



Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 3

The South West Lake Malawi Catchment

Ministry of Water and Sanitation

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Acronyms and Abbreviations

BAWI	BAWI Consultants Lilongwe Malawi
BGS	British Geological Survey
BH	Borehole
BY	Billion Years
°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	Sustainable 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 3 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

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 saprolitic / 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 contaminants e.g. e-coli from pit latrines).

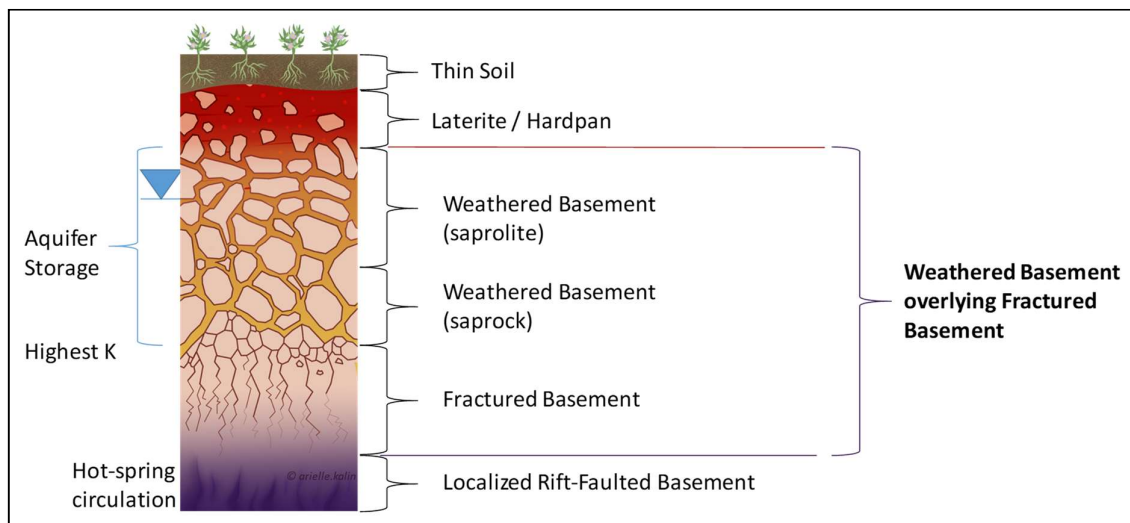


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

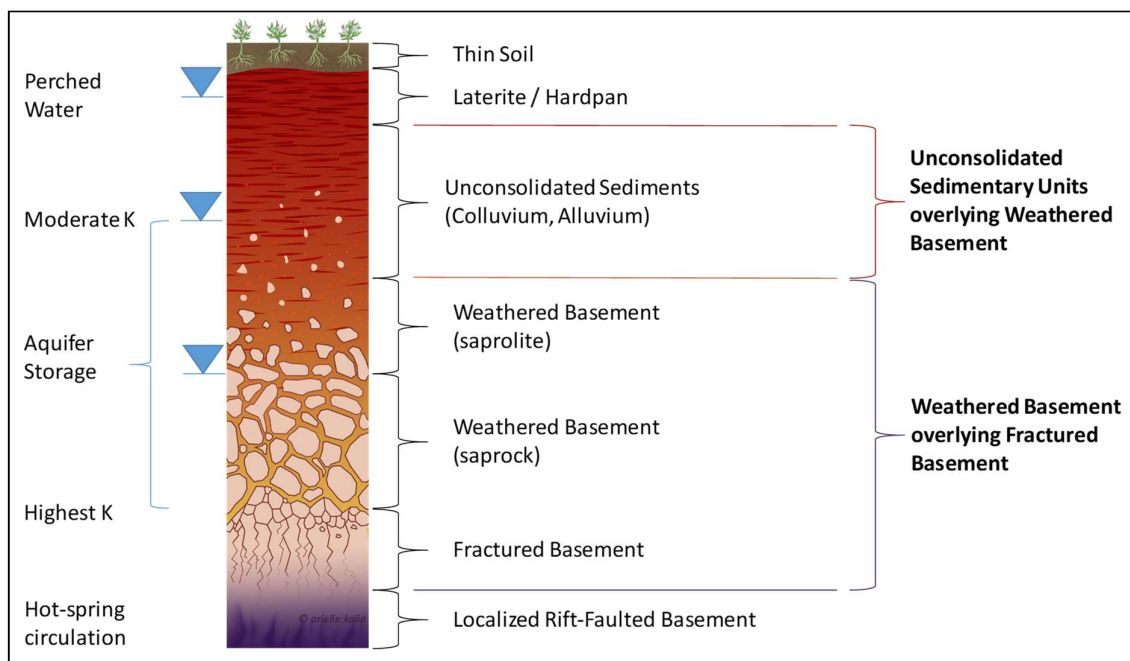


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

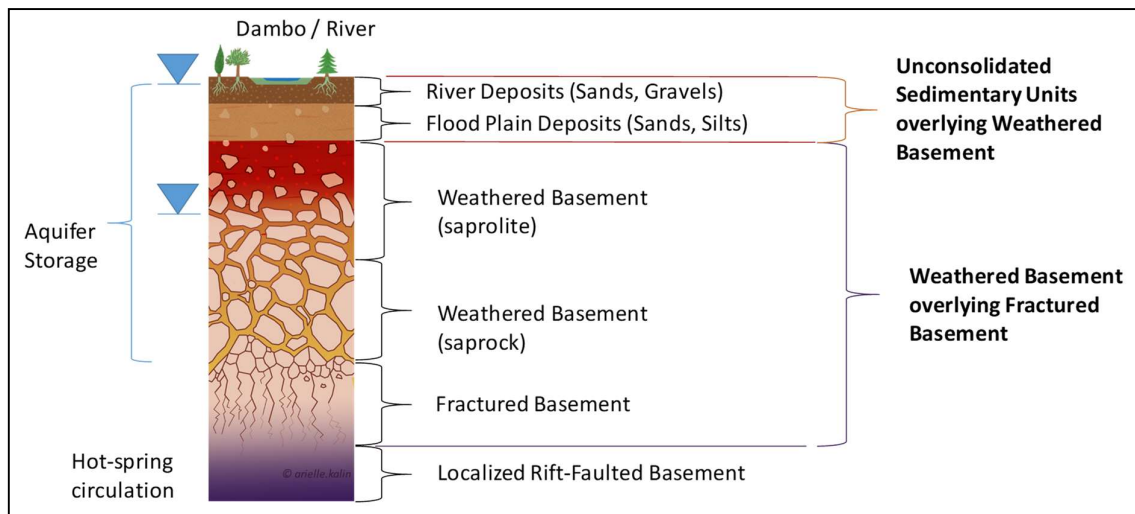


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

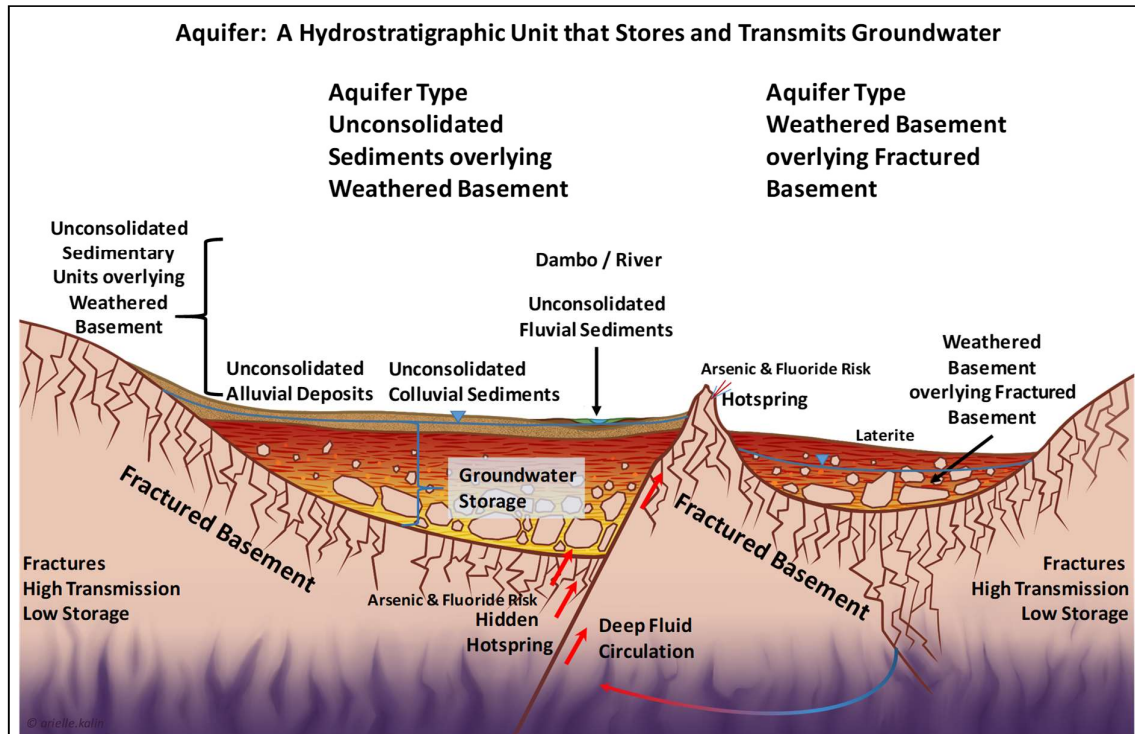


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratigraphic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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>

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Water Resource Area 3 (WRA 3): The South West Lake Malawi Catchment

Water Resource Area (WRA) 3 (**Figure 2a**) occupies a diverse area of 4,998 Km² Southwest of Lake Malawi, hence called the Southwest Lake Malawi Catchment. Its topographic settings are characterised by highlands as high as 2,178 m above sea level (asl) and lowlands as low as 462 m asl, with a mean altitude of 756 m asl. There are six Water Resource Units within WRA 3 (**Figure 2b**) The highlands largely cover the Western and South-western part, whereas the lowlands dominate the North and North-eastern part. It is also characterised by the Rift Valley lakeshore plains and the Rift Valley escarpment. The WRA's major riverine systems consisting of Nazipulu, Livulezi, Bwanje, Namikokwe, Liwadzi, Nakundi, Mamingundi, Kabindira, Nanyangu and Ralitsa rivers, largely drains into Lake Malawi, a key integral part of the Zambezi River Basin system. Generally, the riverine system consists of ephemeral streams, lacking considerable flow in dry season. Notable water reservoirs include the Bwanje Valley dam on Namikokwe river, with a capacity of c. 5.6 million m³, that primarily supplies Bwanje Irrigation Scheme, and has remarkable water supply and hydro-power generation potential. Water Resources Area 3 is trans-boundary for both surface and groundwater and it borders on Lake Malawi which is governed by Trans-boundary water sharing agreements. Therefore, Integrated Water Resources Management (IWRM) must be implemented within international water resources agreements.

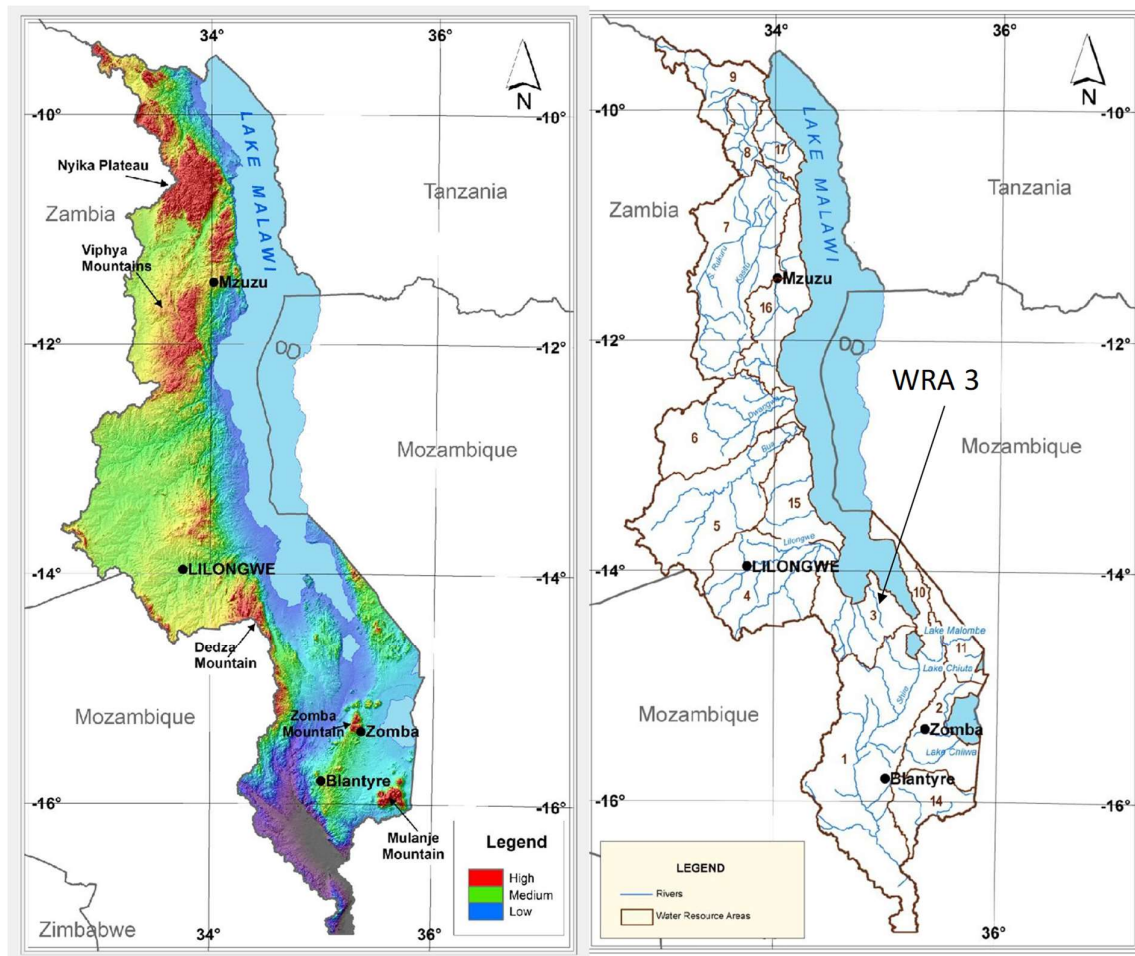


Figure 2. Location of WRA 3 with major rivers and topography shown.

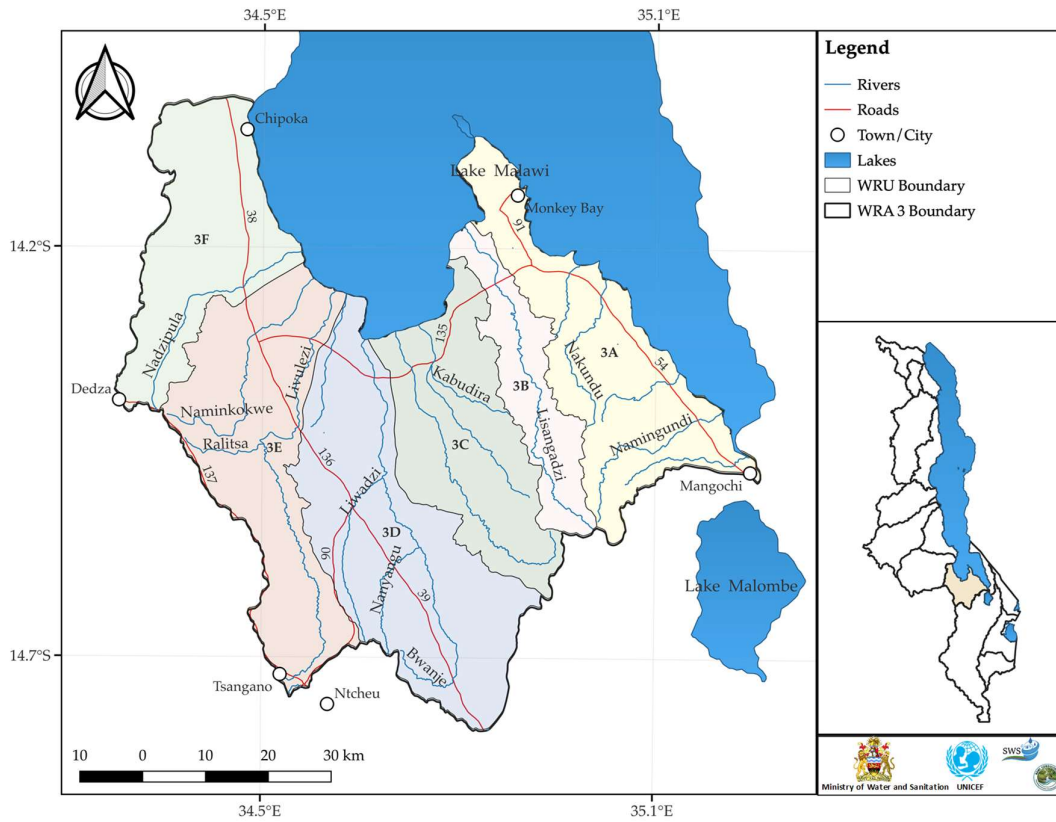


Figure 2b. Location of WRA 3 with Water Resource Units.

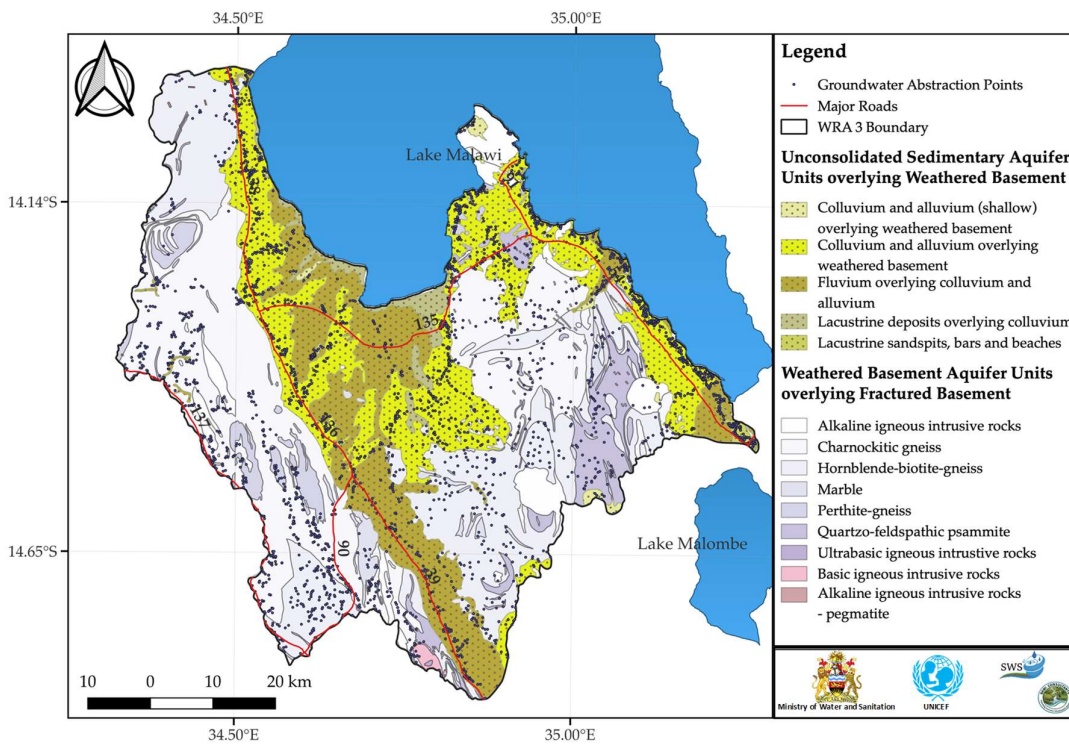


Figure 3. Distribution of groundwater abstraction points in WRA 3.

Groundwater Abstraction in WRA 3

Public abstraction points for groundwater are numerous in WRA 3 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 4,621 known groundwater abstraction points, 96.6% are improved sources (with 401 being protected dug wells and 139 unprotected dug wells). The mid-point distribution of water point yield (at hand pump) is between 0.25 and 0.30 l/s (**Figure 4a**), however it should be noted that this is an expected range of the Afridev, Maldev, Elephant and India Mark 3 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 3, only 49.1% are fully functional (defined as providing water at design specification).

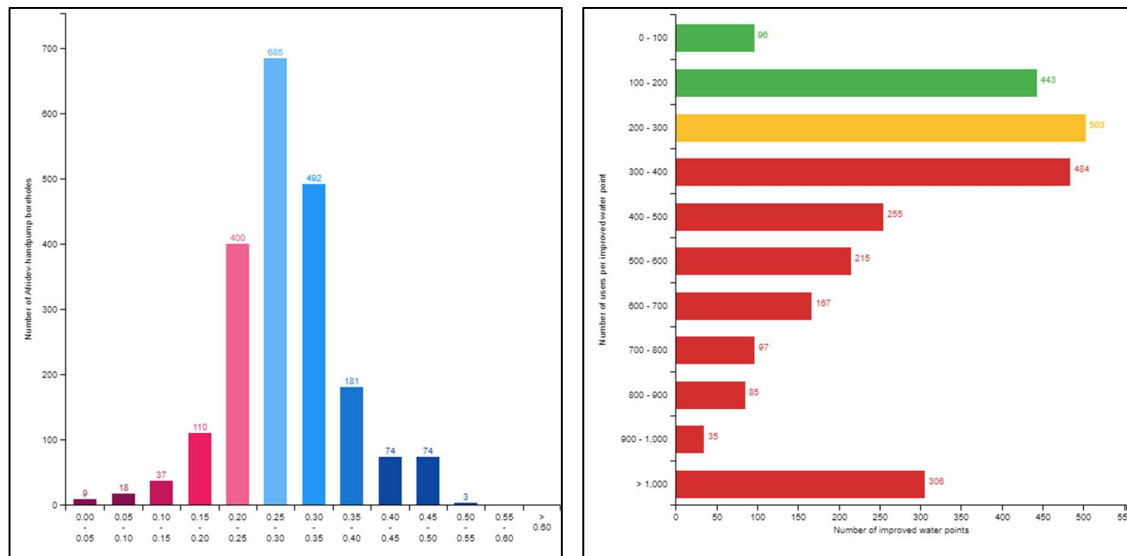


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 3 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point. [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 considerably exceeded and there is an investment need in WRA 3 from a population point of view. Nearly half of the groundwater supply points provide water to 250 or more users per water point, and with the preponderance of dug wells and non-functional boreholes that do not meet the water quality guidelines, the WRA should be considered regulation of self-supplies and self-funded water quality monitoring within investment planning.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 7.1% 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.

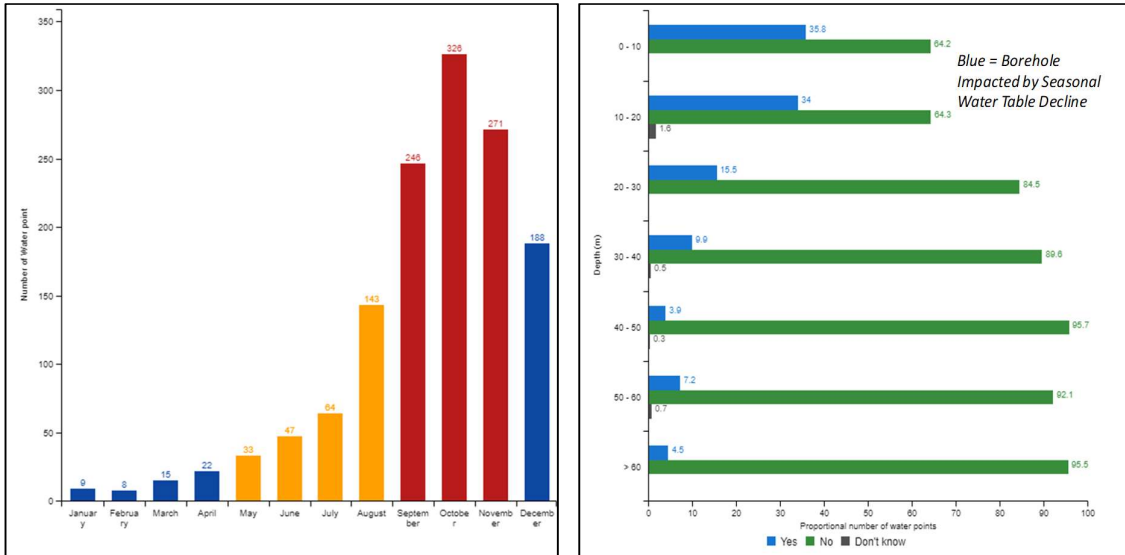


Figure 5a and 5b. Number of groundwater abstraction points in WRA 3 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

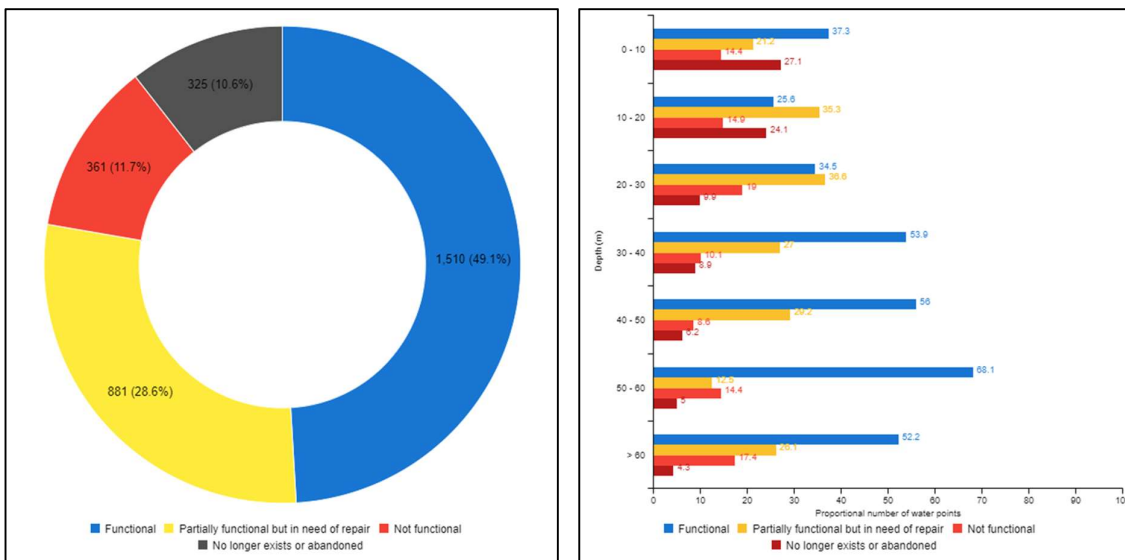


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 3 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water 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 68.1% 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 3 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 3 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	4.055
Protected dug well	401
Protected spring	9
Unprotected dug well	139
Unprotected spring	17

Description of Water Resources WRA 3

Water resources management according to the Water Resource Act (2013) Malawi is devolved to sub-basin Water Resource Units (WRUs), and Integrated Water Resources Management (IWRM) should be managed at this sub-basin scale Water Resources Area (WRA) 7 is in northern part of Malawi and consists of six (6) Water Resource Units (WRUs): WRU 3A, WRU 3B, WRU 3C, WRU 3E, WRU 3D, WRU 3E, WRU 3F (**Figure 7a – 7f**).

The area faces key water resources management challenges emanating from development pressures such as population growth at recorded c. 3% annually. The WRA's major river systems drain into Lake Malawi, a key integral part of the Zambezi River Basin system. Generally, the riverine system consists of ephemeral streams, lacking considerable flow in dry season. Notable water reservoirs include the Bwanje Valley dam on Namikokwe river, with a capacity of c. 5.6 million m³, that primarily supplies Bwanje Irrigation Scheme, and has remarkable water supply and hydro-power generation potential. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of seasonal tropical convergence zone precipitation and adjective storms from moisture carried from the Mozambique channel. WRA 3 is trans-boundary for both surface or groundwater bodies and as it borders on Lake Malawi which is governed by Trans-boundary water sharing agreements, it is important that Integrated Water Resources Management is planned and implemented within the framework of international agreements.

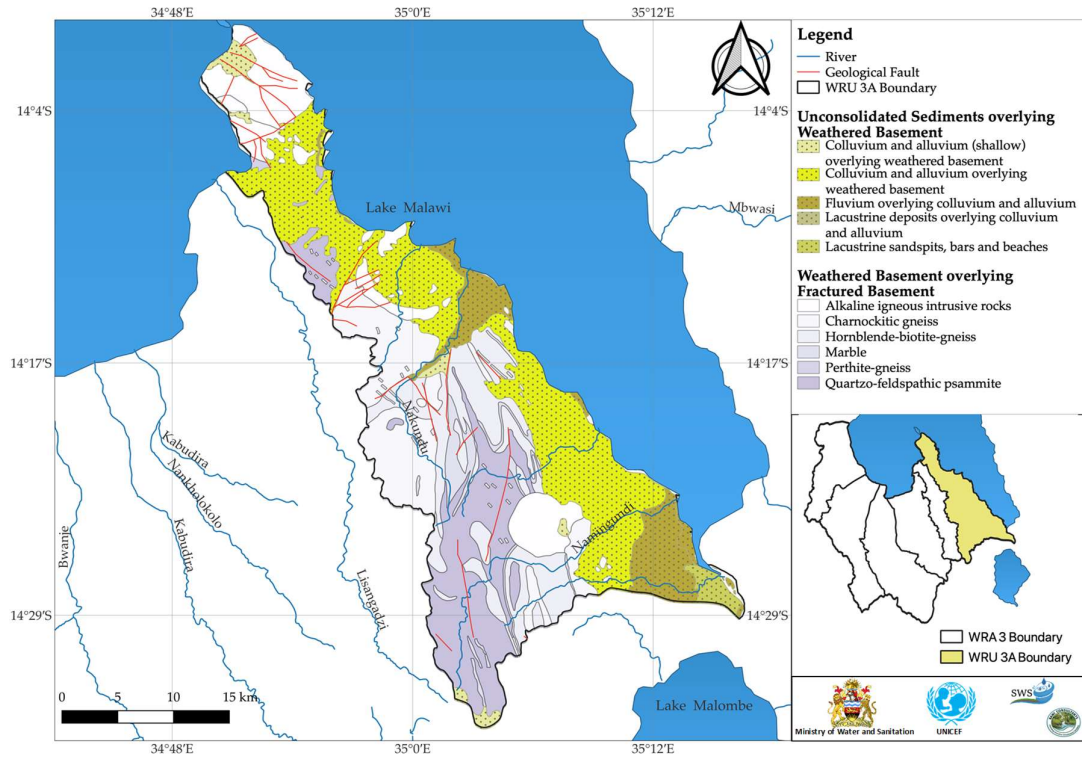


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 3A within Water Resource Area 3 (Southwest Lake Malawi Catchment).

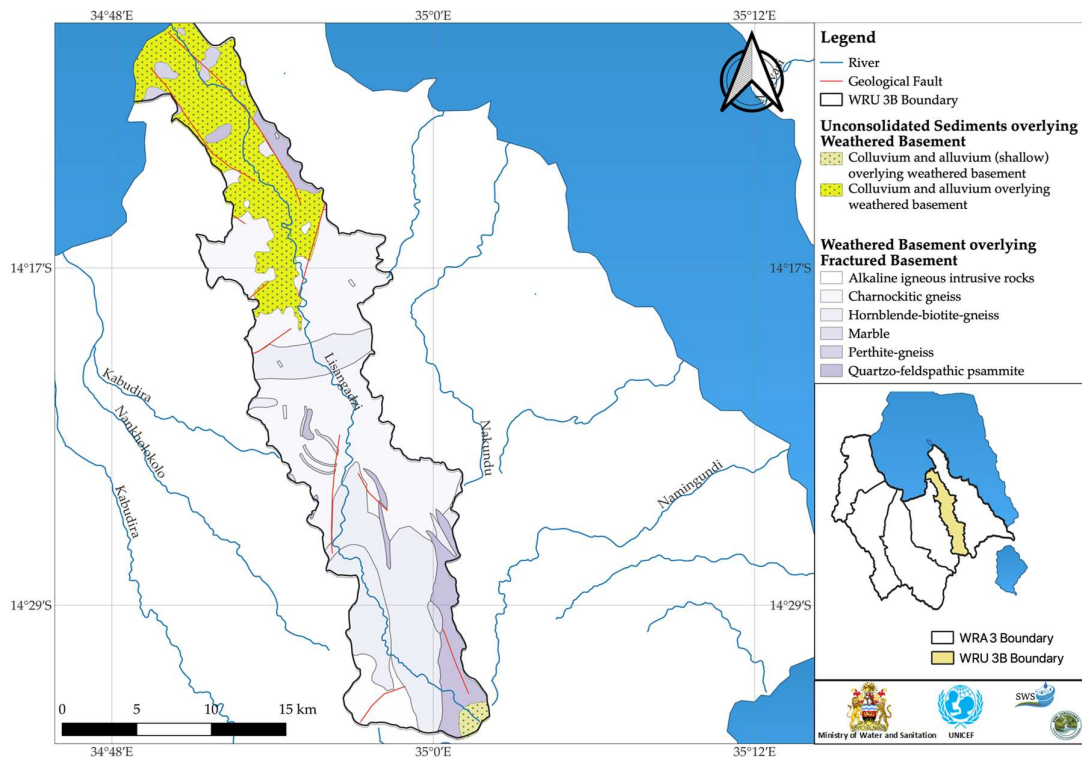


Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 3B within Water Resource Area 3 (Southwest Lake Malawi Catchment).

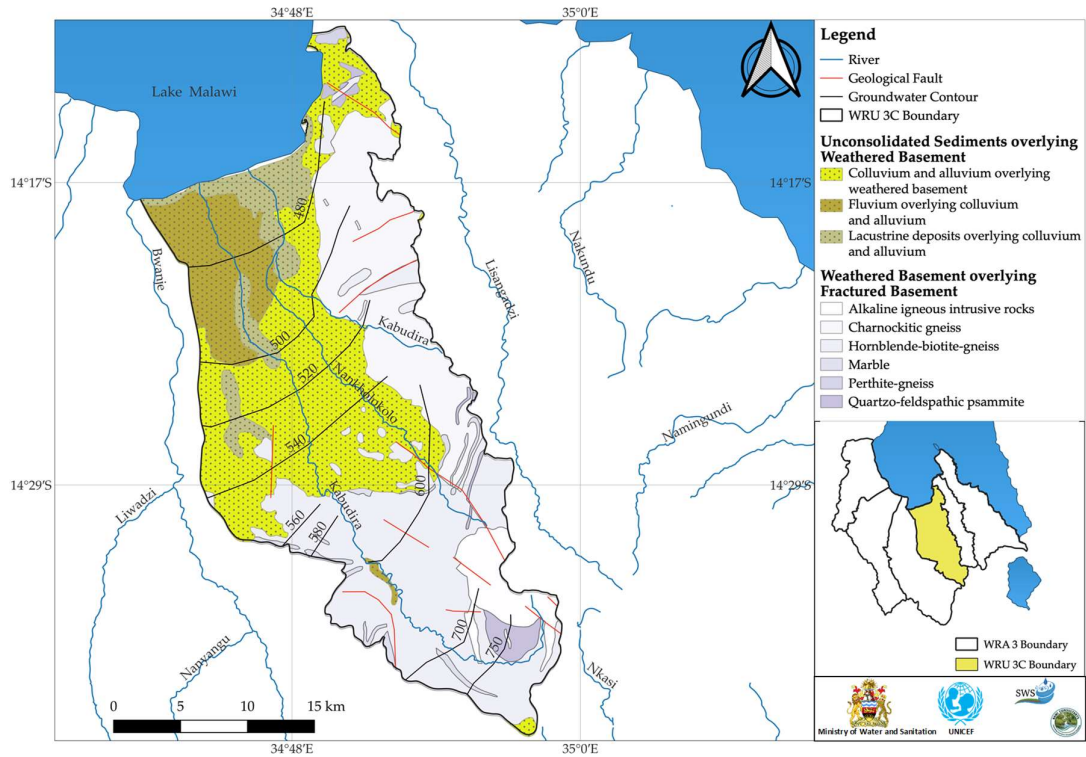


Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 3C within Water Resource Area 3 (Southwest Lake Malawi Catchment).

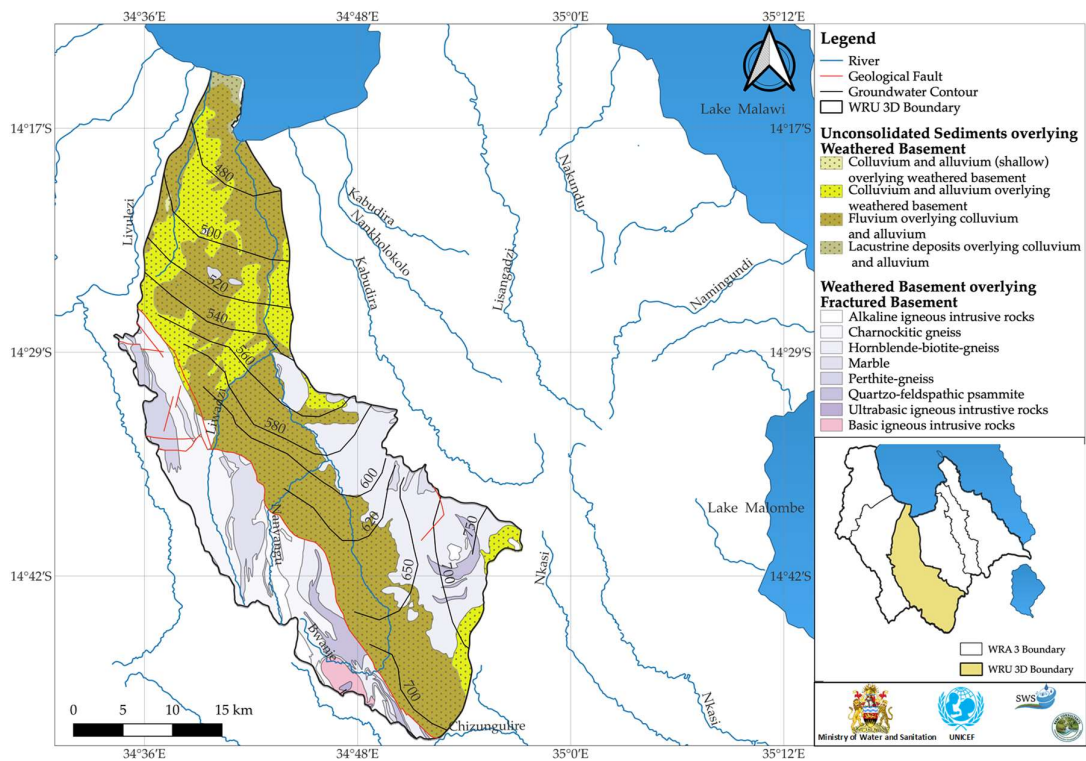


Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 3D within Water Resource Area 3 (Southwest Lake Malawi Catchment).

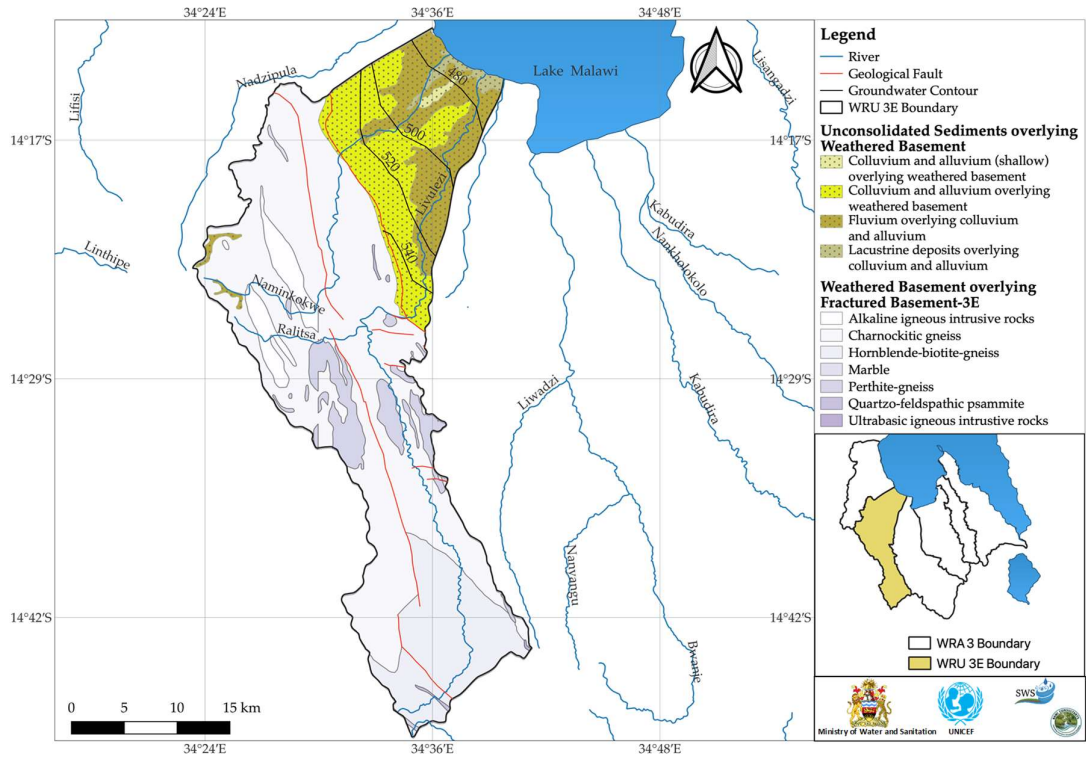


Figure 7e. Map showing the hydrogeologic units and water table for Water Resource Unit 3E within Water Resource Area 3 (Southwest Lake Malawi Catchment).

