Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 17

The Karonga Lake Shore Catchment

Ministry of Water and Sanitation

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It is recommended that citation for this work is made as follows:

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, Karonga Lake Shore Catchment, Water Resource Area 17, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-16-1 69pp*

ISBN 978-1-915509-16-1

Developed with the support of UNICEF (Malawi), BAWI (Malawi), SWS (Scotland) and The University of Strathclyde (Scotland)

1st Digital Edition (22nd March 2022)

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/day	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 17 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.

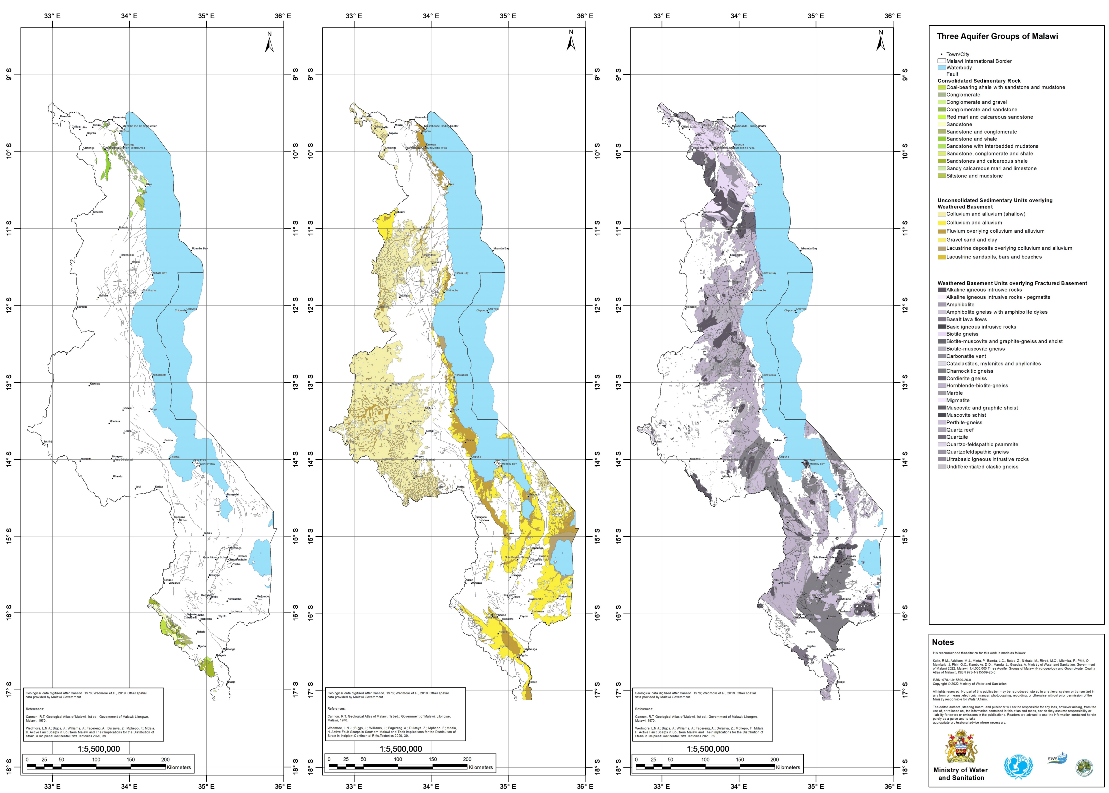

Figure 1a, b, c.   Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most 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).

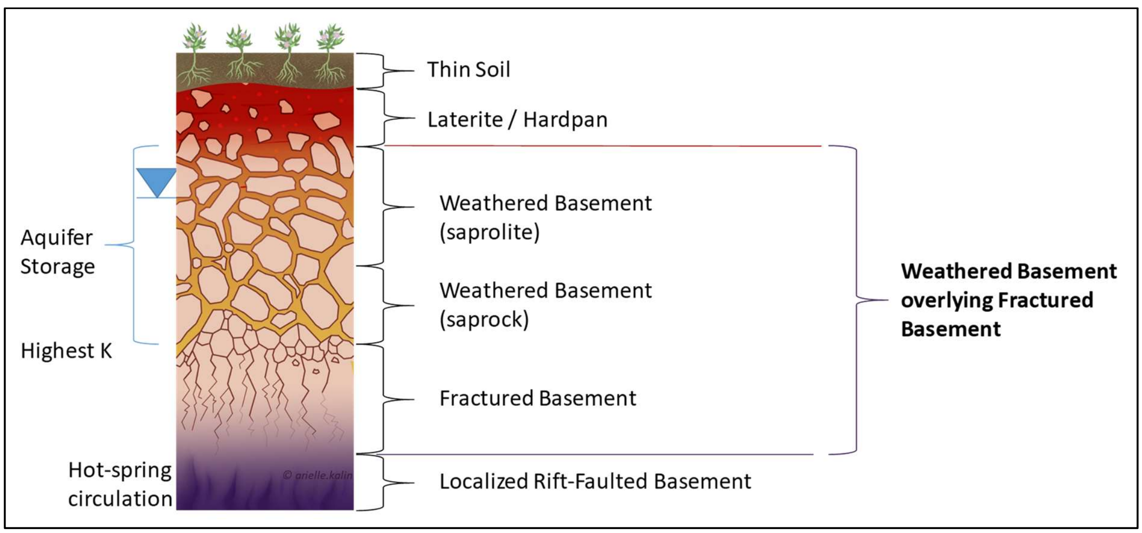

Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

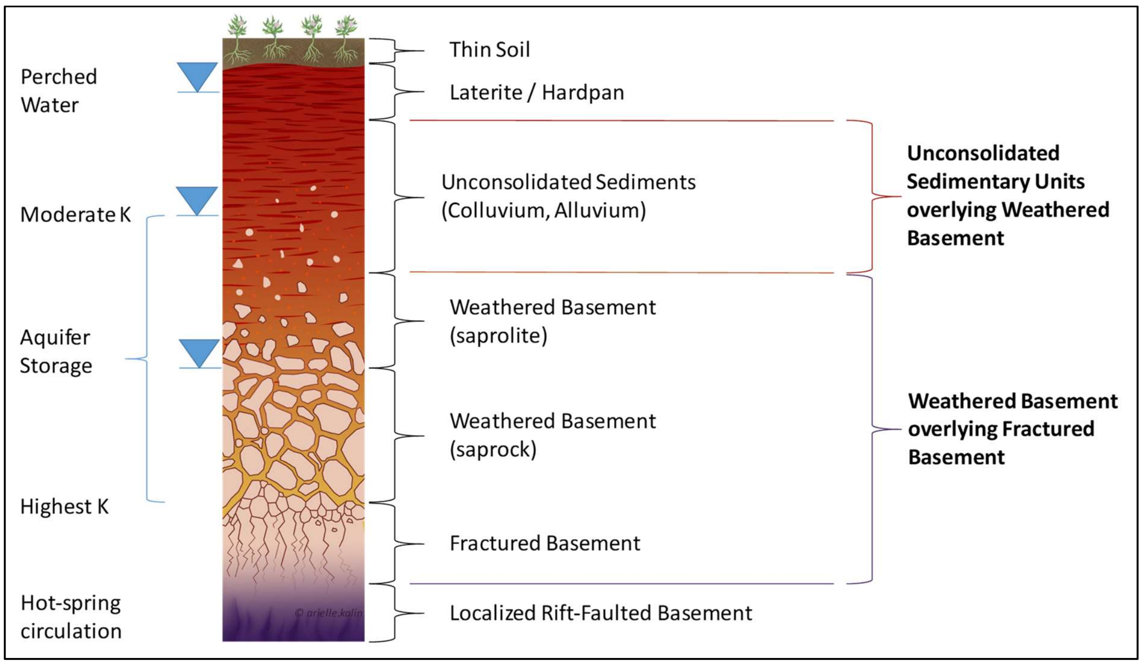

Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

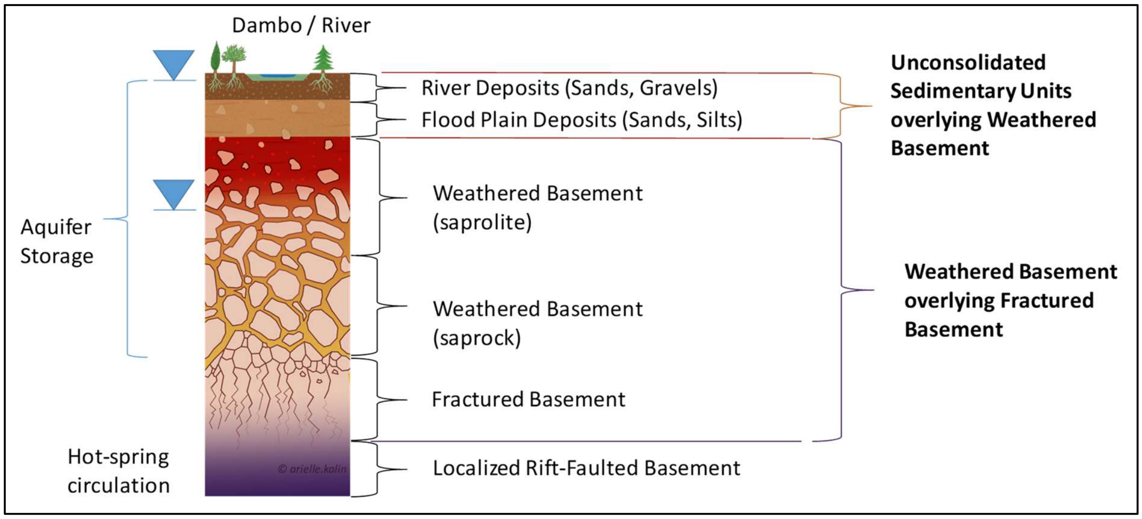

Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

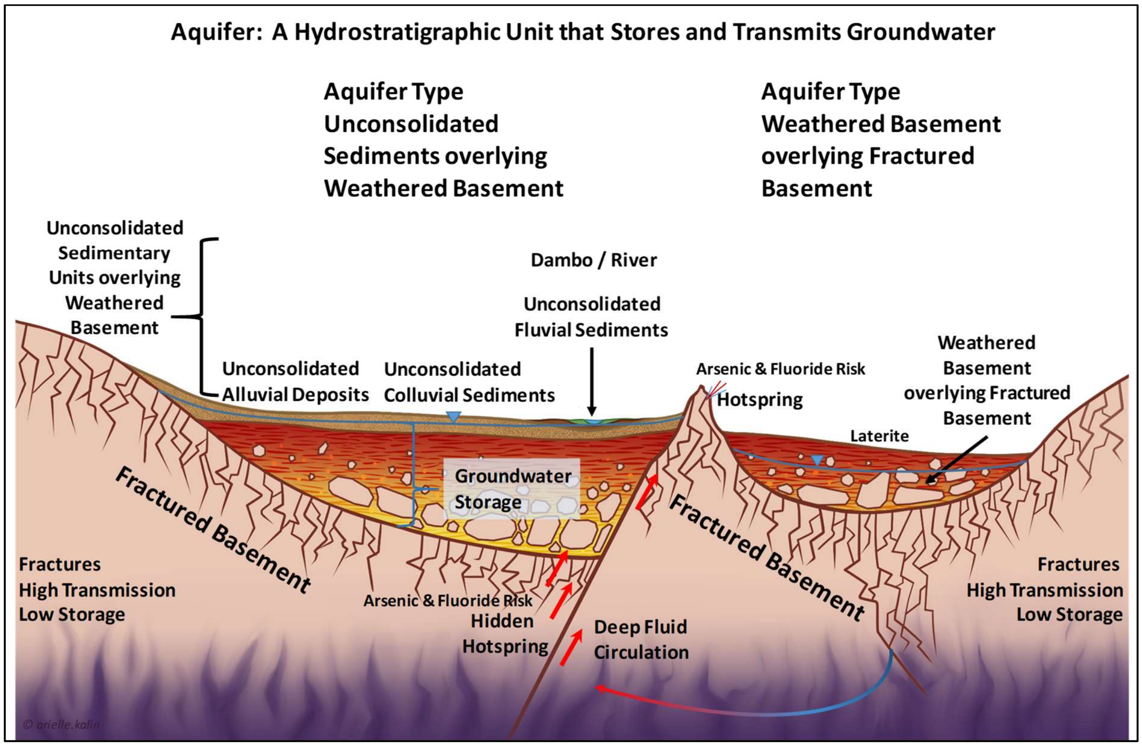

Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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 17 (WRA 17): The Karonga Lakeshore Catchment

Water Resource Area 17 (WRA 17) (**Figure 2a**) in northern Malawi constitutes three (3) sub catchments as Water Resource Units (WRU); WRU 17A, 17B and 17C (**Figure 2b**). It has an area of 1,945 Km^2 and covers the Karonga Lakeshore region, hence called the Karonga 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 17, but it borders on Lake Malawi which is governed by Trans-boundary water sharing agreements.

The Karonga Lakeshore catchment is largely drained by a major riverine flow from Wovwe, Wayi and Nyungwe Rivers. Surface water flows are mainly west easterly, with many of the rivers deriving their headwaters from the western highlands.

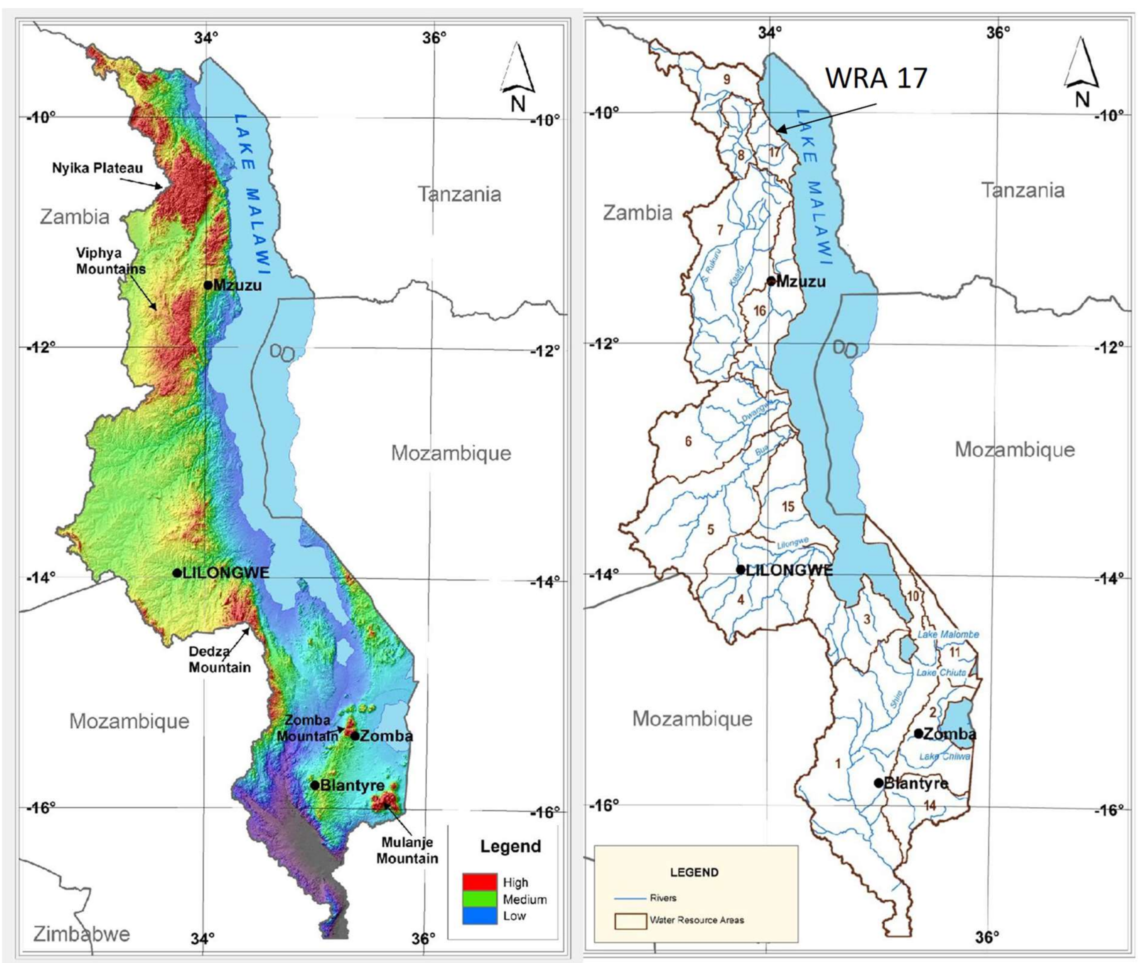

Figure 2a. Location of WRA 17 with major rivers and topography shown.

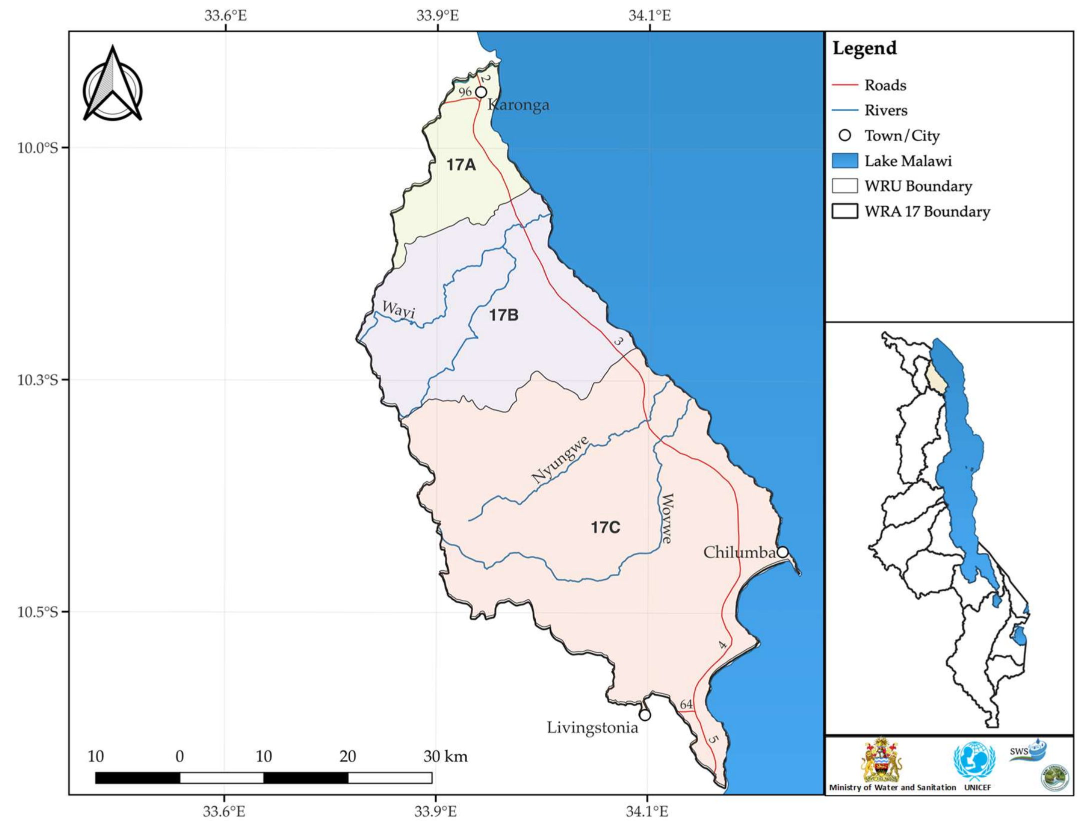

Figure 2b. Water Resource Area 17 boundary with Water Resource Units

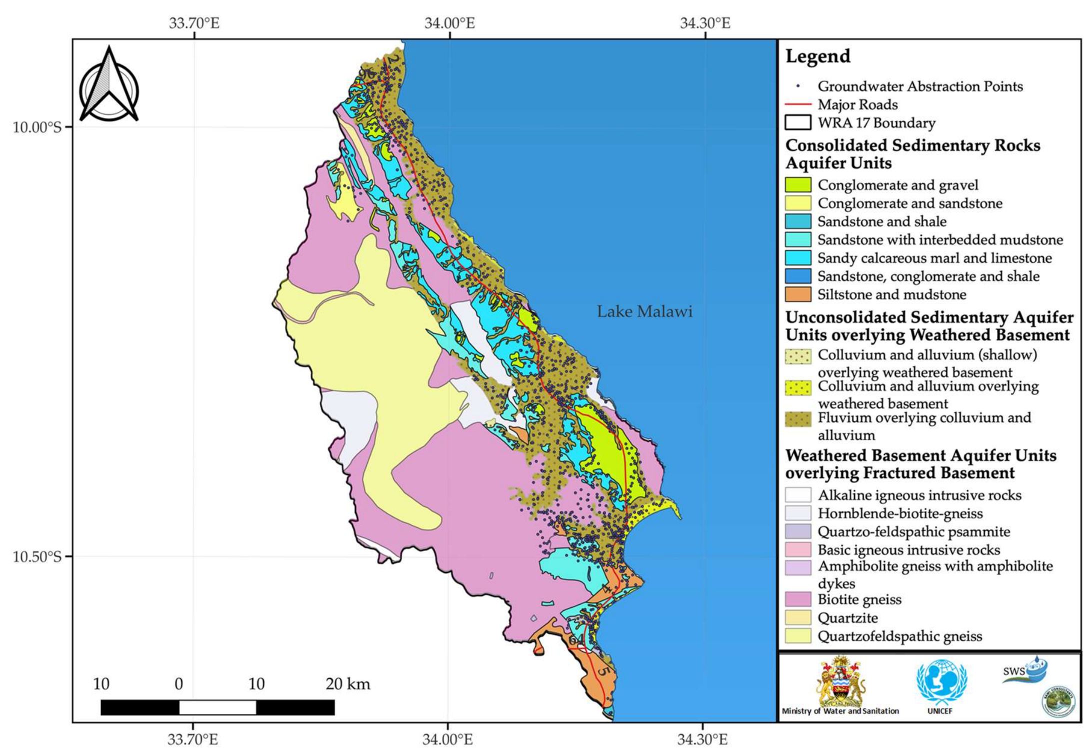

Figure 3. Distribution of groundwater abstraction points in WRA 17.

Groundwater Abstraction in WRA 17

Public abstraction points for groundwater are moderate in WRA 17 (**Figure 3, Table 2**) and it should be noted there are many unaudited private groundwater abstraction points. Of the known groundwater abstraction points, 89.6% are improved sources. The mid-point distribution of water point yield (at hand pump) is between 0.25 and 0.35 l/s (**Figure 4a**), however it should be noted that this 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 17, only 68.4% are fully functional (defined as providing water at design specification).

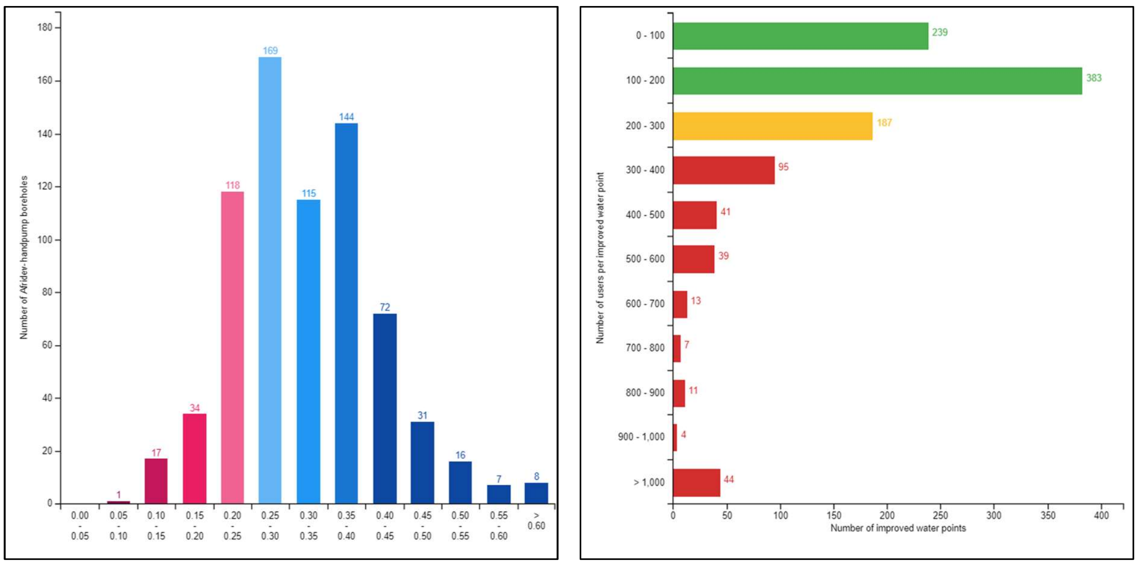

Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 17 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction 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 there is a minor investment need in WRA 17. Most of the groundwater supply points provide water to 250 or less users per water point, and those that do not meet the guideline should be considered within investment planning, and all water points required planning for water quality monitoring.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 26.8% of groundwater abstraction points do not provide sufficient water (September through November) 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. In particular, there is a correlation between the depth of the groundwater water supplies, with shallow supplies are more at risk to lowering water tables resulting in lower functionality during the dry season.

