Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 14

The Ruo 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
°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 14 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.

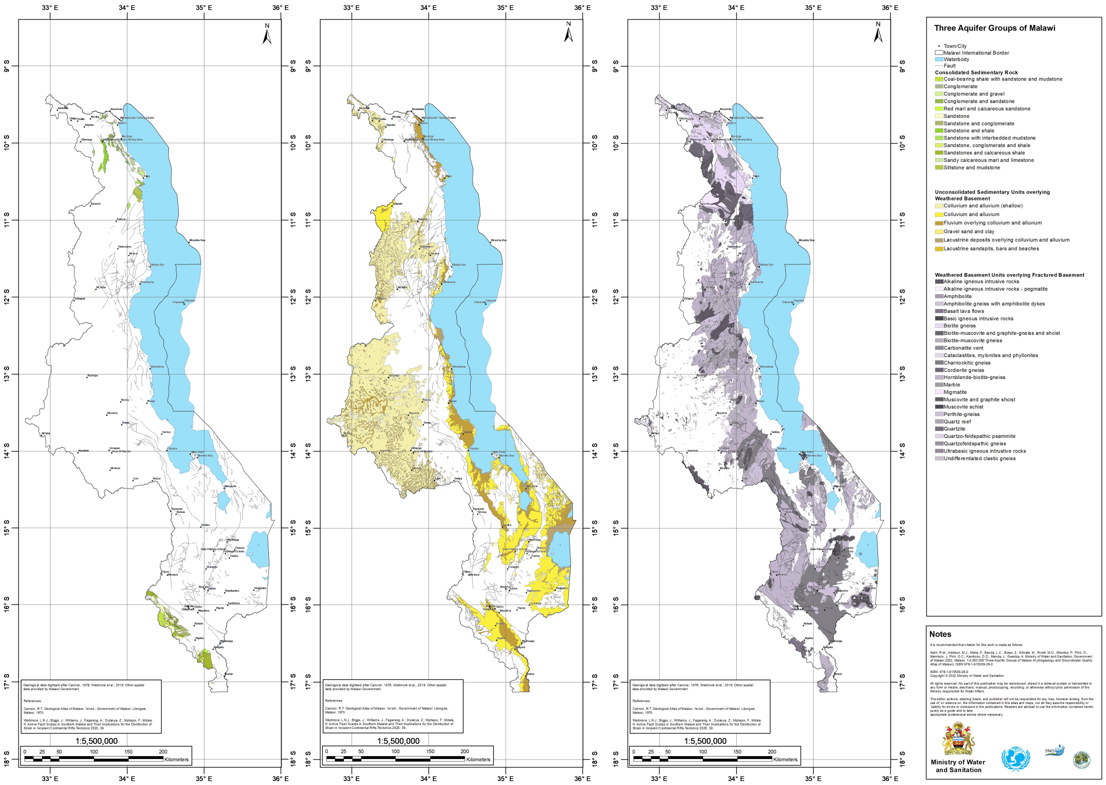

Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure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