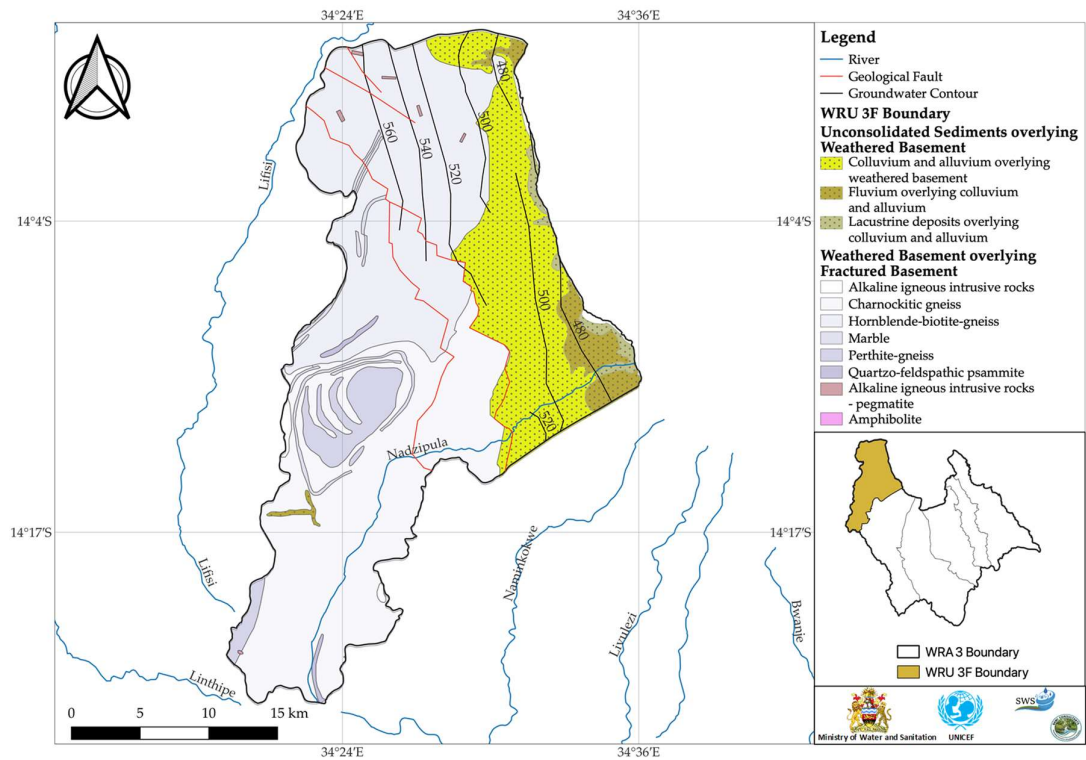


Figure 7f. Map showing the hydrogeologic units and water table for Water Resource Unit 3F within Water Resource Area 3 (Southwest Lake Malawi Catchment).

Topography and Drainage

WRA 3 comprises four contrasting physiographic zones: the highlands; the raised plains areas; the Rift Valley escarpment; and the Lake Malawi shoreline. These distinct geographic features coupled with the occurrence of extensive 'dambo' grass-covered swampy areas influences flow direction towards Lake Malawi. (**Figure 8**). Its topographic settings are characterised by highlands up to 2178 m above sea level (asl) and raised plains area as low as 462 m asl, with a mean altitude of 756 m asl. The highlands largely cover the Western and South-western part, whereas the lowlands dominate the North and North-eastern part.

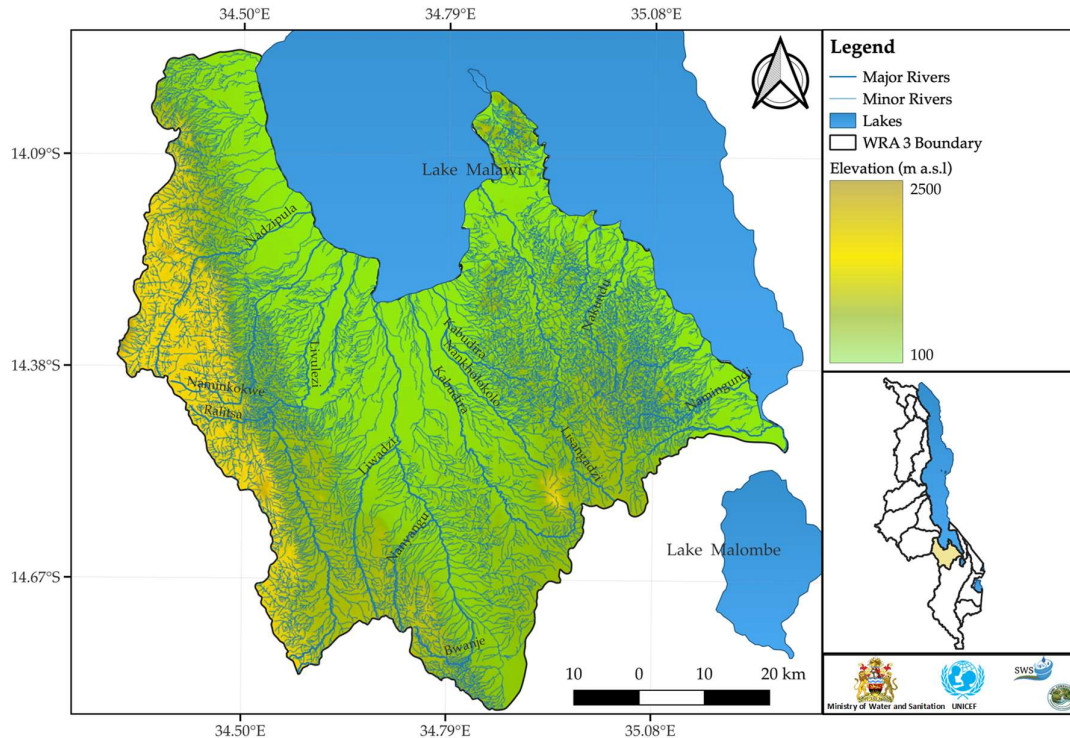


Figure 8. Drainage for the major rivers in Water Resources Area 3.

Geology – Solid

WRA 3 is dominated by Precambrian - Lower Palaeozoic Malawi Basement Complex of metamorphic and igneous rocks (**Figure 7a – 7f**). Geological structure is controlled by the Malawi Rift Valley with a topographically steep rift escarpment along the NNW - SSE-trending Bilila Fault Scarp; a series of basin margin normal faults to the west. West of the fault scarp is the Kirk Plateau which rises precipitously to over 1675 m and is composed of a highly deformed sequence of perthite gneisses, biotite gneisses and charnockitic granulite. Rift-parallel faulting is extensive in those rocks. To the east lies the upper Shire River Valley which hosts a large half-graben composed of basement rock in the centre of the rift valley, extending from Cape McClear southeast into WRA 1. The area is peppered with isolated meta-igneous intrusions of granitic composition which form part of the basement complex. Younger volcanics of the Upper Palaeozoic Lake Malawi Granitic Complex occur at the Cape McClear peninsula as isolated intrusions of biotite granite and biotite-hornblende syenite, topographically distinct due to erosion resistance resulting in a rounded shape and a characteristically pale colour. Younger still

volcanics of the Upper Jurassic Chilwa Alkaline Province occur as minor dykes of Solvsbergite, Lamprophyre, Phonolite, Nepheline, and Trachyte.

Geology – Unconsolidated deposits

Unconsolidated (Superficial) deposits extensively fill the rift Basin from weathering of surrounding highland and underlying Basement rock. A complex mix of Quaternary fluvial, alluvial, and lacustrine deposits occur from extensional rifting of the Malawi Rift and lacustrine deposition along the southern shore of Lake Malawi. Colluvium foothills border the western rift escarpment along the Bilal Fault incised by small streams flowing perpendicular towards the basin centre. Isolated dambo wetlands are present in the low lying terrain near the Lakeshore.

Climate

As part of the Lake Malawi Basin, the WRA 3 experiences a tropical–continental climate with two distinct seasons: a wet season from November to April, and a dry season from May to October. The dry season is characterized by south-easterly trade winds (the Mwera) and the wet season by weaker north-easterly winds (the Mpoto). The Inter Tropical Convergence Zone (ITCZ), the Zaire Air Boundary (ZAB), and tropical cyclones are the three large-scale (synoptic) systems that bring rainfall to the basin.

Based on 2000–2018 precipitation data gathered from Malawi’s Department of Climate Change and Meteorological Services (DCCMS). Annual rainfall in the catchment area exhibits a mean of 915 mm and a GIS modelled average of 944mm+/-31mm and a modelled range of 821 mm – 1,023mm (**Figure 9**). Temperatures are also influenced by the diverse topography, typically decreasing with increasing altitude. Maxima occur in October/November and minima in June/July. Malawi is vulnerable to climate change influence, arguably already occurring based on increased drought and flood event frequencies.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 3. 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)
3	A	Mangochi/Monkey Bay	828	901
	B	- No Station -	-	924
	C	Nankumba	917	933
	D	- No Station -	-	958
	E	Ntcheu/Mlangeni	1,002	966
	F	- No Station -	-	964

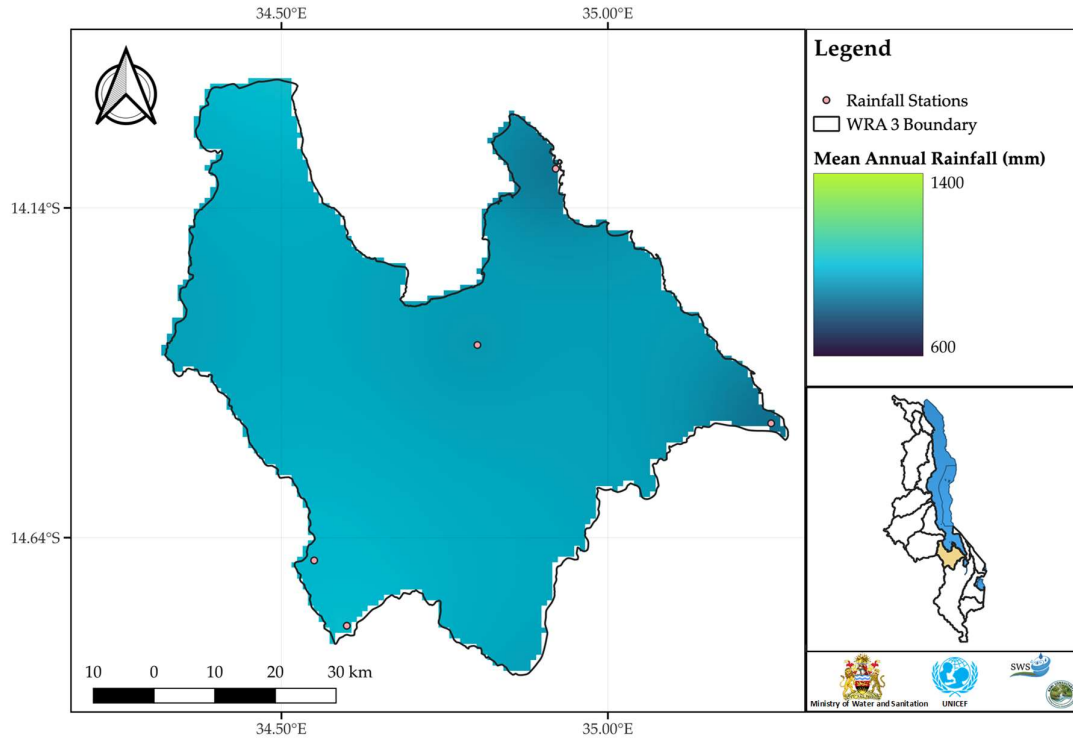


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 3 with the location of weather stations. Average rainfall measured is 915 mm, average rainfall modelled is 944 +/- 31mm (range 821 to 1,023mm).

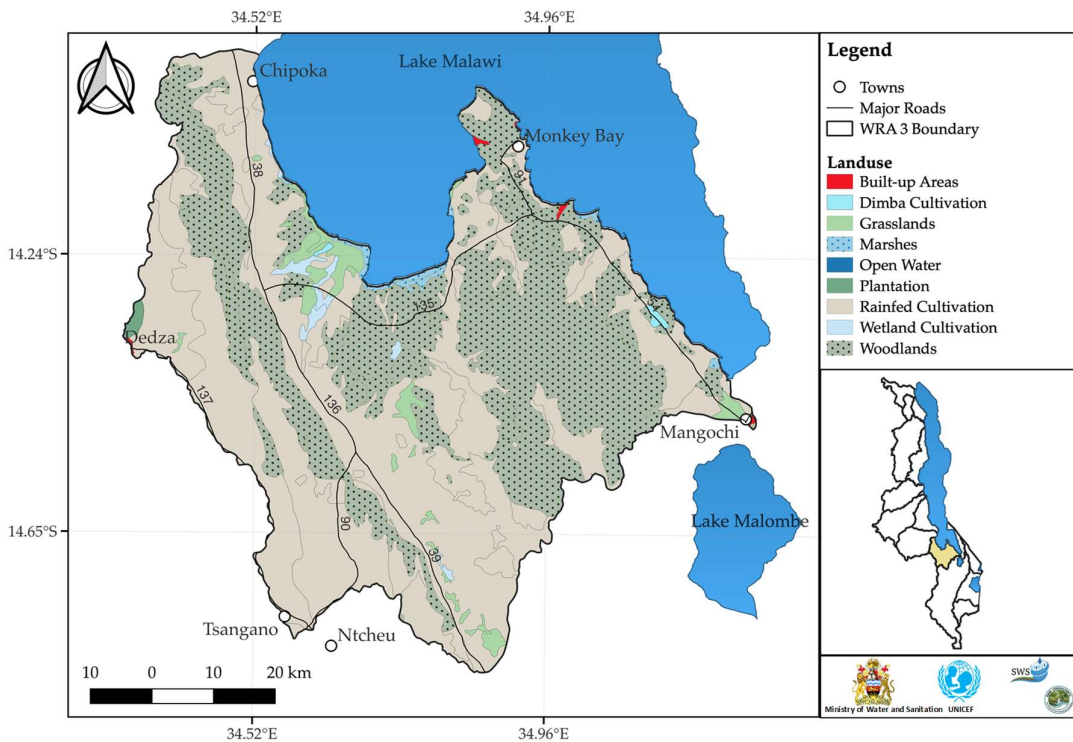


Figure 10. Land use in WRA 3 is dominated by scrub woodlands, grasslands, and rain fed agriculture.

Land use

WRA 3 is characterised by intensive small holder farming by most rural communities. Water is largely use for agriculture, followed by domestic use, municipal water supply and the industrial sector. Lake Malawi plays a pivotal role to socio-economic development in the area and nationally with an array of hospitality (mainly Cape Maclear and Main Mangochi stretch), water transportation (mainly Chipoka and Monkey Bay Harbours) and fishing activities along the lake districts of Dedza and Mangochi. The area faces attendant deforestation posing a potential risk of accelerated runoff, erosion, and reduced aquifer recharge. Increased run off and erosion have the potential of causing sedimentation in surface water bodies which reduces water-supply reservoir capacities.

Hydrogeology of WRA 3

Aquifer Properties

The dominant aquifer type in WRA 3 is colluvium and fluvial/lacustrine sediments overlying weathered and fractured basement. WRA 3 sits within the African Rift and there will be numerous faults of unknown location and trends beneath the sedimentary aquifer units. Groundwater-surface water occurs along the main rivers. Near dambos finer flood deposits interbed with coarser flood deposits. Groundwater abstraction is generally focused on the sedimentary hydro stratigraphic units.

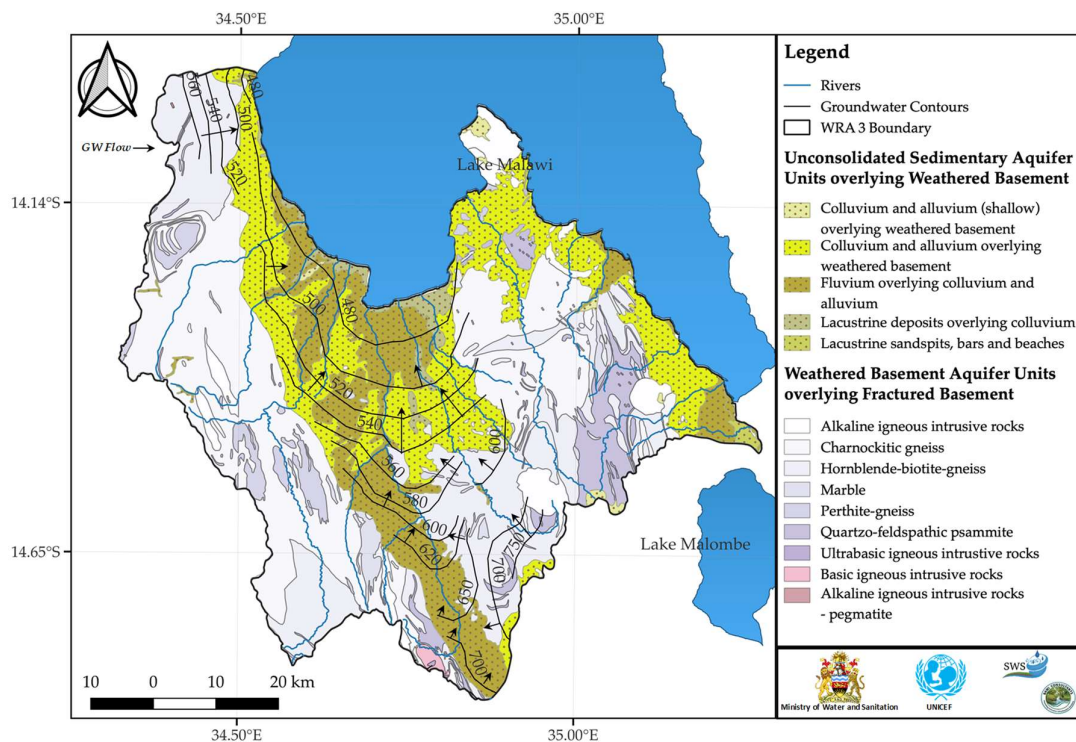


Figure 11. Groundwater level contours and flow direction in WRA 3 [1987 Hydrogeological Reconnaissance data] [water level contour interval 20m]

The details of particle size distribution and detailed drilling logs were not available or were not geospatial referenced and therefore could not be assigned to specific hydro stratigraphic units and it is recommended that continued work is needed to develop the hydrogeological records of the Ministry of Water and Sanitation. Caution is urged not to extrapolate limited data over a wider region in WRA 3 given the localised groundwater – surface water connections.

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 3 is based on prior hydrogeological reconnaissance. Groundwater level data for WRA 3 confirm a basin (rift formed) flow regime dominated by convergent groundwater flow towards Lake Malawi following topographic drainage (**Figure 11**). Groundwater flow in the southern basin in WRUs 3C and 3D is generally northwards towards the lake, but locally towards the Bwanje and Kahudira rivers and tributaries. Head contours are increasingly arcuate and convergent upon the rivers in their mid to upper reaches signifying base flow discharge and strongly gaining river conditions at moderate to higher elevations. Steepest hydraulic gradients of up to around 0.02 occur along the Bwanje valley western flanks near the Basement– unconsolidated aquifer interface reflecting the steeper topography. These aquifers are generally expected to be in hydraulic continuity with flows from the Basement draining into the unconsolidated aquifer. Hydraulic heads decline from 650 m asl in the upper Bwanje valley to 480 m approaching the Kasankha Bay shoreline from which a mean hydraulic gradient of 0.003 is calculated for a 45 km valley length. For a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2 a groundwater velocity of 5.5 m/yr is calculated for a gradient of 0.003 gradient and 36 m/yr for the 0.02 steeper valley flank gradient. Groundwater flows in the west of the basin in WRUs 3E and 3F are north-eastwards commensurate with and perpendicular lake shoreline. This is also found in WRU 3A in the basin east where relatively steep hydraulic gradients occur in the Nkopola area lake shoreline unconsolidated aquifer of around 0.007. These are around twice those found in the Kasankha Bay area and attributed to the proximity of the Basement to that Lake Malawi shoreline. Groundwater in WRU 3A near Lake Malawi is hydraulically linked to Lake Malawi, with a large number of substantial groundwater abstraction points (both mechanical and hand-pumped) along this densely populated shore. During lake high stands it is probable that lake water flows to groundwater units, and during seasonal lake level recession, flow is to Lake Malawi. Given the population base of WRU 3A groundwater contamination is considerable and widespread along the lake shore.

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 12** provides the distribution of the data held by the Ministry of Water and Sanitation for each WRU, and it is clear the distribution is skewed toward values of < 0.25l/s. This 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 WRA 3 there appears to be a trend to higher borehole yields related to alluvium aquifer units, with a number of production boreholes reporting yields in excess of 3l/s. In WRA 3 (**Figures 13a to 13f**) there is

potential in the colluvium, alluvial and fluvial units for higher yielding boreholes, in particular in WRU 3A, 3B, 3C, 3D and 3E where there are reported yields of up to 5l/s, but water quality issues from human activity and from fluid movement along fault zones and evaporation should be carefully evaluated prior in implementation of 'solar pump' groundwater systems. There is potential for artesian confined systems along the escarpment but detailed hydrogeological on-site mapping is needed to confirm, and site specific hydrogeological investigation is strongly recommended for implementation of any 'solar pumped' water supplies before full implementation.

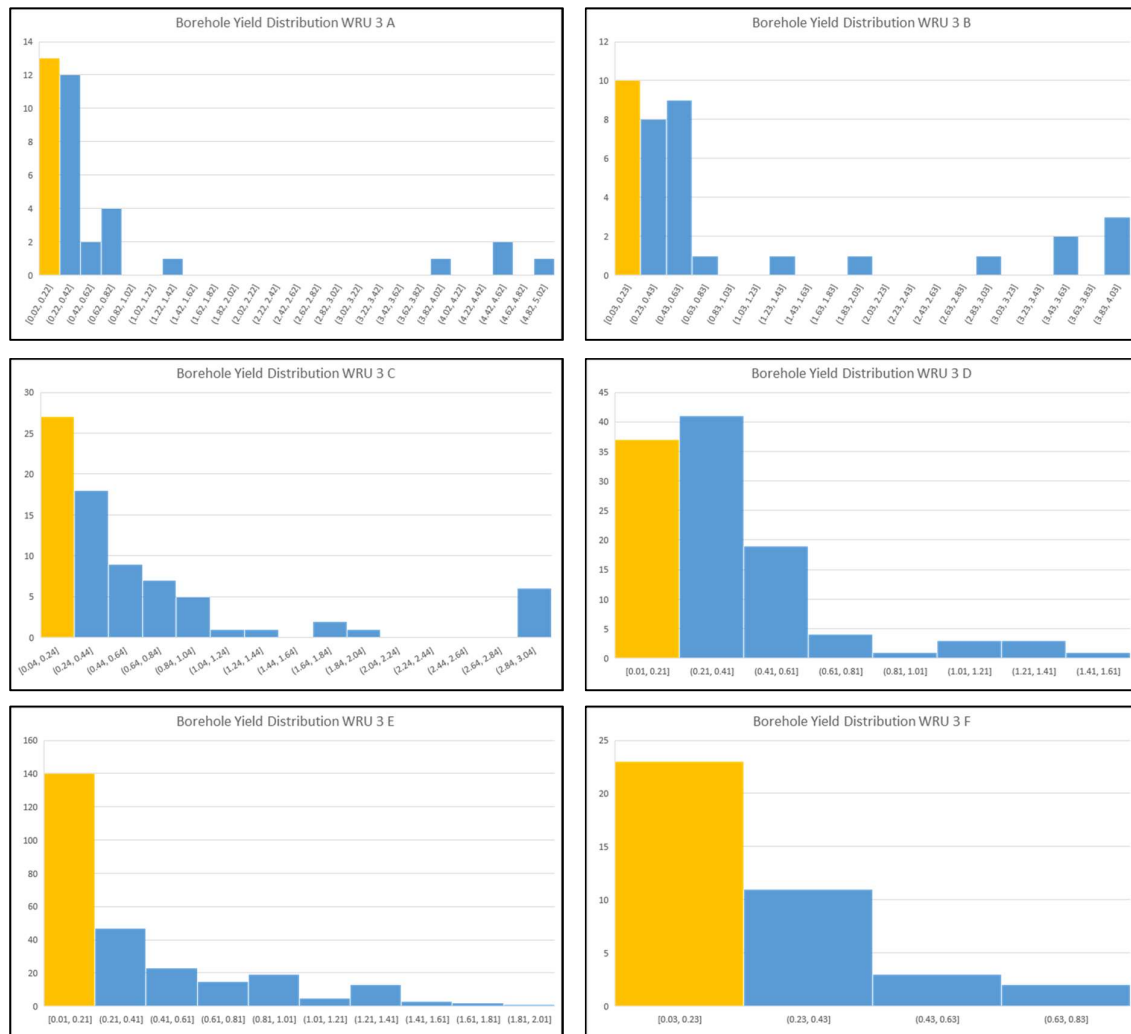


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 3 (WRU 3A, 3B, 3C, 3D, 3E, 3F) (y axis = n observations)

Though there are general trends which suggest the highest borehole yields are found in alluvial aquifers and along Lake Malawi, it is recommended that data on sediment distributions from drilling records in Ministry records are properly geospatially ground-truthed to develop hydrogeological cross sections for interpretation. The highest yielding boreholes in basement aquifers will likely be located mainly along linear structures and main streams and near contacts between different aquifers.

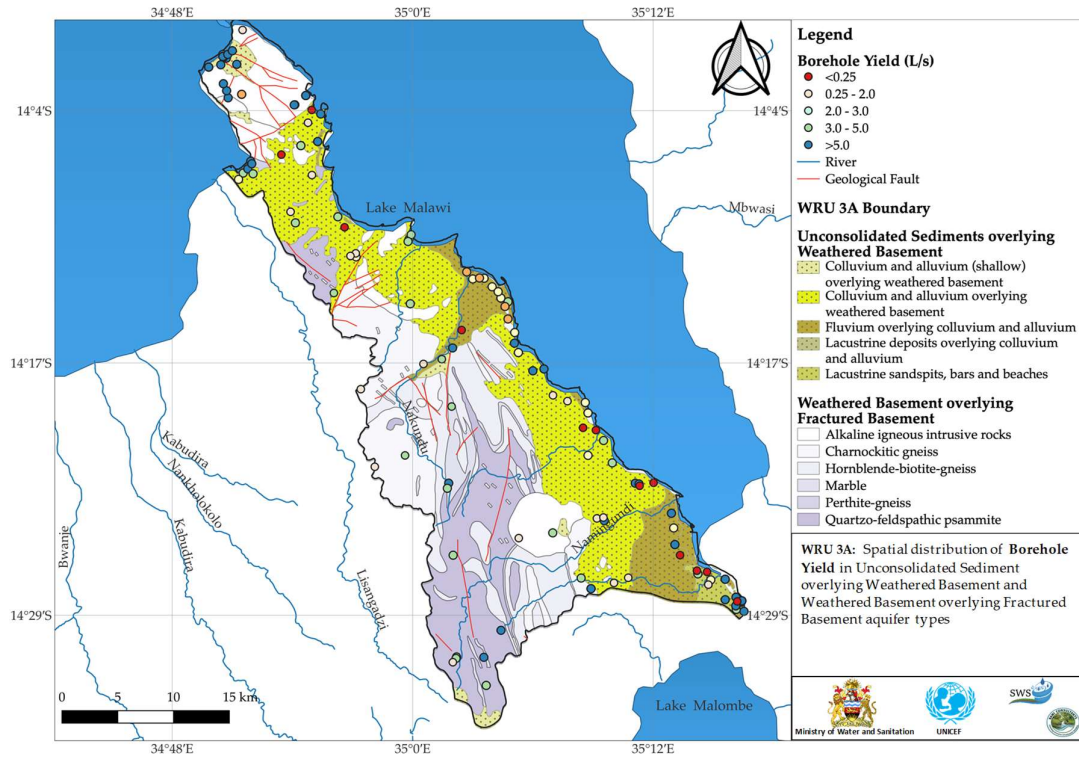


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 3A.

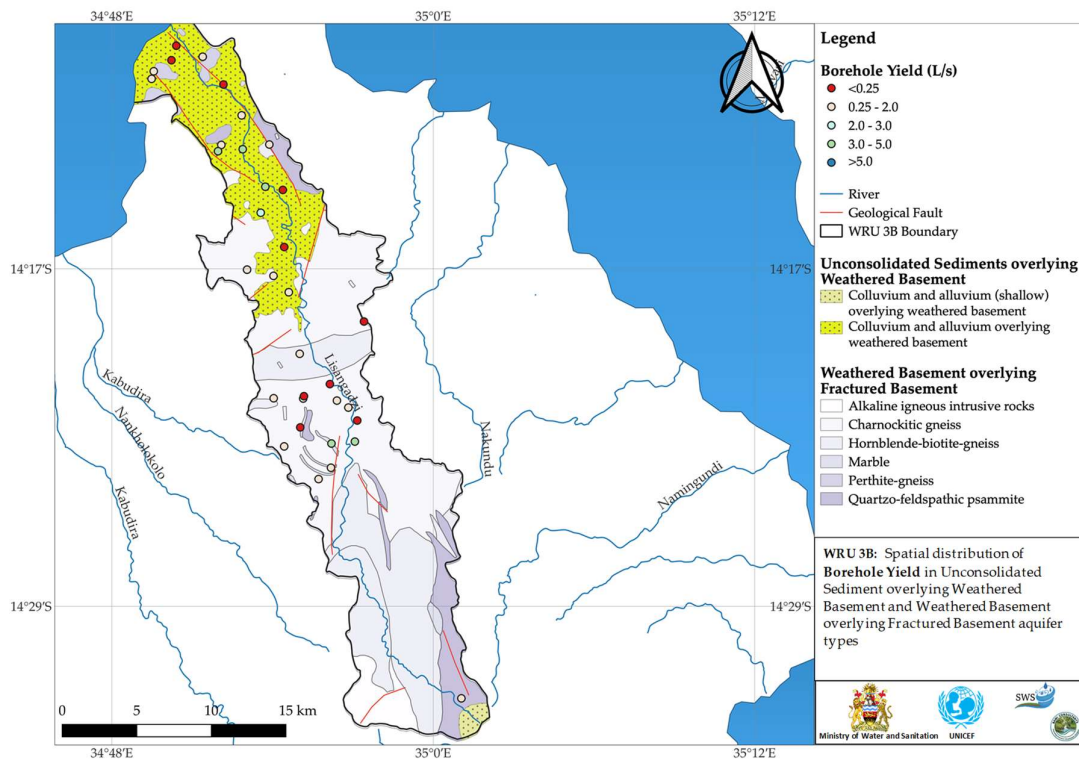


Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 3B.

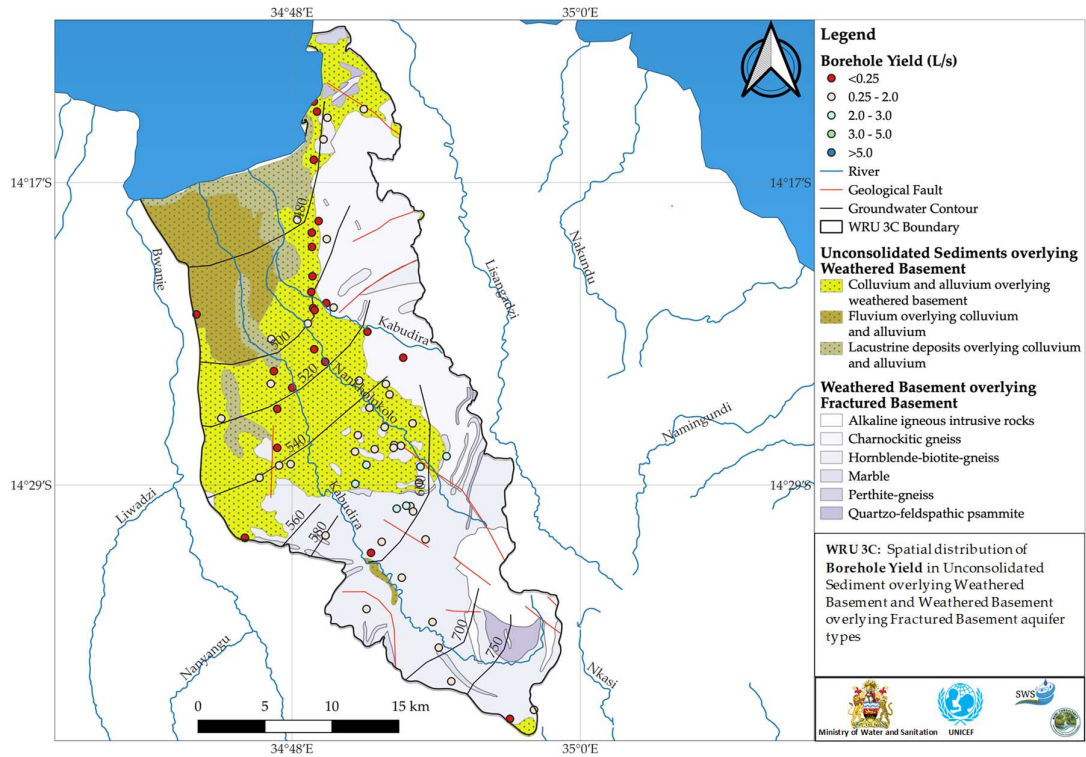


Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 3C.

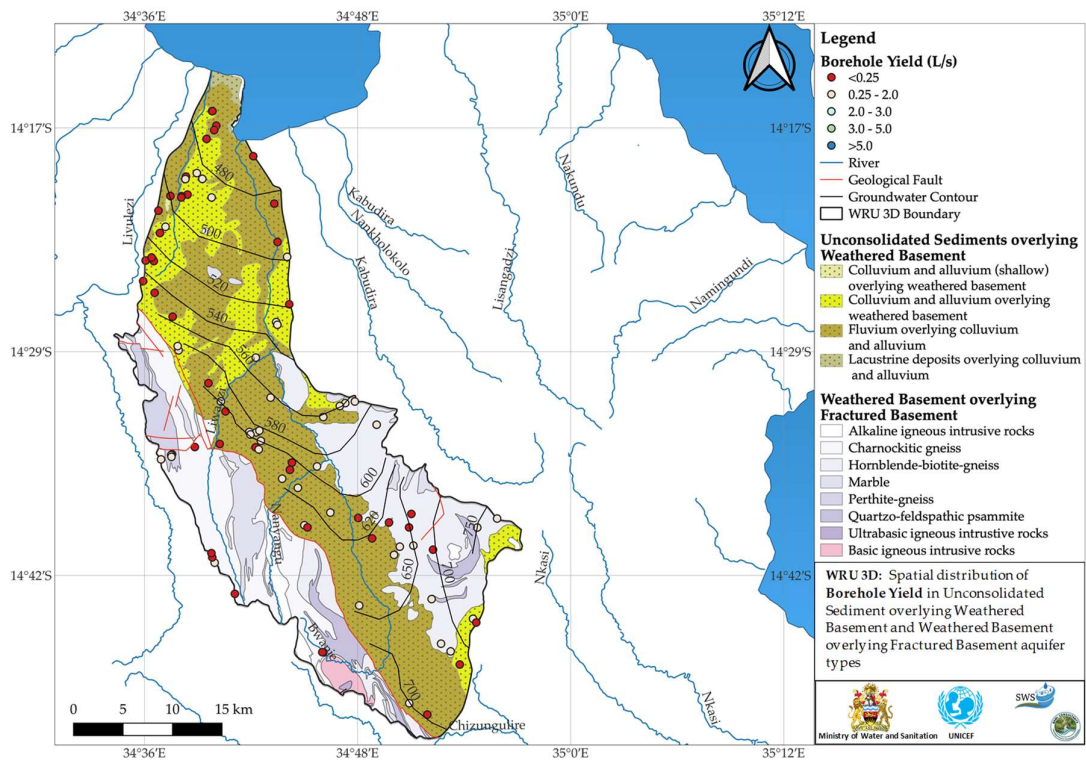


Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 3D.

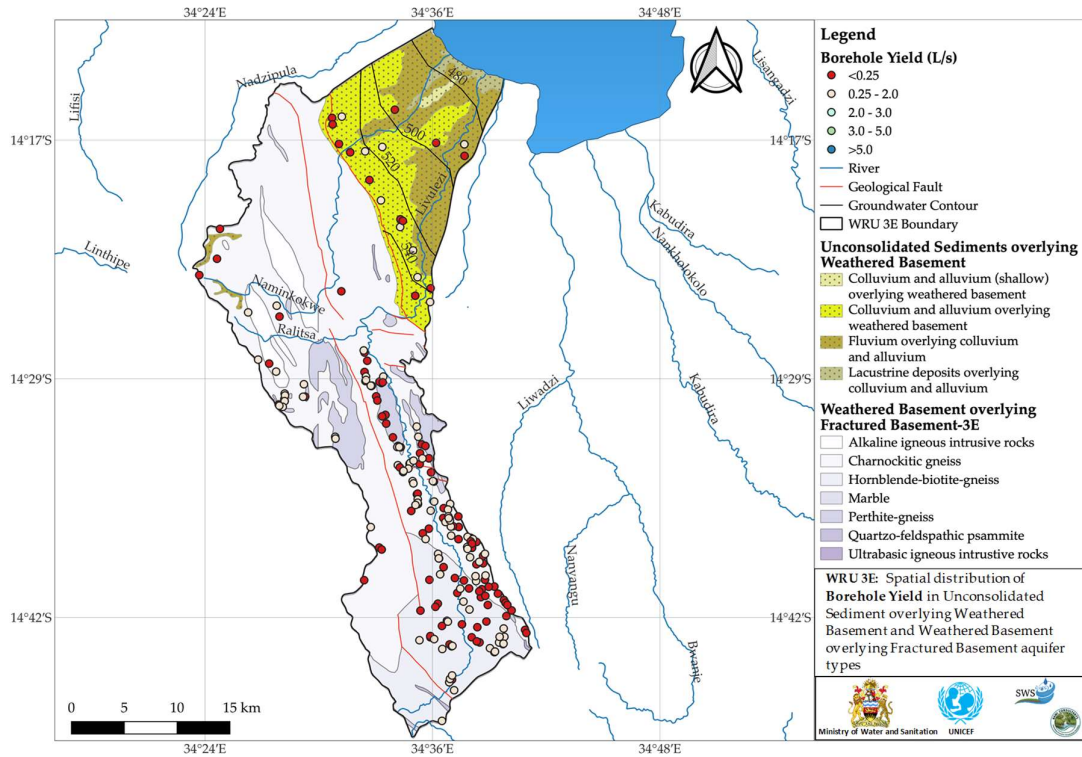


Figure 13e. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 3E.

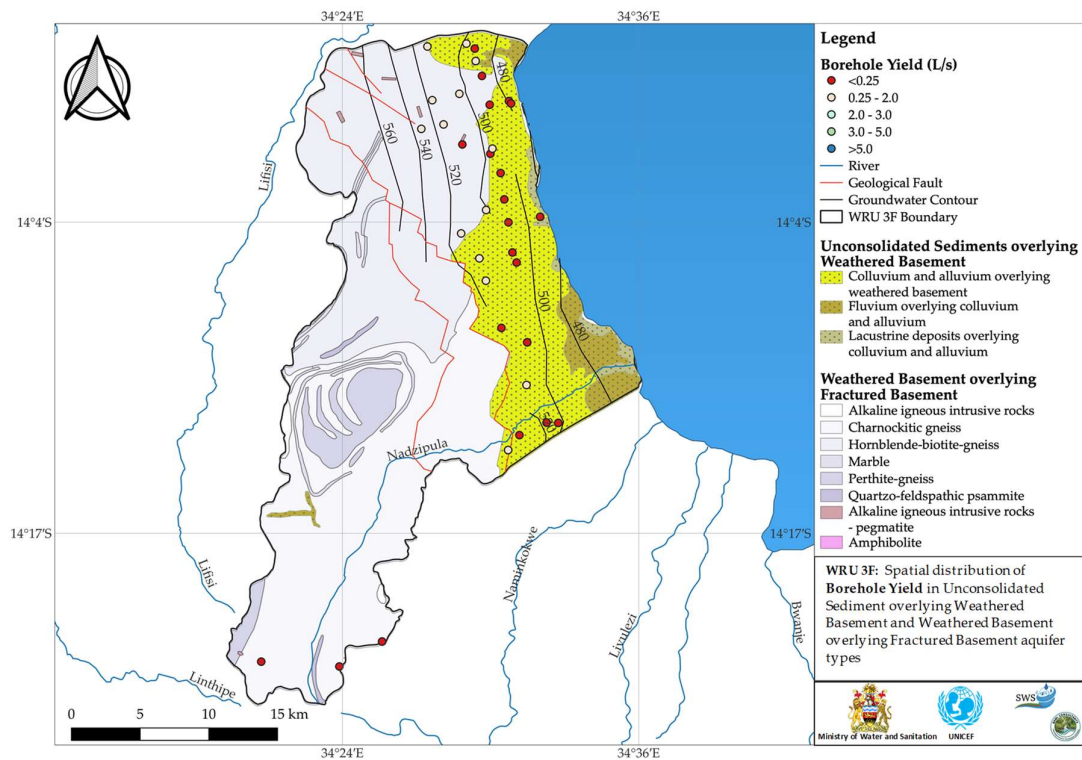


Figure 13f. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 3F.

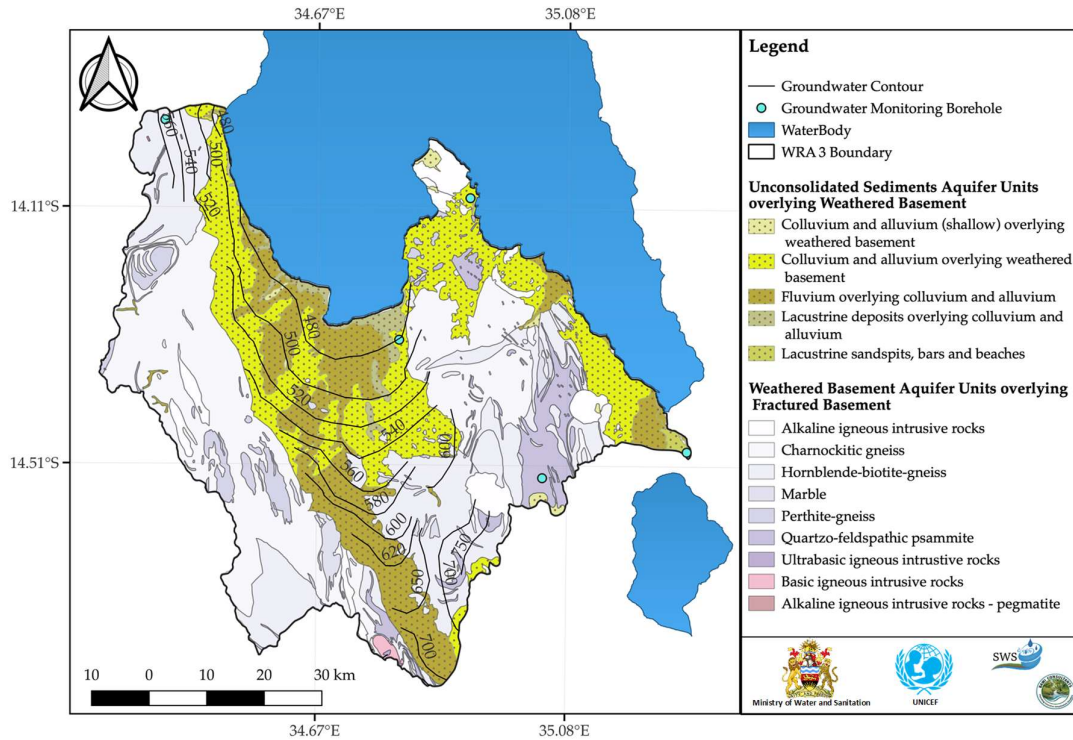


Figure 14a. Location of groundwater monitoring points in WRA 3.

