Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 8

The North Rukuru River 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
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 8 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.

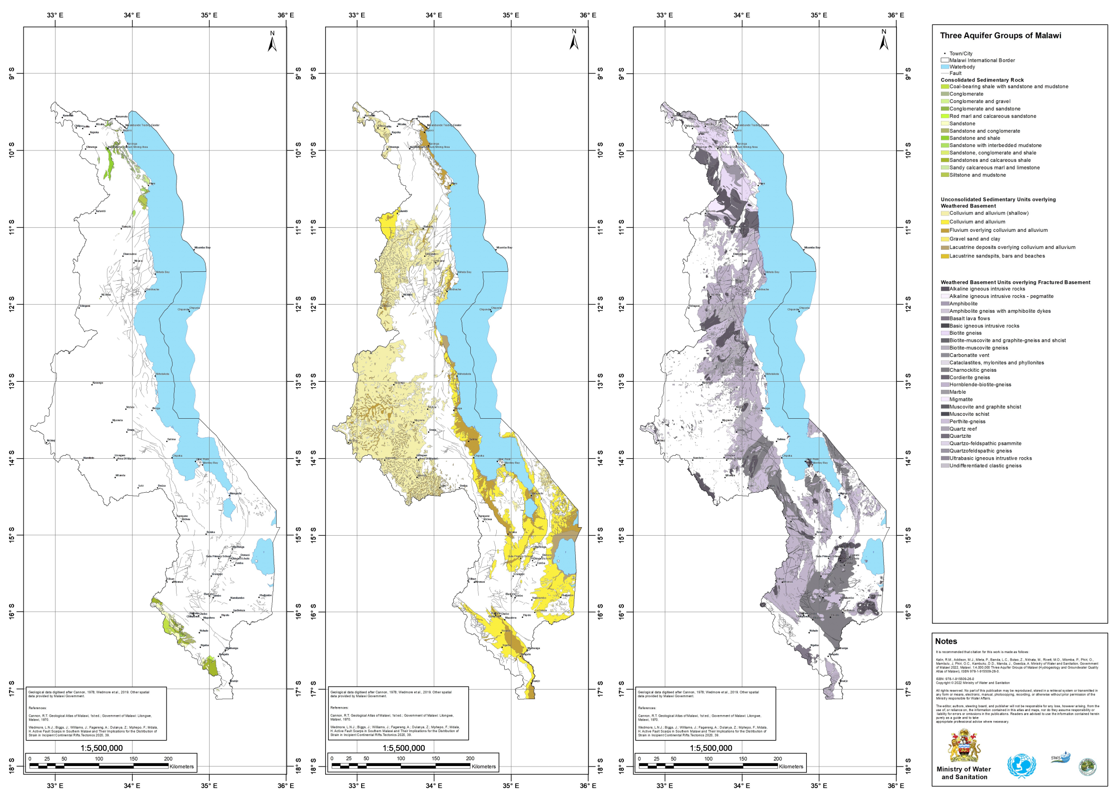


Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure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

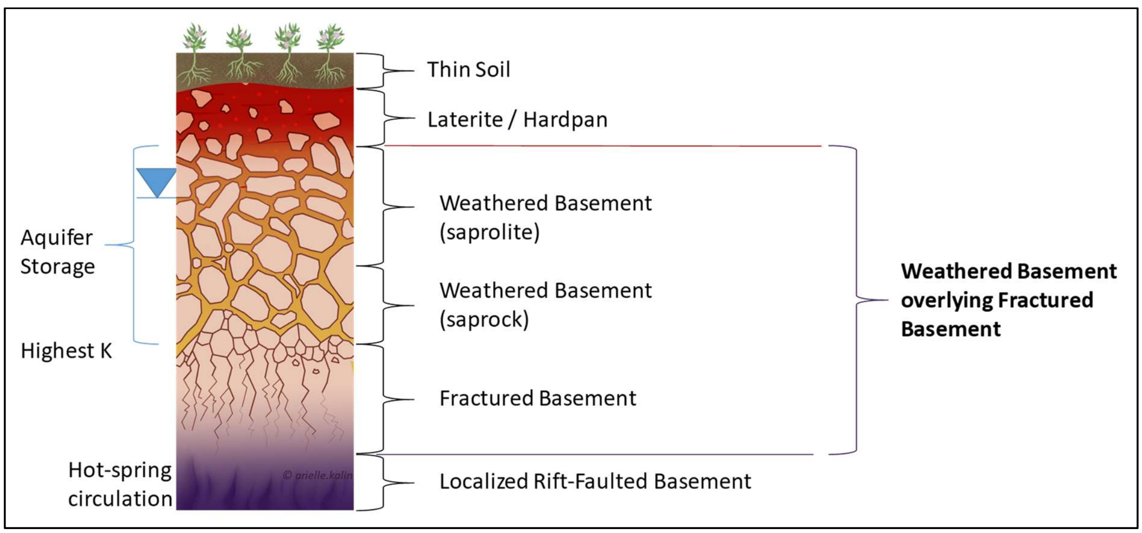


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

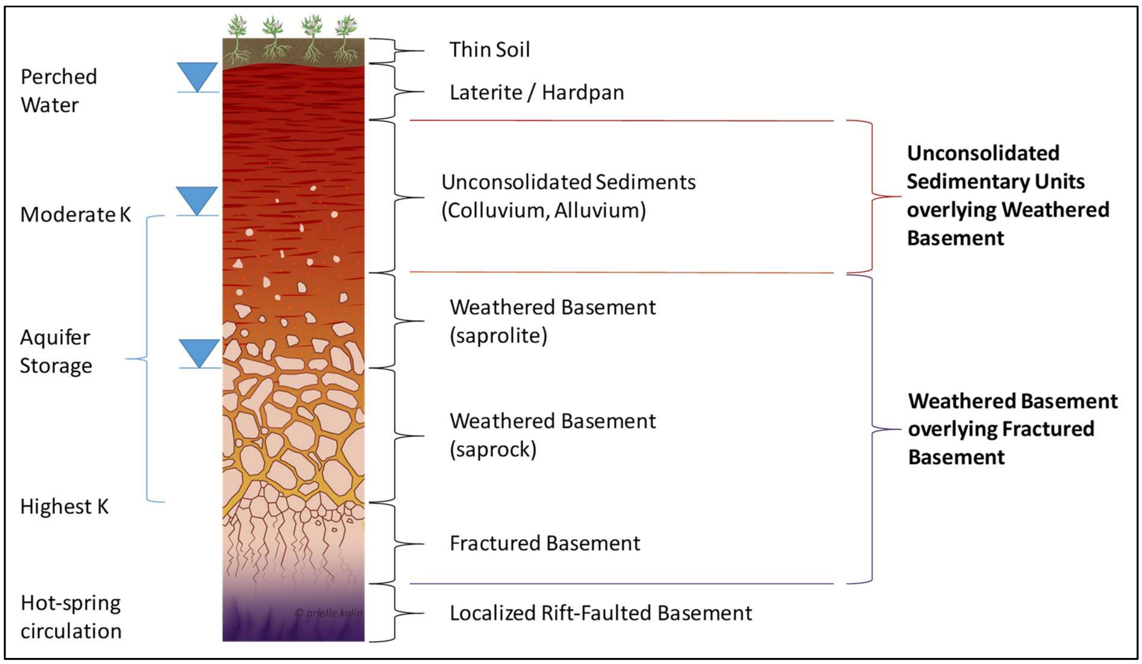


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

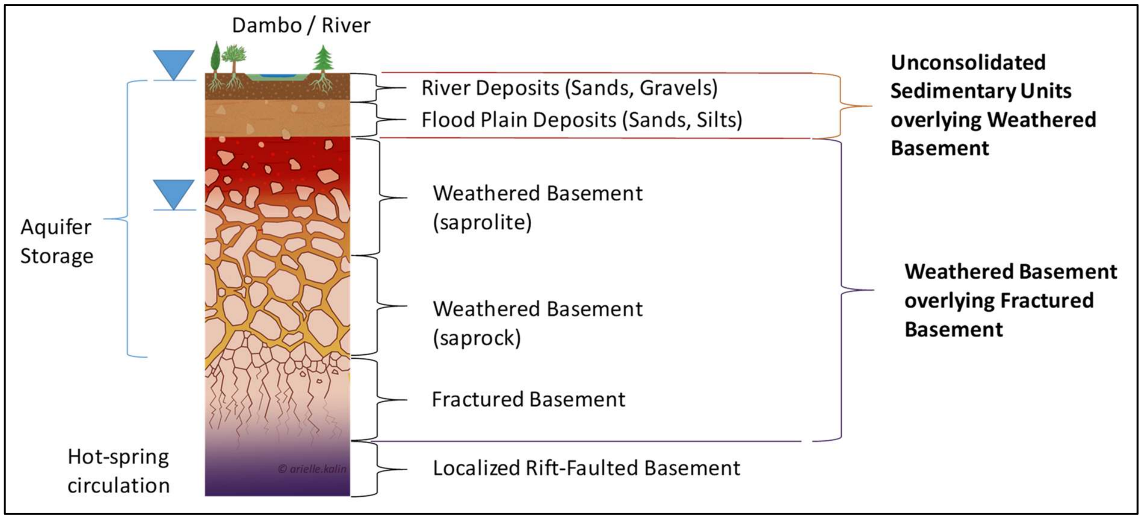


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

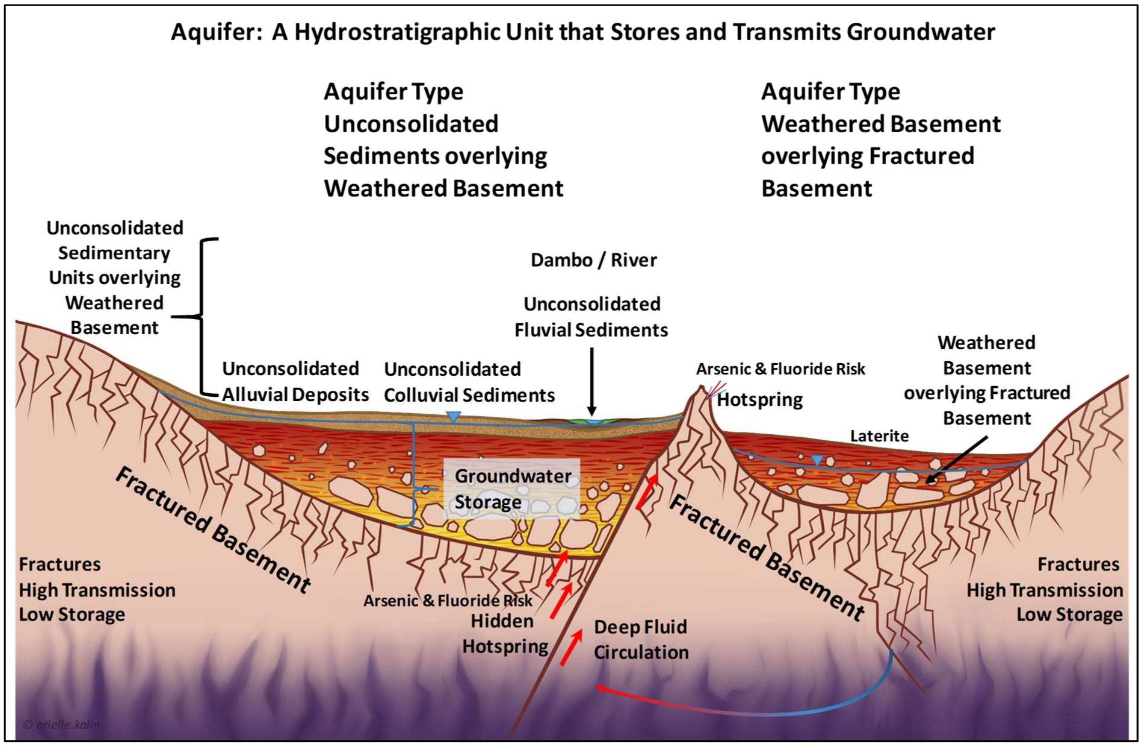


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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 8 (WRA 8): The North Rukuru River Catchment

Water Resource Area 8 in northern Malawi (**Figure 2a**), consisting of only one Water Resource Unit (WRU): WRU 8A (**Figure 2b**). It is mostly drained by North Rukuru River which emerges from Nyika Plateau lying at 2,400m asl, hence called North Rukuru River Catchment. The North Rukuru River drains an area of around 2,088 Km^2 constituting of populated forest areas, broad valleys spanning between 100 and 1,400m asl. As the river emerges from the forested and the mostly uninhabited areas, it sharply flows through a drop in elevation of about 500 m before it makes its course through a lake shore spanning between 450 and 500m asl. 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. Trans-boundary surface and groundwater bodies are found in WRA 8, but it does not directly border on Lake Malawi which is governed by Trans-boundary water sharing agreements. Therefore, consideration of transboundary water agreements should be included within Integrated Water Resources Management.