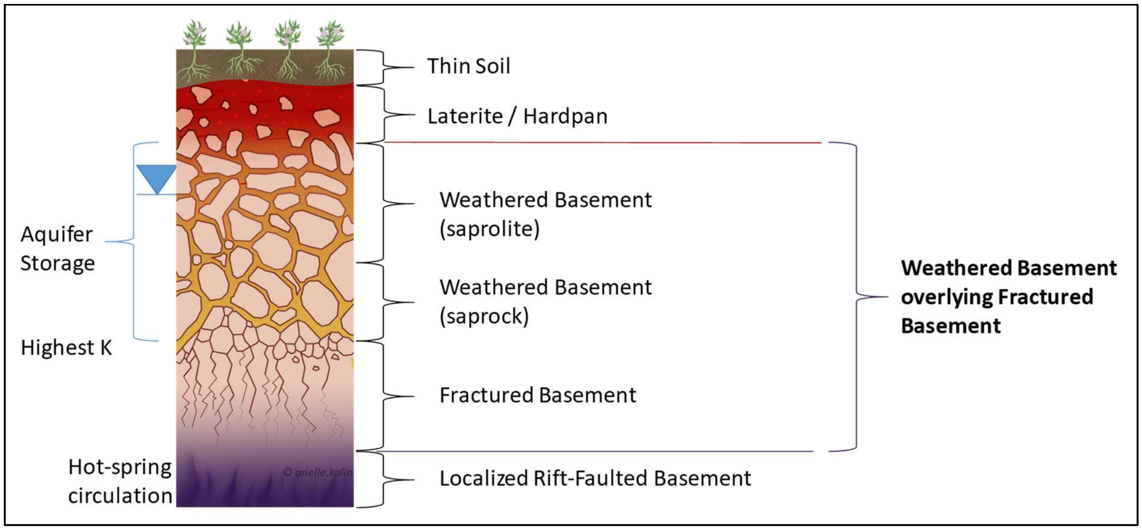

Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

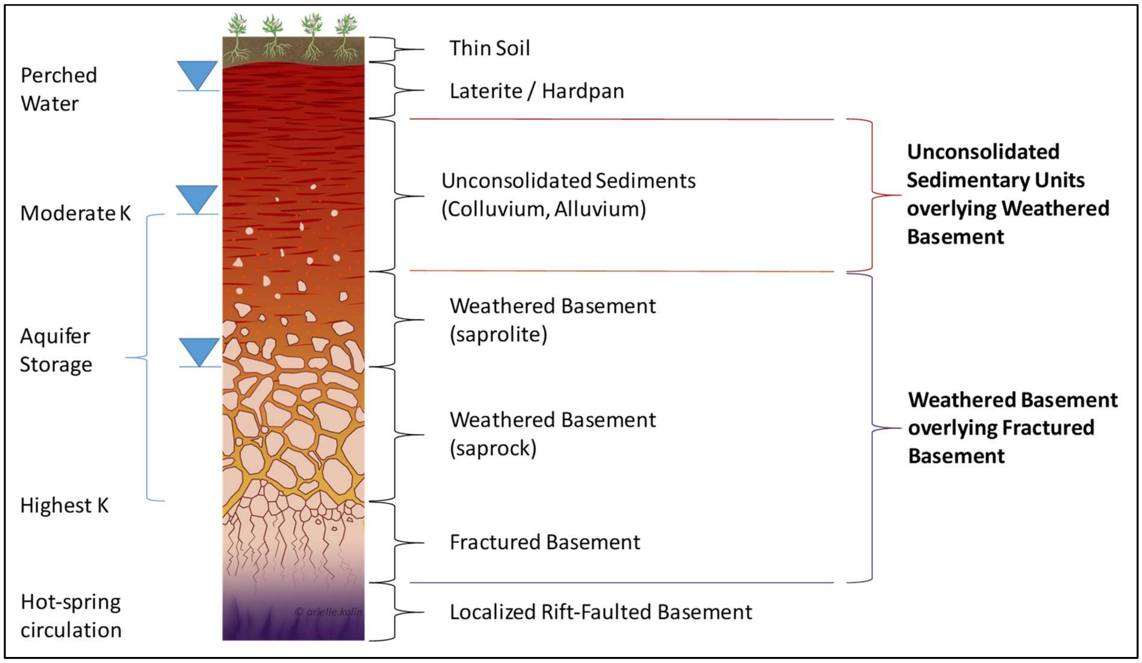

Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

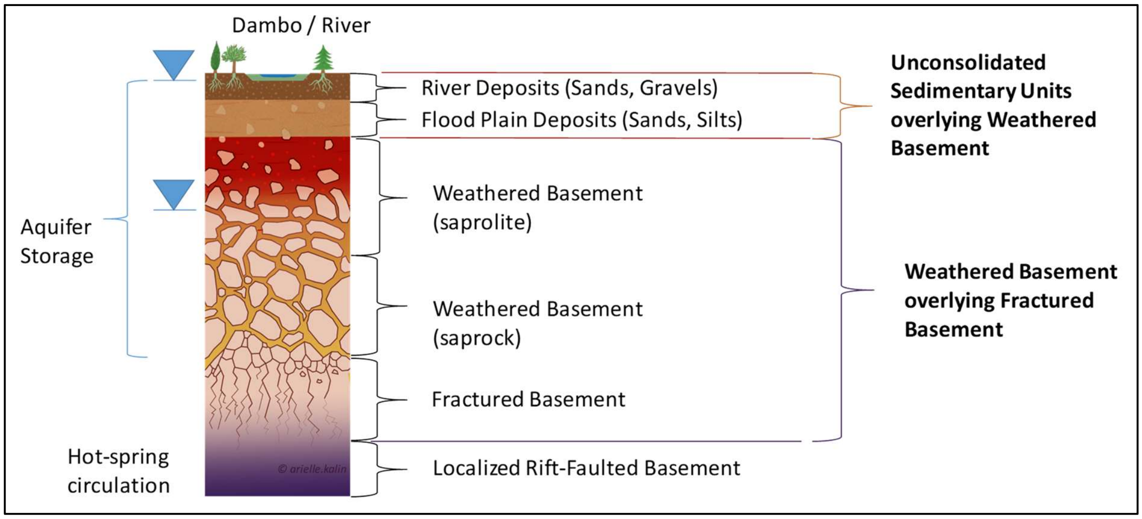

Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

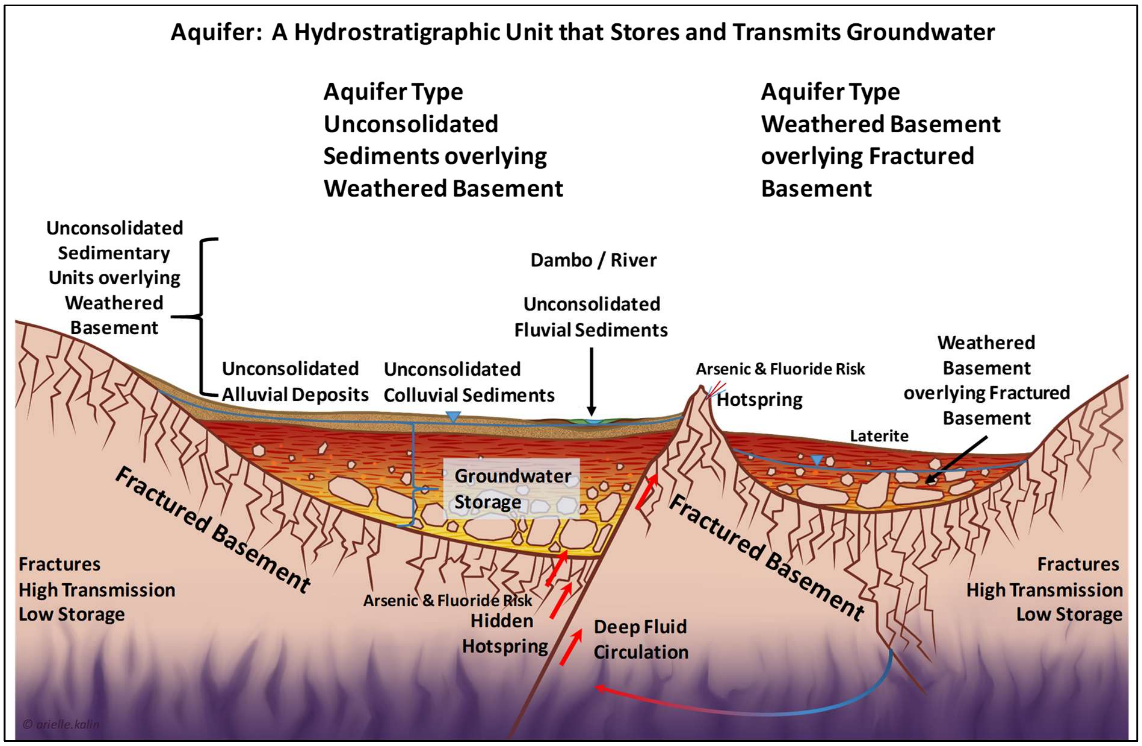

Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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

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Water Resource Area 14 (WRA 14): The Ruo Catchment

The Water Resource Area (WRA) 14 (**Figure 2a**) in southern Malawi constitutes four (4) Water Resource Units (WRU); WRU 14A, 14B, 14C and 14D (**Figure 2b**). It covers an area of 3,519 Km^2 that stretches from the eastern Malawi-Mozambique border in Mulanje district to Lower Shire Valley in Nsanje district. The major riverine flows are from the Ruo River with its headwaters on the slopes of Mulanje Mountain, hence called Ruo River catchment. The catchment has seasonal flash flooding resulting from topographic setting and adjective storms from moisture carried from the Mozambique channel. WRA 14 has both trans-boundary surface and groundwater that are governed by Trans-boundary water sharing agreements.

The catchment is largely drained by the Ruo River and its major tributary; Thuchila River. The other tributaries include Lichenya Chisawani, Likabula, Thuchila, Tangusi, Nansadi and Chisawani Rivers. The Ruo River drains the southern Shire Highlands and discharges into Shire River at Chiromo in Nsanje district. The Ruo River west bank drains a portion of Milanje district in the neighbouring. Thuchila River drains southwestern slopes of Mulanje, southeastern Shire Highlands and Thuchila plain that lies in between before discharging into Ruo River near Sandama, a largely populated place, in Thyolo district.