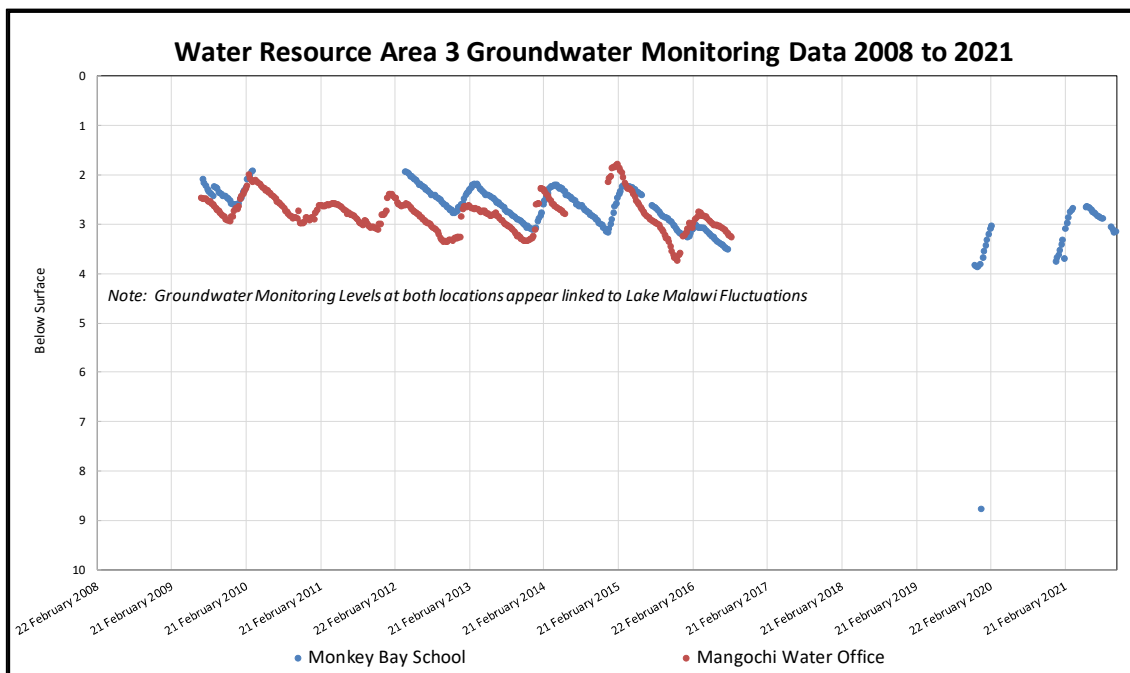


Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 6. (units assumed to be meters below ground level).

Groundwater Table Variations

There is a number of semi-operational groundwater monitoring station within WRA 3 that have data (**Figure 14a** and **Figure 14b**). Unfortunately, the data is not complete for most sites and does not cover enough time or locations to follow climate changes. The long-term data for sites at the Monkey Bay School and Mangochi Water Office sites clearly show low amplitude (ca 1m per annum) variation that can be directly correlated to annual changes in Lake Malawi water levels confirming the sedimentary units are in hydraulic connection with Lake Malawi. Data from the 2020 National Survey suggested seasonal water table declines in shallow groundwater supplies and this is supported by the data in **Figure 14b**. It is possible that long-term trends may relate to climate variability (rainfall, recharge and surface-water groundwater relationships). Given there are no borehole logs and multi-level installations that separate different hydro-stratigraphic units, the true nature of surface water / groundwater interaction and recharge effects cannot be determined from the data or the current monitoring network. It is recommended that multi-level installations are placed into each hydrostratigraphic unit is an area for future investment and in areas of high human activity and geogenic risks that bespoke water quality monitoring is undertaken. Given the relationship of the water table, the Lake and the rivers, monitoring of the surface water and groundwater tables is strongly advised where interaction likely occurs, especially if solar boreholes are used.

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). These are considered to be more accurate than estimates from other studies which suggested up to 120mm of recharge (13% of rainfall), these published estimates are unrealistically high and estimates of between 1 and 7.5% of rainfall are used in here.

Table4a. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 3A, 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 High Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	75.6	10%	35%	0.02	0.10	151.2	2,646.8	
Lacustrine units	10.9	10%	35%	0.02	0.03	21.8	114.5	
Colluvial etc.	277.9	10%	30%	0.02	0.06	555.8	5,002.2	
W & F Basement	532.6	1%	10%	0.02	0.03	106.5	1,597.8	
	Area of WRU (km ²) 897.0	3A WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	835.4	9,361.3	Total Volume Groundwater
		901 Average Rainfall in WRU		9.01	67.575	8.1	60.6	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]						103	154	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 3B, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	0.0	10%	35%	0.02	0.10	0.0	0.0	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	89.4	10%	30%	0.02	0.06	178.8	1,608.8	
W & F Basement	295.9	1%	10%	0.02	0.03	59.2	887.8	
	Area of WRU (km ²)	3B WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	237.9	2,496.6	Total Volume Groundwater
	385.3	924 Average Rainfall in WRU		9.24	69.3	3.6	26.7	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						67	93	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 3C, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	73.3	10%	35%	0.02	0.10	146.7	2,566.8	
Lacustrine units	53.0	10%	35%	0.02	0.03	105.9	556.1	
Colluvial etc.	233.5	10%	30%	0.02	0.06	467.0	4,202.8	
W & F Basement	419.9	1%	10%	0.02	0.03	84.0	1,259.8	
	Area of WRU (km ²)	3C WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	803.6	8,585.5	Total Volume Groundwater
	779.7	933 Average Rainfall in WRU		9.33	69.975	7.3	54.6	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	157	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4d. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 3D, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	477.6	10%	35%	0.02	0.10	955.1	16,715.0	
Lacustrine units	6.5	10%	35%	0.02	0.03	13.1	68.7	
Colluvial etc.	178.6	10%	30%	0.02	0.06	357.2	3,215.0	
W & F Basement	510.9	1%	10%	0.02	0.03	102.2	1,532.7	
	Area of WRU (km ²)	3D WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	1,427.6	21,531.5	Total Volume Groundwater
	1,173.6	958 Average Rainfall in WRU		9.58	71.85	11.2	84.3	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]						127	255	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4e. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 3E, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	106.8	10%	35%	0.02	0.10	213.7	3,739.3	
Lacustrine units	9.9	10%	35%	0.02	0.03	19.7	103.6	
Colluvial etc.	130.3	10%	30%	0.02	0.06	260.5	2,344.8	
W & F Basement	744.1	1%	10%	0.02	0.03	148.8	2,232.4	
	Area of WRU (km ²)	3E WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	642.8	8,420.1	Total Volume Groundwater
	991.1	966 Average Rainfall in WRU		9.66	72.45	9.6	71.8	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]						67	117	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4f. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 3F, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	27.9	10%	35%	0.02	0.10	55.8	976.5	
Lacustrine units	8.9	10%	35%	0.02	0.03	17.8	93.5	
Colluvial etc.	149.2	10%	30%	0.02	0.06	298.4	2,685.4	
W & F Basement	560.9	1%	10%	0.02	0.03	112.2	1,682.8	
	Area of WRU (km ²)	3F WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	484.2	5,438.2	Total Volume Groundwater
	746.9	964 Average Rainfall in WRU		9.64	72.3	7.2	54.0	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]						67	101	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 3 ranges between 47 Million Cubic Meters (MCM) and 352 MCM per year, with a mean age of groundwater of 118 years across the Water Resource Area (**Tables 4a to 4f**). 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 3

Groundwater major-ion water quality in WRA 3 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**). Groundwater in WRA 3 has, in general, higher than average salinity that is likely due to evaporative enrichment due to low groundwater velocities in sedimentary aquifers, or due to fluid movement along rift faults flowing into aquifers from below.

Table 5. Distribution of dissolved species in groundwater WRA 3. 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 3	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	7.4	890	112.6	60.1	4.5	0.9	88.1	5.1	61.4	25.1	0.5
Std Dev	0.7	1,449	257	124	11.3	0.7	246	25.9	72.1	36.3	1.8
Median	7.3	440	30.5	12.1	0.4	0.7	21.8	1.9	36.8	14.9	0.1
Max	9.3	14,471	2,056	875	86	8.0	4,020	630	671	389	13.0
Min	5.0	40.0	10.0	1.0	0.0	0.0	0.9	0.1	0.9	0.4	0.0
n	647	667	471	629	492	542	663	661	661	549	164

Piper plots of the WRA 3 water quality data suggest most water has expected geochemical changes from water-rock interactions dominated by Ca-Mg-HCO₃ type waters with a clear trend within the unconsolidated sediments overlying weathered basement and fractured basement for increasing Na-Cl-SO₄ likely due to either evaporative enrichment or fault zone fluids as for those increases in chloride, sulphate, and high fluoride measurements, geologic sources are likely (**Figure 14a and 14b**). The average groundwater age, precipitation rate and calculated recharge rates together with the moderate-high electrical conductivity points to recent meteoric recharge of much of the groundwater with water-rock interactions and fault-zone water movements, however in low-lying areas near Lake Malawi there are zones of high EC groundwater most likely related to evaporative enrichment.

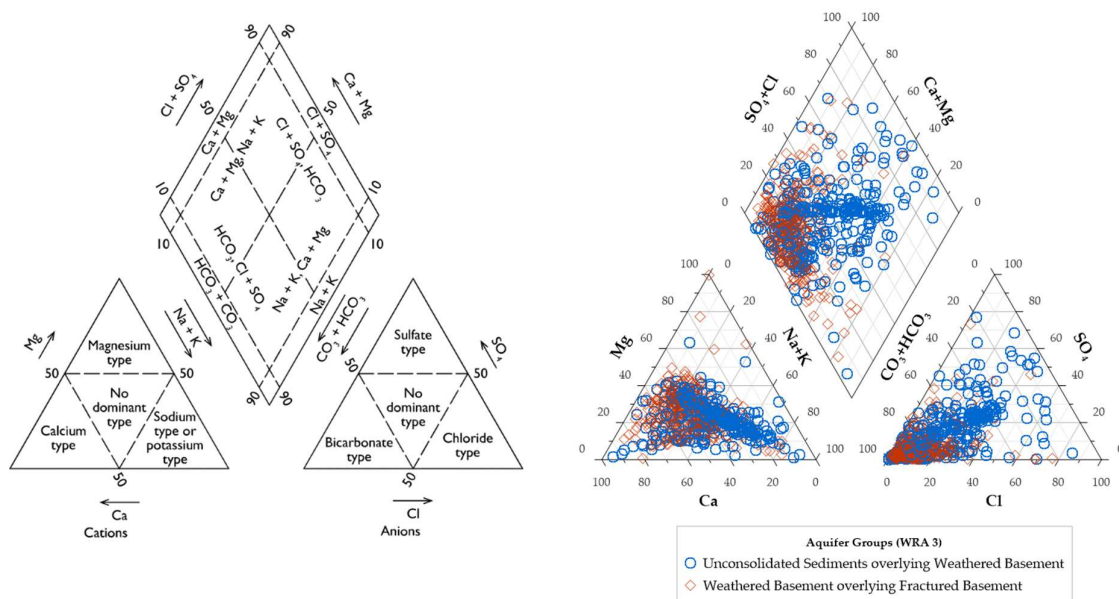


Figure 14a, 14b. Piper Diagrammes of Groundwater Samples in WRA 3 and for each Aquifer Type in WRA 3.

The distribution of key dissolved water quality species in groundwater of WRA 3 is provided in **Figure 15**. Of particular concern in WRA 3 is high salinity, high fluoride and an increasing trend of high nitrate in groundwater likely from pit latrines. However, caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine in WRA 3, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

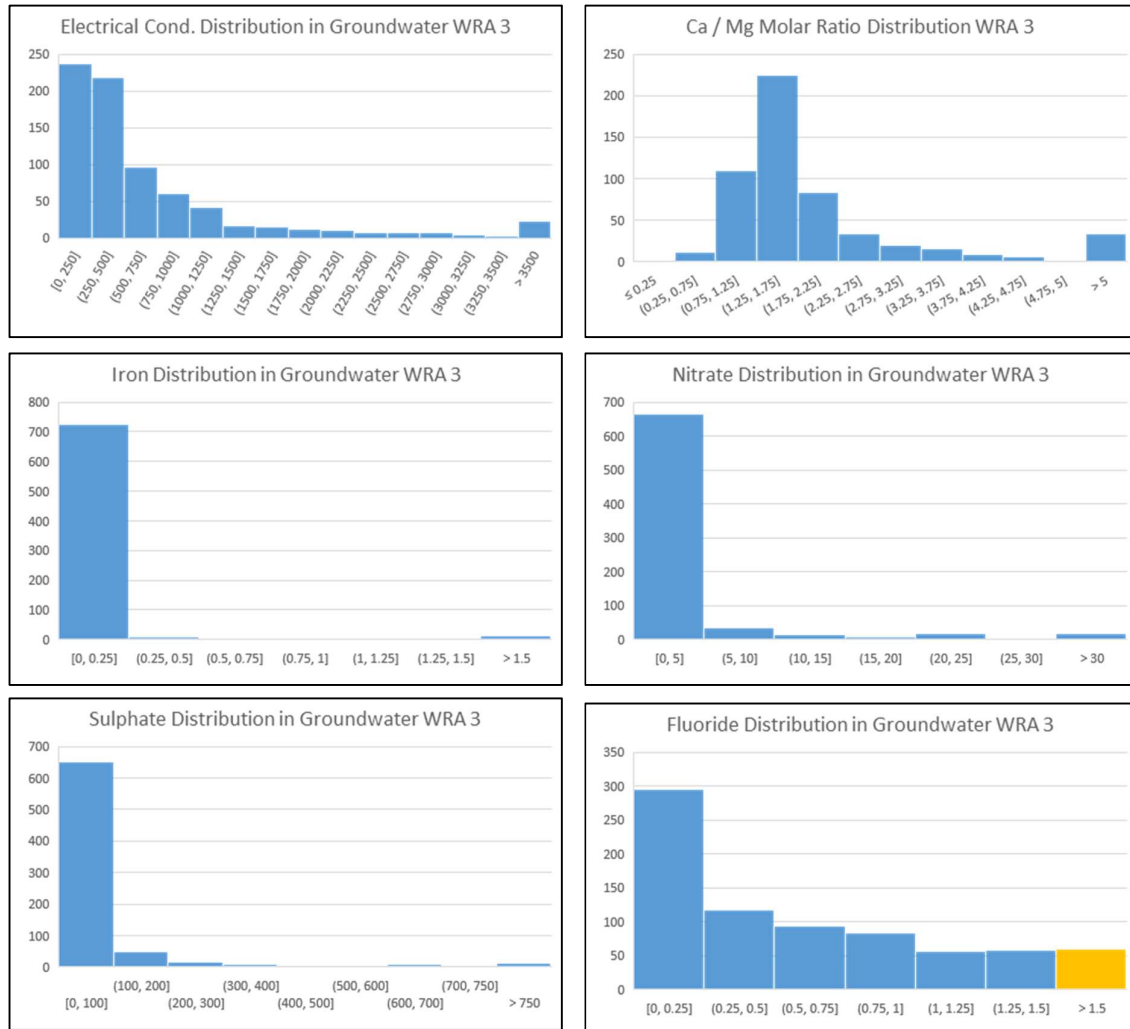


Figure 15 Distribution of chemical species in groundwater within WRA 3 (y axis = n observations).

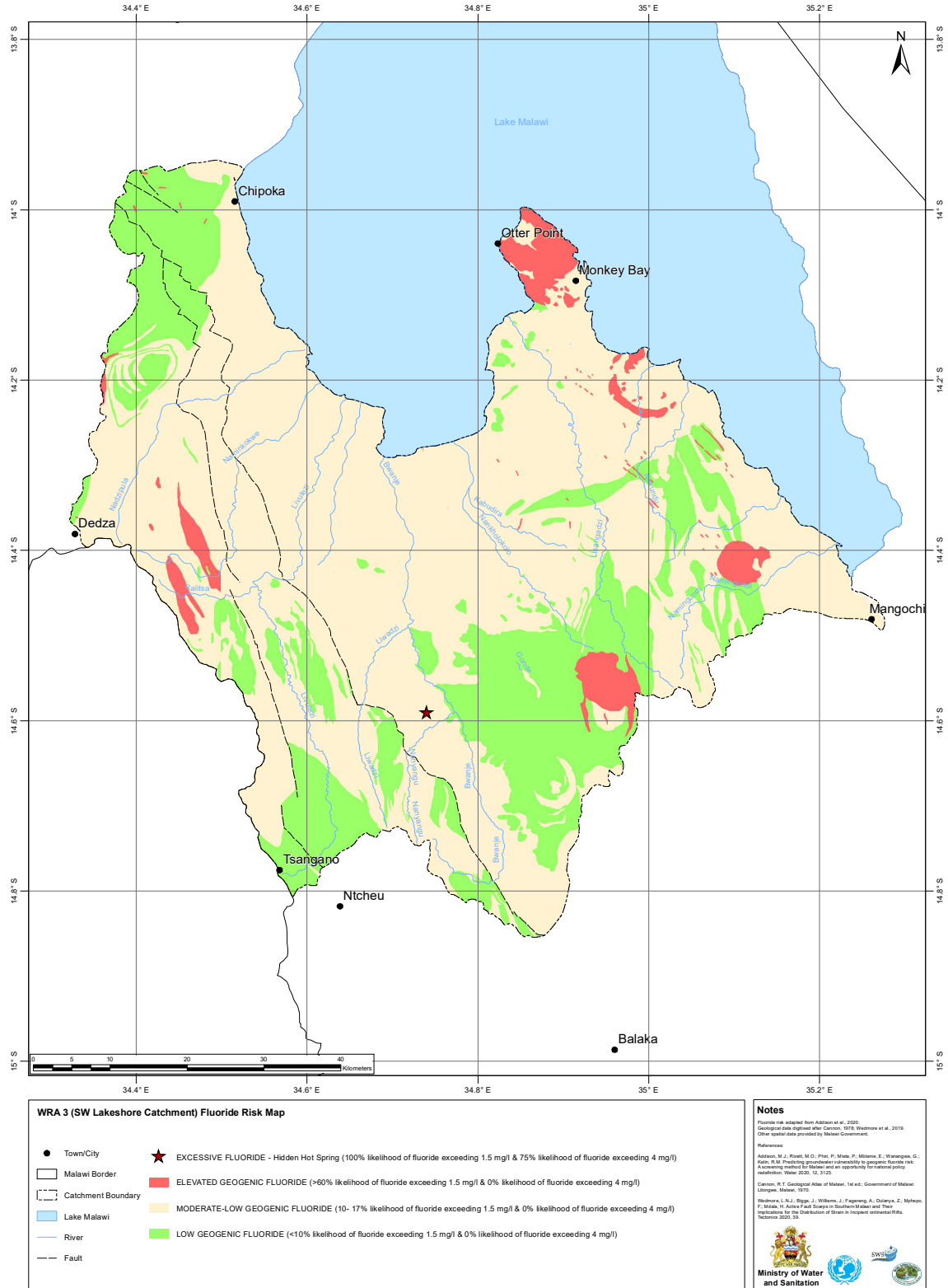


Figure 16. Groundwater Fluoride Risk Map WRA 3 (after Addison et. al. 2021).

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 3 (**Table 4** and **Figure 15**) is above the Malawi average with analysis reporting above the national groundwater limit of 3,500mg/l, 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 specific hydrogeological units or source. Isotope Hydrology study is strongly advised, and it is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation.

Fluoride

Even though there is little prevalence for surface expression of hot springs in WRA 3, the wide range of fluoride-bearing minerals places WRA 3 in a **Higher Risk** category for fluoride in groundwater. There are known areas of fluorosis (Addison et al 2021). Groundwater data drawn from the recent national-scale assessments (**Figure 16**) reveals a significant number of analyses are above 1.5mg/l, known areas where fault zones underlie aquifers (**Figure 16**) should be targeted for re-analysis as 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. Additionally, surface water supplies from the areas where basement geology contains fluoride bearing minerals should be monitored for groundwater and any spring runoff that may contain fluoride. 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 3 is planned and implemented.

Arsenic

A recent national collation of arsenic groundwater survey data (Rivett et al 2018) found widespread low concentrations but with only a few above the WHO 10 µg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. This national dataset did sample WRA 3 with no elevated levels round, however arsenic risks may exist due to the presence of hot springs on the western rift zone, this remain unproven due to a lack of routine, geospatially managed WQ analyses. It is recommended that a detailed and systematic survey of groundwater quality in WRA 3 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 (Hurt 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 3.

Water Resource Unit	Population (Worldpop online)					Projection	Latrine fecal sludge	Cumulative Sludge loading
	Calculated Number of Latrine users							
	Year 2011 - 2012	Year 2013 - 2014	Year 2015 - 2016	Year 2017 - 2018	Year 2019 - 2020	Year 2021 - 2022	Total Volume over 10 year period (Liters)	Estimated Total Loading (metric tonnes fecal sludge 2012 - 2022)
3A	135,500	144,750	153,705	164,336	175,230	202,480	527,040,447	632,449
3B	27,981	30,146	32,317	34,575	36,848	34,976	106,295,808	127,555
3C	55,963	60,424	65,318	70,449	75,364	70,467	214,911,514	257,894
3D	154,231	165,760	178,629	191,780	204,913	191,496	586,877,056	704,252
3E	167,291	179,916	192,095	204,186	216,322	206,445	629,778,099	755,734
3F	99,638	105,438	112,161	120,017	127,728	129,922	375,247,662	450,297
WRA 3	640,603	686,435	734,225	785,343	836,405	835,787	2,440,150,586	2,928,181

A recent publication by Rivett et al (2022) provided strong evidence of pit-latrine induced e-coli contamination of groundwater supplies regardless of season (wet / dry). Water resource unit 7 has a modelled calculated total of 2,928,181 metric tonnes of faecal matter loading over the 10-year period (2012-2022) (Table 6). Over the same 10-year period the modelled number of pit latrine users in the region increased by 195,184. WRA 3 covers roughly 4.1% 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, 8,189 metric tonnes of fertiliser would be used in WRA 3 per year which is 36 times less than faecal matter was added to this WRA this 10-year period.

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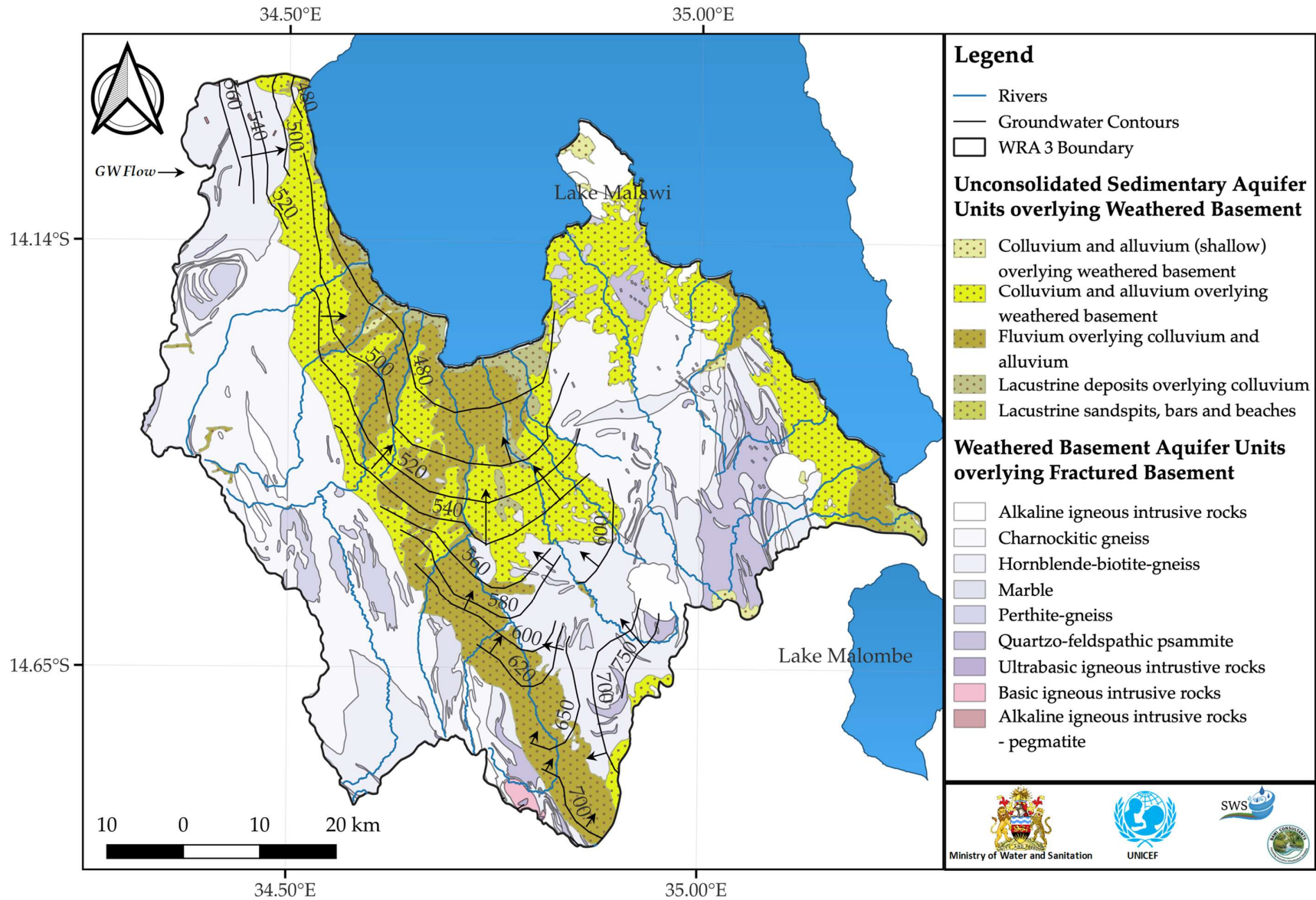
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Water Resource Unit (WRA) 4 Figures

Figure WRA 3.0: Aquifer Units and Groundwater Level Contours Water Resources Area 3

Figure WRA 3.0: Aquifer Units and Groundwater Level Contours WRA 3



WRU 3A Figures

Figure WRU 3A.1 Land Use and Major Roads

Figure WRU 3A.2 Rivers and Wetlands

Figure WRU 3A.3 Hydrogeology Units and Water Table

Figure WRU 3A.4 Groundwater Chemistry Distribution Electrical Conductivity [uS]

Figure WRU 3A.5 Groundwater Chemistry Distribution of Sulphate [ppm]

Figure WRU 3A.6 Groundwater Chemistry Distribution Chloride [ppm]

Figure WRU 3A.7 Groundwater Chemistry Distribution Sodium [ppm]

Figure WRU 3A.8 Groundwater Chemistry Distribution Calcium [ppm]

Figure WRU 3A.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 3A.10 Borehole Yield Map for data held by the Ministry

