwater is transmitted via intergranular pore spaces and where connected to lower Weathered and Fractured Basement, provides groundwater storage to the combined system. As the revised name indicates, these sediments are generally deposited onto weathered basement aquifers at variable sediment depths. Interbedded low-conductive clays and hard-pan is possible and where this stratigraphy occurs in the valleys along the East-African rift system in Malawi, there is the potential for semi-confined to confined groundwater in deeper various unconsolidated or weathered basement units. Where confined conditions occur it is very important to make sure the artesian pressure is sealed at the well head, and that the pressure in the system is monitored continuously (as a means to managed abstraction).

With the potential for semi-confined deposition, there is the likelihood of 'perched' aquifers, water bearing units that are stratigraphically overlying deeper systems. It is critical that each water strike and interim yield is measured during development, and that independent monitoring of each unit (for water quality and water levels) takes place. There is a high probability in Malawi of one or more of these units having higher saline / evaporated water, and the design and installation of rural water points and higher-yield 'Solar' or 'Submersible' pumps are set to only abstract water from the most appropriate and sustainable water bearing unit(s). To date there is not available information on vertical flow directions and recharge as there are no dedicated groundwater monitoring infrastructure installed to evaluate these more complex systems.

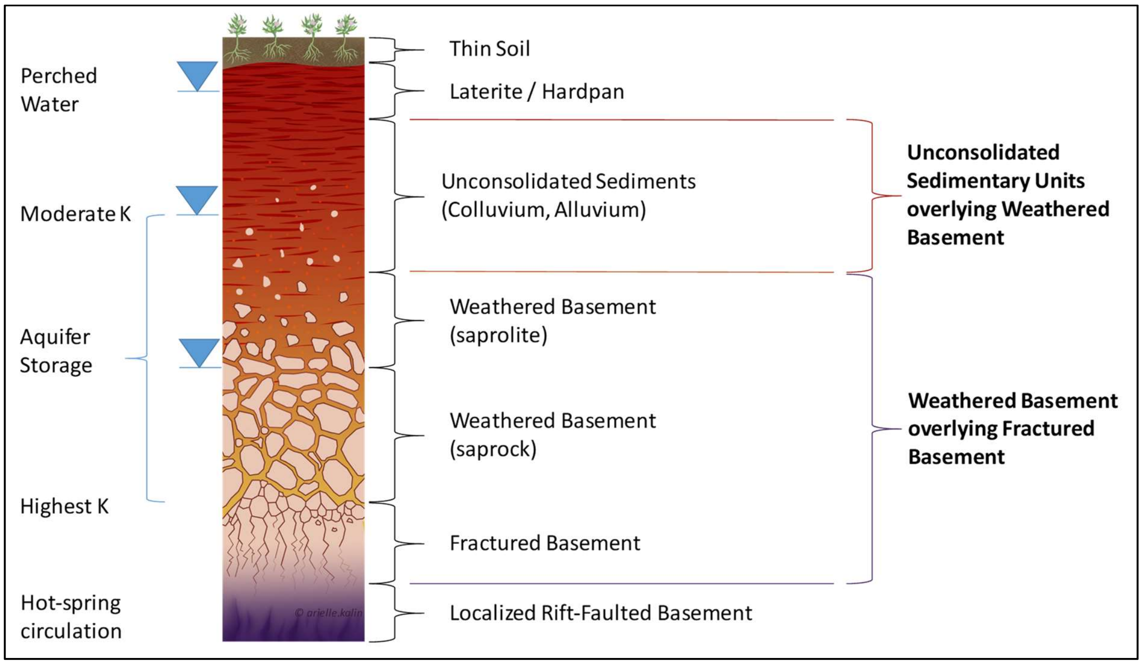

Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Unconsolidated Fluvial Sedimentary Units overlying Weathered Basement

This sub-group of Unconsolidated Sedimentary Units overlying Weathered Basement (**Figure 1f**) contains unconsolidated sediments including water deposited silts, sands, gravels, lacustrine sediments, and fluvial sediments. Surface water is strongly linked with groundwater in Malawi, and much of groundwater flow is controlled by surface topography. Given the long dry season in Malawi, the water resources of Dambo (wet lands) and rivers depend on groundwater discharge during dry months to provide any flow or potential agricultural activity. The storage of groundwater in the upper unconsolidated sediments may or may not be in hydraulic connection with underlying weathered basement, and the storage potential will be dependent on the available porosity of the unconsolidated sediments and saprolitic zones. The underlying fractured basement may have higher hydraulic transmissivity, but will depend on the overlying storage. To date there is little or no available information on vertical flow directions and recharge as there are no dedicated groundwater monitoring infrastructure installed to evaluate these more complex systems, and as before it is highly recommended that site specific detailed hydrogeologic evaluation, pumping tests and water quality monitoring precedes any 'Solar' or 'Submersible' pumping system and that a robust monitoring programme is implemented with such investments.

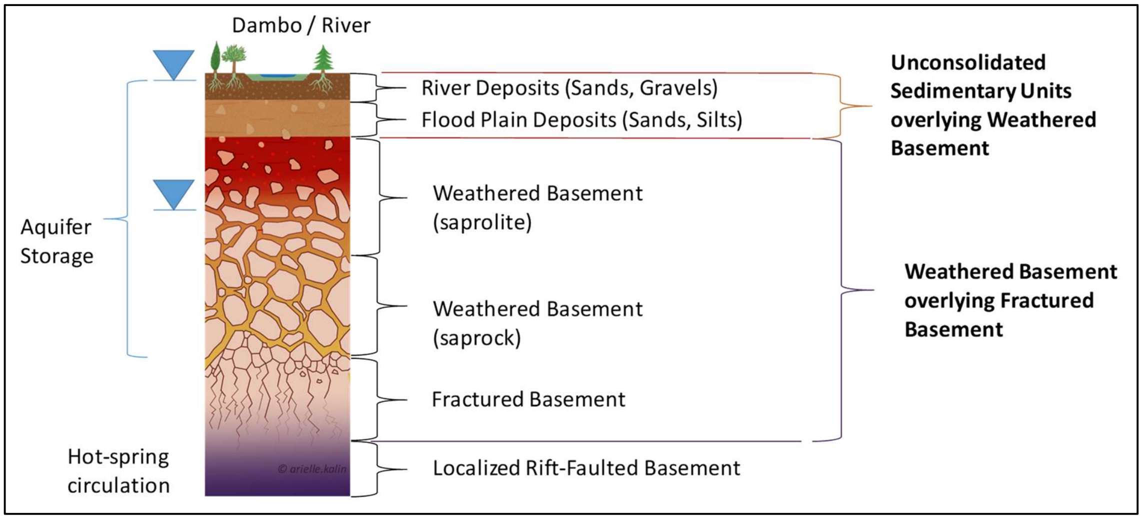

Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Idealised Cross Sectional Representation of Hydrostratigraphic Units (Aquifers)

In reality, an Aquifer is a hydrostratigraphic unit that stores and transmits groundwater. Therefore, to manage groundwater resources in Malawi for the benefit of water use, environment, agriculture and food security, health and well-being, and as a tool for Climate Change adaptation and resilience, it is important to conceptualise these units in 2-D, 3-D and 4-D (include changes over time). The reality of each hydrostratigraphic unit / group is far more complex than many simple assumptions that currently drive groundwater exploration and exploitation in Malawi (**Figure 1g**).

It is important to recognise that fracture flow in the basement rocks will be localised and the groundwater found in this zone is released from storage in weathered basement, or other overlying higher porosity sedimentary units. Therefore, groundwater flow will be largely controlled by topography and the underlying structural geology (either regional stress fields or East-African rift faulting controlled).

The management of groundwater resources in Malawi must move from simplistic idealised considerations of a ubiquitous fractured basement across the country, to a recognition of the compartmentalisation, storage and transmission controls on groundwater resources (**Figure 1g**).

The development of the 2022 Hydrogeology and Groundwater Quality Atlas therefore sought to bring to groundwater management in Malawi a better appreciation of the complexity of groundwater occurrence, and to enhance the maps at national and local scale in such a way as to bring an enhanced appreciation of this complexity to the users of hydrogeologic information.

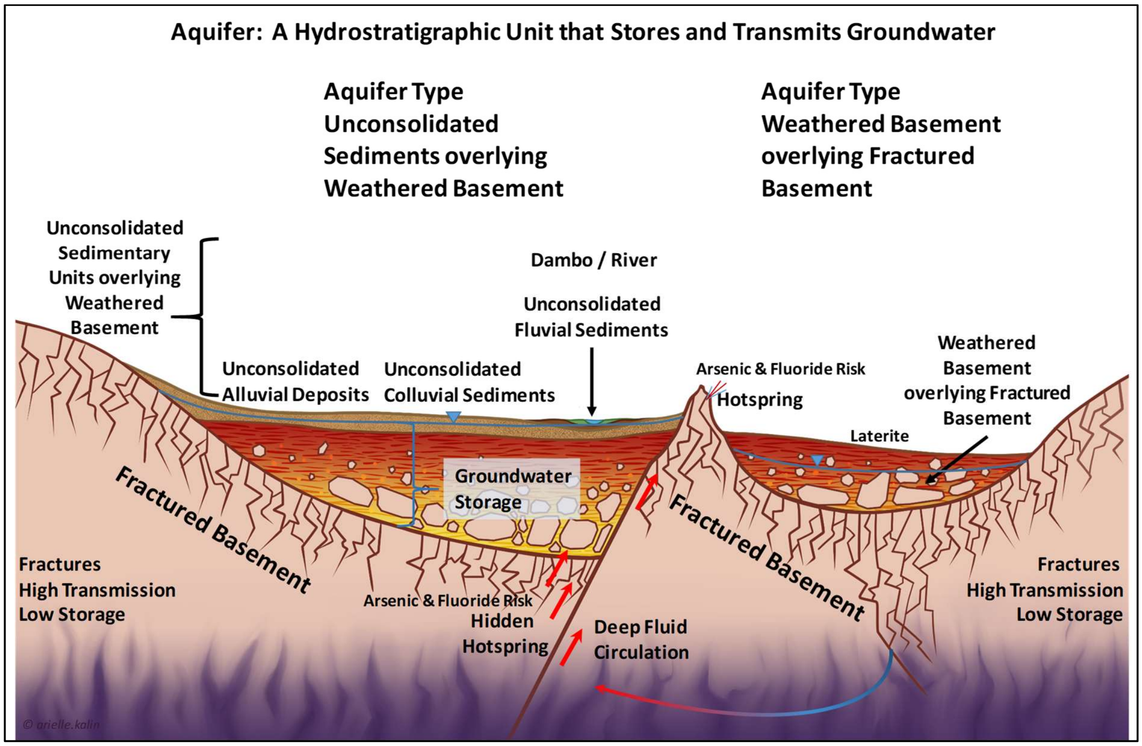

Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

While every attempt has been made to update the conceptual understanding and appreciation of the complexity of the Hydrogeology in Malawi, the editor, authors, steering board and publisher advise any Donor, NGO/CSO or water resources professional to undertake detailed field investigations, providing the conceptual understanding with all results to the Ministry and the NWRA for consideration for determination of the sustainable groundwater abstraction rates at each site.

Boreholes should be designed on site specific hydrogeological conditions. The Government of Malawi has specific guidelines for groundwater abstraction points which must be followed by those implementing groundwater supplies. It is a requirement by the Ministry of Water and Sanitation / NWRA that these guidelines are followed. They include study and testing of the local aquifer conditions, appropriate drilling methods, pump testing and monitoring, and permitting; all of which should be reviewed and followed by the Donor, NGO/CSO and their water resources professional before design and implementation of any groundwater abstraction. This includes any solar / mechanical / submersible groundwater abstraction points. The agency that provides the investment ultimately has the responsibility to assure all appropriate legislation, regulations and standard operating procedures are carried out by their agents and contractors. The following is a list of the current standard operating procedures:

1. Malawi: Technical Manual for Water Wells and Groundwater Monitoring Systems and Standard Operating Procedures for Groundwater, 2016 105pp https://www.rural-water-supply.net/en/resources/details/807
2. Malawi Standard Operating Procedure for Drilling and Construction of National Monitoring Boreholes 2016 15pp https://www.rural-water-supply.net/en/resources/details/807
3. Malawi Standard Operating Procedure for Aquifer Pumping Tests 2016 15pp https://www.rural-water-supply.net/en/resources/details/807
4. Malawi Standard Operating Procedure for Groundwater Level Monitoring 2016 7pp https://www.rural-water-supply.net/en/resources/details/807
5. Malawi Standard Operating Procedure for Groundwater Sampling 2016 16pp https://www.rural-water-supply.net/en/resources/details/807
6. Malawi Standard Operating Procedure for Operation and Management of the National Groundwater Database 2016 12pp https://www.rural-water-supply.net/en/resources/details/807
7. Malawi Standard Operating Procedures for Groundwater Use Permitting 2016 24pp https://www.rural-water-supply.net/en/resources/details/807
8. Malawi Standard Operating Procedure for Drilling and Construction of Production Boreholes 2016 26pp https://www.rural-water-supply.net/en/resources/details/807

Therefore, the editors, authors, steering board and publishers will not be responsible for any loss, however arising, from the use of, or reliance on, the information contained in this atlas and maps, nor do they assume responsibility or liability for errors or omissions in the publications. Readers are advised to use the information contained herein purely as a guide and to take appropriate professional site specific advice as needed.

Water Resource Area 16 (WRA 16): The Nkhata Bay Lakeshore Catchment

The Water Resource Area (WRA) 16 in northern Malawi (**Figure 2a**) occupies the Dwambadzi, Mlowe and Usisya Lakeshores and constitutes three (3) Water Resource Units (WRU); WRU 16E, 16F and 16G (**Figure 2b**). It has an area of 5,533 Km^2 and covers the Nkhata Bay district, hence called the Nkhata Bay Lakeshore Catchment. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of longer seasonal tropical convergence zone precipitation and adjective storms from moisture carried from the Mozambique channel. No trans-boundary surface or groundwater bodies are found in WRA 16, but it borders on Lake Malawi which is governed by Trans-Boundary water sharing agreements.

The Nkhata Bay Lakeshore catchment is largely drained by a major riverine flow from Dwambadzi, Mlowe and Luweya Rivers, and a network of tributaries and minor rivers such as Kakwewa, Limphasa, Ruvuo and Magowe Rivers. Surface water flows are mainly west easterly, with many of the rivers deriving their headwaters from the western highlands (Viphya Mountains). It has several dams mostly in the Luweya and Limphasa areas, however there are no groundwater level monitoring points to study groundwater – surface water interaction in the vicinity of these dams.

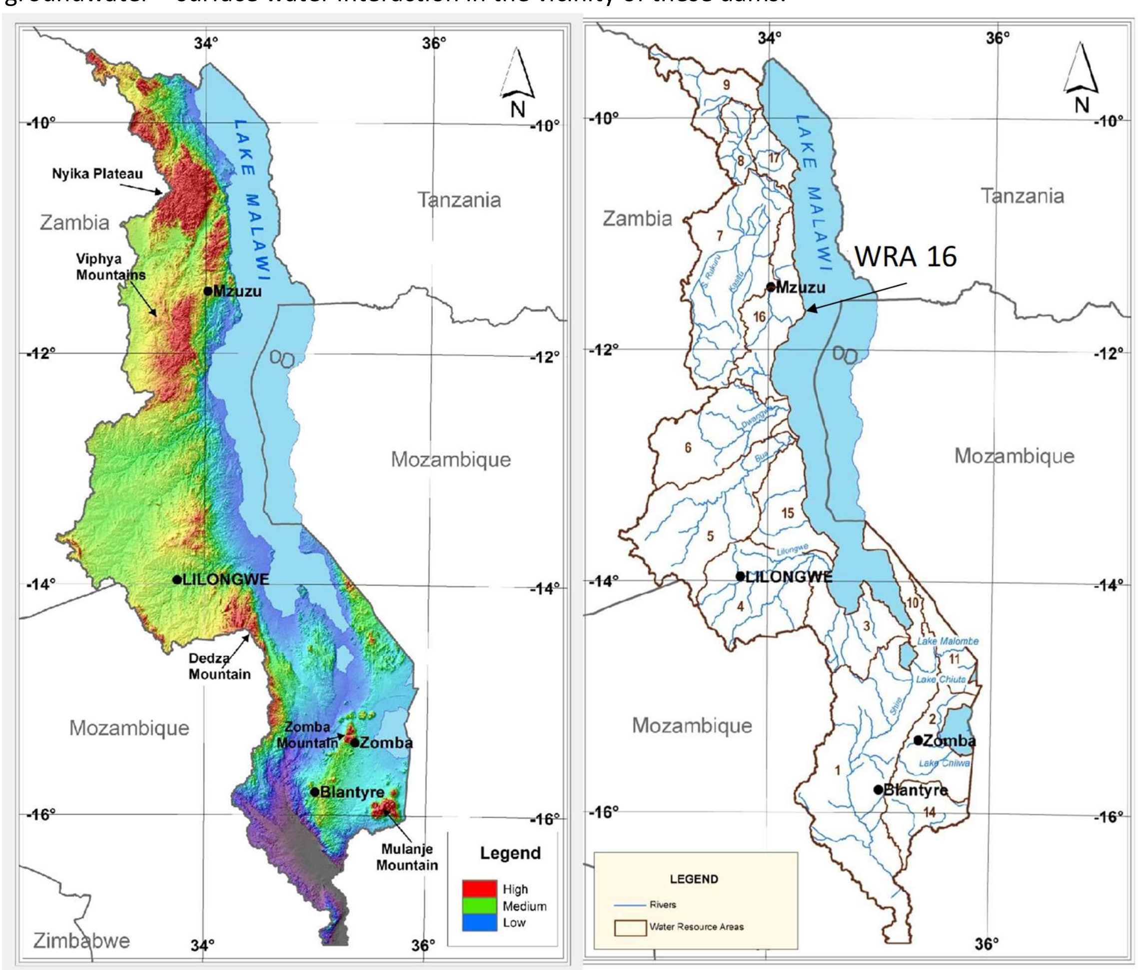

Figure 2a. Location of WRA 16 with major rivers and topography shown.

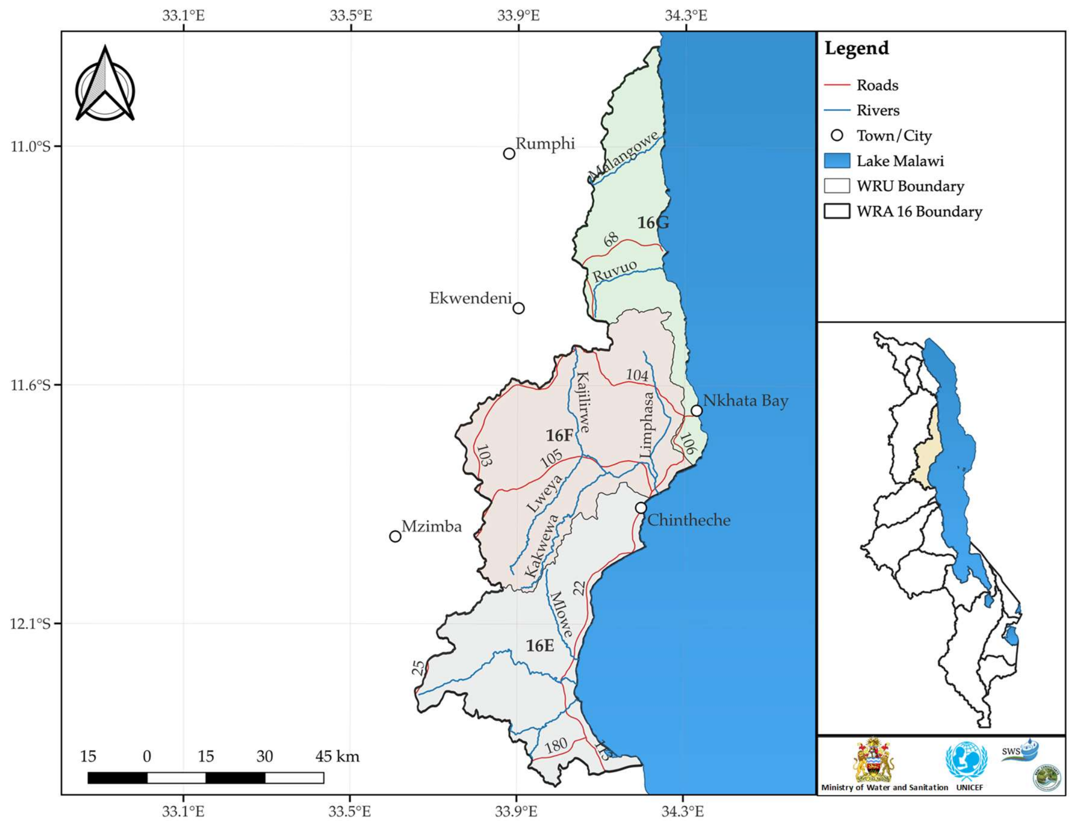

Figure 2b. Water Resource Area 16 and associated Water Resource Units

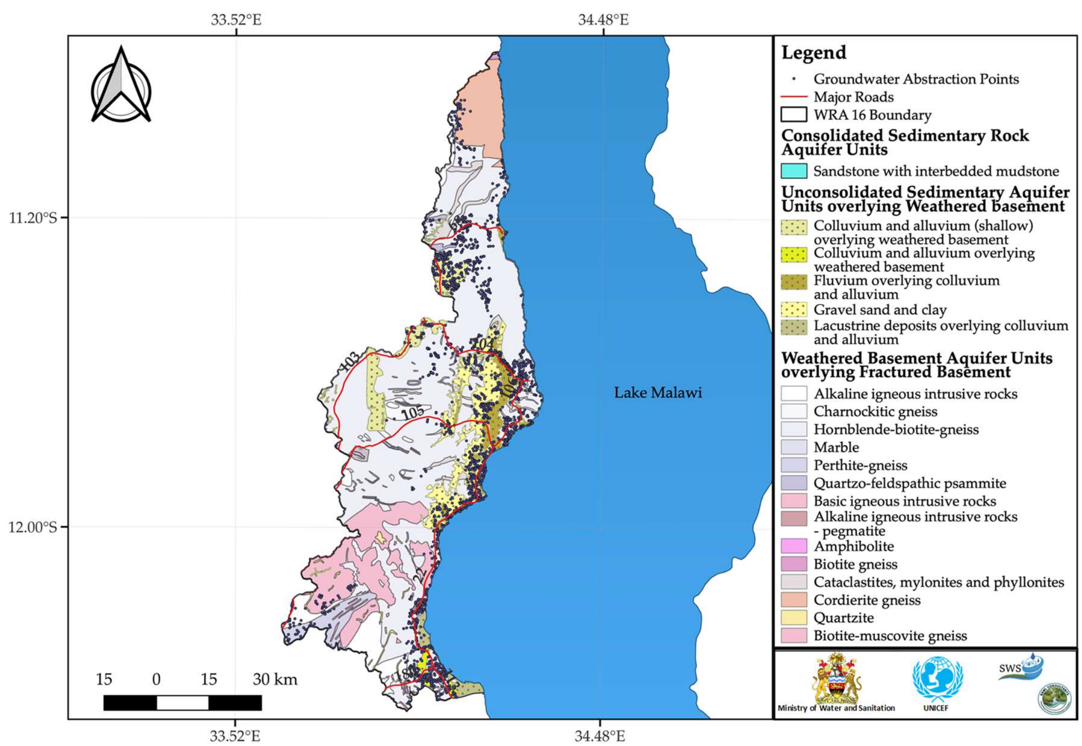

Figure 3. Distribution of groundwater abstraction points in WRA 16.

Groundwater Abstraction in WRA 16

Public abstraction points for groundwater are moderate in WRA 16 (**Figure 3, Table 2**) and it should be noted there are likely a number of unaudited private groundwater abstraction points. Of the 2,734 known groundwater abstraction points, 89.1% are improved sources. The mid-point distribution of water point yield (at hand pump) is between 0.25 and 0.30 l/s (**Figure 4a**), however it should be noted that this is an expected range of the Afridev, Maldev and India MK3 hand-pumps that dominate the WRA, and likely does not represent the aquifer potential, rather a combination of aquifer properties, borehole construction quality, and hand-pump efficiency. For all groundwater supplies in WRA 16, only 55.7% are fully functional (defined as providing water at design specification).

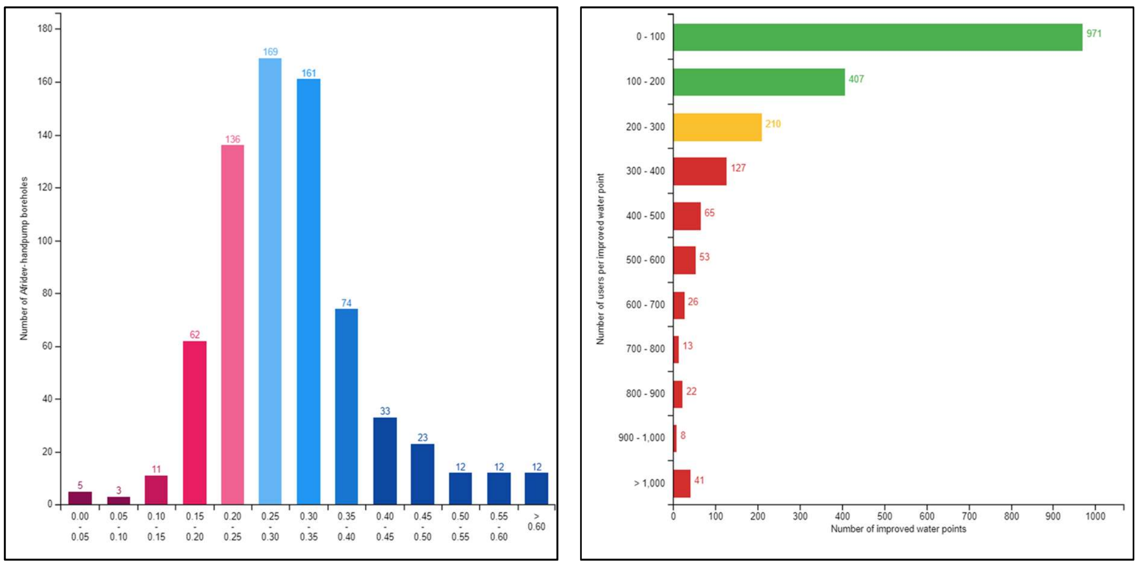

Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 16 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point. [Data from the 2020 National Water Point Survey]

Government guidelines recommend no more than 250 users per hand pump water point and 120 for protected shallow well, and the degree to which this is exceeded points to a need for additional investment (as new or rehabilitated groundwater abstraction points). The data in **Figure 4b** shows the guidelines are nearly met and thus a minor investment need in WRA 16 from a population point of view. Most of the groundwater supply points provide water to 250 or less users per water point, but the preponderance of dug wells are a contamination risk and those that do not meet the water quality guidelines should be considered within investment planning.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 14.6% of groundwater abstraction points do not provide sufficient water (September through November) most likely due to water table declines (**Figure 5a and 5b**). Shallow boreholes and dug wells (protected and unprotected) are the most heavily impacted, impacting the functionality of these water supplies. Unlike other WRAs, there is a weaker correlation between the depth of the groundwater water supplies and the decline in seasonal water availability, but is assumed this is due to the preponderance of shallow dug well supplies that are more at risk to lowering water tables resulting in lower functionality during the dry season.