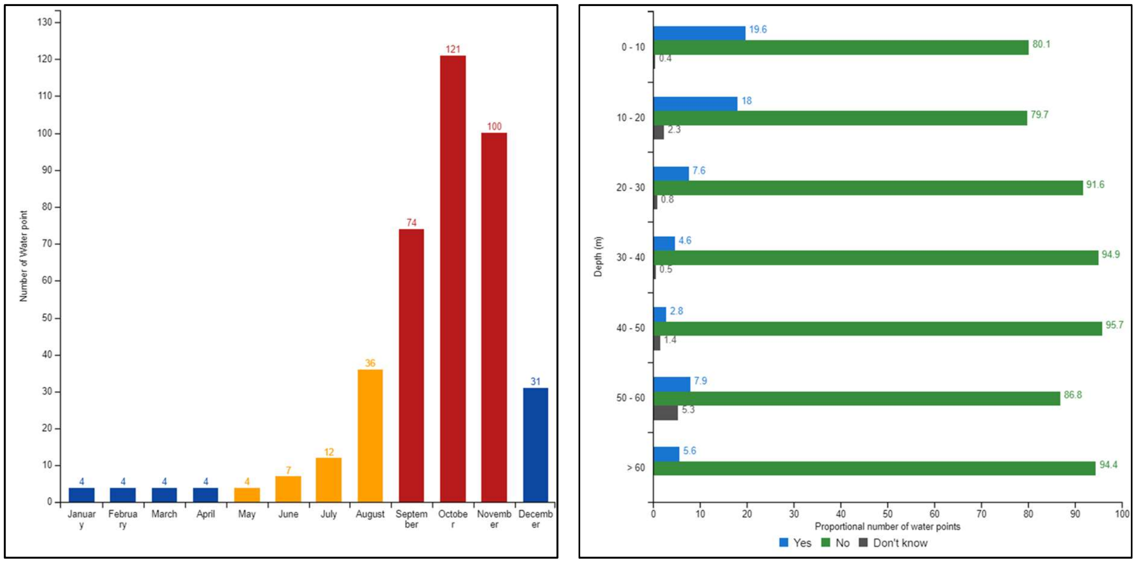

Figure 5a and 5b. Number of groundwater abstraction points in WRA 17 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

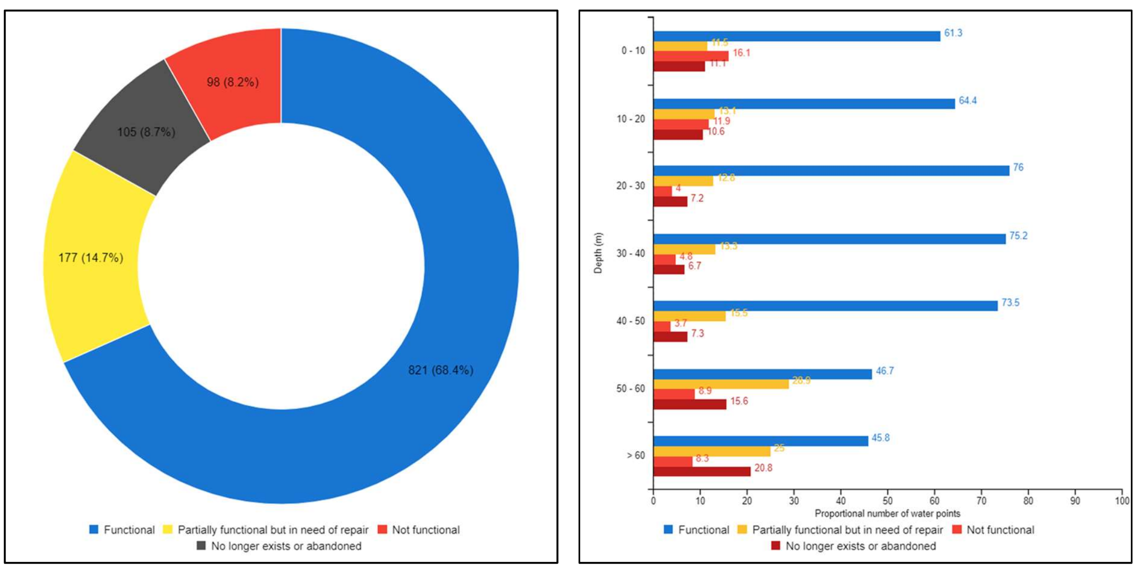

Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 17 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National 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, non-functional 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 17 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 17 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	1,291
Protected dug well	351
Protected spring	2
Unprotected dug well	189
Unprotected spring	1

Description of Water Resources WRA 17

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. The Karonga Lake Shore basin incorporates (in Malawi) the 3 Water Resources Units: 17A, 17B, and 17C (**Figure 7a, 7b, 7c**), and it should be noted that this basin is not Internationally Trans-Boundary, given Lake Malawi is, IWRM should engage with international agreements to manage surface and groundwater for this Water Resource Area.

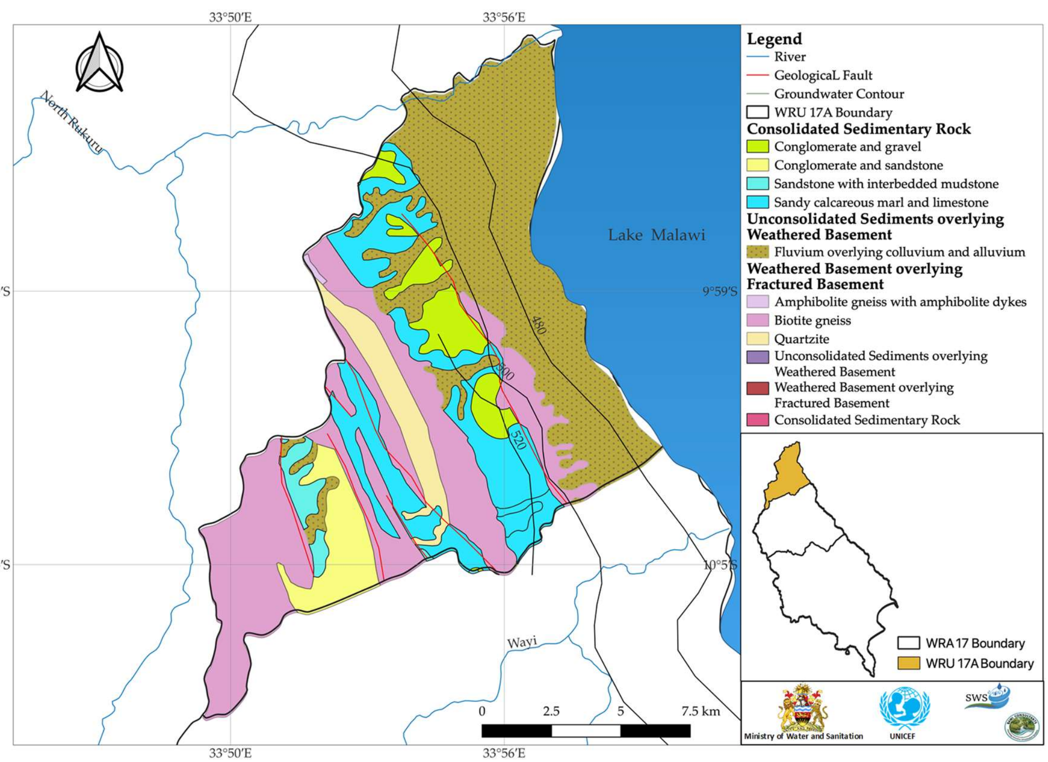

Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 17A wtihin Water Resource Area 17 (Karonga Lake Shore Basin). [water level contour interval 20m]

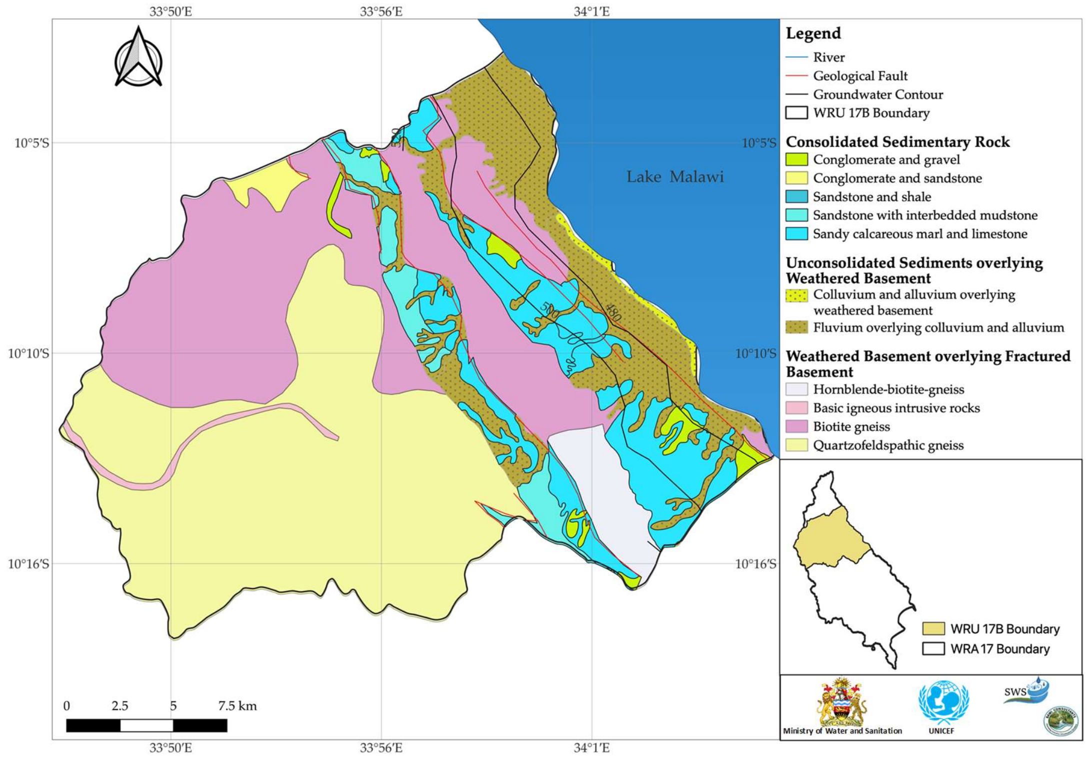

Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 17B wtihin Water Resource Area 17 (Karonga Lake Shore Basin). [water level contour interval 20m]

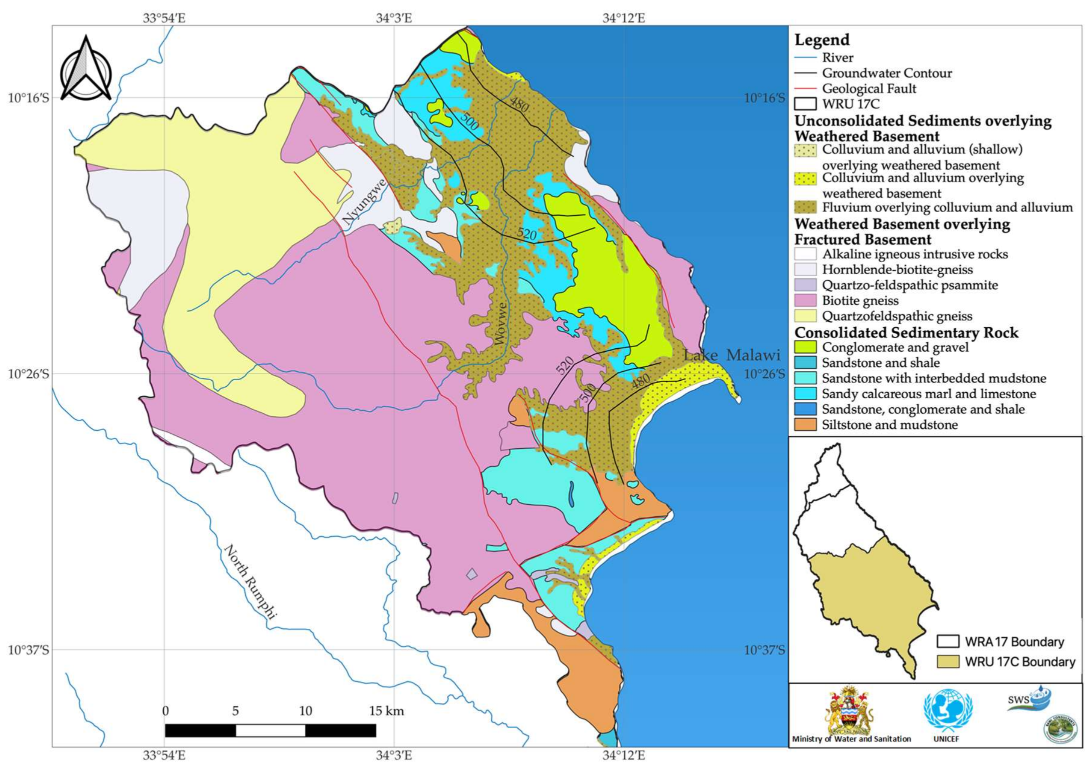

Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 17C wtihin Water Resource Area 17 (Karonga Lake Shore Basin). [water level contour interval 20m]

Topography and Drainage

The topographical setting of Water Resource Area 17 is dominated by uplands of about 2,000 meters in the west of the catchment, moving across the rift escarpment 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 17 solid geology (**Figures 7a, 7b, 7c**) is a complex mix of Precambrian to Lower Palaeozoic basement rock and Permian to Triassic sedimentary rocks of the Karoo System. Basement rocks occur west of the eastern basin margin rift faults and comprise regional outcrops of biotite gneiss and quartzo-feldspathic gneiss (with hornblende). Minor occurrences of granite and quartz with muscovite are common. Karoo sedimentary sequences lie unconformably east of the basement lithologies at lower elevations, separated by rift margin normal faults. Lithologies include calcareous siltstones and mudstones, arkosic sandstones, coal measures and basal beds, and the Mwesia beds. Consolidated lacustrine sedimentary sequences of Cretaceous-Miocene-Pleistocene age also occur in this area: the Chitimwe and Chiwondo Beds, and the well-known Dinosaur beds of sandstones, marls, and clays which contain the remains of dinosaur bones.

Geology – Unconsolidated deposits

Unconsolidated sediments within Water Resource Area 17 are common east of the rift faults. Colluvium, alluvium, and major fluvial deposits occur extensively between the rift faults and the lakeshore, overlying consolidated sedimentary sequences of the Karoo and younger.

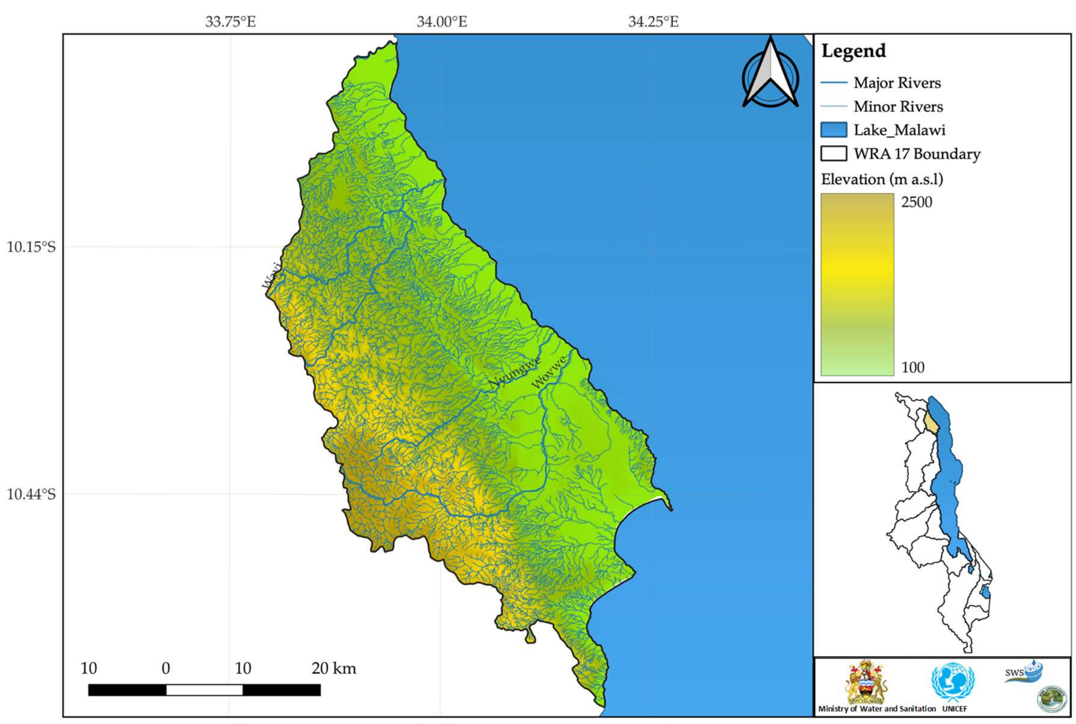

Figure 8. Drainage for the major rivers in Water Resources Area 17.

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 843 to >1800 mm (extrapolated for high elevations in locations without 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 17. 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)
17	A	- No Station -	-	886
	B	Lupembe	843	898
	C	Vinthukutu	1,177	1,046

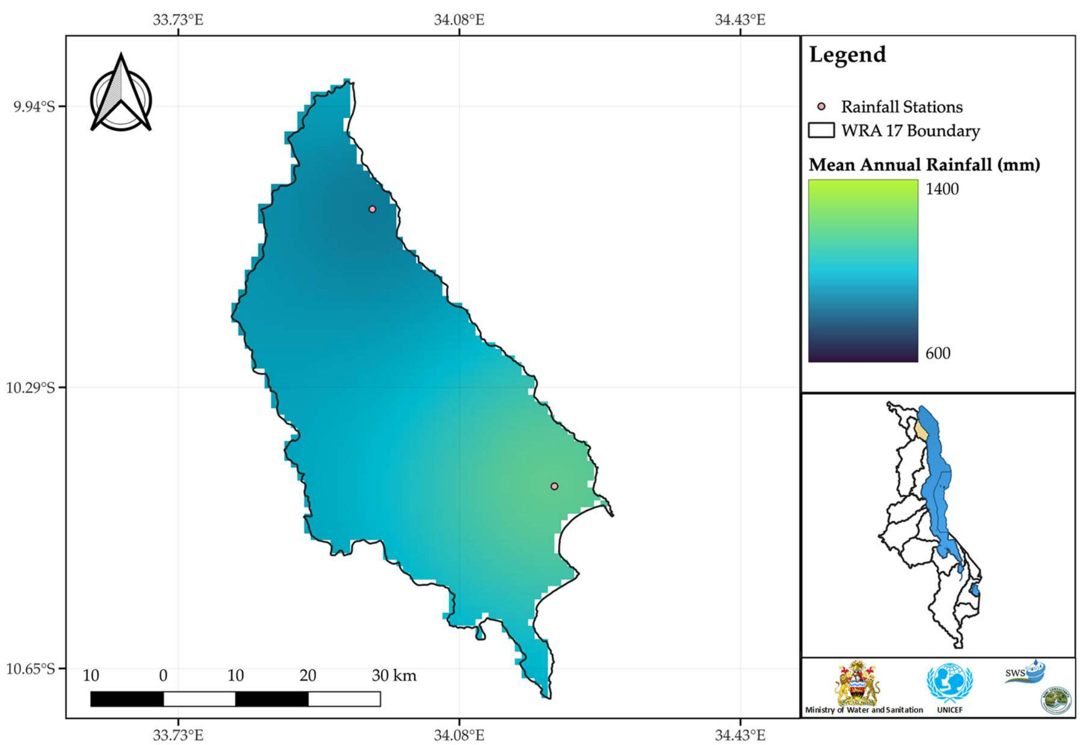

Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 17 with the location of weather stations. Average rainfall measured is 1,016mm, average rainfall modelled is 1,057 +/- 65mm (range 876 to 1,418mm).

Land use

Land use is largely characterised by woodlands in the central and western parts, with rain fed cultivation and open grasslands dominating the eastern and western approach to Lake Malawi (**Figure**

10). Wetland cultivation is common in south-western side of Chilumba Harbour where the catchment drains to Lake Malawi.

Karonga Lakeshore catchment has huge potential for development due to its locale in a fertile flood plain at the estuary of North Rukuru River, on a transport route, and close to major mining sites. However, the low altitude due to rift valley location of the town, its high-water table. However, the increasing settlement in low-lying areas prone to flood channels, raises the potential for damage from flooding.

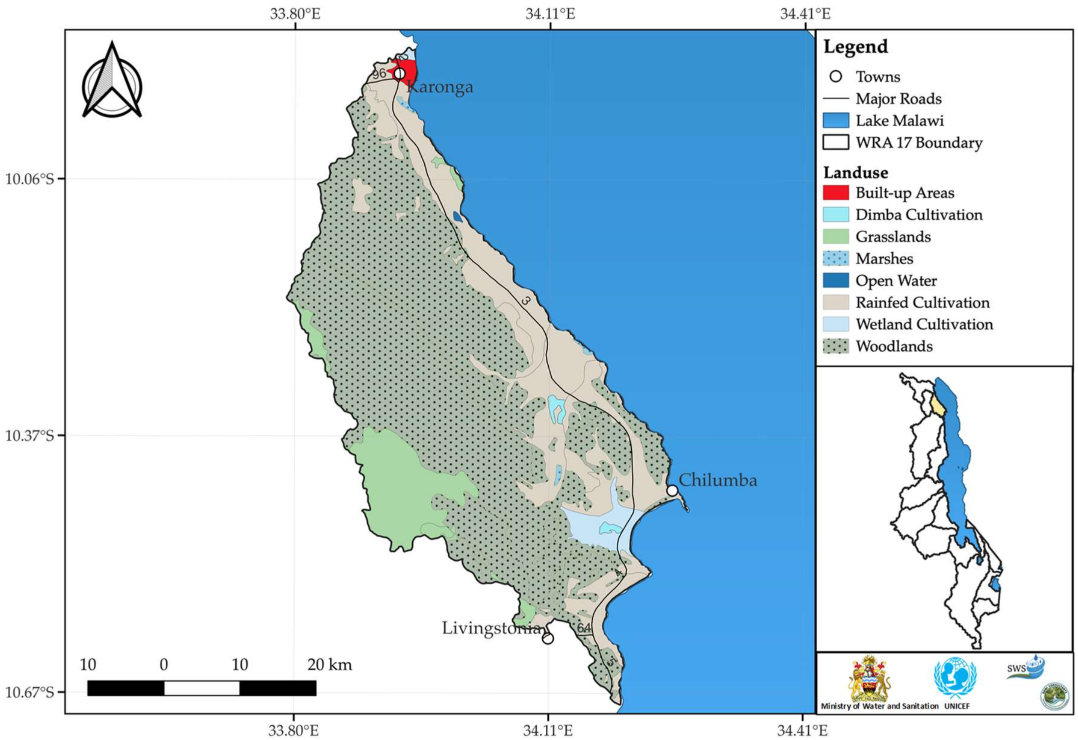

Figure 10. Land use in WRA 17 is dominated by woodland cultivation and rain fed cultivation.

Hydrogeology of WRA 17

Aquifer properties

Water Resources Area 17 comprises the edge of the Rift Valley with associated potential for increased outwash and colluvium overlying weathered and fractured bedrock. Lacustrine deposits of low-energy deposition that comprise predominantly finer-grained lithologies and more along the lake shore may be expected to be of modest aquifer potential (hydraulically connected to the lake near-shore). In the escarpment layered unconsolidated, anisotropic aquifer systems may be expected, and down slope individual layers may trend to an aquitard nature where very fine-grained silt/clay deposits are laterally extensive. Better aquifer units for water supply in WRA 17 are most likely associated with riverine environments where fluvial deposit accumulations are more extensive.