Figure WRU 3A.1 Land Use and Major Roads

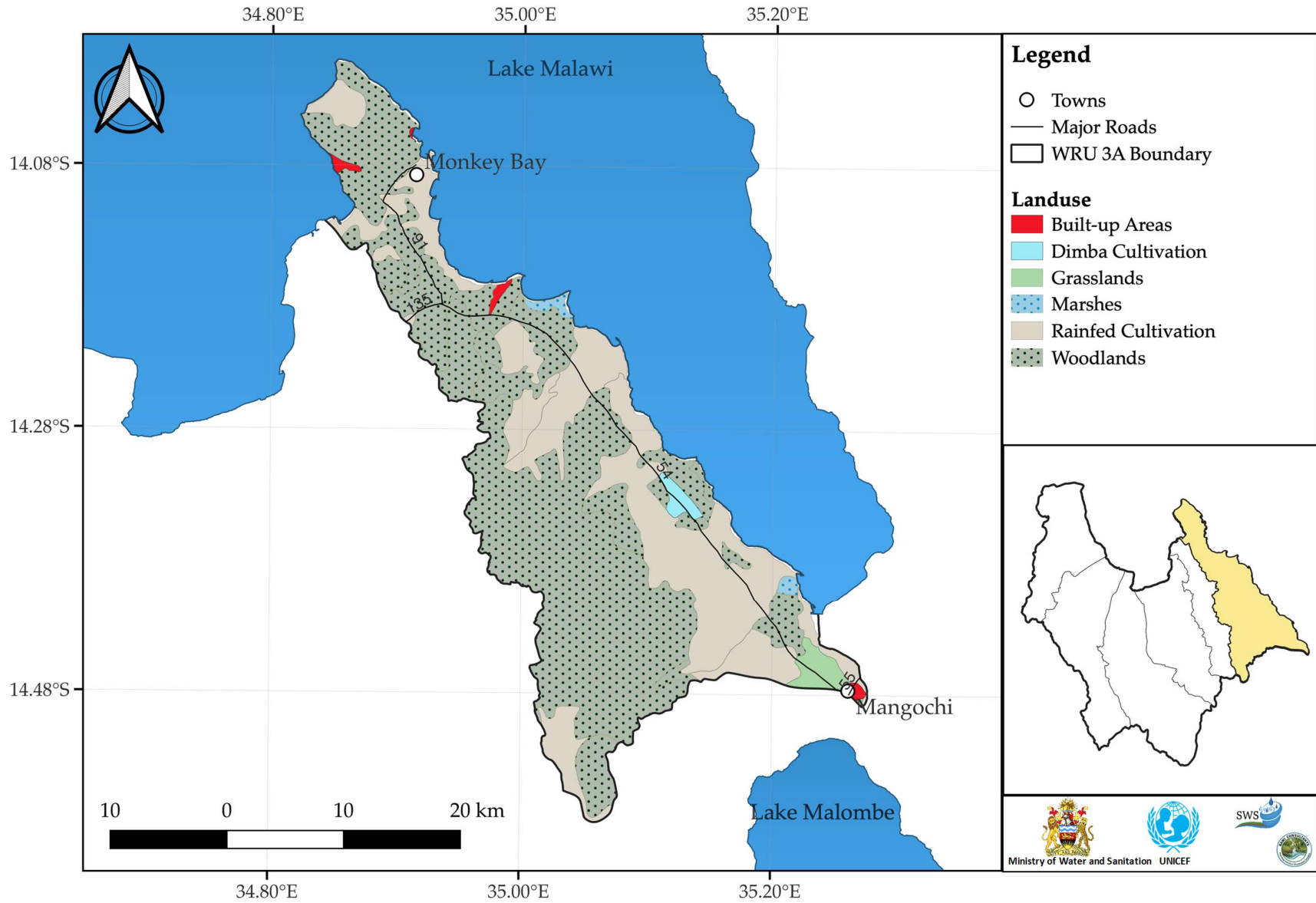


Figure WRU 3A.2 Rivers and Wetlands

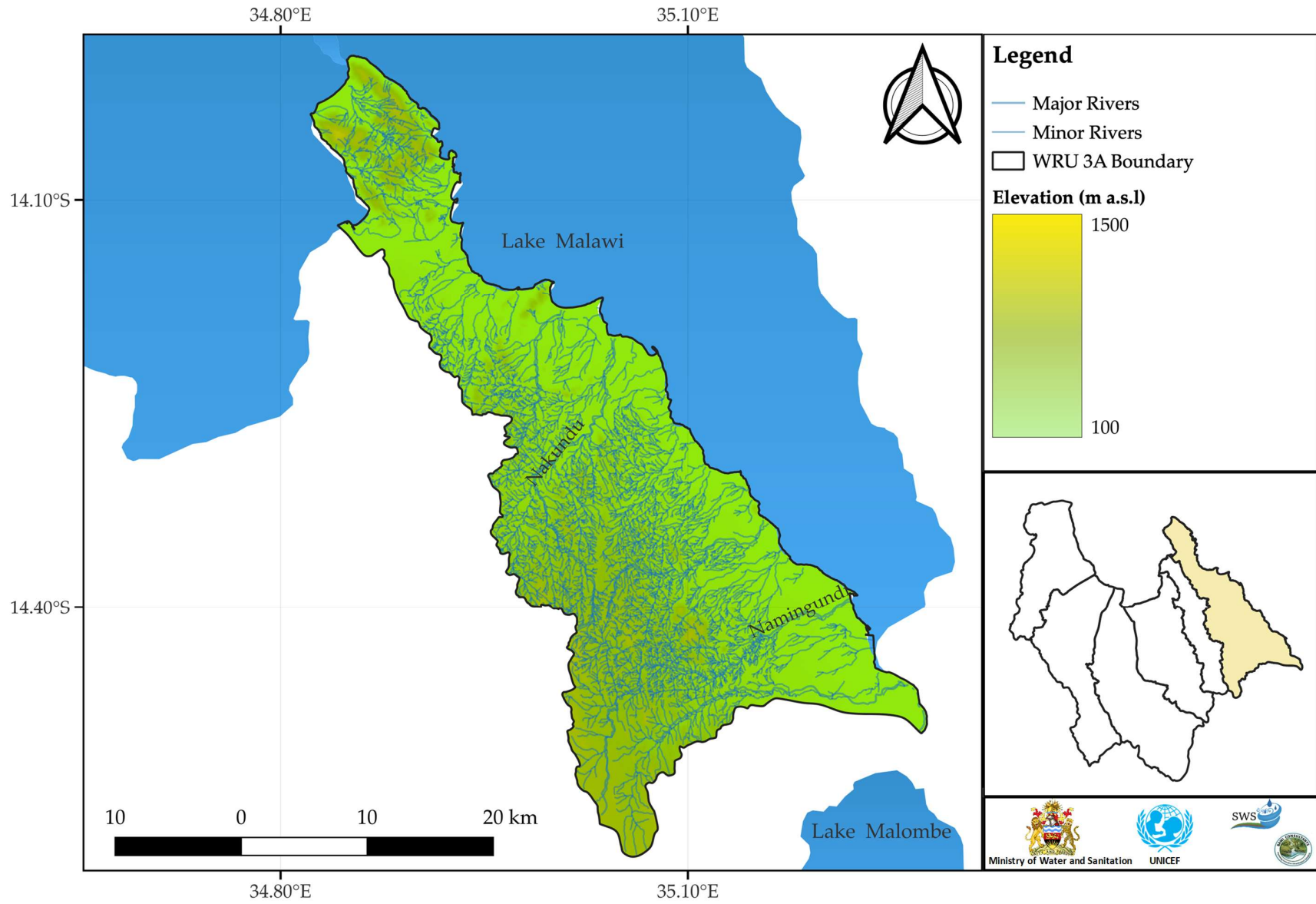


Figure WRU 3A.3 Hydrogeology Units and Water Table

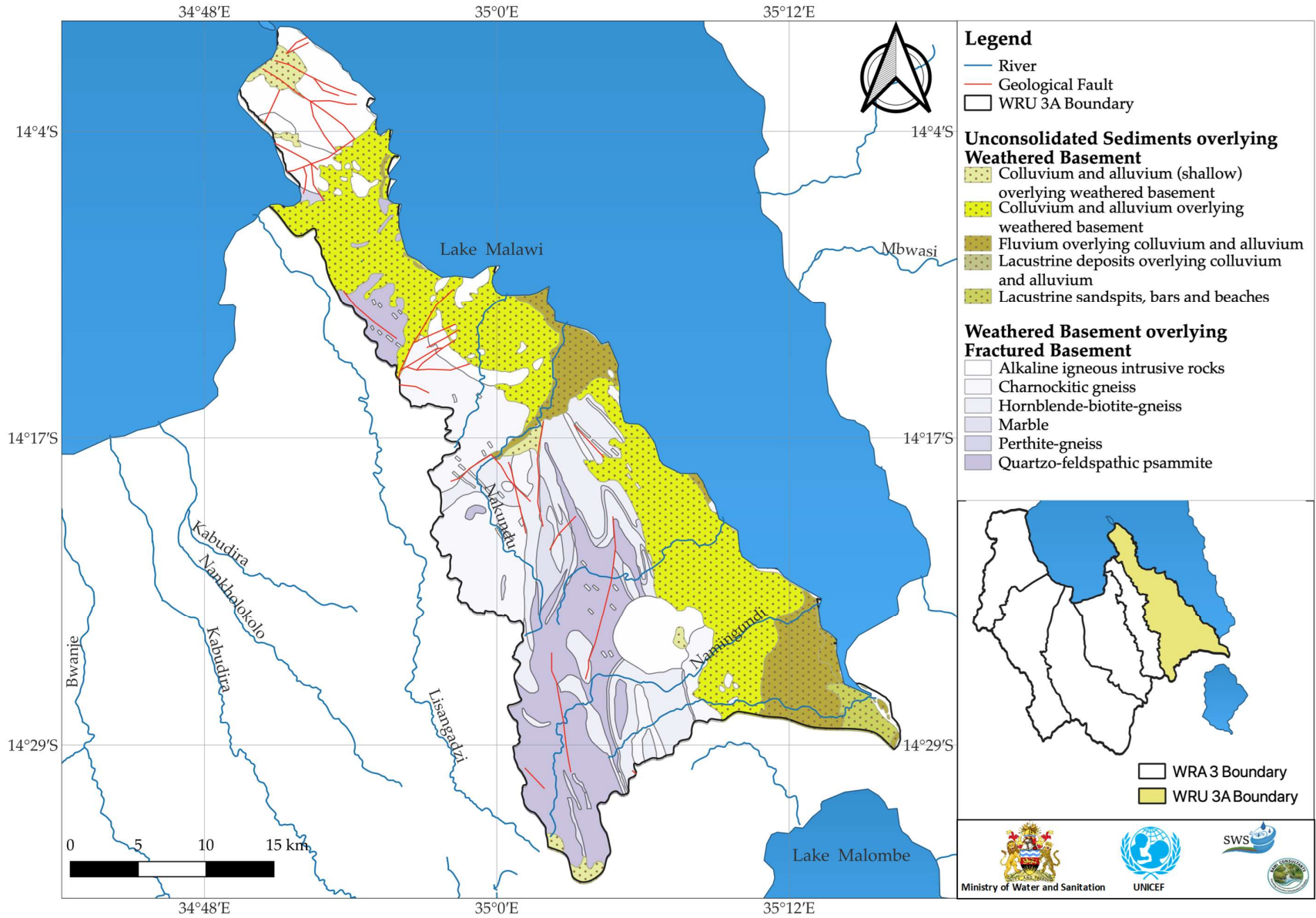


Figure WRU 3A.4 Groundwater Chemistry Distribution Electrical Conductivity

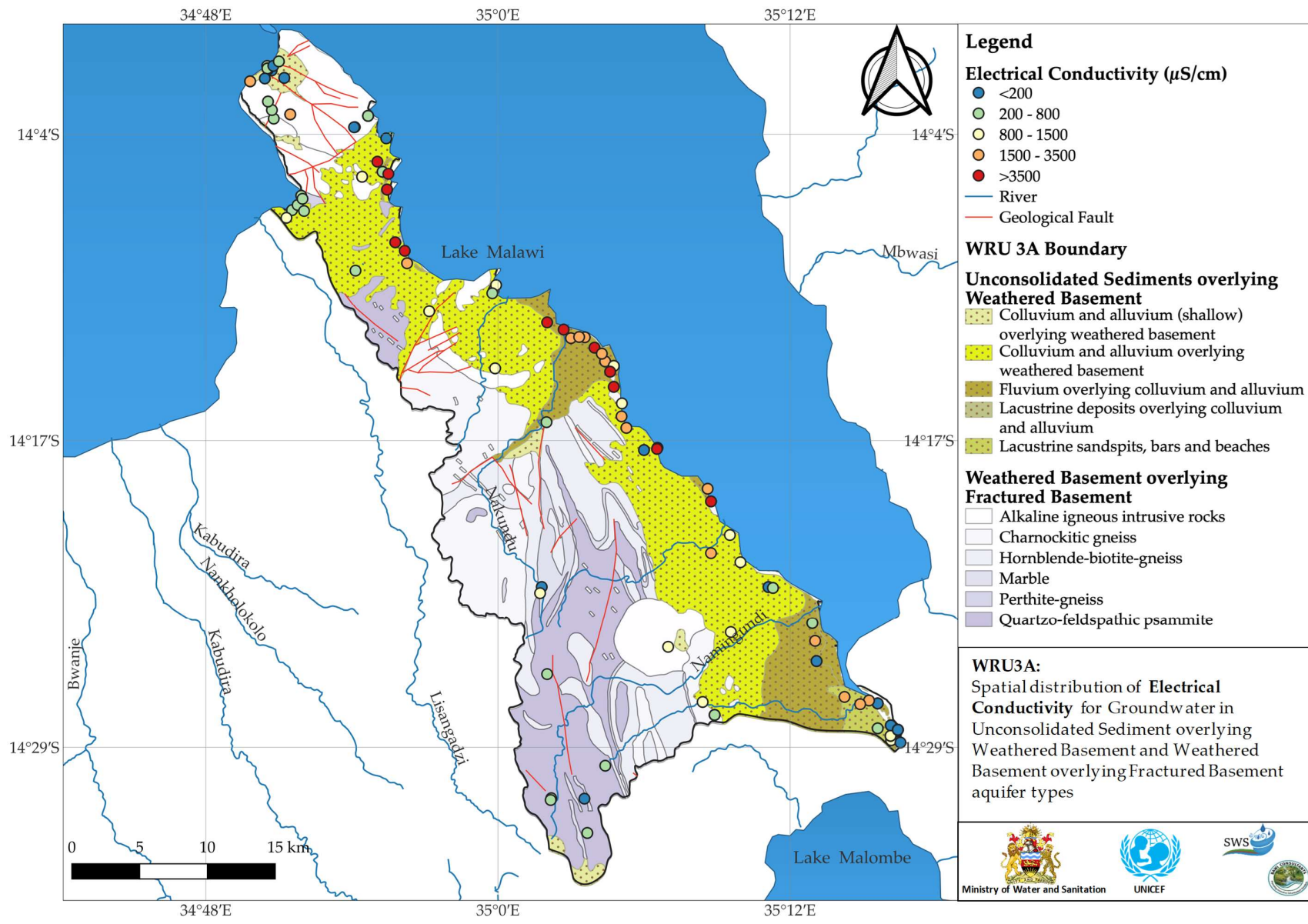


Figure WRU 3A.5 Groundwater Chemistry Distribution Sulphate

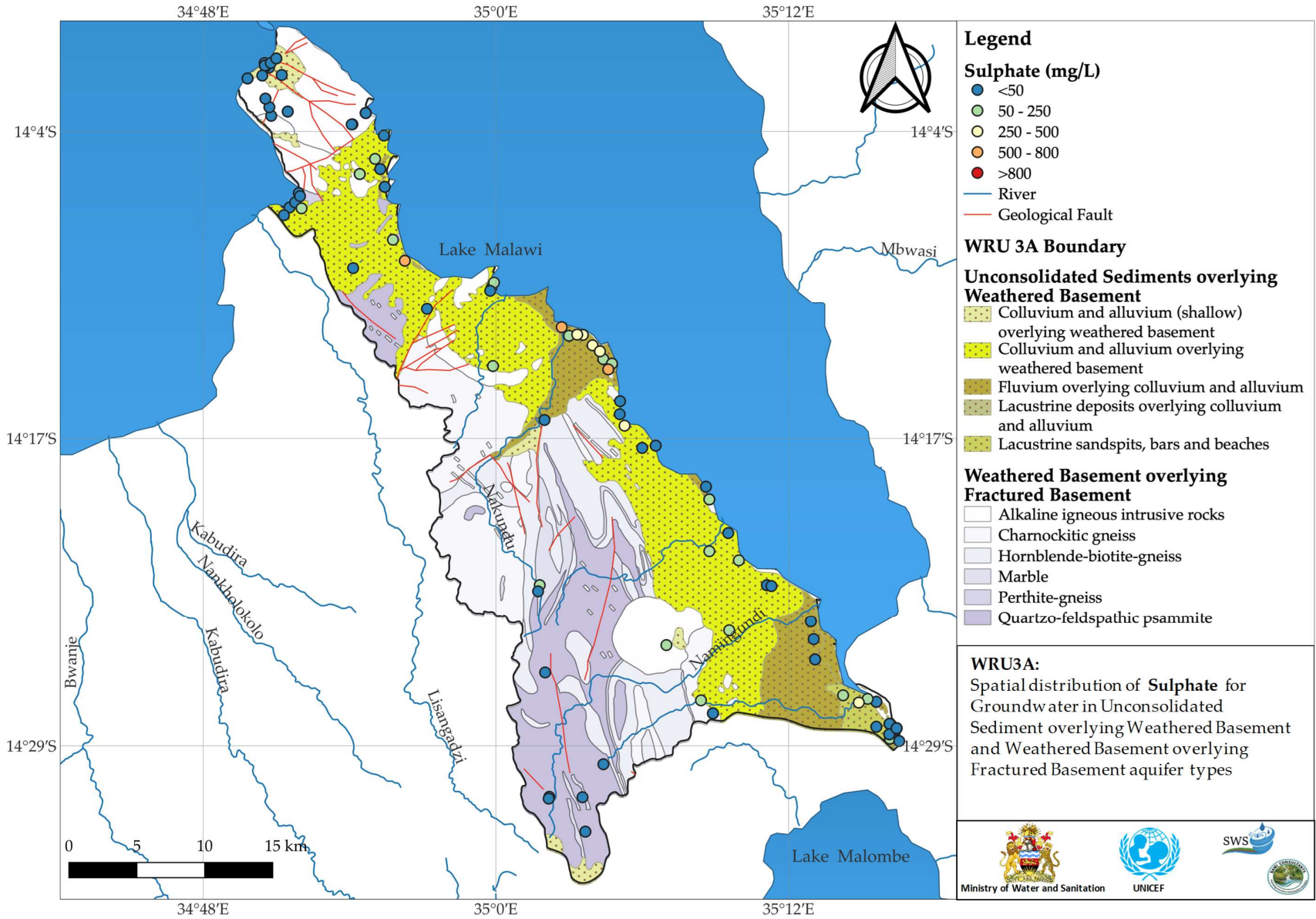


Figure WRU 3A.6 Groundwater Chemistry Distribution Chloride

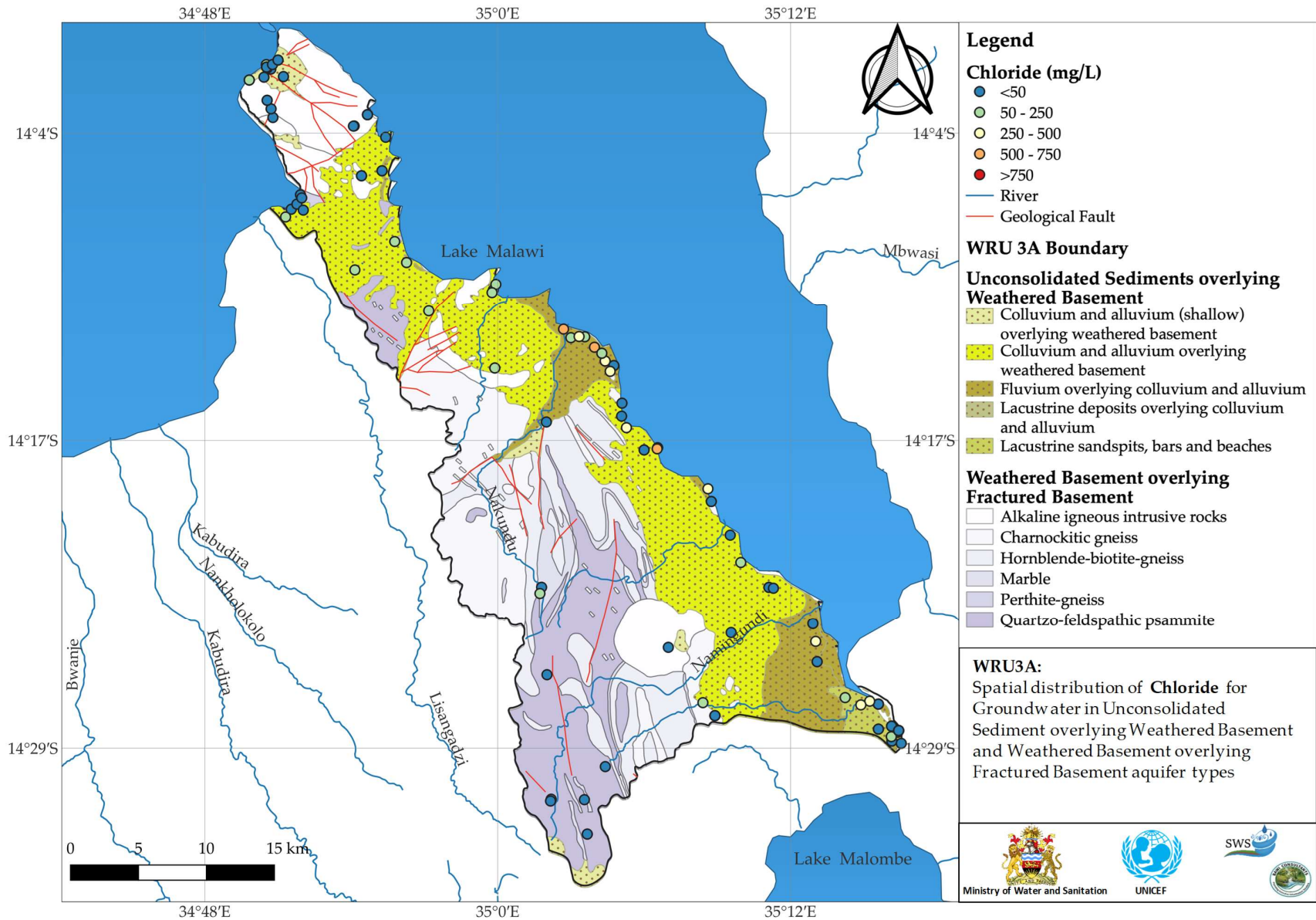


Figure WRU 3A.7 Groundwater Chemistry Distribution Sodium

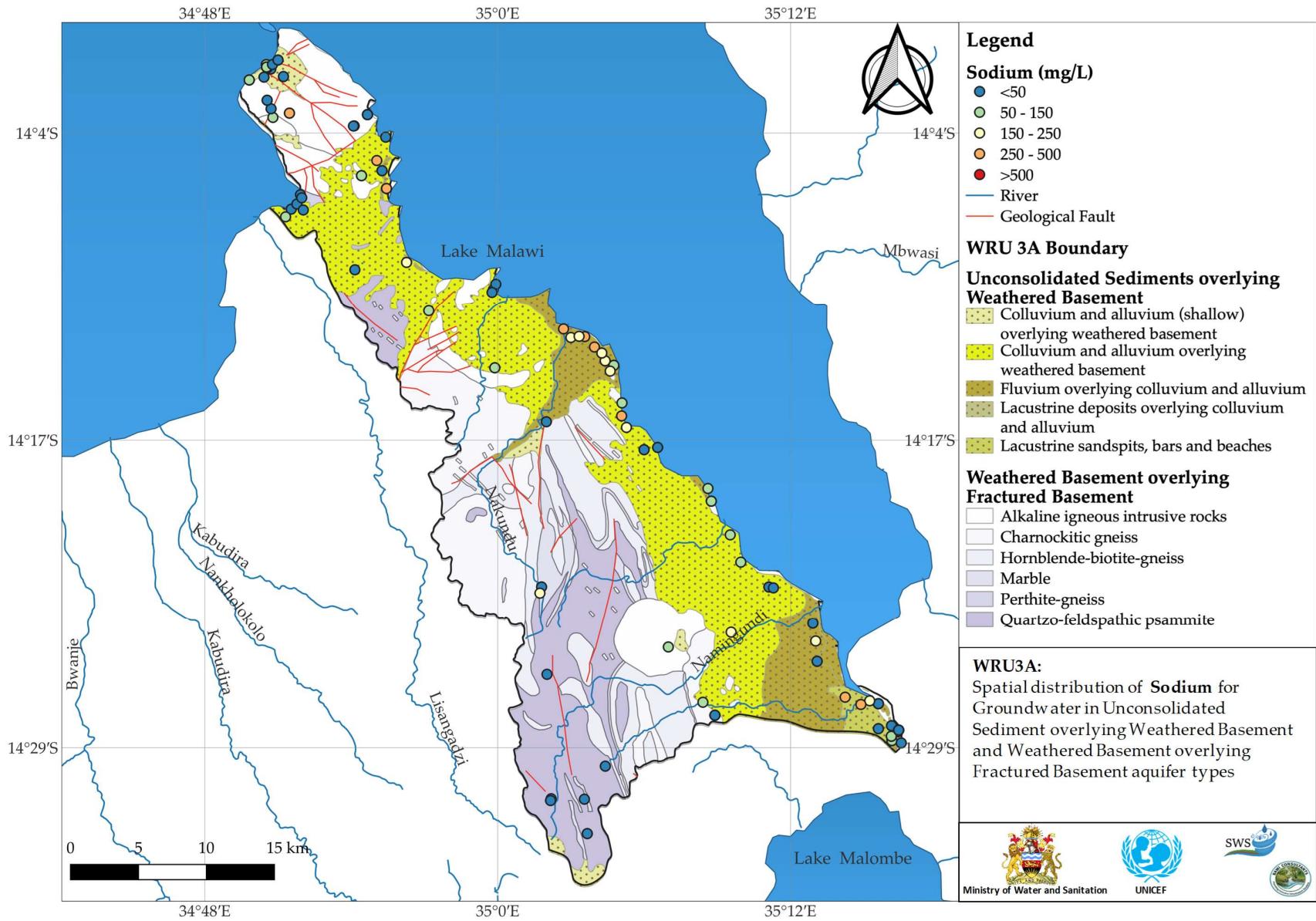


Figure WRU 3A.8 Groundwater Chemistry Distribution Calcium

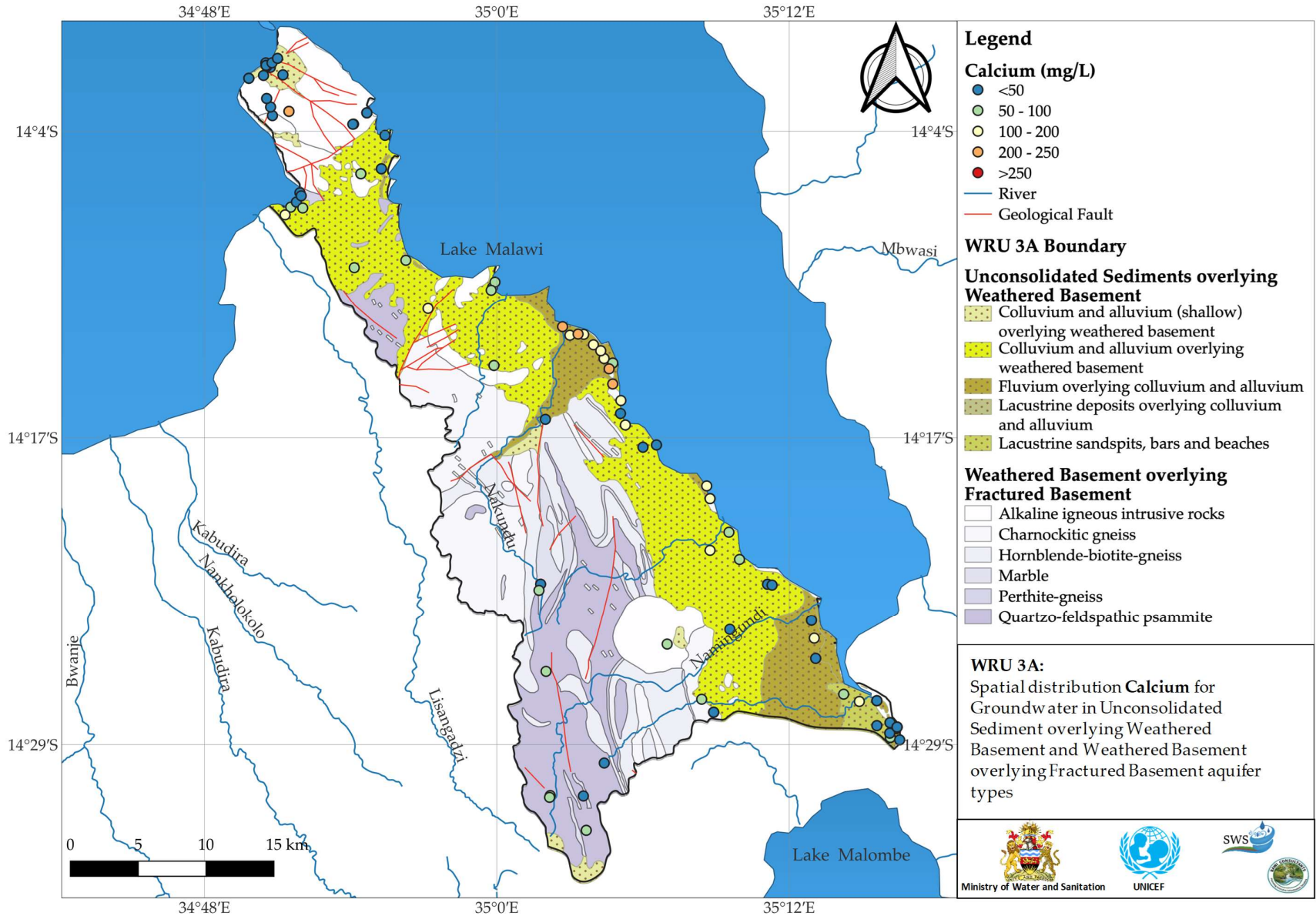


Figure WRU 3A.9 Piper Diagram of water quality results with respect to the major aquifer type

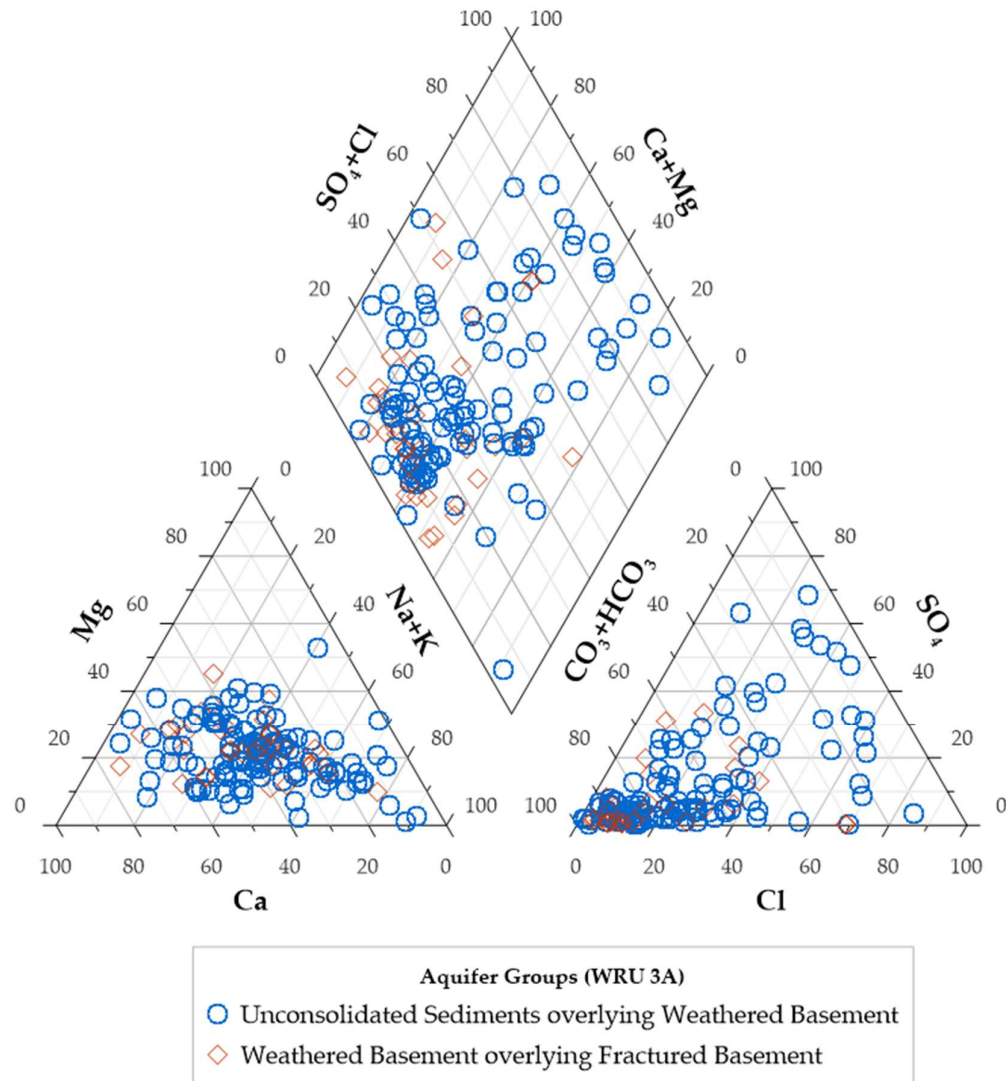
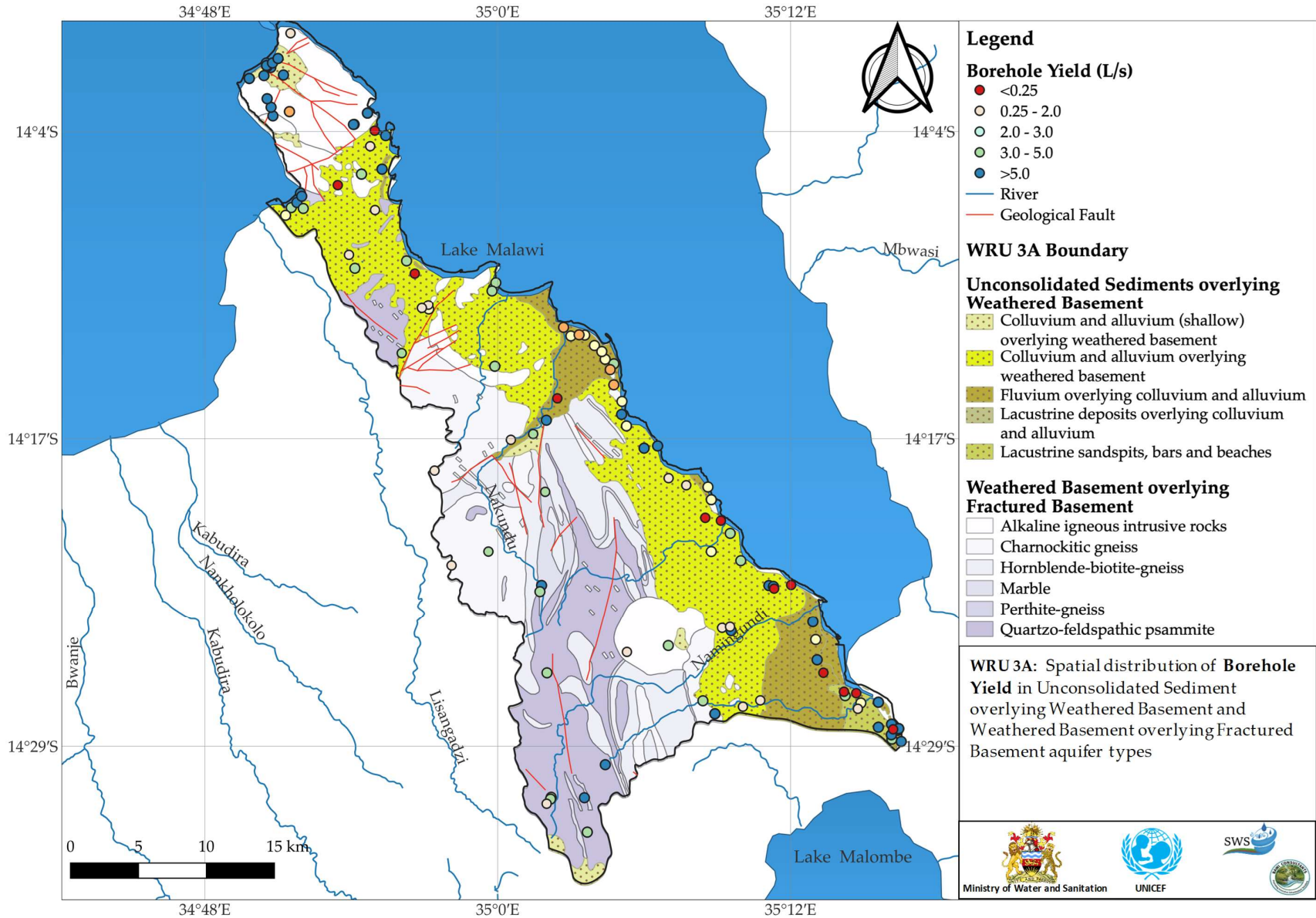


Figure WRU 3A.10 Borehole Yield Map for data held by the Ministry



WRU 3B Figures

Figure WRU 3B.1 Land Use and Major Roads

Figure WRU 3B.2 Rivers and Wetlands

Figure WRU 3B.3 Hydrogeology Units and Water Table

Figure WRU 3B.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 3B.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 3B.6 Groundwater Chemistry Distribution Chloride

Figure WRU 3B.7 Groundwater Chemistry Distribution Sodium

Figure WRU 3B.8 Groundwater Chemistry Distribution Calcium

Figure WRU 3B.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 3B.10 Borehole Yield Map for data held by the Ministry