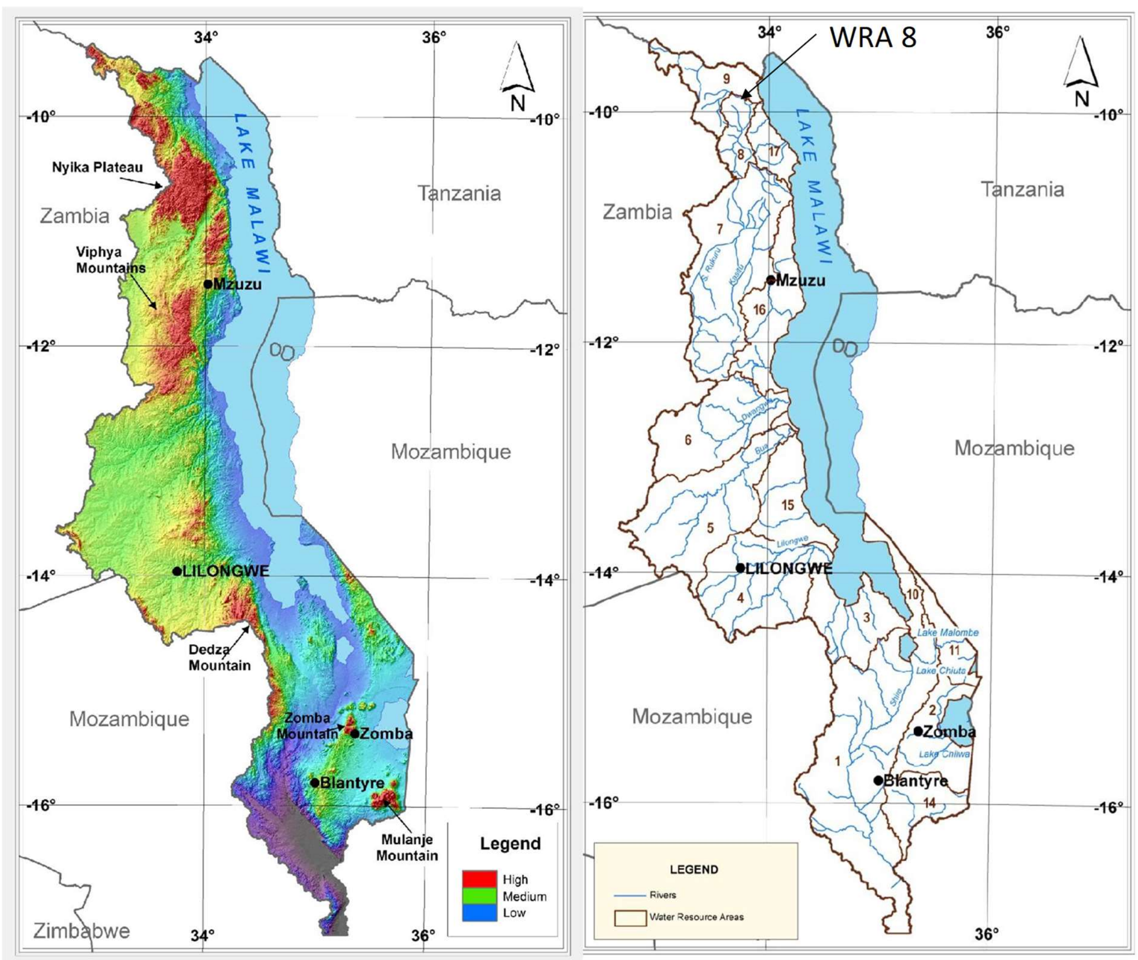


Figure 2a. Location of WRA 8 with major rivers and topography shown.

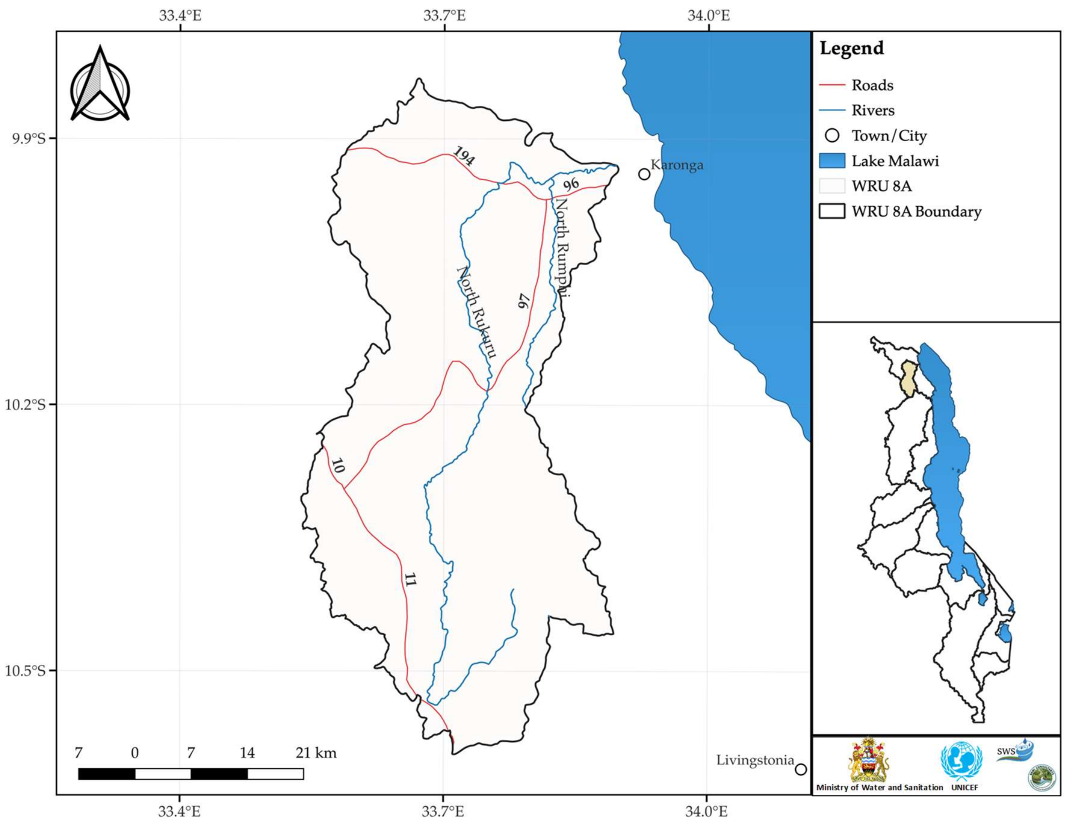


Figure 2b. Water Resource Area and Water Resource Units

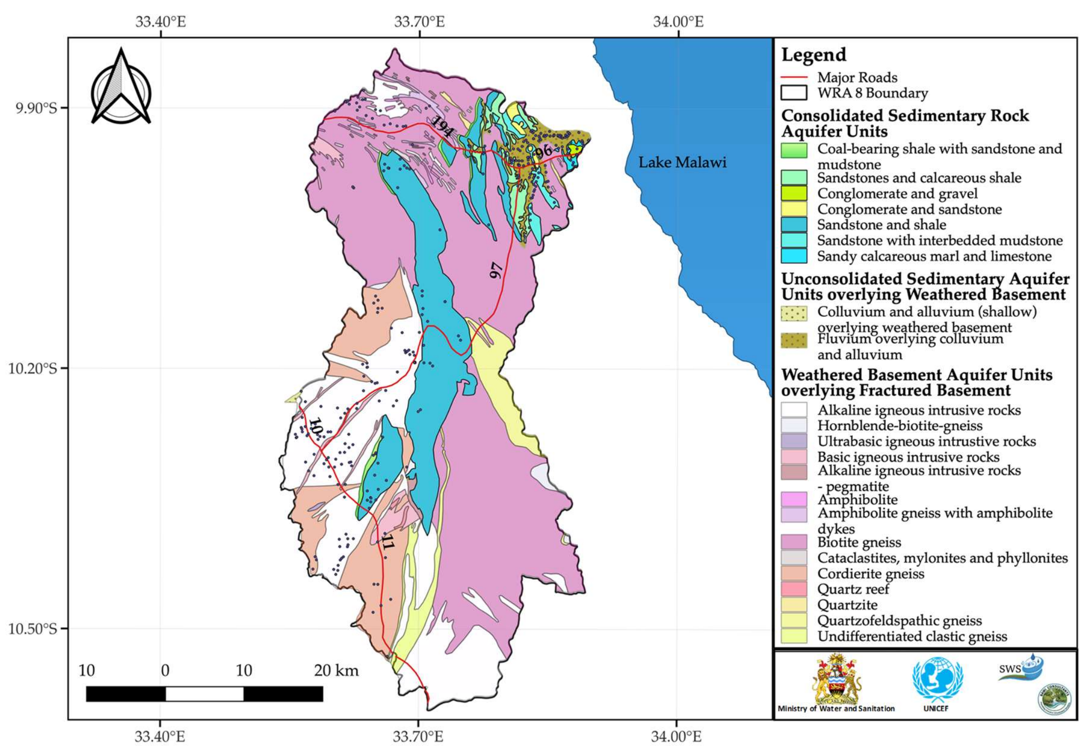


Figure 3. Distribution of groundwater abstraction points in WRA 8.

Groundwater Abstraction in WRA 8

Public abstraction points for groundwater are numerous in WRA 8 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 554 known groundwater abstraction points, 92.2% are improved sources. The dataset contains public water supplies that use groundwater and does not include non-standard unprotected household sources using rope pumps. 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 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 8, only 53.4% are fully functional (defined as providing water at design specification).

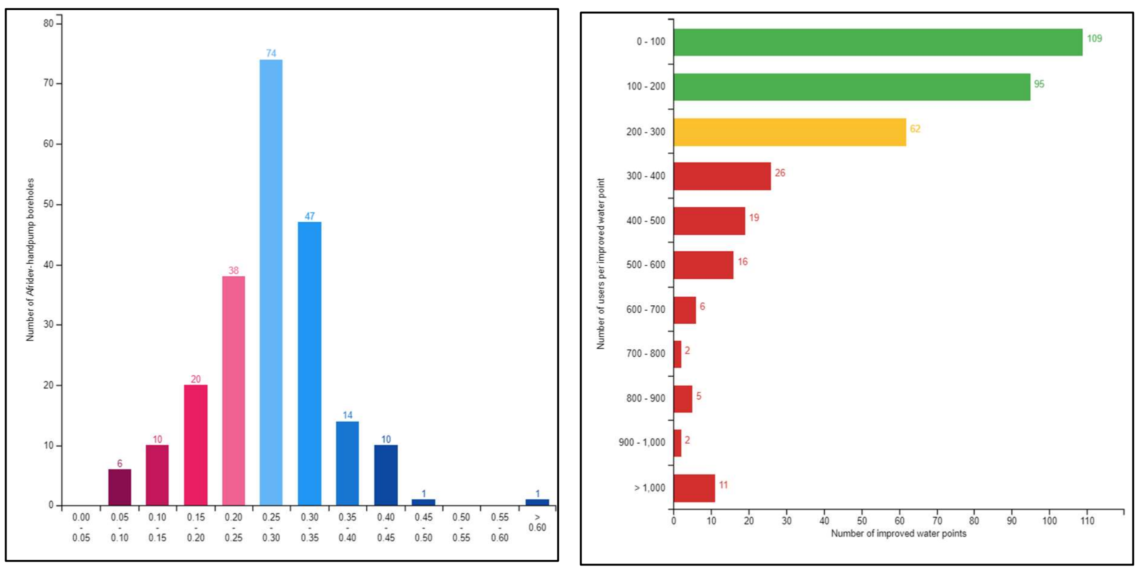


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 8 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point. [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 somewhat exceeded and there is an investment need to explore meeting guidelines in WRA 8 from a population point of view (likely through better routine maintenance). The preponderance of unregistered dug wells, in particular 'self-supply' points with rope pumps have an extreme contamination risk and may not meet the water quality guidelines, the WRA should be considered within investment planning and regulations that legally require self-supply payments for water quality testing.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 6.9% 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. There is a strong correlation between the depth of the groundwater water supplies and the decline in seasonal water availability, and is assumed this is due to shallow dug well supplies or improperly installed boreholes that are more at risk to lowering water tables resulting in lower functionality during the dry season.