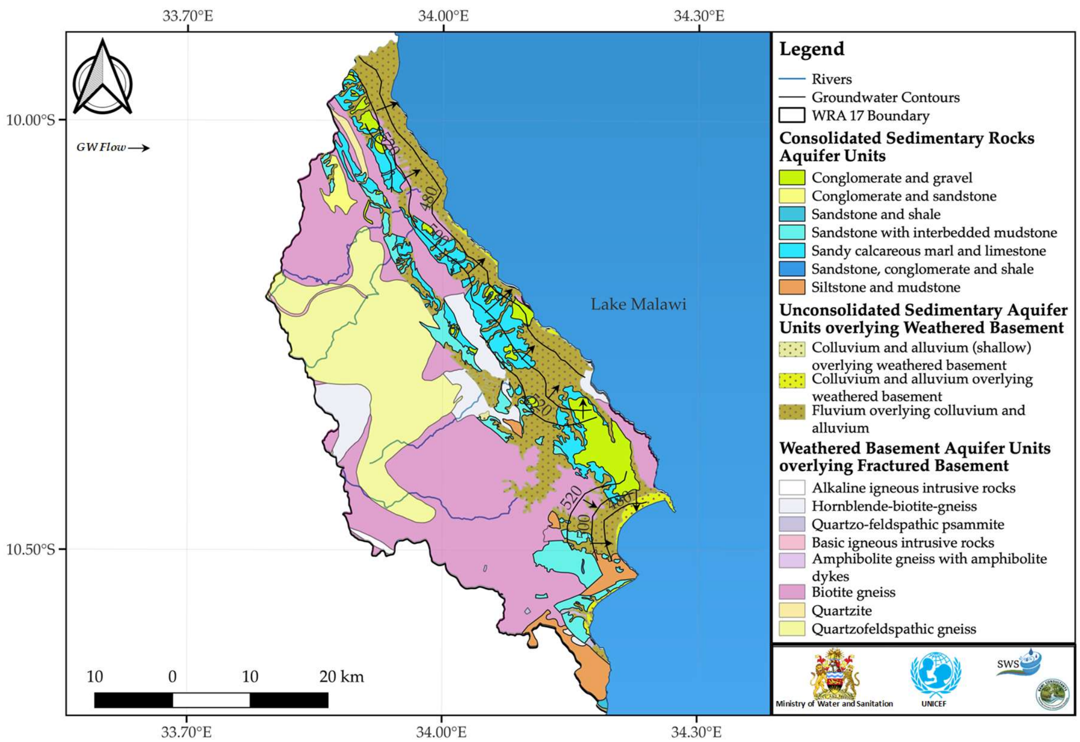

Figure 11. Groundwater level contours [20m interval] and flow direction in WRA 17 [1987 Hydrogeological Reconnaissance data].

Accordingly note the sediments in the Karonga Lake Shore Basin appear to be dominantly fine-grained ascribed to the low energy environment of deposition. There is expectation of coarser sediments derived from the Mountains however there were no detailed lithological records for existing boreholes available (**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 data, therefore groundwater level data for WRA 17 is based on prior hydrogeological reconnaissance and confirm Basin groundwater flows are convergent on Karonga Lake Shore generally following topography (see **Figure 11**). Steepest gradients occur in the uplands with gradients becoming shallower in areas covered by the high-level deposits and shallowest beneath the lake terrace deposits nearing Karonga Lake Shore. Groundwater divides at the basin boundary mimic those for surface-water drainage.

Groundwater level data for WRA 17 based on prior hydrogeological reconnaissance are only found for the discrete area of lakeshore plain - lowland from 20 to 30 km inland from of the Lake Malawi shoreline. Heads confirm groundwater flows follow topographic drainage towards the lake (Figure X). The lowlands widen southwards with unconsolidated sediments extending further inland from the more significant river estuary, for instance the Wovwe and Nyugwe rivers near Mdoka and also more continuous along the shoreline northwards of the Mulale Lagoon area. Most of WRA 17 is covered by fractured Basement resulting in elevated terrain and Rift Valley escarpment that is often steep, approaching the lakeshore plain. Groundwater flows in Basement escarpment may be expected to drain into the lakeshore plain aquifer units where head contours roughly parallel the shoreline indicative of flows generally towards the lake. In the shoreline southern promontory at Chilumba, however, the Basement shoreline outcrop causes a groundwater flow divide in land with flows locally northwards towards the Wovwe River and southwards towards Youngs Bay. Hydraulic gradients appear relatively uniform throughout the WRA 17 lakeshore area varying from around 0.006 to 0.009 (0.6 to 0.9 %) giving rise to groundwater velocity estimates of 11 - 16 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2.

Aquifer / Borehole Yield

As with most WRA's in Malawi, borehole yields do 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 standard Afridev pump rather than to drill and test each groundwater well to determine the exact aquifer properties at each location. In WRA 17 the high average rainfall and potential for research suggests there is some potential in the lower elevations for higher yielding boreholes and for artesian confined systems along the rift escarpment but detailed hydrogeological on-site mapping should be undertaken to confirm.

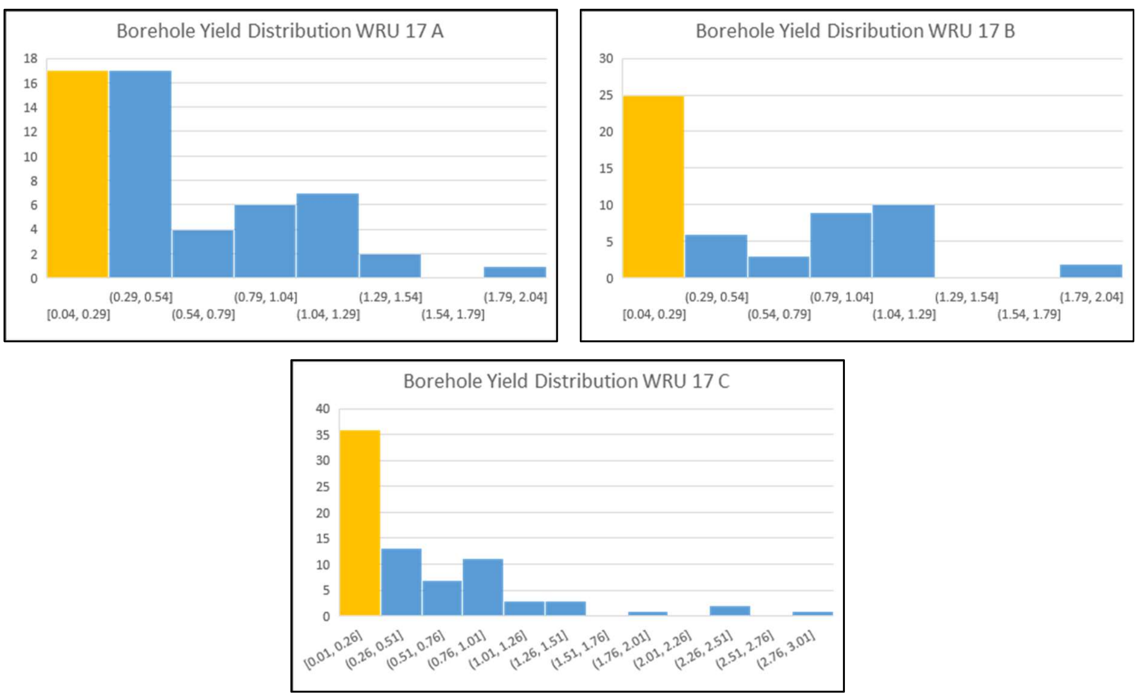

Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 17 (y axis = *n* observations)

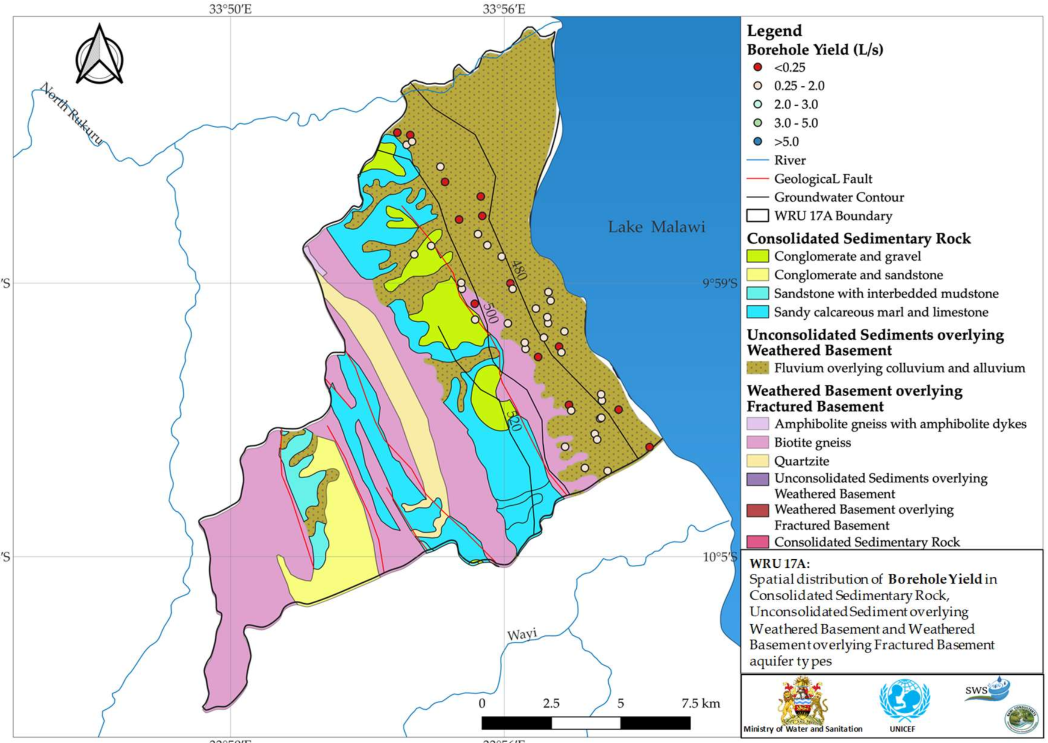

Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 17A.

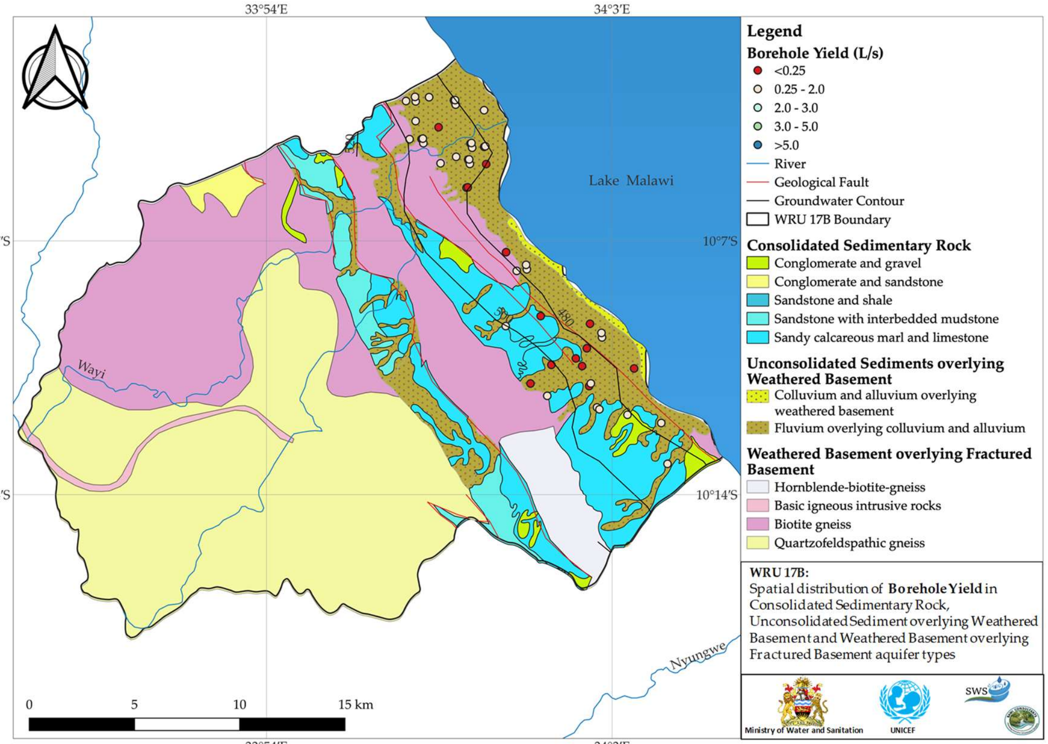

Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 17B.

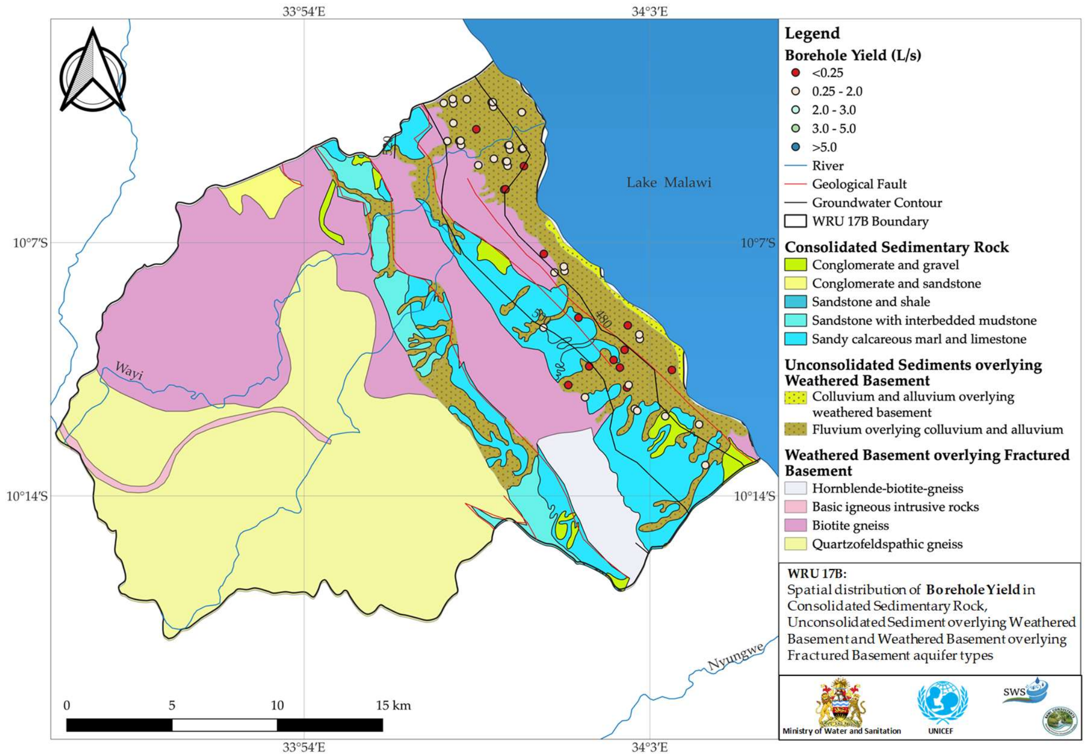

Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 17C.

There are general trends which suggest the highest borehole yields are found in alluvial aquifers in the order of 2 l/s (**Figures 13a, 13b, 13c**). The highest yielding boreholes in basement aquifers will likely be located mainly along linear structures and main streams and near contacts between different aquifers.

Groundwater Table Variations

There is only one operational groundwater monitoring stations within WRA 17 (**Figure 14a** for location and **Figure 14b** for data), a second was vandalised shortly after installation. The Karonga water office record is one of the most complete for the period 2008 to 2021. Data from the 2020 National Survey suggested seasonal water table declines, supported by the data in **Figure 14**. From the data that is held by the Ministry of Water and Sanitation, there is between a 2- and 4-meter annual change in groundwater table, with 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 into each unit is an area for future investment.

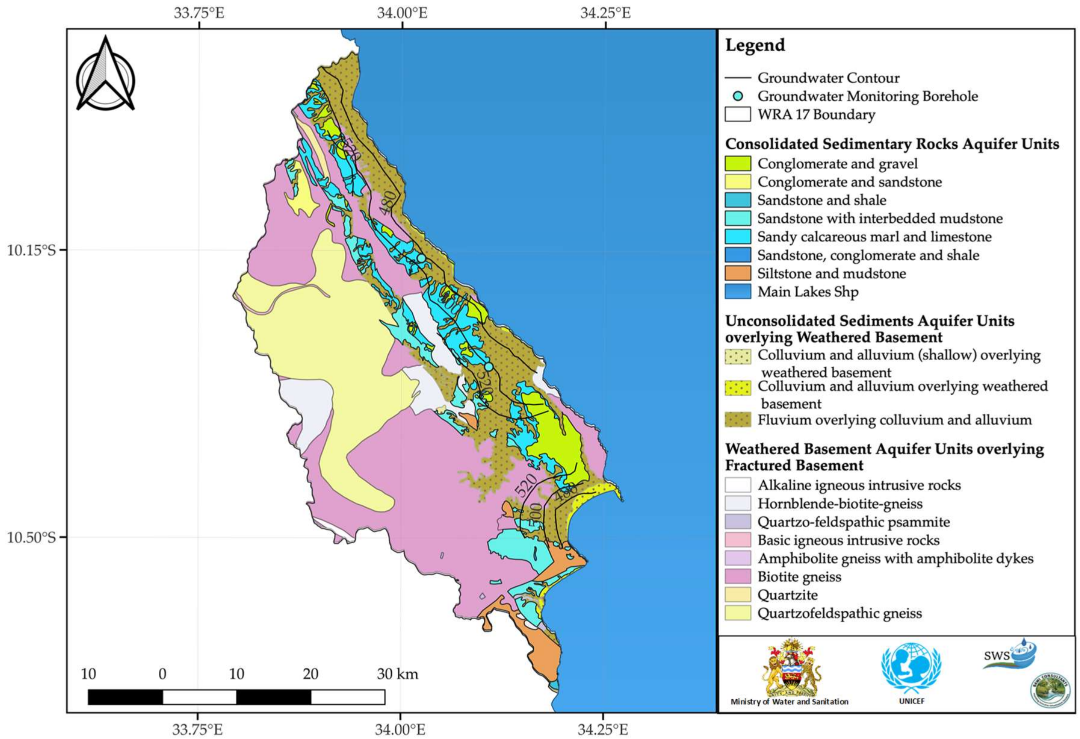

Figure 14a. Location of Groundwater Monitoring Stations in Water Resources Area 17

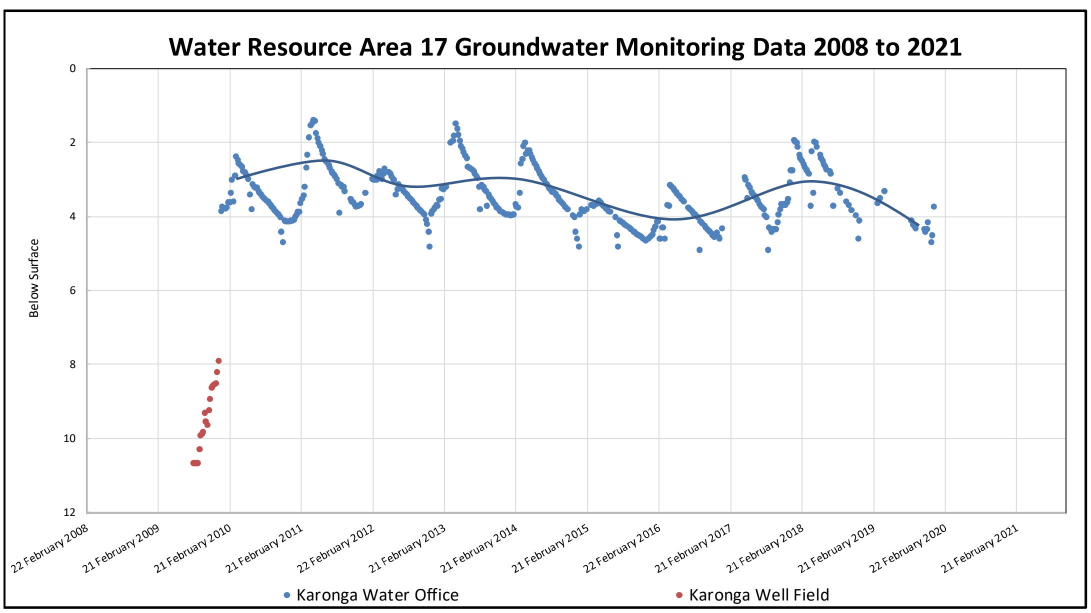

Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 17 (units assumed to be meters below ground level).

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 17 ranges between 19.2 Million Cubic Meters (MCM) and 144 MCM per year, with a mean age of groundwater of 184 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 17A, 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	51.6	3%	15%	0.02	0.10	31.0	774.7	
Fluvial Units	66.2	10%	35%	0.02	0.10	132.4	2,317.2	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	0.0	10%	30%	0.02	0.06	0.0	0.0	
W & F Basement	63.2	1%	10%	0.02	0.03	12.6	189.6	
	Area of WRU (km^2)	17A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*176.0*	*3,281.4*	*Total Volume Groundwater*
	181.1	886	Average Rainfall in WRU	8.86	66.45	1.6	12.0	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]						110	273	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 17B, 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	88.8	3%	15%	0.02	0.10	53.3	1,331.3	
Fluvial Units	73.5	10%	35%	0.02	0.10	147.0	2,571.7	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	3.0	10%	30%	0.02	0.06	5.9	53.4	
W & F Basement	374.9	1%	10%	0.02	0.03	75.0	1,124.7	
	Area of WRU (km^2)	17B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*281.1*	*5,081.1*	*Total Volume Groundwater*
	540.1	898	Average Rainfall in WRU	8.98	67.35	4.9	36.4	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]						58	140	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 17C, 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	237.8	3%	15%	0.02	0.10	142.7	3,566.5	
Fluvial Units	198.5	10%	35%	0.02	0.10	397.0	6,947.6	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	18.7	10%	30%	0.02	0.06	37.3	336.0	
W & F Basement	763.0	1%	10%	0.02	0.03	152.6	2,289.1	
	Area of WRU (km^2)	17C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*729.6*	*13,139.1*	*Total Volume Groundwater*
	1,218.0	1046	Average Rainfall in WRU	10.46	78.45	12.7	95.5	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]						57	138	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Groundwater quality WRA 17

Groundwater major-ion water quality in WRA 17 for data available within the Ministry of Water and Sanitation is very limited (**Table 5**).

Table 5. Distribution of dissolved species in groundwater WRA 17. 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 17	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	1,371	5.6	9.1	0.0	0.4	61.7	5.5	32.8	16.5	0.9
Std Dev	0.4	1,080	2	14	0.0	0.2	79	4.4	28.5	18.0	1.7
Median	7.3	1,543	5.0	3.3	0.0	0.5	32.3	4.2	25.1	10.1	0.1
Max	7.7	2,310	9	29	0	0.6	178	12	73	43	3.4
Min	6.9	90.0	3.7	0.4	0.0	0.1	4.0	1.8	8.2	2.8	0.0
n	4	4	4	4	4	4	4	4	4	4	4

Piper plots of the WRA 17 limited water quality data suggest most water has expected major geochemical changes from water-rock interactions dominated by Ca-Mg-HCO_3 type waters with a clear trend for increasing Na-Cl likely due to either water movement along faults or evaporative enrichment (**Figure 15a and 15b**). The average groundwater age, precipitation rate and calculated recharge rates together with the moderately high electrical conductivity points to water-rock interactions, however in low-lying areas there is potential that high EC groundwater are related to evaporative enrichment.

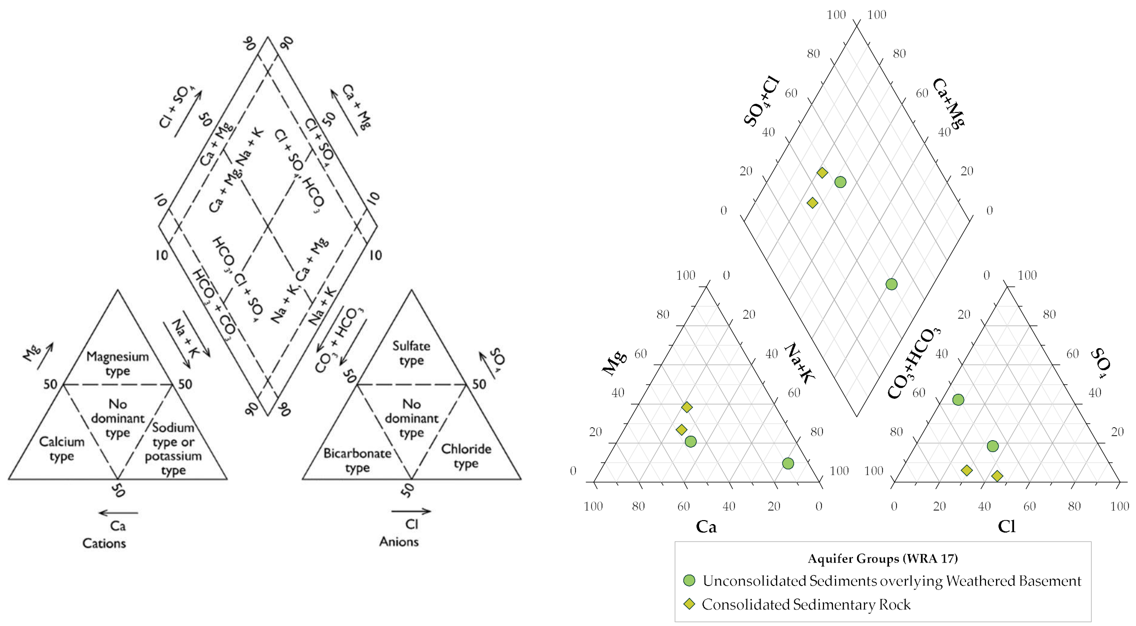

Figure 15a, 15b. Piper Diagrams of Groundwater Samples in WRA 17 and for each Aquifer Type in WRA 17.