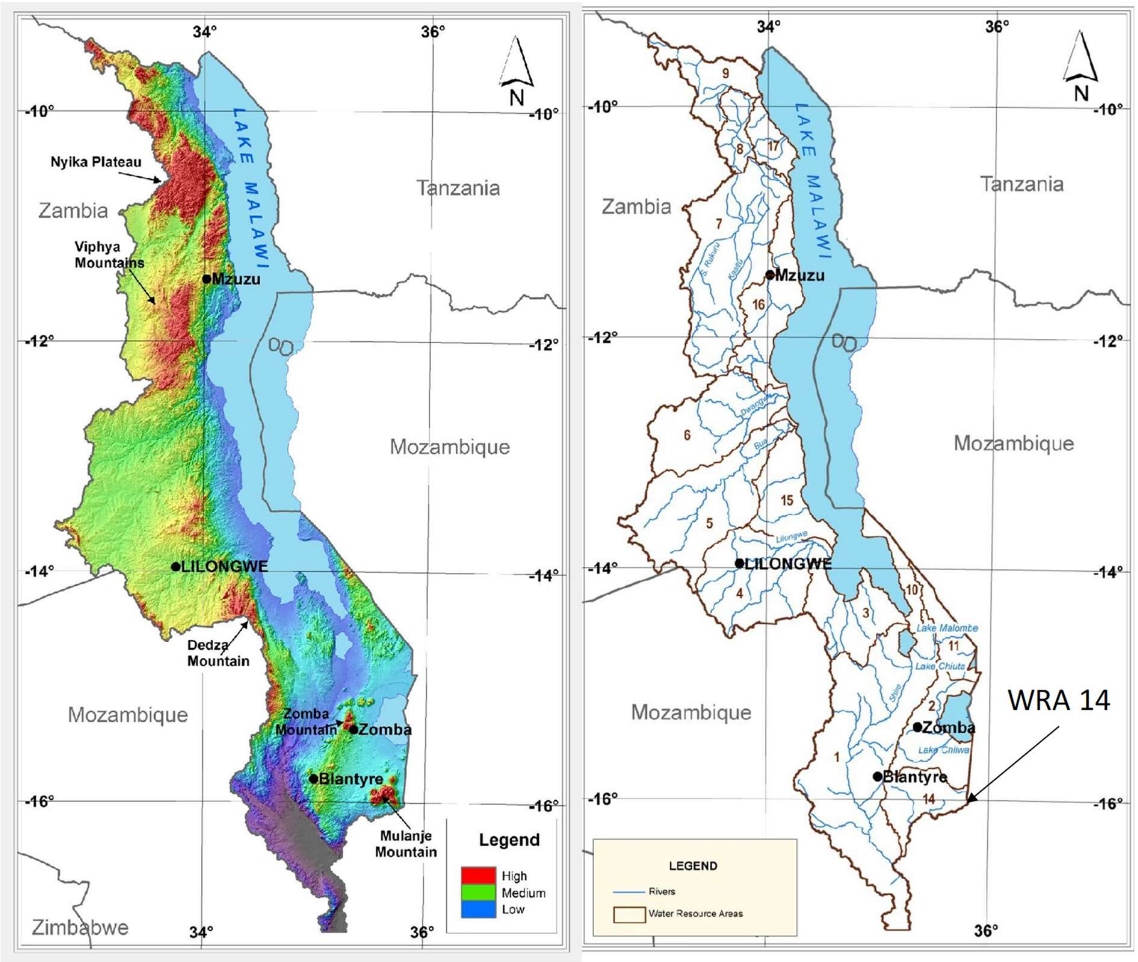


Figure 2. Location of WRA 14 with major rivers and topography shown.