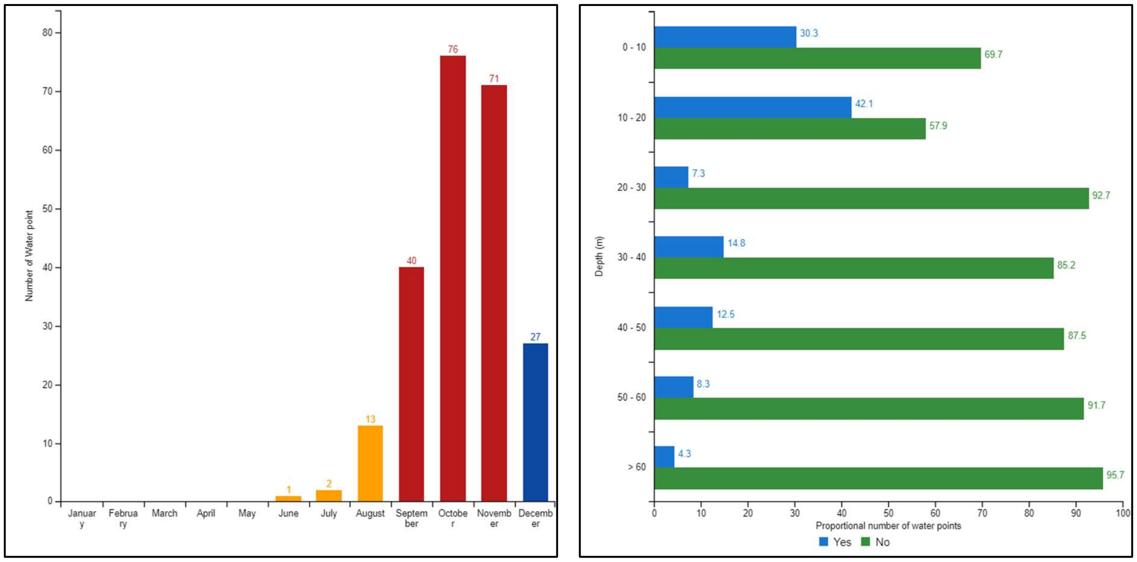


Figure 5a and 5b. Number of groundwater abstraction points in WRA 8 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

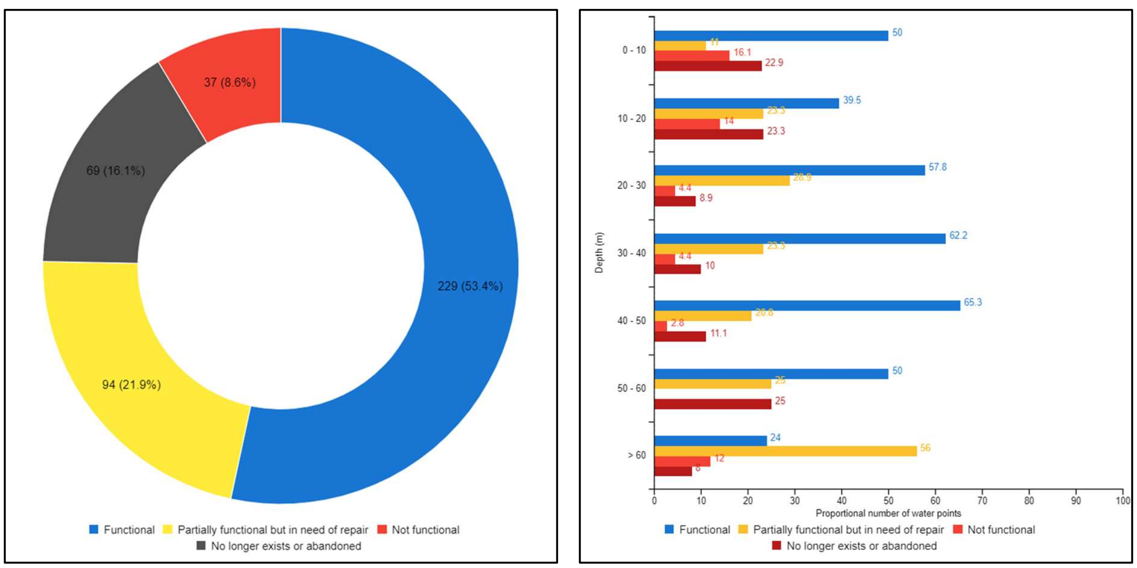


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 8 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water 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. There are only 53.4% of groundwater abstraction supplies which are operation at design parameters, and 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 8 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 8 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	350
Protected dug well	160
Protected spring	1
Unprotected dug well	36
Unprotected spring	7

Description of Water Resources WRA 8

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 Water Resource Area (WRA) 11 in southern Malawi constitutes one Water Resource Unit (WRU); WRU 8A (**Figure 7**).

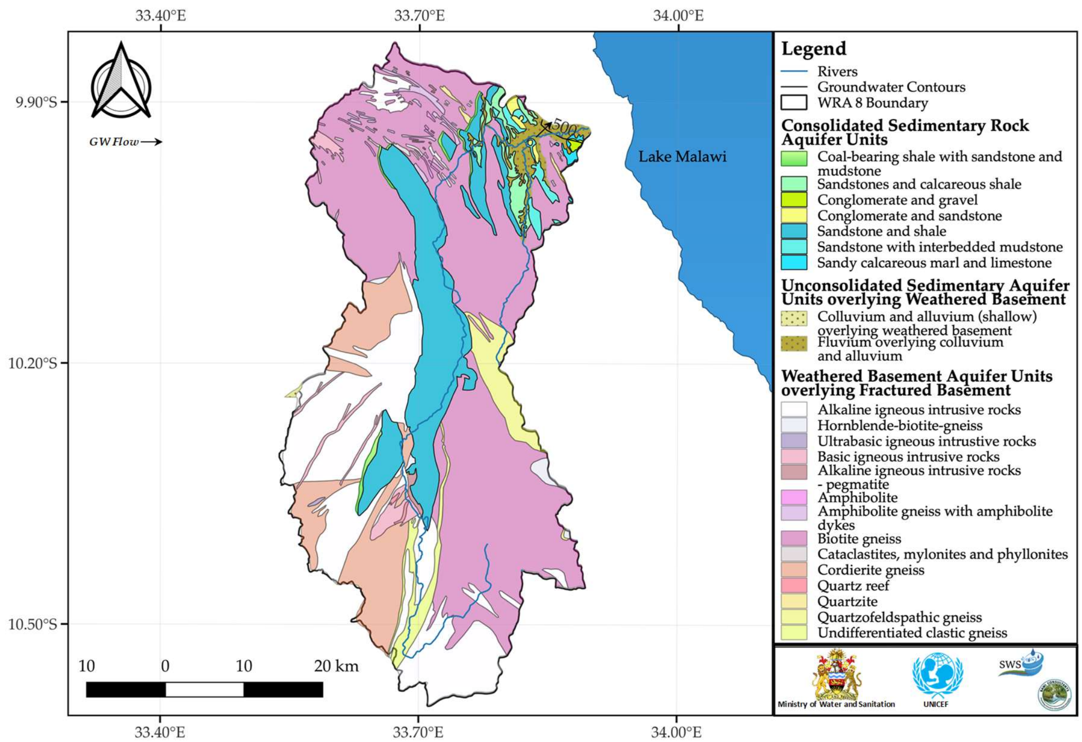


Figure 7. Map showing the hydrogeologic units and water table for Water Resource Unit 8A wtihin Water Resource Area 8 (North Rukuru River Catchment).

Water resources consumptive use is dominated by rural water supply schemes such as Nthalire and Karonga rural water supply. The main users of water in North Rukuru River basin are Karonga water supply and Nthalire rural water supply. General groundwater flow is from the western highlands toward the lake in the east. The catchment, and groundwater, are Trans Boundary and therefore IWRM management and planning must include inclusive discussions at a regional level.

Topography and Drainage

Highlands occupy the south-eastern part, lowlands in north-eastern part, with midlands mostly occupying central and western part of the catchment. WRU 8A, is mostly drained by North Rukuru River which emerges from Nyika Plateau lying at 2,400 m asl, hence called North Rukuru River Catchment. The North Rukuru River drains an area of about 2,088 Km^2 constituting of populated forest areas, broad valleys spanning between 100 and 1,400 m asl. As the river emerges from the forested and the mostly uninhabited areas, it sharply flows through a drop in elevation of about 500 m before it makes its course through a lake shore spanning between 450 and 500 m asl. (**Figure 8**). The catchment has huge potential for socioeconomic development being an active local and international trade hub (mostly with Tanzania), located on a major transport route, with fertile flood plains especially at North Rukuru River estuary.

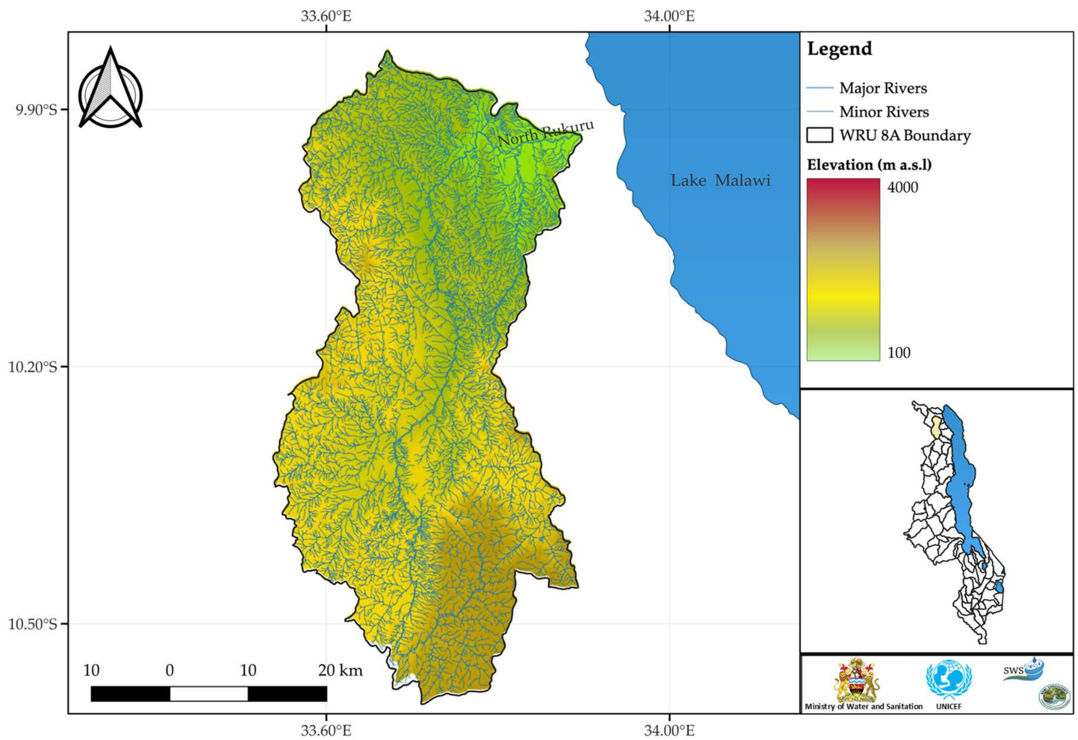


Figure 8. Drainage for the major rivers in Water Resources Area 8.

Geology – Solid

WRA 8 solid geology is dominated by a complex and highly deformed mix of Precambrian to Lower Palaeozoic basement rock and Permian to Triassic consolidated sedimentary rocks of the Karoo Supergroup (**Figure 7**). The area is bordered by the Zambia border to the west and a series of large normal faults to the east. High grade metamorphic basement rocks are composed of predominantly cordierite-silliconite gneiss and quartz with muscovite. Gneissic foliations strike WWN-EES dipping 50-75° N and NNE. Karoo sedimentary rocks occur in narrow, north-trending fault basins and comprise the Mweisa beds: a sequence of clastic sediments of grits, carbonaceous shales, limestones, mudstones and coal.

Geology – Unconsolidated deposits

Topography is uneven and where it is low, residual deposits and colluvium occur of unknown thickness. River alluvium, lacustrine deposits and dambo soils occur in the lower elevations. Fluvial deposits of unknown character require hydrogeological mapping.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 8. These values are used to calculate the annual estimated groundwater recharge in each WRU.