The distribution of key dissolved water quality species in groundwater of WRA 17 is not possible due to the paucity of data in the WRA with only Electrical Conductivity data of sufficient quantity to evaluate (**Figure 16**). Detailed cluster analysis was undertaken by Mapoma et al 2016 on groundwater in the Rukuru–Songwe alluvial aquifers but from the national data set Water quality results with geospatial coordinates were rare in WRA 17, there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

Groundwater quality - Health relevant / aesthetic criteria

Salinity

There are a number of water quality results that show elevated EC (**Figure 16**), 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

Fluoride Basin groundwater data drawn from the recent national-scale assessments (**Figure 17**) reveals Hot Spring exceeds 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 17 is planned and implemented.

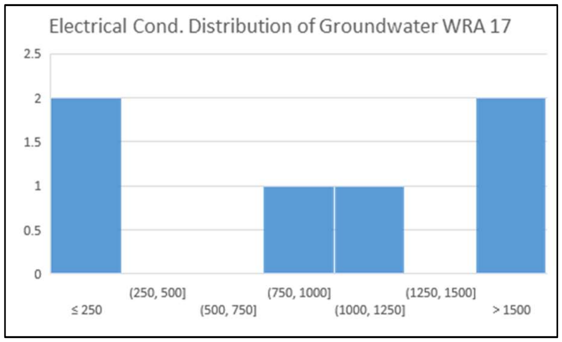

Figure 16. Distribution of chemical species (EC [uS]) in groundwater within WRA 17 (y axis = *n* observations).

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 the Karonga Lake Shore Basin 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.

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.

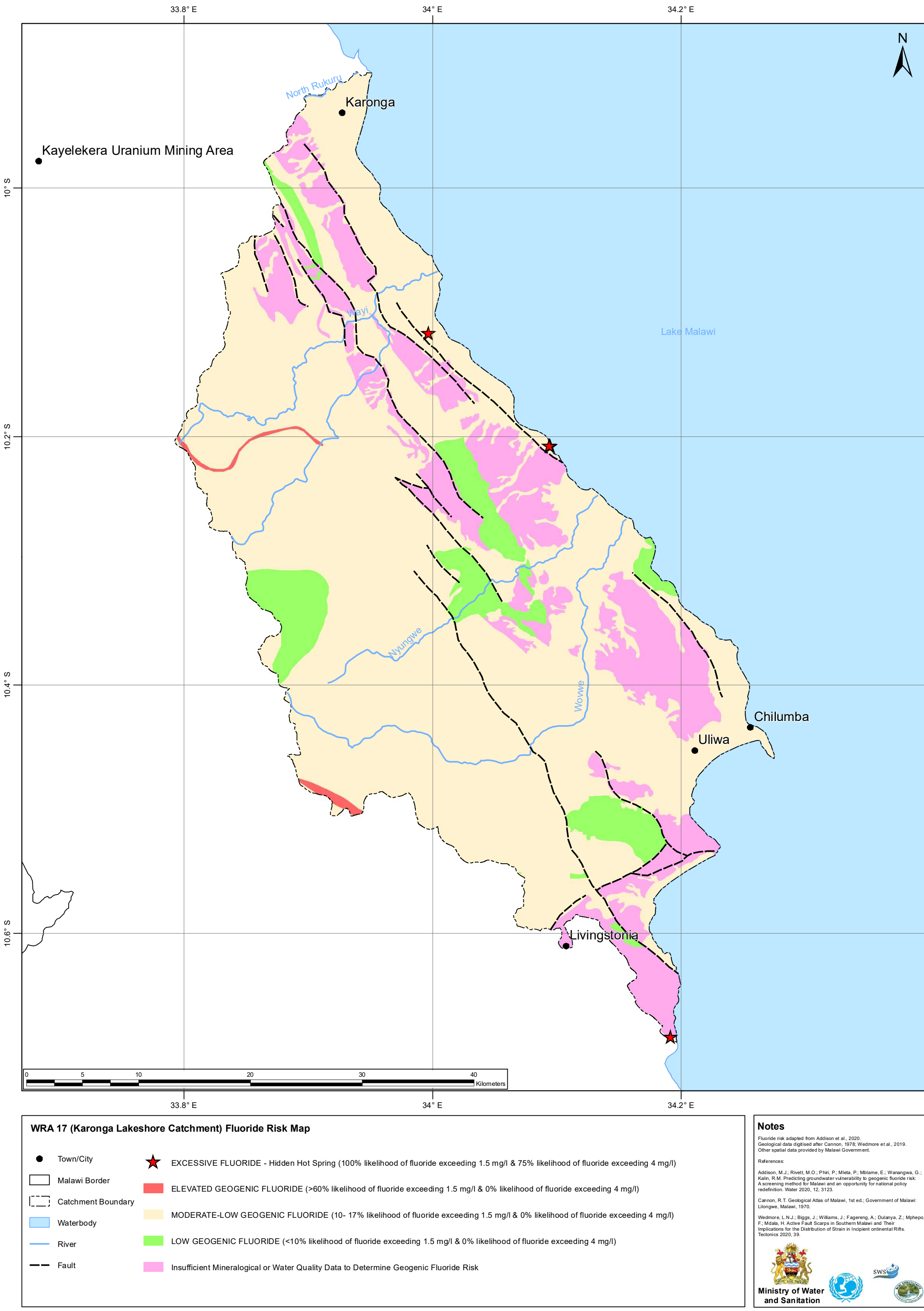

Figure 17. Groundwater Fluoride Risk Map WRA 17 (after Addison et. al. 2021).

Table 6. Calculated pit latrine loading 2012 to 2022 within WRA 17.

	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**
17A	44,201	45,776	48,154	50,218	52,079	55,435	159,766,549	191,720
17B	18,115	18,710	20,131	21,331	22,497	19,692	65,057,214	78,069
17C	84,236	88,039	94,299	100,005	105,361	104,187	311,108,751	373,331
WRA 17	**146,551**	**152,525**	**162,584**	**171,555**	**179,937**	**179,315**	**535,932,514**	**643,119**

Modelled results in **Table 6** show Water Resource Area 17 has a calculated total of 643,119 metric tonnes of faecal matter loading over the 10-year period (2012-2022). Over the 10-year period the number of pit latrine users in the region increased by 32,764. WRA17 covers roughly 0.157 % 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, 3,187 metric tonnes of fertiliser would be used in WRA1 per year; the modelled loading shows 20 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

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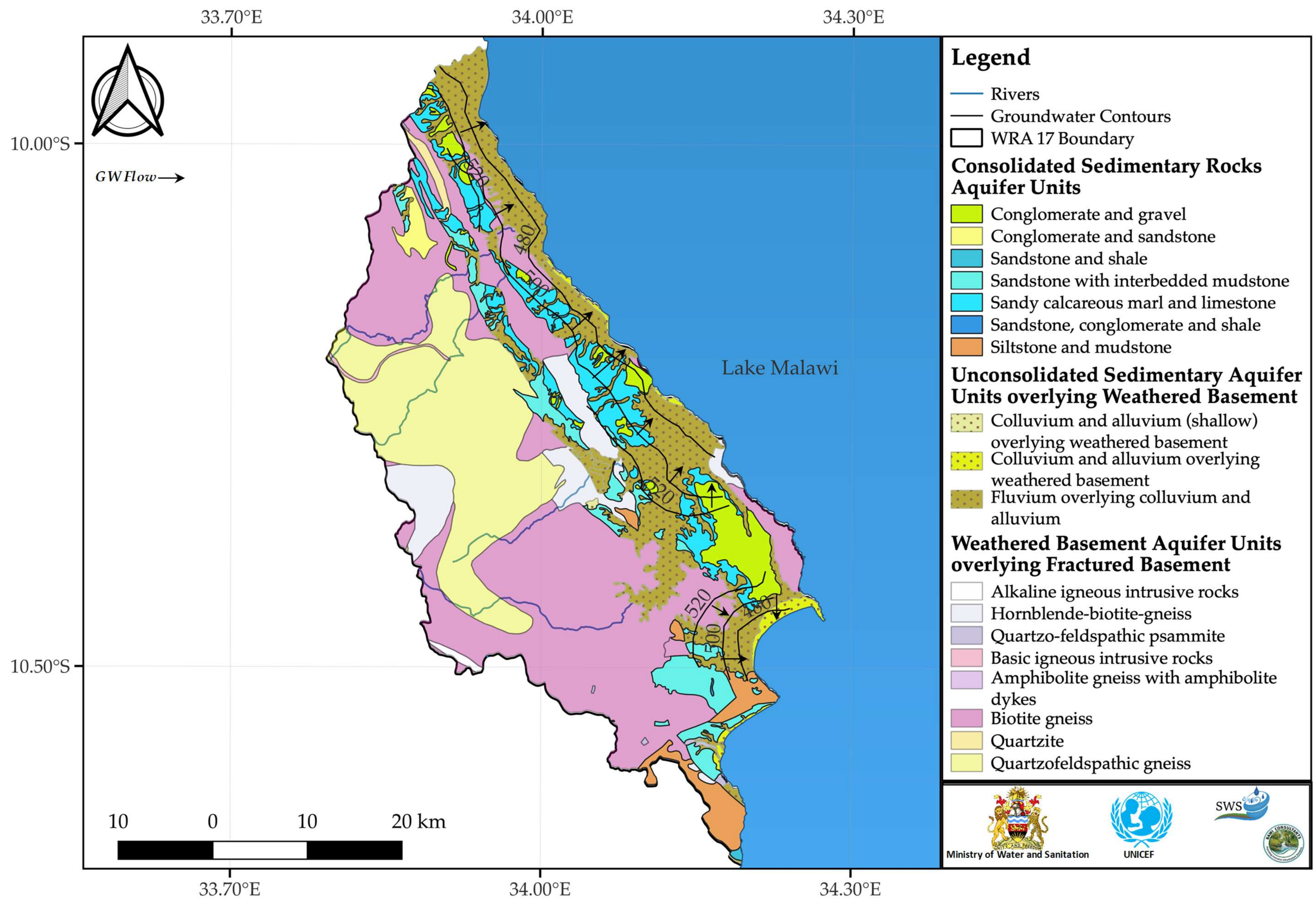
Water Resource Area 17 Figures

Figure WRA 17.0: Aquifer Units and Groundwater Level Contours Water Resources Area 17