Figure WRU 3B.1 Land Use and Major Roads

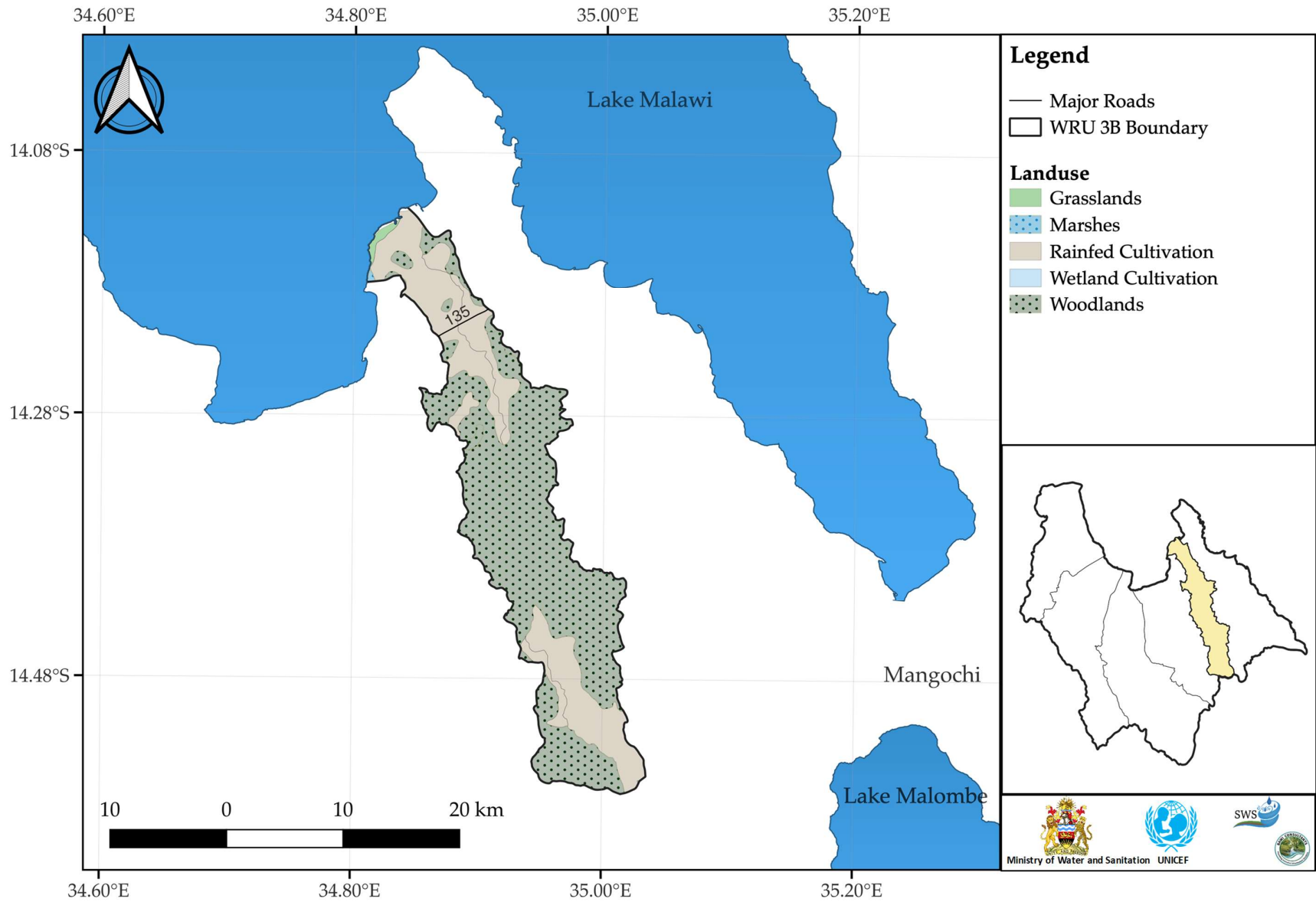


Figure WRU 3B.2 Rivers and Wetlands

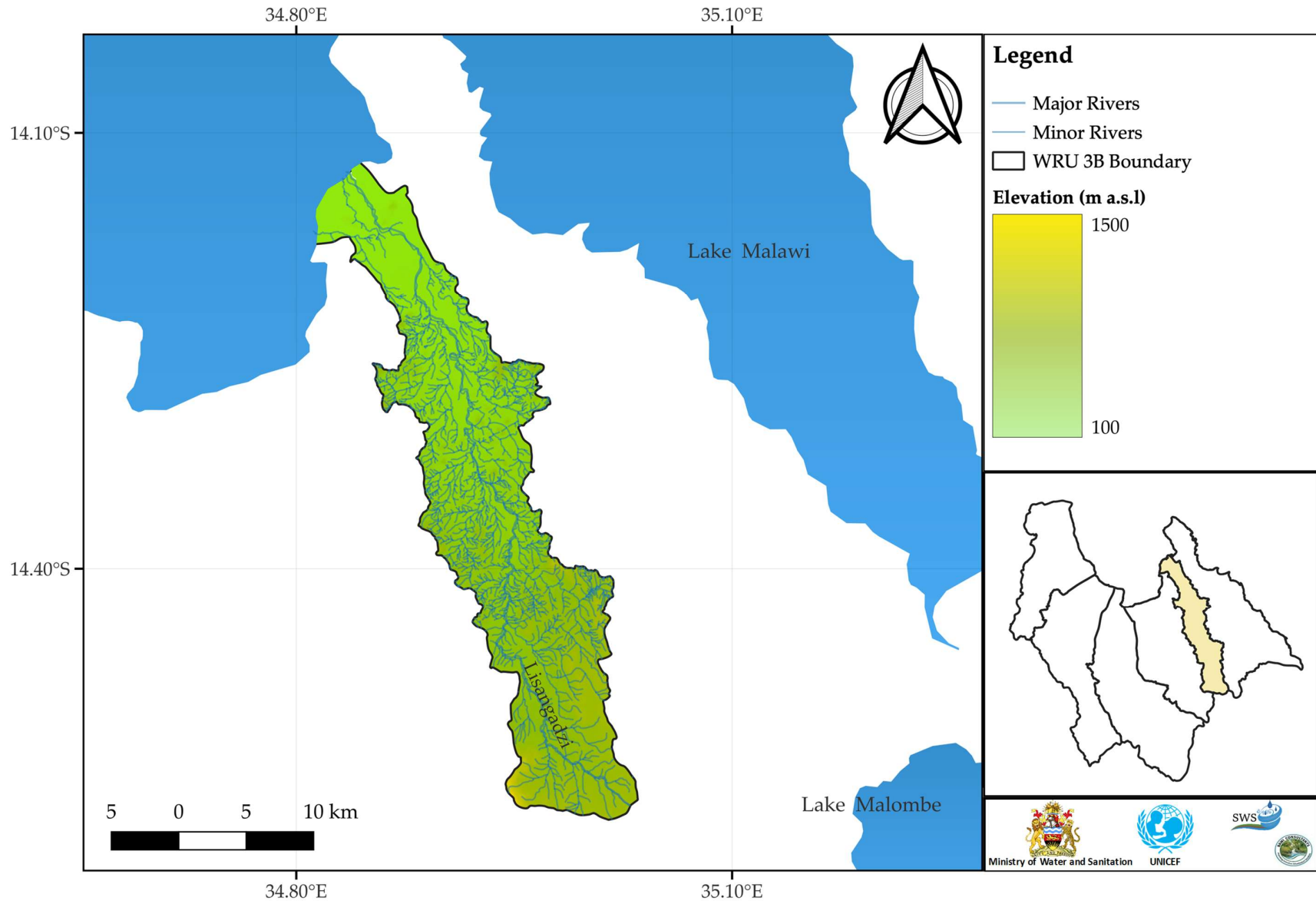


Figure WRU 3B.3 Hydrogeology Units and Water Table

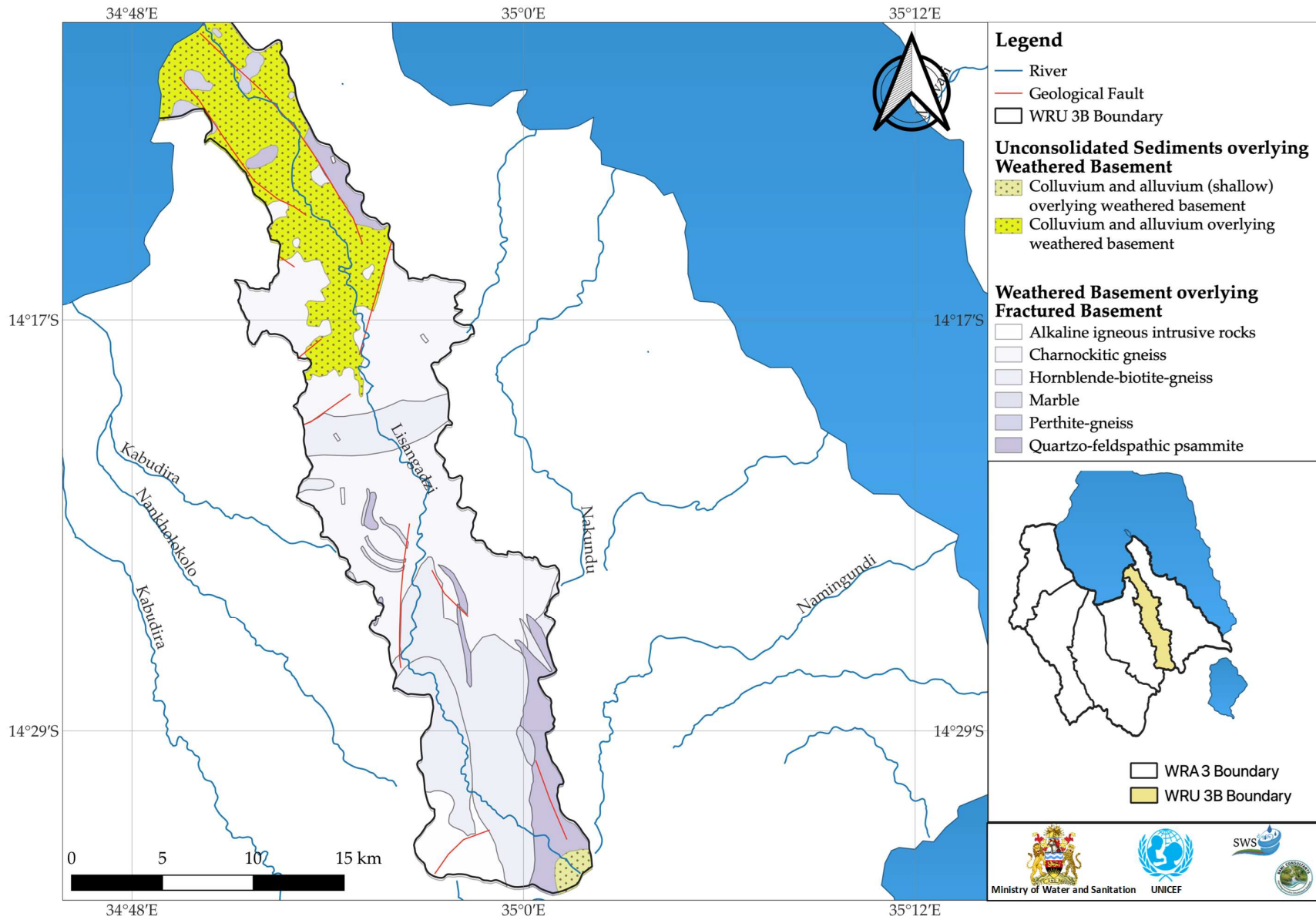


Figure WRU 3B.4 Groundwater Chemistry Distribution Electrical Conductivity

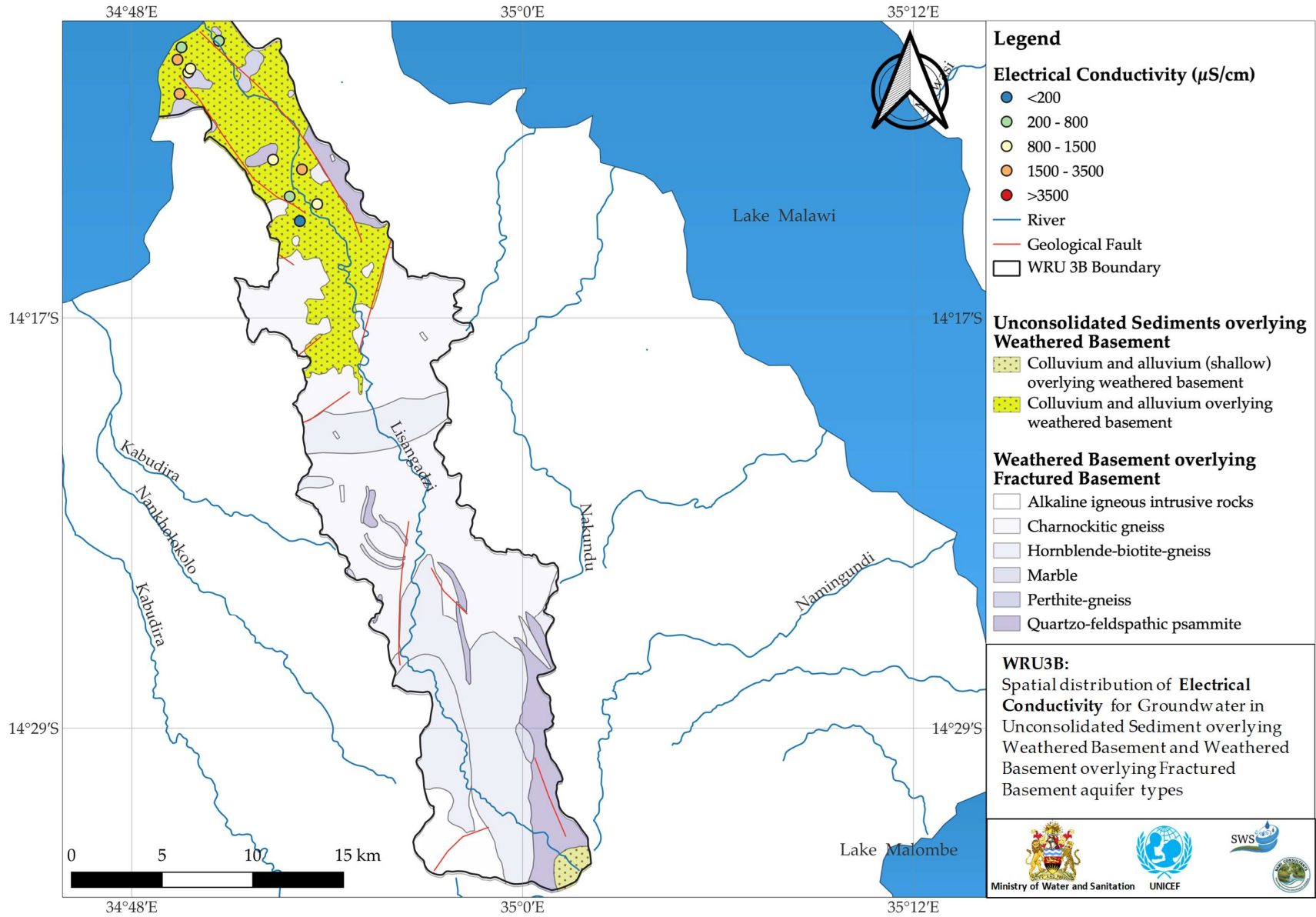


Figure WRU 3B.5 Groundwater Chemistry Distribution of Sulphate

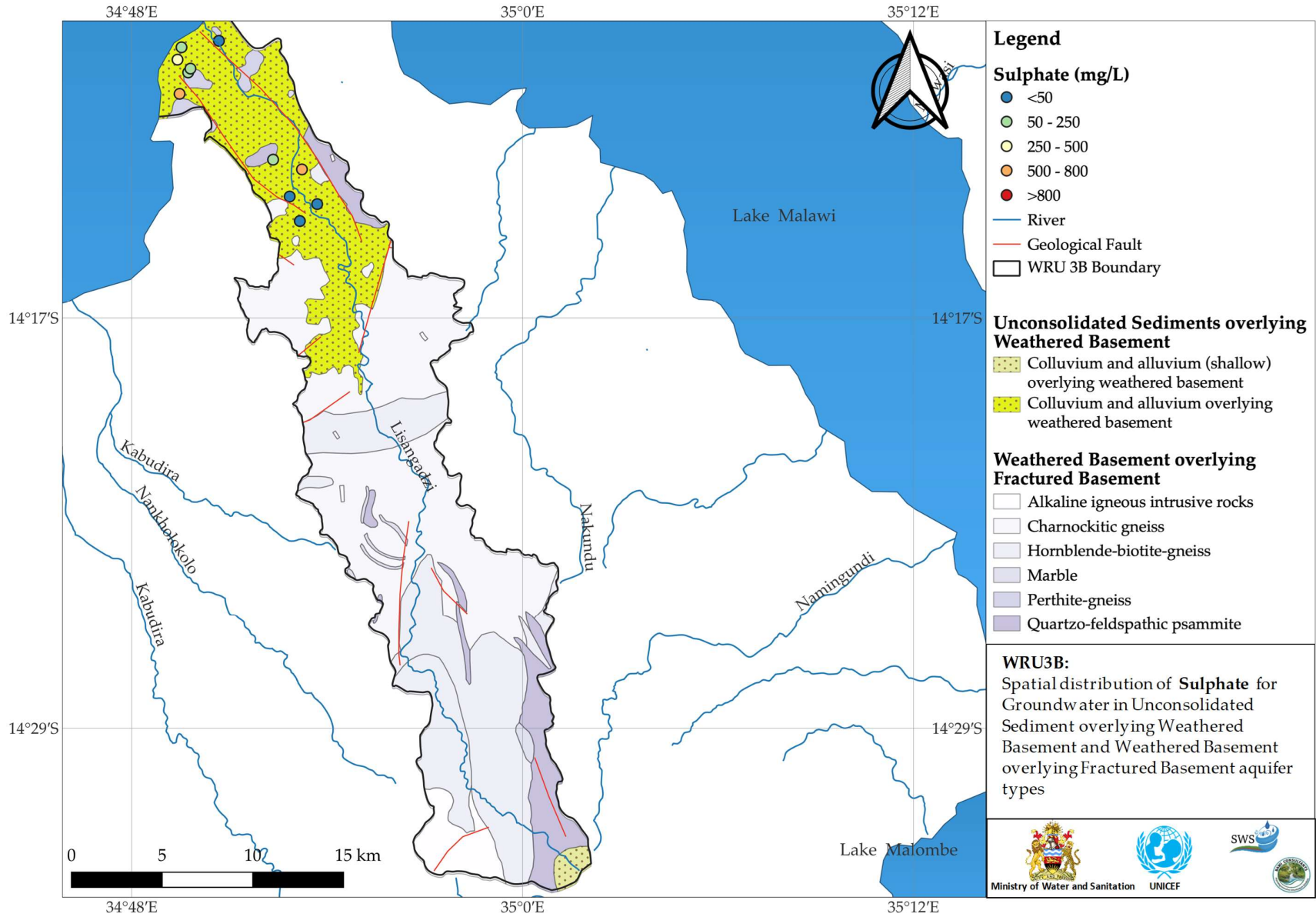


Figure WRU 3B.6 Groundwater Chemistry Distribution Chloride

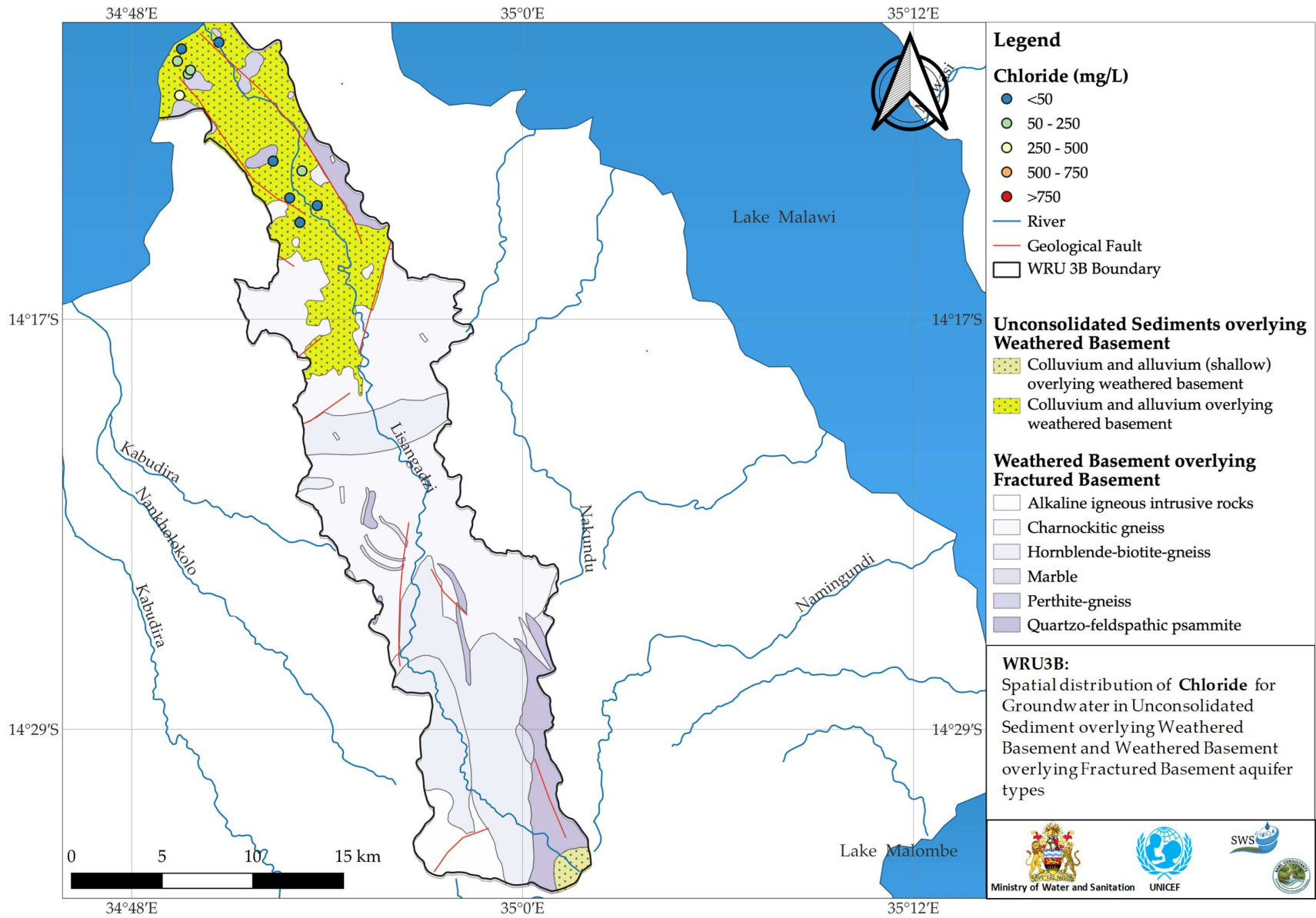


Figure WRU 3B.7 Groundwater Chemistry Distribution Sodium

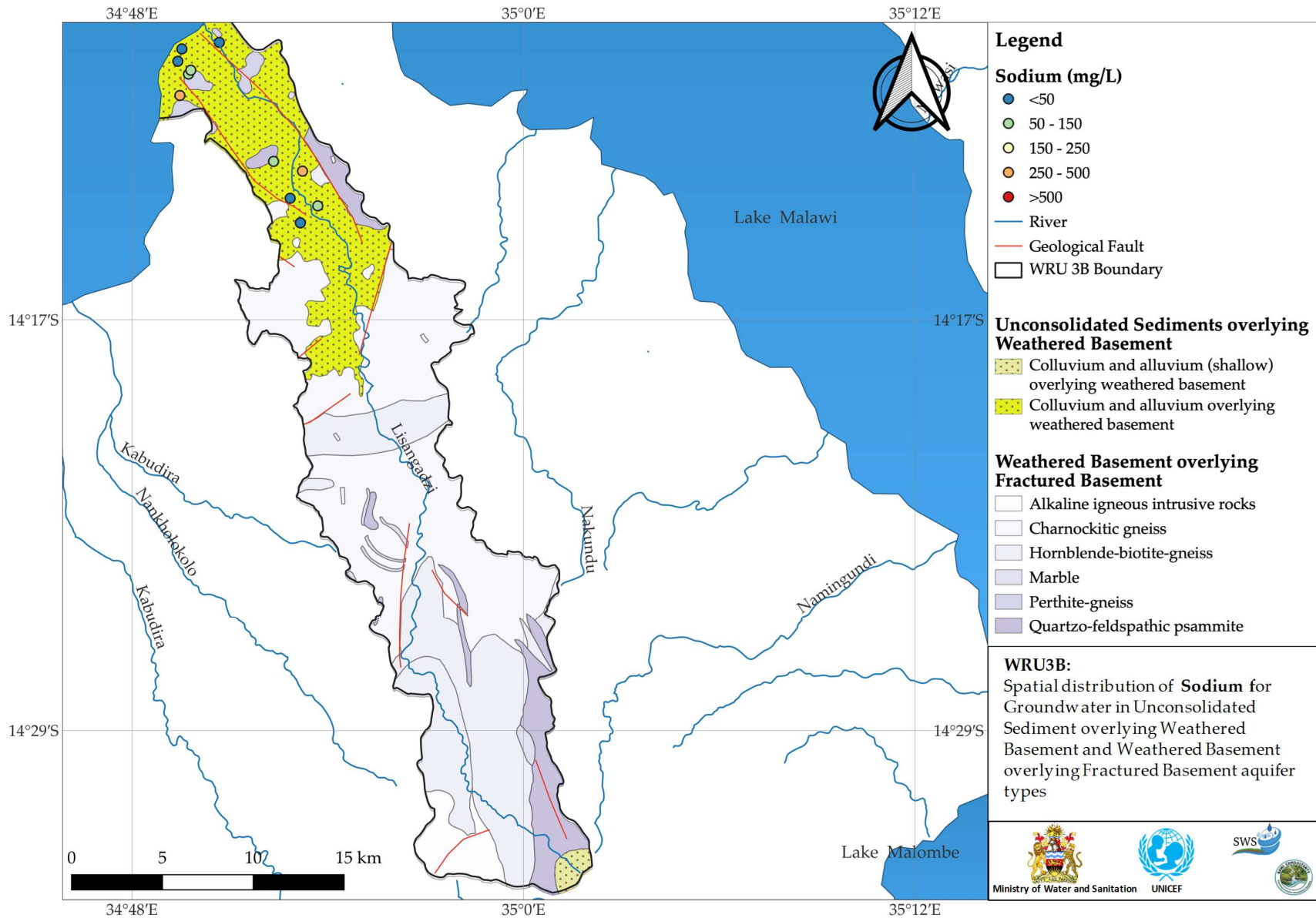


Figure WRU 3B.8 Groundwater Chemistry Distribution Calcium

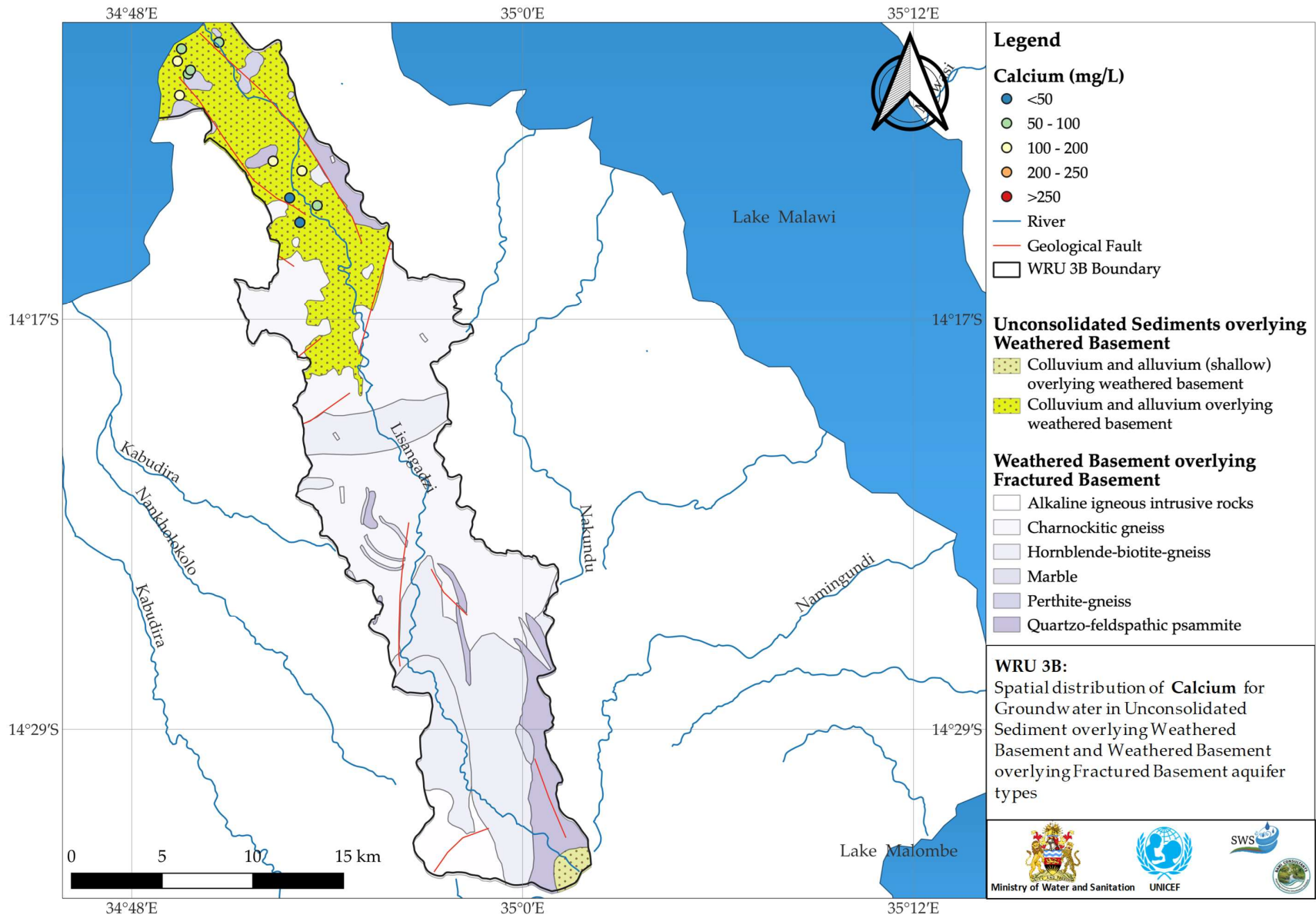


Figure WRU 3B.9 Piper Diagram of water quality results with respect to the major aquifer type

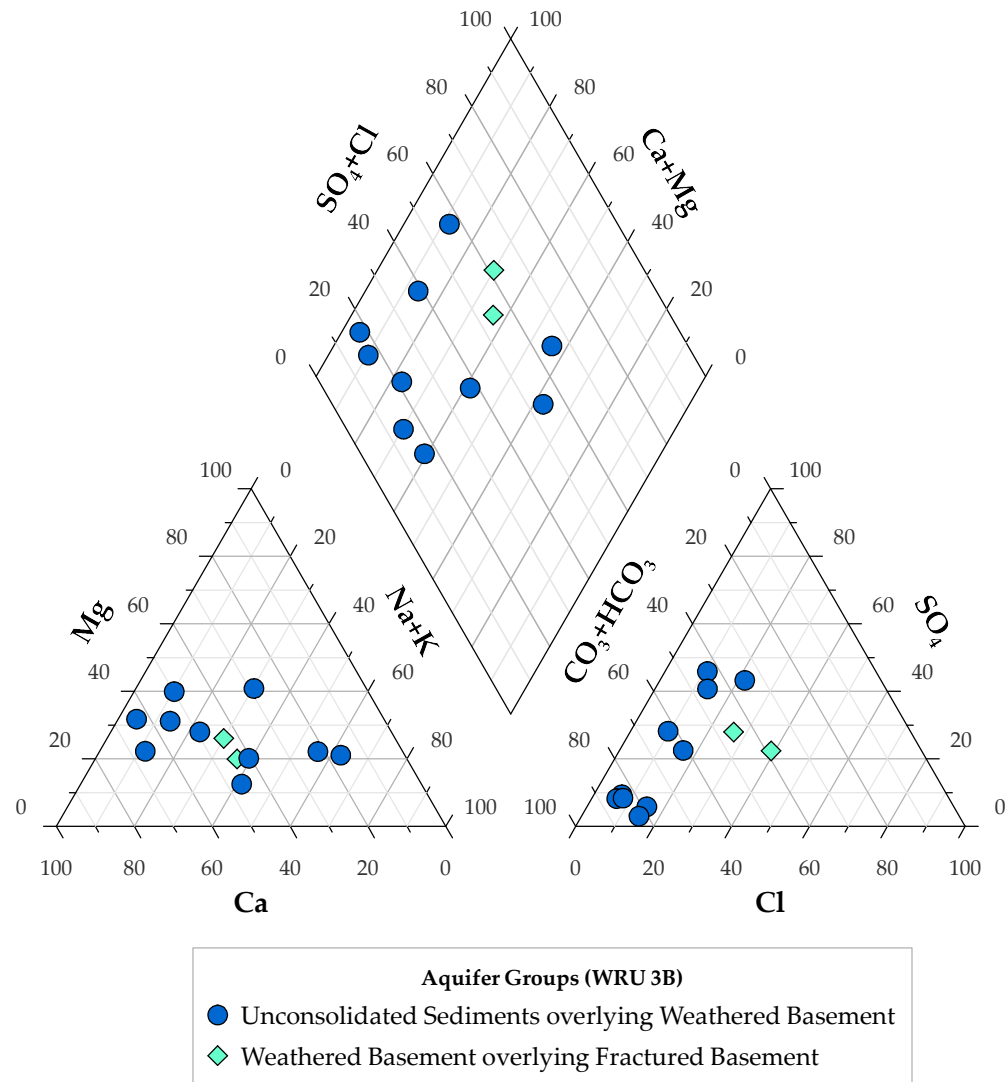
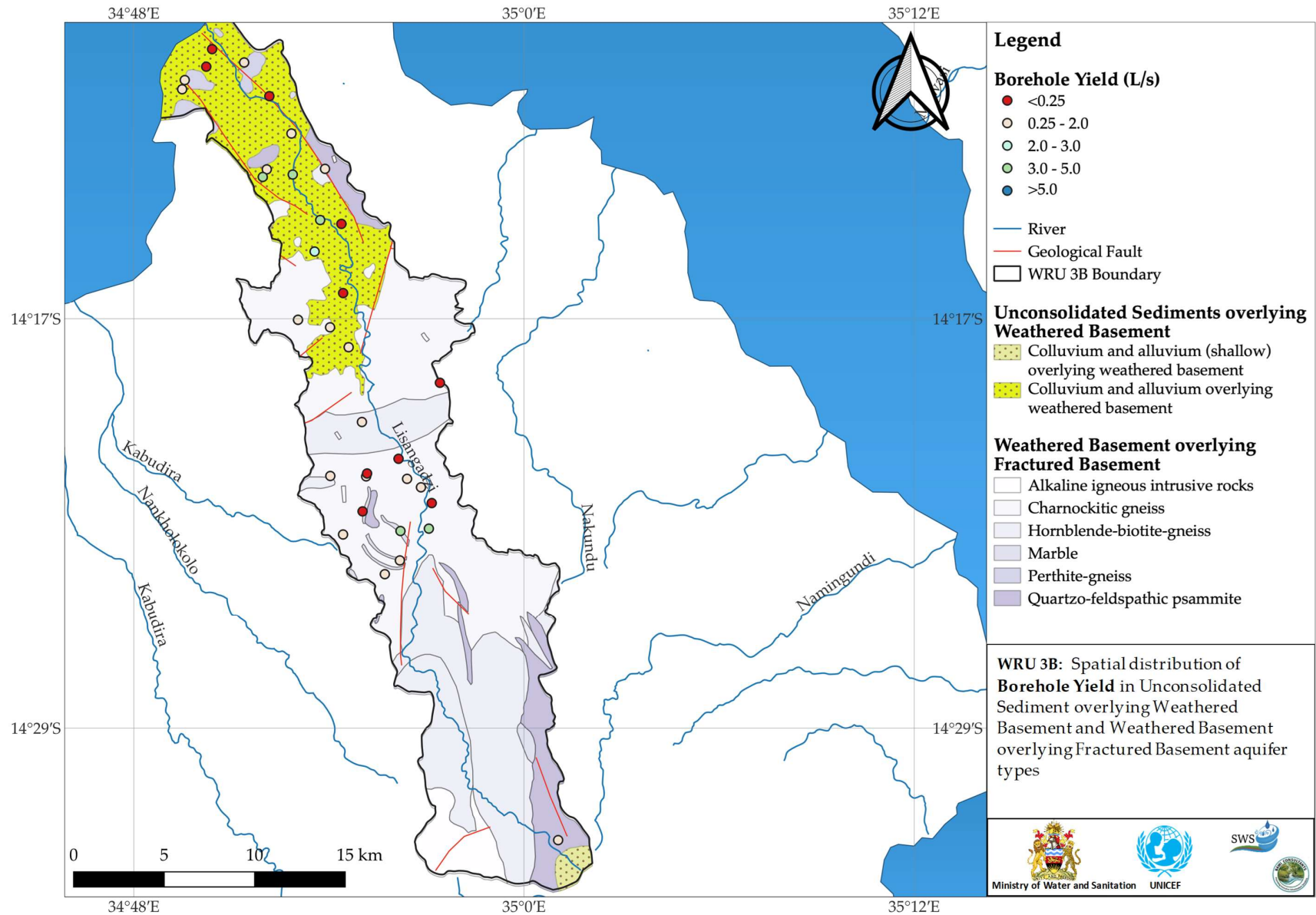


Figure WRU 3B.10 Borehole Yield Map for data held by the Ministry



WRU 3C Figures

Figure WRU 3C.1 Land Use and Major Roads

Figure WRU 3C.2 Rivers and Wetlands

Figure WRU 3C.3 Hydrogeology Units and Water Table

Figure WRU 3C.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 3C.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 3C.6 Groundwater Chemistry Distribution Chloride

Figure WRU 3C.7 Groundwater Chemistry Distribution Sodium

Figure WRU 3C.8 Groundwater Chemistry Distribution Calcium

Figure WRU 3C.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 3C.10 Borehole Yield Map for data held by the Ministry