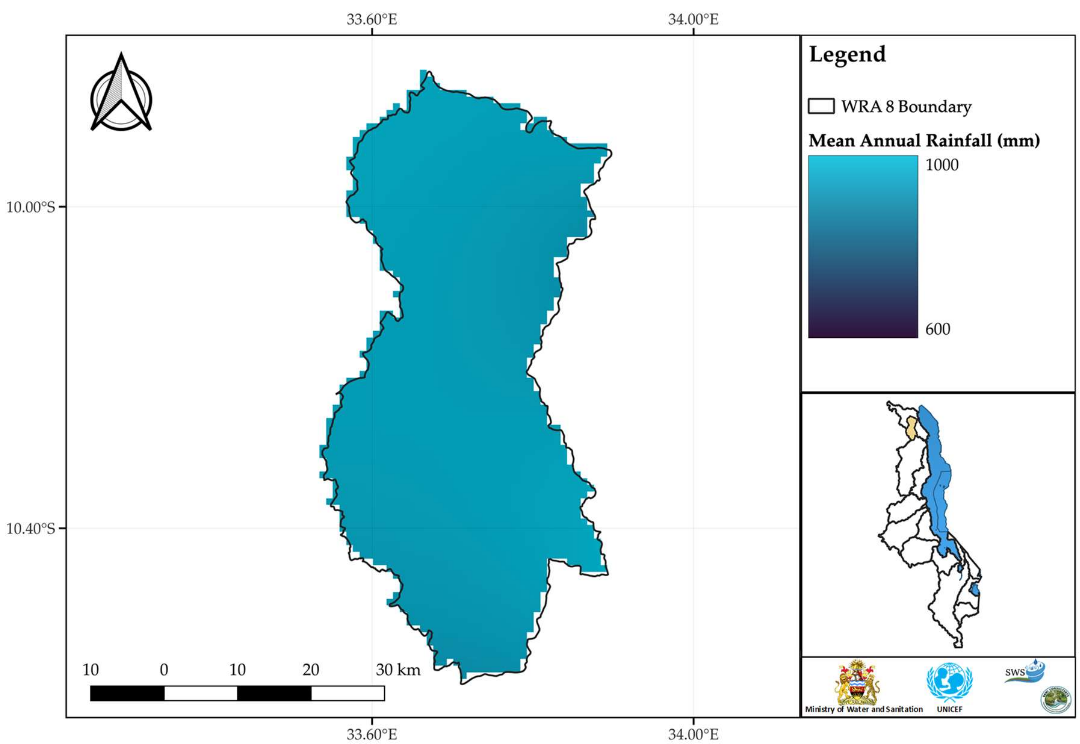
WRA	WRU	Station Names	Mean Rainfall-Station Data	Mean Rainfall-Interpolated Data (IDW)
8	A	- No Station -	-	921

Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 8 with the location of weather stations. Average rainfall measured is estimated at 900mm, average rainfall modelled is 921 +/- 11mm (range 881 to 952mm).

Climate

Climate in the area is subtropical with dual seasons: rainy season (November to May) and dry season (June to October). There is no full-time meteorological station with data available for the period 1999-2019 but existing data shows the catchment receives low rainfall of about 900 mm annually, and average temperatures span between 24.4 ± 5.2 °C. (**Figure 9**).

Land use



WRA 8 Land use is mainly by open woodlands and plantation, followed by rain fed cultivation on western side and delta area as the North Rukuru River flows towards Lake Malawi.

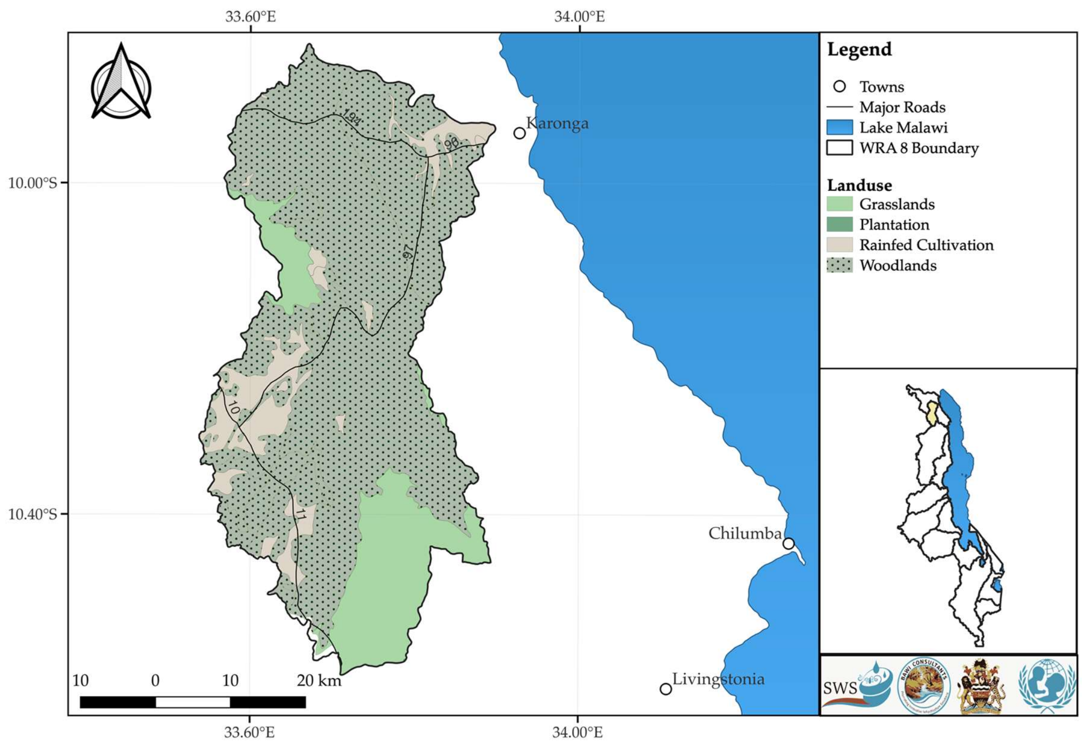


Figure 10. Land use in WRA 8 is dominated by rain fed cultivation.

Hydrogeology of WRA 8

Aquifer properties

Groundwater abstraction is focused around population centres in the uplands and near the western rift valley / Lake Malawi approach. In the uplands groundwater supplies are predominantly in the saprolitic zone of weathered basement overlying fractured basement. Near Lake Malawi colluvium, fluvial and lacustrine sediments overlying weathered and fractured basement provide groundwater resources. Detailed drilling logs and sedimentary analysis were not available for this study and there is a need to link existing records with geospatial coordinates to enhance hydrogeological interpretation of aquifer units.

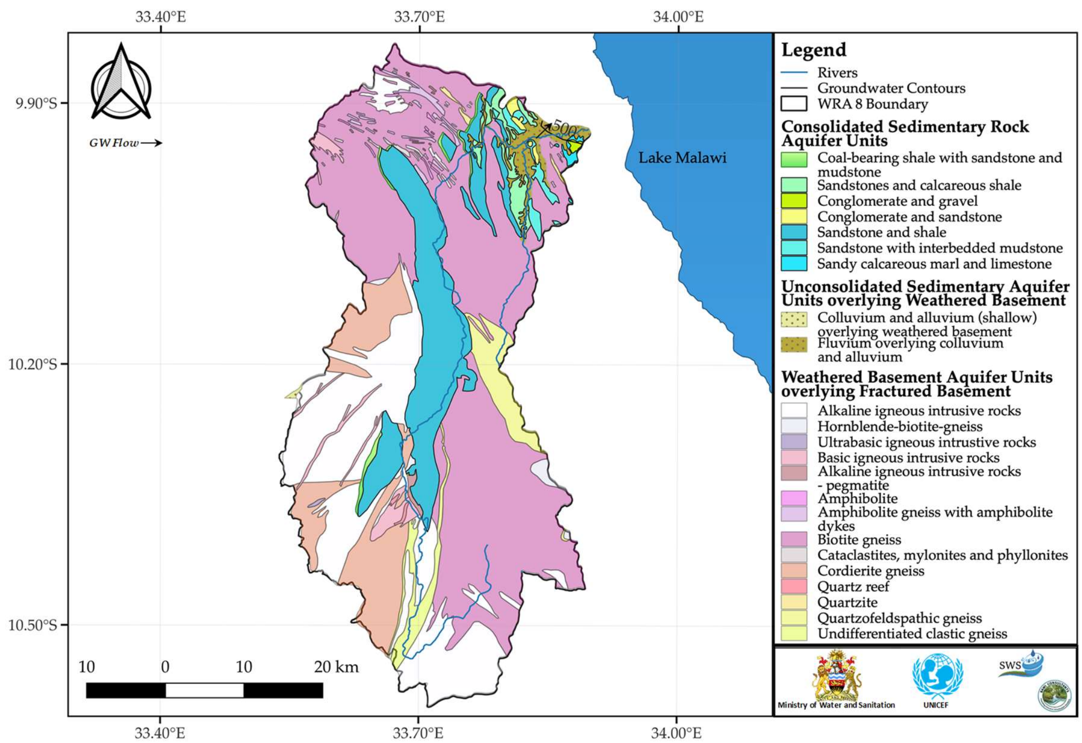


Figure 11. Groundwater level contours and flow direction in WRA 8 [1987 Hydrogeological Reconnaissance data] [water level contour interval 20m]

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 data, therefore groundwater level data for WRA 8 is based on prior hydrogeological reconnaissance.

Groundwater level data for WRA 8 based on prior hydrogeological reconnaissance was limited and restricted to the Lake Malawi lakeshore unconsolidated aquifer sediments (**Figure 11**). The catchment narrows at the lakeshore focused on the North Rukuru river estuary area where the lowland deposits extend to around 10 km inland. Hydraulic gradients calculated from the 500 m and 480 m asl contours (latter contour not shown) are around 0.004 to 0.009 giving groundwater velocities of 7 – 16 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2. Significant convergence of head contours on the river suggest groundwater base flow discharge to the North Rukuru is high, and increases up the river valley draining the surrounding steep topography, fractured Basement. The groundwater in WRA 8 should be considered a Trans-boundary water resources and it is recommended it should be evaluated within international water resource agreements.

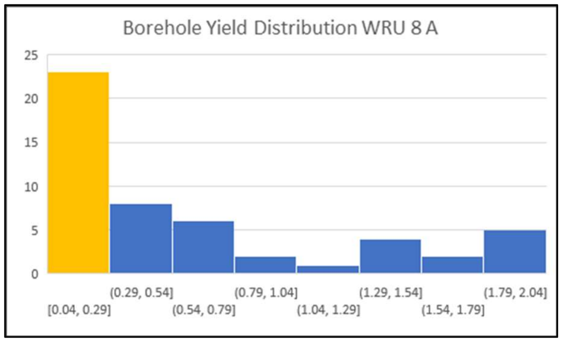


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 8 (y axis = *n* observations).

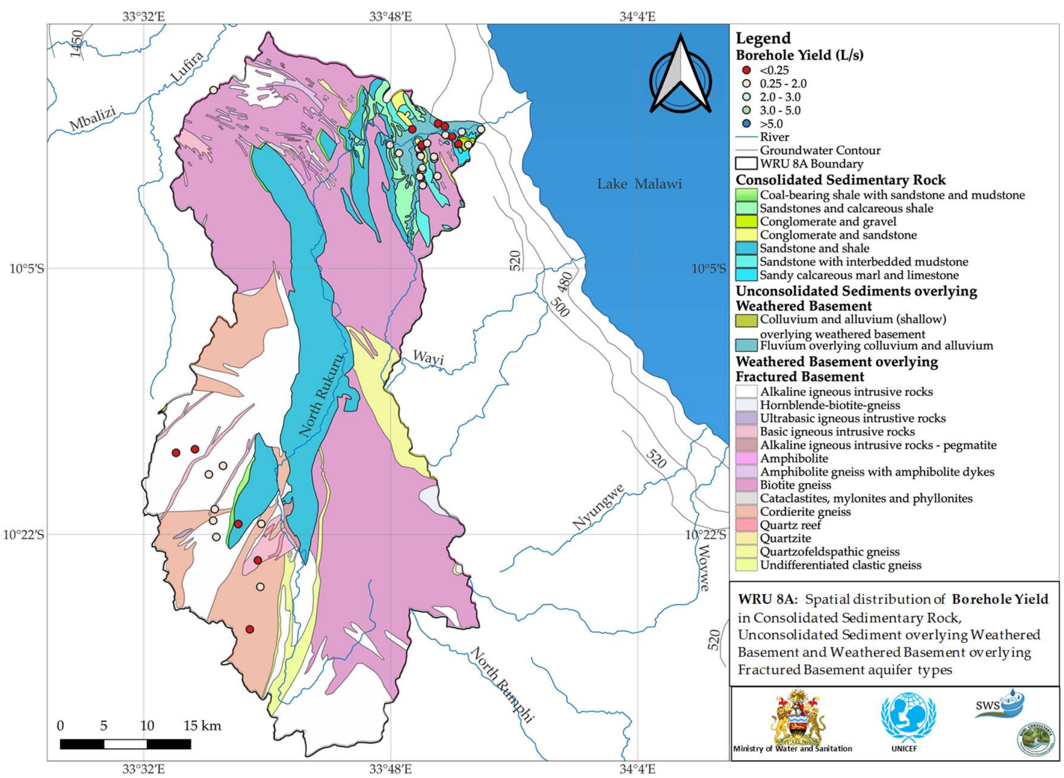


Figure 13. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 8A.