Figure WRA 17.0: Aquifer Units and Groundwater Level Contours WRA 17



WRU 17A Figures

Figure WRU 17A.1 Land Use and Major Roads

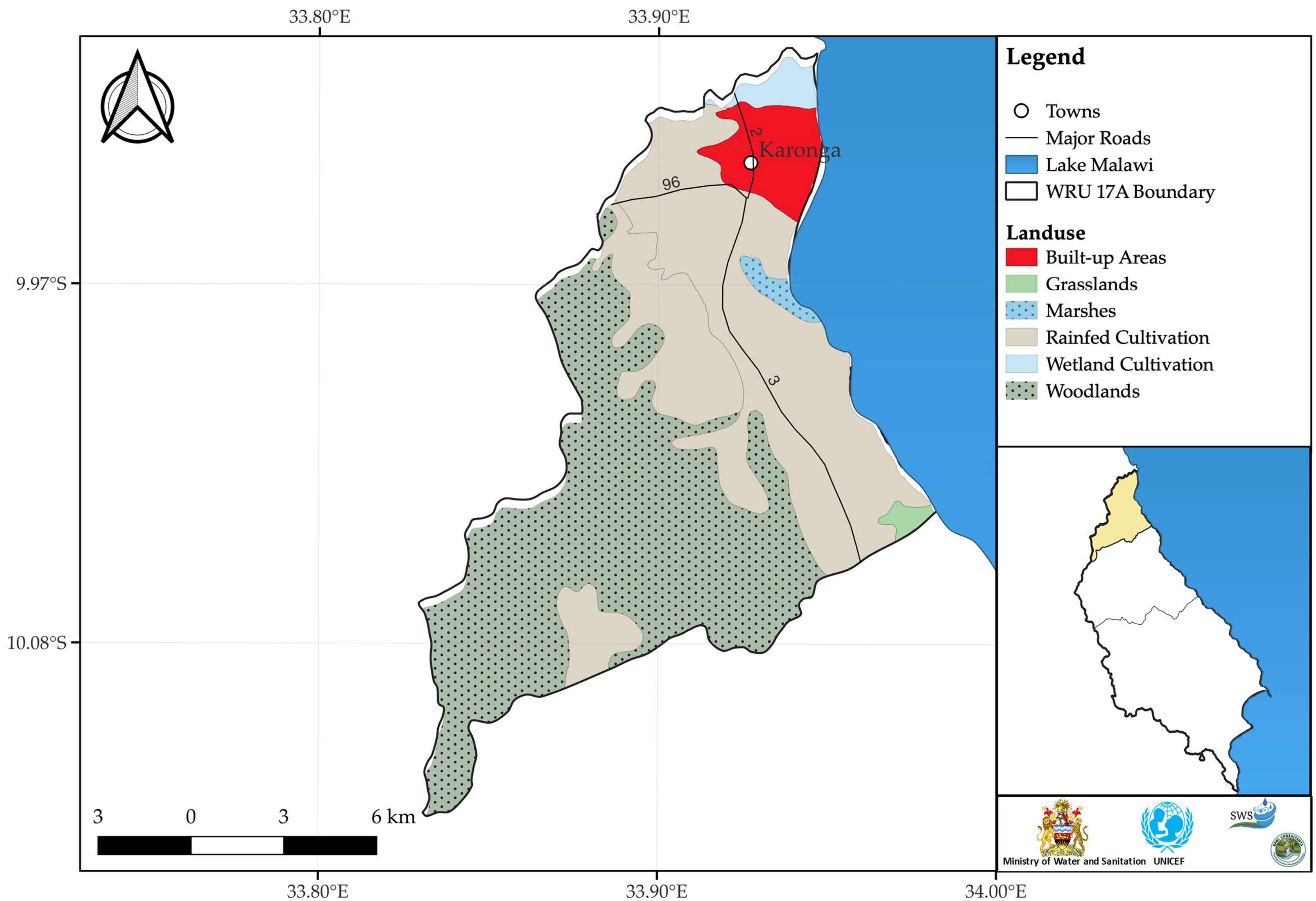


Figure WRU 17A.2 Rivers and Wetlands

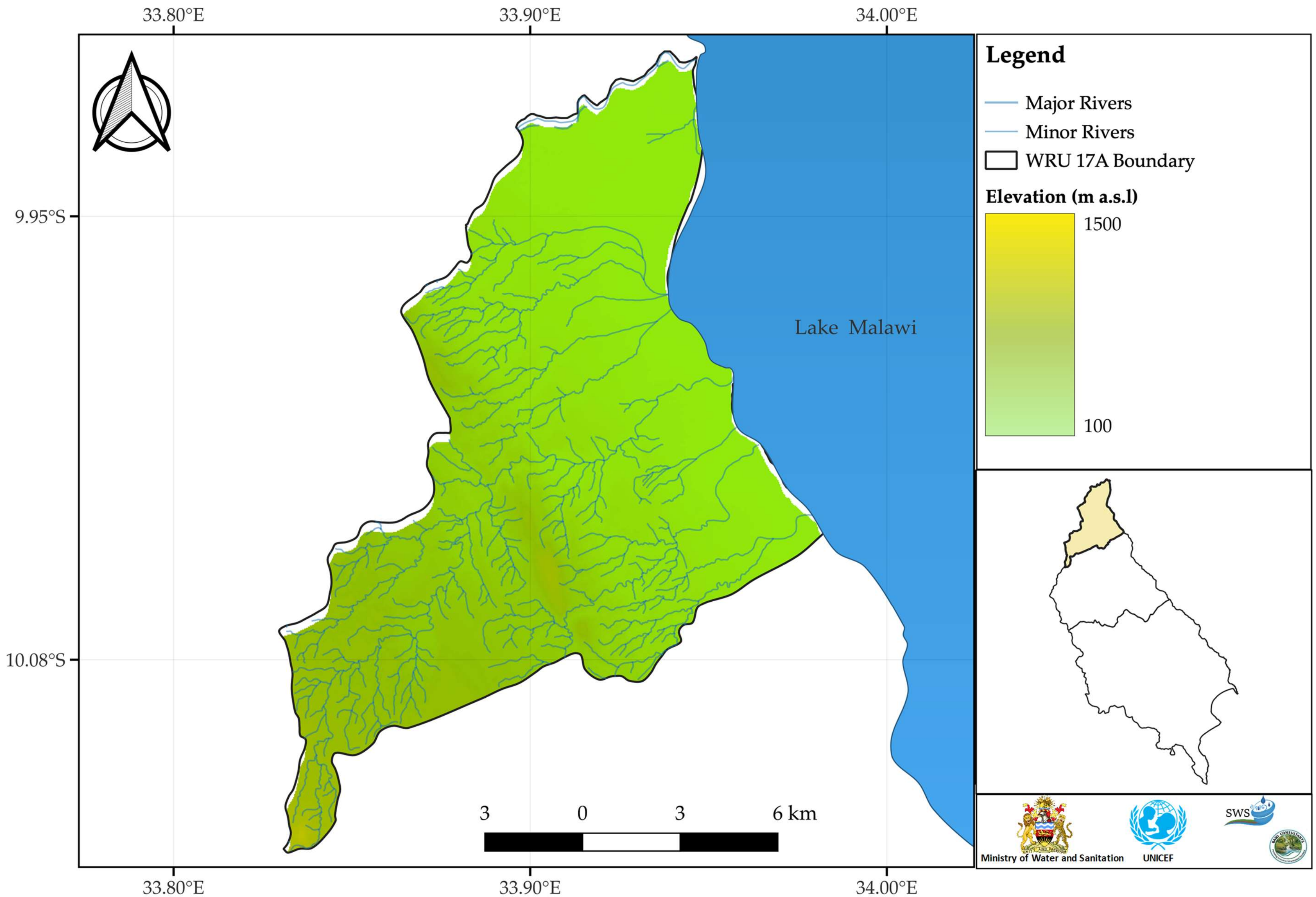


Figure WRU 17A.3 Hydrogeology Units and Water Table

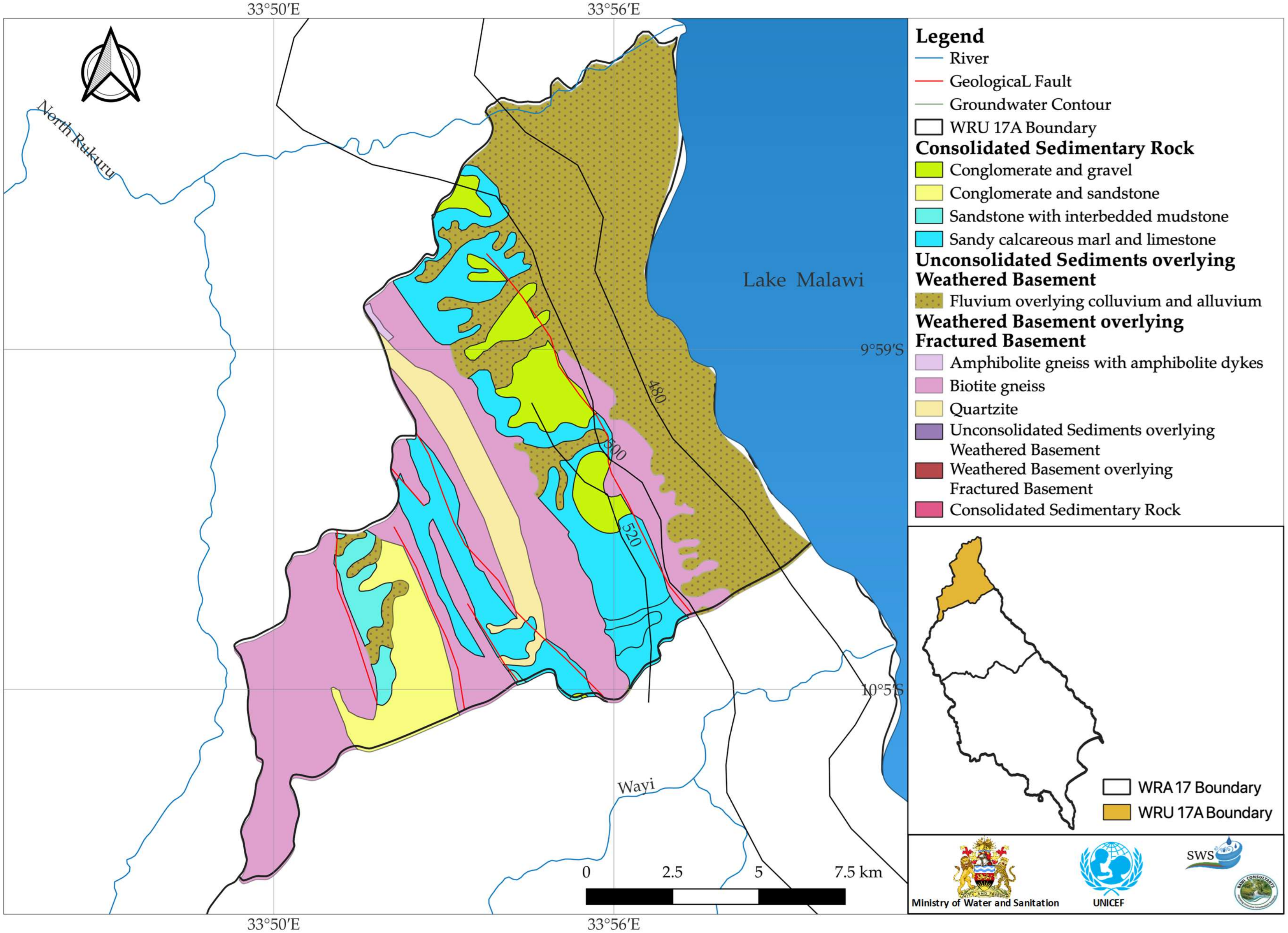


Figure WRU 17A.4 Groundwater Chemistry Distribution Electrical Conductivity

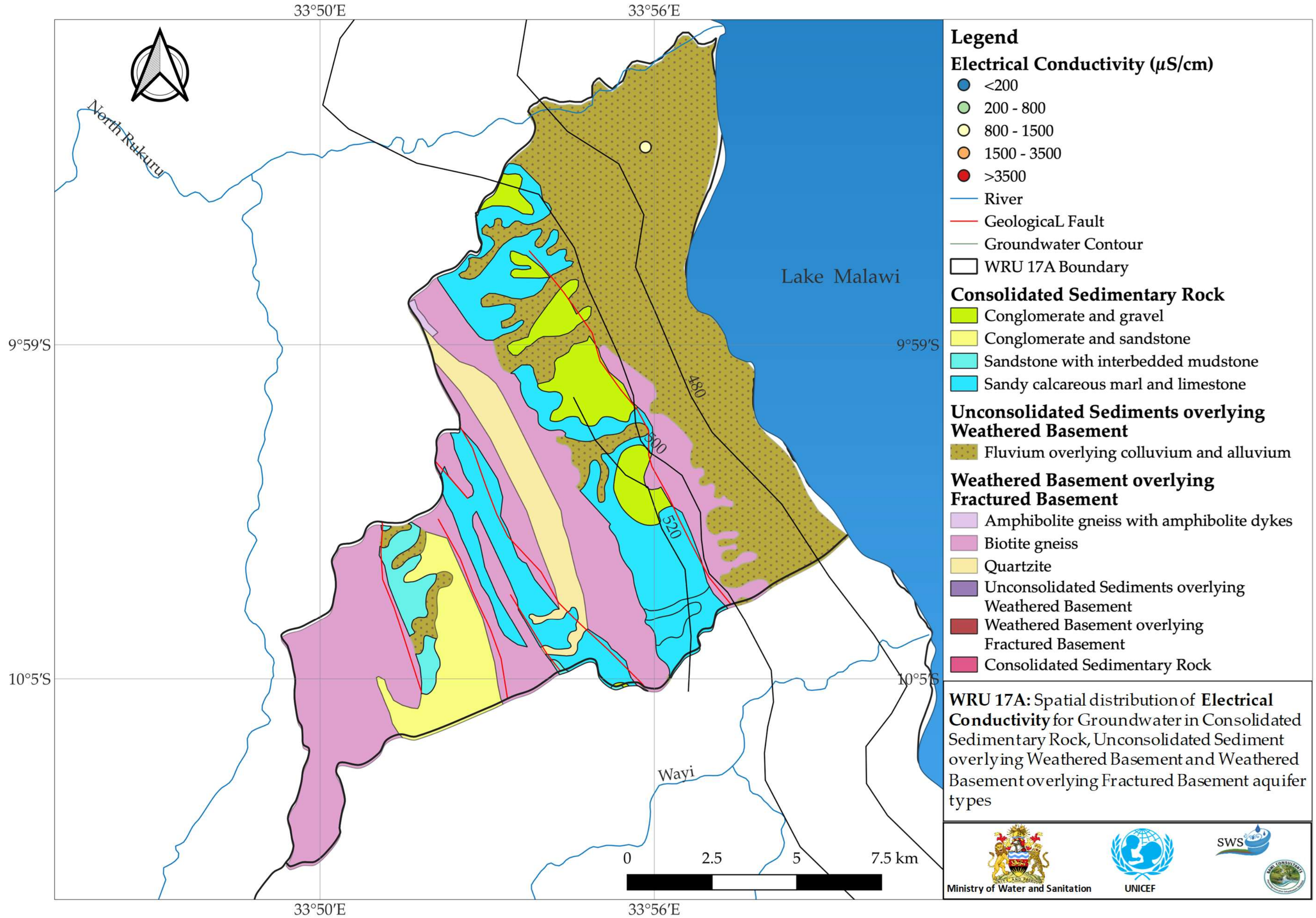


Figure WRU 17A.5 Groundwater Chemistry Distribution of Sulphate