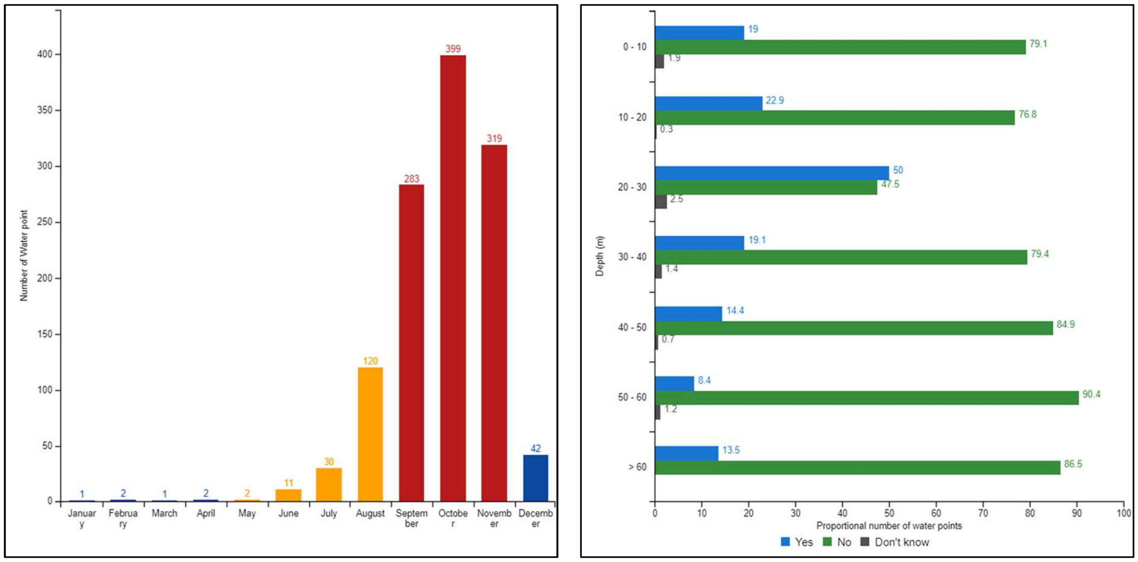

Figure 5a and 5b. Number of groundwater abstraction points in WRA 16 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

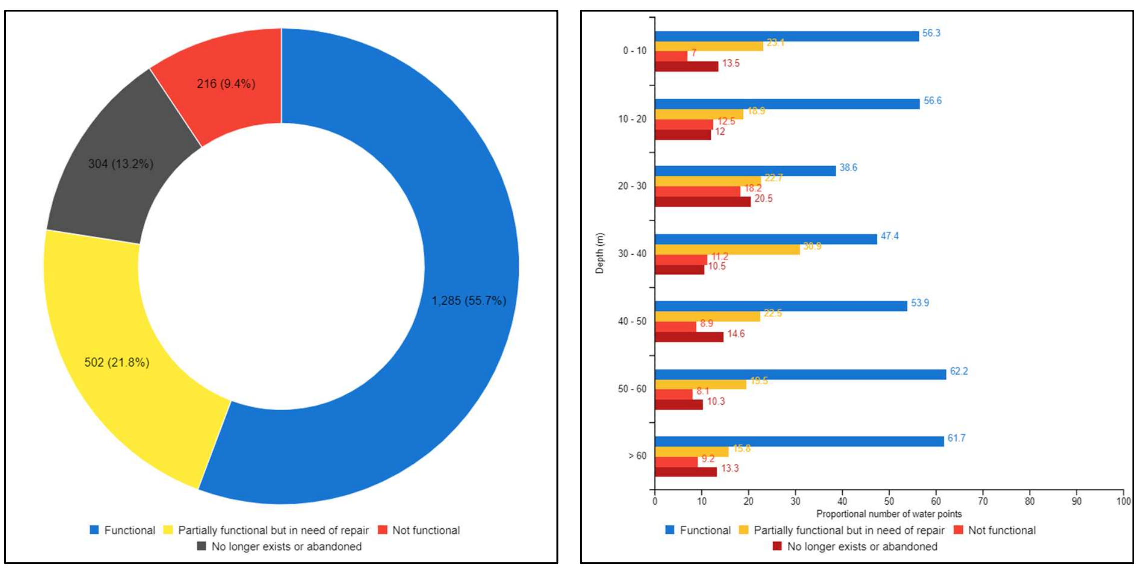

Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 16 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water Point Survey]

The operational status of groundwater abstraction points is also linked to issues of infrastructure (e.g. pump / borehole) as well as aquifer stress. The distribution of functional, partly functional, nonfunctional and abandoned groundwater abstraction points is relatively constant with depth of abstraction point (**Figure 6a and 6b**). This indicates groundwater supply is impacted by both infrastructure quality and aquifer stress, and there is a need to undertake evaluation of stranded groundwater assets in WRA 16 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 16 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	1,100
Protected dug well	1.336
Protected spring	1
Unprotected dug well	269
Unprotected spring	28

Description of Water Resources WRA 16

Water resources management according to the Water Resource Act (2013) Malawi is devolved to sub-basin Water Resource Units (WRUs), and Integrated Water Resources Management (IWRM) should be managed at this sub-basin scale. Water Resource Area (WRA) 16 constitutes three (3) Water Resource Units (WRU); WRU 16E, 16F and 16G (**Figures 7a, 7b, 7c**).

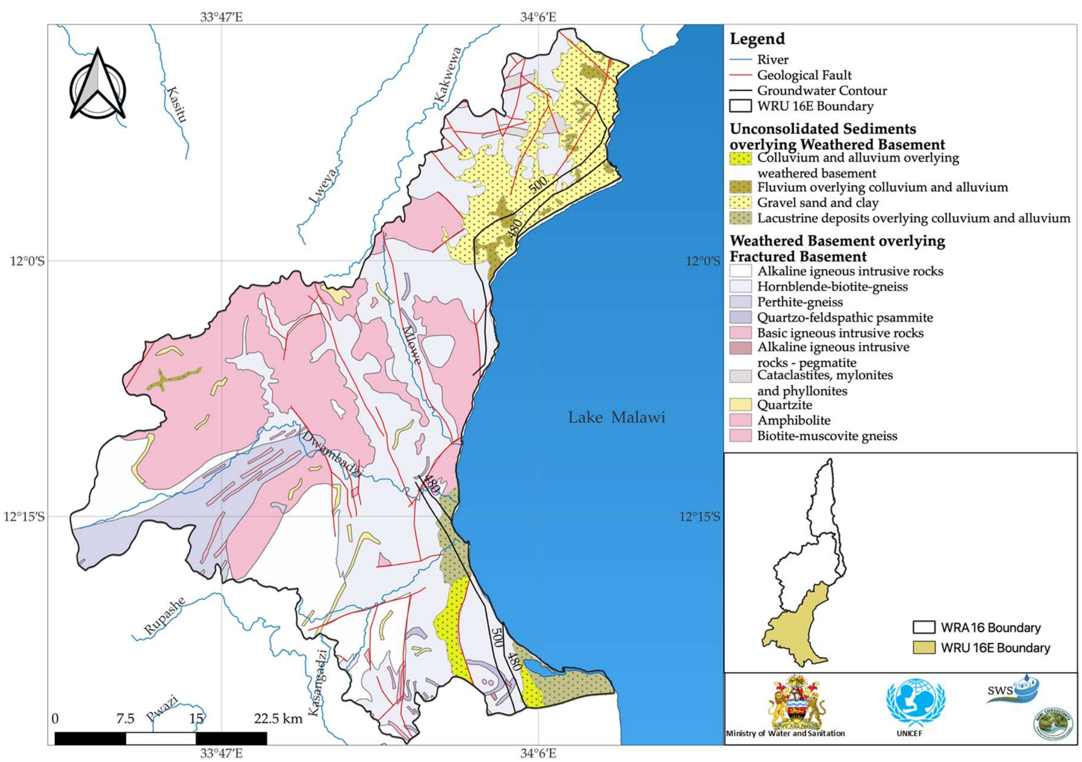

Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 16E wtihin Water Resource Area 16 (Nkhata Bay Lakeshore Catchment).

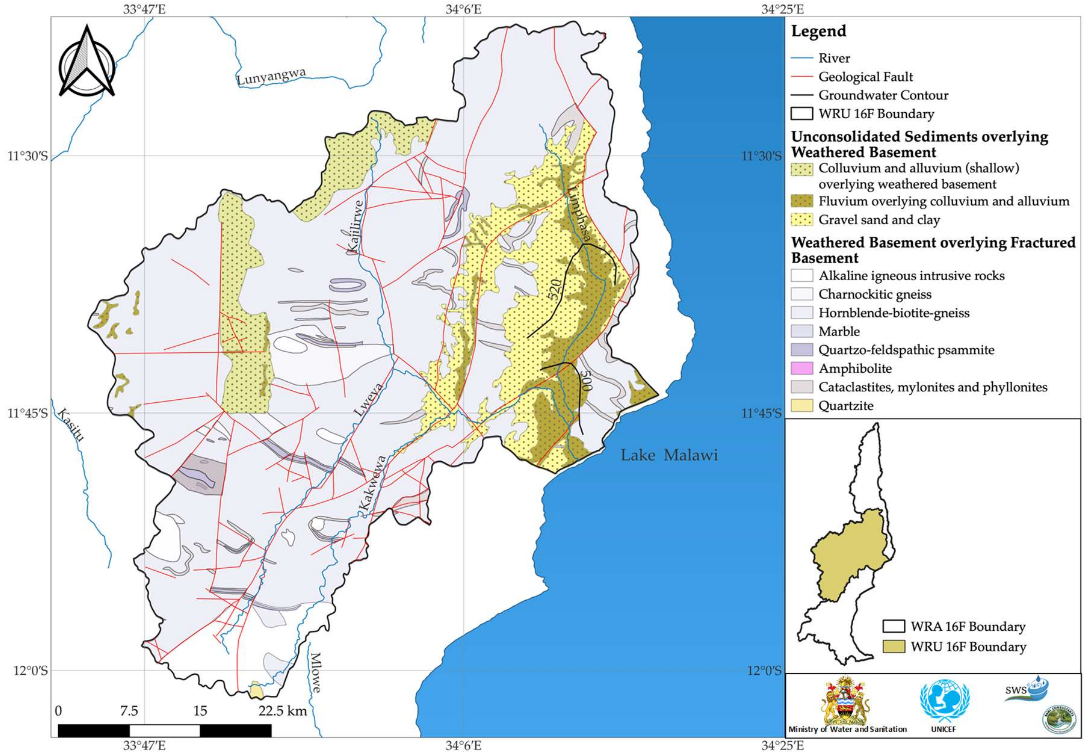

Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 16F wtihin Water Resource Area 16 (Nkhata Bay Lakeshore Catchment).

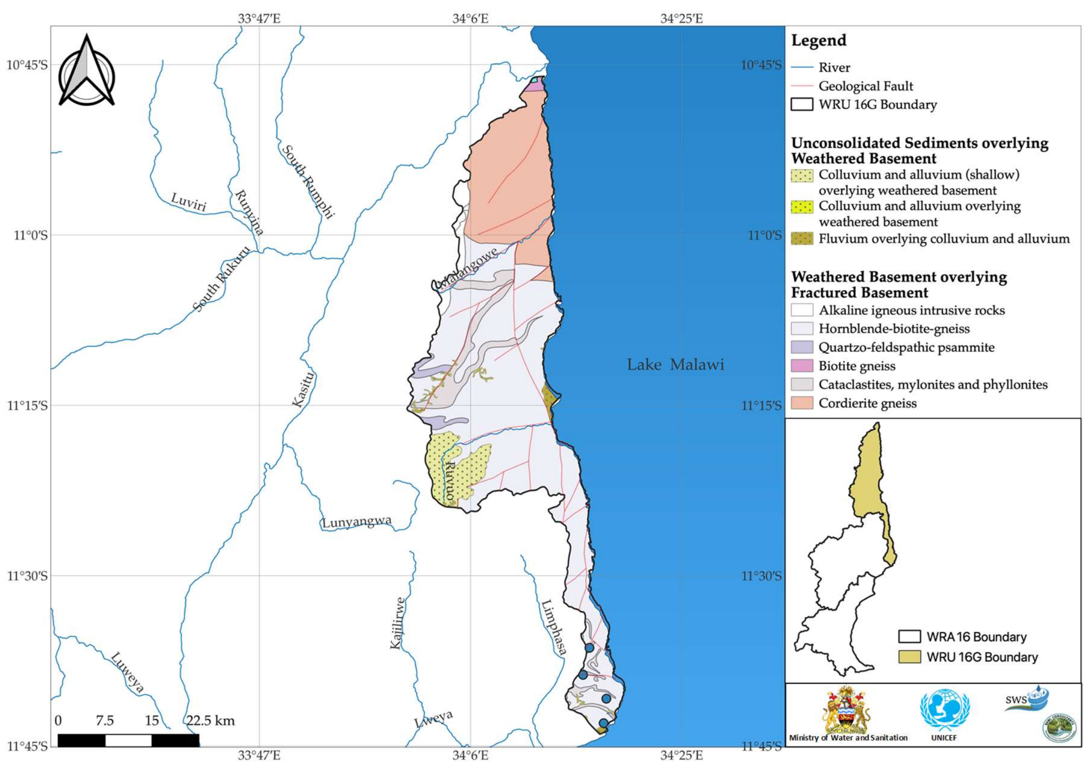

Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 16G wtihin Water Resource Area 16 (Nkhata Bay Lakeshore Catchment).

WRA 16 has an area of 5,533 Km^2 and covers the Nkhata Bay district, hence called the Nkhata Bay Lakeshore Catchment. It should be noted that this basin is not Internationally Trans-Boundary, however given that Lake Malawi is, IWRM should engage with international agreements to manage surface and groundwater for this Water Resource Area.

Topography and Drainage

The topographical setting of Water Resource Area 16 (**Figure 8**) is dominated by uplands of over 2,000 meters in the west of the catchment, declining in elevation across the East African Rift Fault zone to lowlands dominating the eastern side of the catchment where it drains into Lake Malawi (**Figure 8**). This largely influences surface water flows eastwards to Lake Malawi and enhances the occurrence of frequent seasonal flash flooding in the Water Resource Area.

Geology – Solid

WRA 16 solid geology (Figure 7a, 7b, 7c) is dominated by Precambrian to Lower Palaeozoic basement rock. Dominant lithologies are hornblende-biotite gneiss and muscovite gneiss and schist, with minor folded assemblages of micaceous phyllonites, and quartzofeldspathic gneiss and granulite. Fault-dissected biotite granite is present in the north of the WRA. The basement rock is highly fractured and forms a complex section of the western Malawi Rift Escarpment in the southern section of the WRA. A set of smaller sub-rift basins filled with unconsolidated sediment occurs immediately west of the Kandoli Mountain range which flanks Lake Malawi to the East.

Geology – Unconsolidated deposits

The sub-basin immediately west of the Kandoli mountains is filled with sediments of the Timbiri Beds - a series of gravels, sands, and clays believed to be deposited during the late Tertiary or Pleistocene. This sub-basin also contains a large dambo region called the Limphasa Dambo which contains extensive fluvial sediments. Colluvium and alluvium occur at the southern end of the Vipya Mountains with minor fluvial deposits within isolated pockets along river courses.

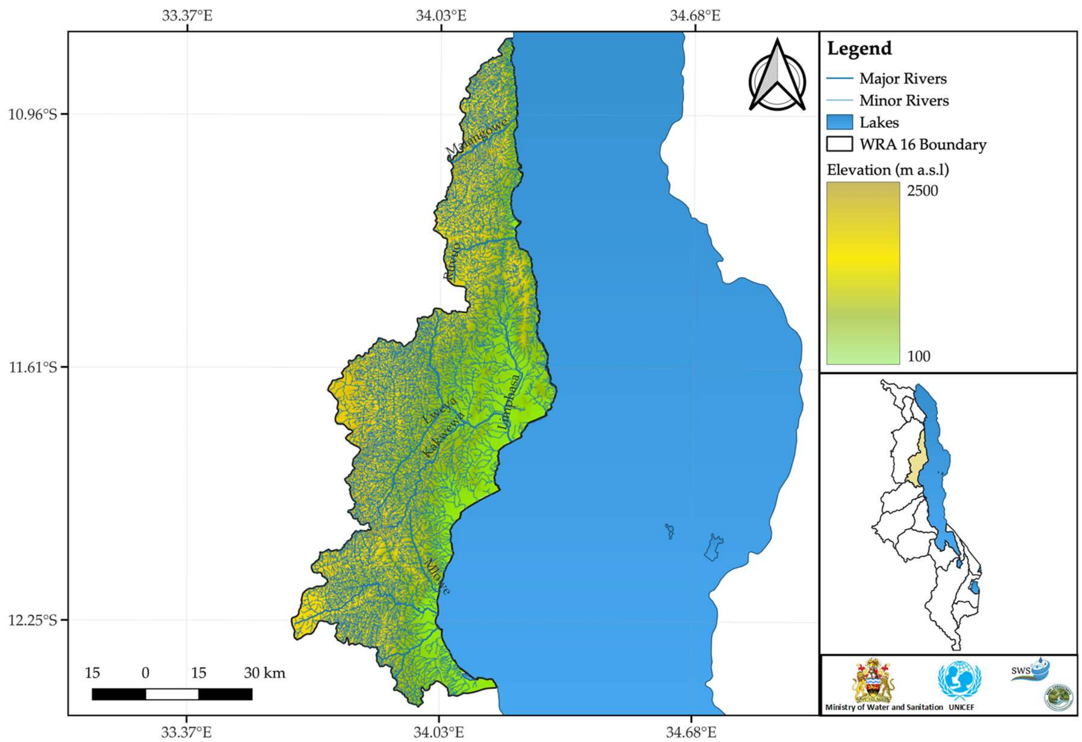

Figure 8. Drainage for the major rivers in Water Resources Area 16.

Climate

Around 80% rainfall occurrence between September and May due to both Inter- Tropical Convergence Zone moisture and north easterly monsoon and south easterly trade wind convergence. Annual rainfall averages from is 1,621 (with greater precipitation likely in the highlands in areas not covered by weather stations), (**Figure 9**). The mean annual temperature is 21–24 °C, with a climate described as tropical wet and dry.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 16. These values are used to calculate the annual estimated groundwater recharge in each WRU.

WRA	WRU	Station Names	Mean Rainfall-Station Data	Mean Rainfall-Interpolated Data (IDW)
16	E	Chintheche	1,655	1,103
	F	- No Station -	-	1,147
	G	Nkhata Bay	1,587	990

Land use

Land use is largely characterised by open woodlands, rain fed cultivation, open grasslands, plantations, marshes, wetland and dimba cultivation. The central stretch north to south and eastwards is largely dominated by woodlands and rain fed cultivation, while grasslands and plantations dominate the western side. Marshes, wetland cultivation and dimba cultivation are common along the of Nkhata Bay district lakeshore areas.

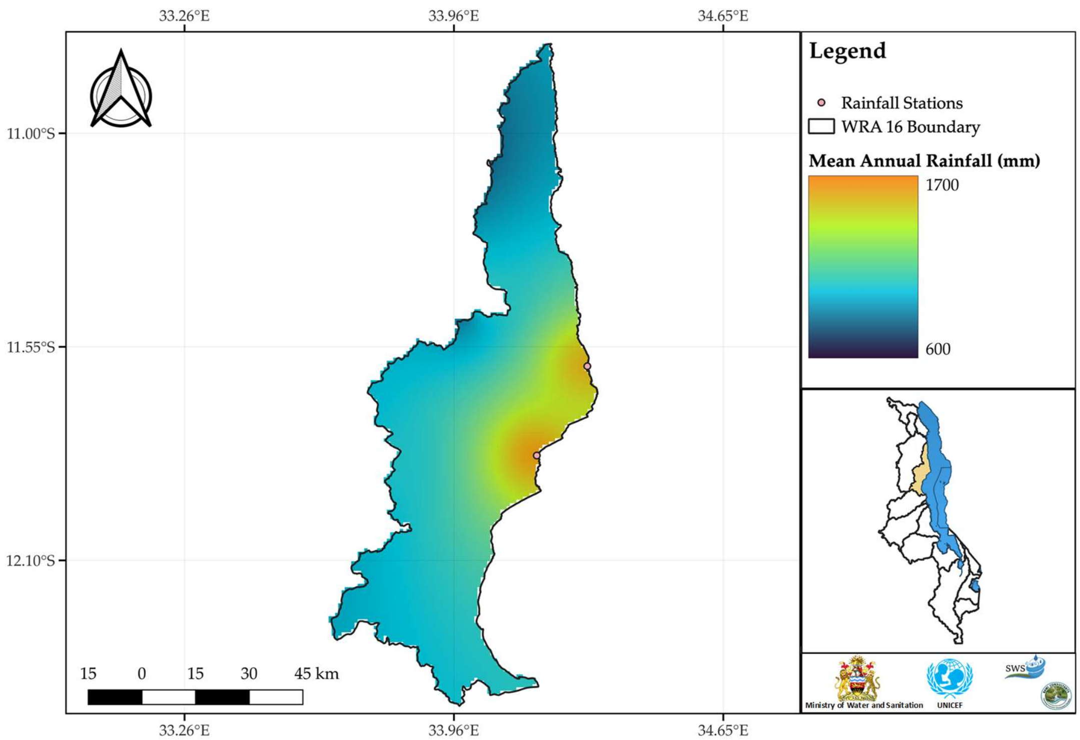

Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 16 with the location of weather stations. Average rainfall measured is 1,016mm, average rainfall modelled is 1,096 +/- 179mm (range 793 to 1,654mm).

The Nkhata Bay Lakeshore is a hub or marine transportation with the Nkhata Bay port harbour on the western shore of Lake Malawi near the mouth of the Luweya River in Nkhata Bay district. This allows access export of agricultural produce of the vicinity. The catchment is also characterised by scenic sites to tourist interests such as the Viphya Mountains close to the Lake Malawi shore. There are extensive Tea and rubber plantations in the area coupled with considerable subsistence fishing along the lakeshores and Luweya River. These socio-economic activities form major income streams for the hinterland.

Hydrogeology of WRA 16

Aquifer properties

The WRA is perched on the western edge of the Rift Valley in which Lake Malawi resides. Limited lacustrine deposits that comprise predominantly finer-grained lithologies along the lake shore generally may be expected to be of modest aquifer potential. Layered unconsolidated, anisotropic aquifer systems may be expected along escarpment drainage channels and where heavy faulting is present.

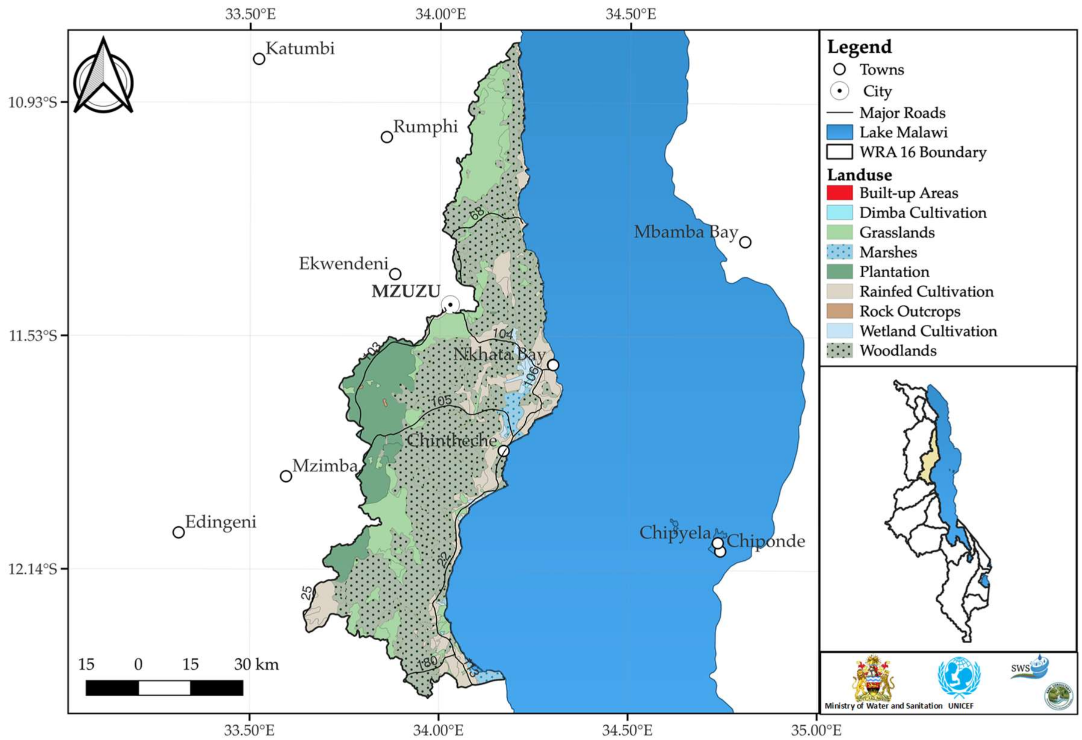

Figure 10. Land use in WRA 16 is dominated by woodlands.