Aquifer / Borehole Yield

In 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 13** 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. The number of values in this range is suspect and likely represents substandard well construction for 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. However, in WRA8 there appears to be a trend to higher borehole yields related to alluvium aquifer units, with a number of production boreholes reporting yields of ca. 1 to 2 l/s.

There are general trends which suggest the highest borehole yields are found in alluvial/fluvial valleys near the lake in weathered bedrock in the order of 1 to 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.

Groundwater Table Variations

There is no Groundwater Monitoring Data for WRA 8.

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).

Table 4. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 8A, 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	345.2	3%	15%	0.02	0.10	207.1	5,178.5	
Fluvial Units	43.9	10%	35%	0.02	0.10	87.8	1,535.9	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	0.2	10%	30%	0.02	0.06	0.5	4.3	
W & F Basement	1,695.9	1%	10%	0.02	0.03	339.2	5,087.6	
	Area of WRU (km^2)	8A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*634.6*	*11,806.3*	*Total Volume Groundwater*
	2,085.2	921	Average Rainfall in WRU	9.21	69.075	19.2	144.0	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]						33	82	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 8 ranges between 23.9 Million Cubic Meters (MCM) and 178.9 MCM per year, with a mean age of groundwater of 200 years across the Water Resource Area **(Table 4**). There is a need to better constrain water volume/balance aspects of the basin and to expand the use of Isotope Hydrology and properly modelled and measured groundwater age constraints.

Groundwater quality WRA 8

Groundwater major-ion water quality in WRA 8 for data available within the Ministry of Water and Sanitation is available but is limited to those analyses which have geospatial information and data which was reported as ‘zero’ or below reported minimum detection limits were ignored (**Table 5**). The lack of data does not allow for detailed evaluation.

The distribution of EC for groundwater of WRA 8 is provided however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine in WRA 8, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

Table 5. Distribution of dissolved species in groundwater WRA 8. 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 8	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	6.7	917	12.8	0.4	0.0	0.1	35.2	2.8	105.2	17.3	0.0
Std Dev	0.2	503	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Median	6.7	850	12.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Max	7.0	2,200	13	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Min	6.2	250.0	12.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
n	11	11	1	1	1	1	1	1	1	1	1

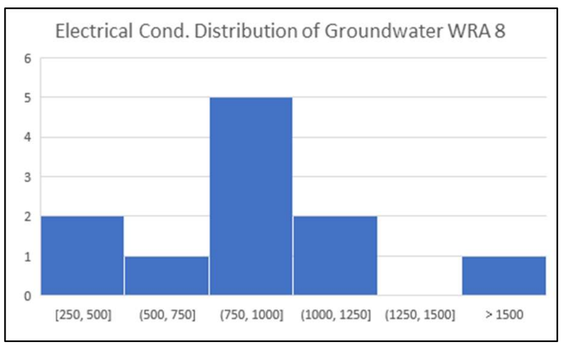


Figure 14 Distribution of EC for groundwater within WRA 8 (y axis = *n* observations).

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 8 (**Figure 14**) is low based on limited water quality analyses held by the Ministry of Water and Sanitation. It is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation.

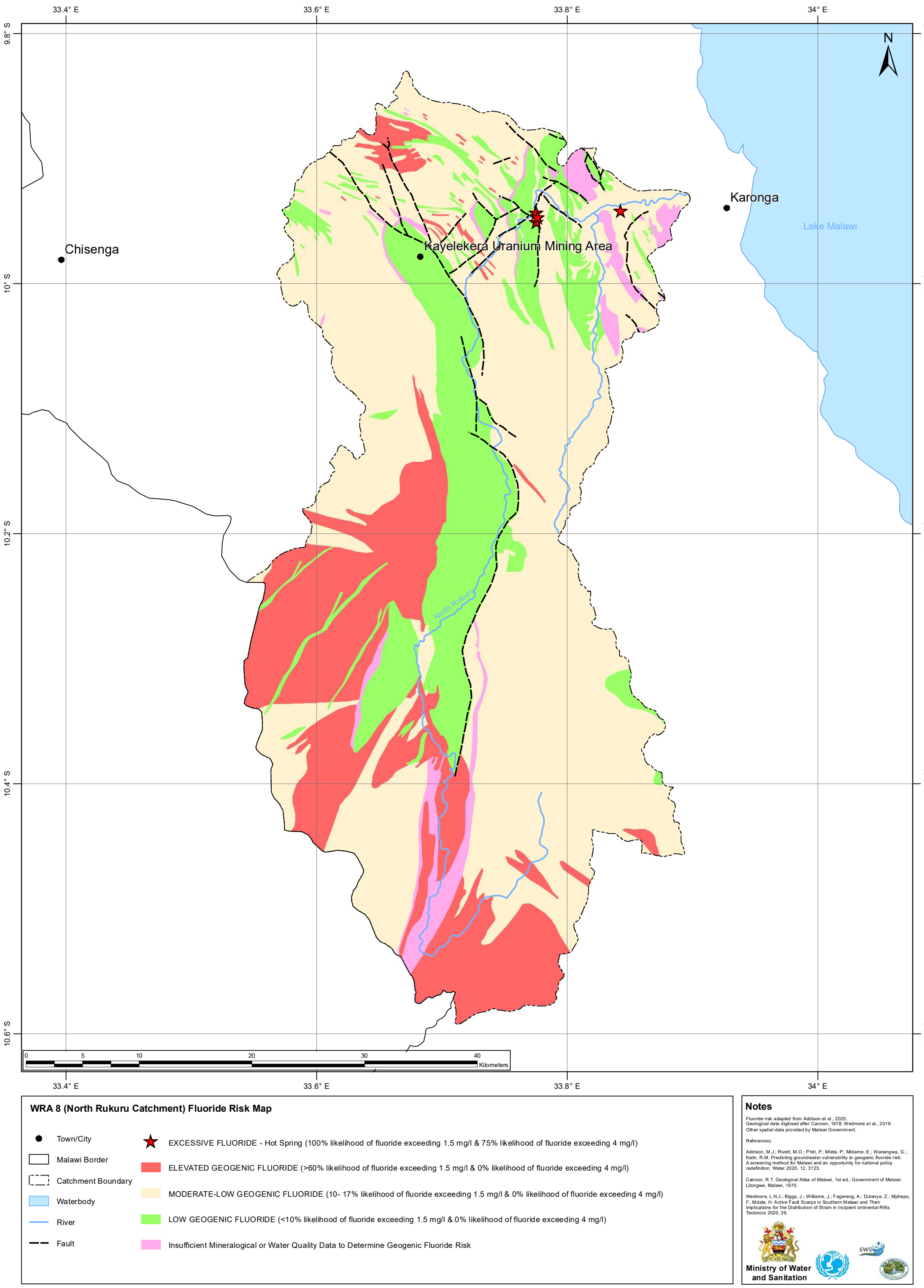


Figure 15. Groundwater Fluoride Risk Map WRA 8 (after Addison et. al. 2021).

Fluoride

There are hot springs in WRA 8 co-located with rift valley faulting and various hydrogeologic units which weathering may result in fluoride in groundwater, placing much of the catchment in **Elevated Risk** category for fluoride in groundwater. Groundwater data drawn from the recent national-scale assessments (**Figure 15**) reveals only a handful of existing analyses are above 1.5mg/l, these areas should be targeted for re-analysis as given the co-location with major faults is unknown and those water points in proximity to faults may 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 Fluoride risk and it is recommended that a detailed and systematic survey of groundwater quality in WRA 8 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. There is no systematic analysis for Arsenic in WRA 8 and it is recommended that a detailed and systematic survey of groundwater quality in WRA 8 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 8.

	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**
8A	49,399	53,163	57,255	61,552	65,763	61,835	188,441,991	226,130
WRA 8	**49,399**	**53,163**	**57,255**	**61,552**	**65,763**	**61,835**	**188,441,991**	**226,130**

Water resource unit 8 has a modelled total of 226,130 metric tonnes of faecal matter loading over the 10-year period (2012-2022) (**Table 6**). Over the 10-year period the modelled number of pit latrine users in the region increased by 12,436. WRA 8 covers roughly 1.97% 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. 3,442 metric tonnes of fertiliser would be used in WRA1 per year. The model results indicate 7 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

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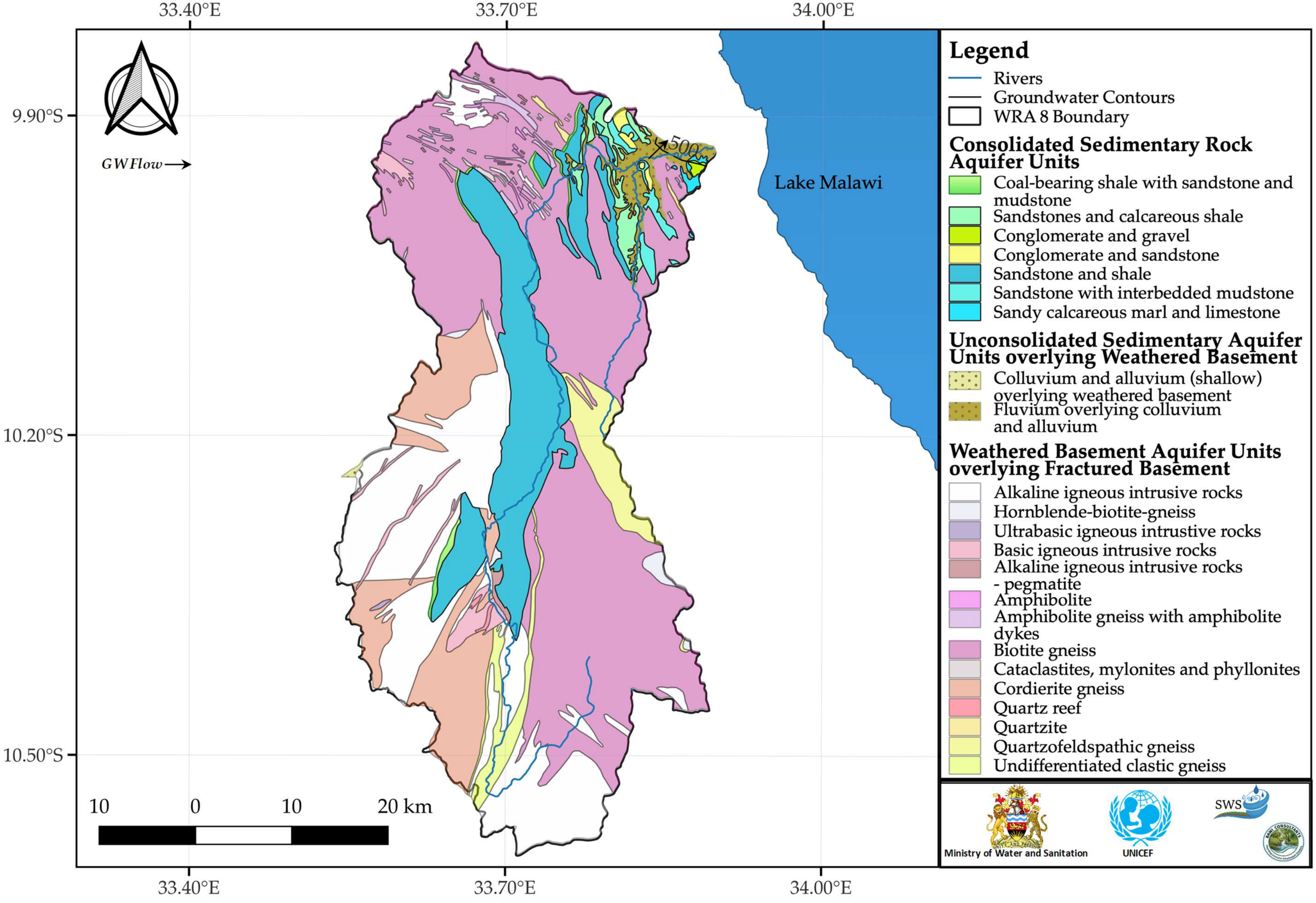
Water Resource Unit (WRA) 8 Figures

Figure WRA 8.0: Aquifer Units and Groundwater Level Contours Water Resources Area 8