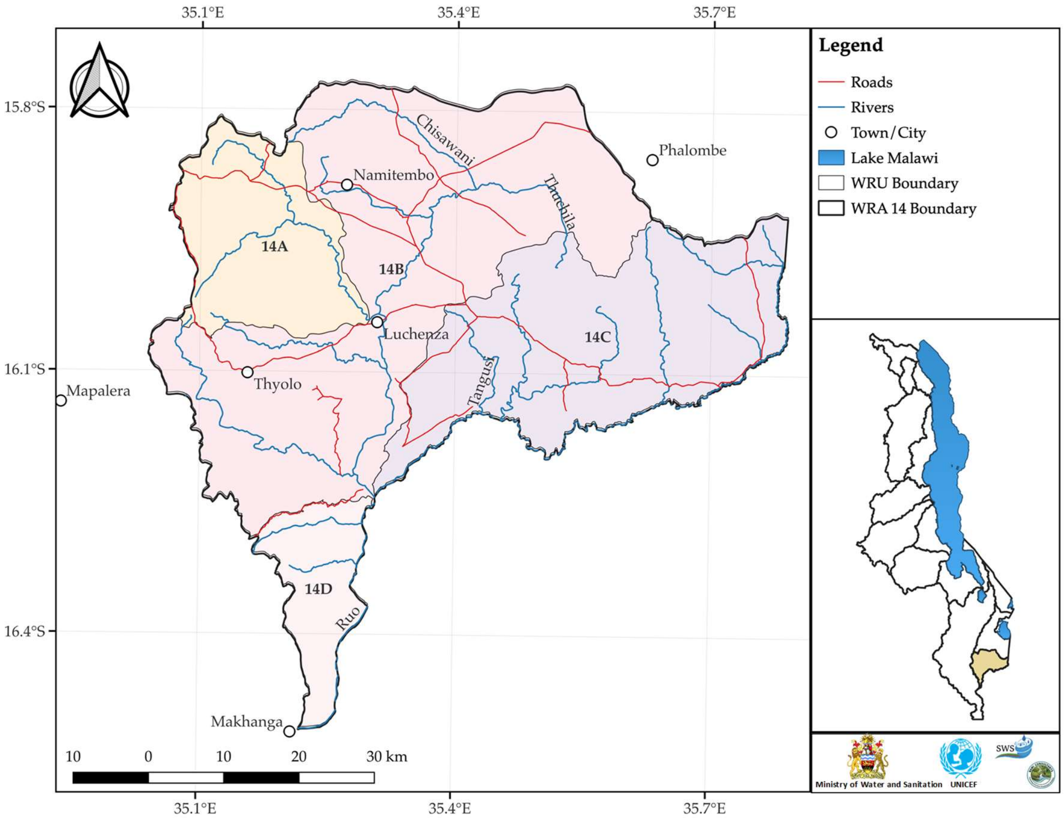


Figure 2b. Water Resource Area 14 and Water Resource Unit Boundaries

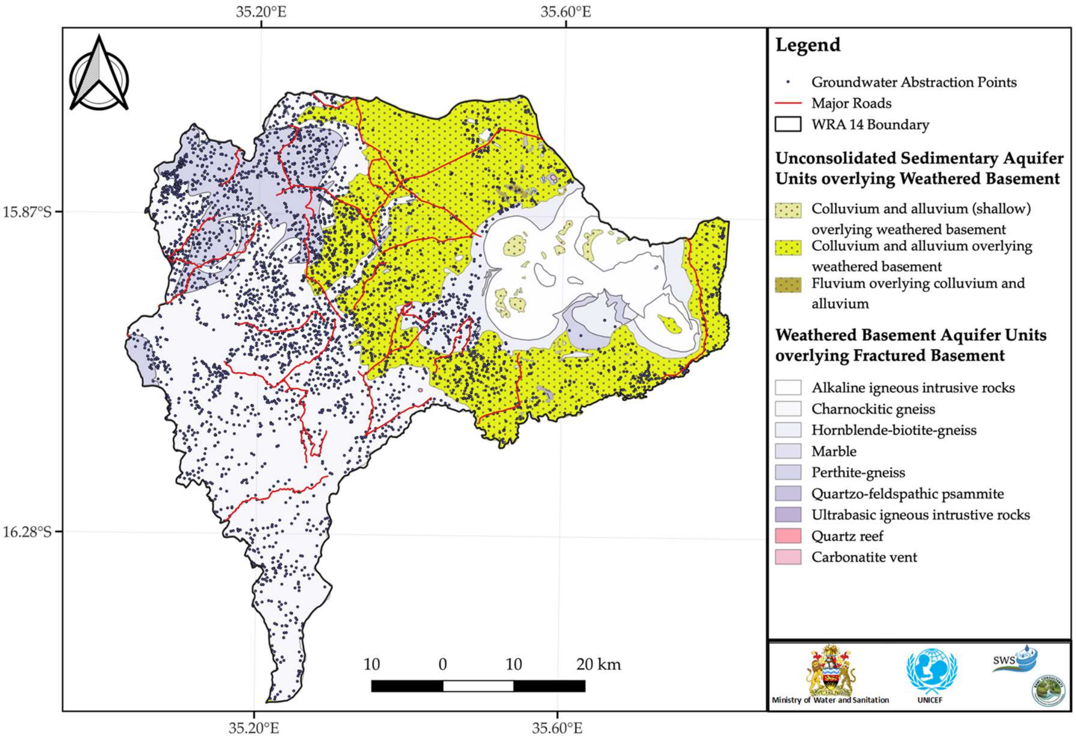


Figure 3. Distribution of groundwater abstraction points in WRA 14.

Groundwater Abstraction in WRA 14

Public abstraction points for groundwater are numerous in WRA 14 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 6,992 known groundwater abstraction points, 84.9% are improved sources. The mid-point distribution of water point yield (at hand pump) is between 0.25 and 0.30 l/s (**Figure 4a**), however it should be noted that this is an expected range of the Afridev, Maldev and India MK3 hand-pumps that dominate the WRA, and likely does not represent the aquifer potential, rather a combination of aquifer properties, borehole construction quality, and hand-pump efficiency. For all groundwater supplies in WRA 14, only 67.5% are fully functional (defined as providing water at design specification).

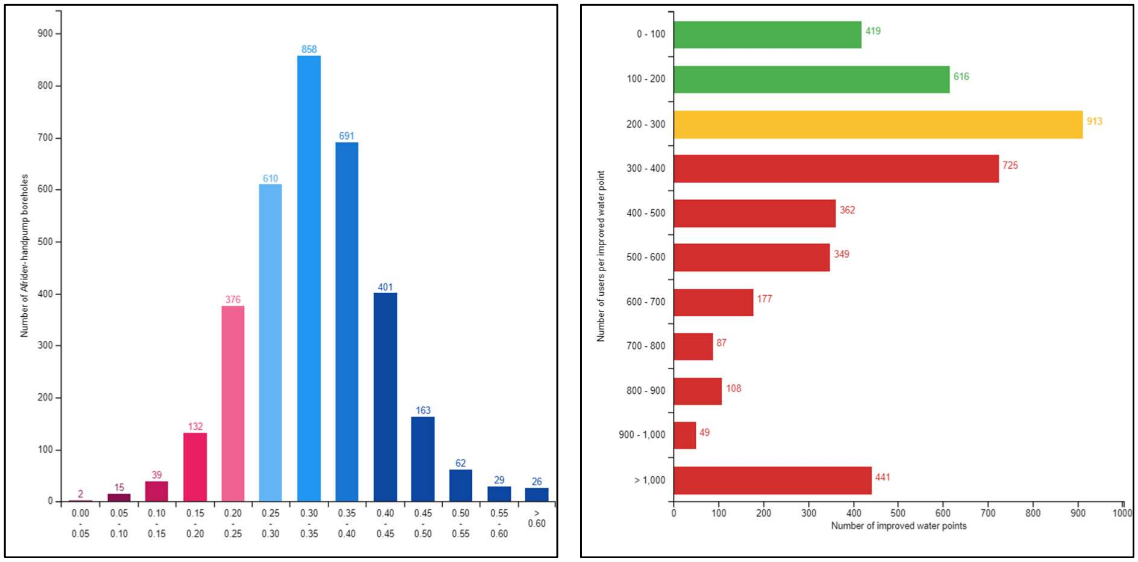


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 14 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction 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 grossly exceeded and there is an investment need in WRA 14 from a population point of view. Most of the groundwater supply points provide water to 250 or more users per water point, and with the preponderance of dug wells which have a contamination risk and may not meet the water quality guidelines, the WRA should be considered within investment planning. Given the high rainfall and groundwater recharge potential, this WRA could be considered for higher yielding borehole installations such as Solar pumps.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 9.3% 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.

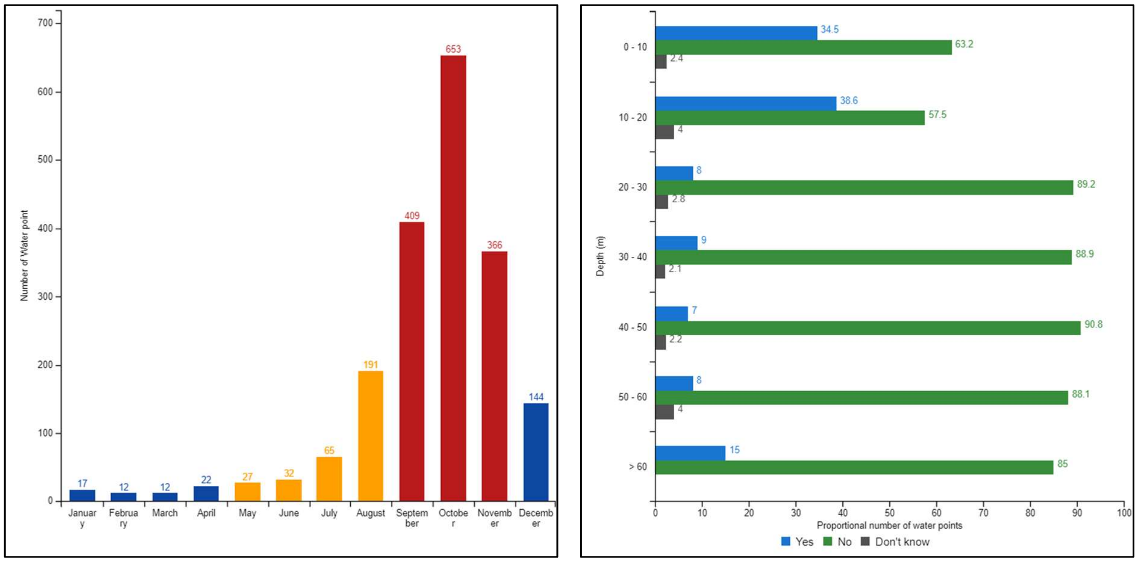


Figure 5a and 5b. Number of groundwater abstraction points in WRA 14 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