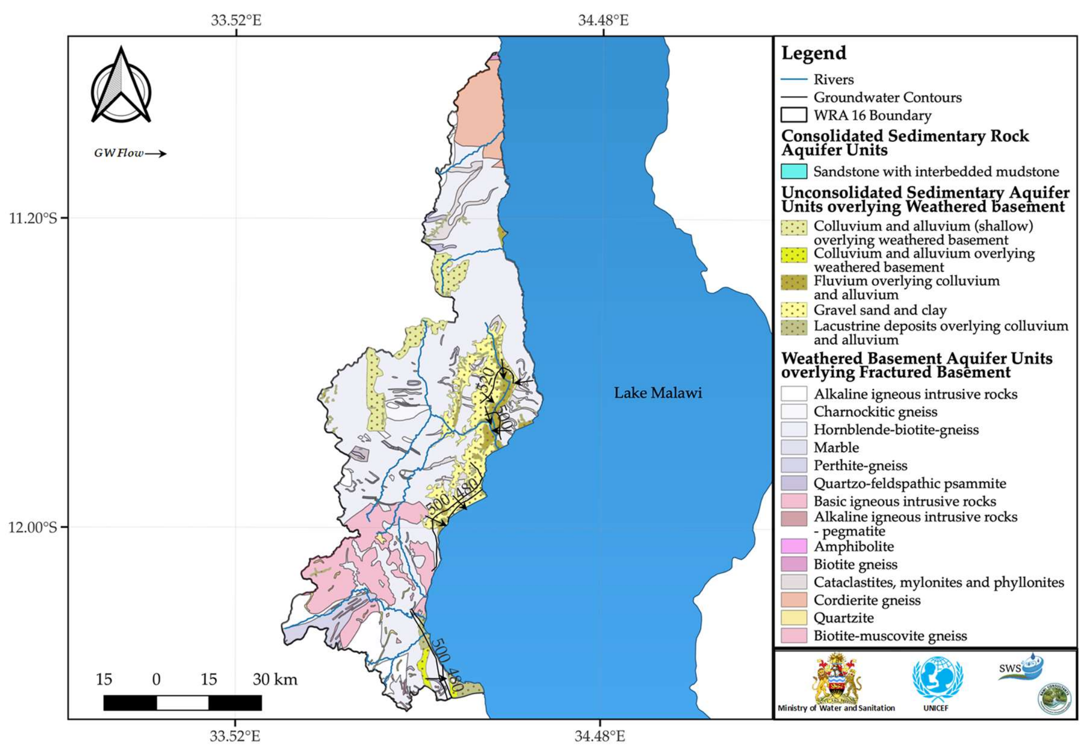

Figure 11. Groundwater level contours and flow direction in WRA 16 [1987 Hydrogeological Reconnaissance data] [water level contour interval 20m]

There is no detailed record of particle size distributions or drilling records but sediments in the Karonga Lake Shore Basin appear to be dominantly med to fine-grained ascribed to the low energy environment of deposition. There is expectation of coarser sediments derived from rift escarpments but lateral extent is not apparent from irregular lithological records for existing boreholes (**Figure 11**).

Groundwater levels and flow regime

The Ministry of Water and Sanitation database has measurements of resting water levels in many boreholes, however there is no high resolution elevation data that corresponds with this WRA, therefore groundwater level data for WRA 16 is based on prior hydrogeological reconnaissance and it can be confirmed that basin groundwater flows are convergent on the Lake Shore generally following topography with indication of groundwater discharge to rivers (see **Figure 11**).

The unconsolidated sediments would generally be expected to receive some recharge via drainage from the adjoining basement. Head contours in the lakeshore aquifer units approximately parallel the shoreline, but are notably steep compared to the WRAs to south that is attributed to the frequent steep topography just inland and narrow lakeshore. Hydraulic gradients in the southern basin in WRU 16E near Mzoza and Mtunu Bay are around 0.015 to 0.02 which suggest groundwater velocities up to around 35 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2. Further north in WRU 16F, inland from Nkhata Bay where the sediment filled Limphasa River/Dambo valley aquifer system extends 30 km inland gradients are much lower at around 0.001 to 0.005.

Aquifer / Borehole Yield

As with most WRA's in Malawi, the borehole yield data held by the Ministry does not appear to follow the anticipated distribution based on aquifer lithology. **Figure 12** provides the distribution of the data held by the Ministry of Water and Sanitation, and it is clear the distribution is skewed toward values of < 0.25l/s. This is suspect and likely represents substandard well construction for nearly 70% of the boreholes to meet a minimum borehole yield for the Afridev pump rather than to drill and test each groundwater well to determine the exact aquifer properties at each location. In WRA 16 (**Figures 13a, 13b and 13c**) the high average rainfall and potential for research suggests there is some potential in the lower elevations for higher yielding boreholes, in particular there are reported yields of >5l/s, and for artesian confined systems along the escarpment but detailed hydrogeological on-site mapping should be undertaken to confirm.

There are general trends which suggest the highest borehole yields are found in alluvial aquifers in the order of 2 l/s. The highest yielding boreholes in basement aquifers will likely be located mainly along linear structures and main streams and near contacts between different aquifers.

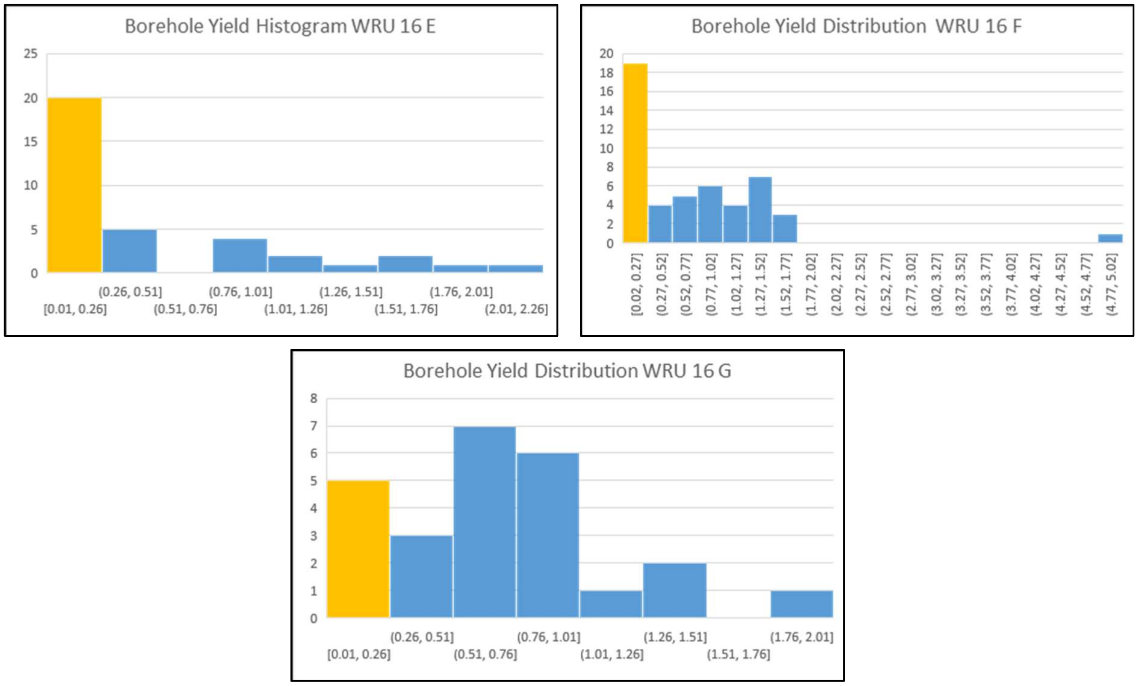

Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 16 (y axis = *n* observations).

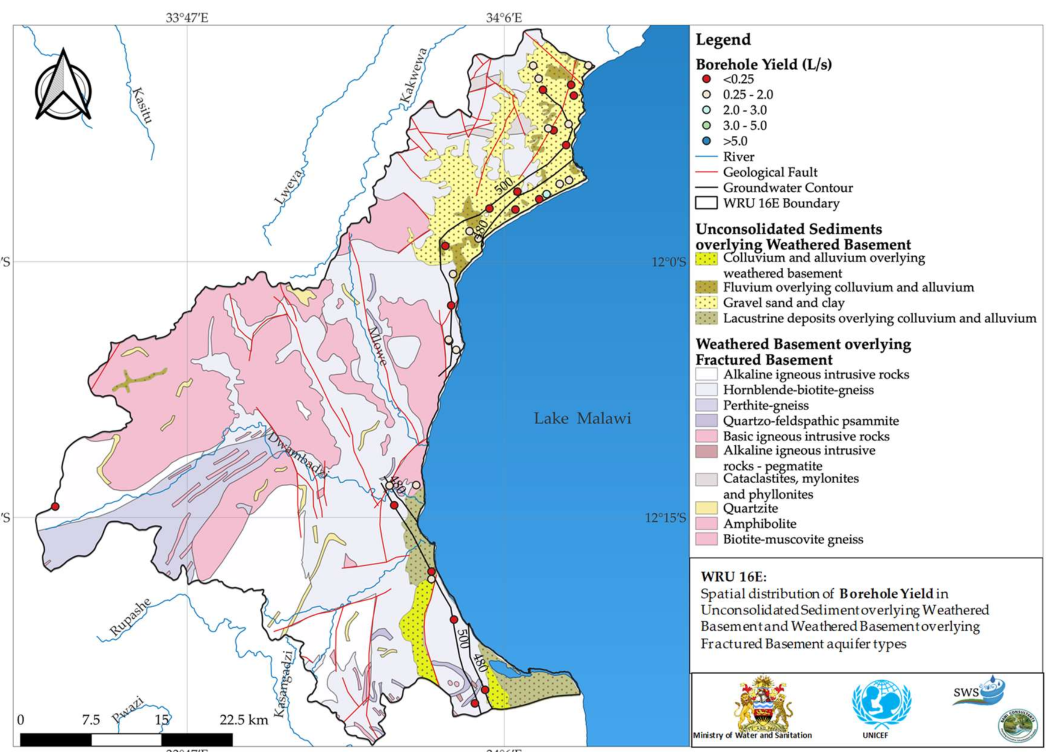

Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 16E.

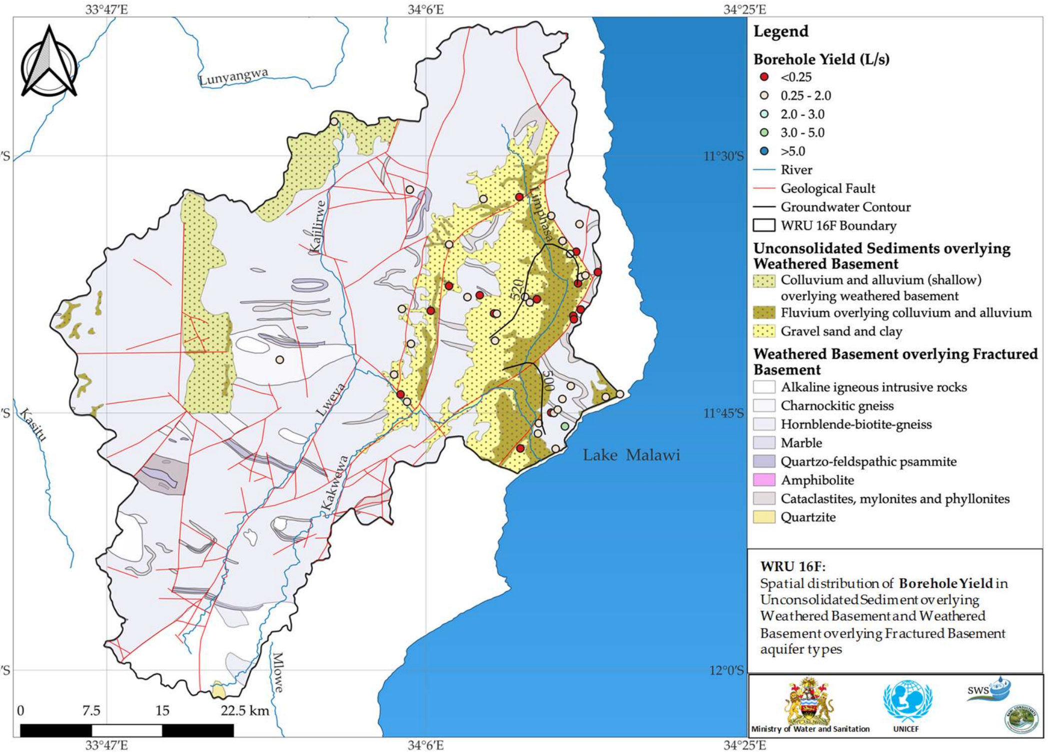

Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 16F.

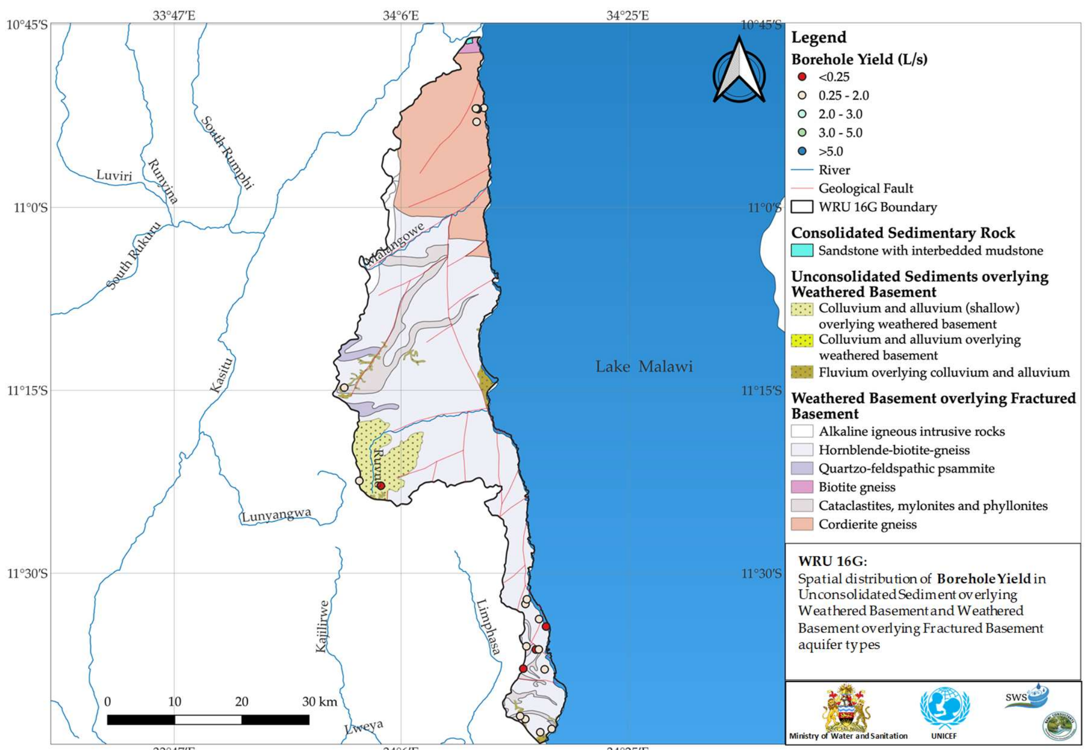

Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 16G.

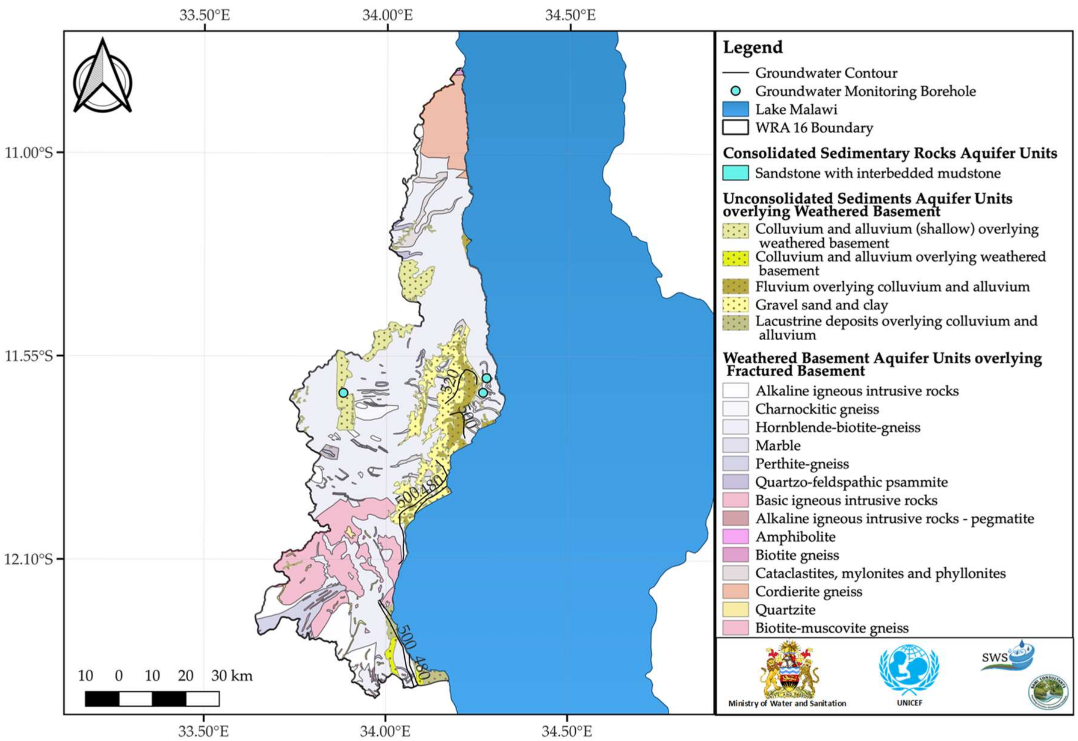

Figure 14a. Location of groundwater monitoring points in WRA 16

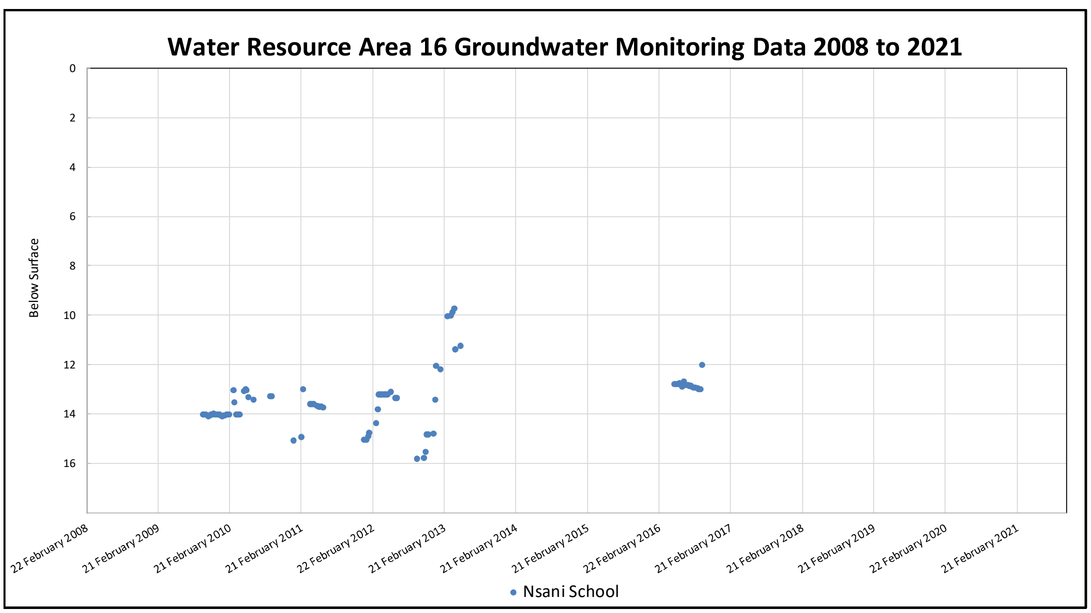

Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 16 (units assumed to be meters below ground level).

Groundwater Table Variations

There is only one operational groundwater monitoring stations within WRA 16, and the data is not complete nor continuous in any segment (annual cycle) (**Figure 14a** location of groundwater monitoring points and **Figure 14b** monitoring data). Data from the 2020 National Survey suggested seasonal water table declines, supported by the data in **Figure 14b**. From the data that is held by the Ministry of Water and Sanitation, there is between a 2- and 6- meter annual change in groundwater table, but it is not possibly to determine any long-term trends that may relate to climate variability (rainfall and recharge relationships). The magnitude of the seasonal variation suggests the aquifers these monitoring points intersect are unconfined and receive annual seasonal recharge. However, there are no borehole logs or multi-level installations that separate different hydro-stratigraphic units and it is recommended that multi-level installations are placed into each hydrostratigraphic unit is an area for future investment.

Groundwater recharge

The groundwater volume in each WRU was calculated using the estimated range of porosities published by McDonald et al. (2021) and the range of saturated thickness for each aquifer type (based on the depth of boreholes and water strikes per agreement with the Ministry of Water and Sanitation). The calculated volume of groundwater recharge in WRA 16 ranges between 60.8 Million Cubic Meters (MCM) and 456 MCM per year, with a mean age of groundwater of 82 years across the Water Resource Area **(Tables 4a, 4b, 4c**). There is a need to better constrain water volume/balance aspects of the basin.

Table 4a. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 16E, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	196.0	10%	35%	0.02	0.10	392.0	6,860.2	
Lacustrine units	48.2	10%	35%	0.02	0.03	96.5	506.6	
Colluvial etc.	27.8	10%	30%	0.02	0.06	55.7	501.0	
W & F Basement	1,562.2	1%	10%	0.02	0.03	312.4	4,686.5	
	Area of WRU (km^2)	16E	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*856.6*	*12,554.4*	*Total Volume Groundwater*
	1,834.2	1103	Average Rainfall in WRU	11.03	82.725	20.2	151.7	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						42	83	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4b. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 16F, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	383.3	10%	35%	0.02	0.10	766.7	13,417.1	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	138.9	10%	30%	0.02	0.06	277.8	2,500.5	
W & F Basement	1,880.9	1%	10%	0.02	0.03	376.2	5,642.6	
	Area of WRU (km^2)	16F	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,420.7*	*21,560.2*	*Total Volume Groundwater*
	2,403.1	1147	Average Rainfall in WRU	11.47	86.025	27.6	206.7	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						52	104	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4c. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 16G, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.6	3%	15%	0.02	0.10	0.4	9.1	
Fluvial Units	18.3	10%	35%	0.02	0.10	36.5	638.8	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	79.0	10%	30%	0.02	0.06	158.0	1,421.6	
W & F Basement	1,220.1	1%	10%	0.02	0.03	244.0	3,660.3	
	Area of WRU (km^2)	16G	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*438.8*	*5,729.9*	*Total Volume Groundwater*
	1,317.9	990	Average Rainfall in WRU	9.9	74.25	13.0	97.9	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						34	59	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 5. Distribution of dissolved species in groundwater WRA 16. It should be noted that data which was reported as zero or negative numbers by the Ministry Water Quality laboratory have not been included in this table. Additionally, where the result was reported below the minimum detection level of the method, the results have not been included in this table. Non-detect and below detection limit results have been included in the graphs providing the distribution of dissolved species in groundwater for each of the WRAs.

WRA 16	pH	EC (as TDS mg/l)	Cl (mg/l)	SO_4 (mg/l)	NO_3 (mg/l)	F (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Fe (mg/l)
Mean	7.3	224	7.8	11.4	4.0	1.2	6.3	2.6	23.7	11.4	2.3
Std Dev	0.8	241	5	15	7.4	1.7	4	2.6	17.5	16.0	4.2
Median	7.5	175	7.7	5.9	0.1	0.3	7.6	2.1	20.0	6.2	0.2
Max	8.4	1,148	16	53	22	4.9	15	13	69	68	12.0
Min	5.5	12.0	0.2	0.4	0.0	0.0	0.2	0.0	2.1	1.1	0.0
n	28	28	27	27	11	12	26	26	27	27	18

Groundwater quality WRA 16

Groundwater major-ion water quality in WRA 16 for data available within the Ministry of Water and Sanitation is limited (**Table 5**).

Piper plots of the WRA 16 water quality data suggest most water has expected major geochemical changes from water-rock interactions dominated by Ca-Mg-HCO_3 type waters (Figure 15a and 15b). The average groundwater age, precipitation rate and calculated recharge rates together with the relatively low electrical conductivity points to recent meteoric recharge of much of the groundwater with water-rock interactions, given the number of hot springs it is possible some higher EC groundwater is linked to movement along fault zones but additional study would be required to confirm the geochemical signatures of fault-fluid groundwater.

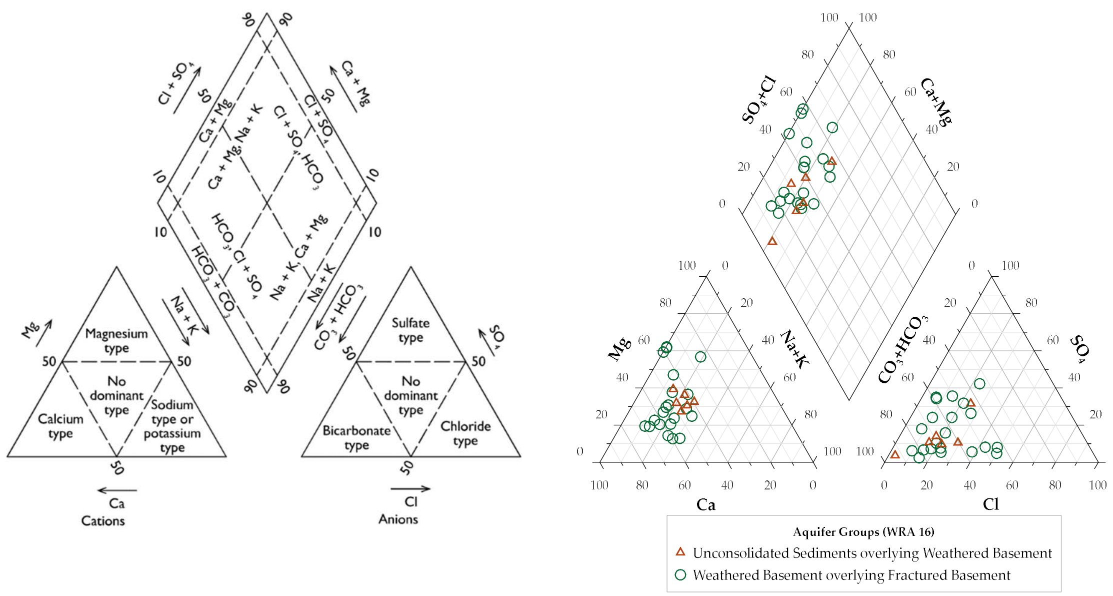

Figure 15a, 15b. Piper Diagramme of Groundwater Samples in WRA 16 and for each Aquifer Type in WRA 16.