Figure WRA 8.0: Aquifer Units and Groundwater Level Contours WRA 8



WRU 8A Figures

Figure WRU 8A.1 Land Use and Major Roads

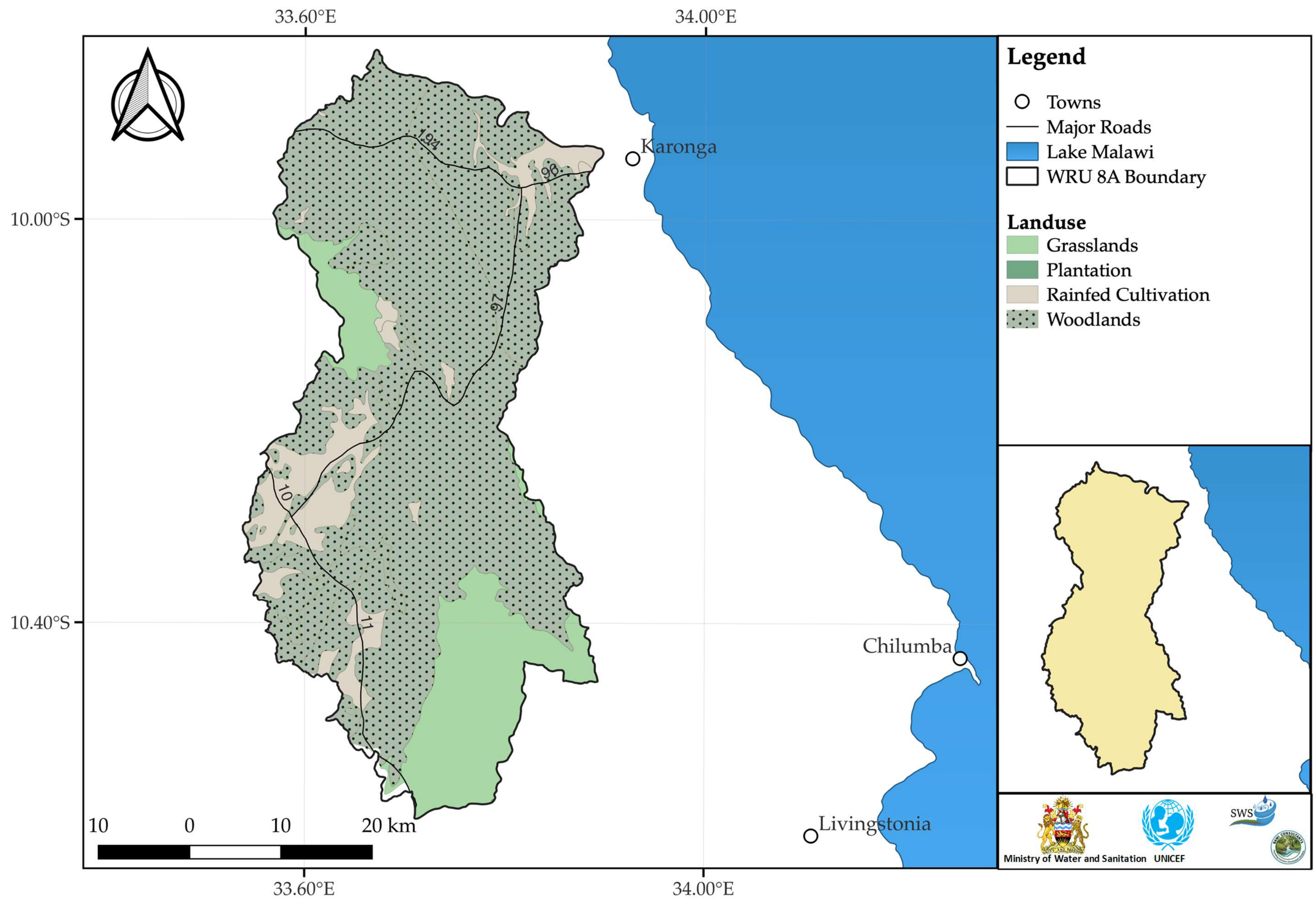


Figure WRU 8A.2 Rivers and Wetlands

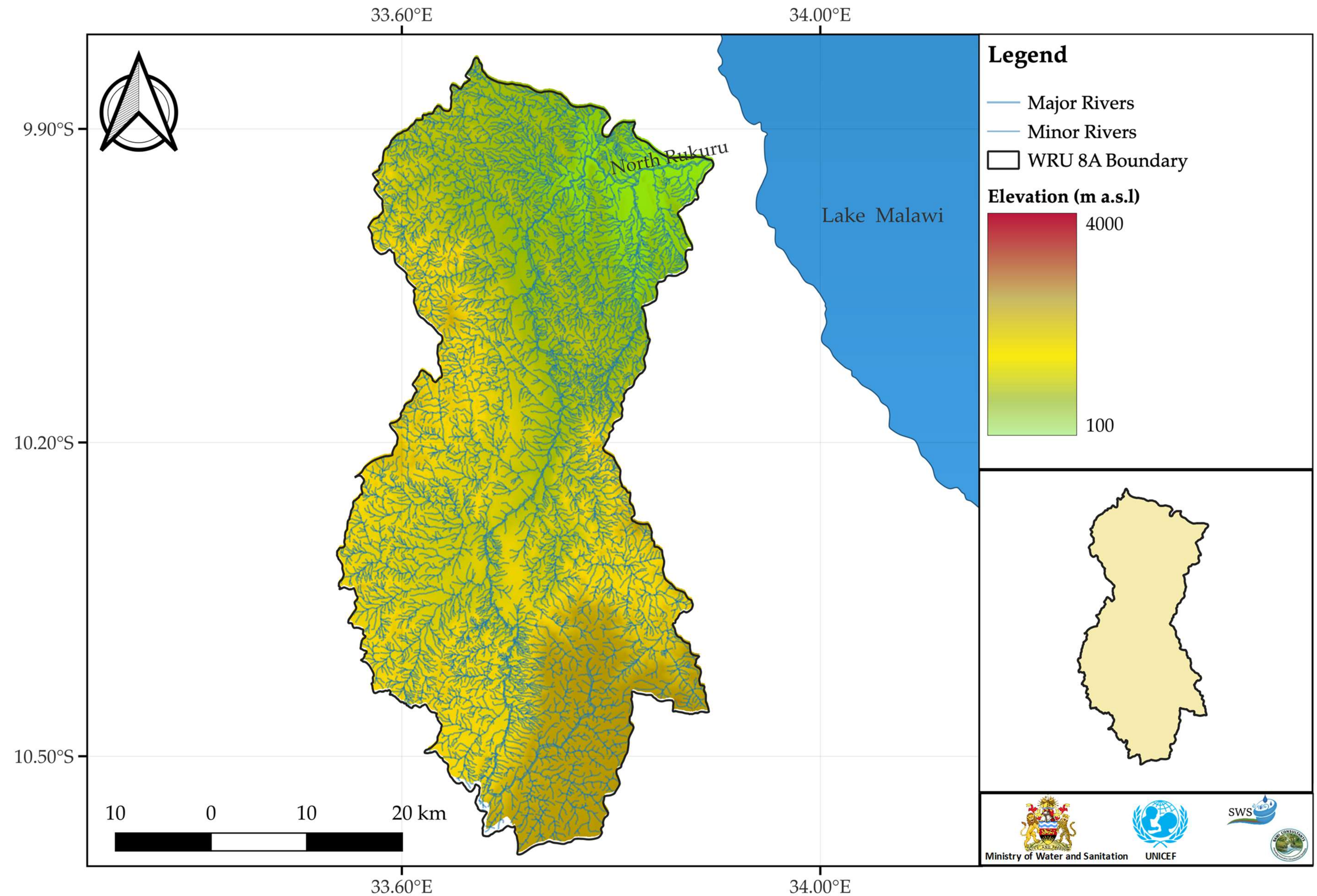


Figure WRU 8A.3 Hydrogeology Units and Water Table

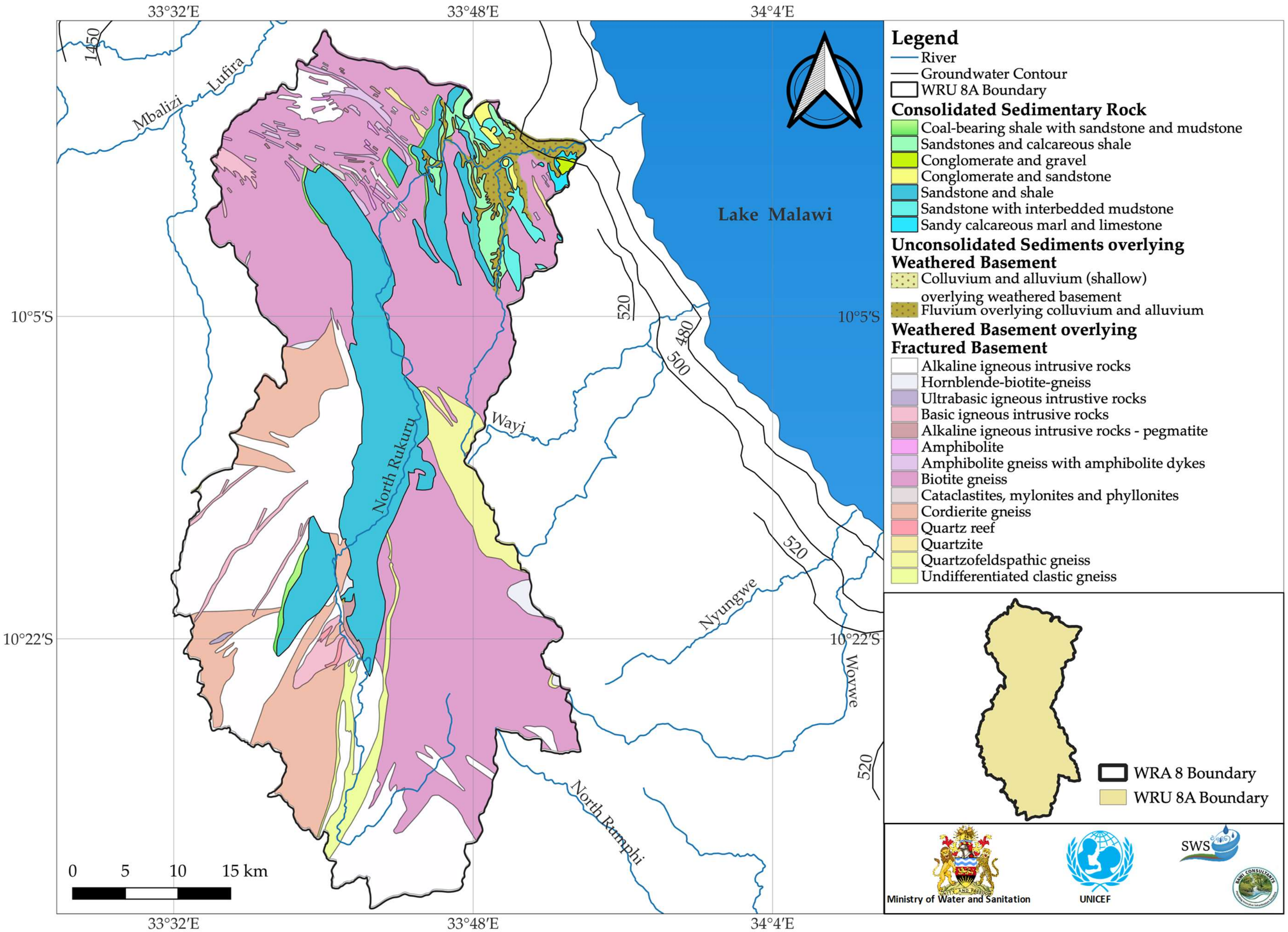


Figure WRU 8A.4 Groundwater Chemistry Distribution Electrical Conductivity