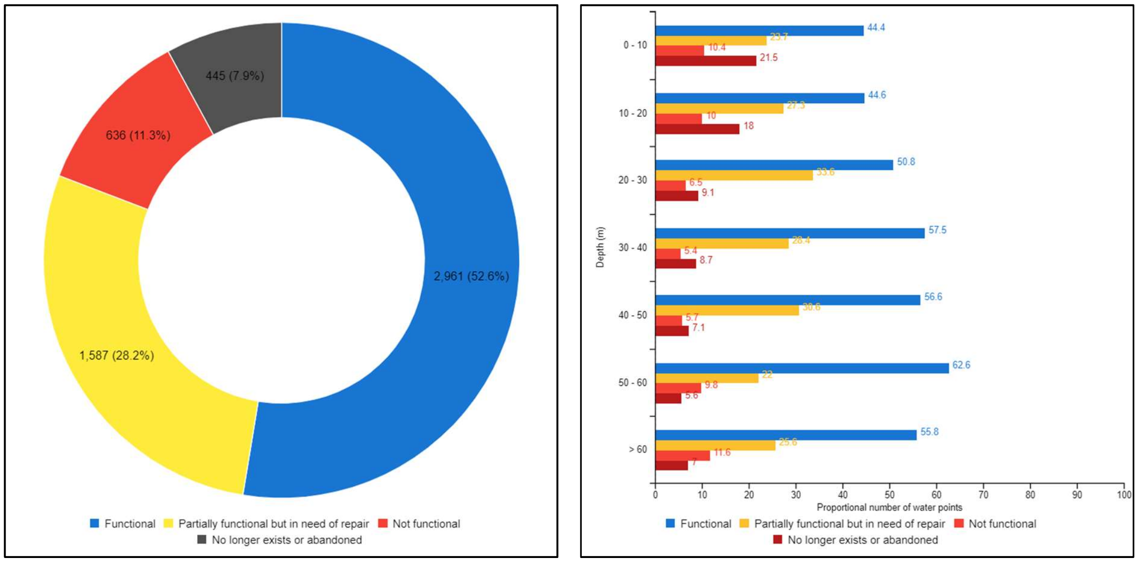


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 14 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National 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 52.6% 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 14 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 14 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	5,319
Protected dug well	554
Protected spring	65
Unprotected dug well	769
Unprotected spring	285

Description of Water Resources WRA 14

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) 14 in southern Malawi constitutes four (4) Water Resource Units (WRU); WRU 14A, 14B, 14C and 14D (**Figures 7a, 7b, 7c, 7d**).

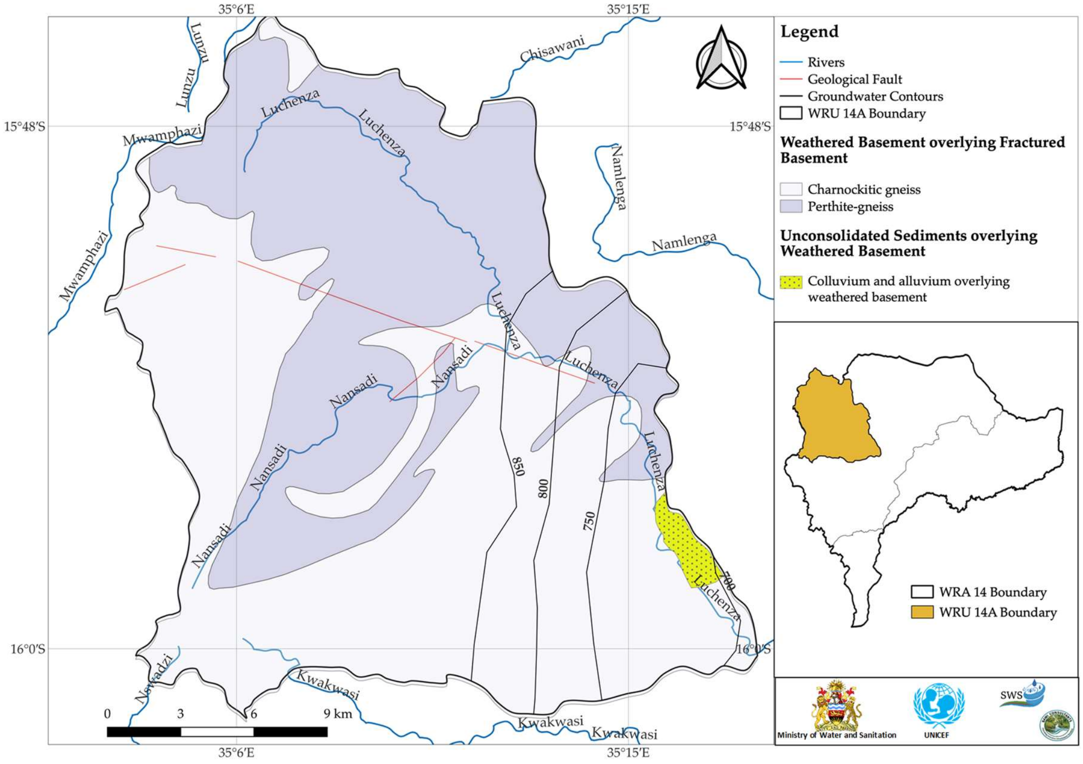


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 14A wtihin Water Resource Area 14 (Ruo River catchment).

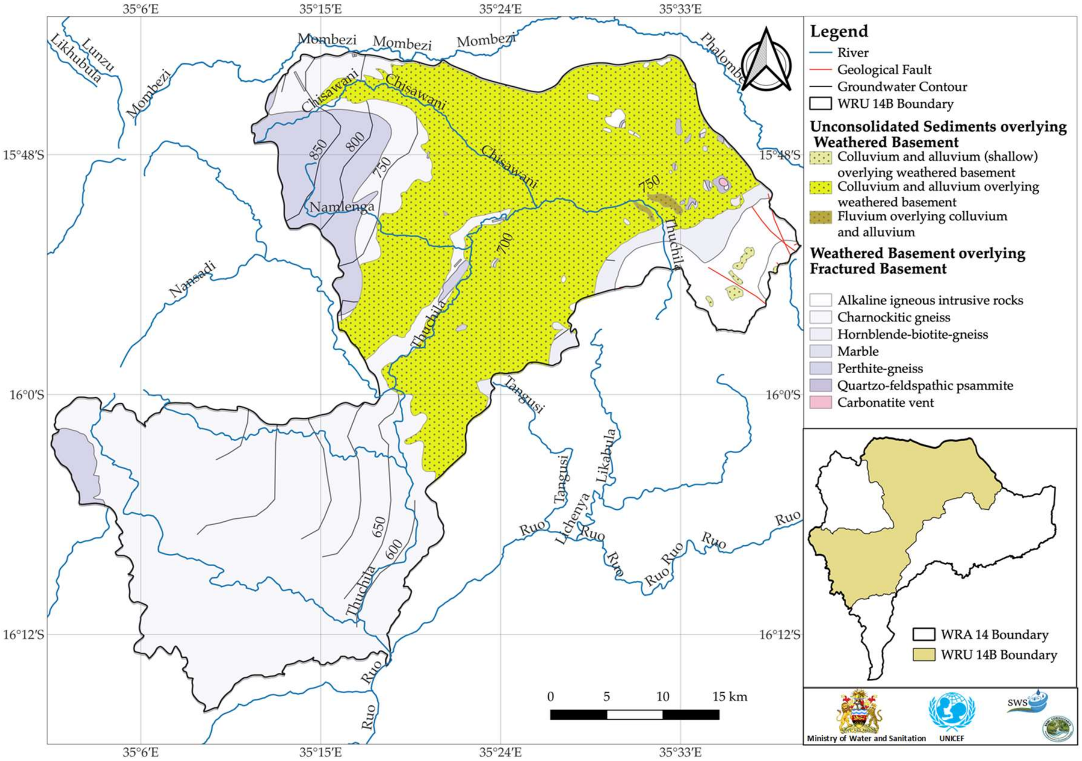


Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 14B wtihin Water Resource Area 14 (Ruo River catchment).