The distribution of key dissolved water quality species in groundwater of WRA 16 is provided however caution for over interpretation is advised due to the paucity of data held by the Ministry of Water and Sanitation in the WRA. There are a number of know hot springs in WRA 16 and a full reconnaissance of groundwater – fault fluid interaction is warranted in WRA 16. Importantly as water quality results with geospatial coordinates were rare in WRA 16 there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

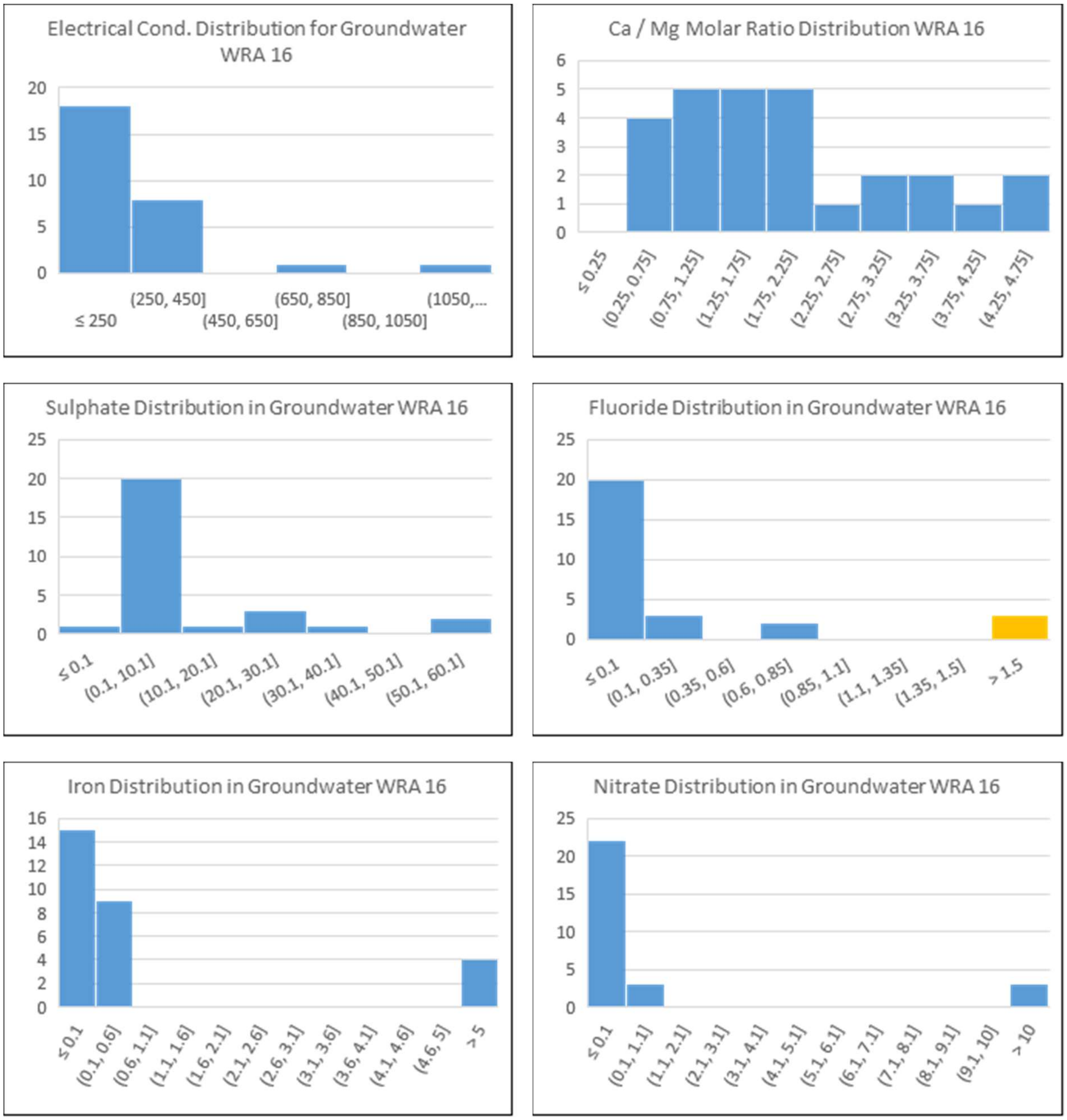

Figure 16 Distribution of chemical species in groundwater within WRA 16 (y axis = *n* observations)

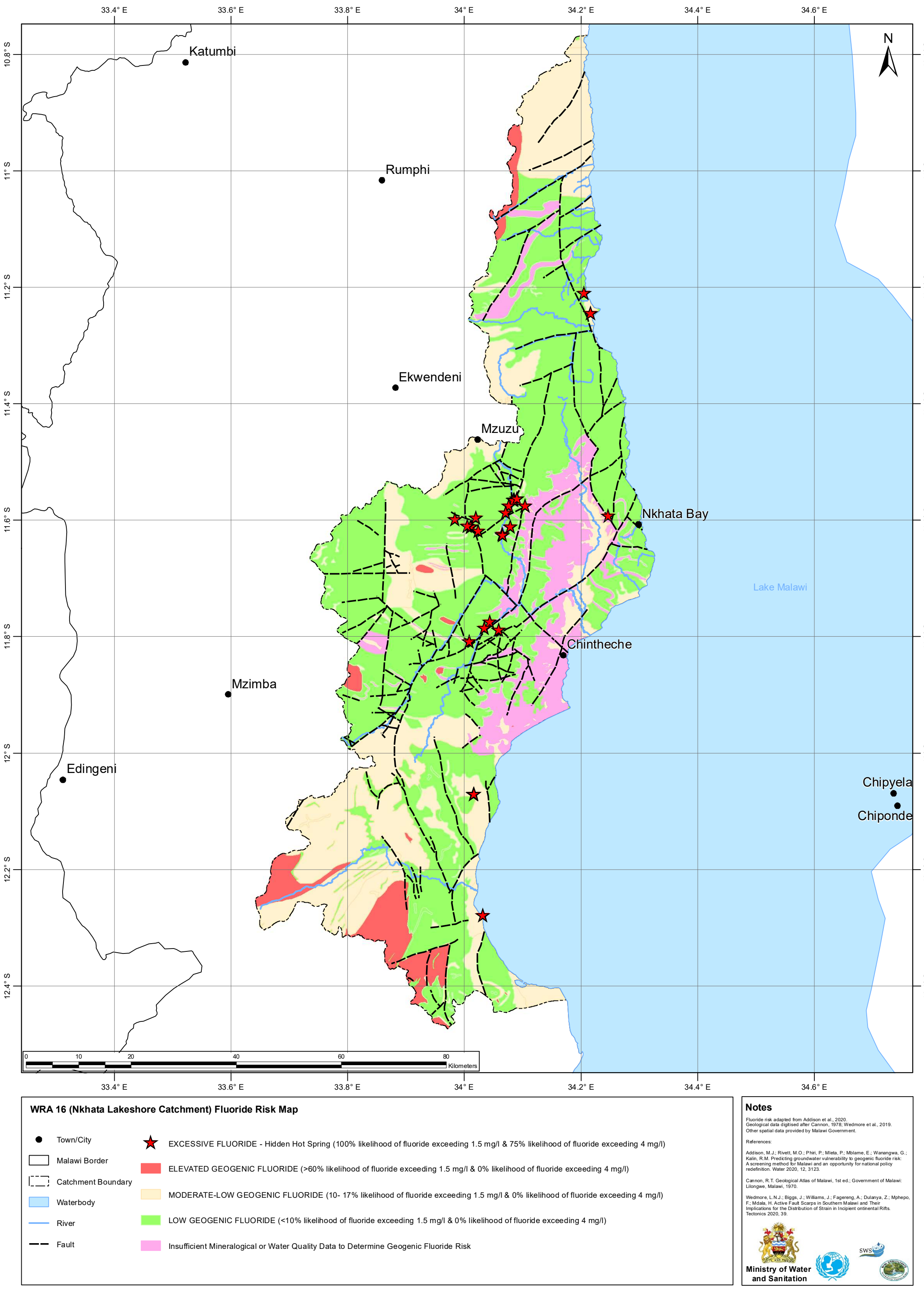

Figure 17. Groundwater Fluoride Risk Map WRA 16 (after Addison et. al. 2021).

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 16 is low. There are a number of water quality results that show minor elevated EC, however the lack of routine and wide-spread water quality analyses held by the Ministry of Water and Sanitation does not allow for interpretation with respect to hydrogeologic units. It is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation.

Fluoride

The prevalence of hot springs resulting from rift faulting places WRA 16 into the **High Risk** category for fluoride in groundwater. Groundwater data drawn from the recent national-scale assessments (**Figure 17**) reveals many Hot Spring exceed the current Malawi drinking water 6 mg/L and given the co-location with major faults, those water points in proximity to the faults have an increased risk of F > 1.5 mg/l. The current water quality monitoring data held by the Ministry of Water and Sanitation is insufficient to manage this risk and it is recommended that a detailed and systematic survey of groundwater quality in WRA 16 is planned and implemented.

Arsenic

A recent national collation of arsenic groundwater survey data (Rivett et al 2018) found widespread low concentrations but with only a few above the WHO 10 µg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. This national dataset did not sample WRA 16 where arsenic risks may exist due to the presence of hot springs, but remain unproven due to a lack of routine, geospatially managed WQ analyses. It is recommended that a detailed and systematic survey of groundwater quality in WRA 16 is planned and implemented

E-Coli and Pit Latrine Loading to Groundwater

There are few measurements by the Ministry of Water and Sanitation for groundwater e-coli that are georeferenced or with details of source. Recent studies (Rivett et al 2022) show recurrent rebound of e-coli from groundwater supplies after chlorination is common, the most likely source being a preponderance of pit latrines. We have therefore modelled the loading of pit latrine sludge as widely distributed point sources of groundwater contamination within the WRA. The spatial population distribution for the years 2012-2020 was accessed through WorldPop distributions (WorldPop2022). WorldPop generates spatial distributions from census data as outlined in Stevens et al. 2015. For the 2021-2022 population projection, the methodology outlined in Boke-Olén et al 2017 was used to produce a future population projection. The spatial distribution is broken down into urban and rural areas through using the urban fraction for 0.25-degree regions of Malawi (Hurtt et al. 2020). Census and DHS data was then used to indicate the latrine adoption in different districts and by rural compared to urban areas, this was then multiplied by the spatial population distribution in each district to provide a spatial distribution of latrine users across Malawi accounting for variation in latrine usage in urban and rural areas and across districts.

The overall latrine adoption data across Malawi was split into individual water resource units to give an indication of the number of latrine users in each water resource unit. The quantity of the average amount of faecal matter produced by each latrine user (270L) is multiplied by the average number of users to give an estimate of the faecal load for each water resource unit.

Table 6. Calculated pit latrine loading 2012 to 2022 within WRA 16.

	Population (Worldpop online)					*Projection*	*Latrine fecal sludge*	*Cumulative Sludge loading*
	Calculated Number of Latrine users							
Water Resource Unit	**Year 2011 - 2012**	**Year 2013 - 2014**	**Year 2015 - 2016**	**Year 1017 - 2018**	**Year 2019 - 2020**	**Year 2021 - 2022**	**Total Volume over 10 year period (Liters)**	**Estimated Total Loading (metric tonnes fecal sludge 2012 - 2022**
16E	87,951	89,274	96,109	101,005	104,240	99,721	312,281,733	374,738
16F	115,717	121,587	128,837	137,024	141,586	139,274	423,373,438	508,048
16G	58,740	56,980	58,466	59,616	59,923	59,660	190,827,595	228,993
WRA 16	**262,408**	**267,841**	**283,412**	**297,645**	**305,749**	**298,655**	**926,482,766**	**1,111,779**

The model results shown in **Table 6** show that for Water Resource Unit 2 a calculated total of 1,111,779 metric tonnes of faecal matter loading over the 10-year period (2012-2022). Over the 10-year period the modelled number of pit latrine users in the region increased by 36,247. WRA16 covers roughly 4.47% of Malawi's area, if it assumed that the approximately 202,741 metric tonnes of fertiliser used in Malawi each year (World bank 2022, data for Malawi 2018) is equally spread around Malawi, 9,065 metric tonnes of fertiliser would be used in WRA1 per year; modelling suggests 12 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

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Relevant Hydrogeological Reconnaissance Maps

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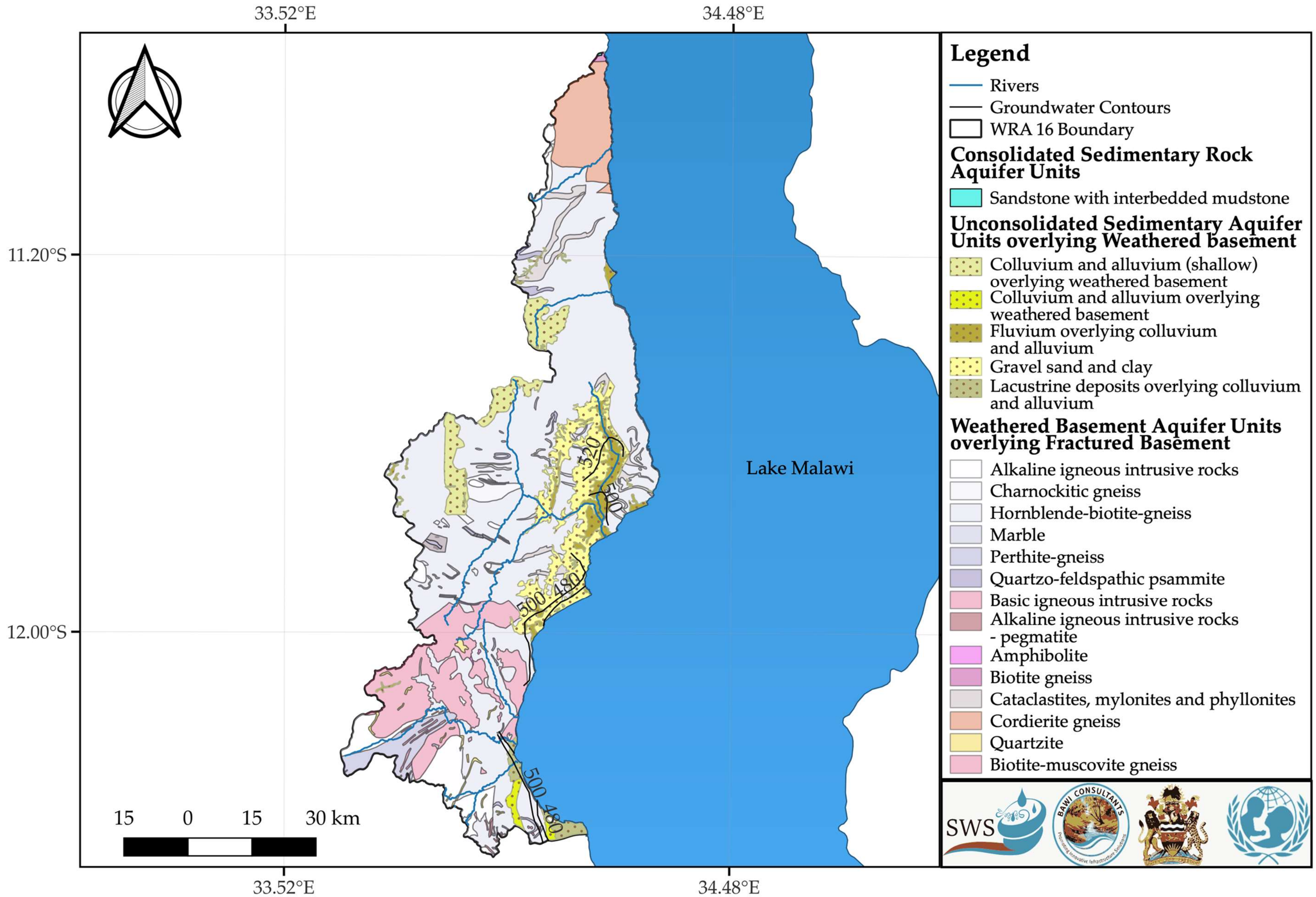
Water Resource Unit (WRA) 16 Figures

Figure WRA 16.0: Aquifer Units and Groundwater Level Contours Water Resources Area 16