Figure WRU 3C.1 Land Use and Major Roads

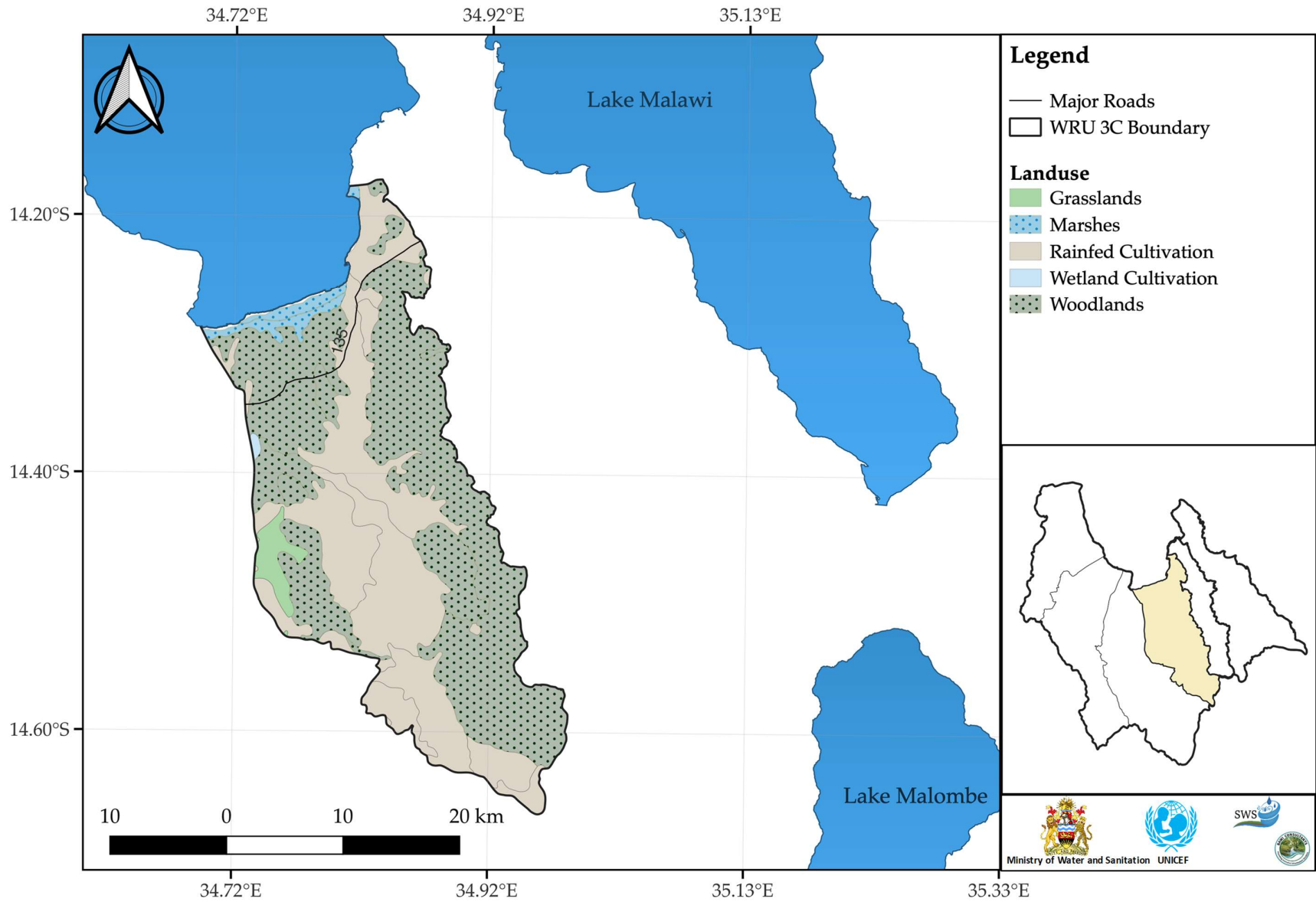


Figure WRU 3C.2 Rivers and Wetlands

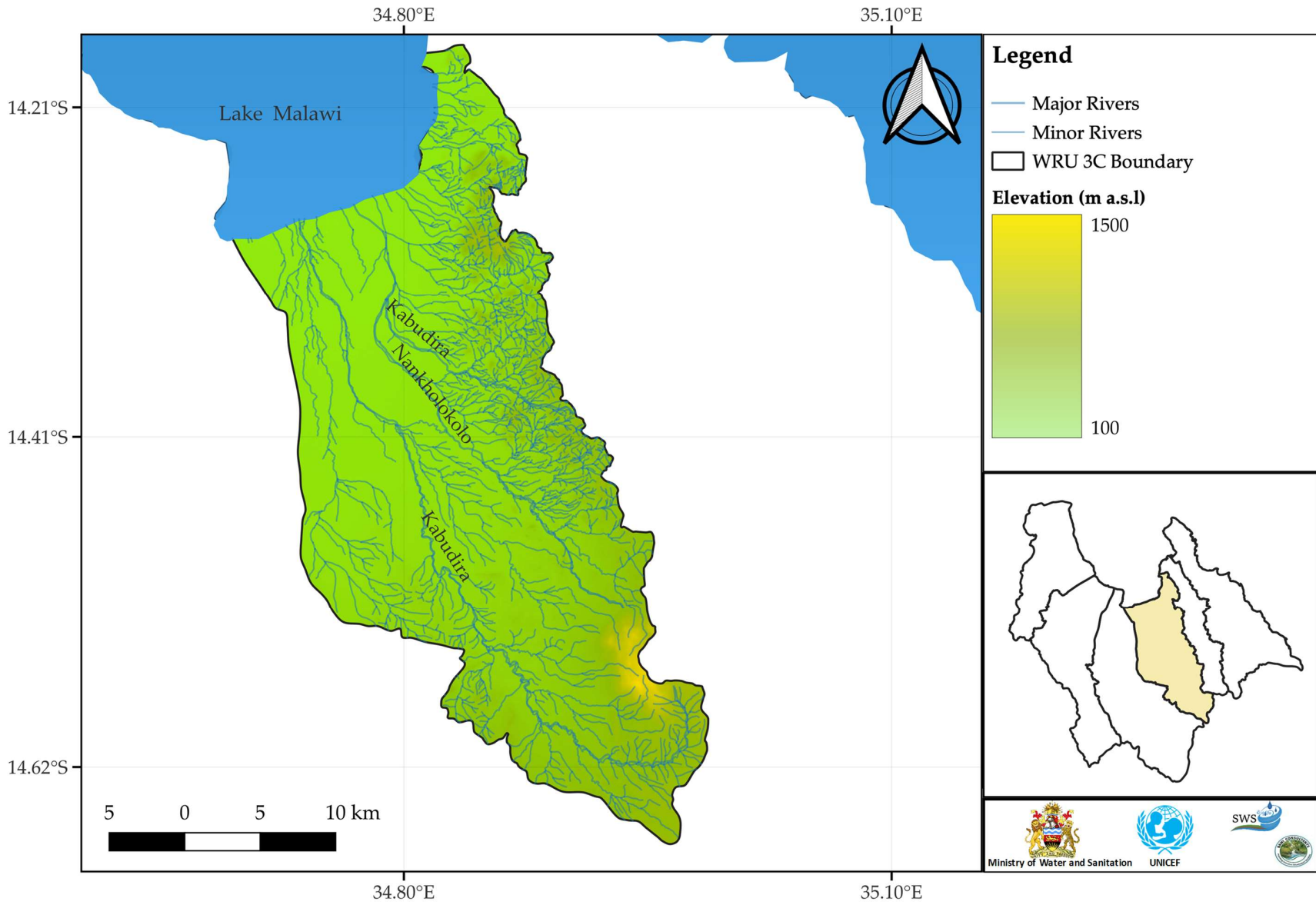


Figure WRU 3C.3 Hydrogeology Units and Water Table

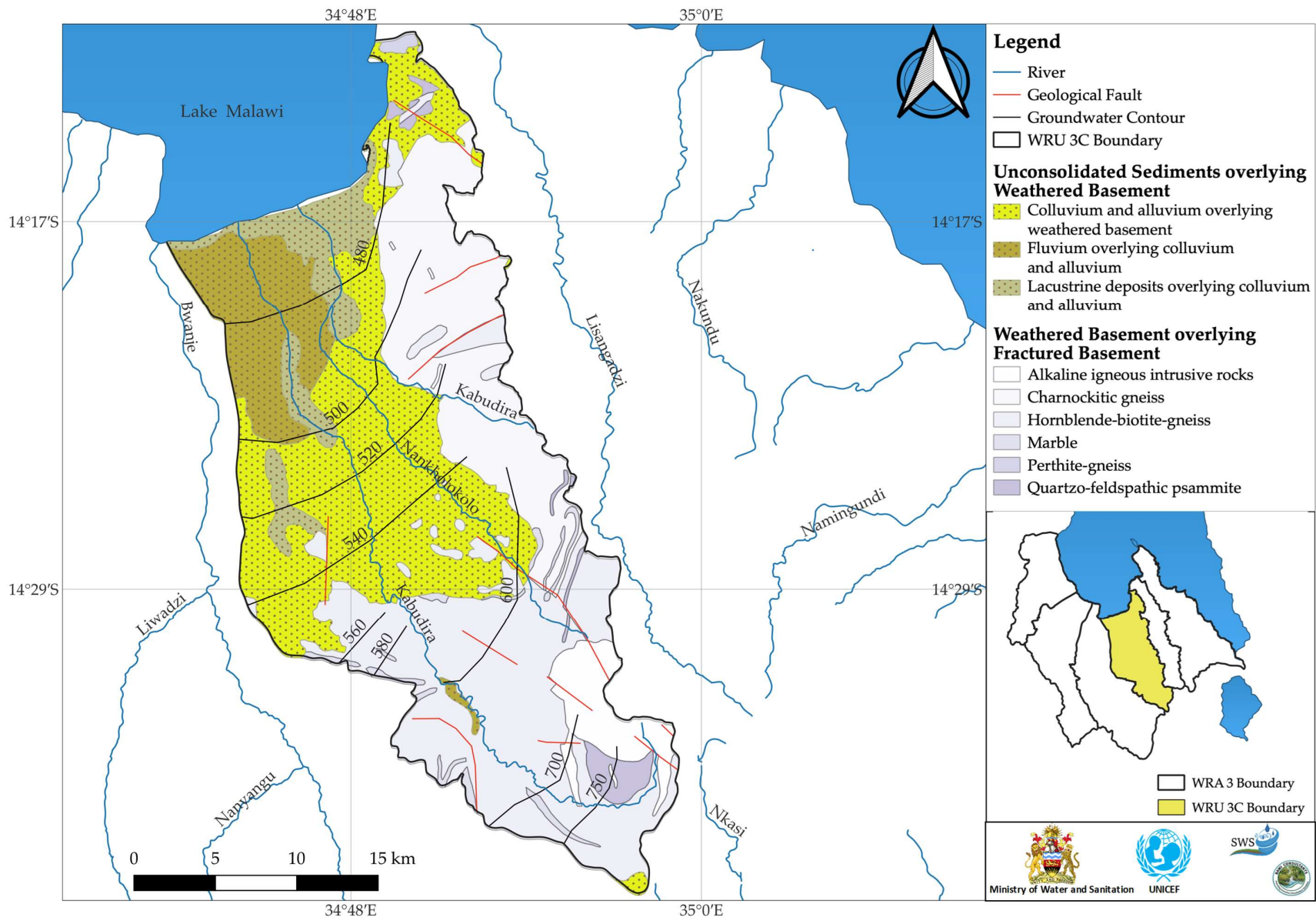


Figure WRU 3C.4 Groundwater Chemistry Distribution Electrical Conductivity

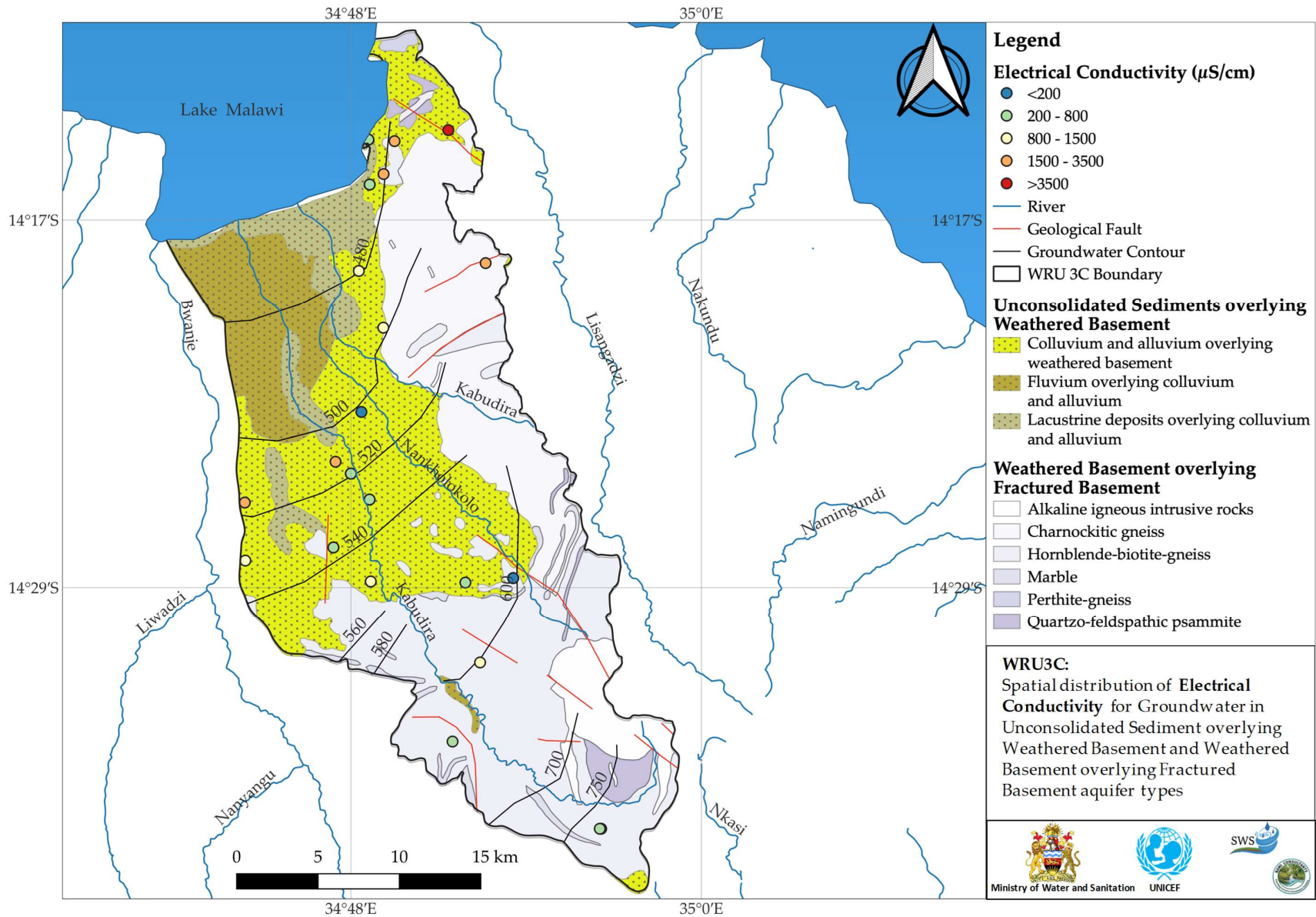


Figure WRU 3C.5 Groundwater Chemistry Distribution of Sulphate

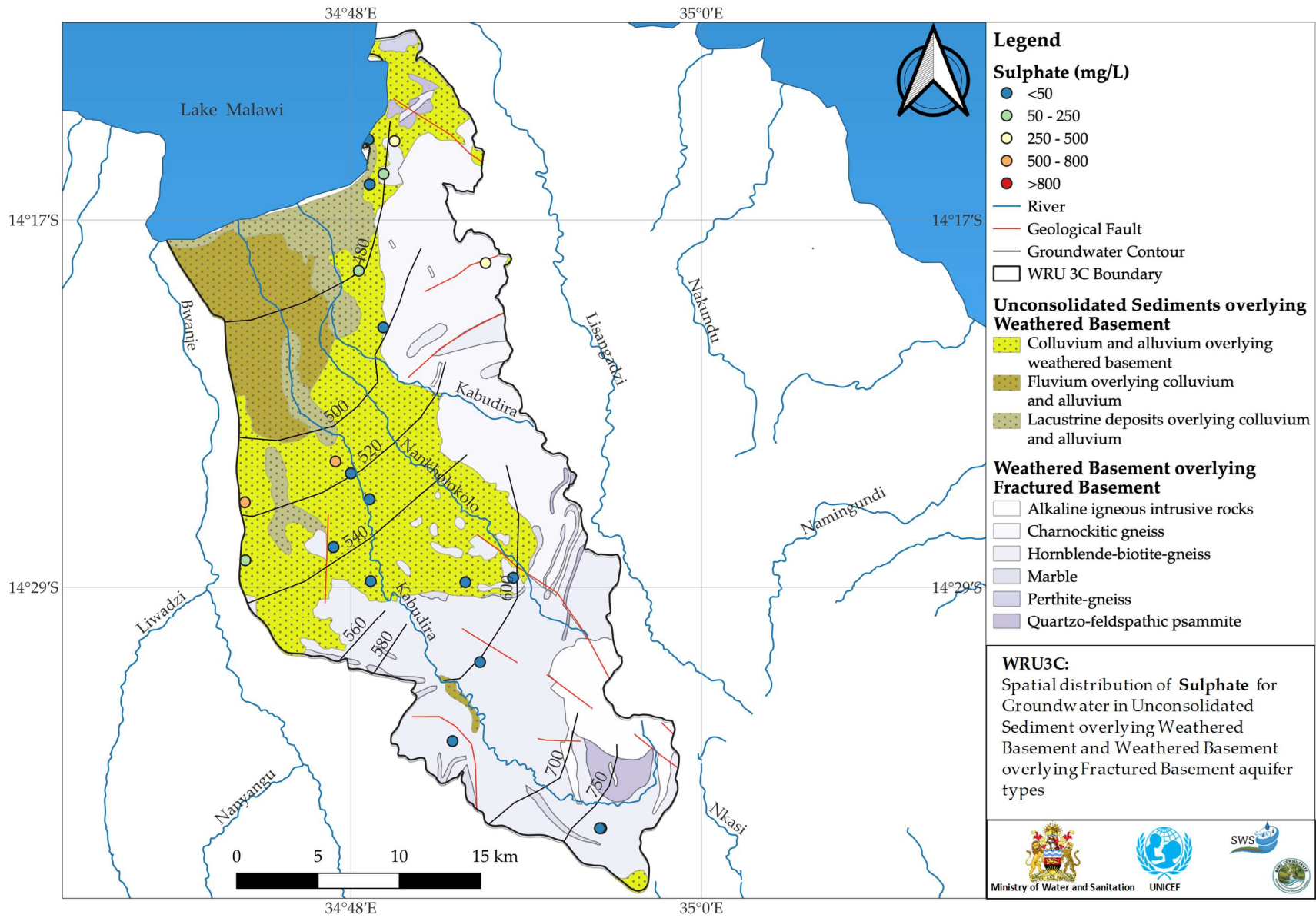


Figure WRU 3C.6 Groundwater Chemistry Distribution Chloride

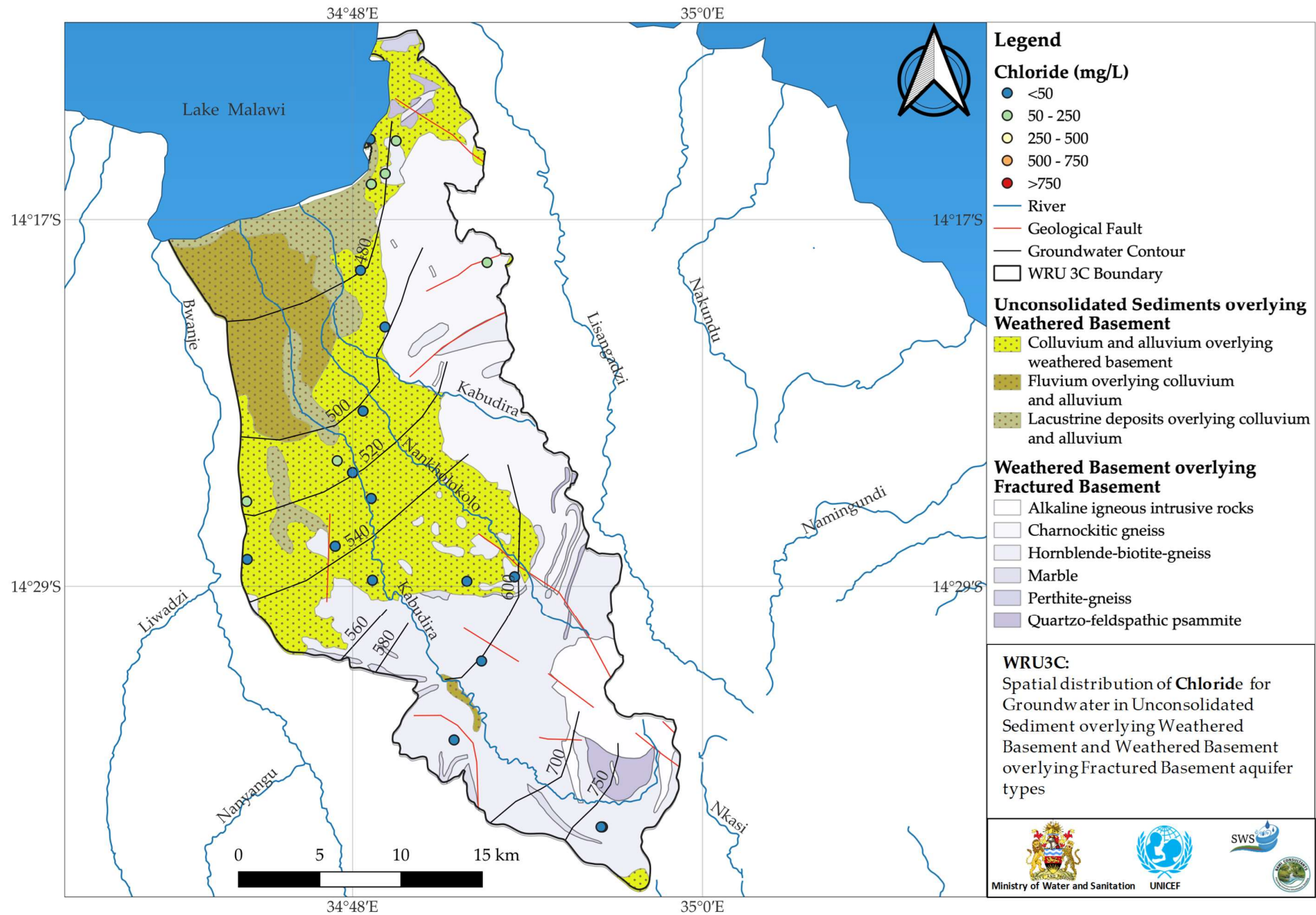


Figure WRU 3C.7 Groundwater Chemistry Distribution Sodium

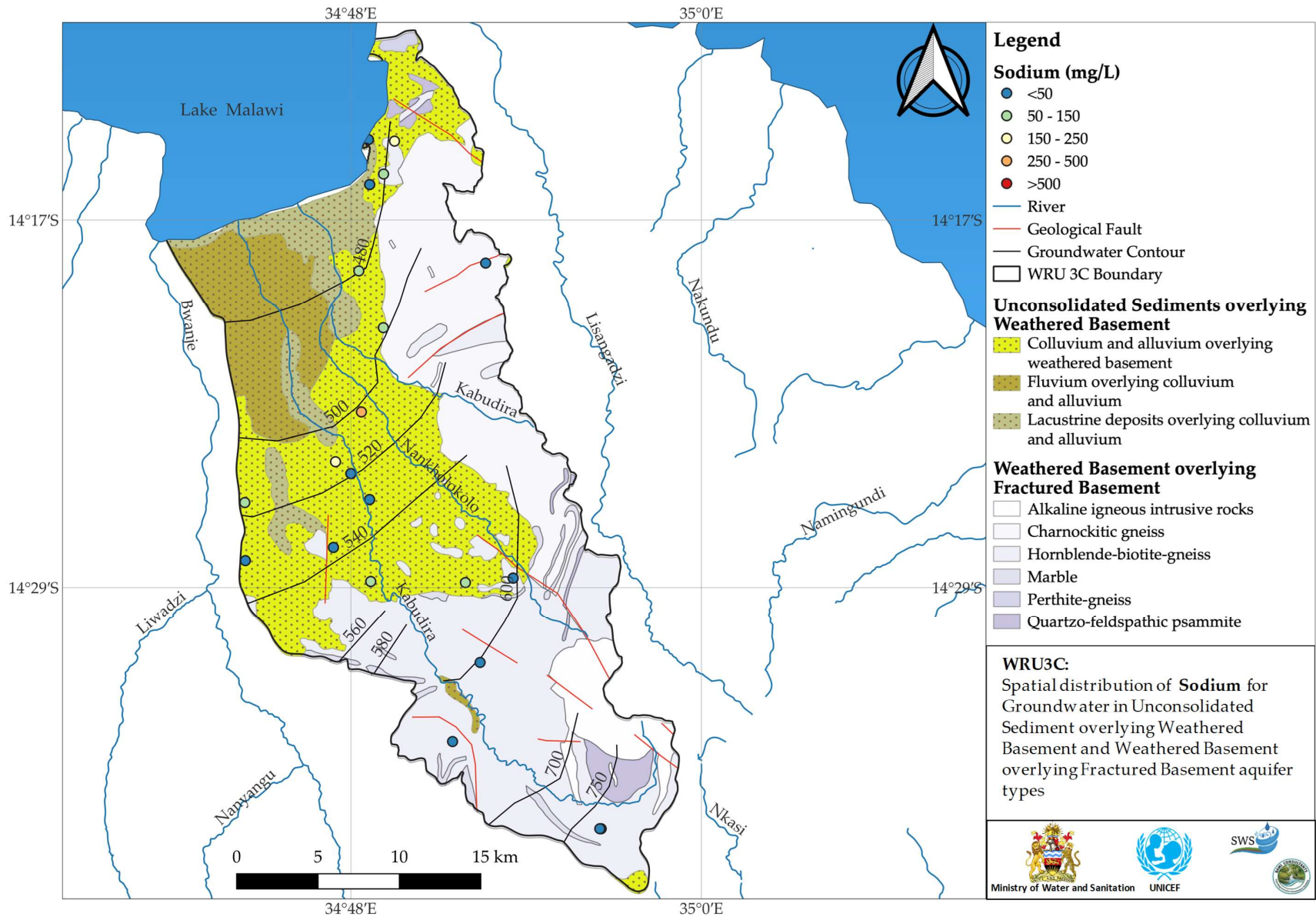


Figure WRU 3C.8 Groundwater Chemistry Distribution Calcium

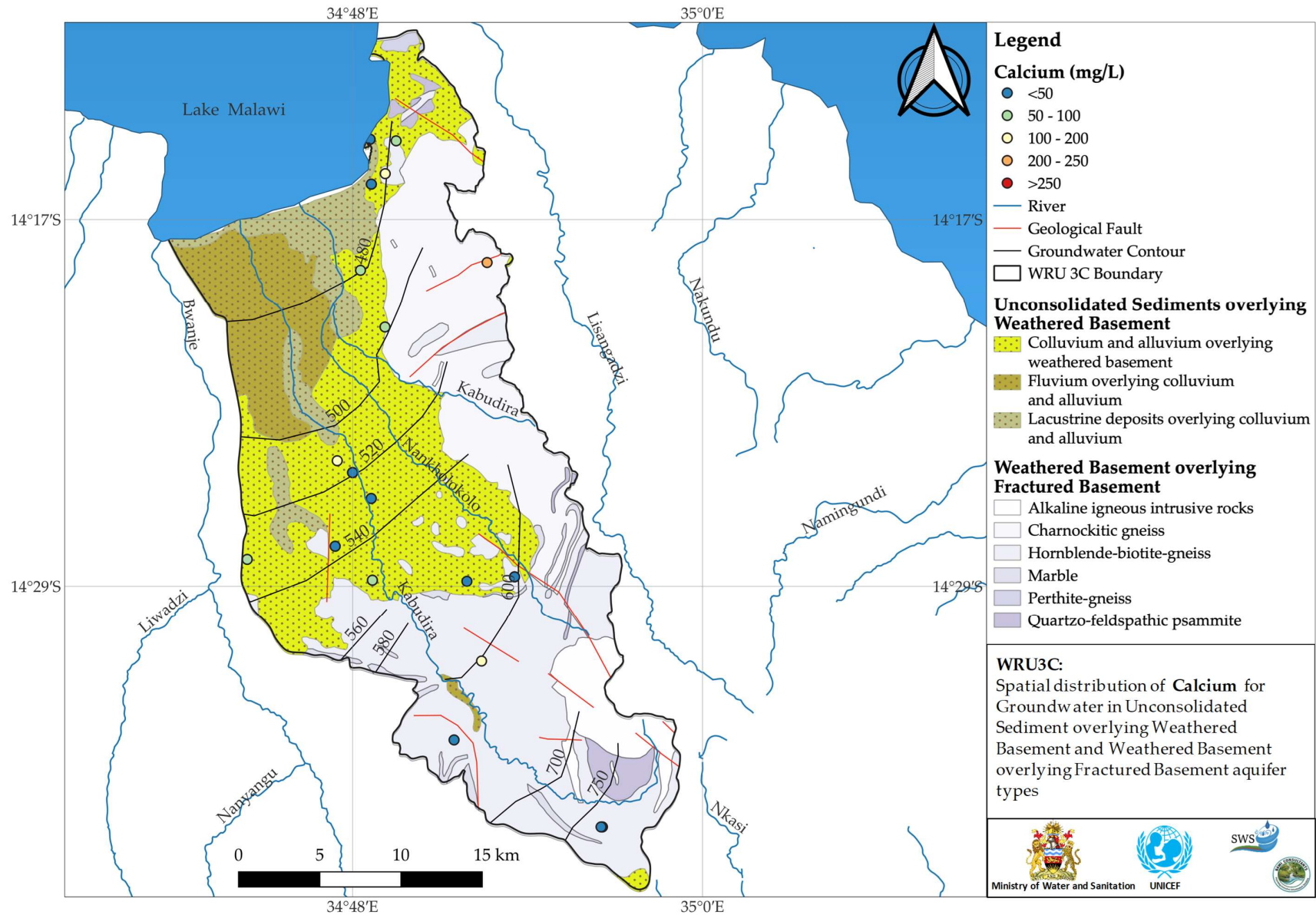


Figure WRU 3C.9 Piper Diagram of water quality results with respect to the major aquifer type

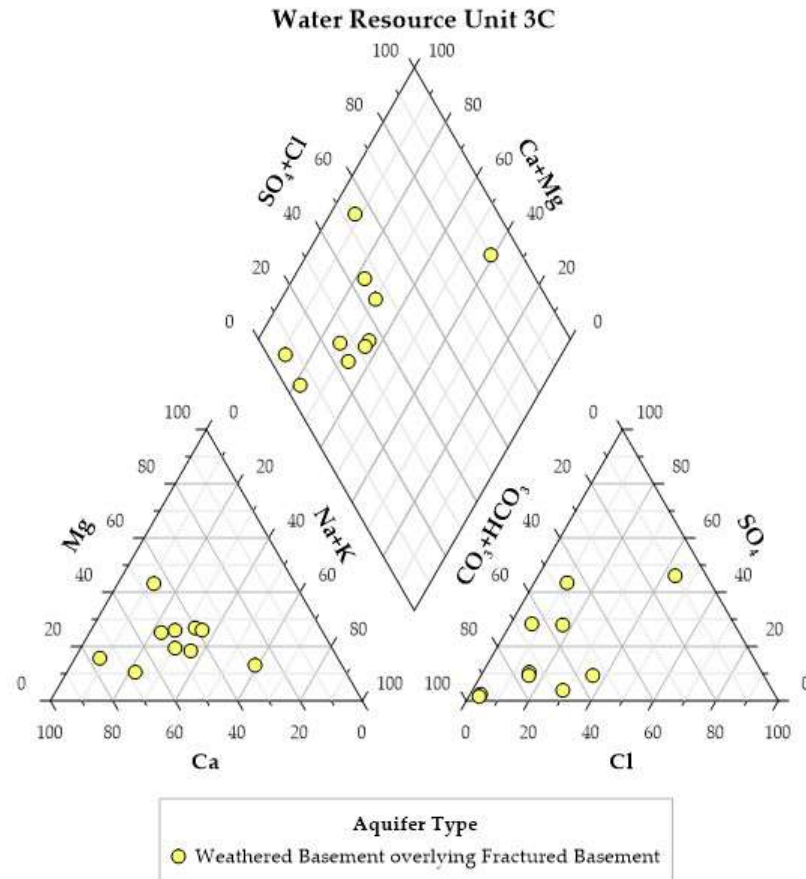
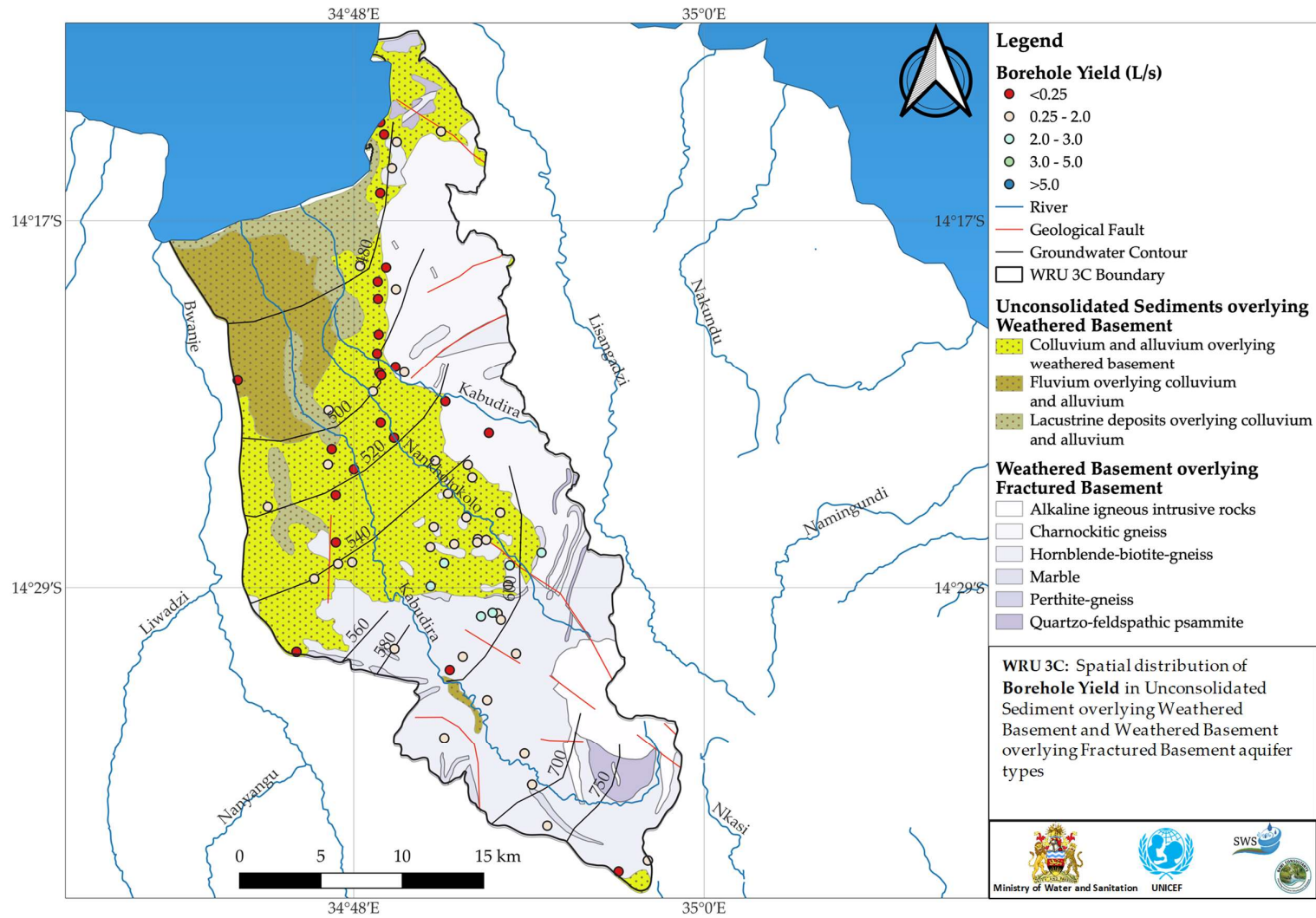


Figure WRU 3C.10 Borehole Yield Map for data held by the Ministry



WRU 3D Figures

Figure WRU 3D.1 Land Use and Major Roads

Figure WRU 3D.2 Rivers and Wetlands

Figure WRU 3D.3 Hydrogeology Units and Water Table

Figure WRU 3D.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 3D.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 3D.6 Groundwater Chemistry Distribution Chloride

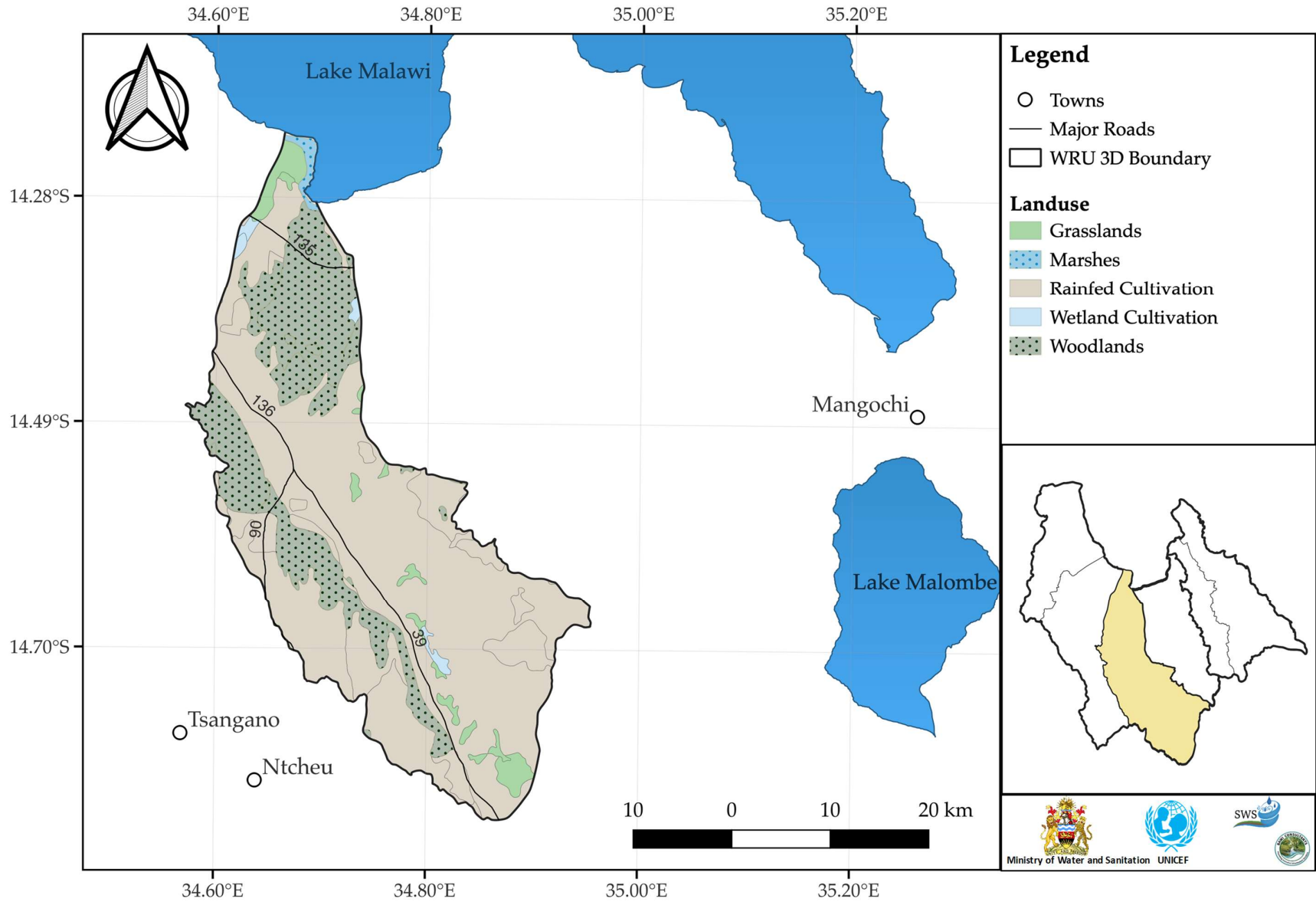
Figure WRU 3D.7 Groundwater Chemistry Distribution Sodium

Figure WRU 3D.8 Groundwater Chemistry Distribution Calcium

Figure WRU 3D.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 3D.10 Borehole Yield Map for data held by the Ministry

Figure WRU 3D.1 Land Use and Major Roads



Legend

- Towns
- Major Roads
- WRU 3D Boundary

Landuse

- Grasslands
- Marshes
- Rainfed Cultivation
- Wetland Cultivation
- Woodlands

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Figure WRU 3D.2 Rivers and Wetlands

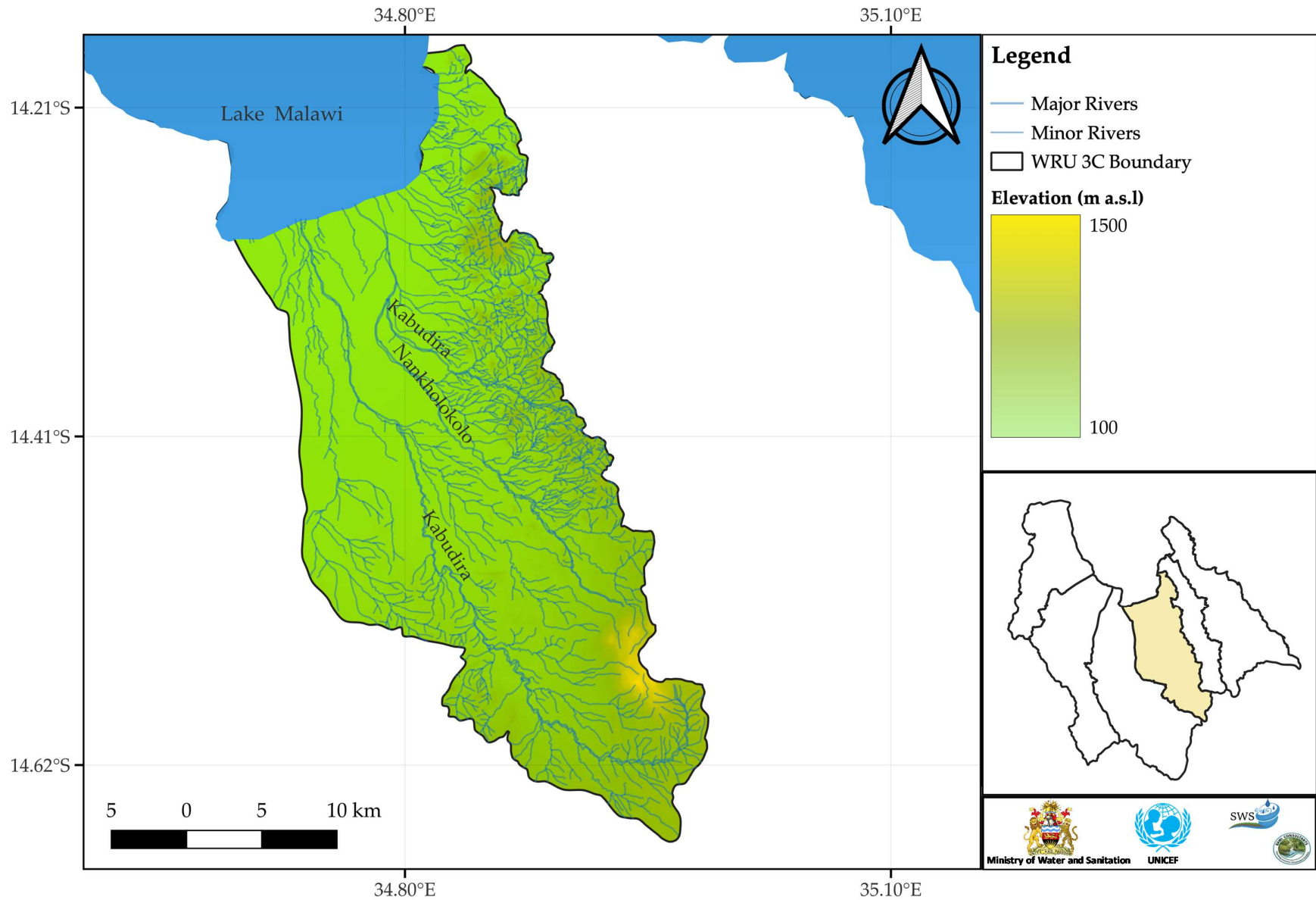


Figure WRU 3D.3 Hydrogeology Units and Water Table

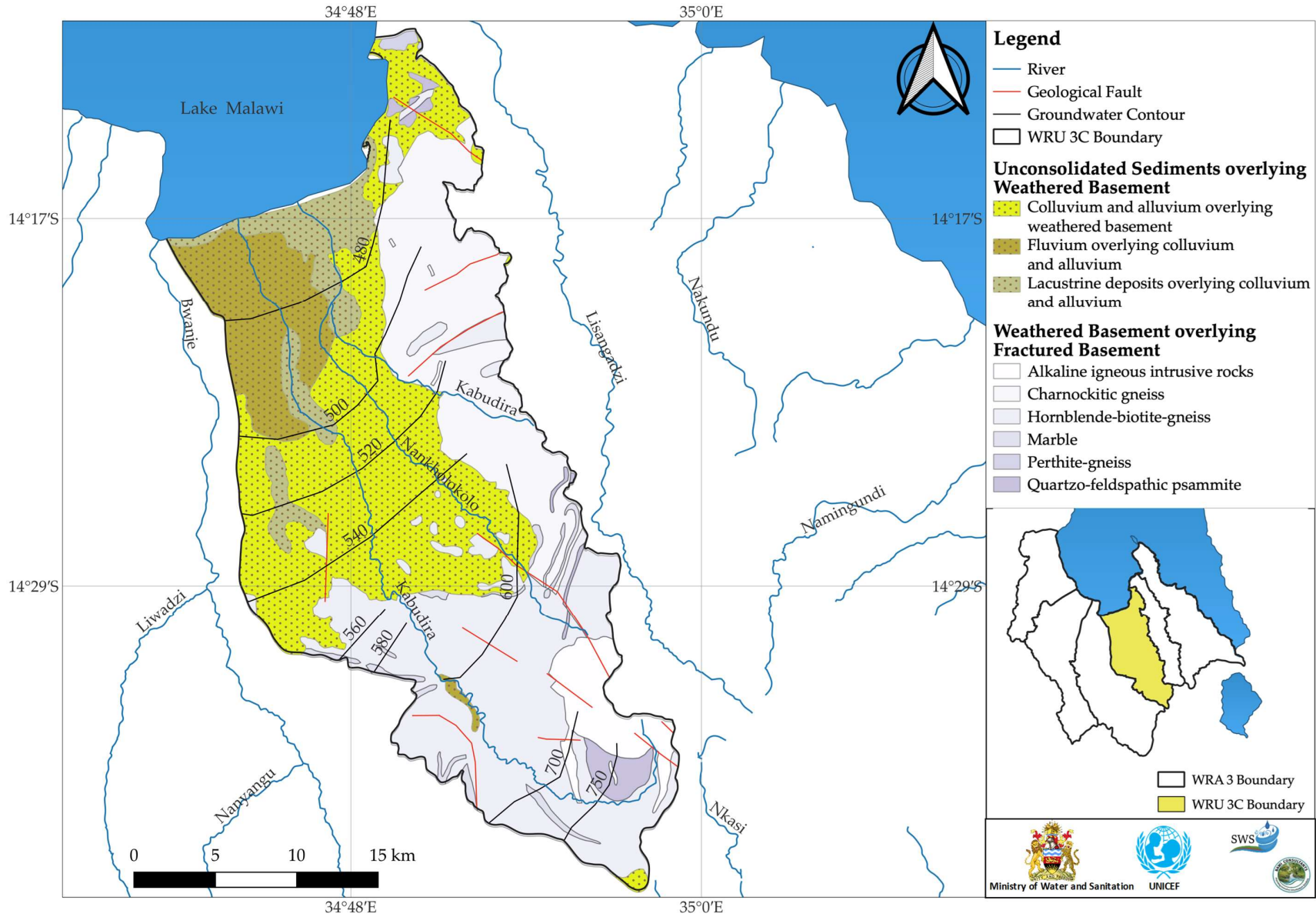


Figure WRU 3D.4 Groundwater Chemistry Distribution Electrical Conductivity

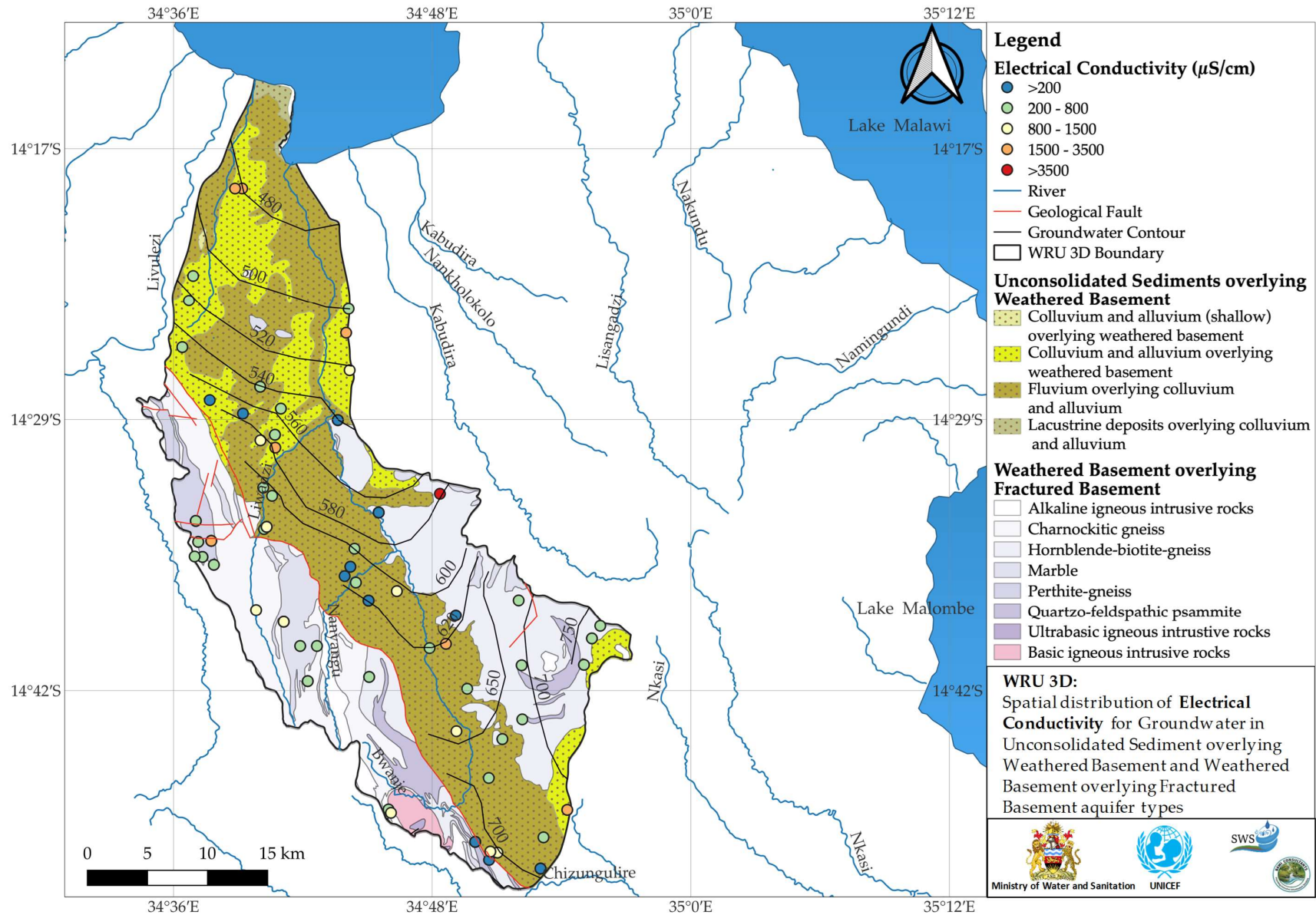


Figure WRU 3D.5 Groundwater Chemistry Distribution of Sulphate

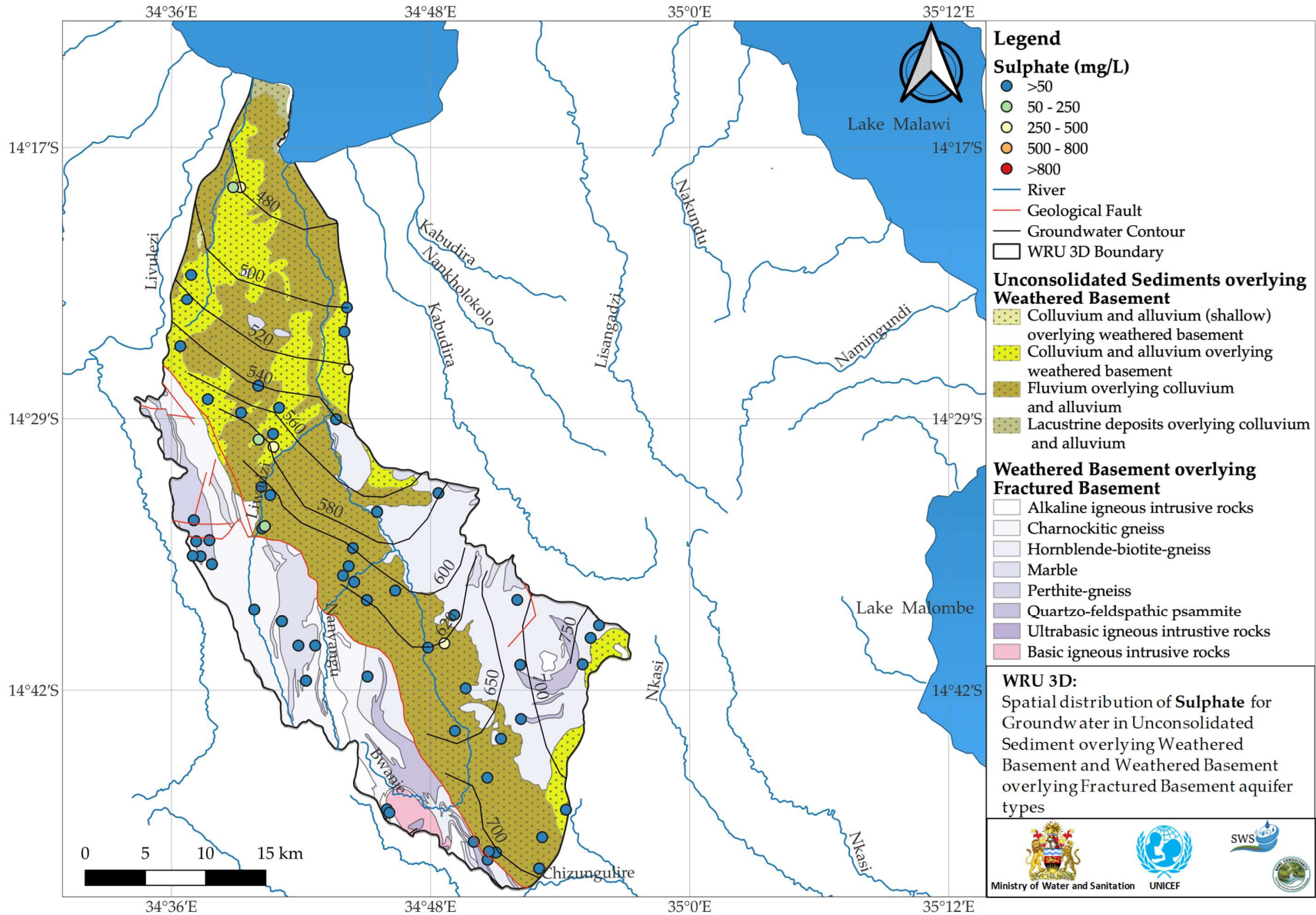


Figure WRU 3D.6 Groundwater Chemistry Distribution Chloride

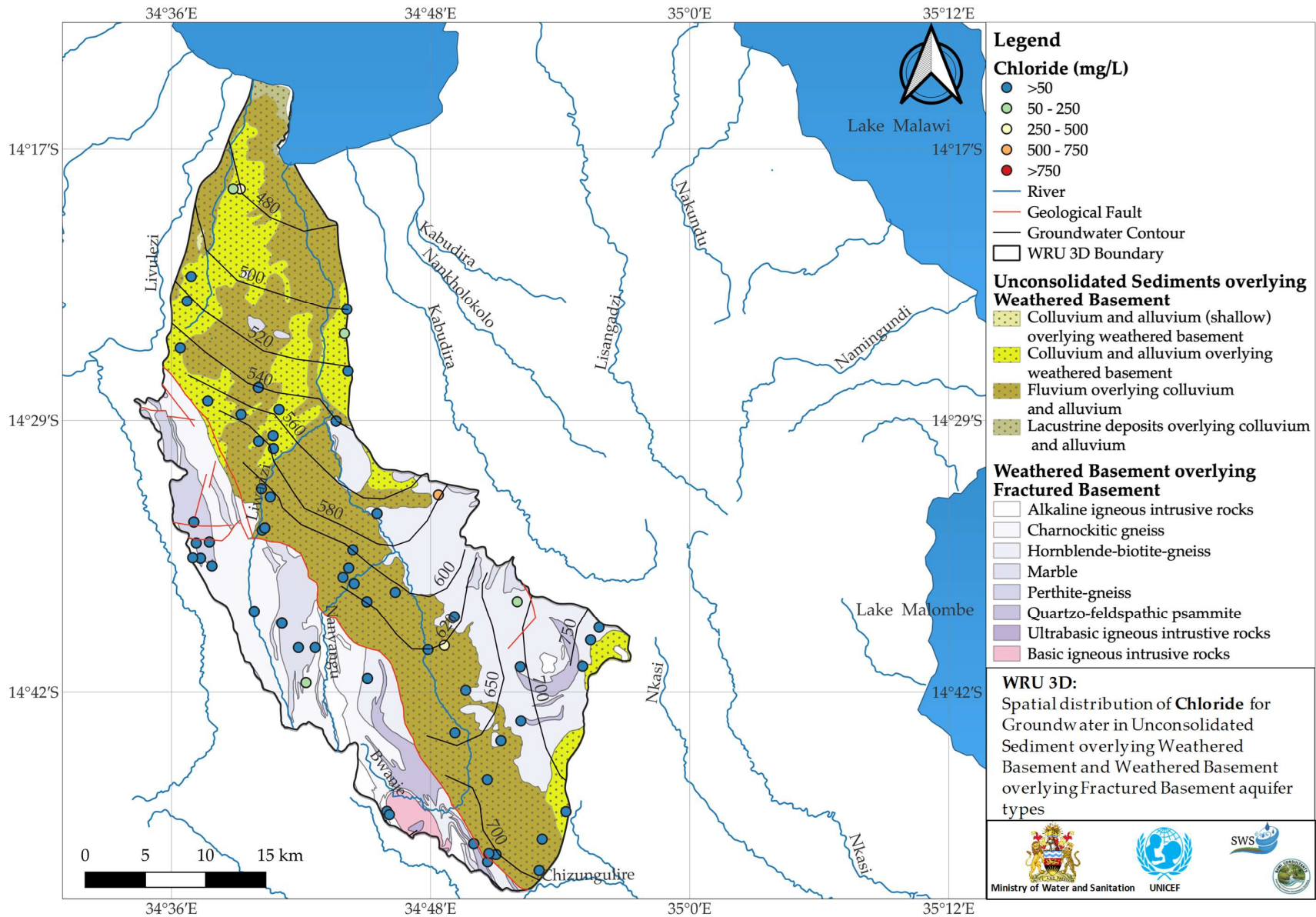


Figure WRU 3D.7 Groundwater Chemistry Distribution Sodium

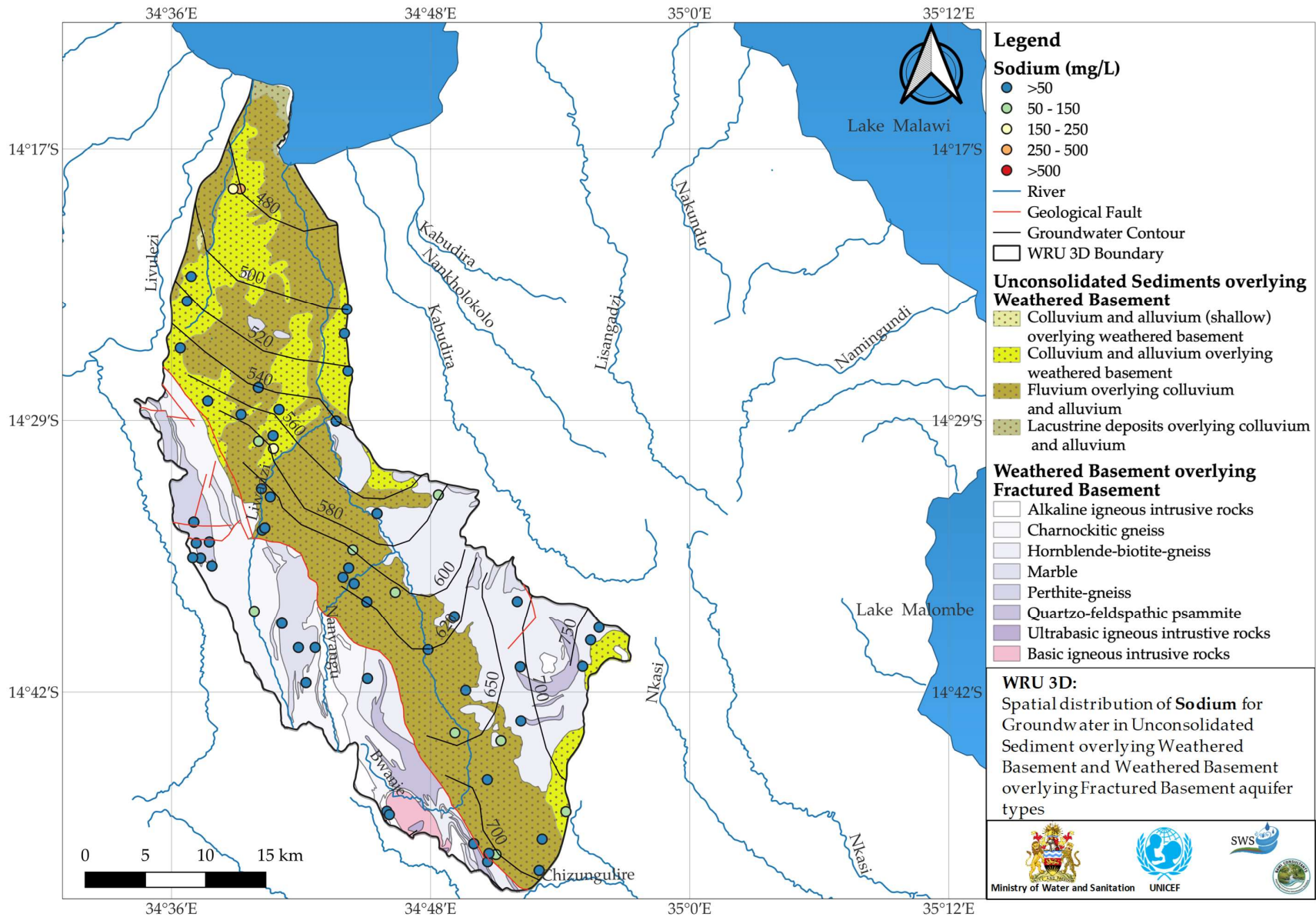


Figure WRU 3D.8 Groundwater Chemistry Distribution Calcium

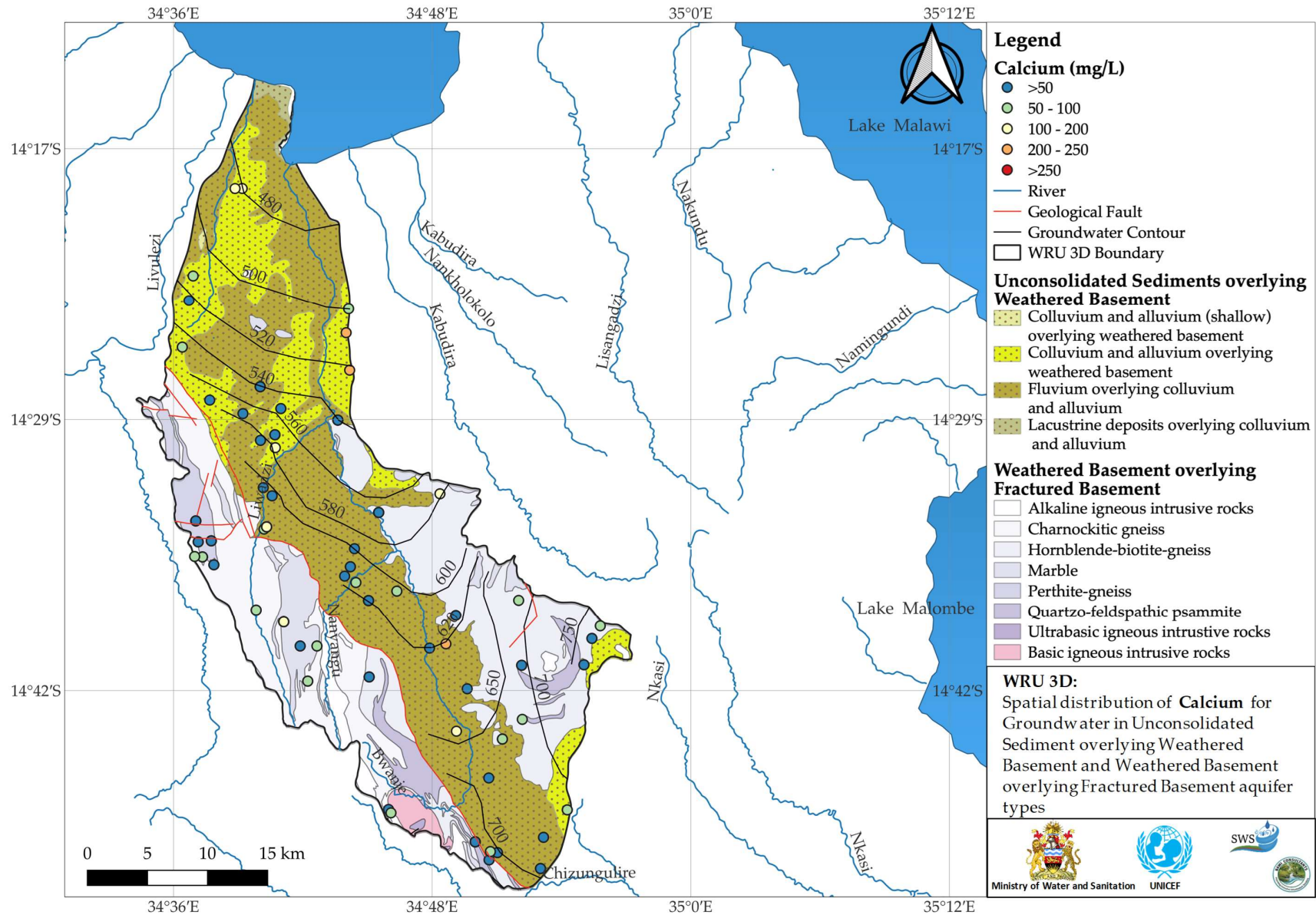
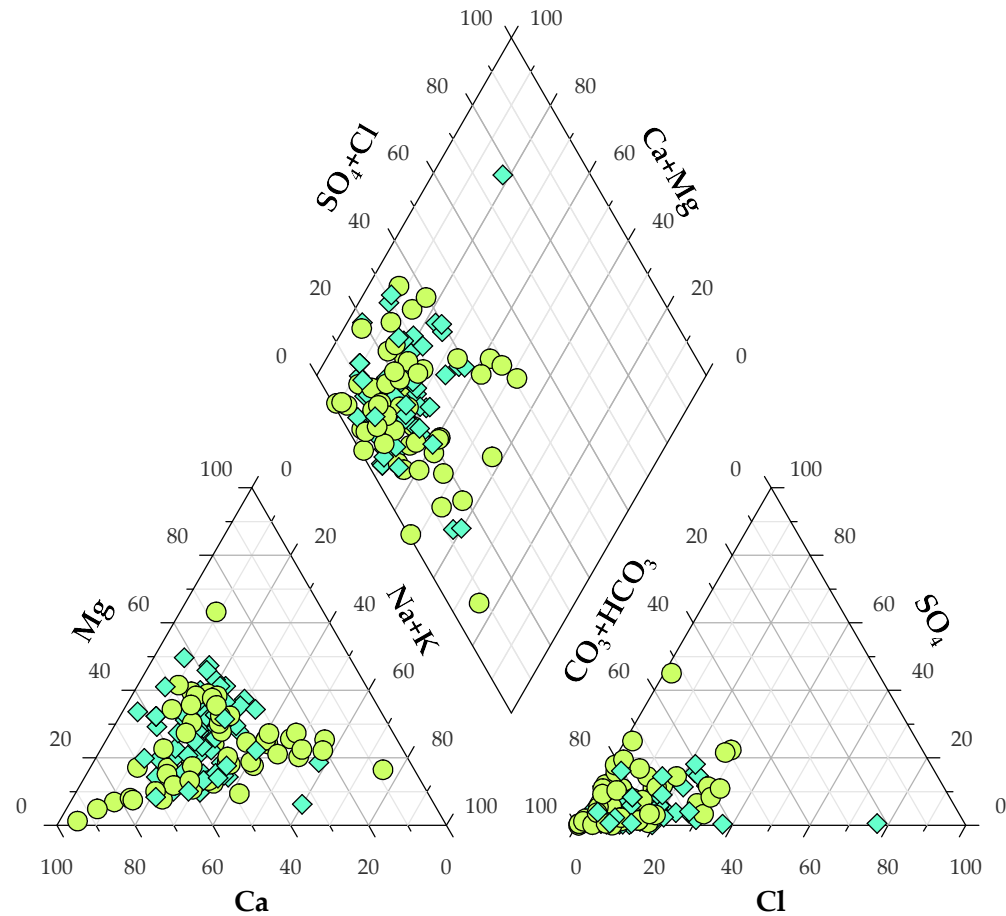