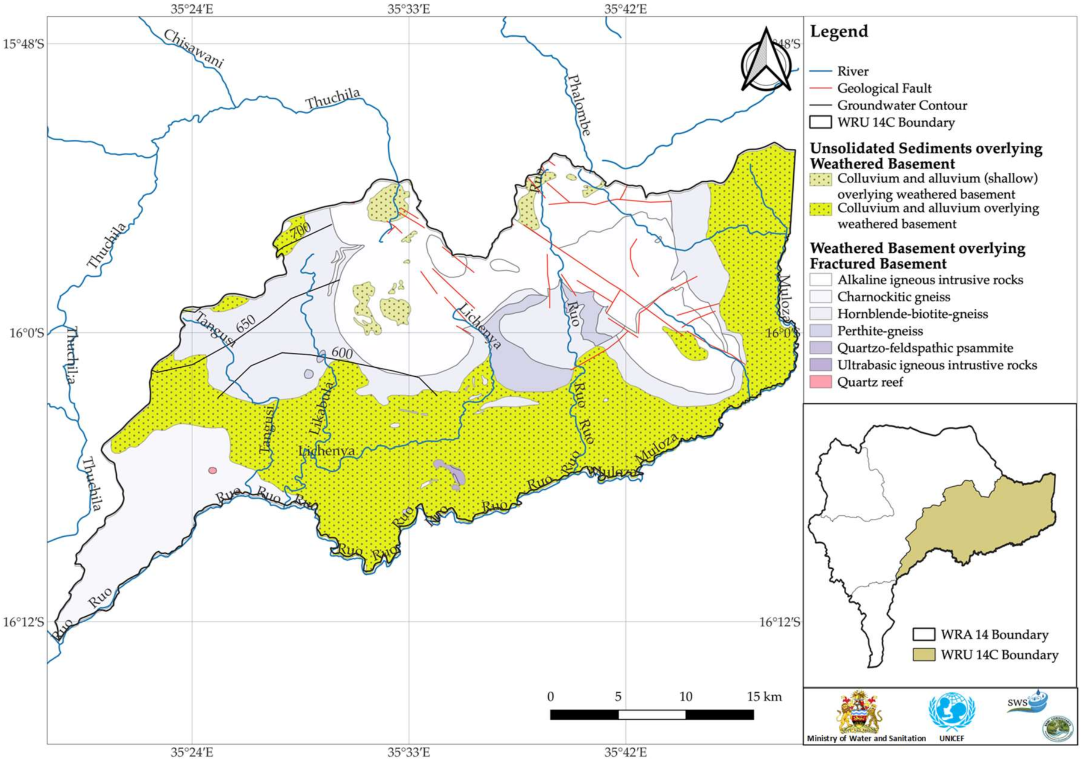


Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 14C wtihin Water Resource Area 14 (Ruo River catchment).

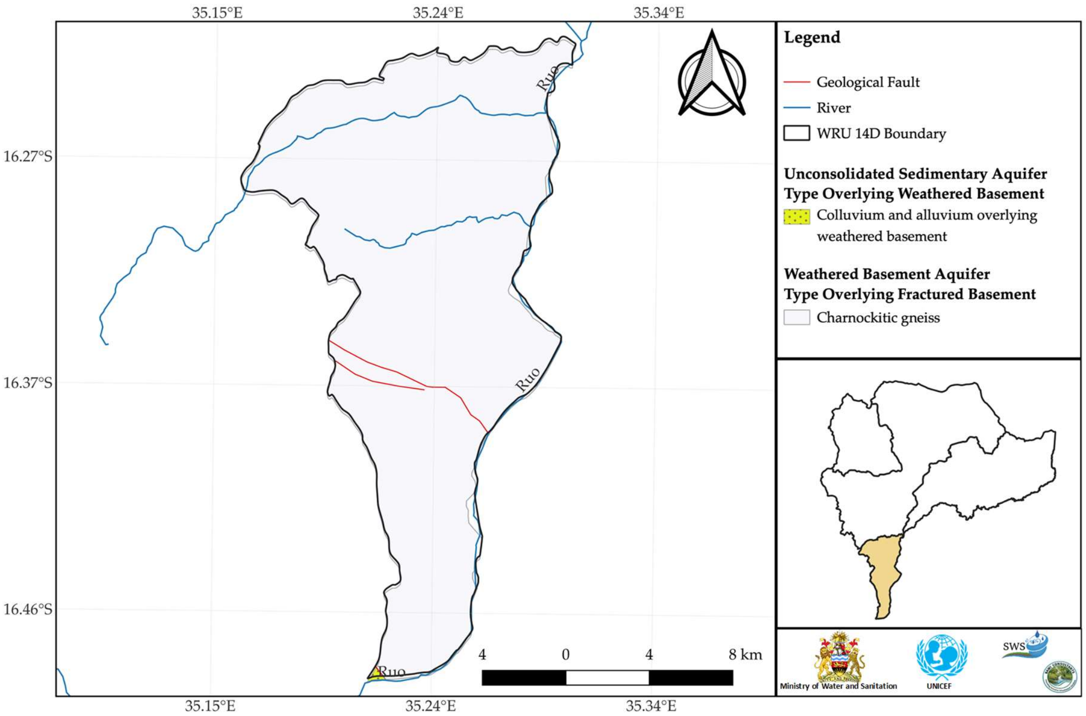


Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 14D wtihin Water Resource Area 14 (Ruo River catchment).

Topography and Drainage

The catchment has diverse relief, dominated by the East African Rift System (EARS) valley and plains. It occupies the southern slopes of Mulanje Massif and Shire Highlands. Relief lies on low altitudes in the south side and as high as about 3000 masl in Mulanje massif in the eastwards that are igneous Intrusions typically comprise granites and syenites. Valley land is relatively flat and devoted largely to intensive agriculture and hosts many tea plantations as well as some animal farming with freely roaming livestock. Groundwater is mostly used to supply populations dispersed in small settlements, or agriculture. (**Figure 8**). The catchment is largely drained by the Ruo River and its major tributary; Thuchila River. The other tributaries include Lichenya Chisawani, Likabula, Thuchila, Tangusi, Nansadi and Chisawani Rivers. The Ruo River drains the southern Shire Highlands and discharges into Shire River at Chiromo in Nsanje district. The Ruo River west bank drains a portion of Milanje district in the neighbouring. Thuchila River drains south-western slopes of Mulanje, south eastern Shire Highlands and Thuchila plain that lies in between before discharging into Ruo River near Sandama, a largely populated place, in Thyolo district. The Ruo River catchment's periodic intense discharge results in severe flood events as it flows towards the Shire River System.