Figure WRA 16.0: Aquifer Units and Groundwater Level Contours WRA 16



WRU 16E Figures

Figure WRU 16E.1 Land Use and Major Roads

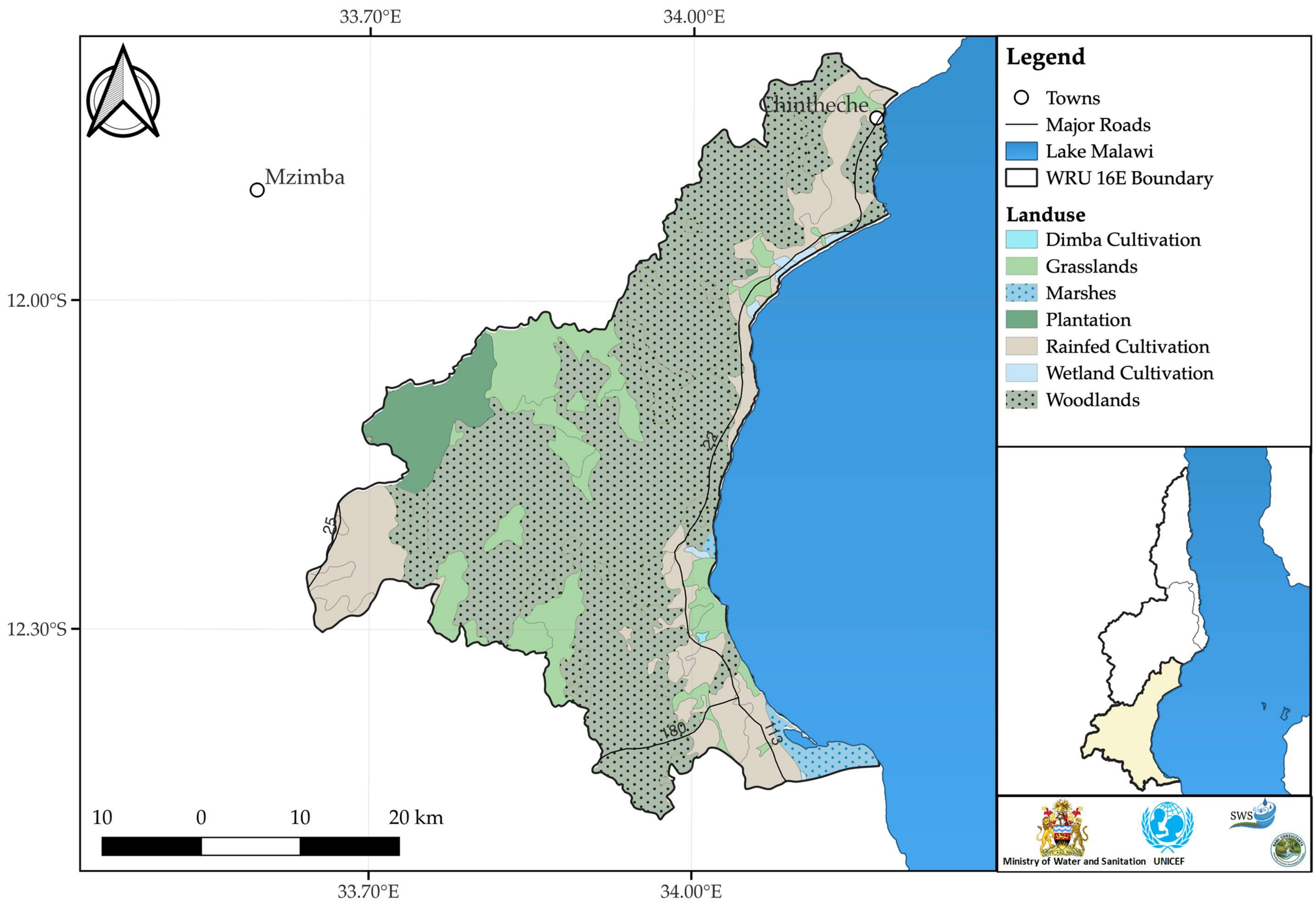


Figure WRU 16E.2 Rivers and Wetlands

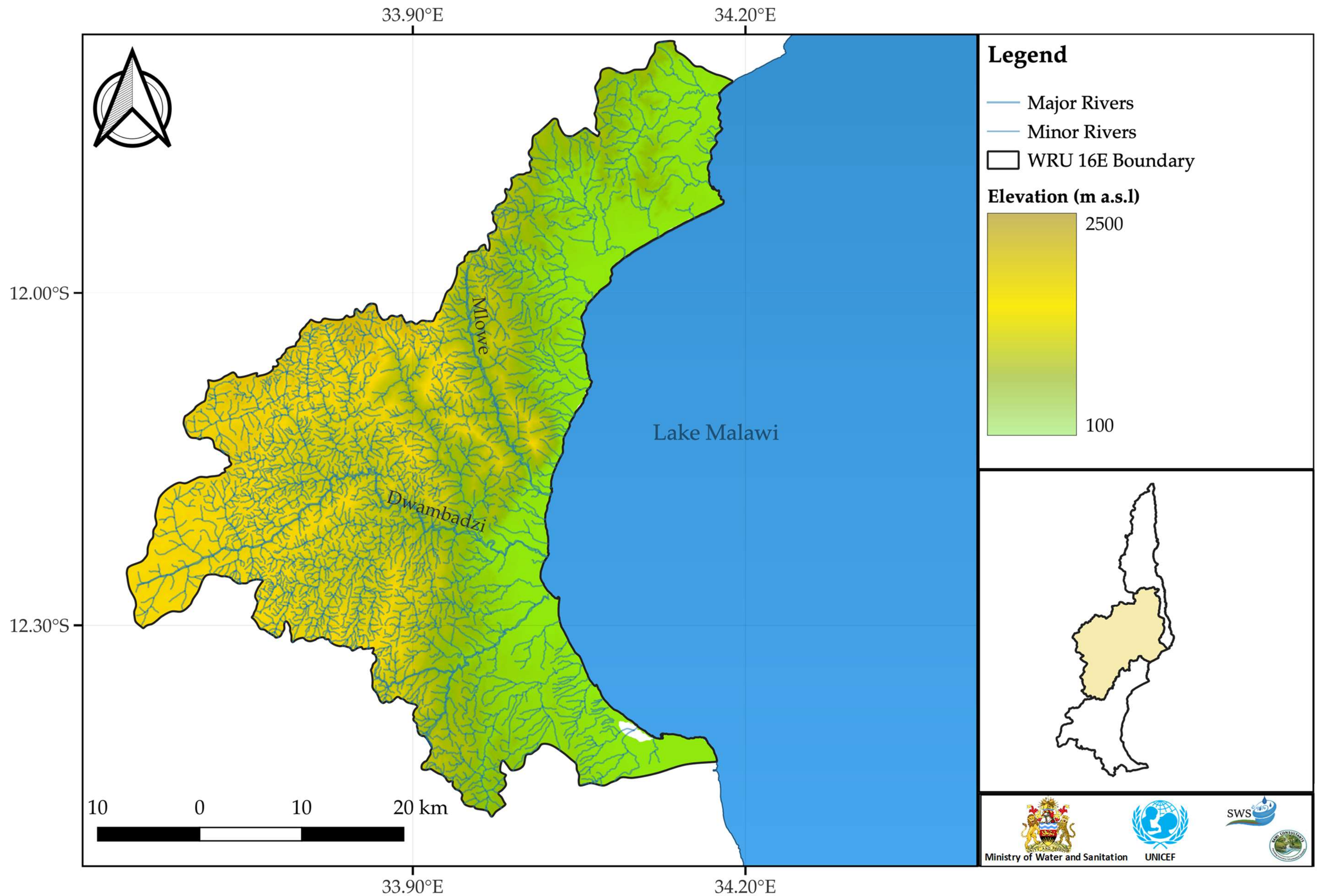


Figure WRU 16E.3 Hydrogeology Units and Water Table

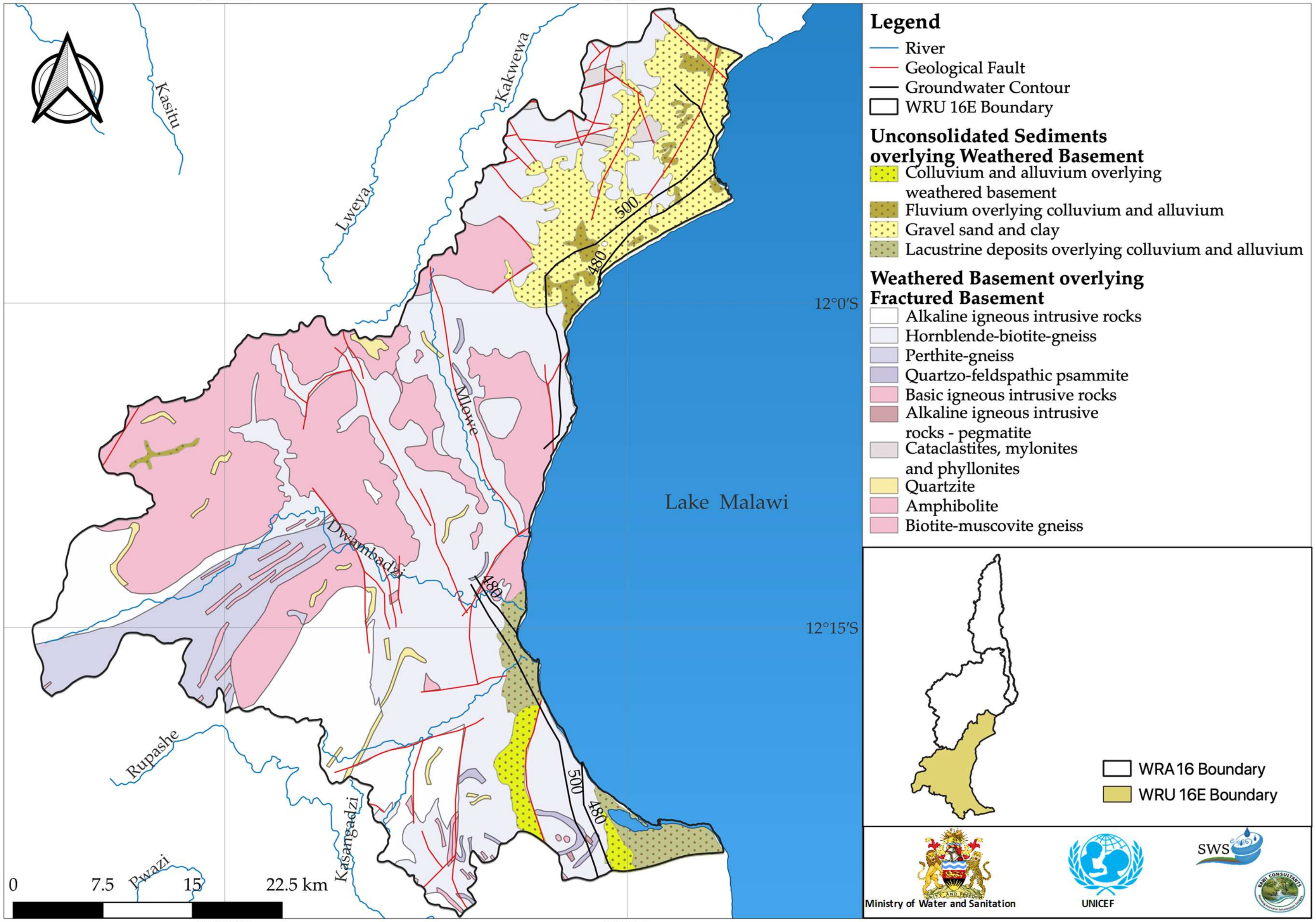


Figure WRU 16E.4 Groundwater Chemistry Distribution Electrical Conductivity

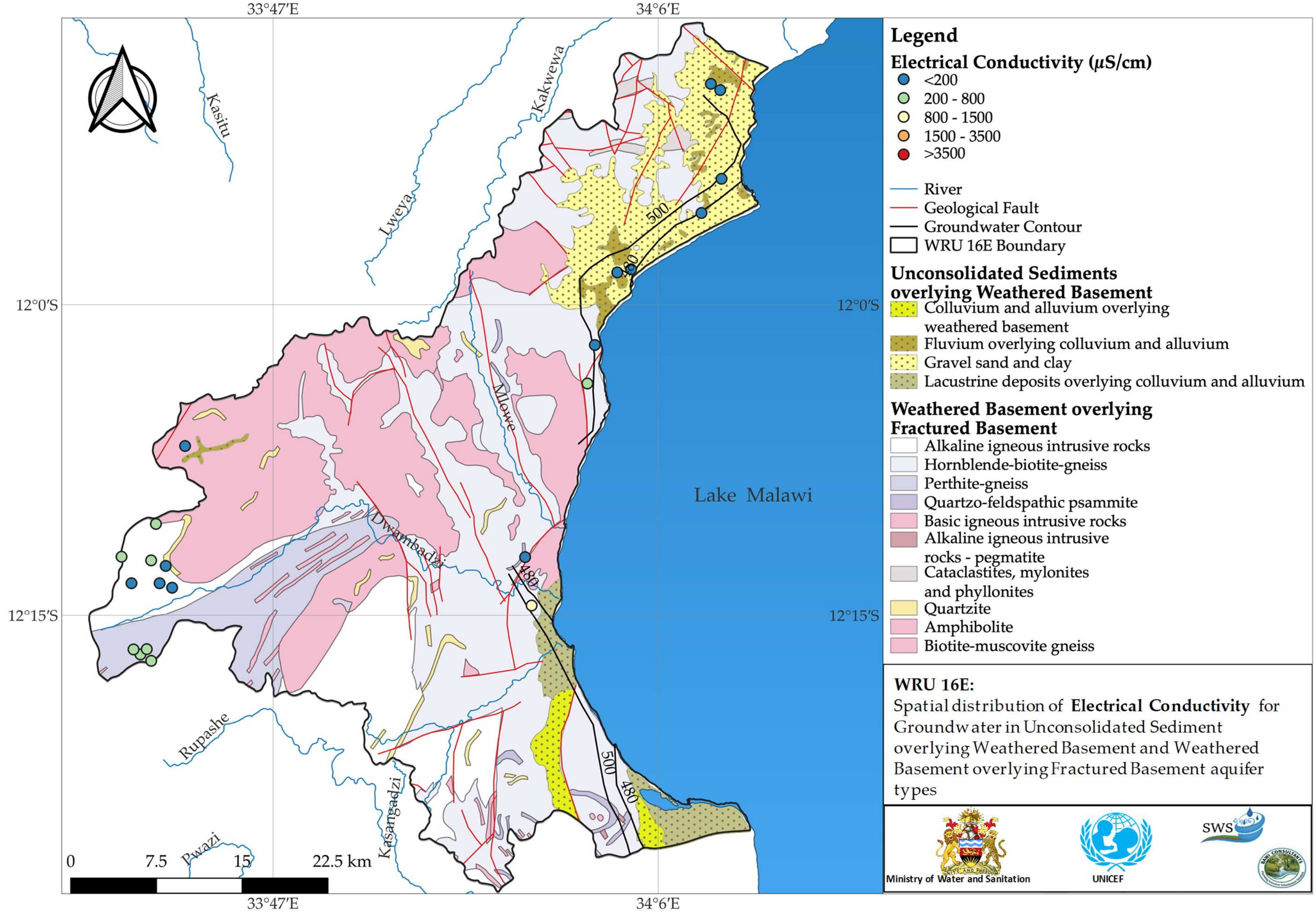


Figure WRU 16E.5 Groundwater Chemistry Distribution of Sulphate

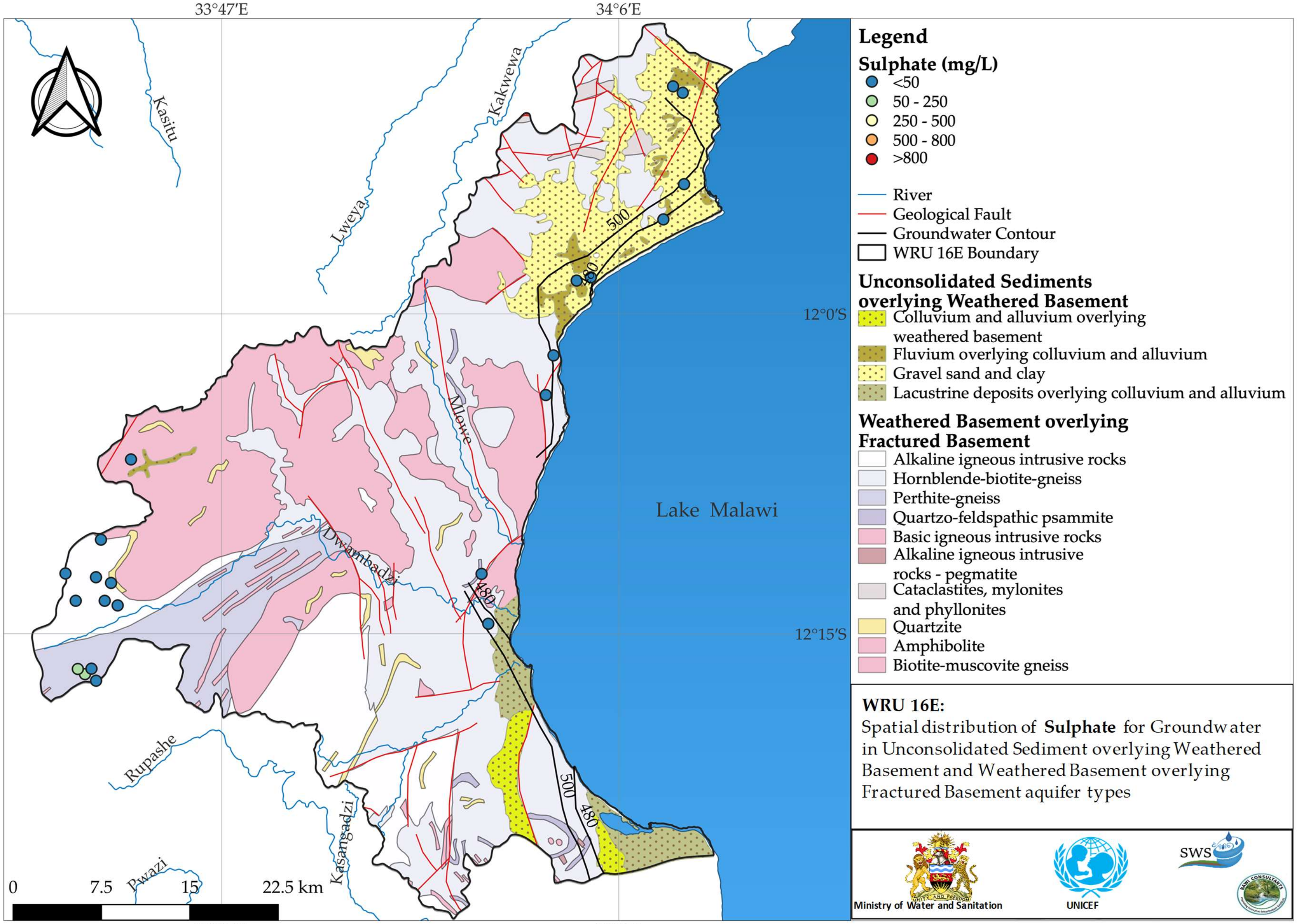


Figure WRU 16E.6 Groundwater Chemistry Distribution Chloride

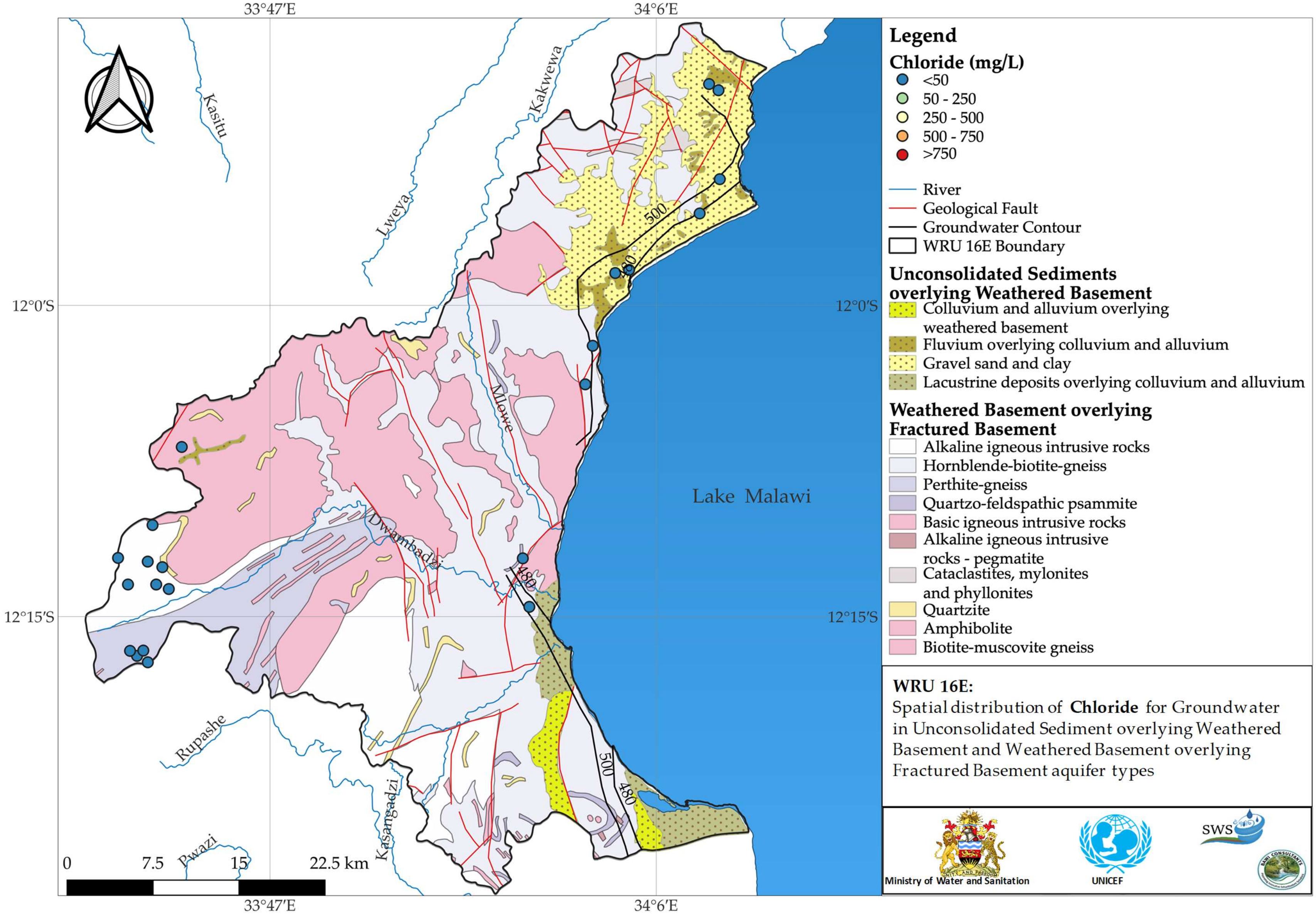


Figure WRU 16E.7 Groundwater Chemistry Distribution Sodium

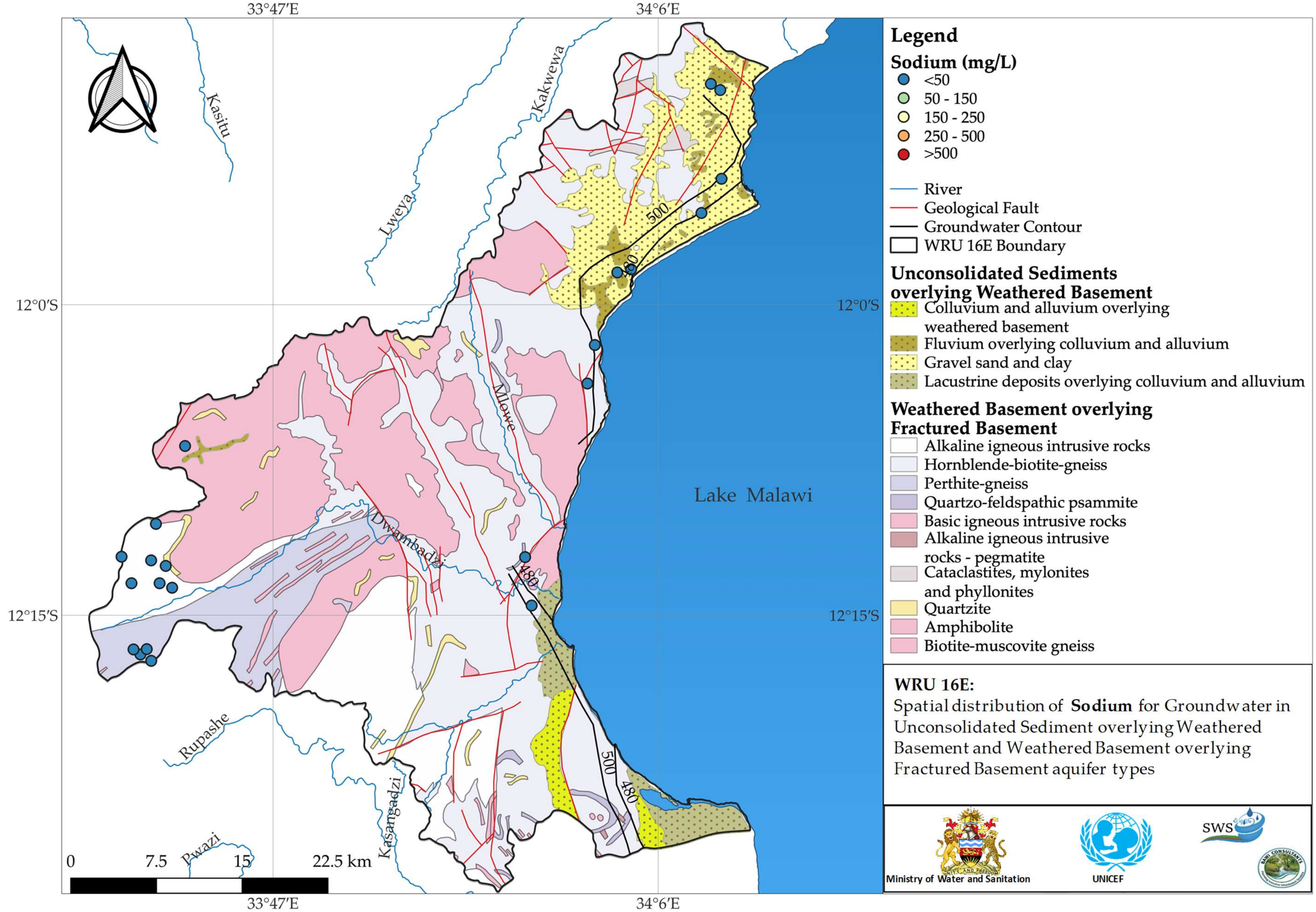


Figure WRU 16E.8 Groundwater Chemistry Distribution Calcium

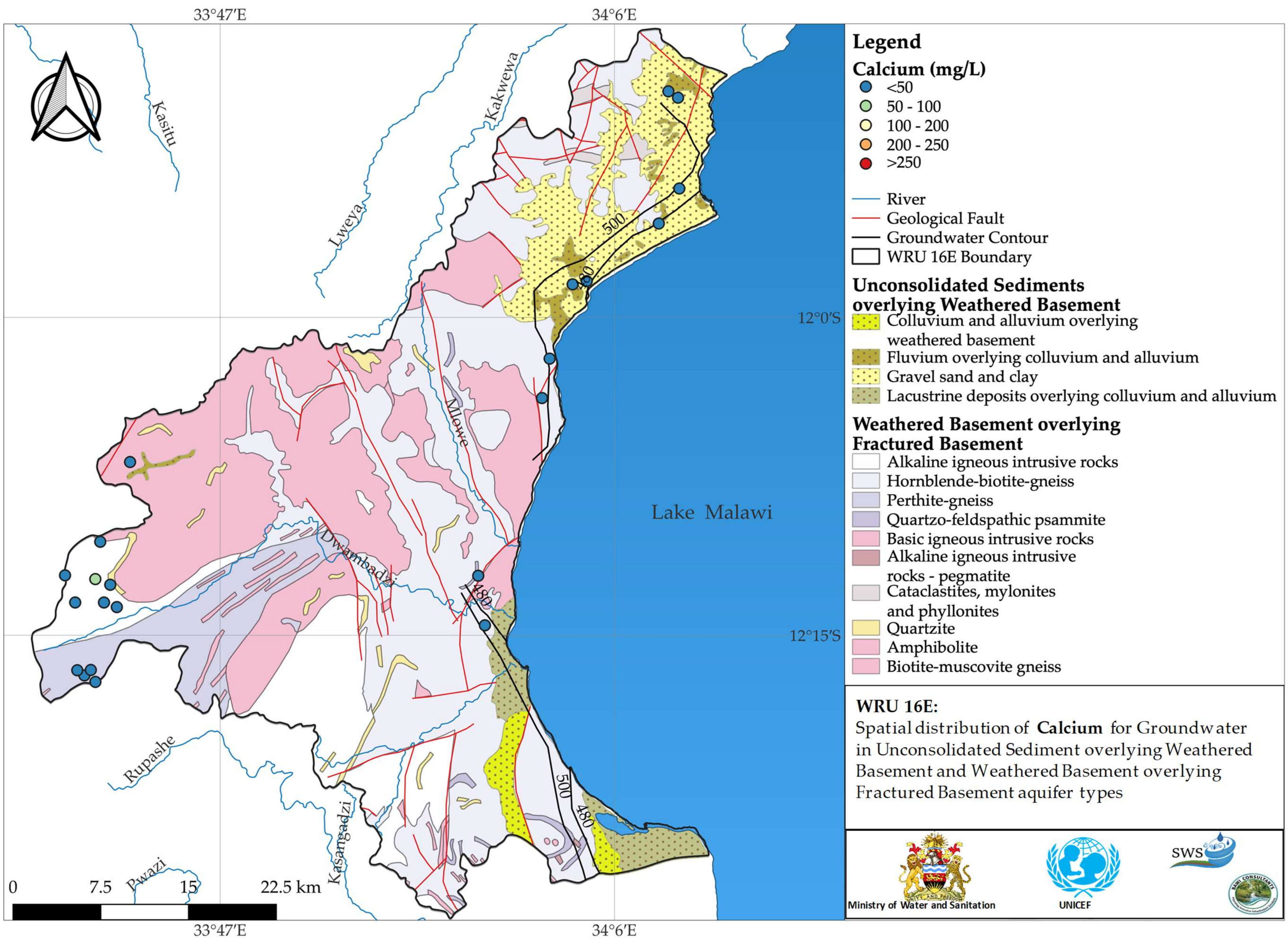


Figure WRU 16E.9 Piper Diagram of water quality results with respect to the major aquifer type

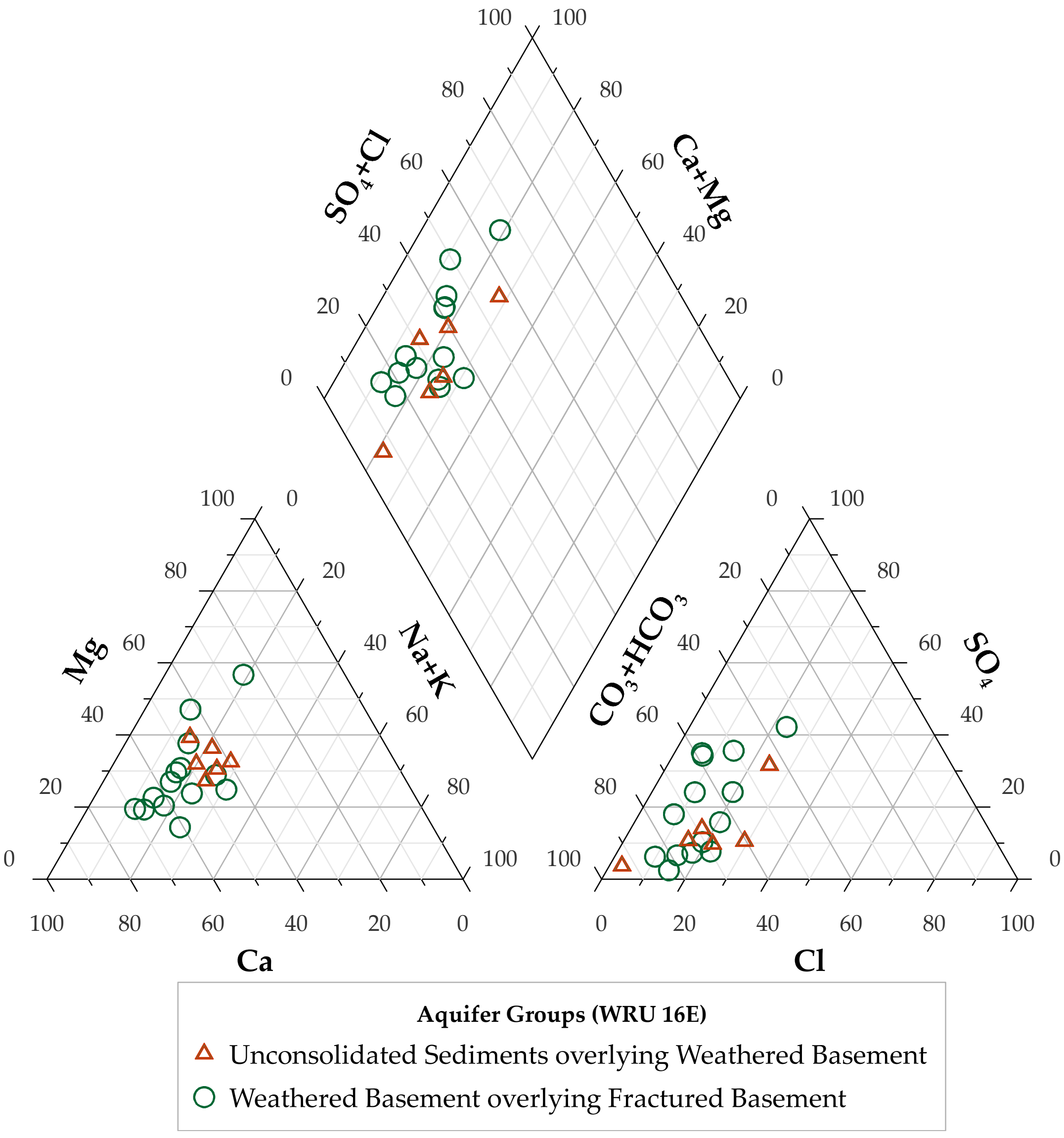
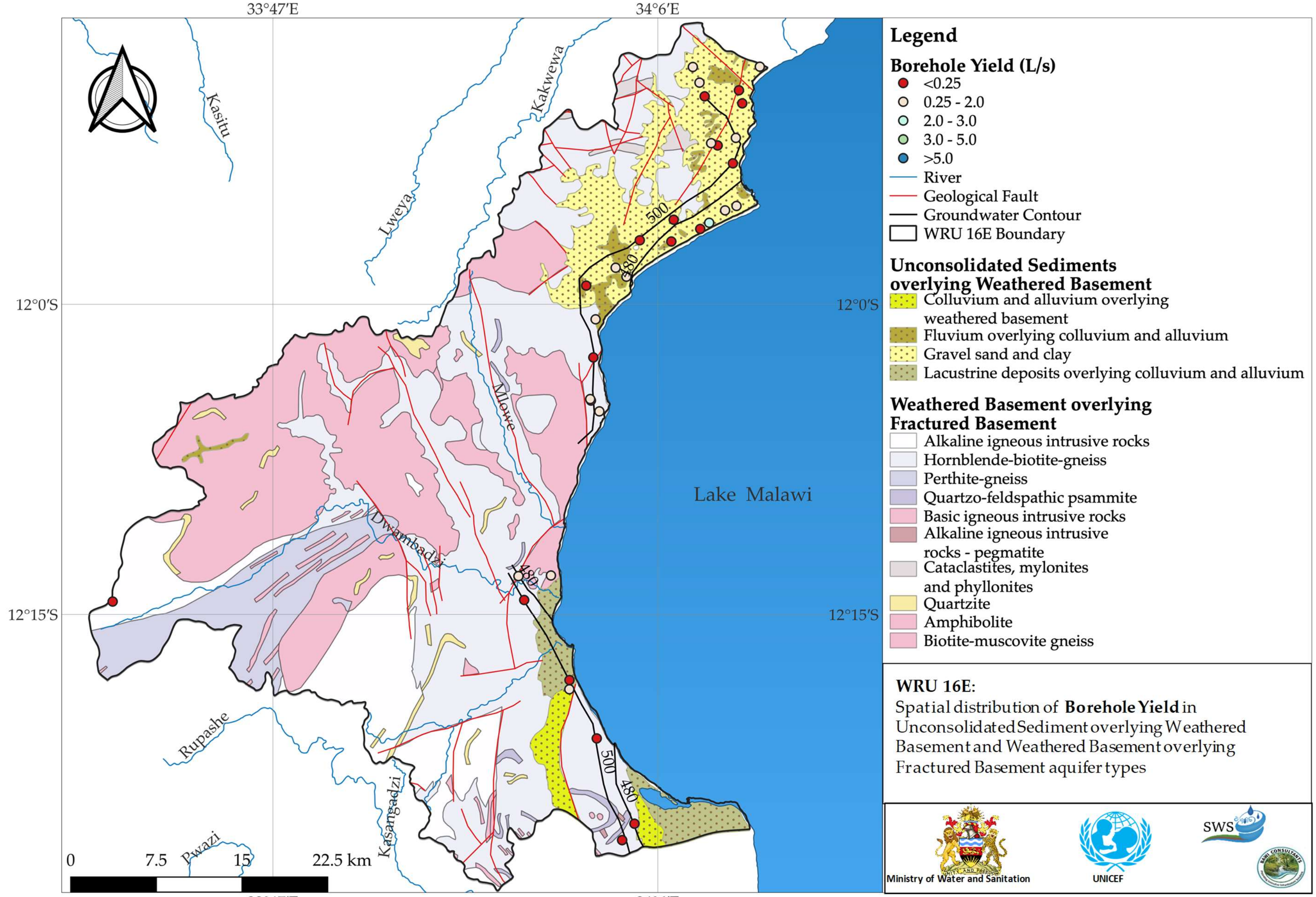