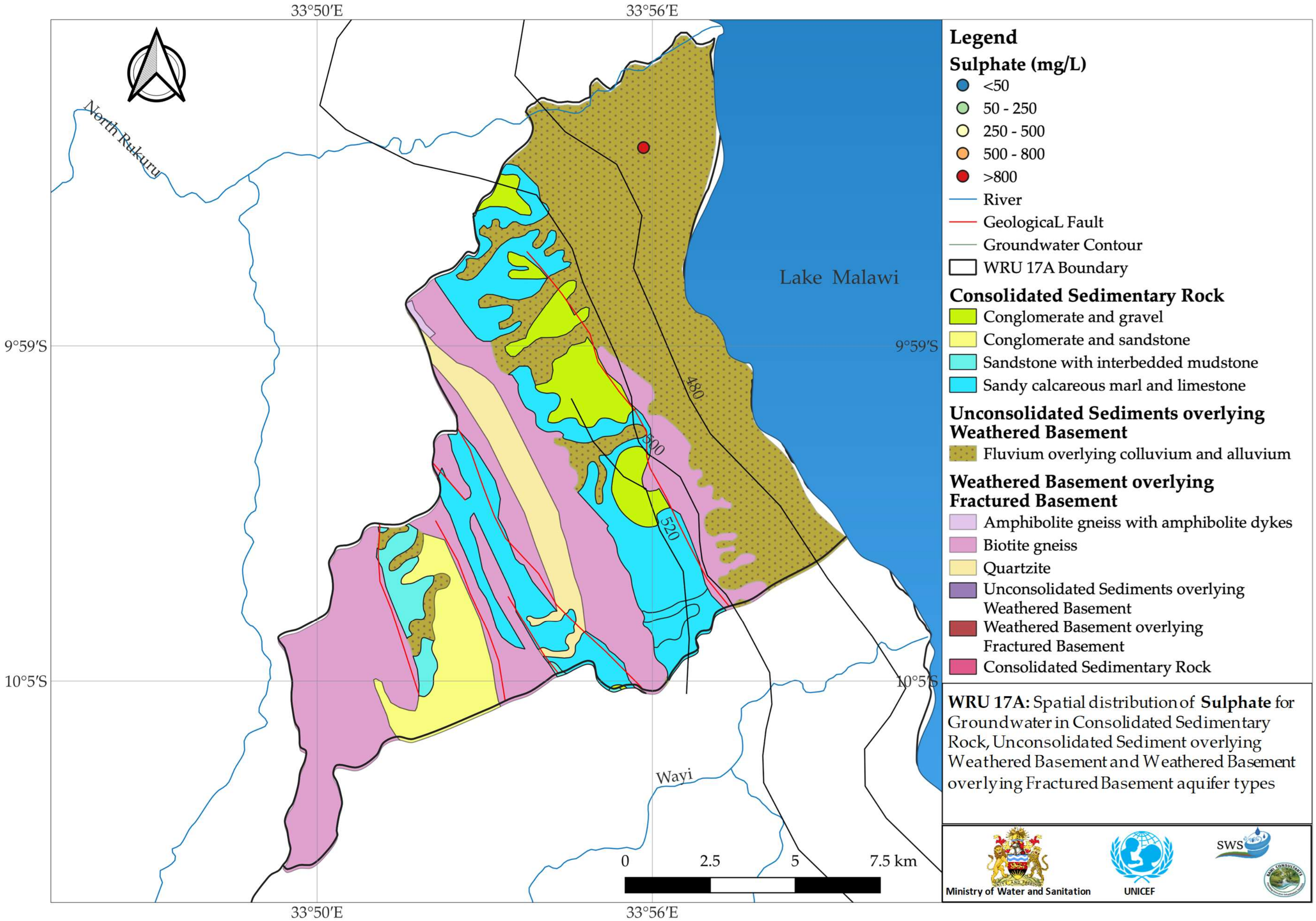


Figure WRU 17A.6 Groundwater Chemistry Distribution Chloride

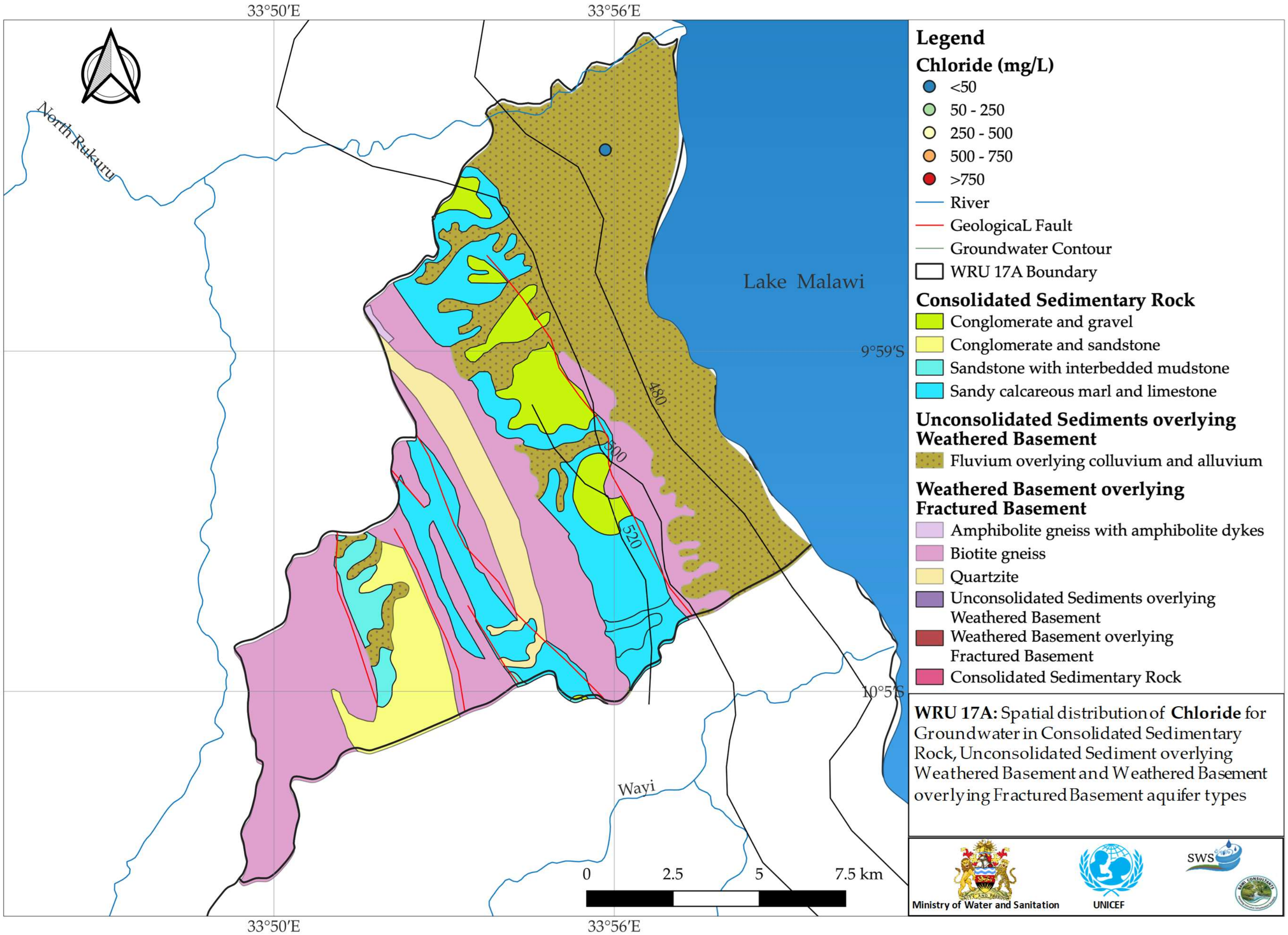


Figure WRU 17A.7 Groundwater Chemistry Distribution Sodium

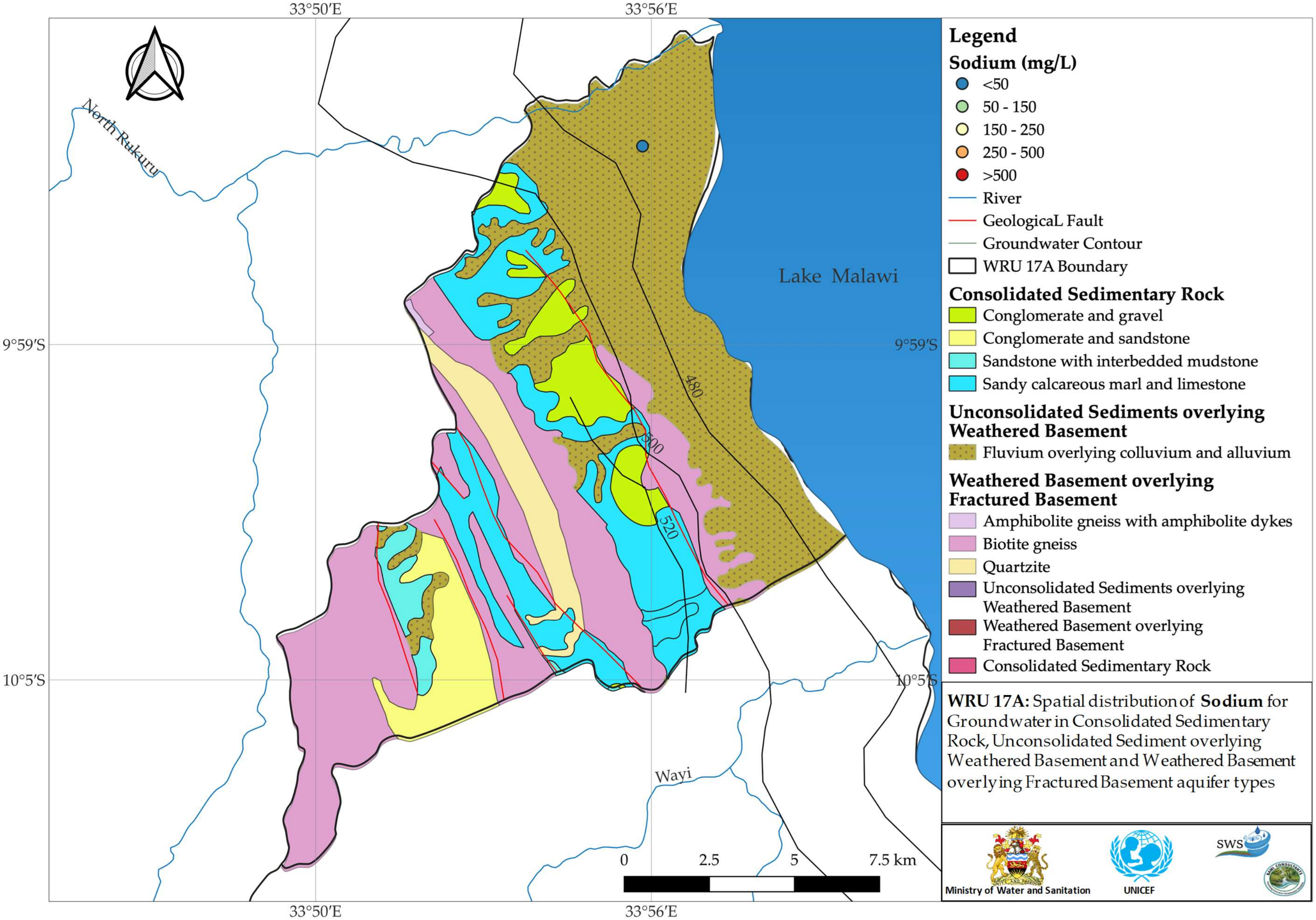


Figure WRU 17A.8 Groundwater Chemistry Distribution Calcium

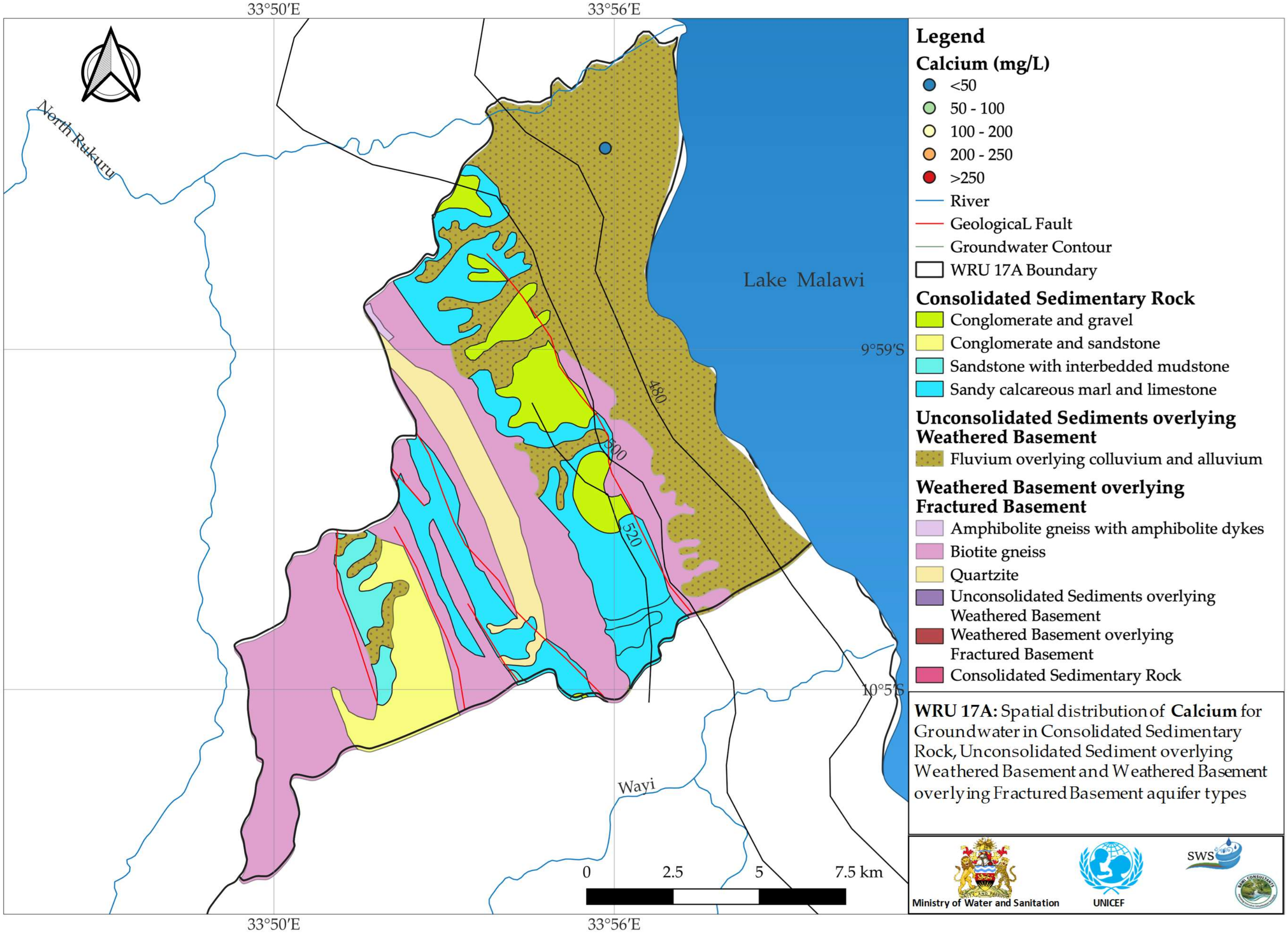


Figure WRU 17A.9 Piper Diagram of water quality results with respect to the major aquifer type

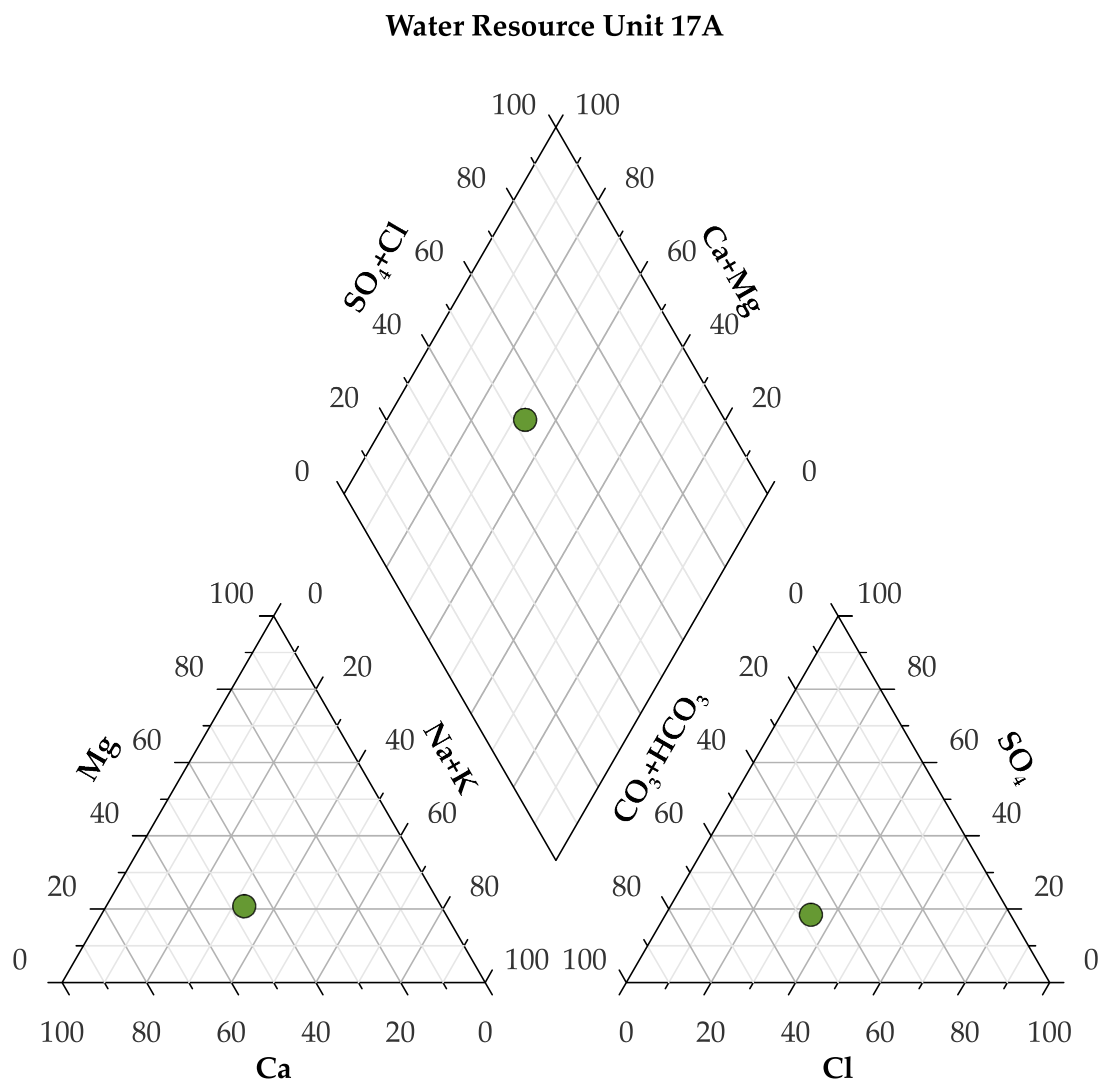
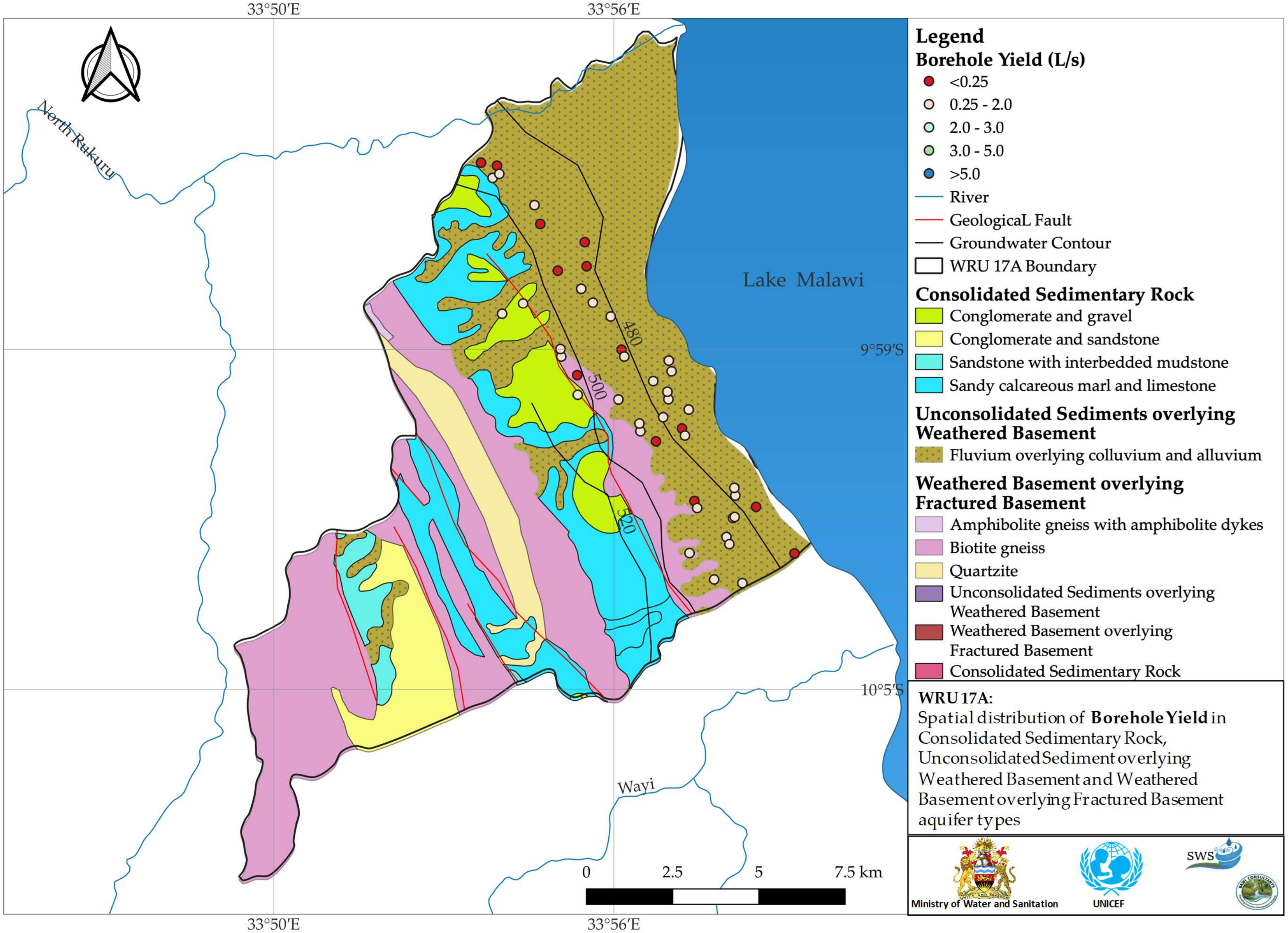