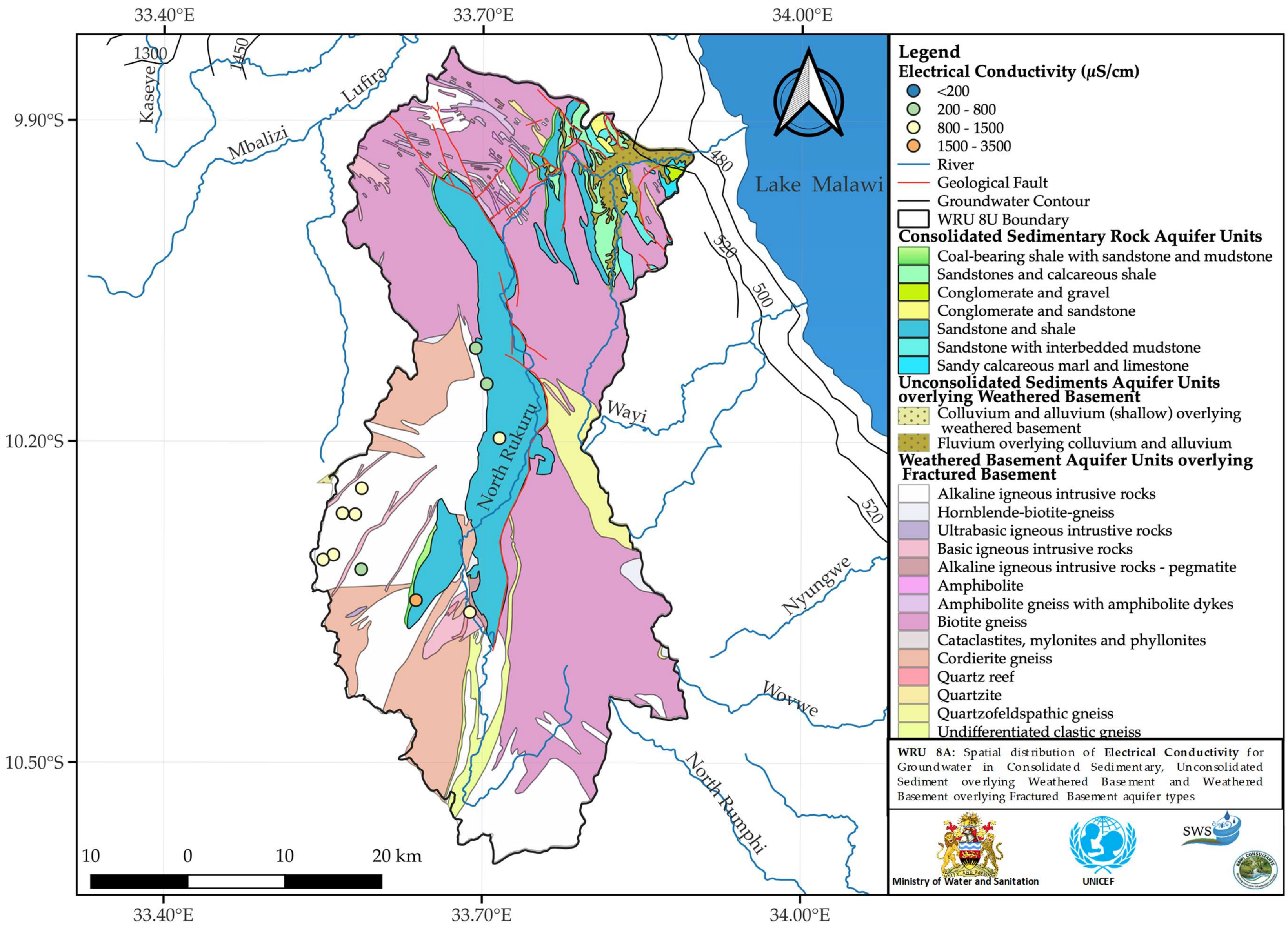


Figure WRU 8A.5 Groundwater Chemistry Distribution Sulphate

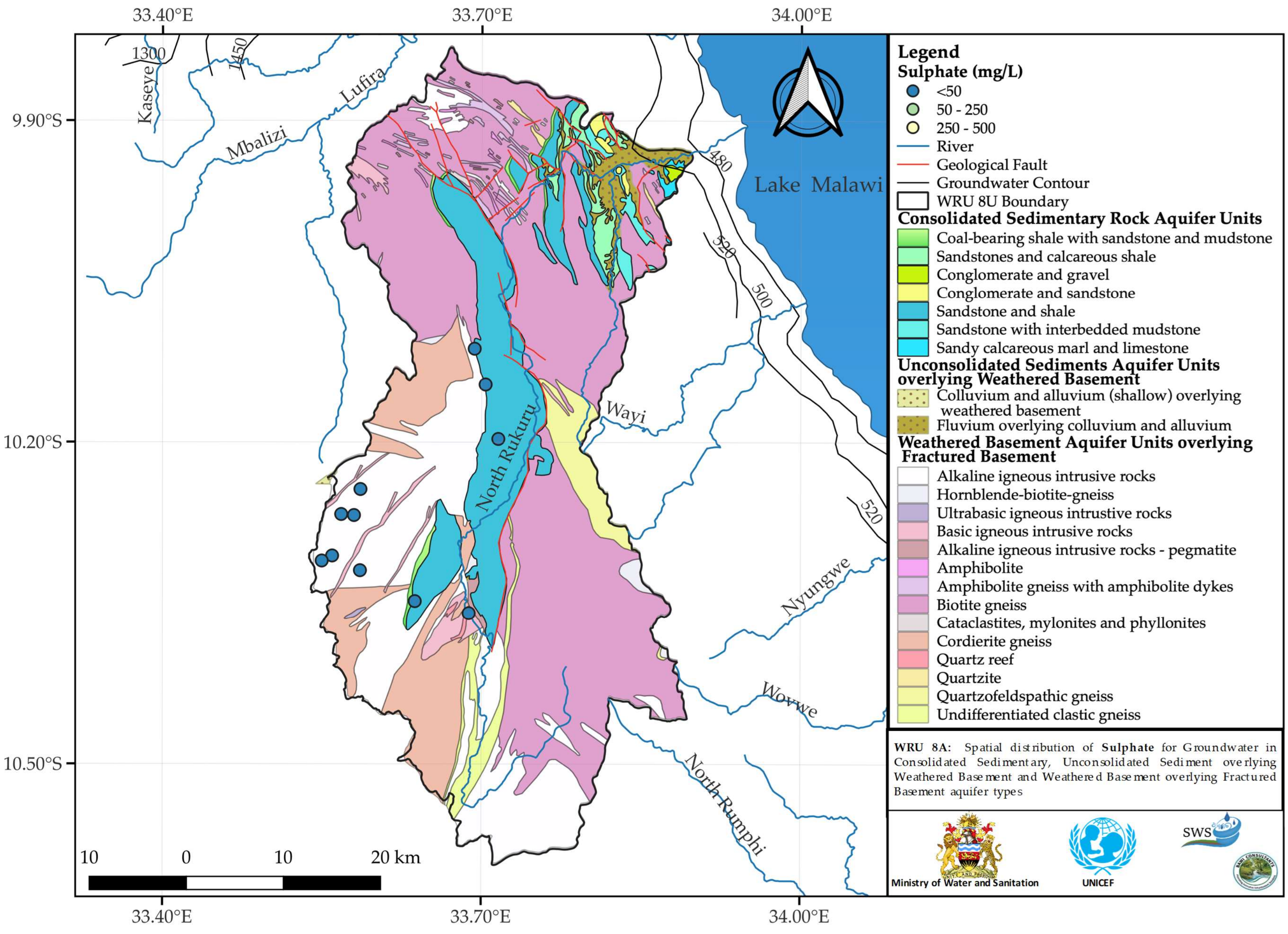


Figure WRU 8A.6 Groundwater Chemistry Distribution Chloride

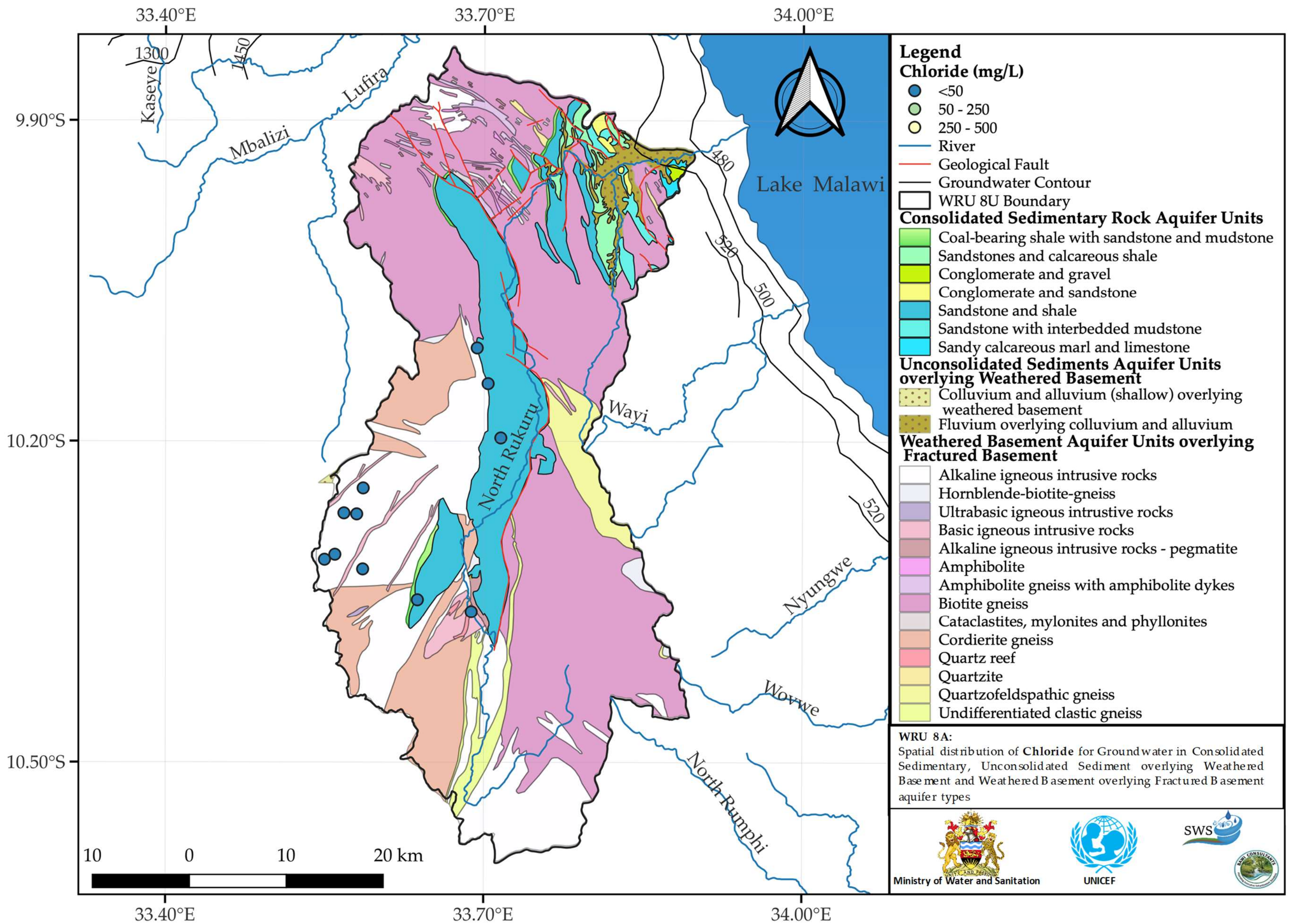


Figure WRU 8A.7 Groundwater Chemistry Distribution Sodium

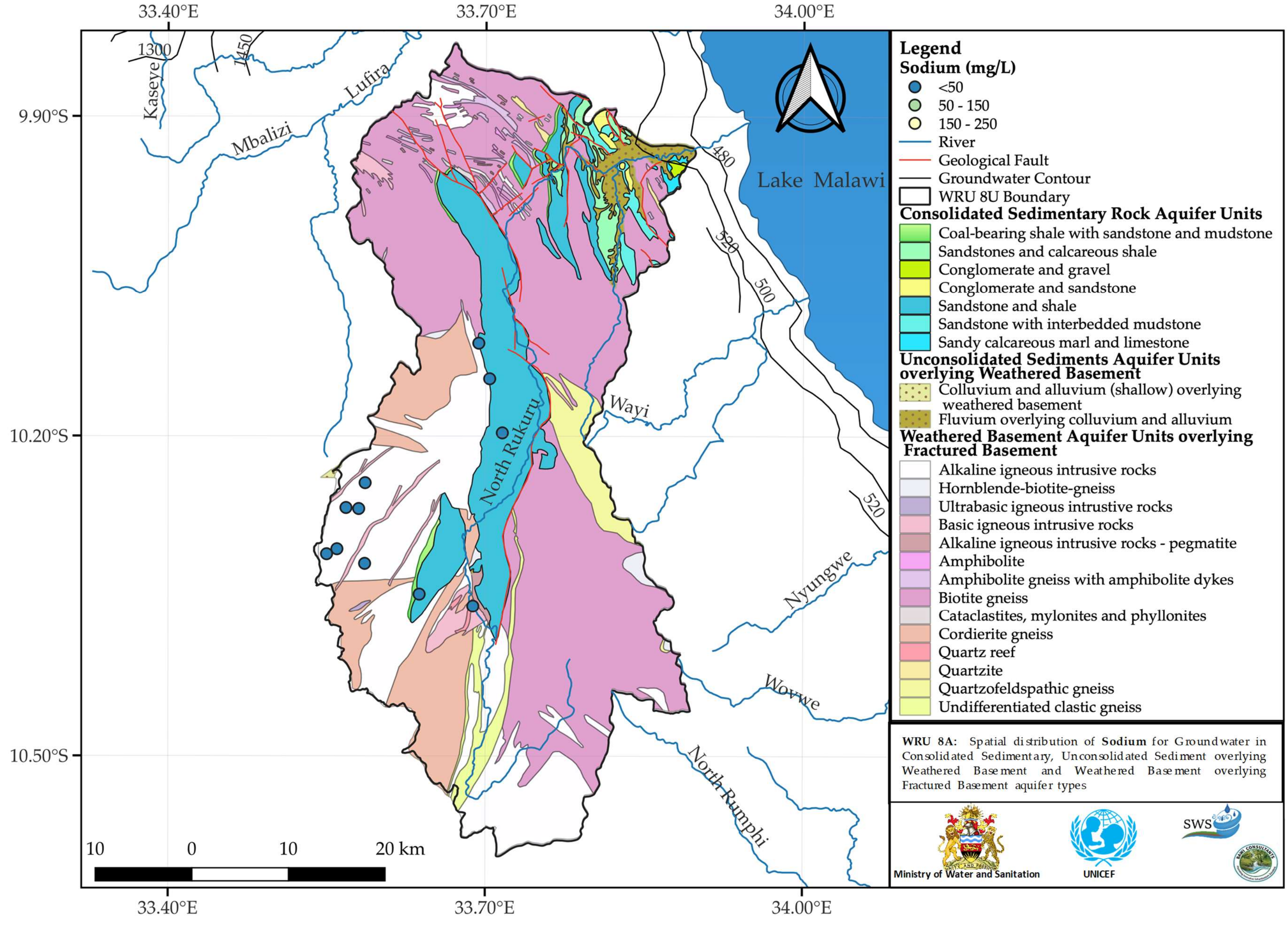


Figure WRU 8A.8 Groundwater Chemistry Distribution Calcium