Figure WRU 16E.10 Borehole Yield Map for data held by the Ministry



WRU 16F Figures

Figure WRU 16F.1 Land Use and Major Roads

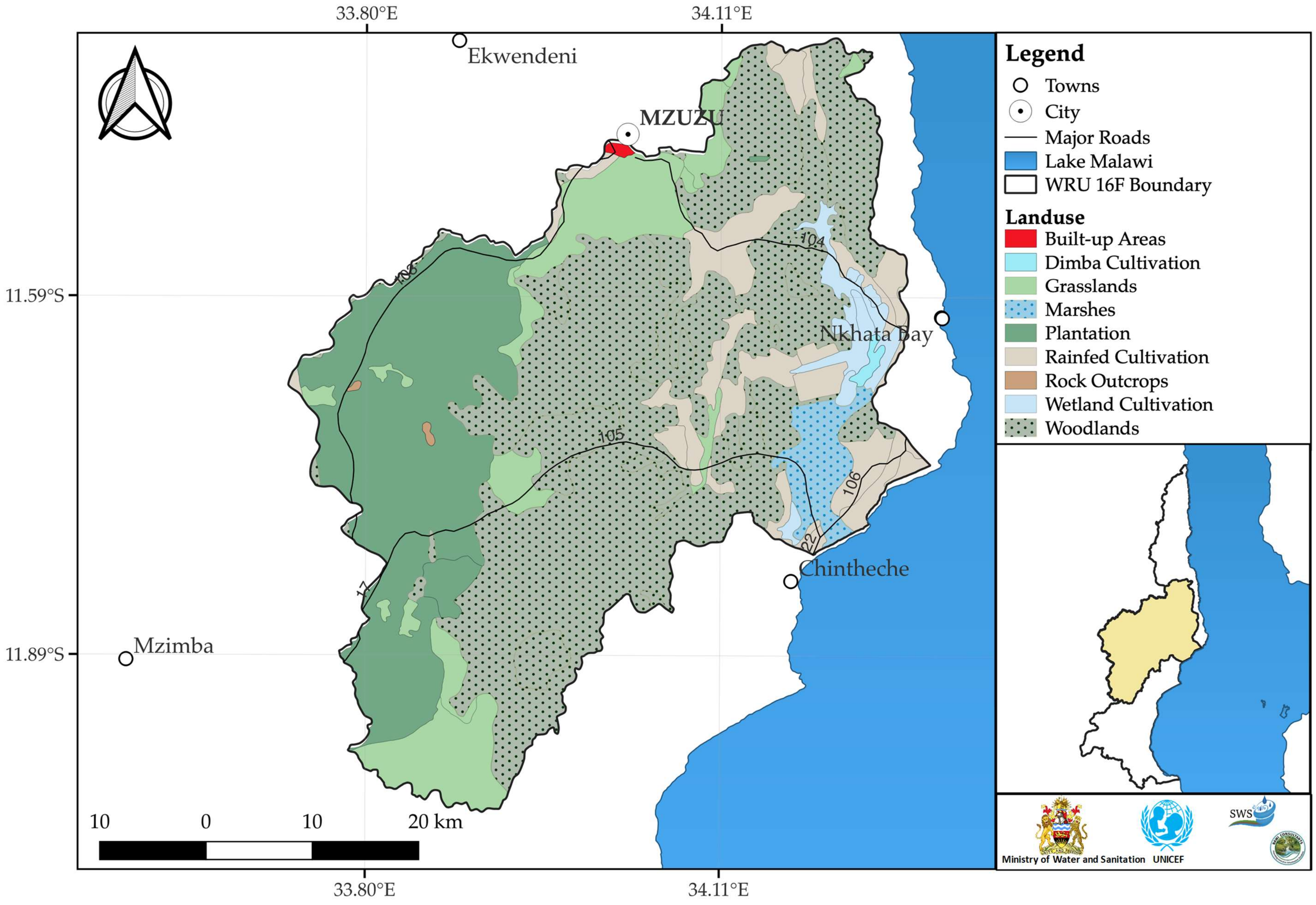


Figure WRU 16F.2 Rivers and Wetlands

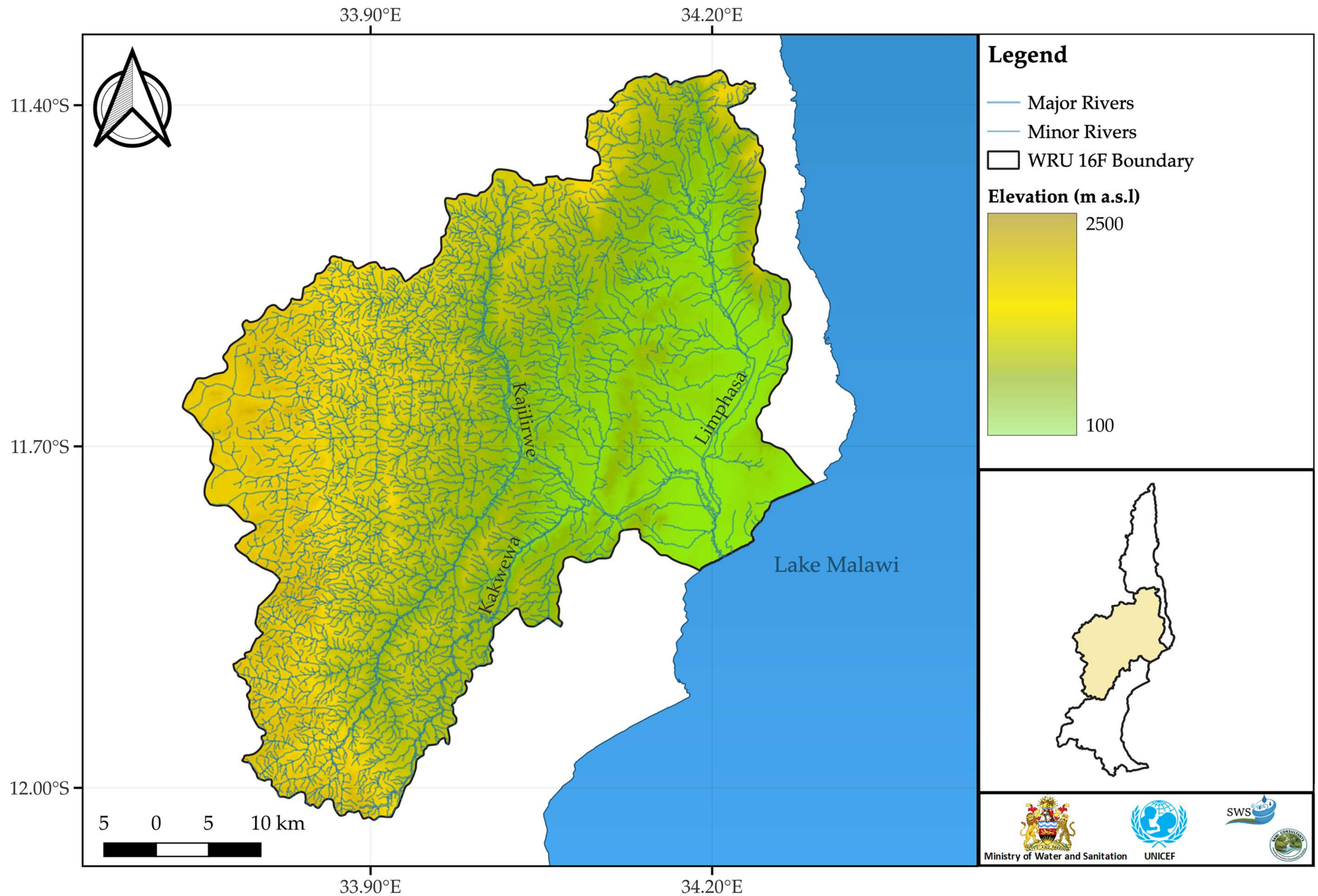


Figure WRU 16F.3 Hydrogeology Units and Water Table

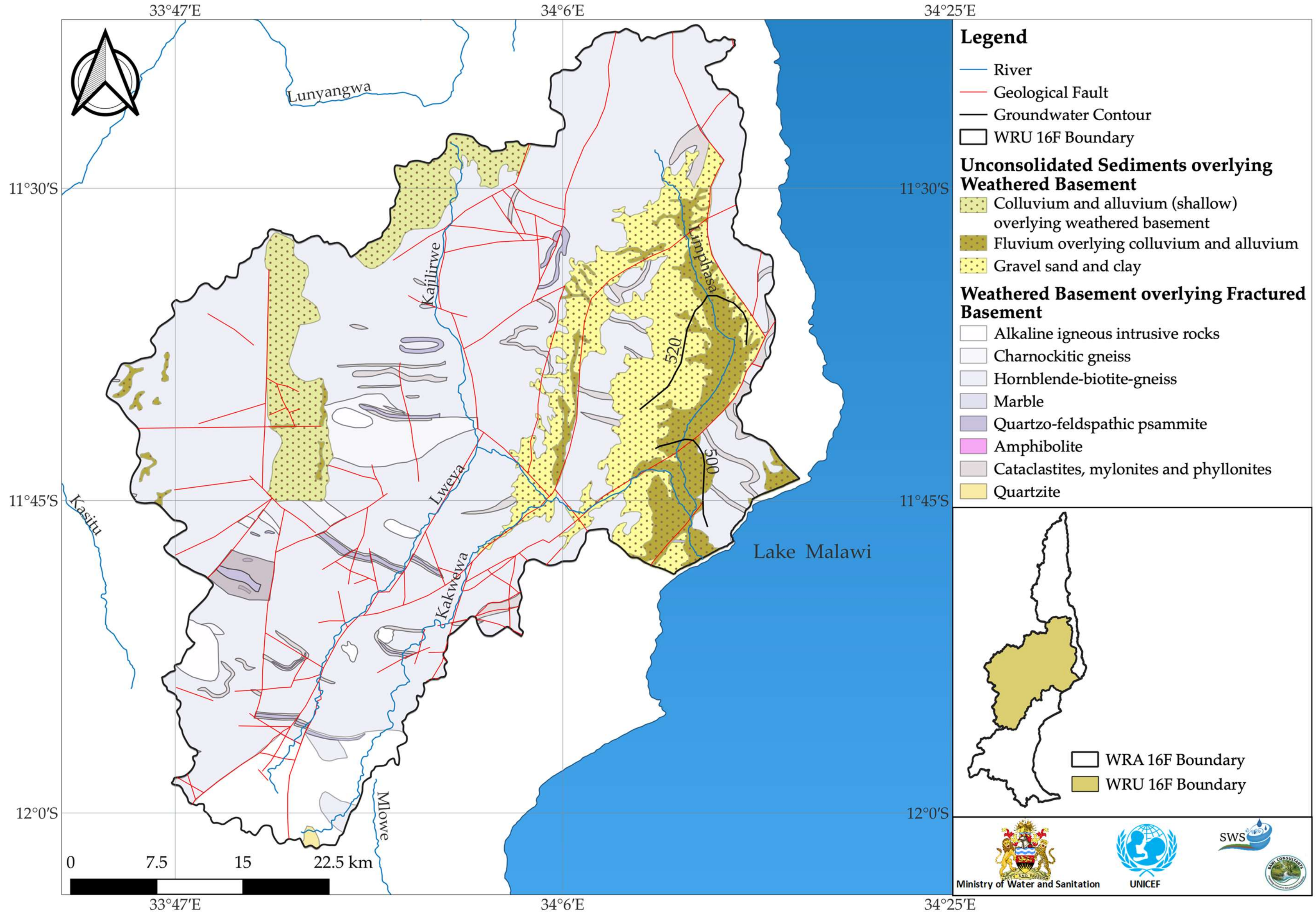


Figure WRU 16F.4 Groundwater Chemistry Distribution Electrical Conductivity

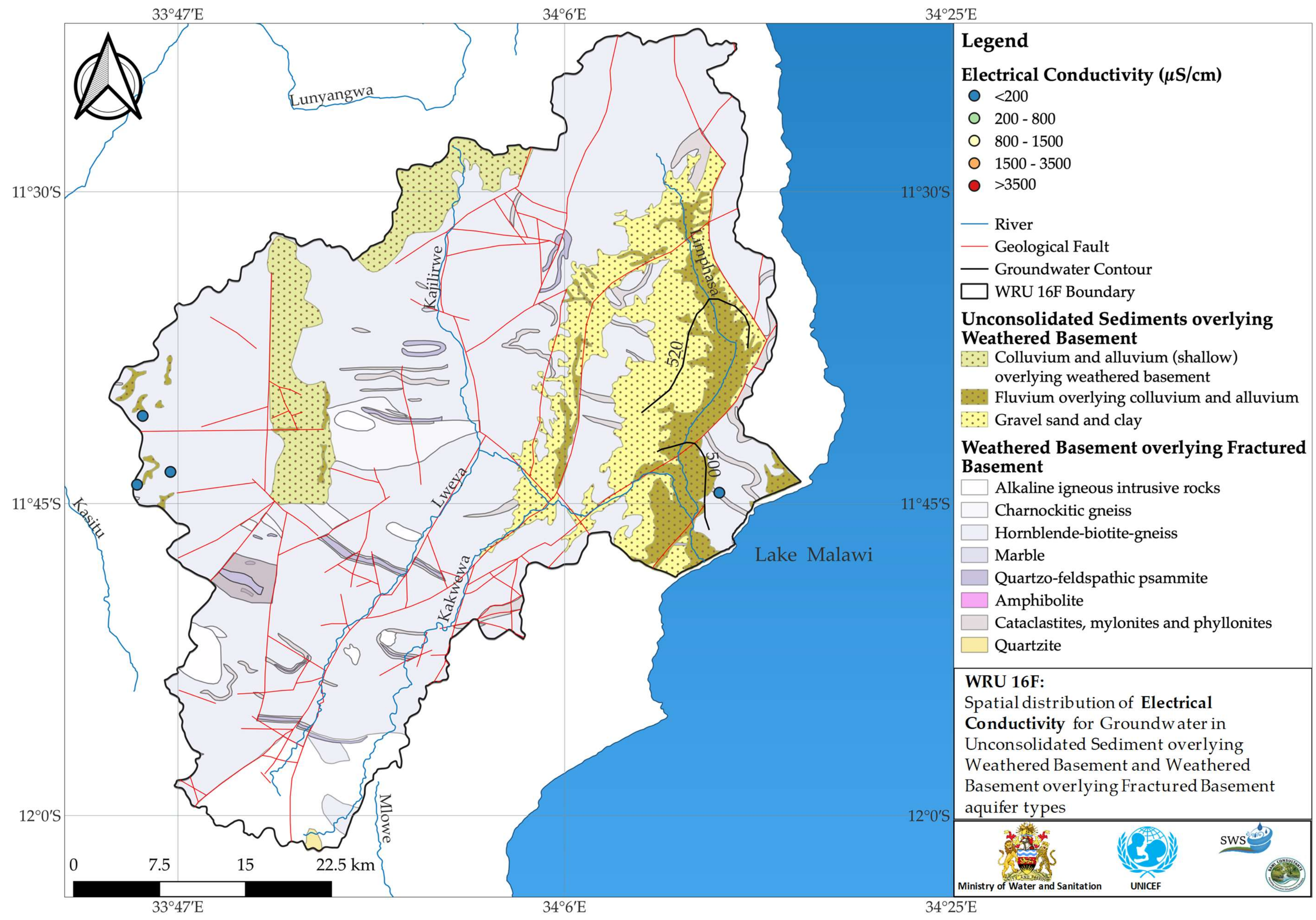


Figure WRU 16F.5 Groundwater Chemistry Distribution of Sulphate

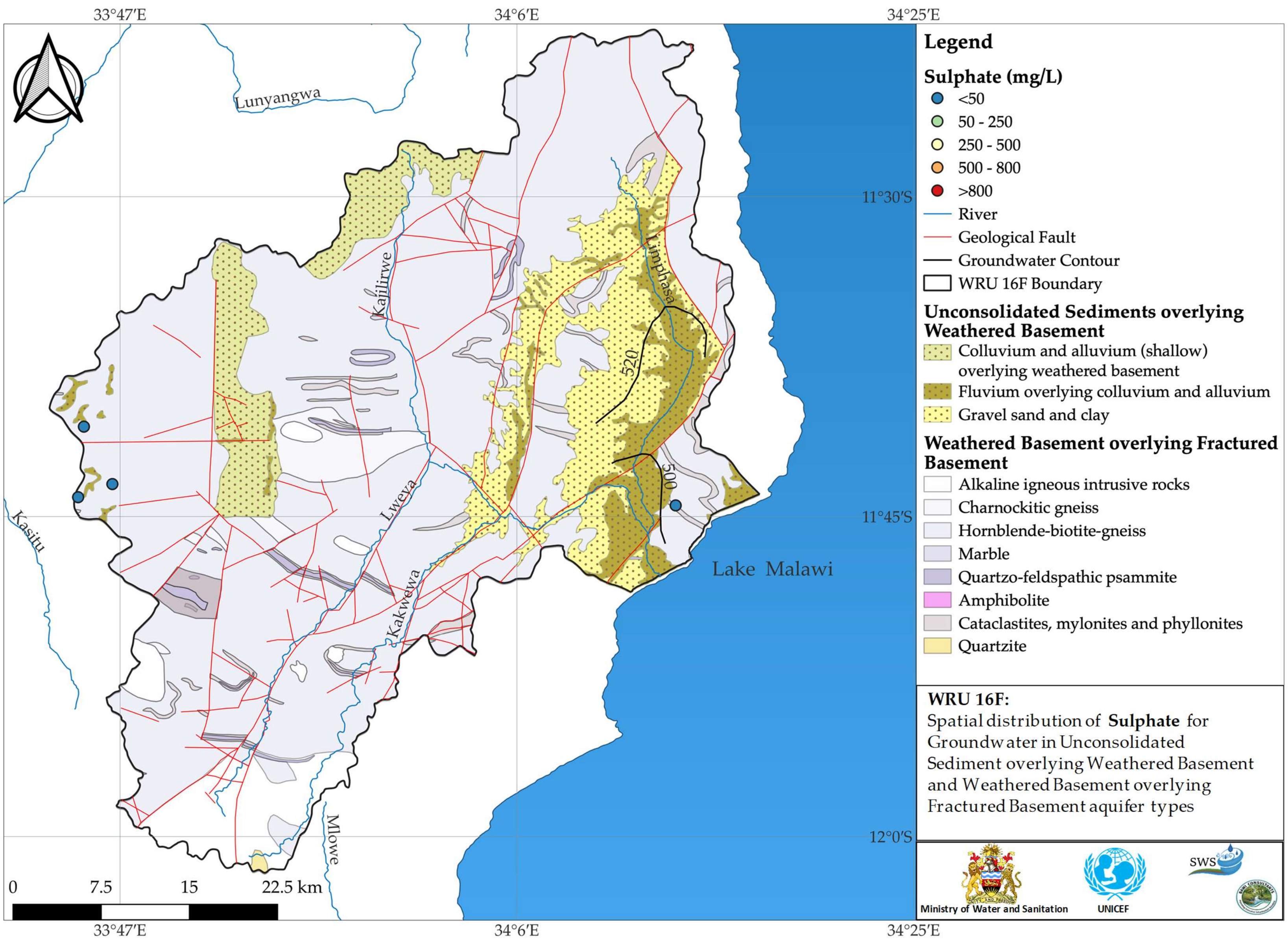


Figure WRU 16F.6 Groundwater Chemistry Distribution Chloride

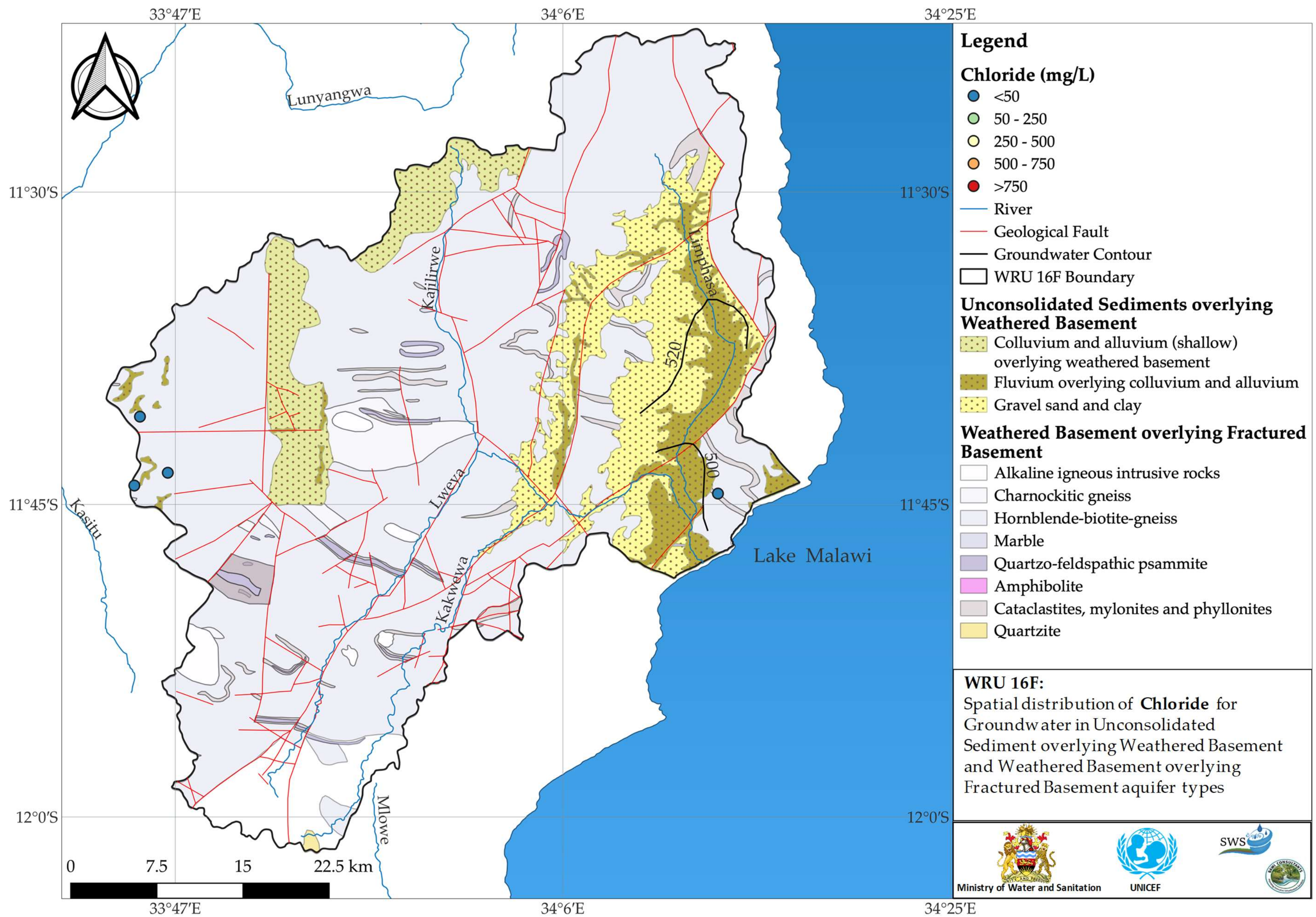


Figure WRU 16F.7 Groundwater Chemistry Distribution Sodium

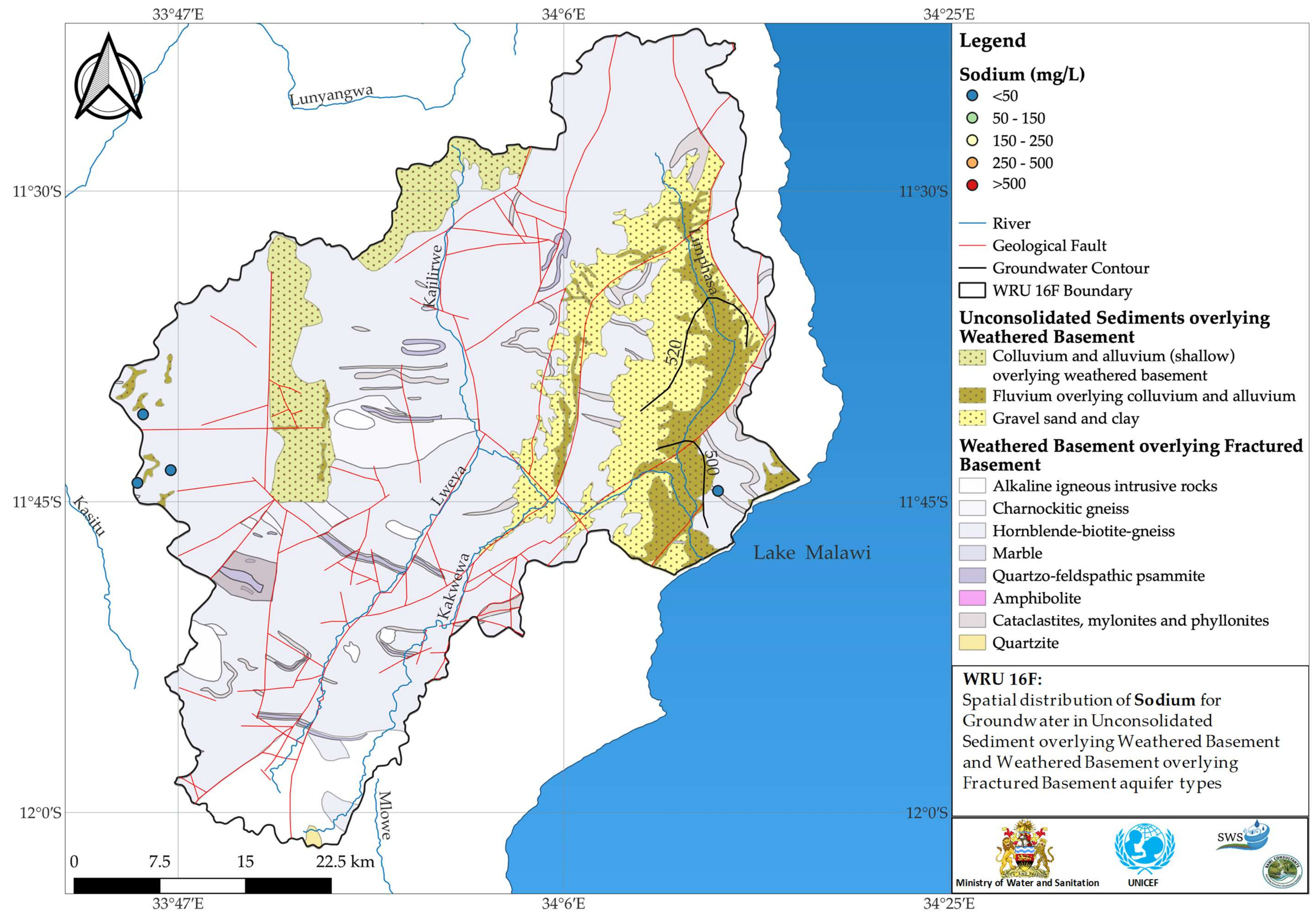


Figure WRU 16F.8 Groundwater Chemistry Distribution Calcium

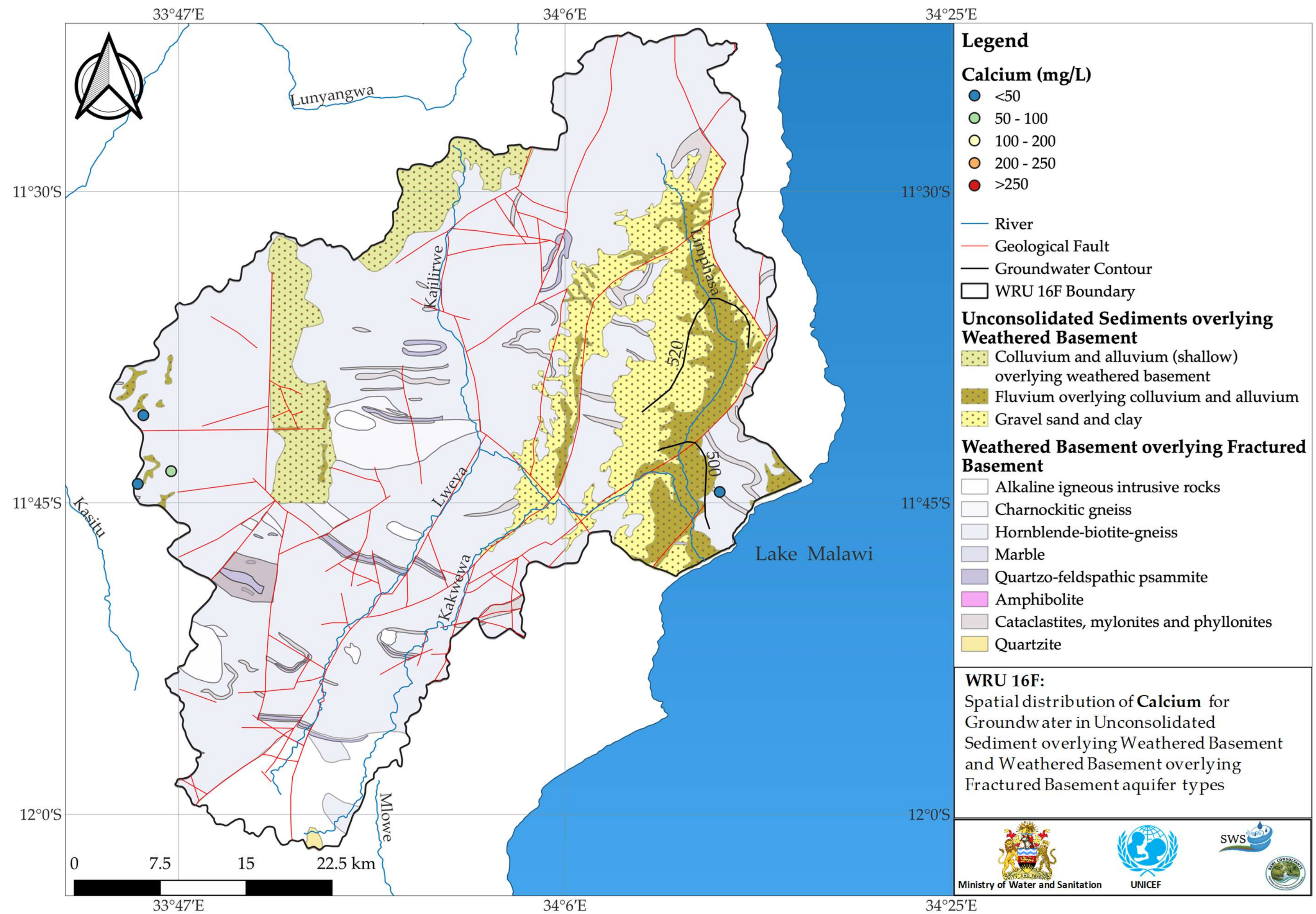


Figure WRU 16F.9 Piper Diagram of water quality results with respect to the major aquifer type

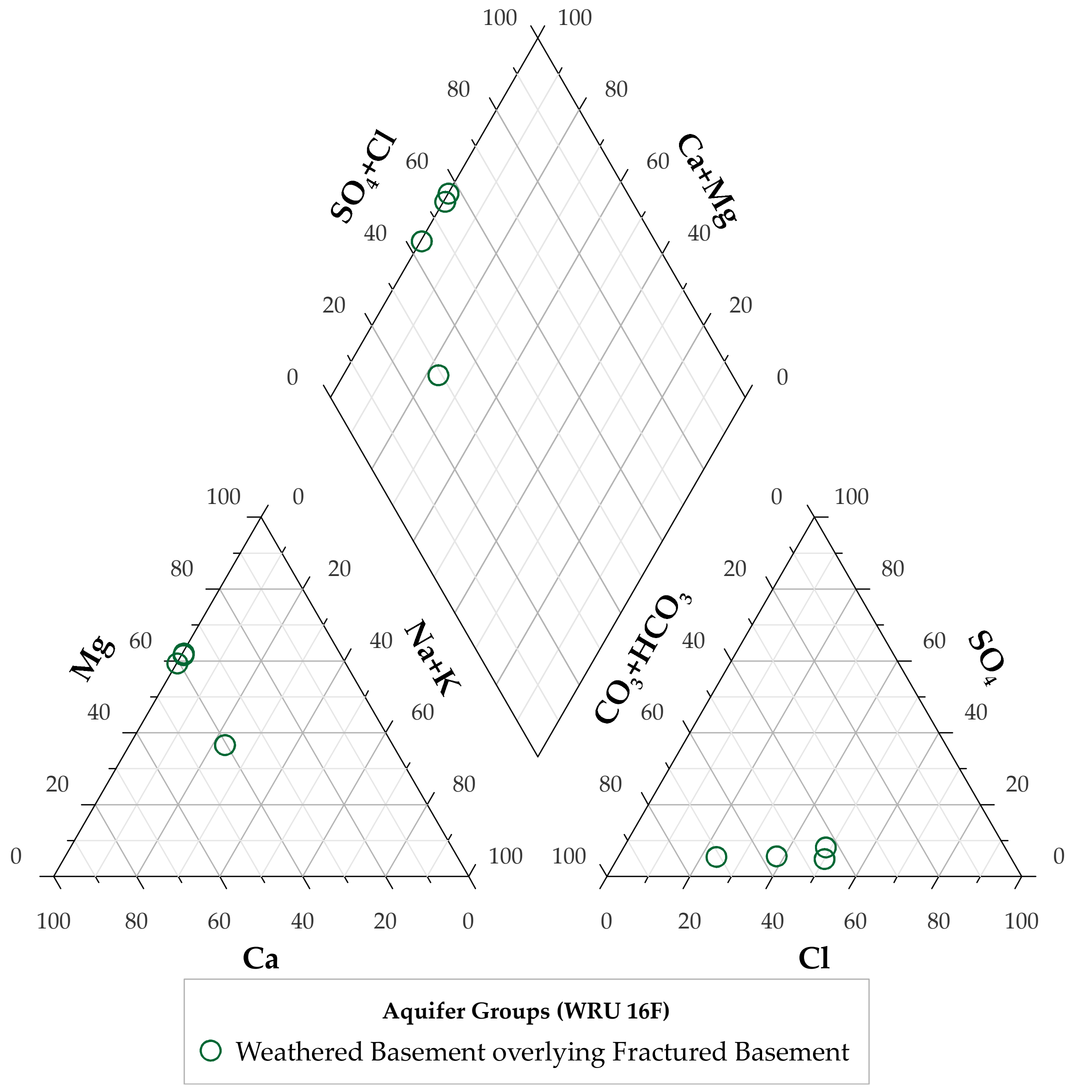
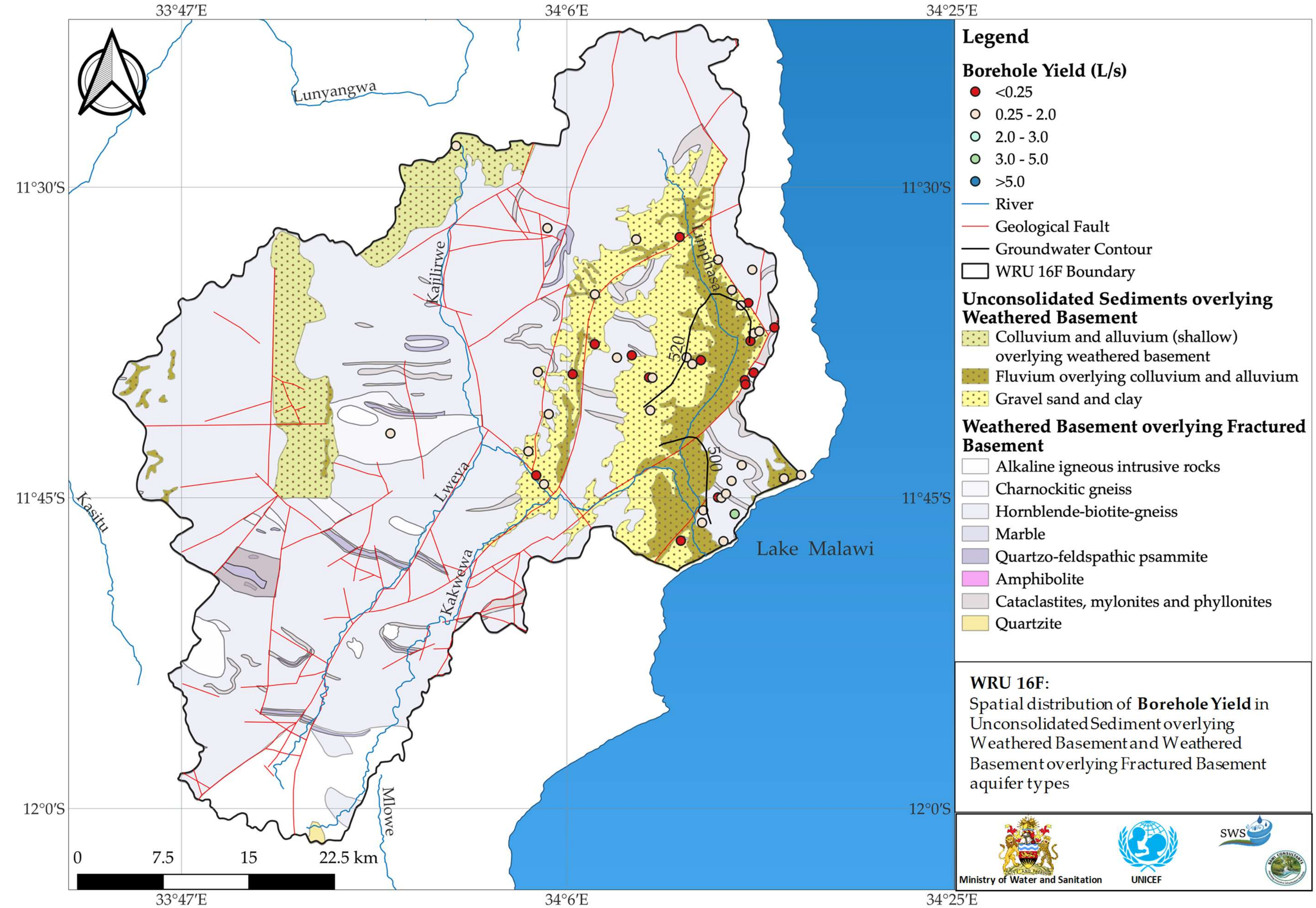