Figure WRU 17A.10 Borehole Yield Map for data held by the Ministry



WRU 17B Figures

Figure WRU 17B.1 Land Use and Major Roads

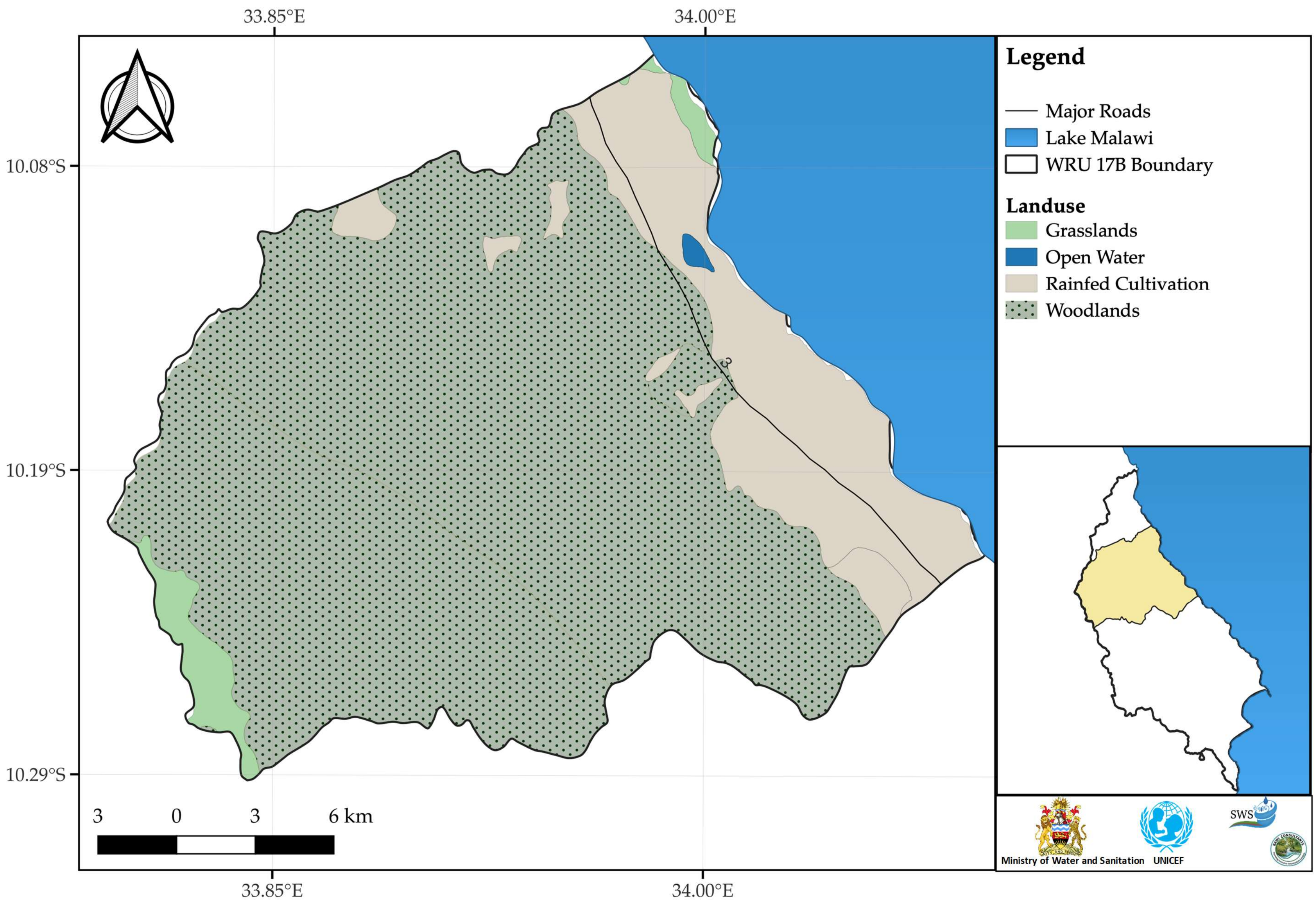


Figure WRU 17B.2 Rivers and Wetlands

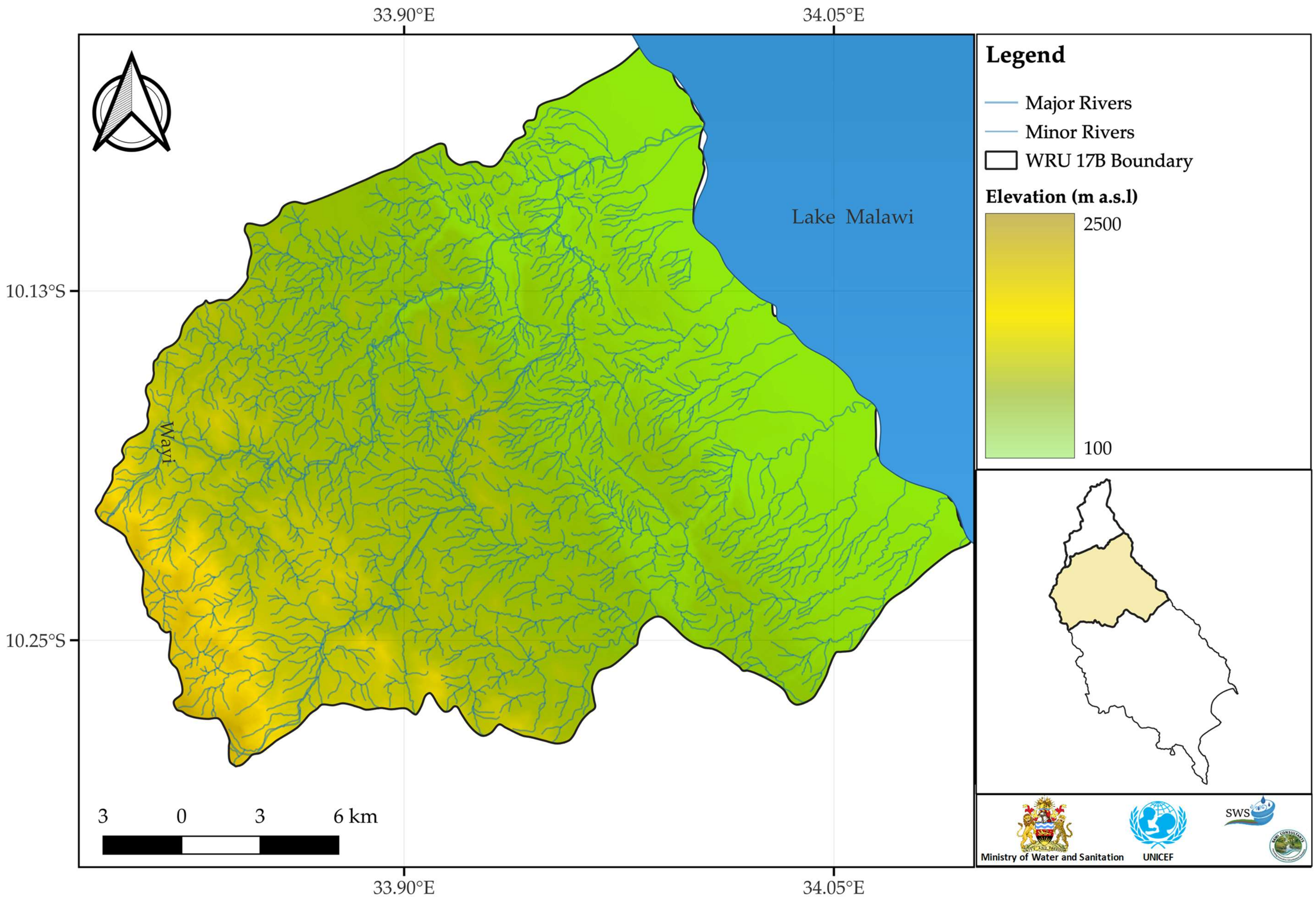


Figure WRU 17B.3 Hydrogeology Units and Water Table

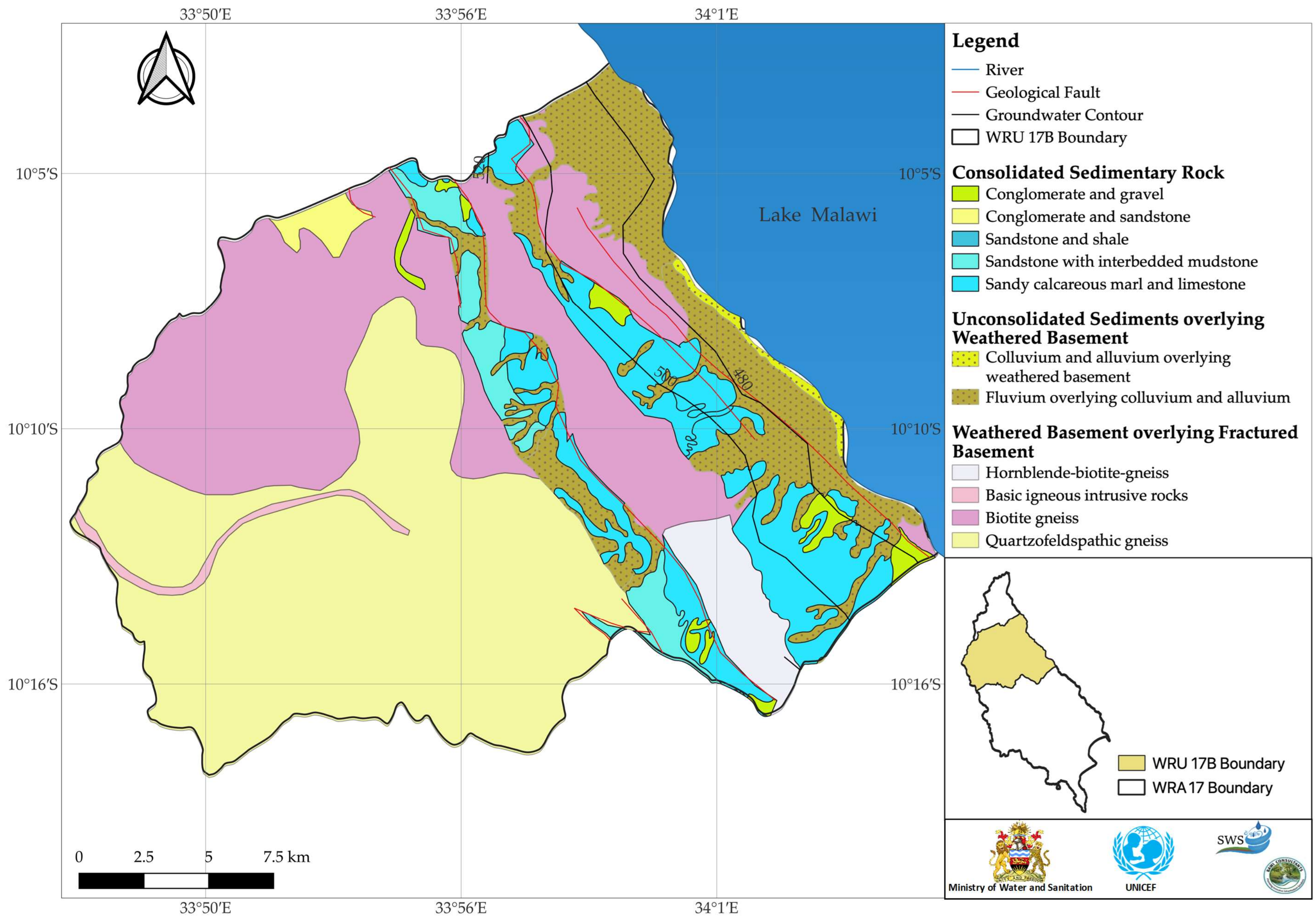


Figure WRU 17B.4 Groundwater Chemistry Distribution Electrical Conductivity

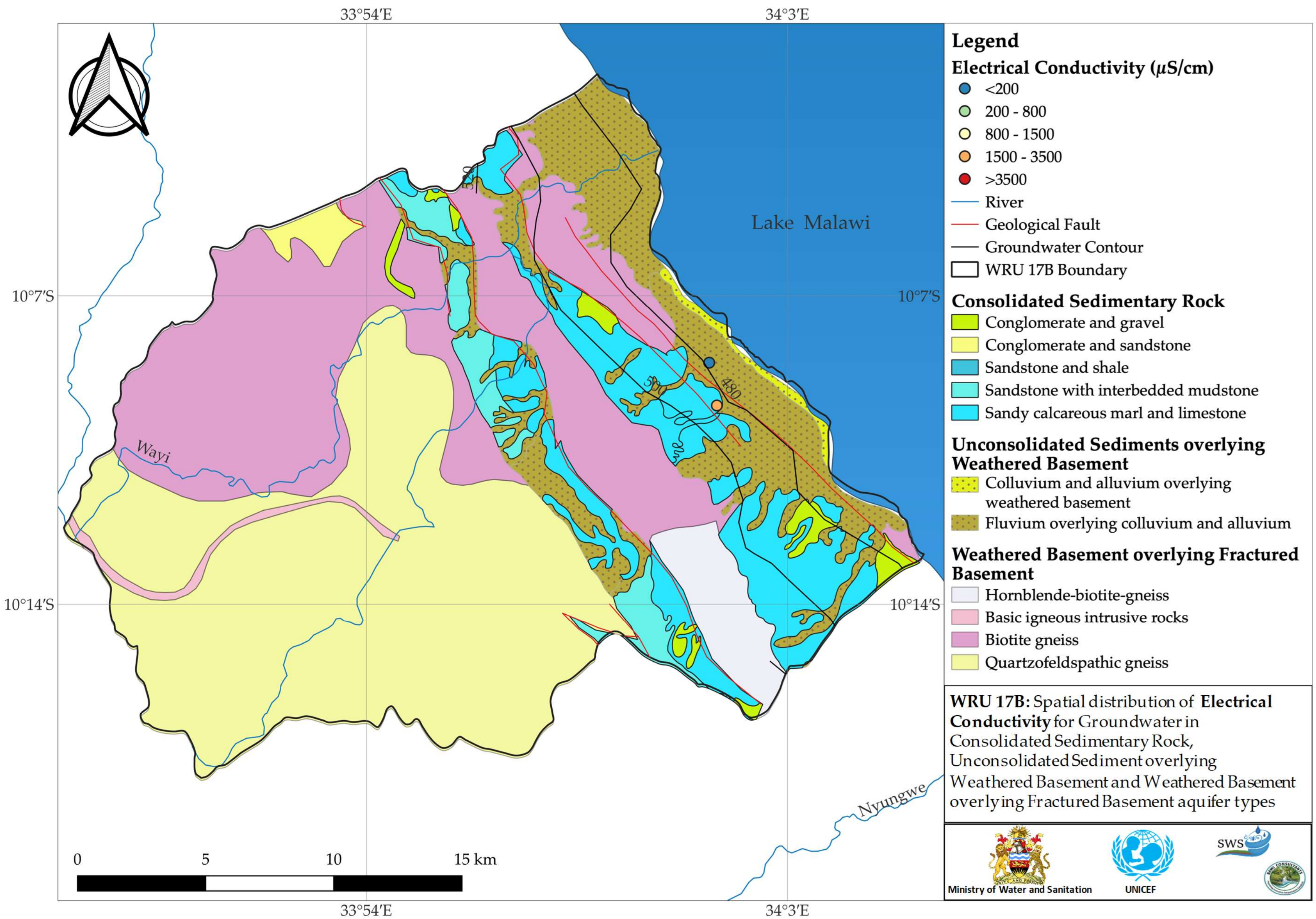


Figure WRU 17B.5 Groundwater Chemistry Distribution of Sulphate

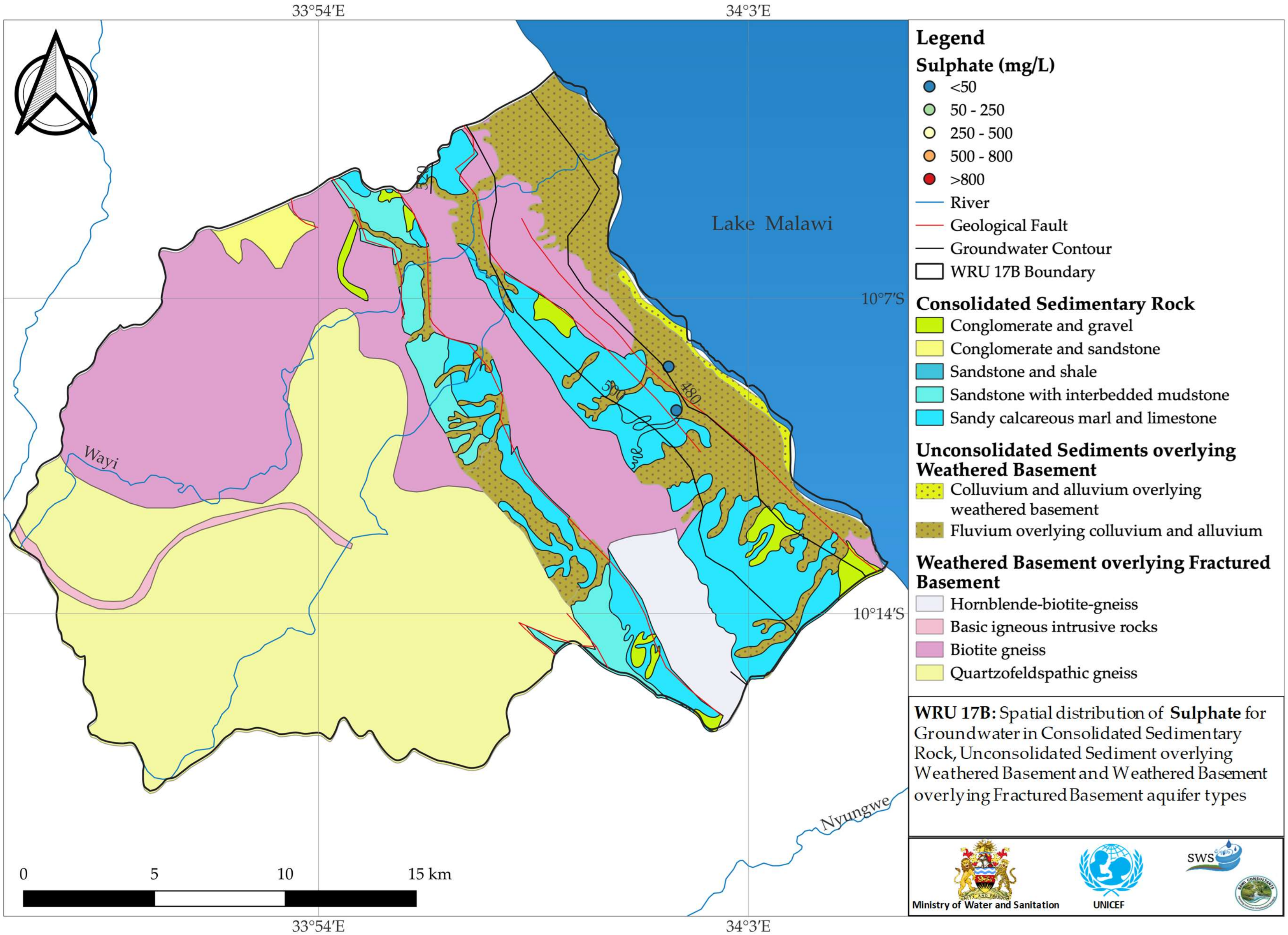


Figure WRU 17B.6 Groundwater Chemistry Distribution Chloride

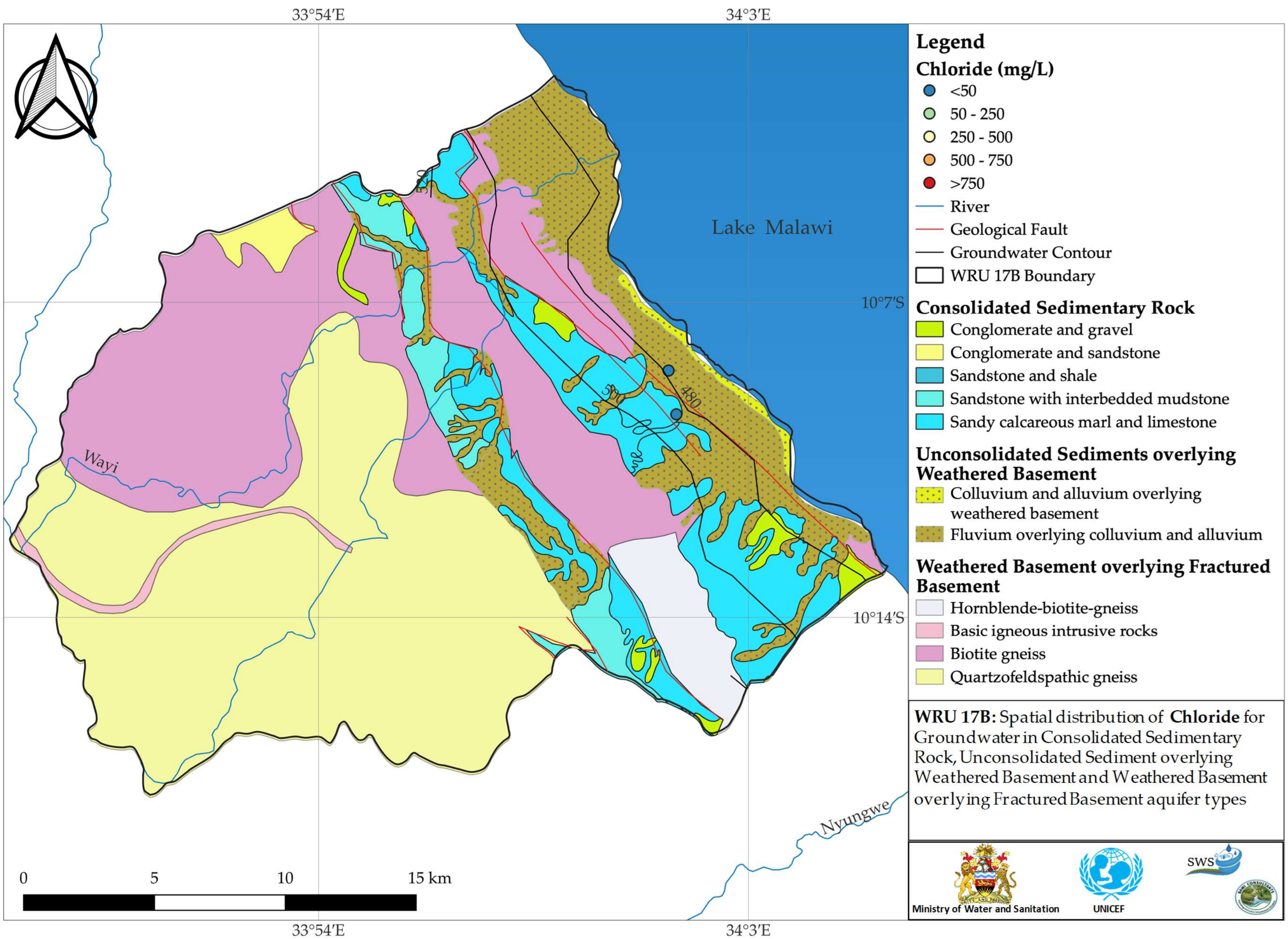


Figure WRU 17B.7 Groundwater Chemistry Distribution Sodium

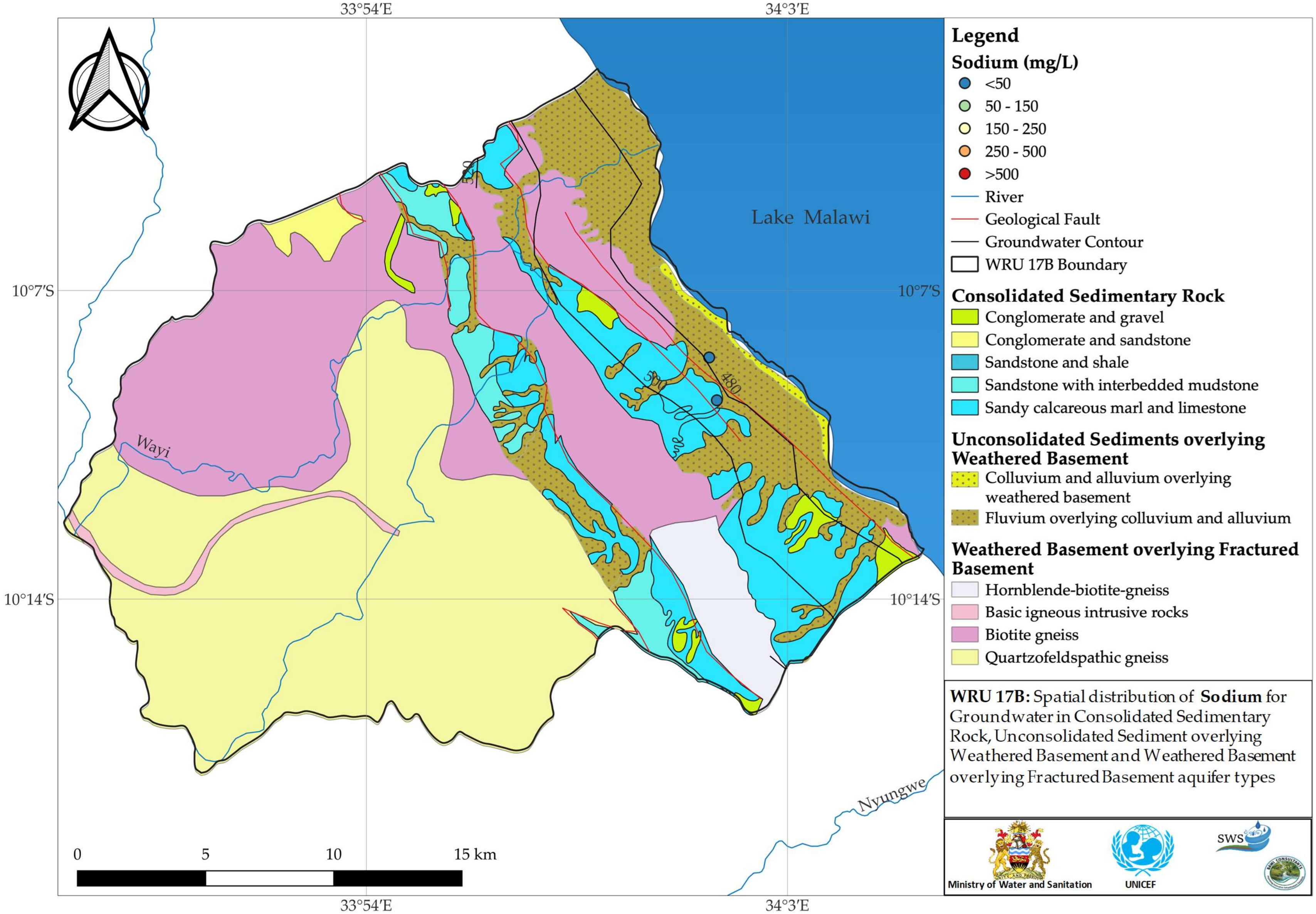


Figure WRU 17B.8 Groundwater Chemistry Distribution Calcium

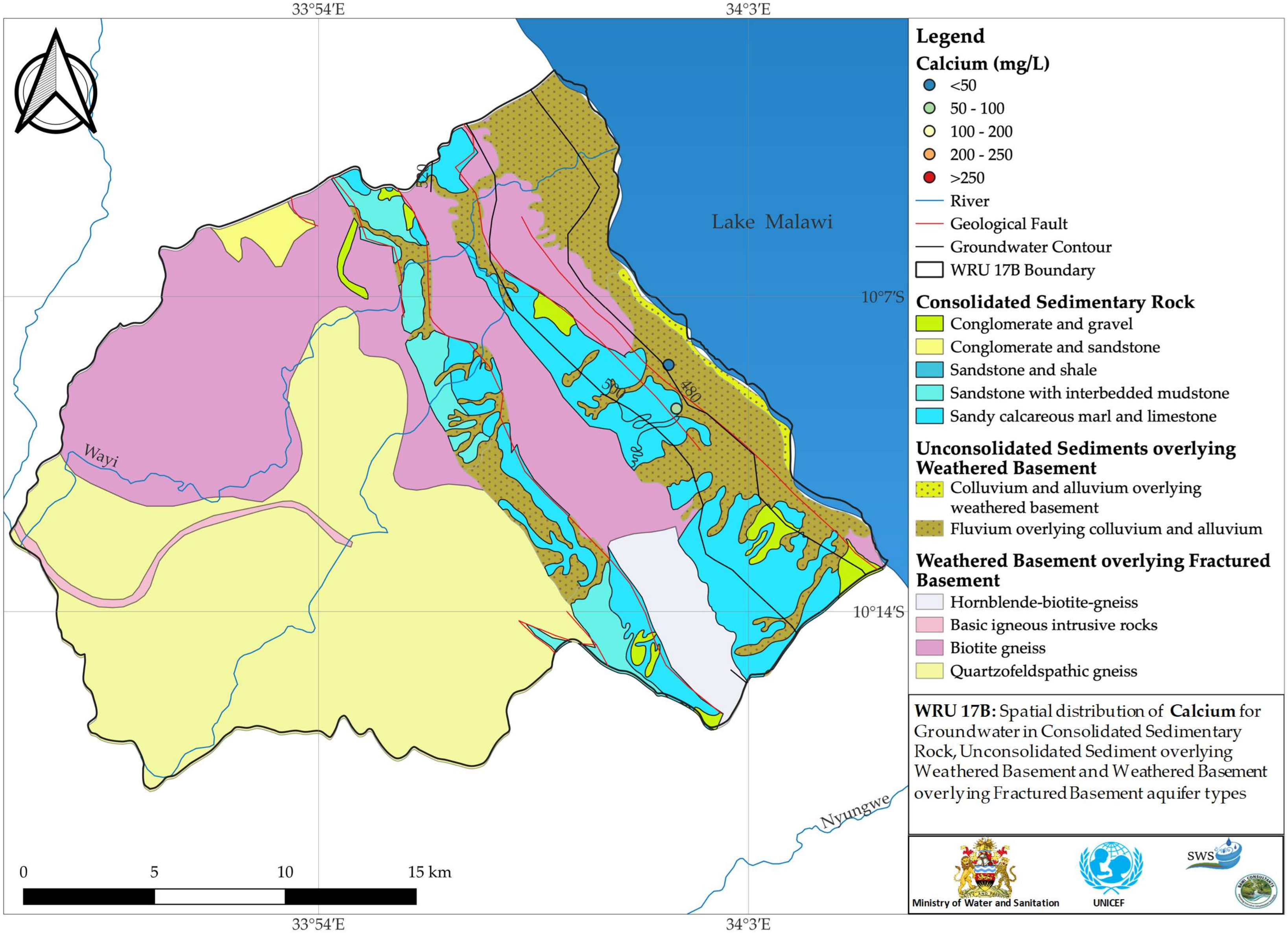


Figure WRU 17B.9 Piper Diagram of water quality results with respect to the major aquifer type

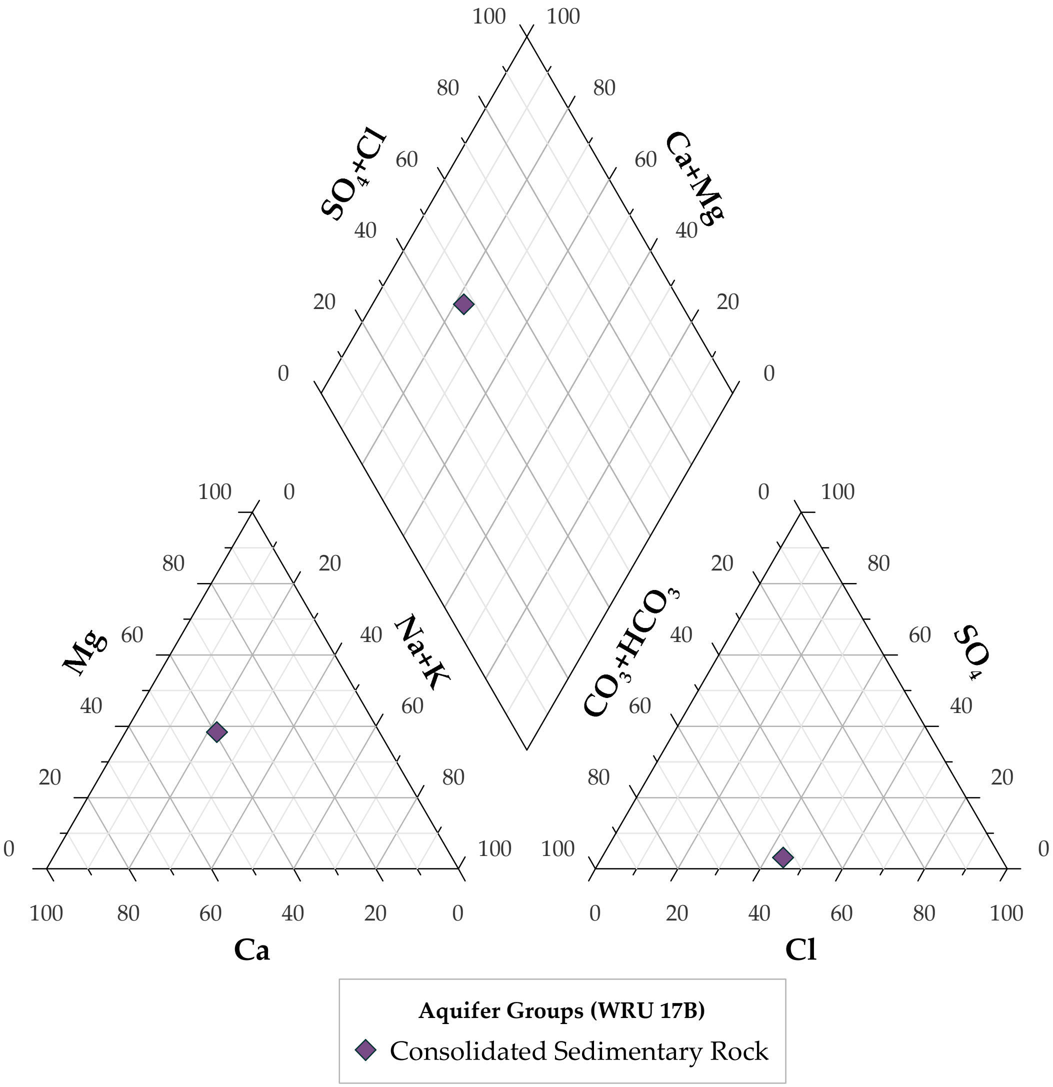
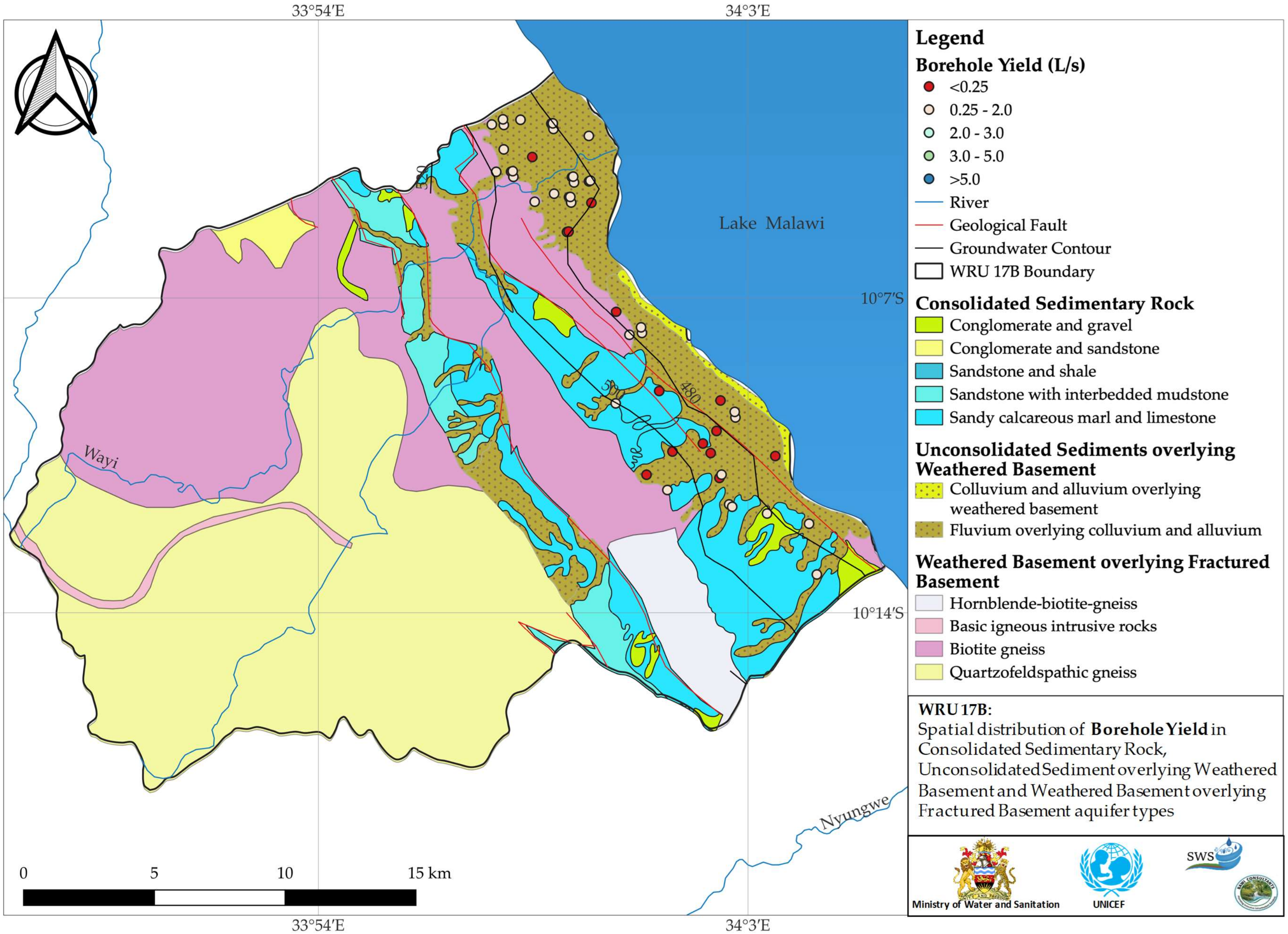