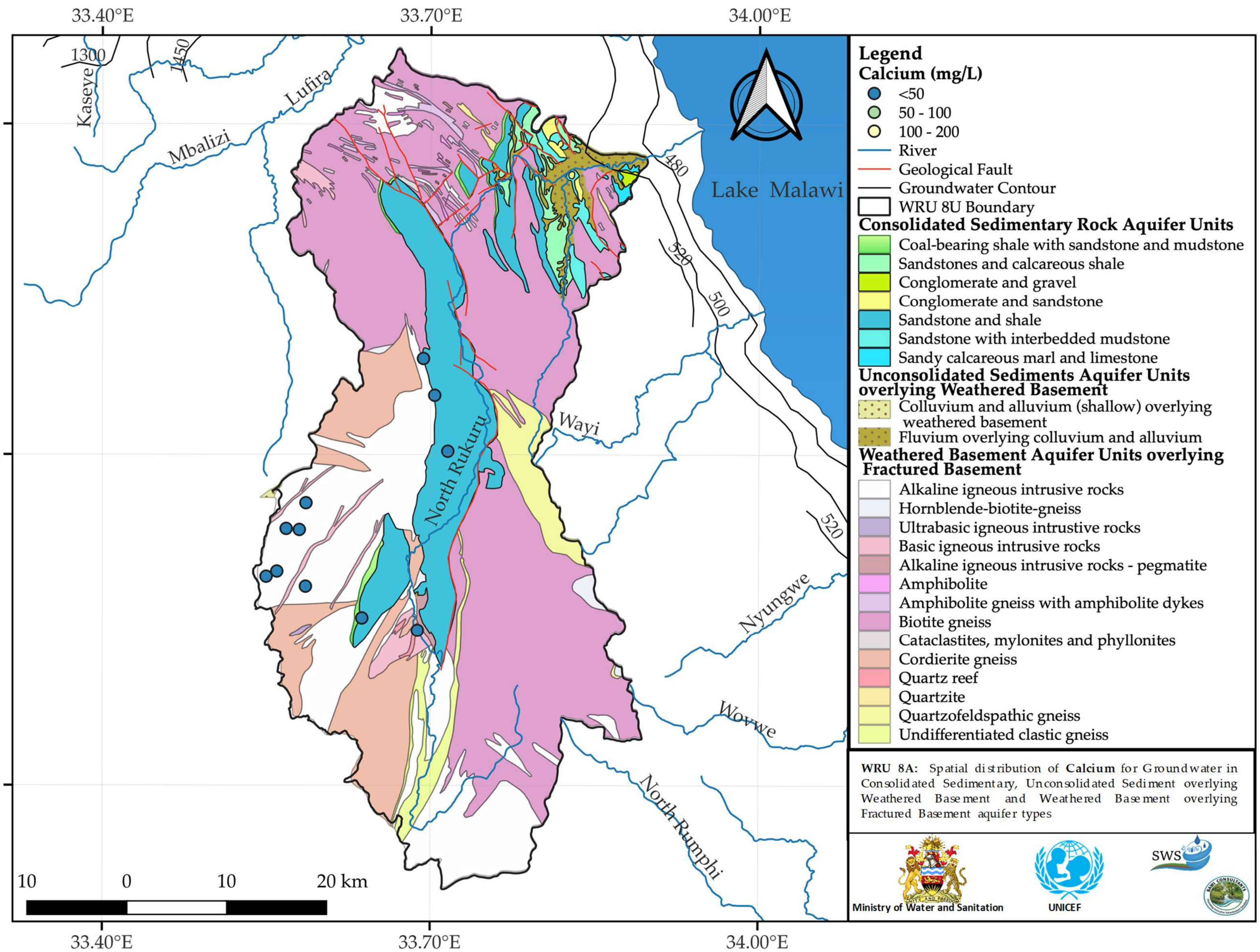


Figure WRU 8A.9 Piper Diagram of water quality results with respect to the major aquifer type

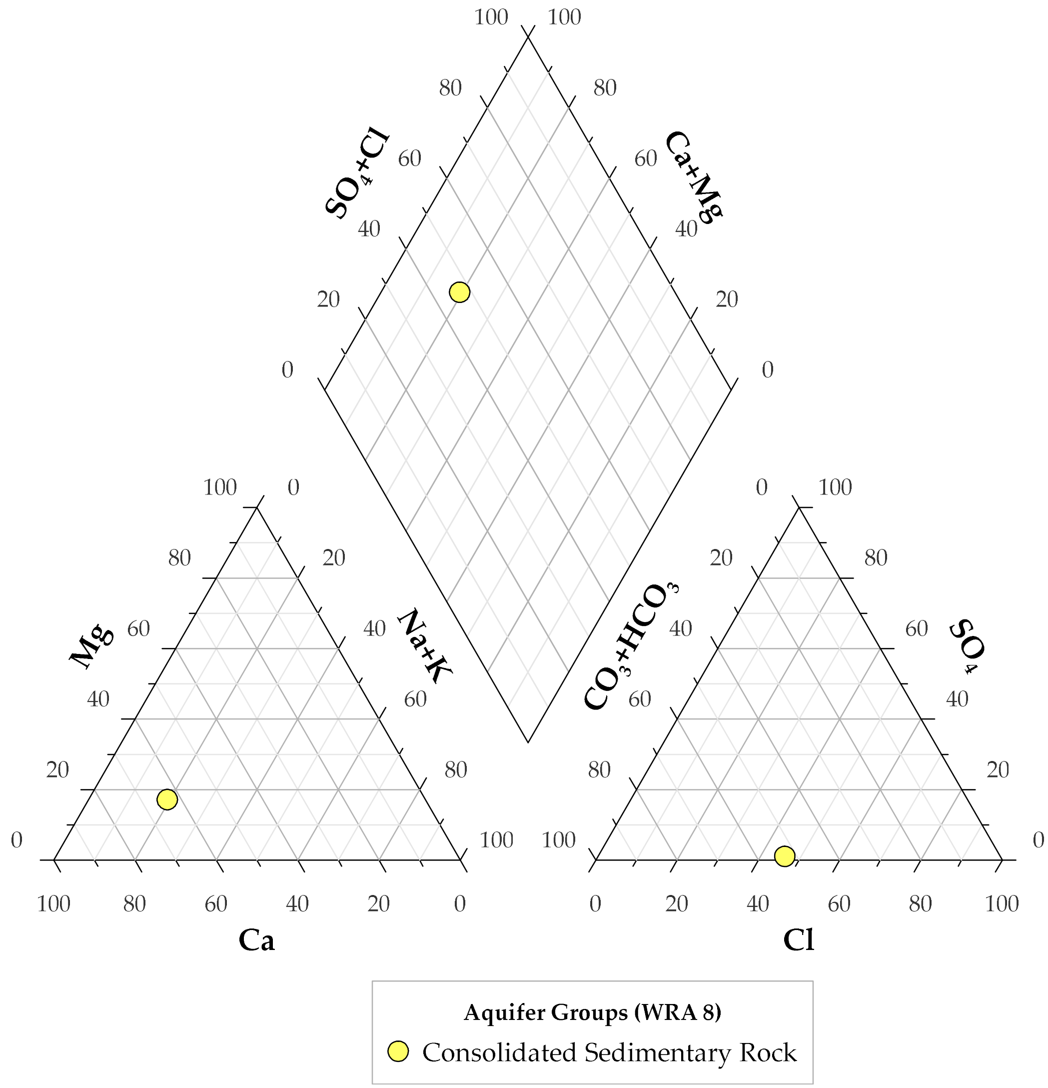
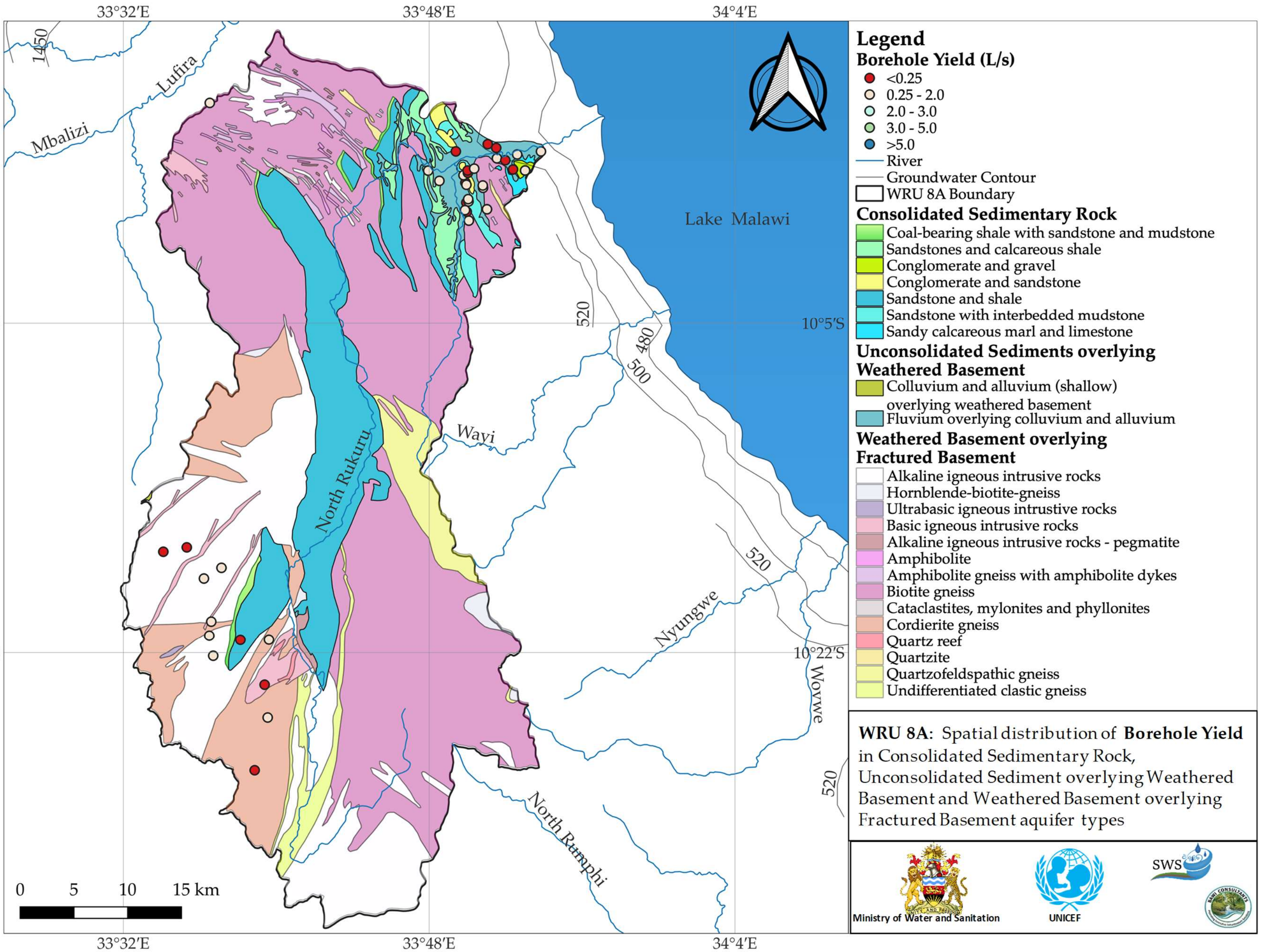


Figure WRU 8A.10 Borehole Yield Map for data held by the Ministry



Ministry of Water and Sanitation

Hydrogeology and Groundwater Quality Atlas of Malawi

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