Figure WRU 16F.10 Borehole Yield Map for data held by the Ministry



WRU 16G Figures

Figure WRU 16G.1 Land Use and Major Roads

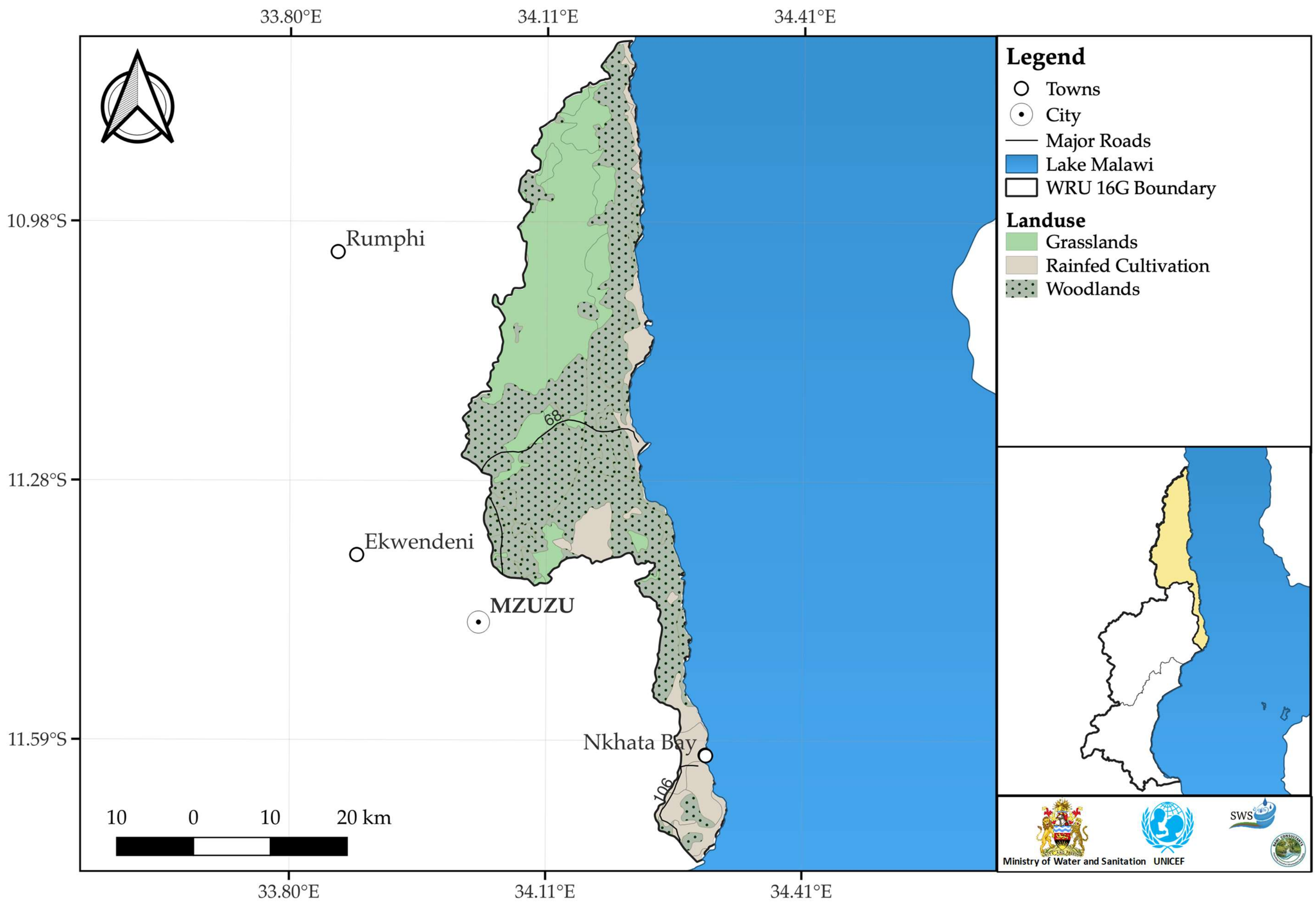


Figure WRU 16G.2 Rivers and Wetlands

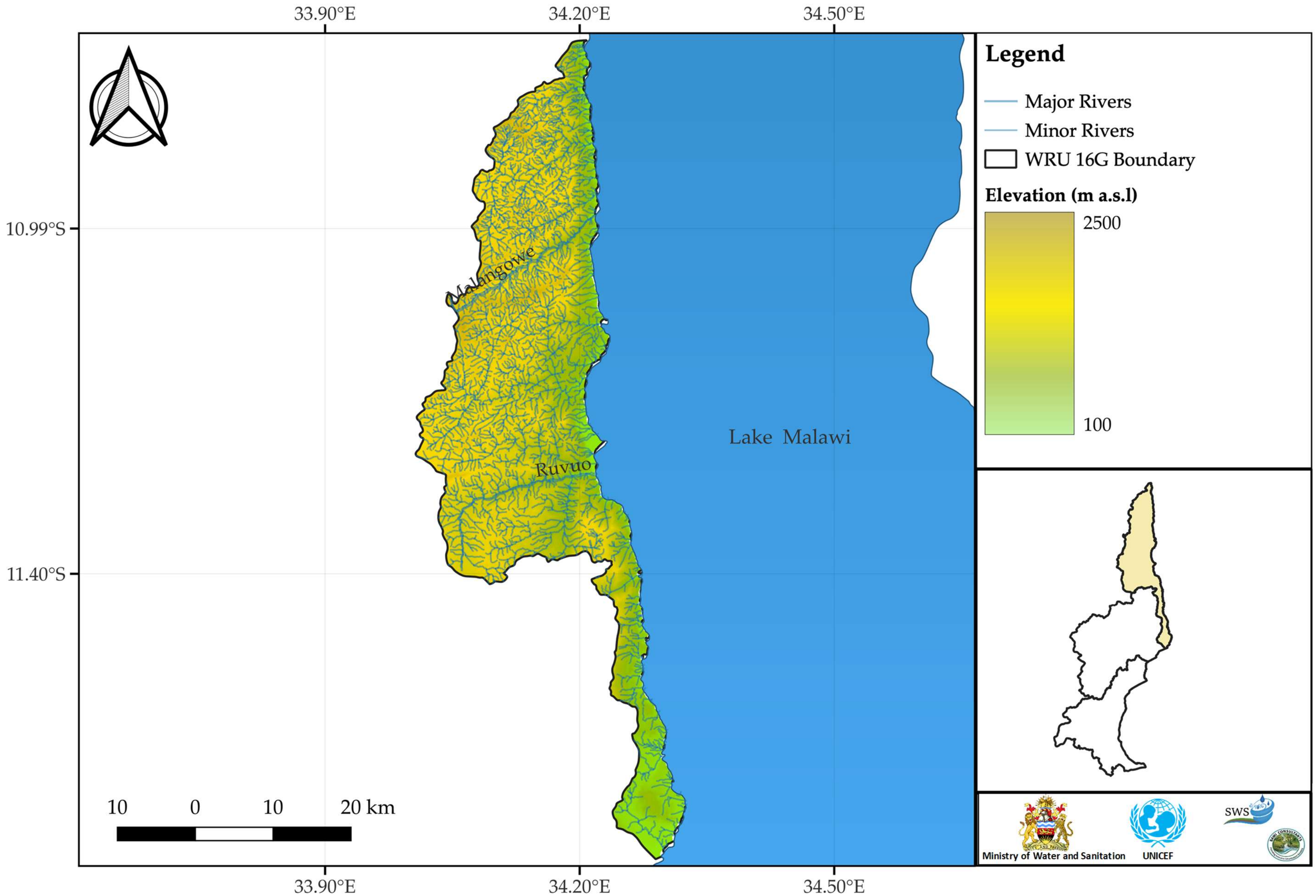


Figure WRU 16G.3 Hydrogeology Units and Water Table

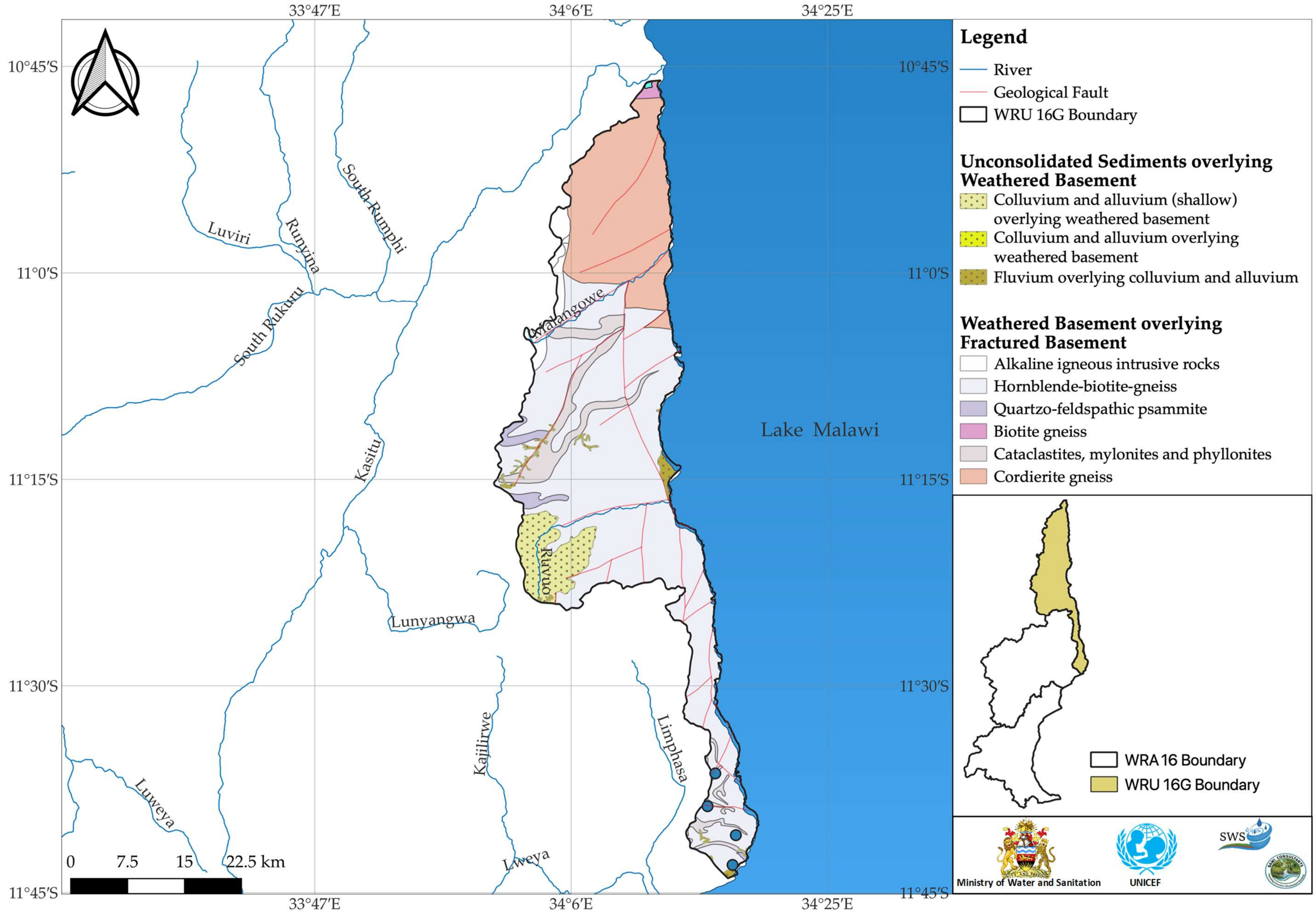


Figure WRU 16G.4 Groundwater Chemistry Distribution Electrical Conductivity

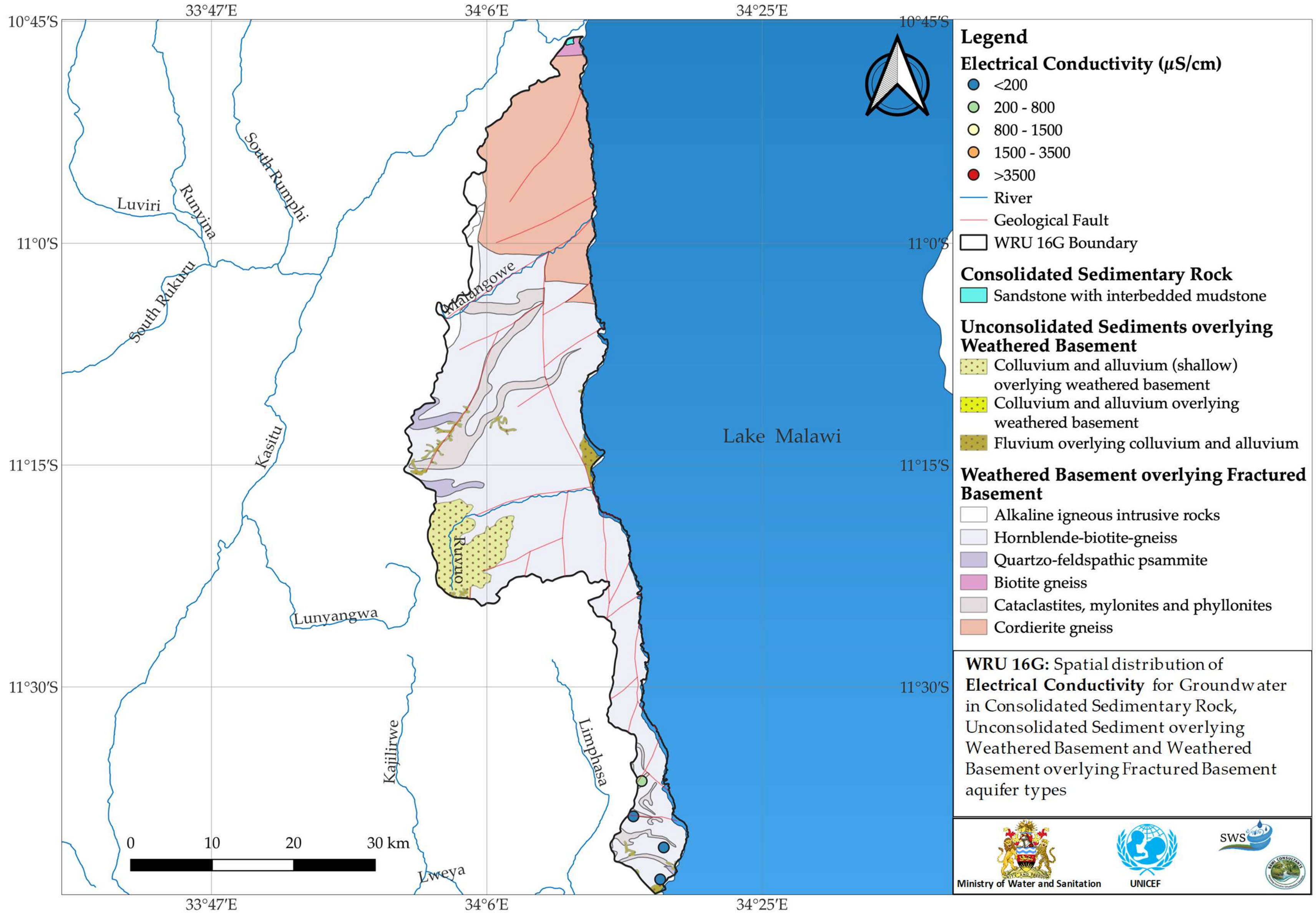


Figure WRU 16G.5 Groundwater Chemistry Distribution of Sulphate

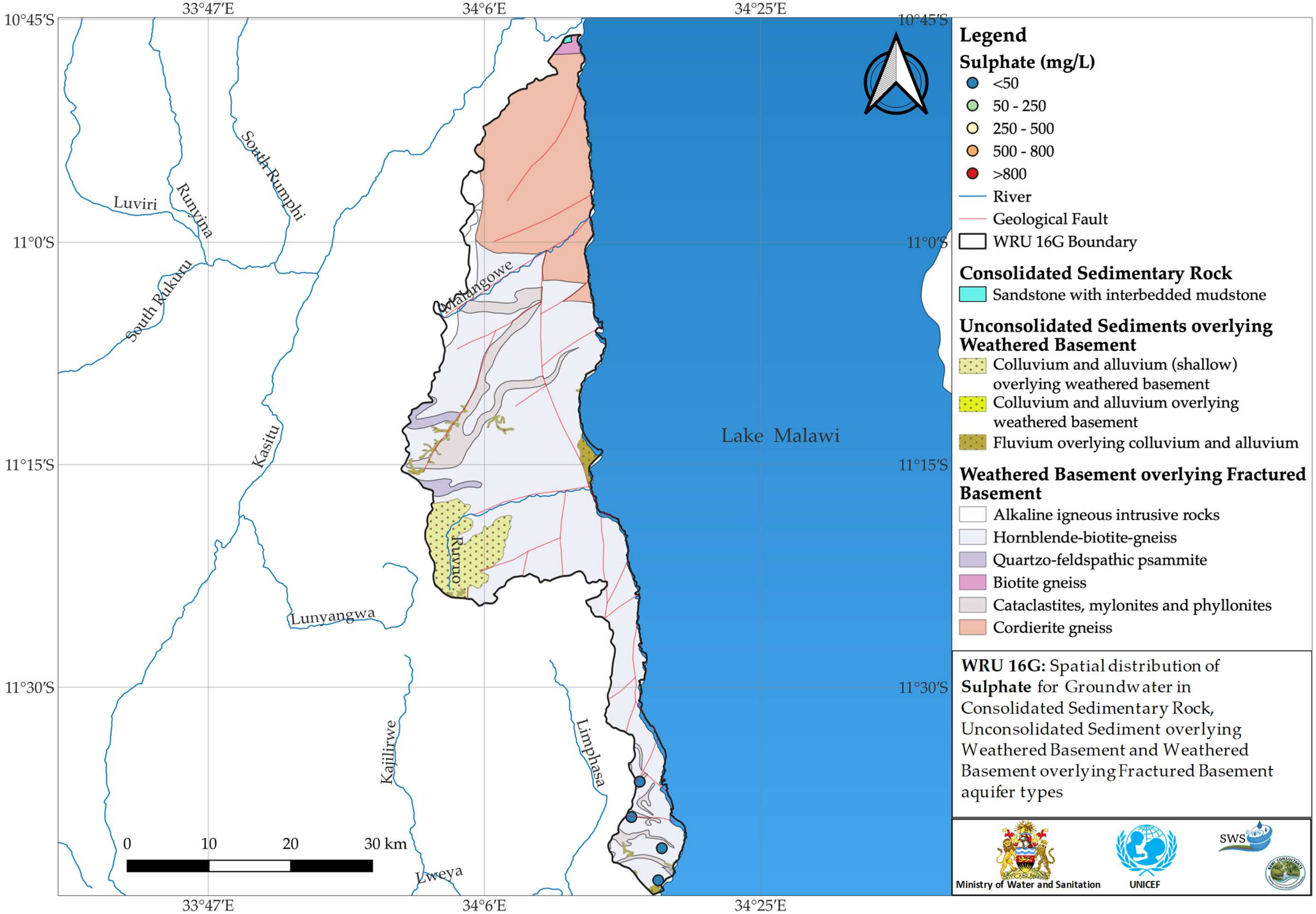


Figure WRU 16G.6 Groundwater Chemistry Distribution Chloride

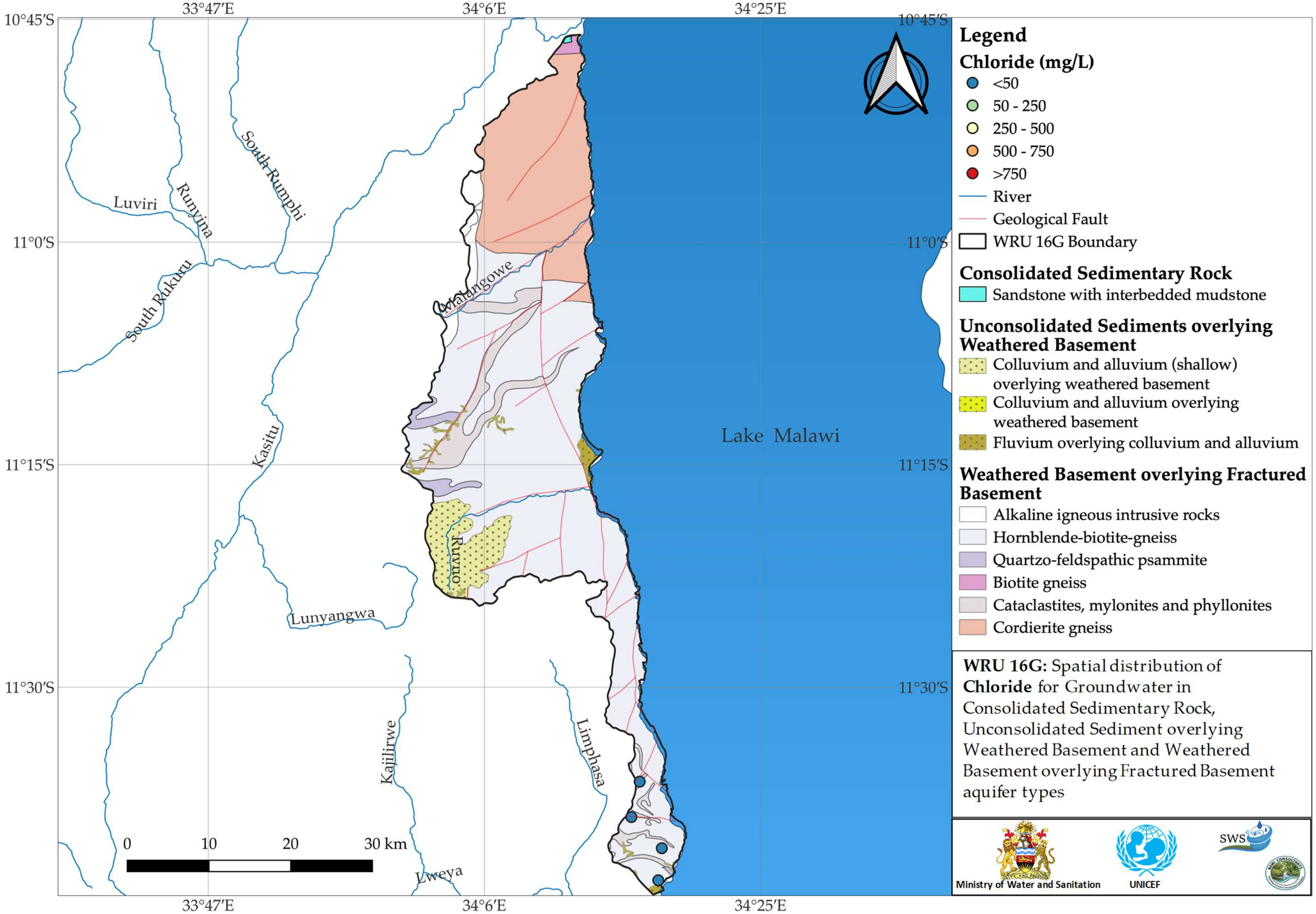


Figure WRU 16G.7 Groundwater Chemistry Distribution Sodium