Figure WRU 17B.10 Borehole Yield Map for data held by the Ministry



WRU 17C Figures

Figure WRU 17C.1 Land Use and Major Roads

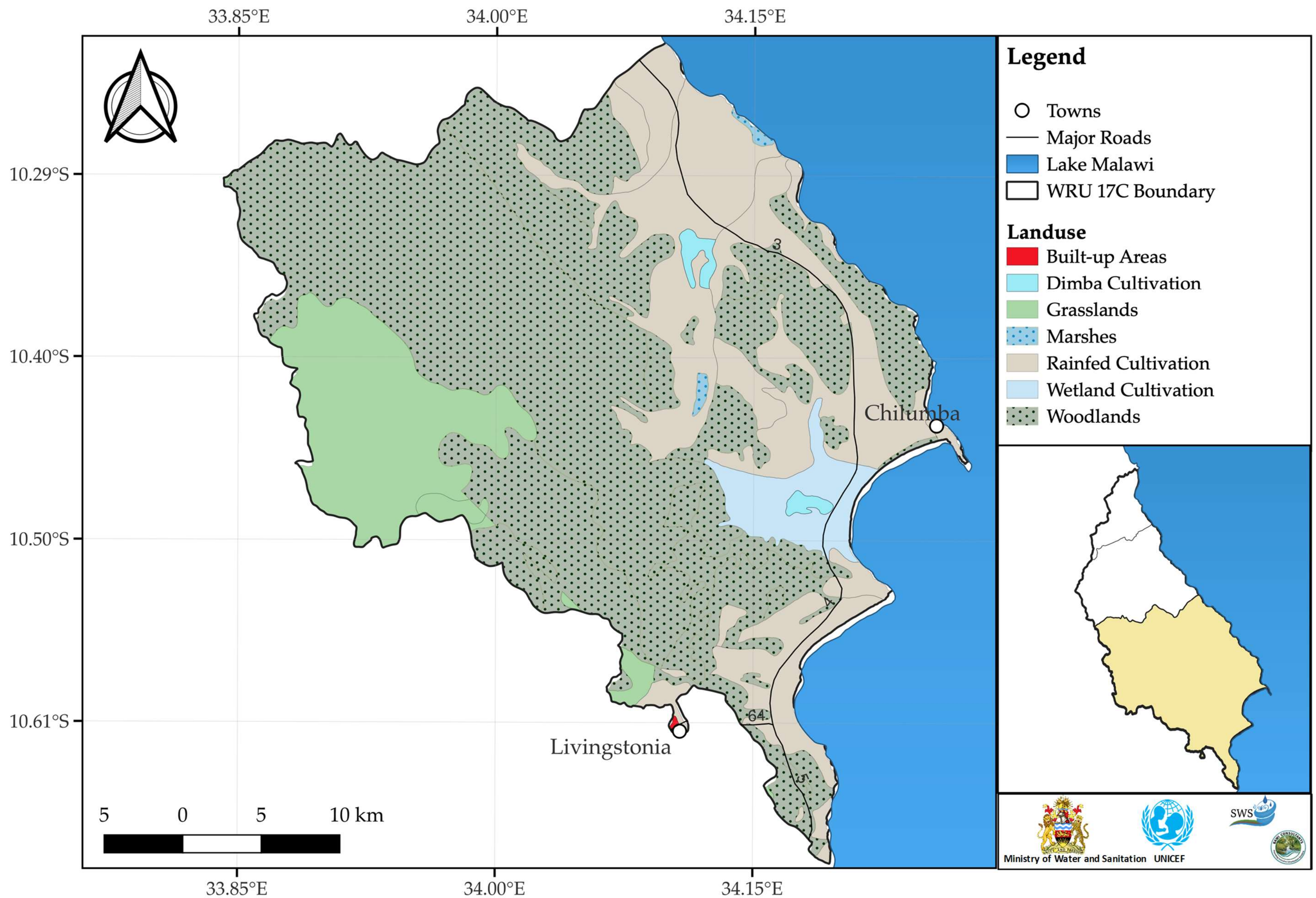


Figure WRU 17C.2 Rivers and Wetlands

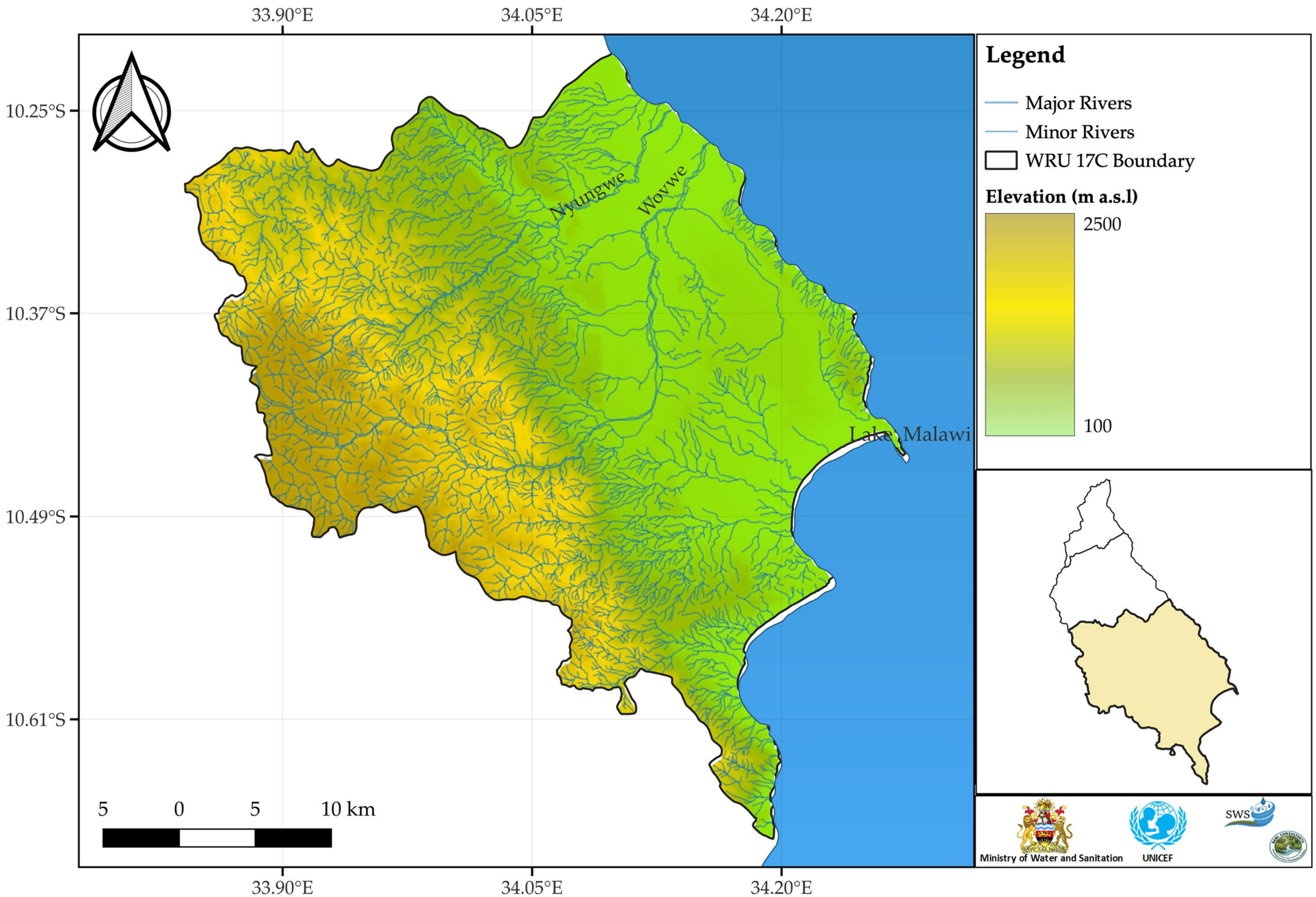


Figure WRU 17C.3 Hydrogeology Units and Water Table

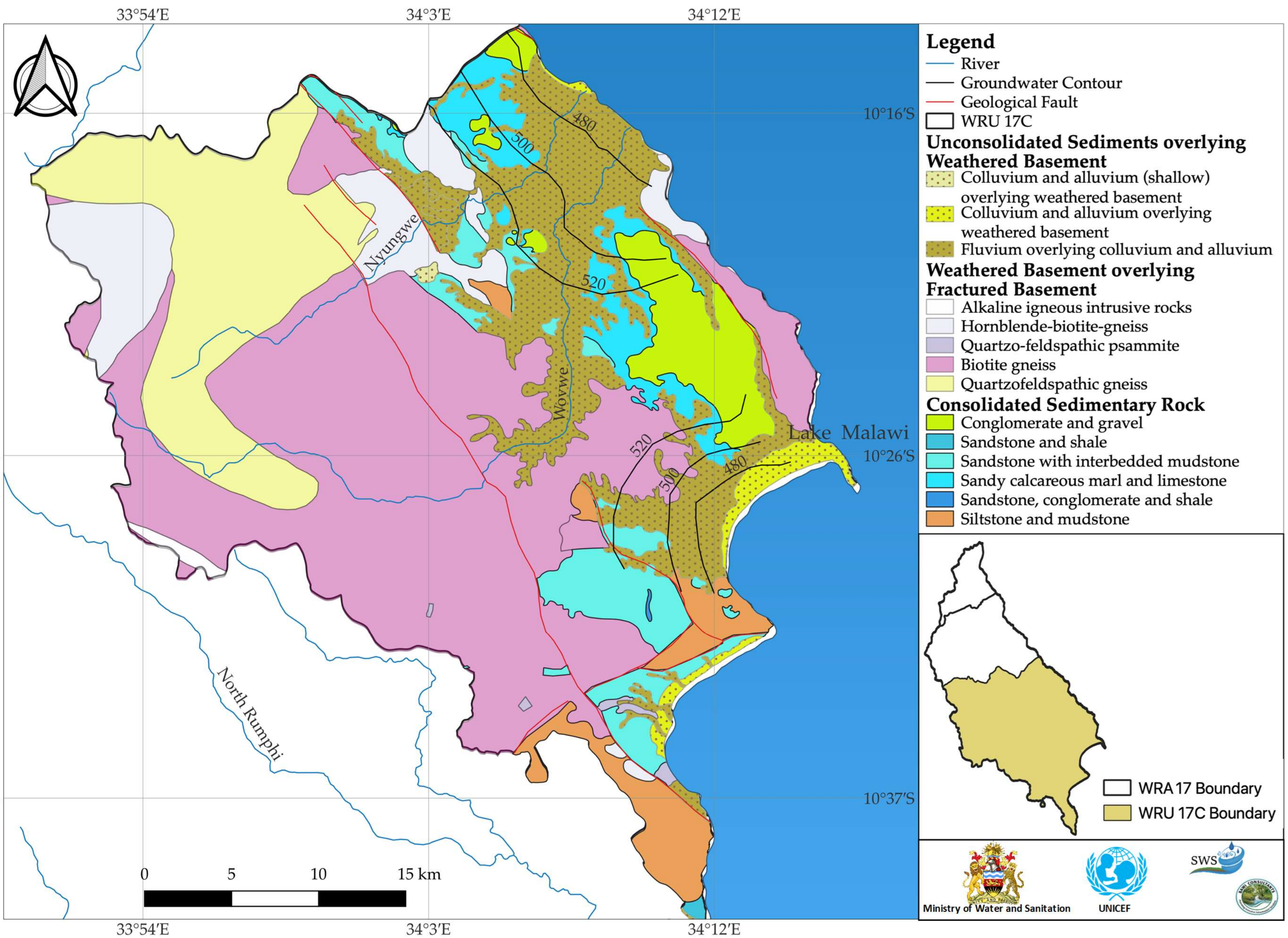


Figure WRU 17C.4 Groundwater Chemistry Distribution Electrical Conductivity

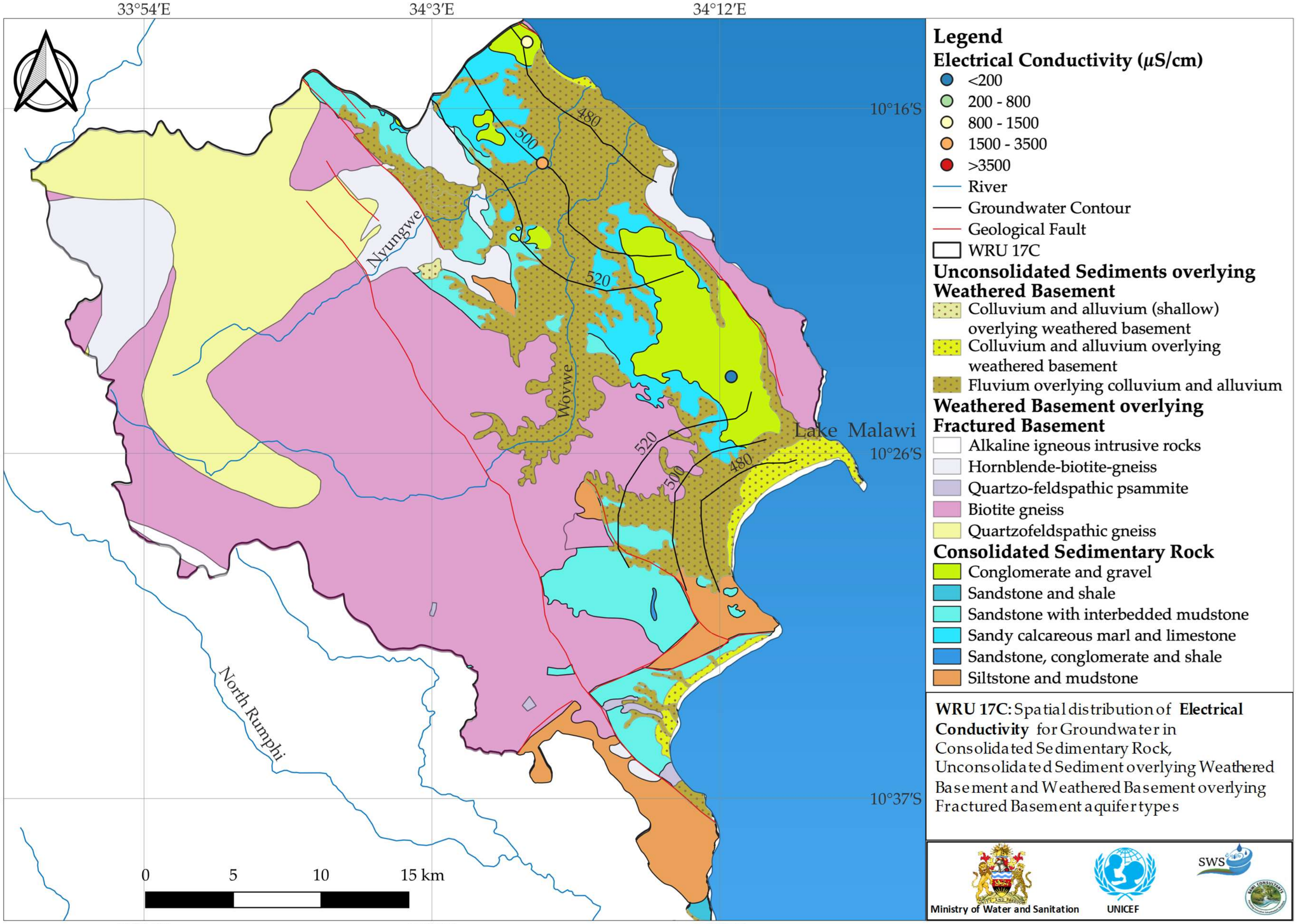


Figure WRU 17C.5 Groundwater Chemistry Distribution of Sulphate

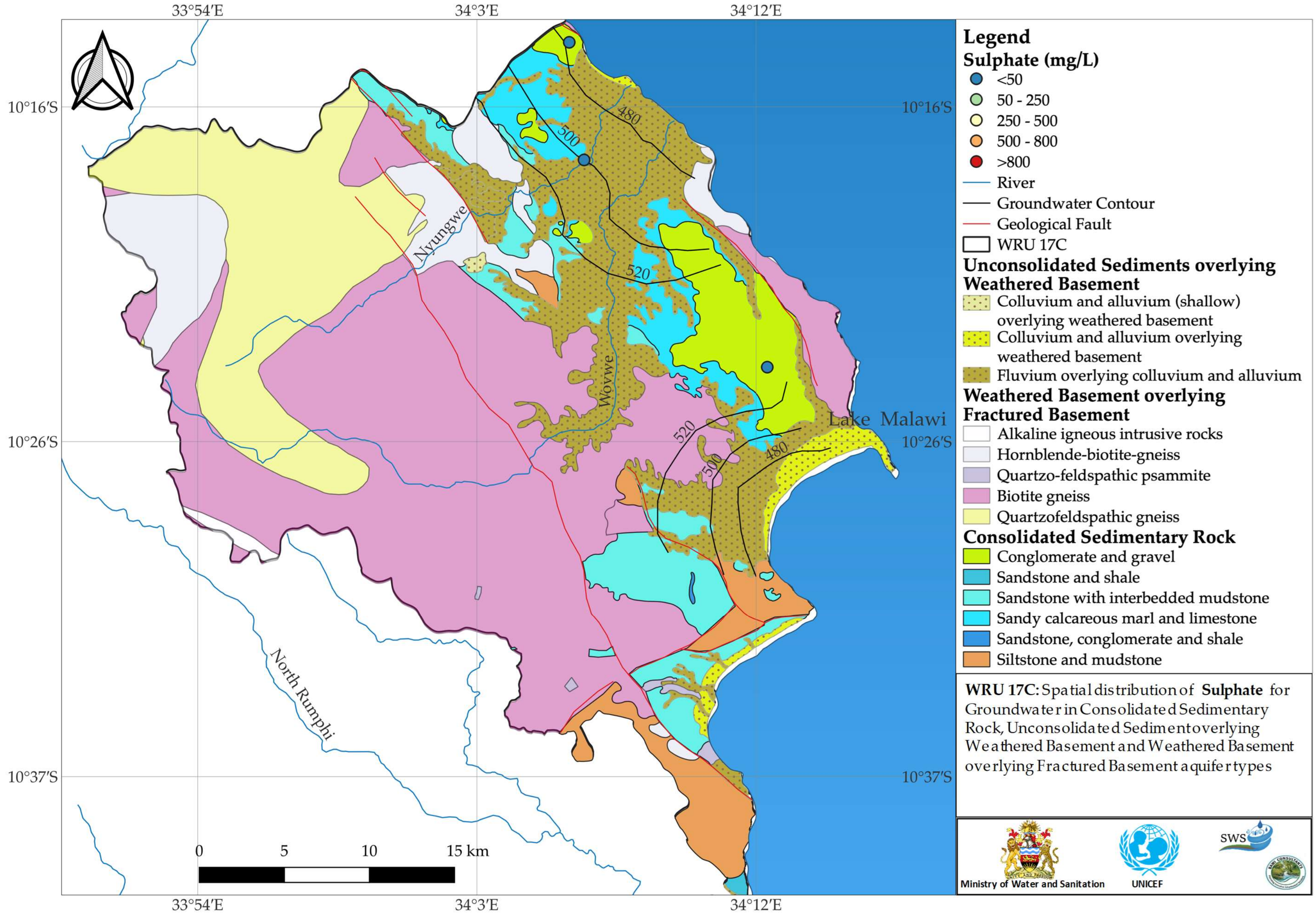


Figure WRU 17C.6 Groundwater Chemistry Distribution Chloride

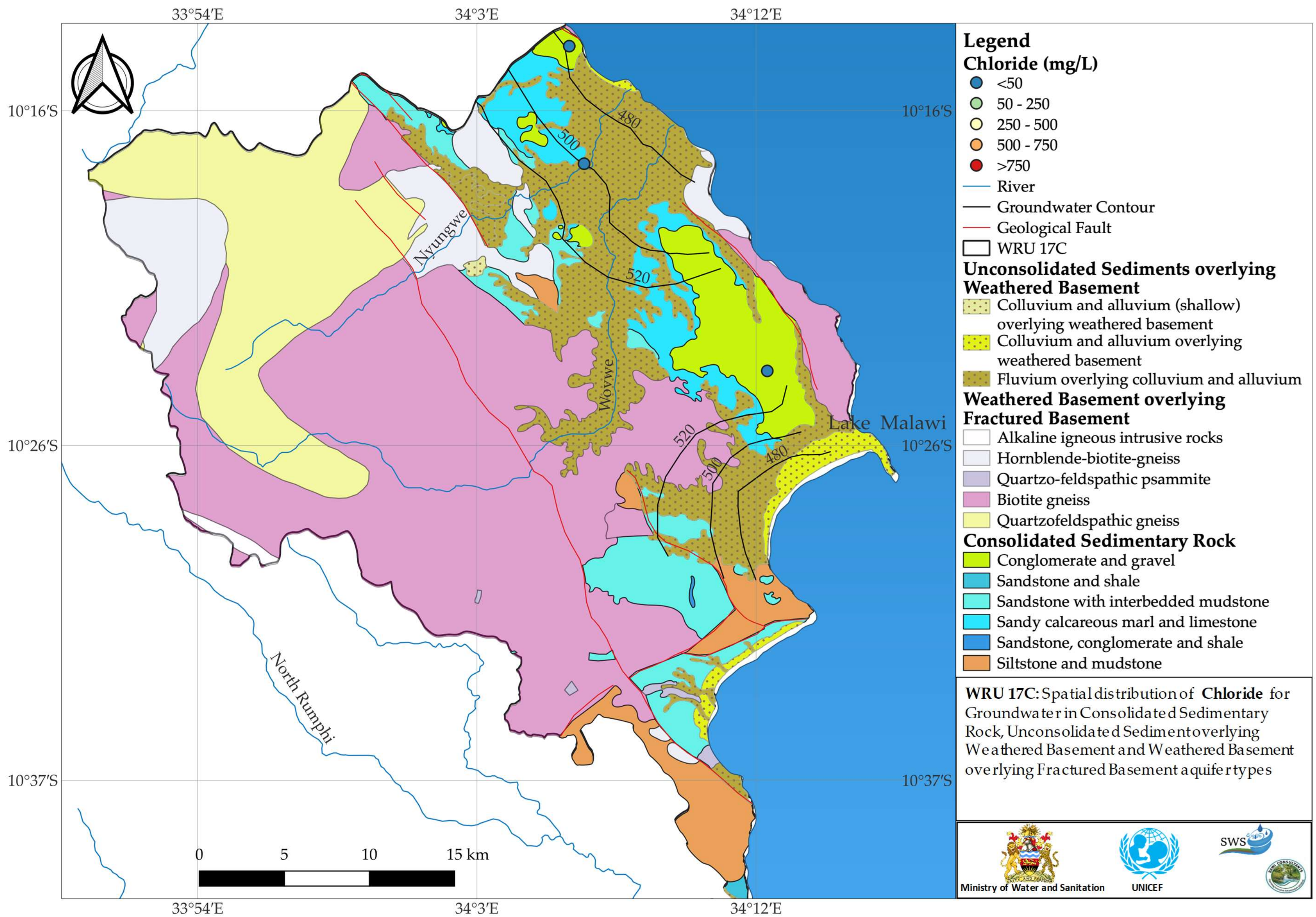


Figure WRU 17C.7 Groundwater Chemistry Distribution Sodium

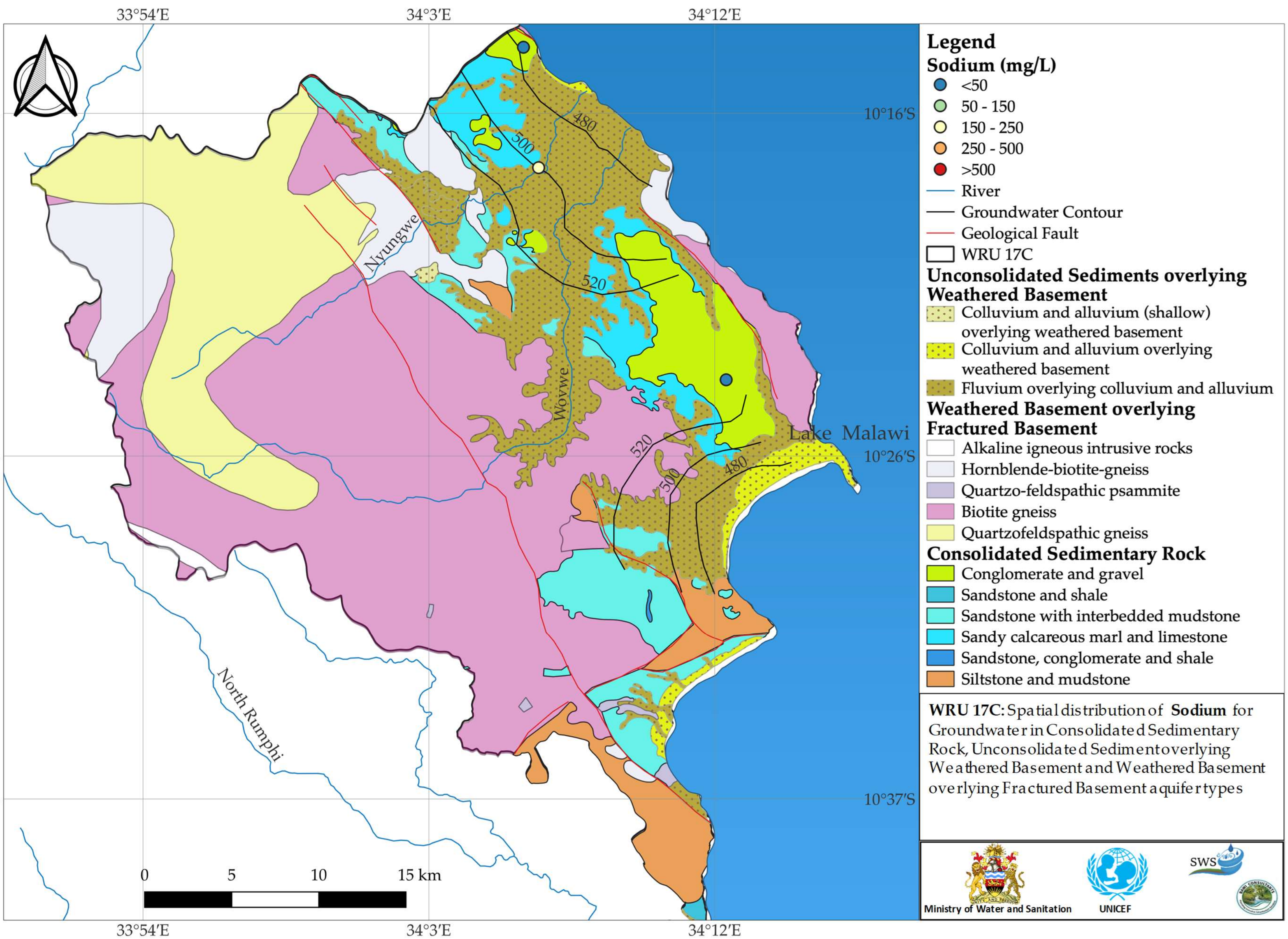


Figure WRU 17C.8 Groundwater Chemistry Distribution Calcium

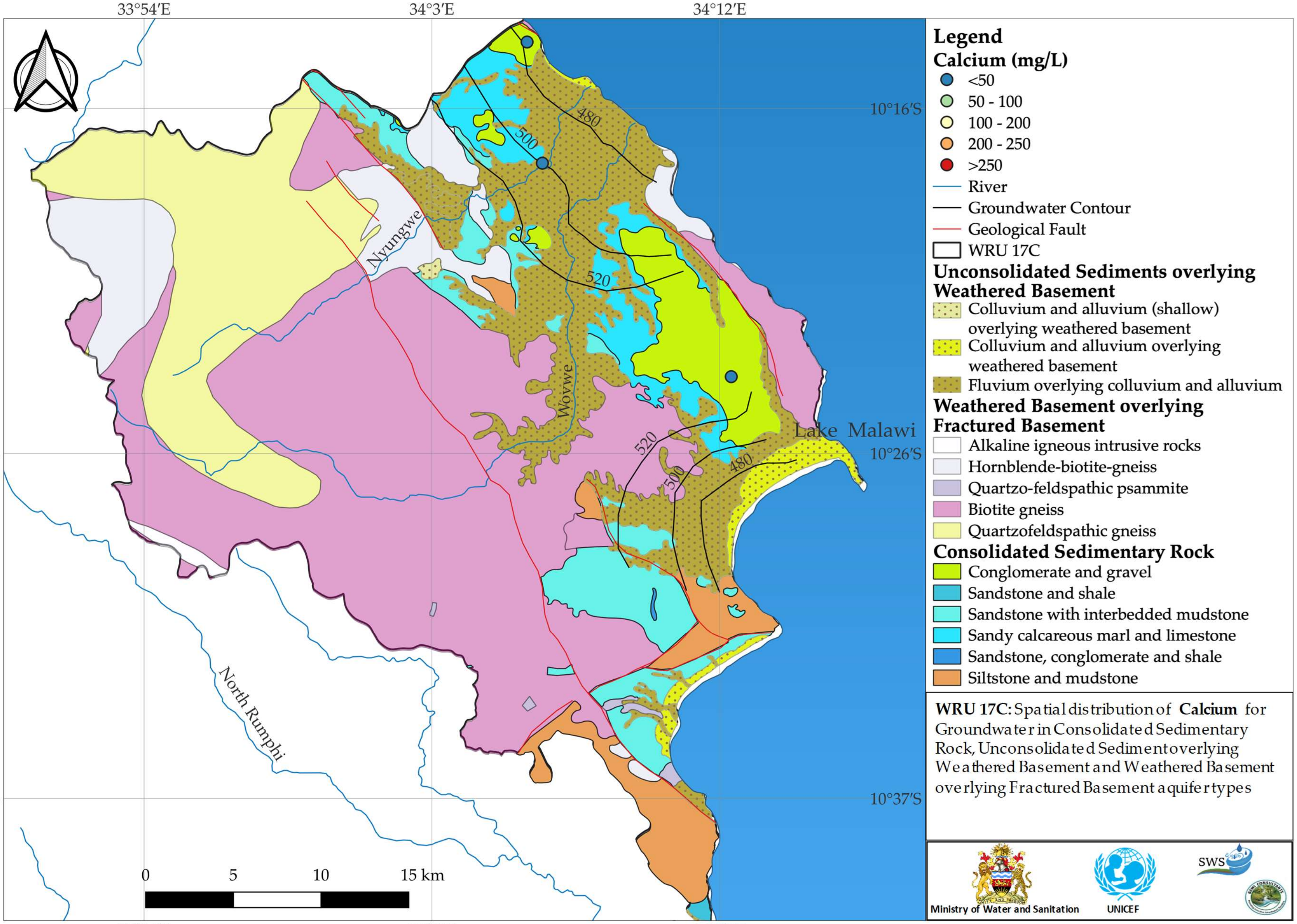
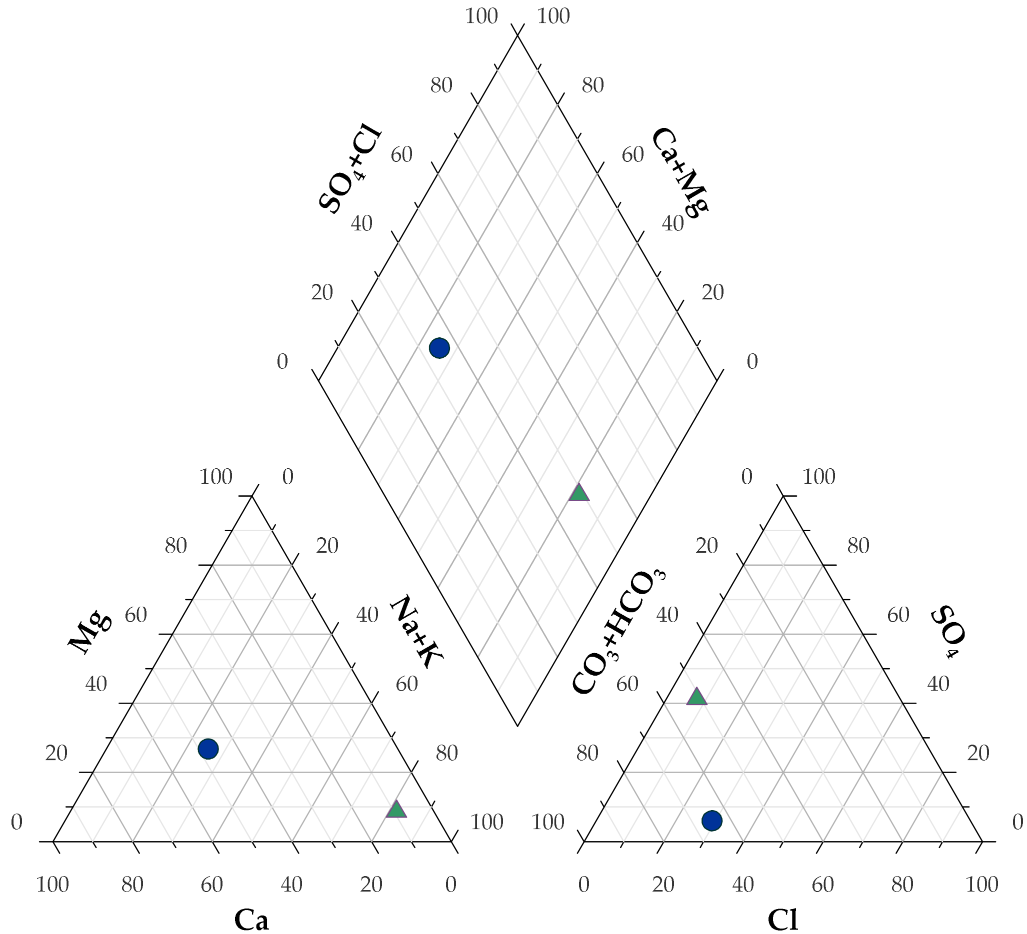


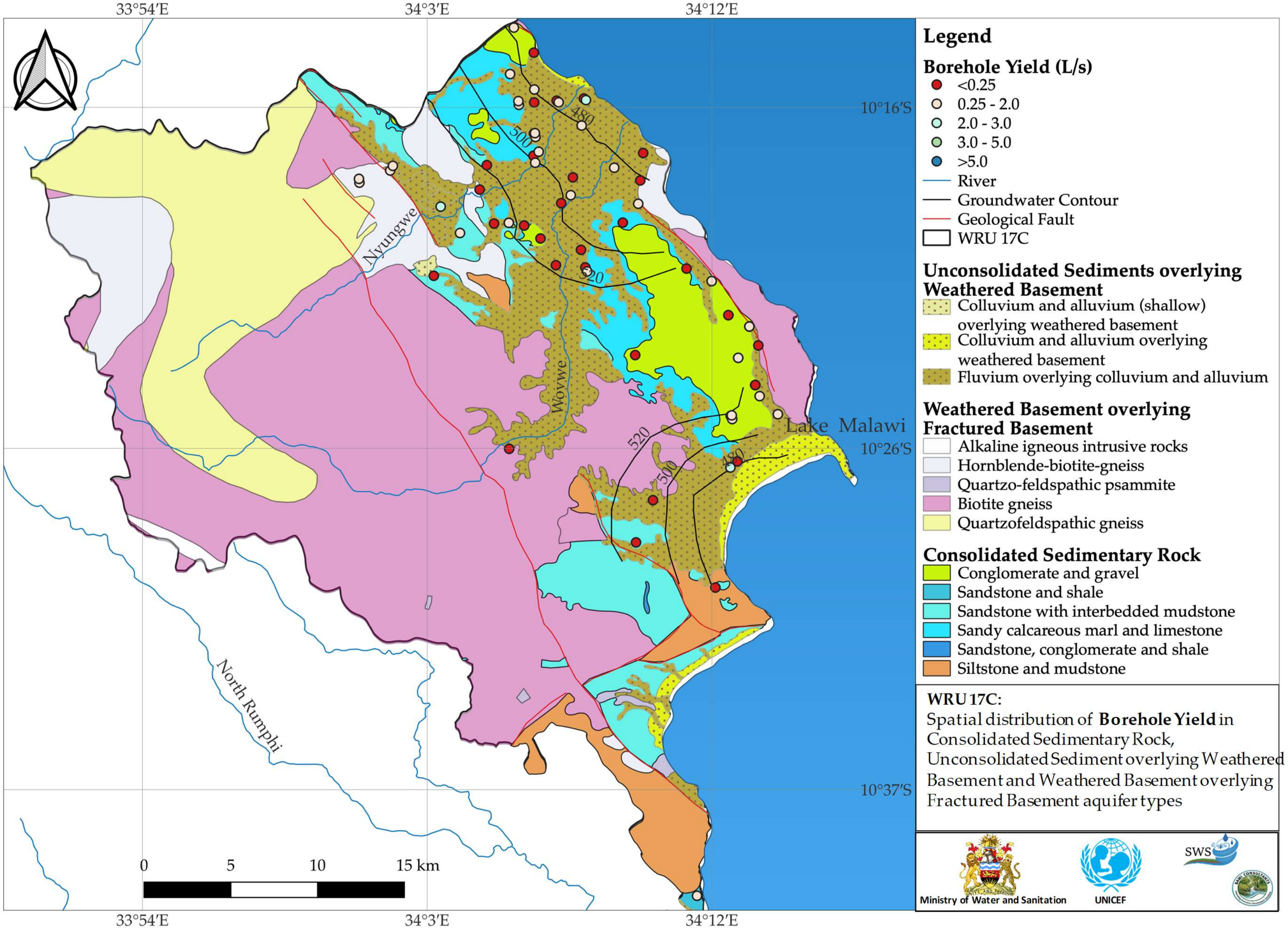
Figure WRU 17C.9 Piper Diagram of water quality results with respect to the major aquifer type



Aquifer Groups (WRU 17C)

- Consolidated Sedimentary Rock
- Unconsolidated Sediments overlying Weathered Basement

Figure WRU 17C.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, Karonga Lake Shore Catchement, Water Resource Area 17, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-16-1 69pp*