Geology – Solid

WRA 14 is dominated by the Mulanje Massif in the northeast (**Figures 7a, 7b, 7c, 7d**). The Mulanje Massif is part of southern Malawi's Chilwa Alkaline Province (CAP) of alkaline igneous rocks. The range rises to 3008 m elevation and occurs as an isolated mountain range of syenites and granites which were intruded into the host semi-pelitic hornblende-biotite gneiss during the Upper Jurassic- Lower Cretaceous. The range is surrounded on all sides by unconsolidated sediments. Isolated occurrences of charnockitic gneiss and hornblende-pyroxene gneiss are exposed where streams incise the sediments exposing the underlying bedrock. Fractures occur within the plutons but do not extend into the host rock.

Geology – Unconsolidated deposits

The Mulanje Massif is surrounded on all sides by colluvium deposits which extend radially outward. Alluvial fans of poorly sorted, coarse-grained sediments occur at the base of the mountains on all sides, and near escarpment and fluvial gravel deposits may have considerable groundwater potential. Fluvial deposits occur where there are rivers and dambos in the colluvium.

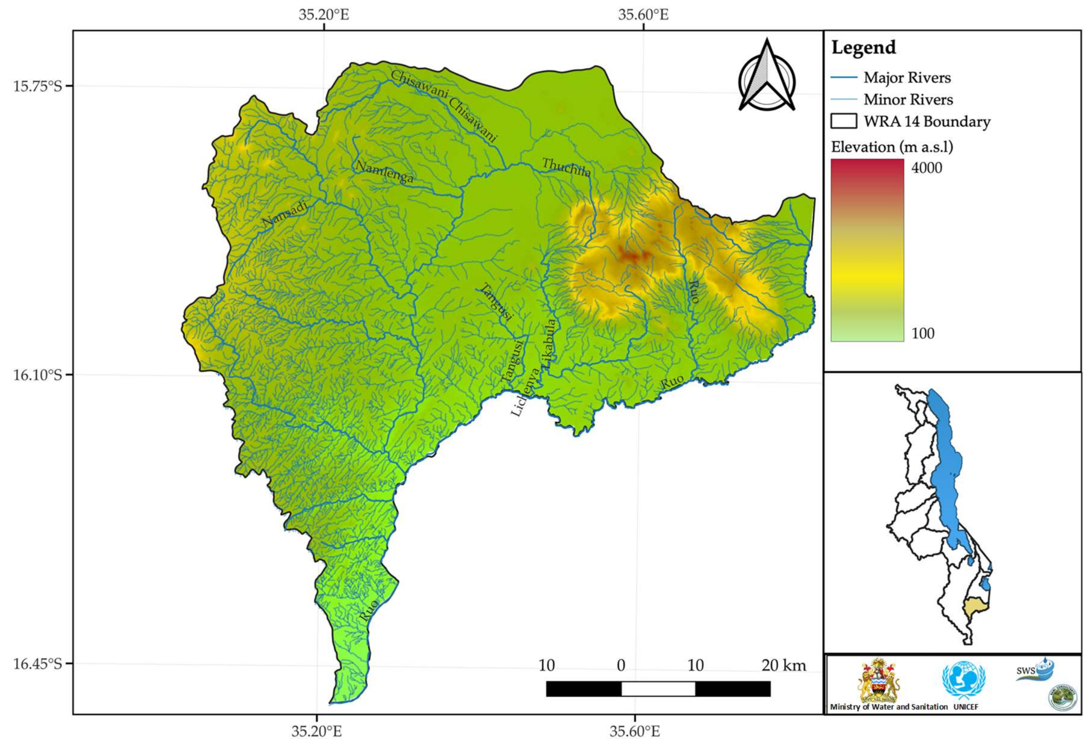


Figure 8. Drainage for the major rivers in Water Resources Area 14.

Climate

A tropical climate occurs in the catchment with two distinctive seasons—a wet season and a dry season, with both cool dry and hot dry periods. The wet season starts in November ending in April. The first part of the dry season, cool-dry, starts in May ending in August and the last part, hot-dry, commences in September ending in October. Annual mean rainfall is 1,514mm distributed between 700mm in lowlands and 2500mm highlands (**Figure 9**), peak rainfall occurs between December and March. High rainfall in the mountain region results in periodic and severe flooding in the catchment. Mean temperatures for the cool-dry season vary between 17 and 27 ◦C, with occasional temperature drops spanning from 4 to 10 ◦C. Wet season mean temperatures range from 25 to 37 ◦C.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 14. 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)
14	A	Thuchila	1,089	1,088
	B	Thyolo	1,200	1,146
	C	Mulanje/Mimosa/Lujeri	1,761	1,549
	D	- No Station -	-	1,035

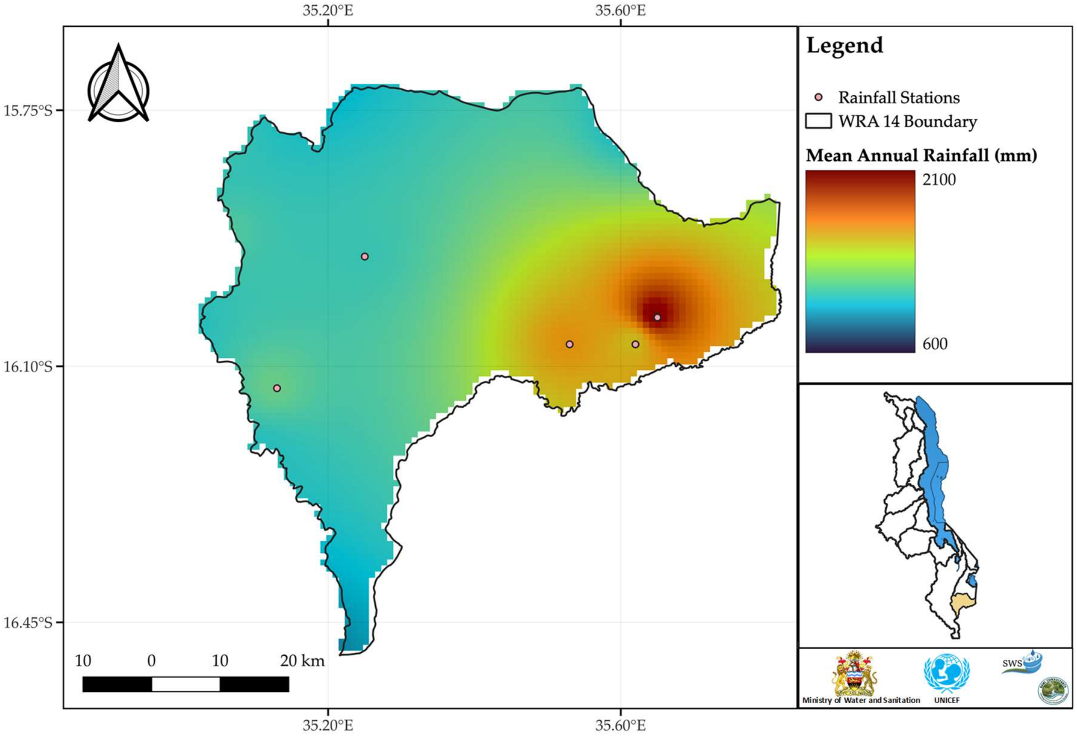


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 14 with the location of weather stations. Average rainfall measured is 1,514mm, average rainfall modelled is 1,250 +/- 226mm (range 866 to 2,086mm).