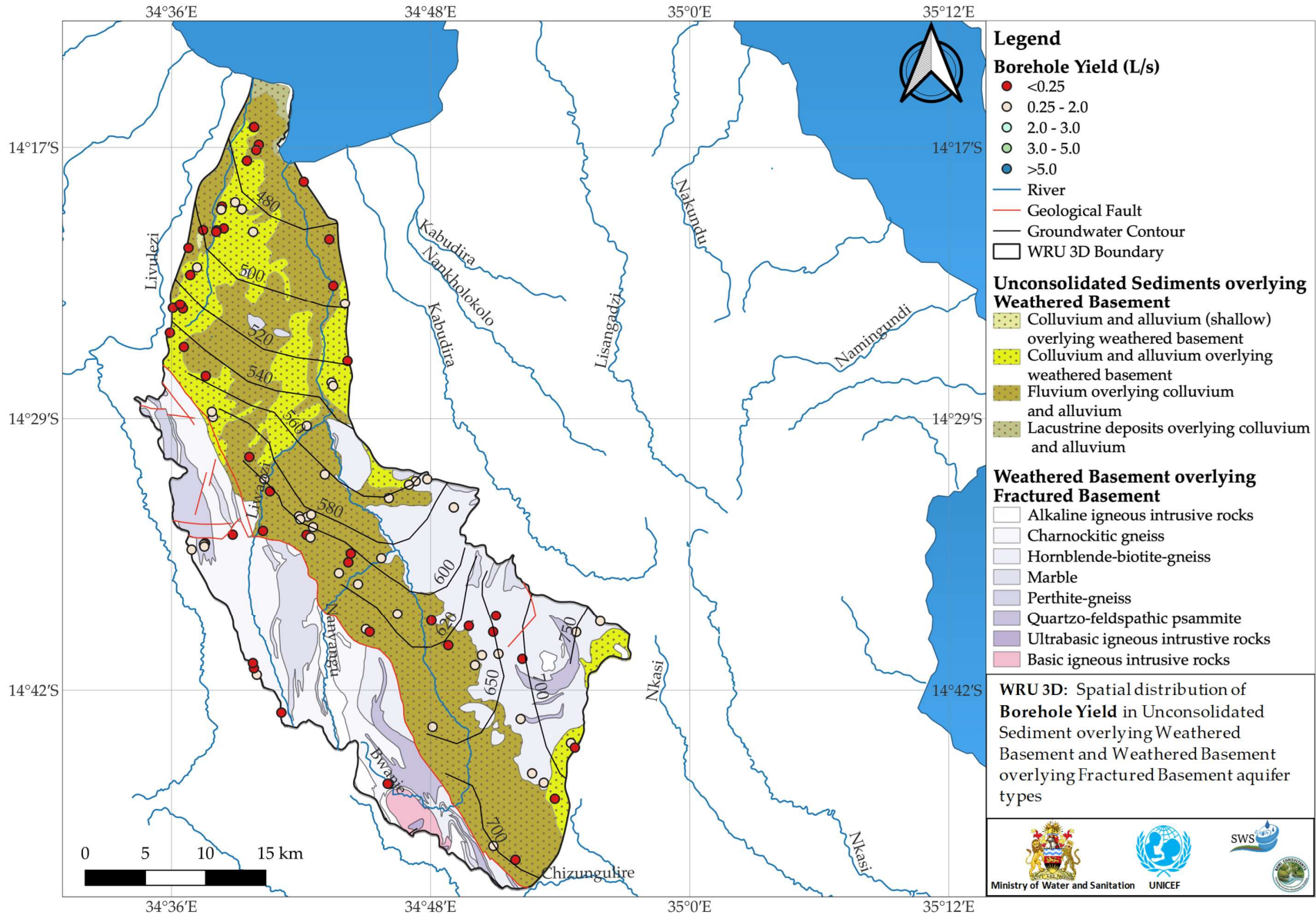
Figure WRU 3D.9 Piper Diagram of water quality results with respect to the major aquifer type



Aquifer Groups (WRU 3D)

- Unconsolidated Sediments overlying Weathered Basement
- ◆ Weathered Basement overlying Fractured Basement

Figure WRU 3D.10 Borehole Yield Map for data held by the Ministry



WRU 3E Figures

Figure WRU 3E.1 Land Use and Major Roads

Figure WRU 3E.2 Rivers and Wetlands

Figure WRU 3E.3 Hydrogeology Units and Water Table

Figure WRU 3E.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 3E.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 3E.6 Groundwater Chemistry Distribution Chloride

Figure WRU 3E.7 Groundwater Chemistry Distribution Sodium

Figure WRU 3E.8 Groundwater Chemistry Distribution Calcium

Figure WRU 3E.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 3E.10 Borehole Yield Map for data held by the Ministry

Figure WRU 3E.1 Land Use and Major Roads

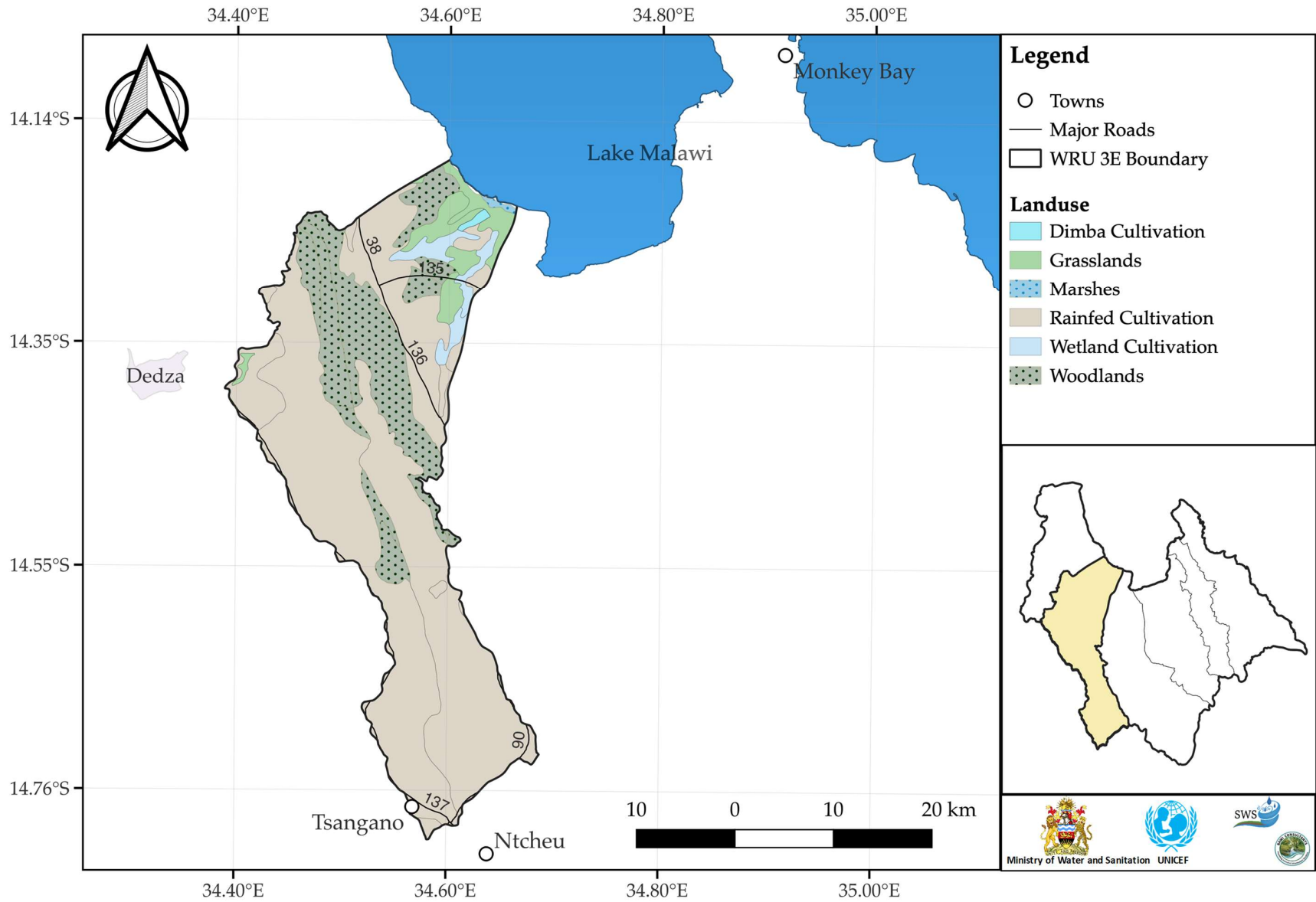


Figure WRU 3E.2 Rivers and Wetlands

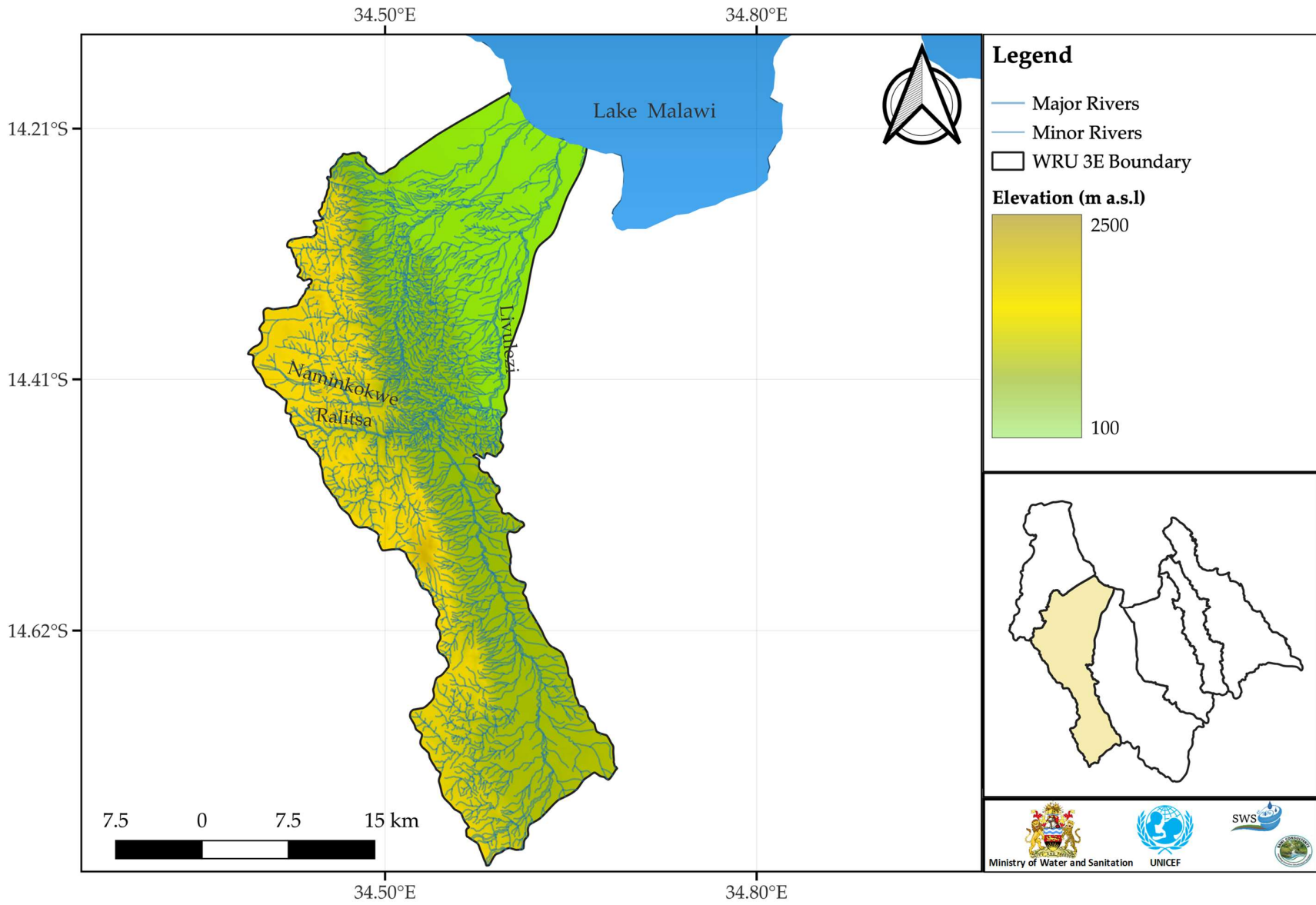


Figure WRU 3E.3 Hydrogeology Units and Water Table

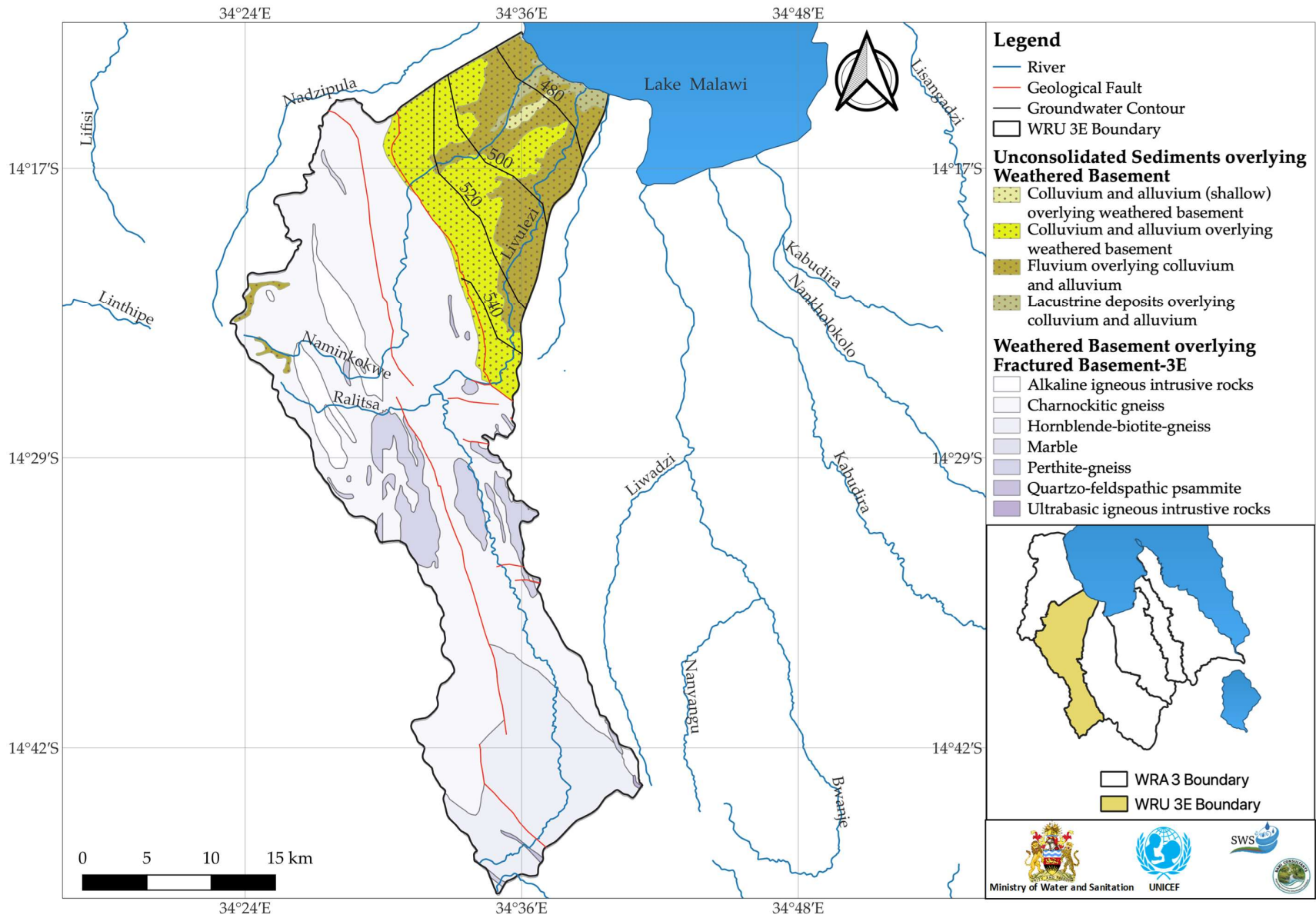


Figure WRU 3E.4 Groundwater Chemistry Distribution Electrical Conductivity

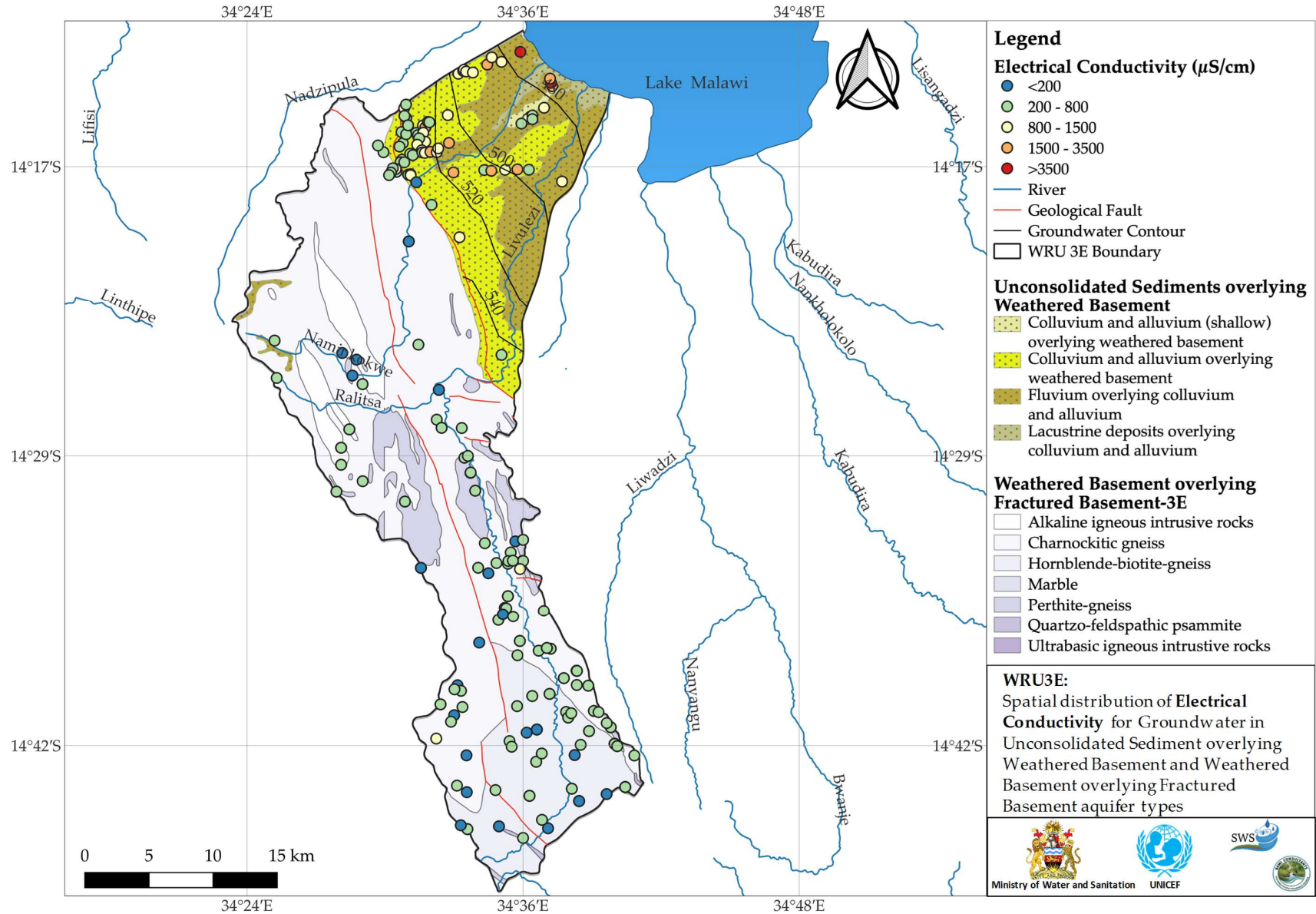


Figure WRU 3E.5 Groundwater Chemistry Distribution of Sulphate

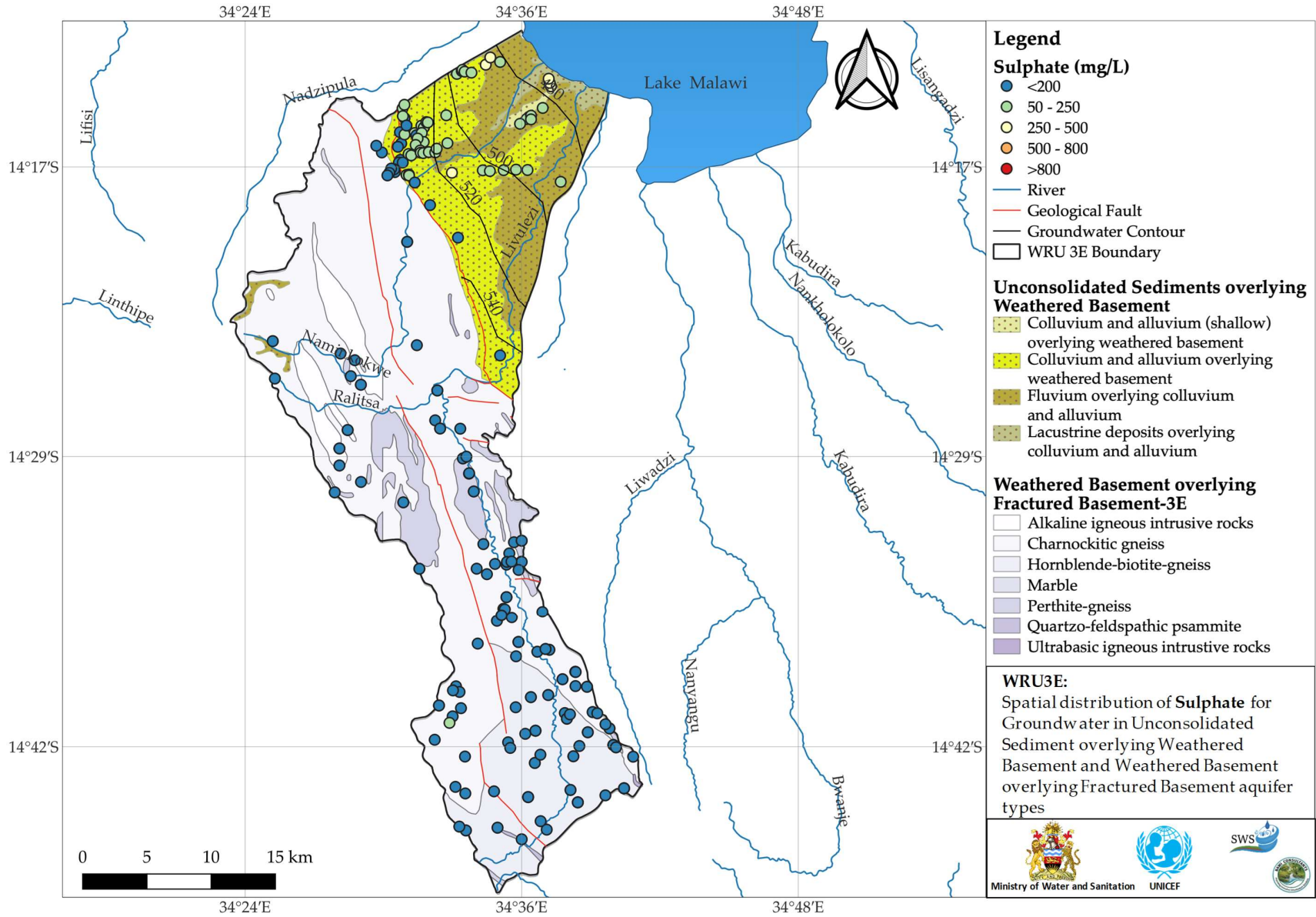


Figure WRU 3E.6 Groundwater Chemistry Distribution Chloride

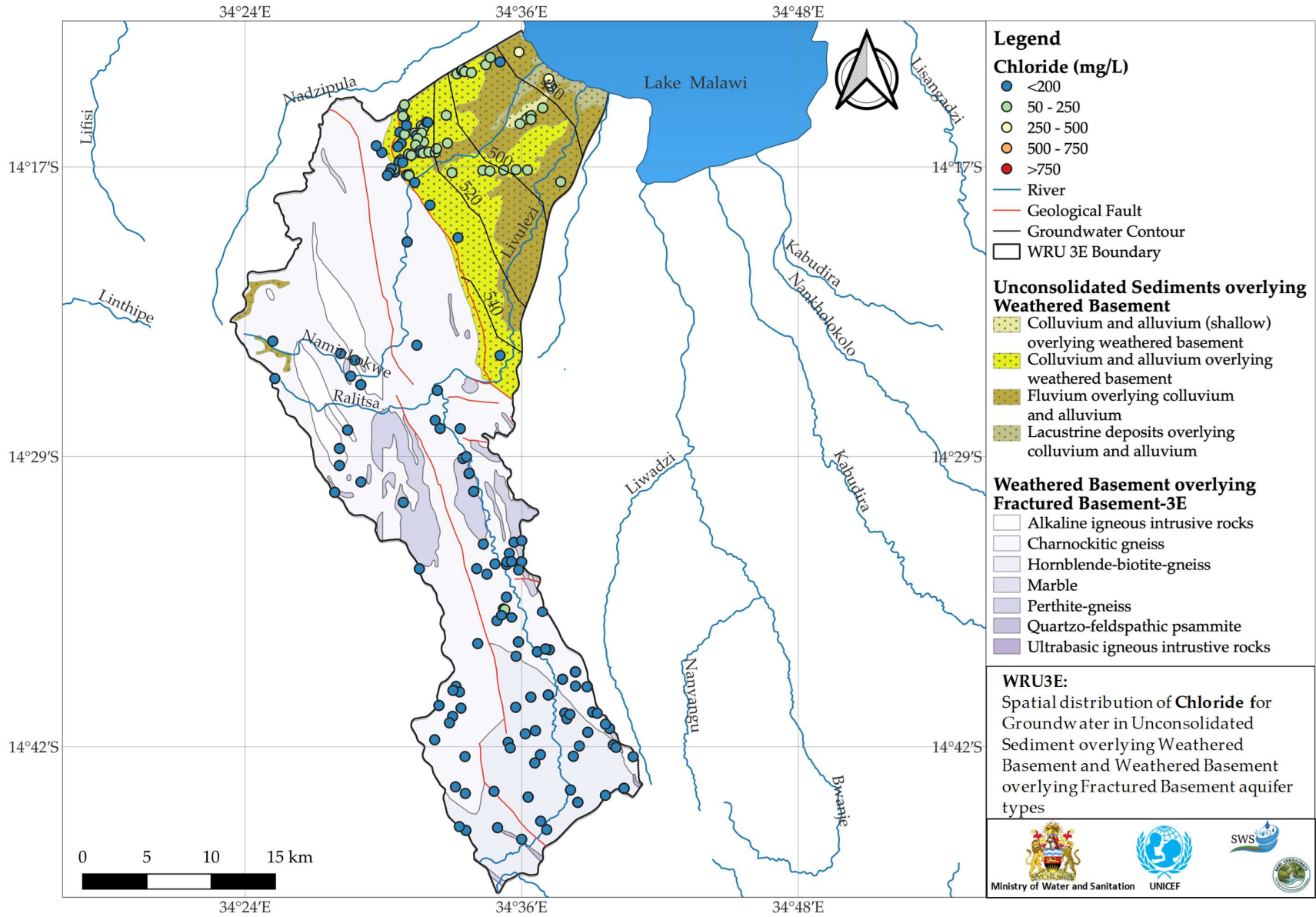


Figure WRU 3E.7 Groundwater Chemistry Distribution Sodium

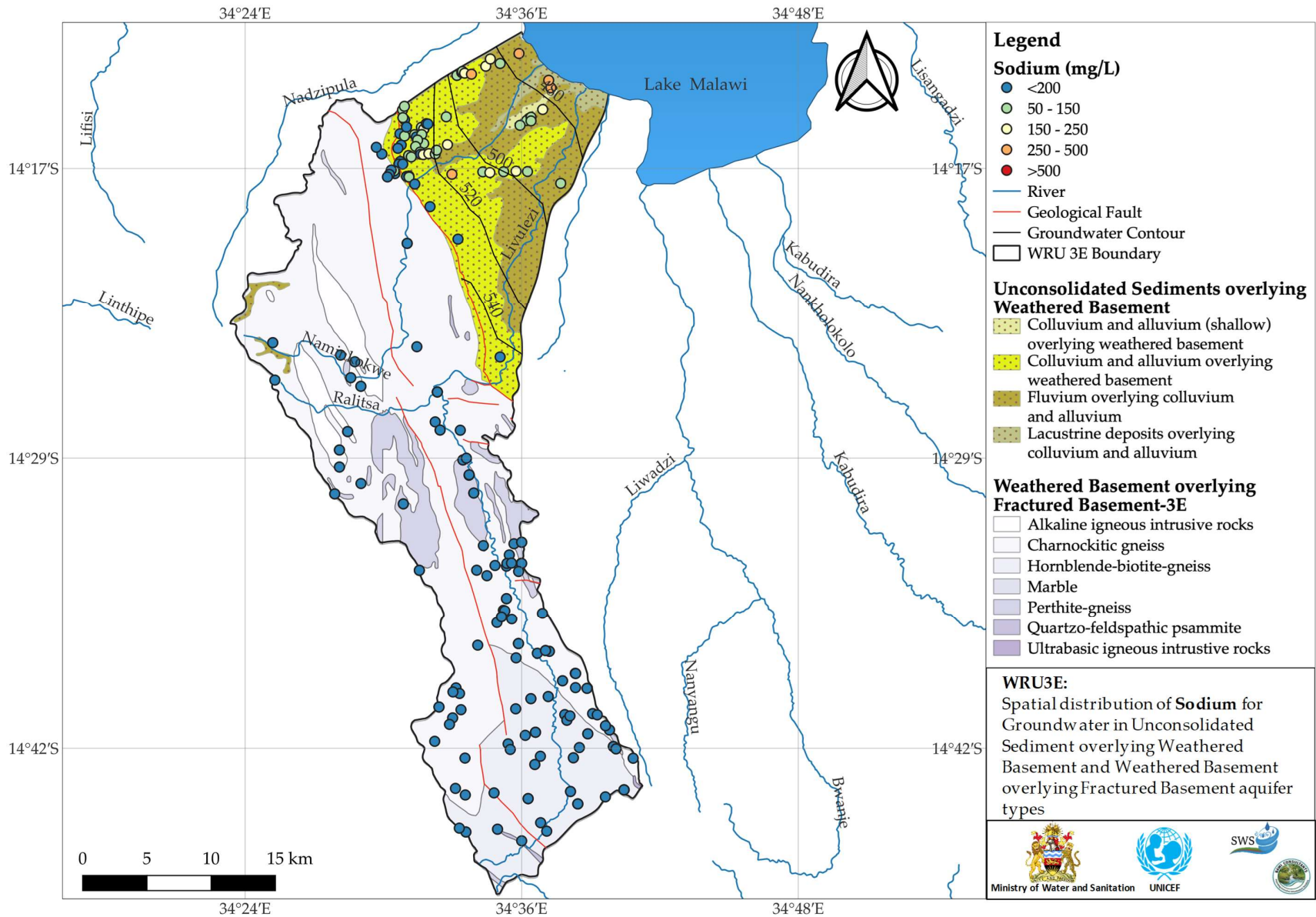


Figure WRU 3E.8 Groundwater Chemistry Distribution Calcium

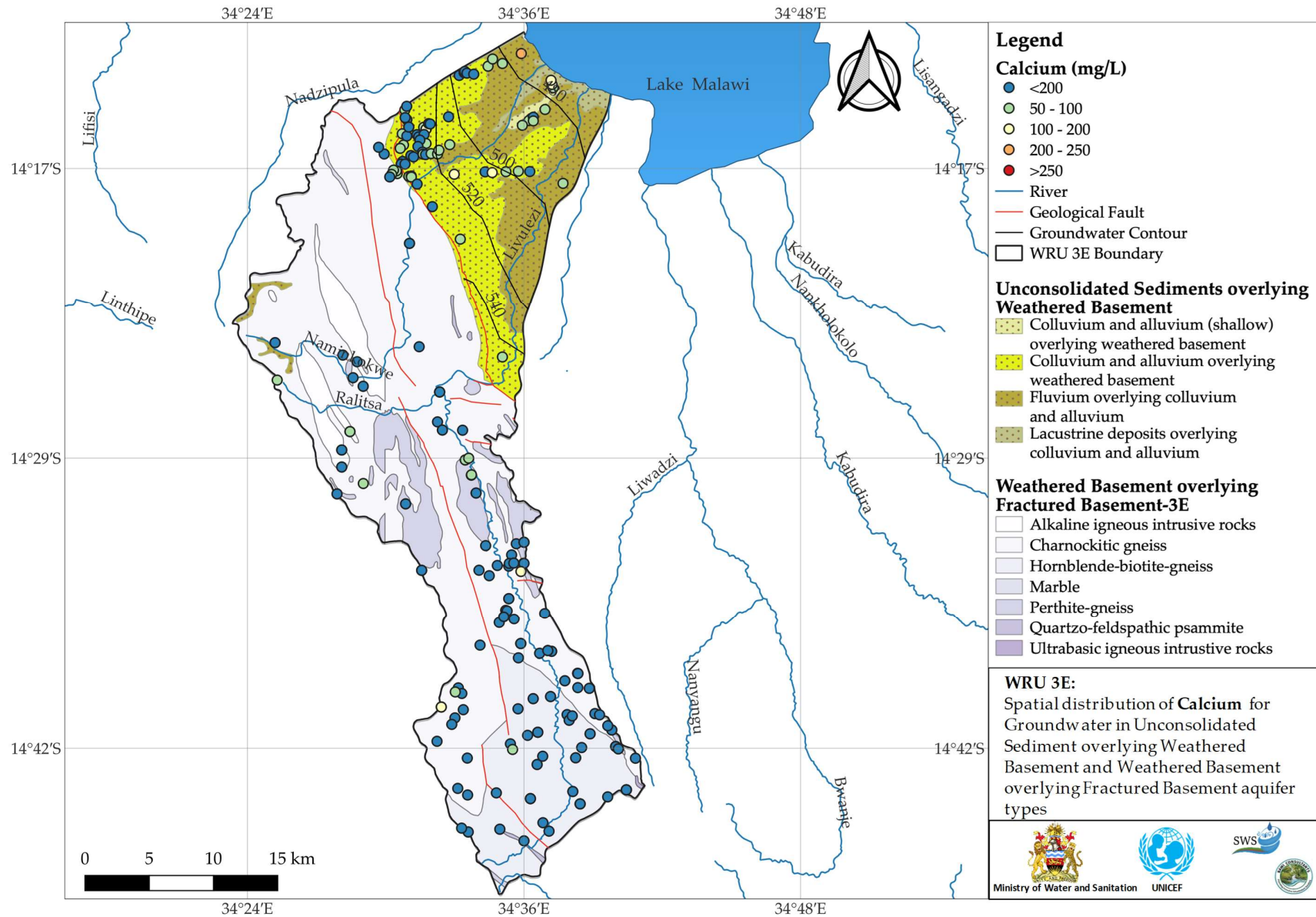


Figure WRU 3E.9 Piper Diagram of water quality results with respect to the major aquifer type