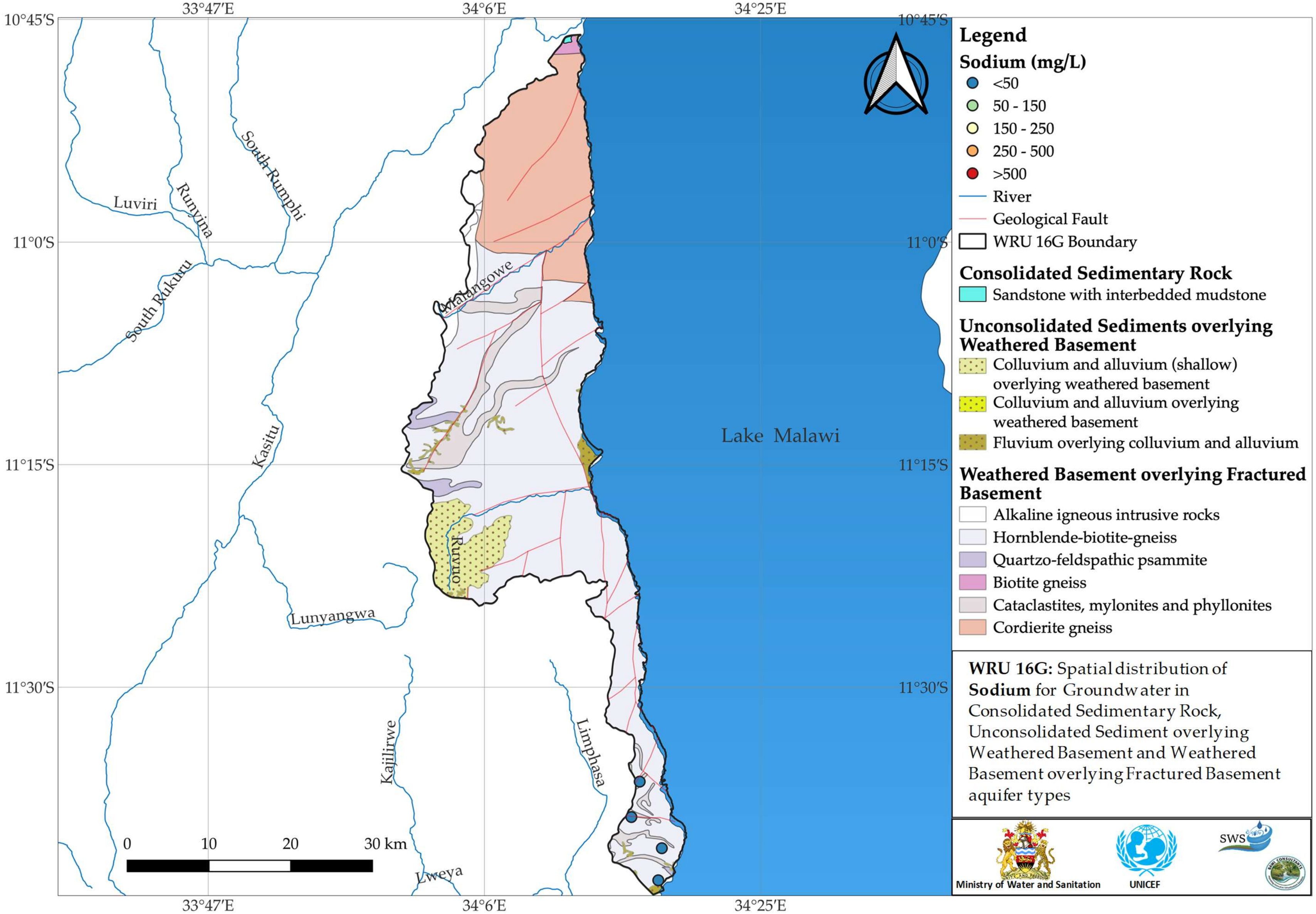


Figure WRU 16G.8 Groundwater Chemistry Distribution Calcium

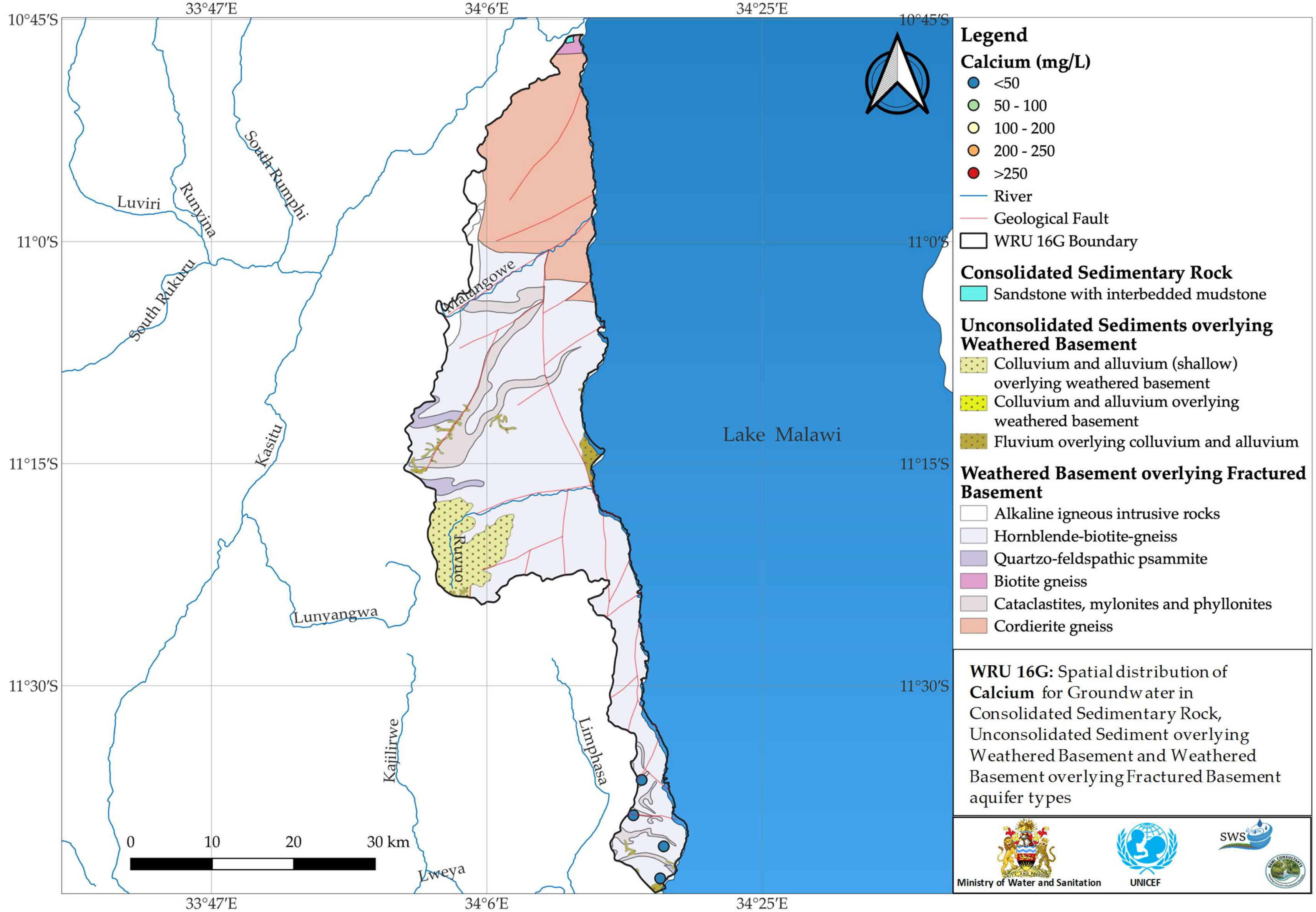


Figure WRU 16G.9 Piper Diagram of water quality results with respect to the major aquifer type

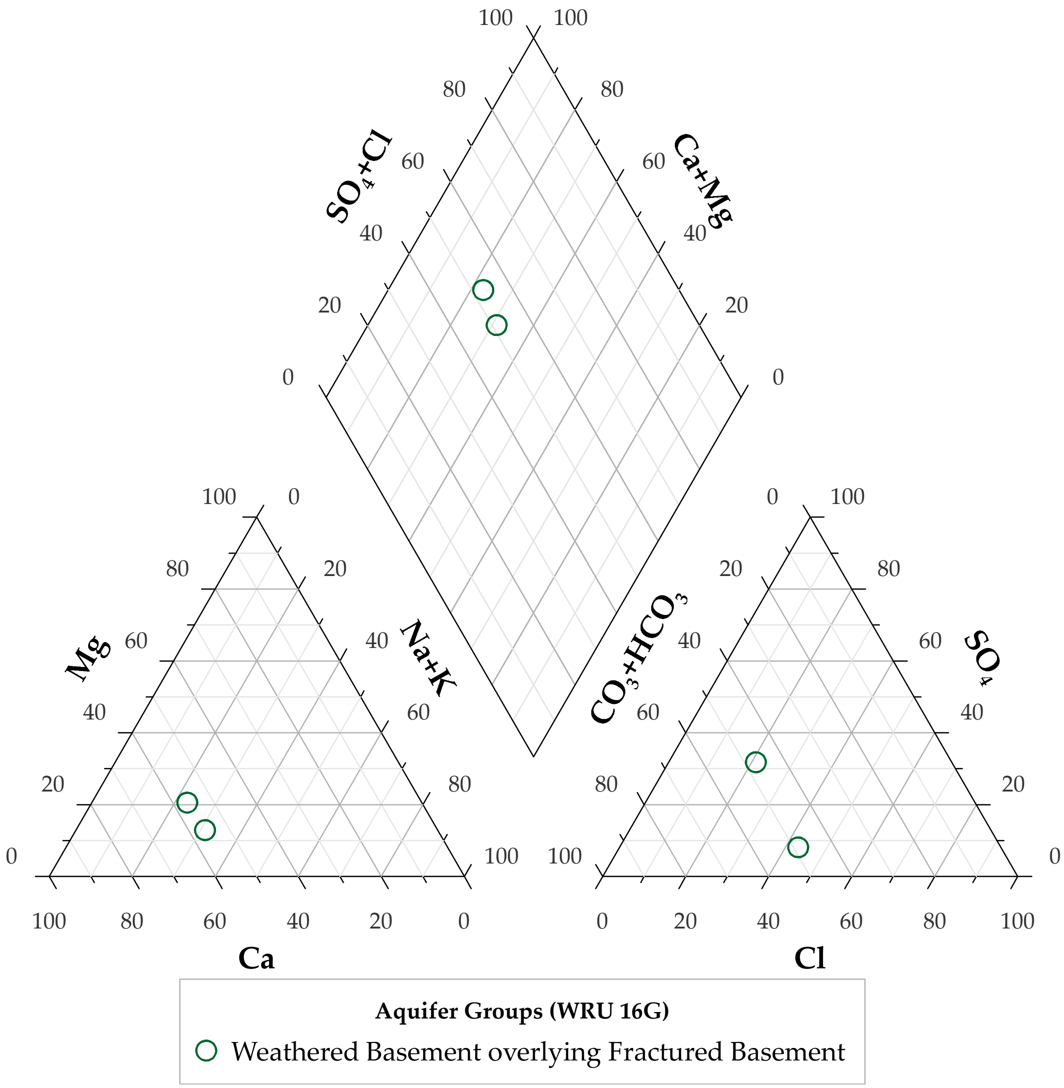
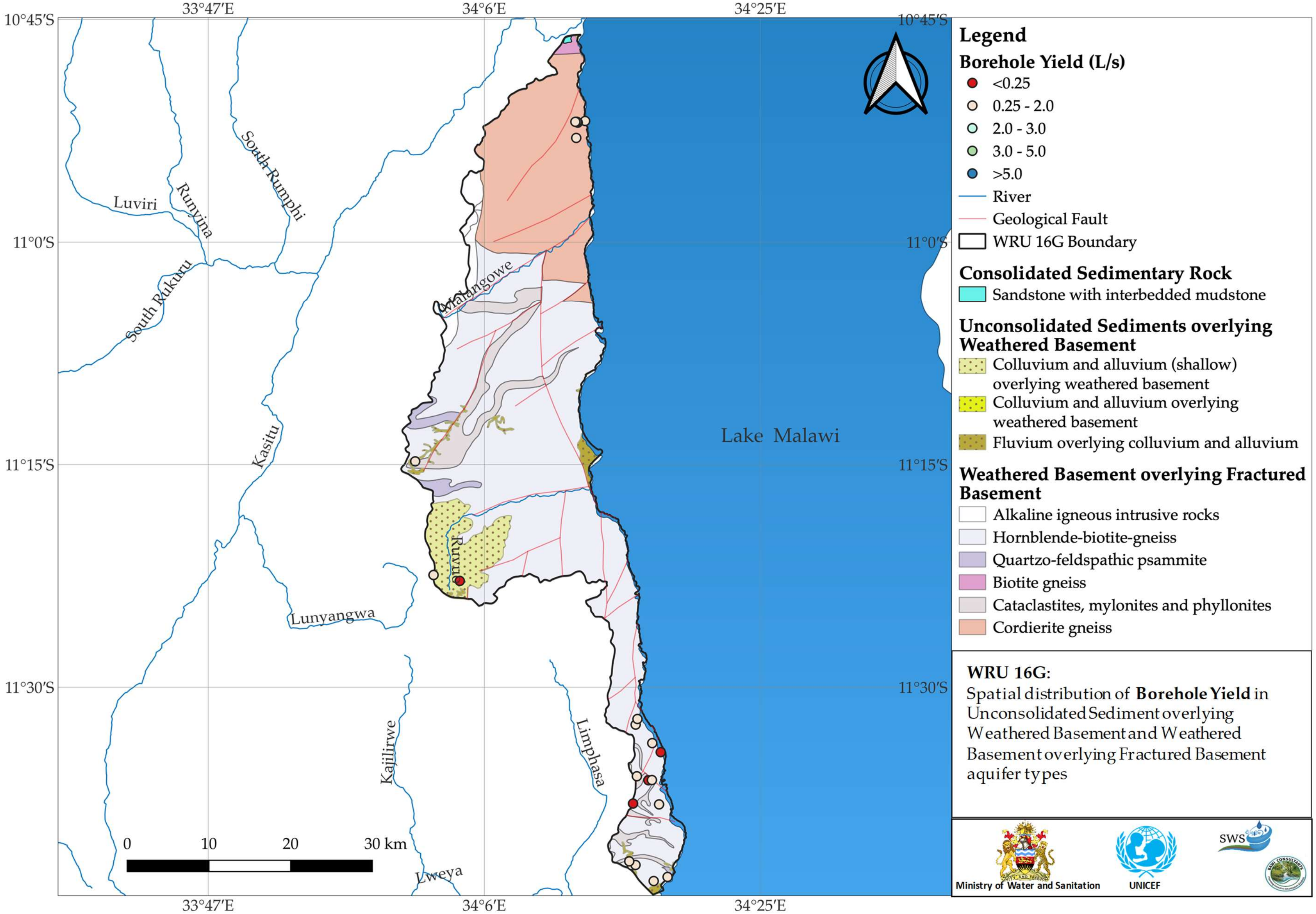


Figure WRU 16G.10 Borehole Yield Map for data held by the Ministry



Ministry of Water and Sanitation

Hydrogeology and Groundwater Quality Atlas of Malawi

Reference: Kalin, R.M., Mleta, P., Addison, M.J., Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A., Hinton, R. (2022) *Hydrogeology and Groundwater Quality Atlas of Malawi, Nkhata Bay Lakeshore Catchment, Water Resource Area 16, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-15-4 70pp*