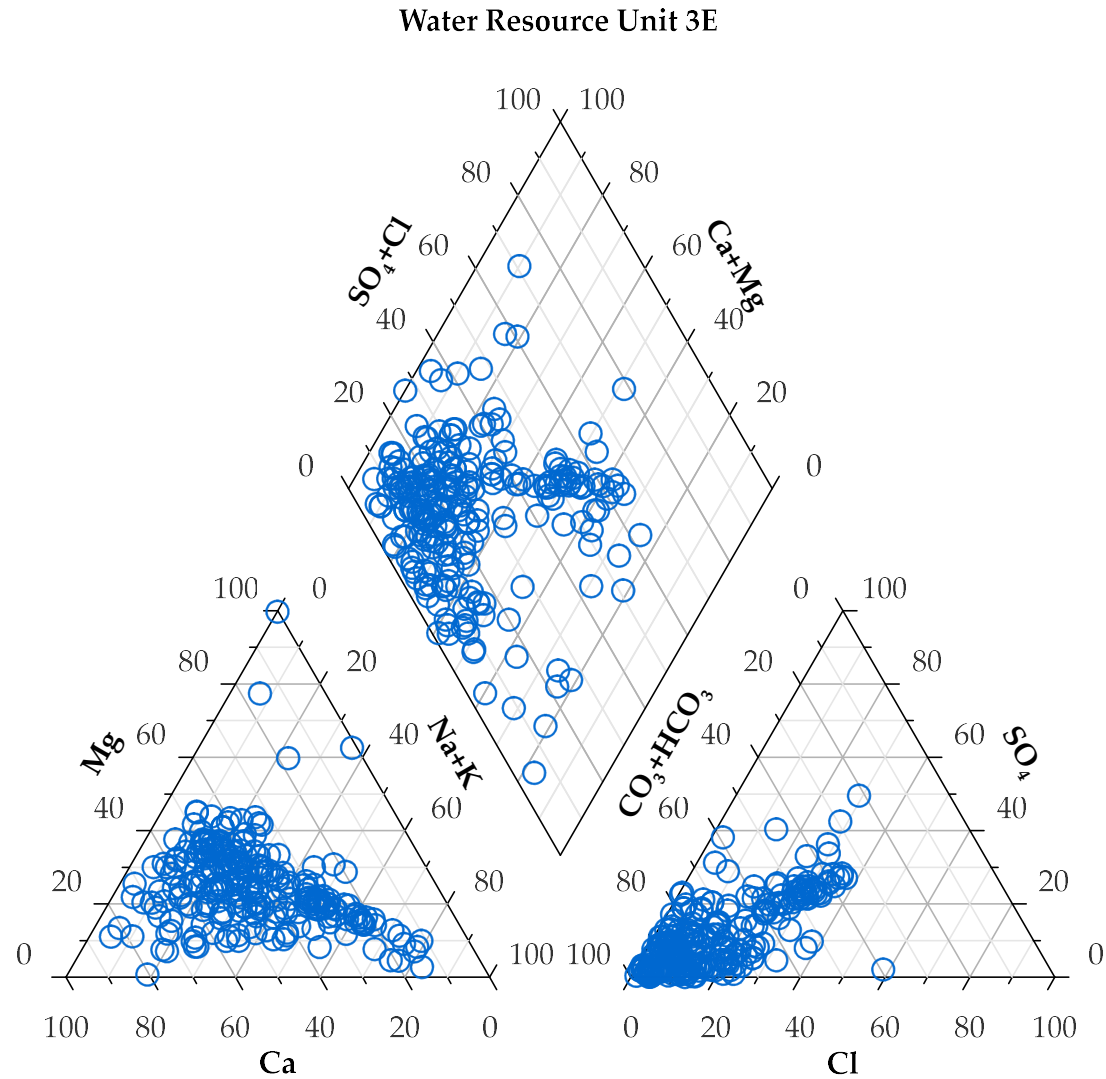
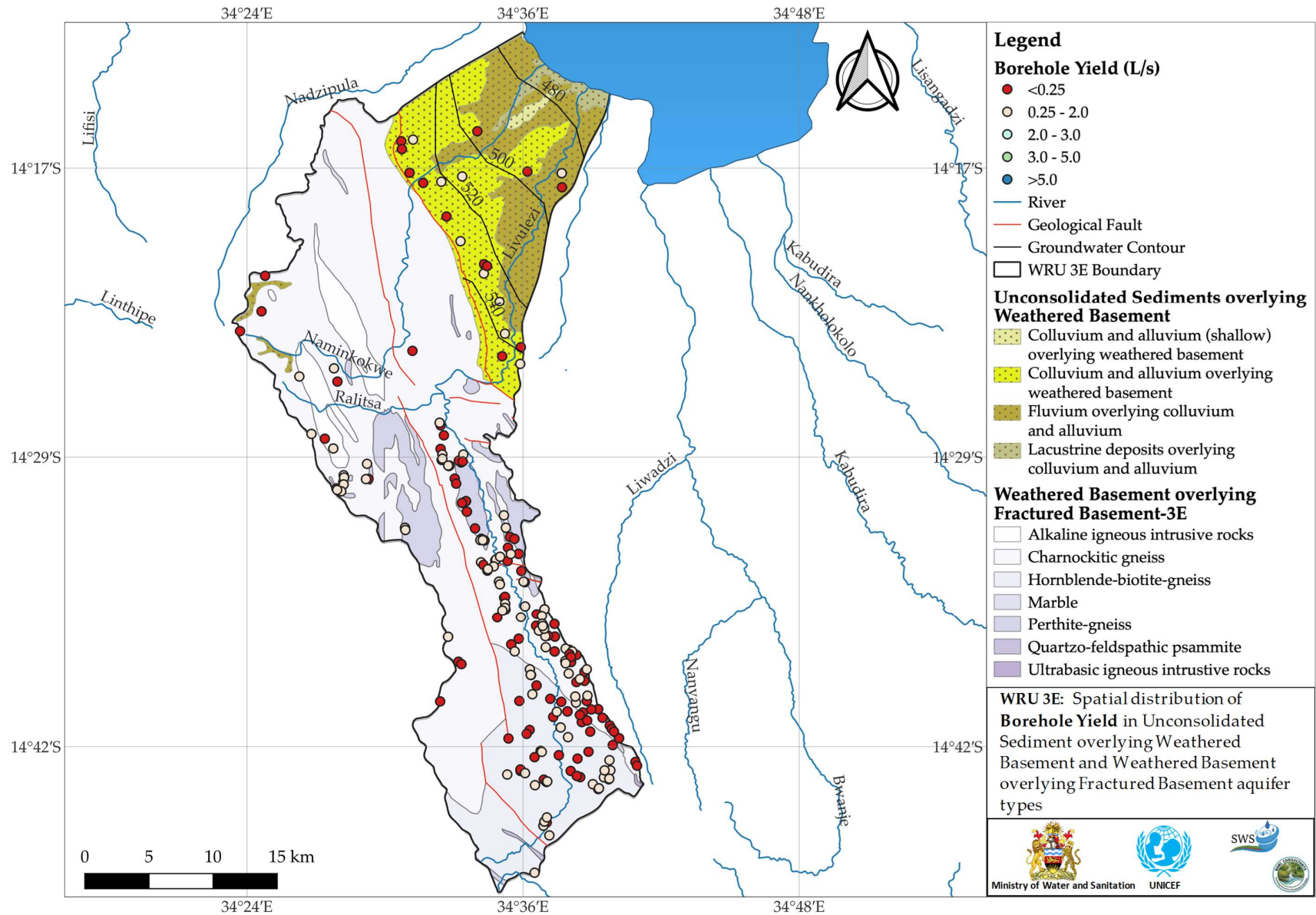


Figure WRU 3E.10 Borehole Yield Map for data held by the Ministry



WRU 3F Figures

Figure WRU 3F.1 Land Use and Major Roads

Figure WRU 3F.2 Rivers and Wetlands

Figure WRU 3F.3 Hydrogeology Units and Water Table

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Figure WRU 3F.5 Groundwater Chemistry Distribution of Sulphate

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Figure WRU 3F.7 Groundwater Chemistry Distribution Sodium

Figure WRU 3F.8 Groundwater Chemistry Distribution Calcium

Figure WRU 3F.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 3F.10 Borehole Yield Map for data held by the Ministry

Figure WRU 3F.1 Land Use and Major Roads

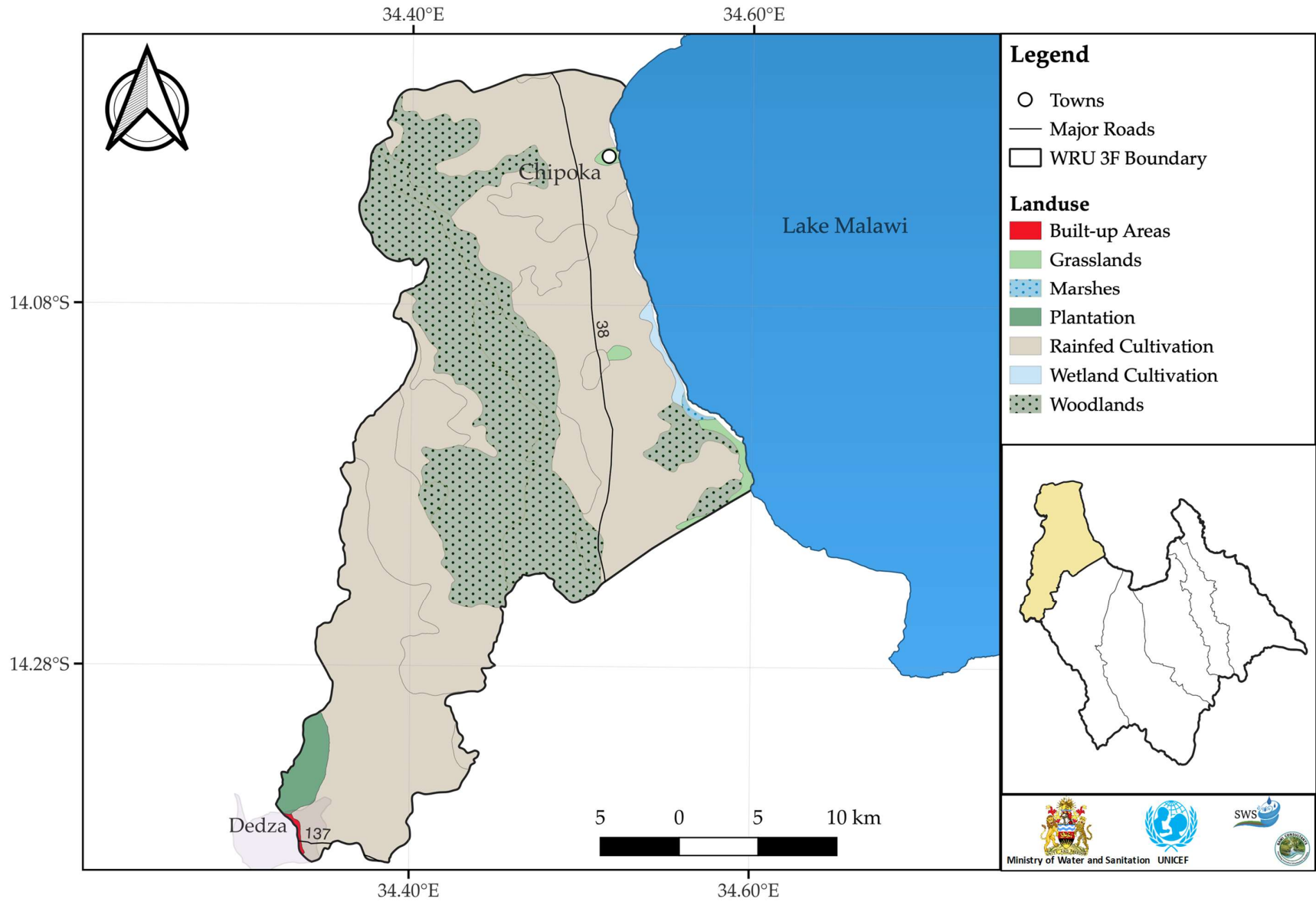


Figure WRU 3F.2 Rivers and Wetlands

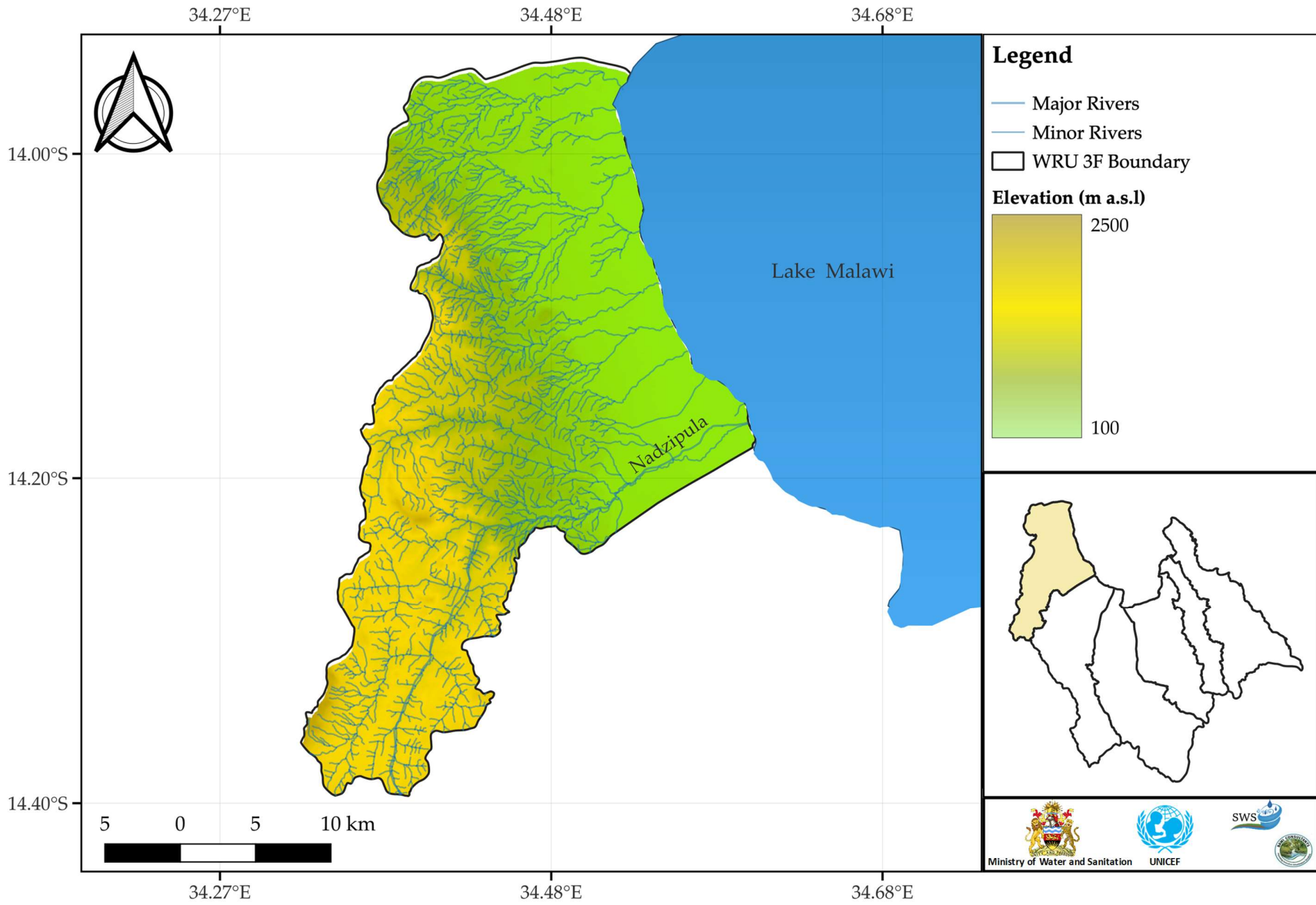


Figure WRU 3F.3 Hydrogeology Units and Water Table

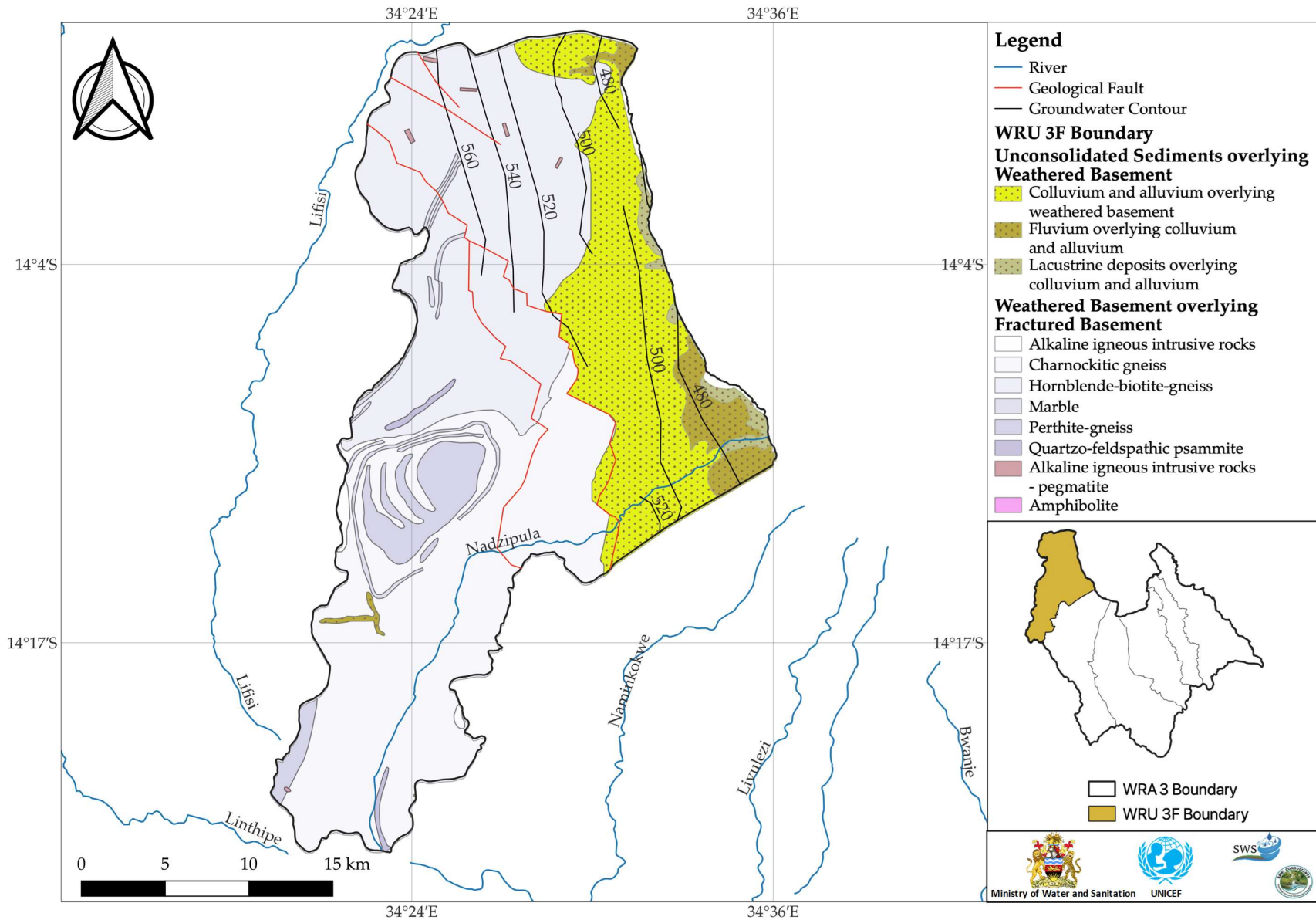


Figure WRU 3E.4 Groundwater Chemistry Distribution Electrical Conductivity

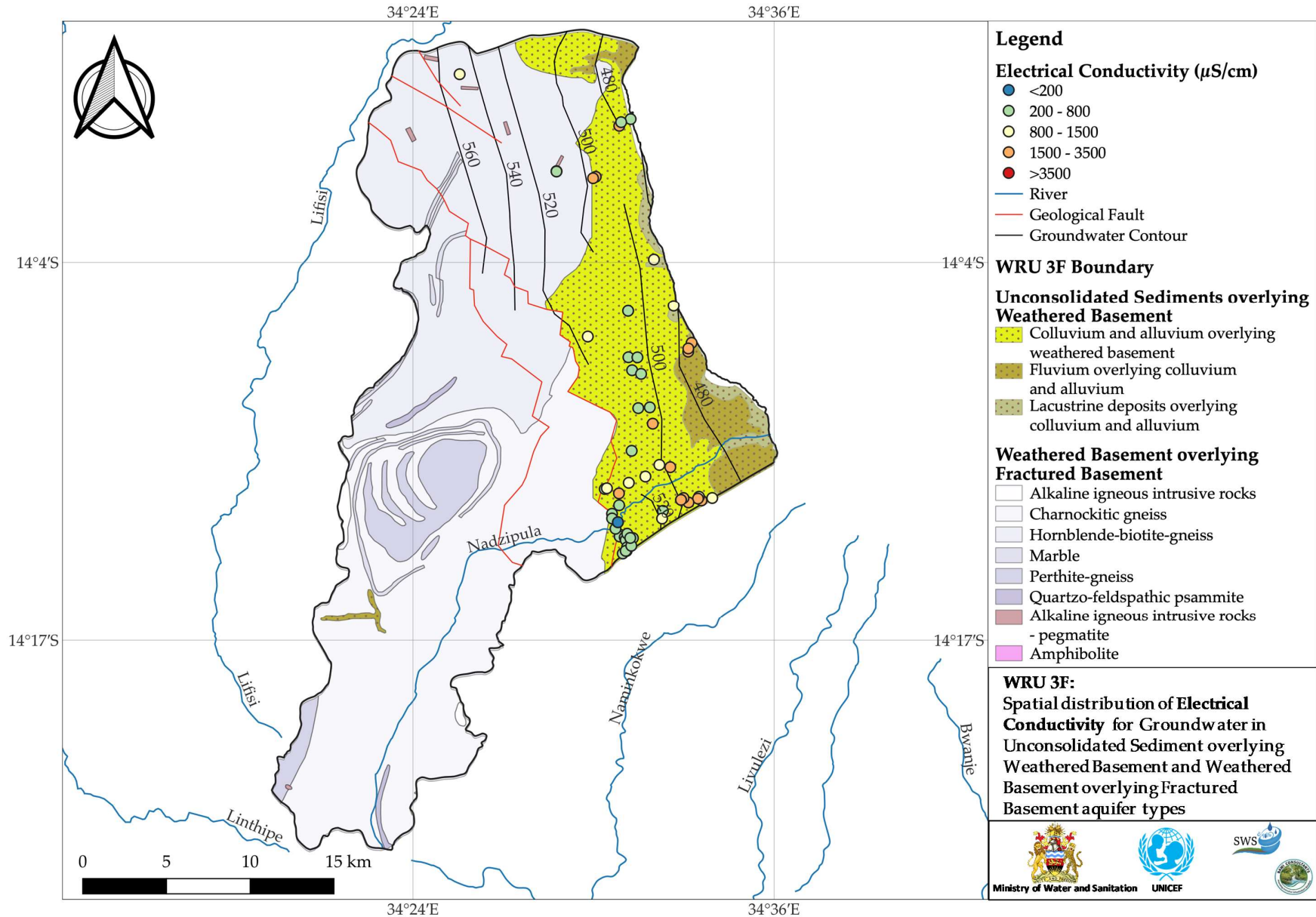


Figure WRU 3F.5 Groundwater Chemistry Distribution of Sulphate

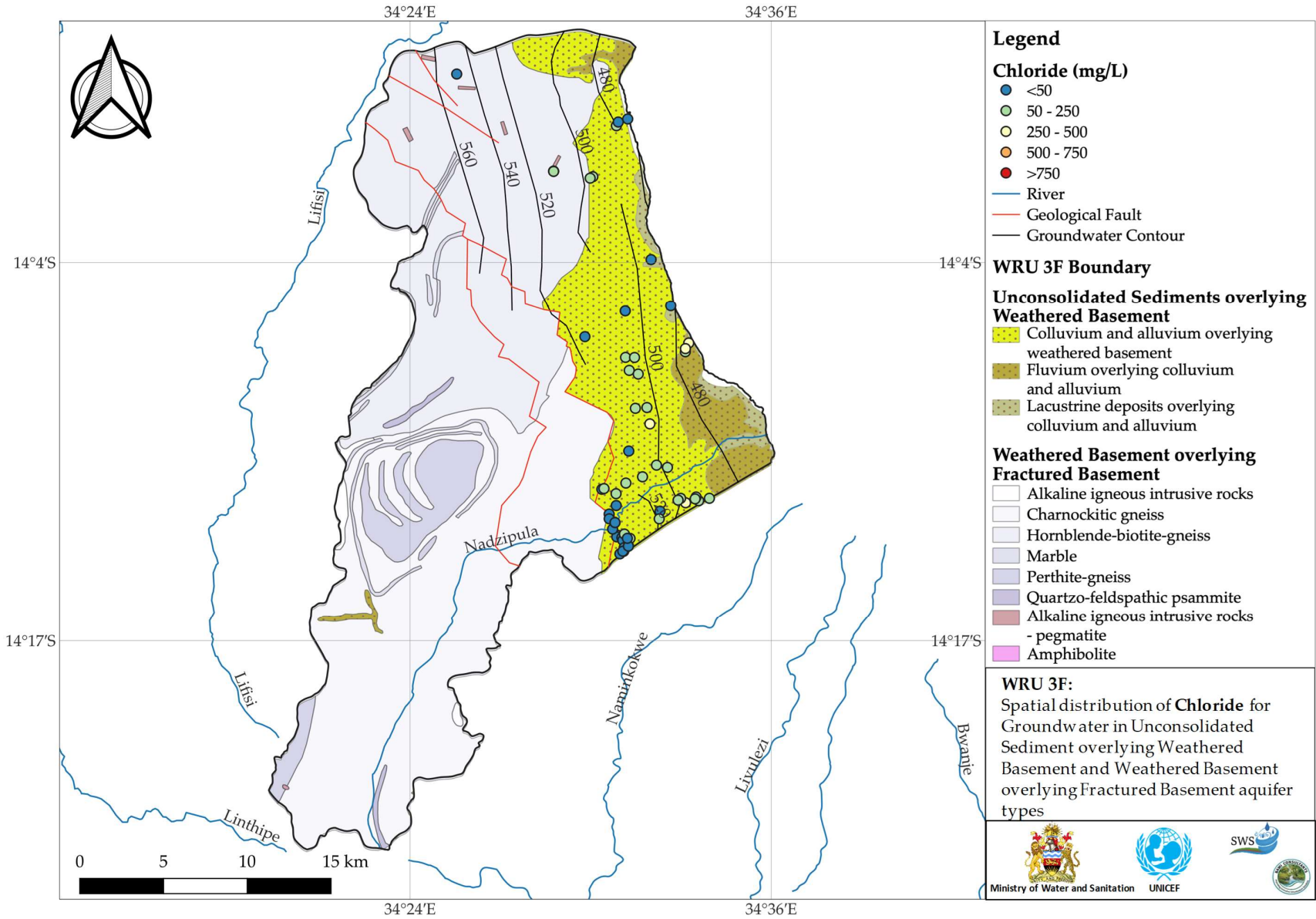


Figure WRU 3F.6 Groundwater Chemistry Distribution Chloride

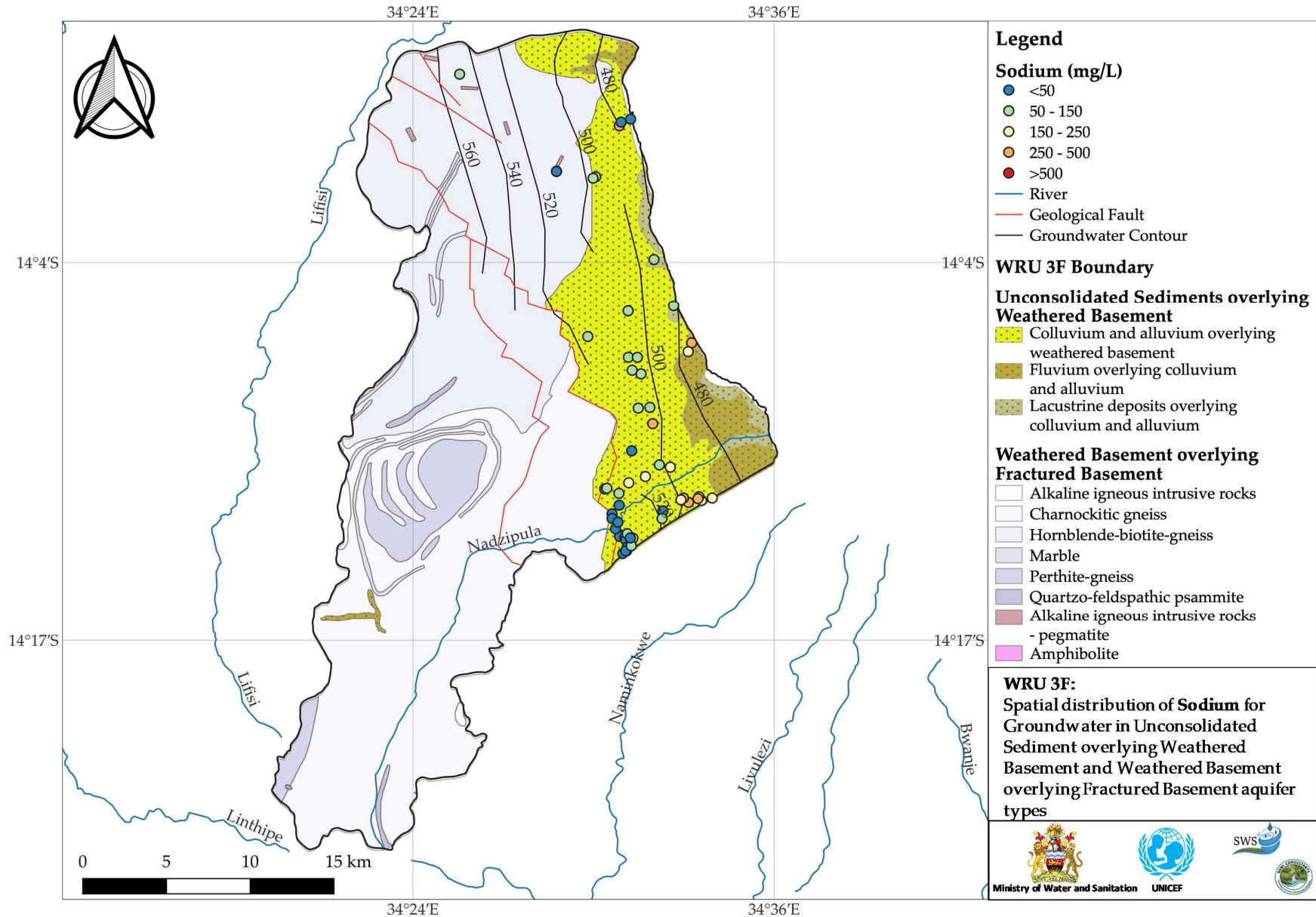


Figure WRU 3F.7 Groundwater Chemistry Distribution Sodium

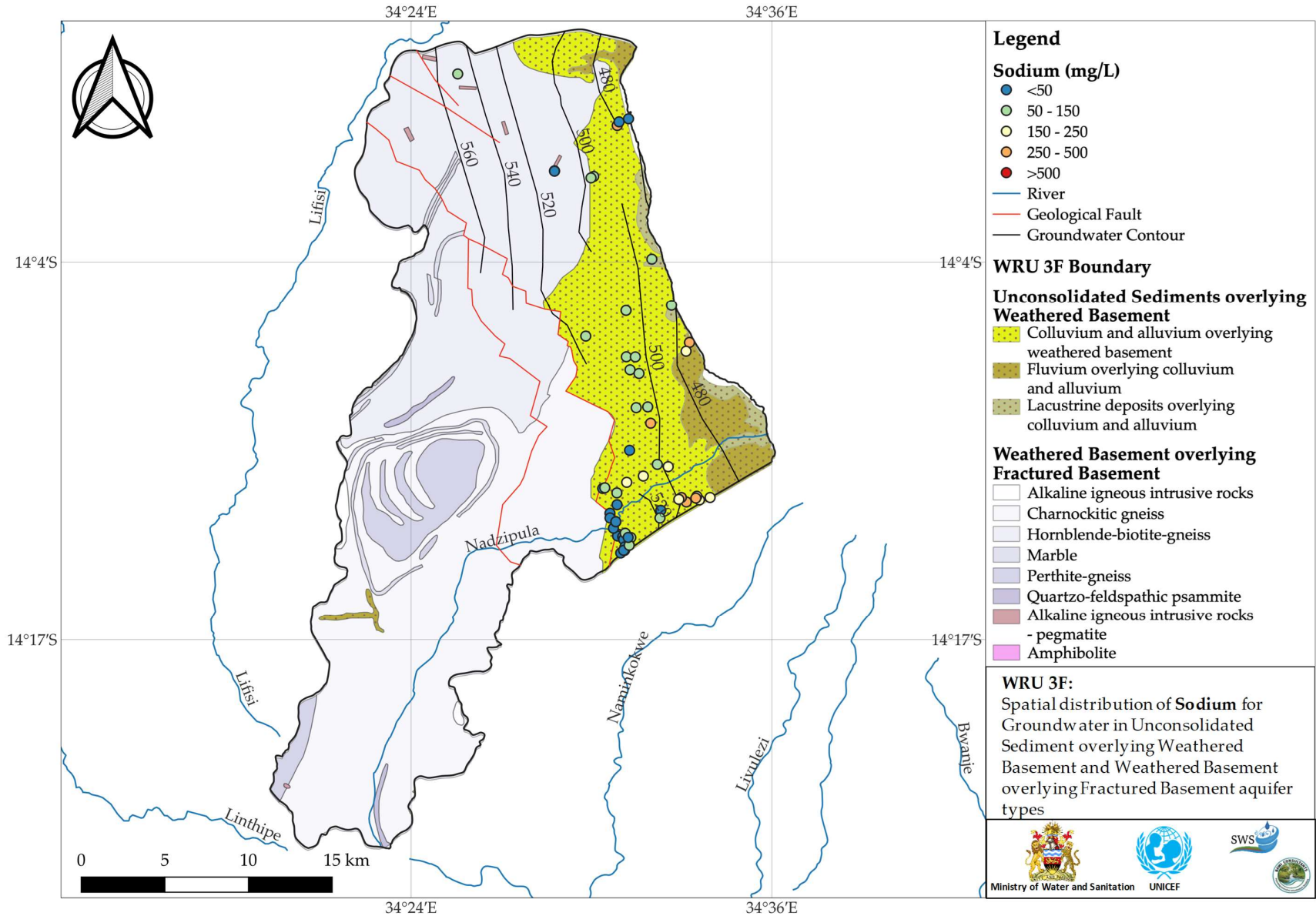


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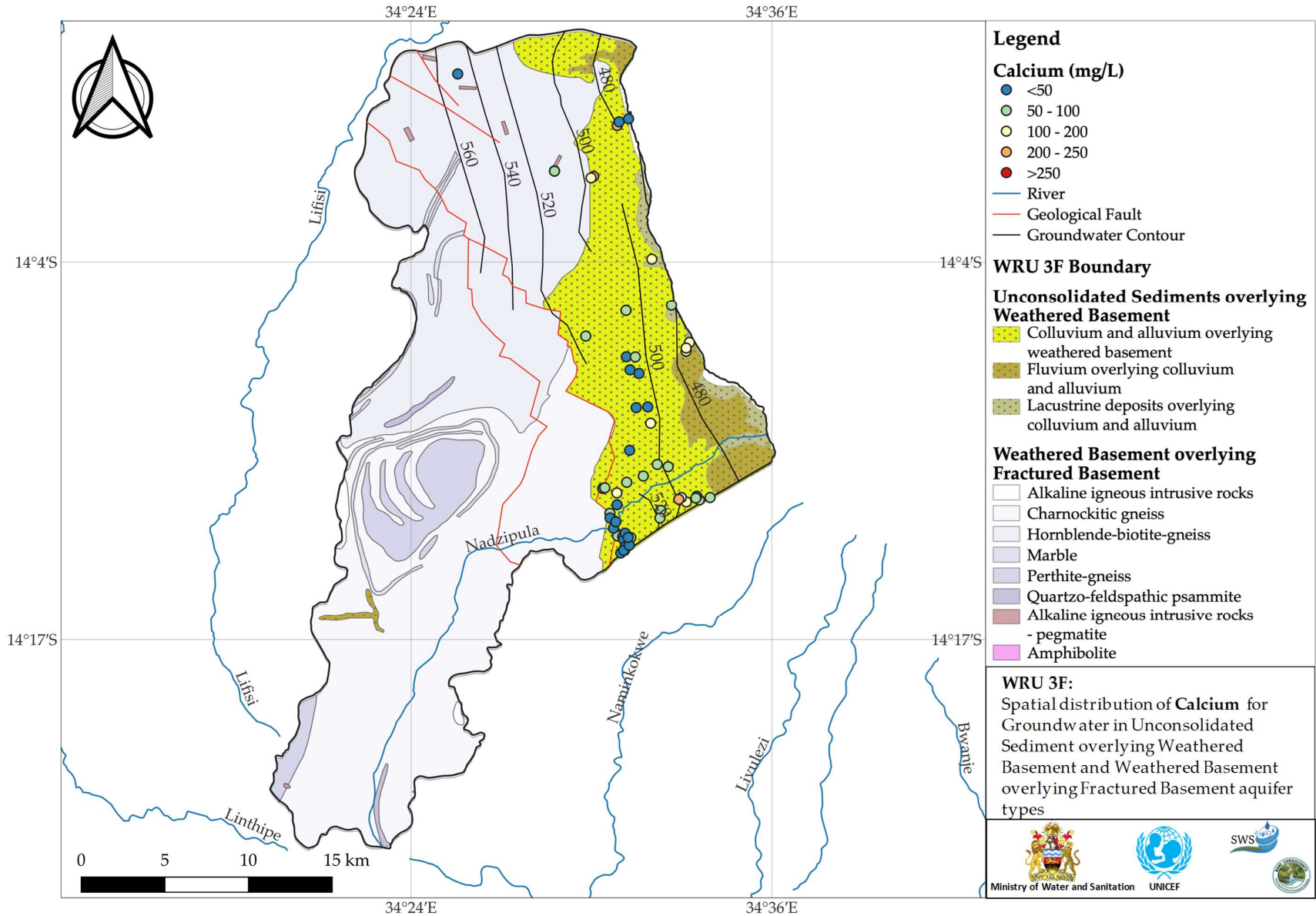


Figure WRU 3F.9 Piper Diagram of water quality results with respect to the major aquifer type

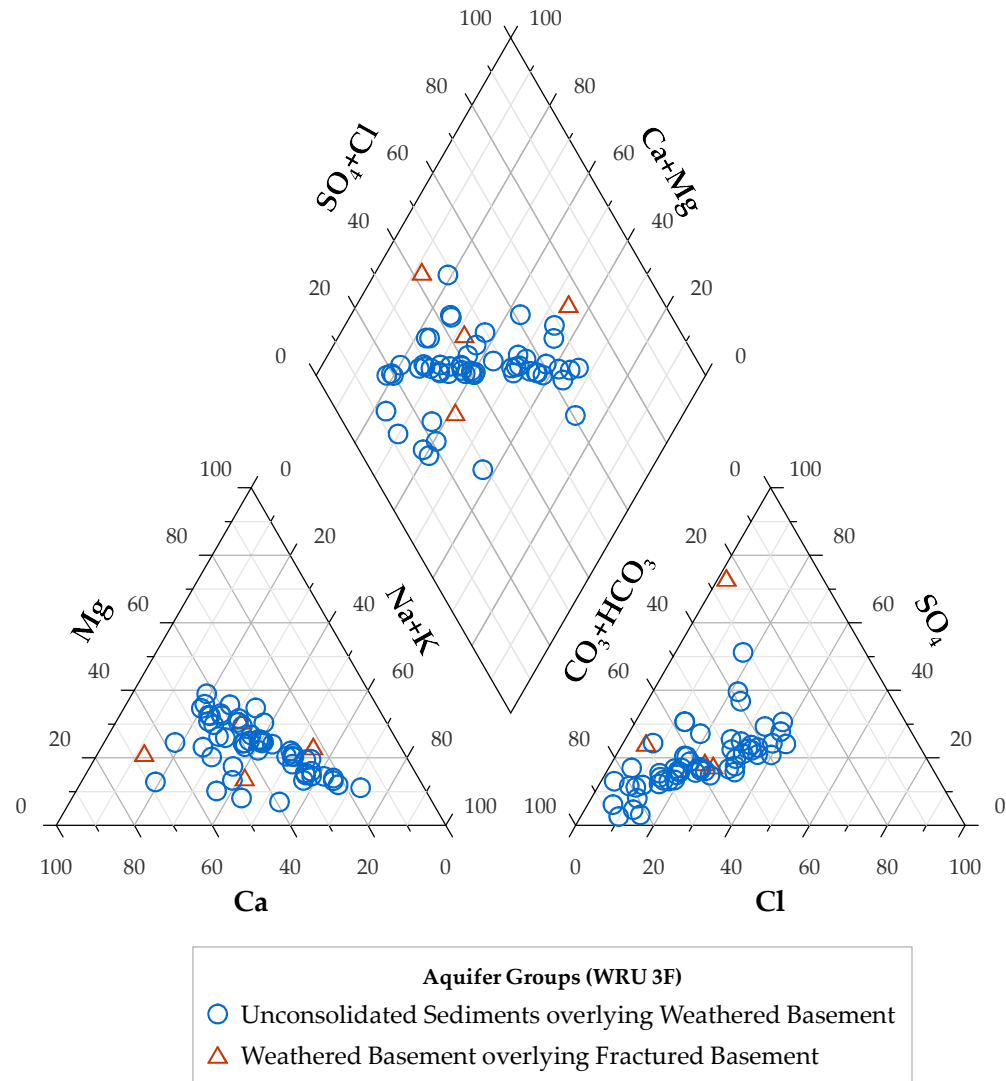
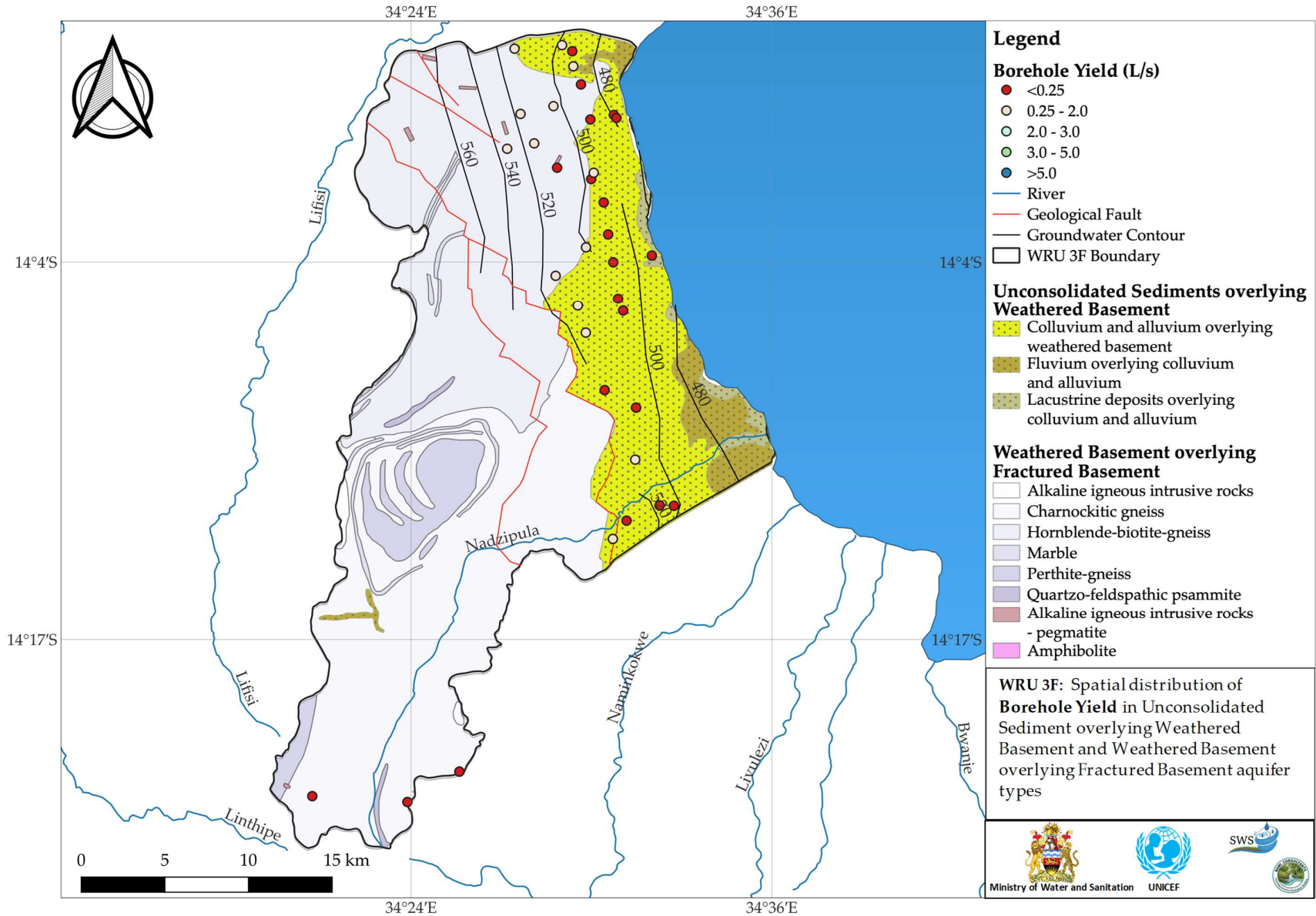


Figure WRU 3F.10 Borehole Yield Map for data held by the Ministry





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., Mambululu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A., Hinton, R. (2022) Hydrogeology and Groundwater Quality Atlas of Malawi, South West Lake Malawi Catchment Water Resource Area 3, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-04-8 108pp