Land use

The WRA 14 is largely dominated by rain fed cultivation areas followed by open grasslands and woodlands. It has considerable rock outcrops in the eastern side and further north-western side. There is also plantation coverage in the North-western side around Blantyre city. There is intensive Tea, Coffee, and Banana cultivation, both rain-fed and irrigated especially in Thyolo and Mulanje districts.

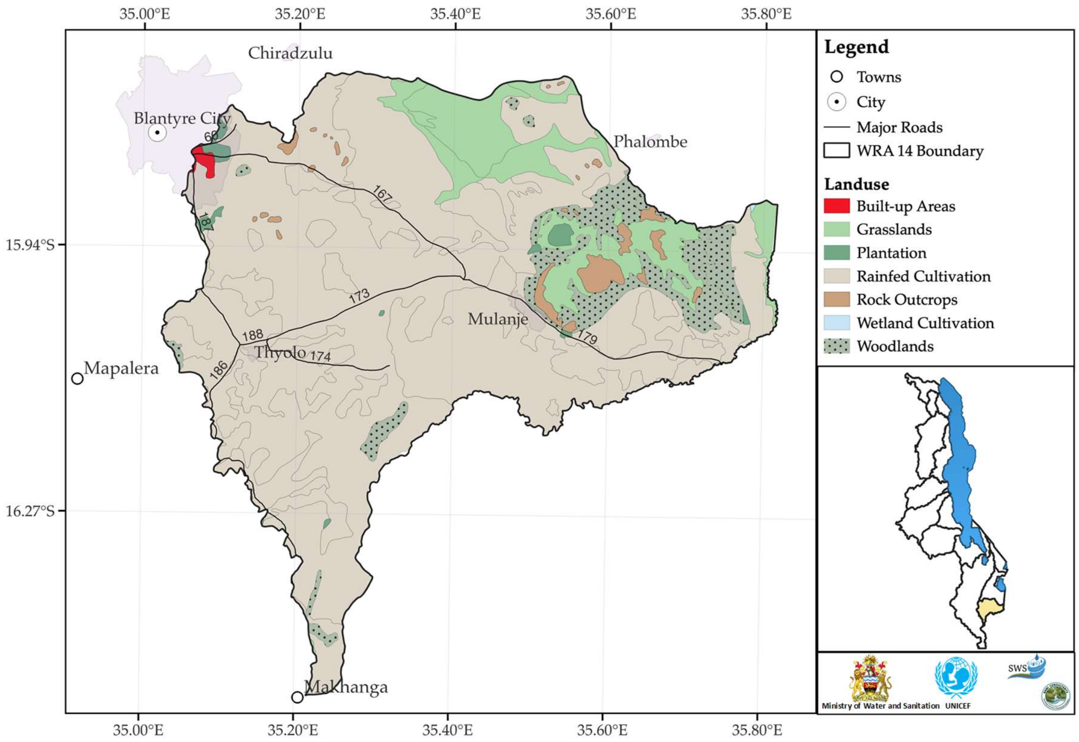


Figure 10. Land use in WRA 14 is dominated by cultivation with high elevation woodlands.

Hydrogeology of WRA 14

Aquifer properties

WRA 14 mostly comprises fractured basement rock overlain in the north by Quaternary colluvium and residual soil deposits that tends to have higher yielding aquifers than the basement (**Figure 11**). Both units meet modest 0.25 L/s requirements for hand pumped boreholes for community supply. Intrusions typically comprise granites and syenites and form the prominent Mount Mulanje (Mulanje Massif) range rising precipitously to over 3000 m in WRA 14 with a network of rivers and streams draining from this high point depositing fluvial sediments in valleys and flood plains. This valley land is relatively flat and devoted largely to intensive agriculture and hosts many tea plantations as well as some animal farming with freely roaming livestock and groundwater is used to supply populations dispersed in small settlements.

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 14 is based on prior hydrogeological reconnaissance.

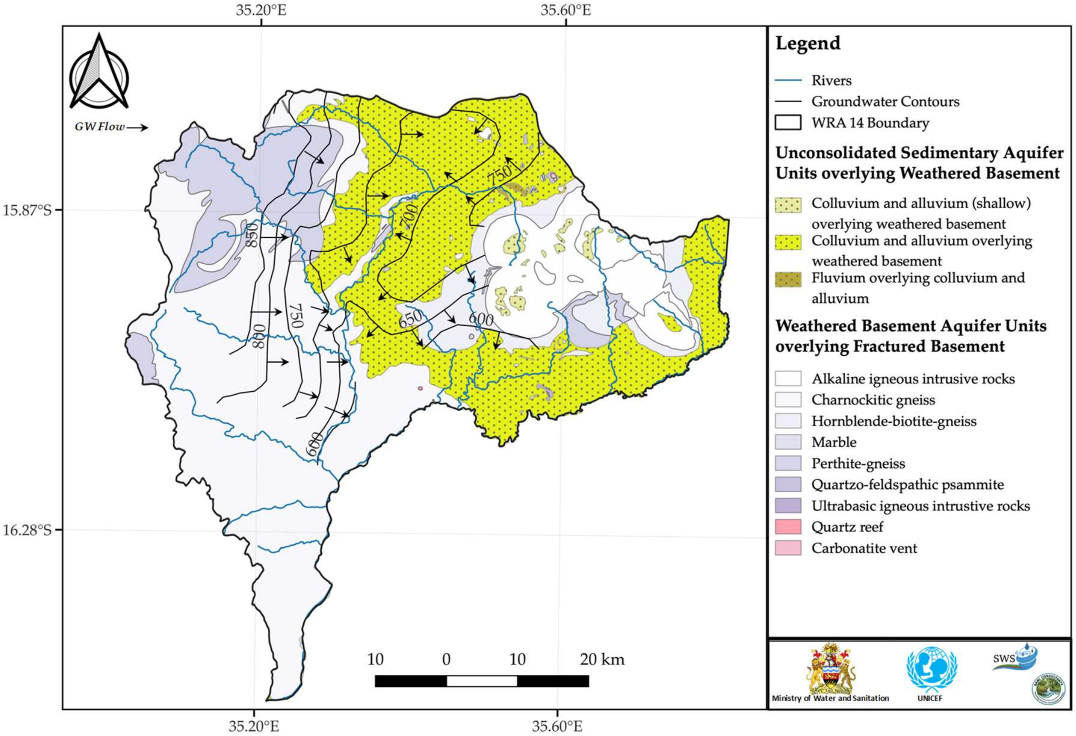


Figure 11. Groundwater level contours and flow direction in WRA 14 [1987 Hydrogeological Reconnaissance data] [water level contour interval 50m]

Groundwater level data for WRA 14 based on prior hydrogeological reconnaissance confirm groundwater flows follow topographic drainage (**Figure 11**). Groundwater in the northern basin headwaters drain towards the Thuchila River. All groundwater divides appear consistent with the surface-water divide WRA 14 boundaries including the most northern boundary in WRU 14. This is a relatively flat, open valley with distinct 700 m asl contours in WRA 14B with flows towards the Rift Valley and in neighbouring WRA 2 where groundwater remains outside the Rift Valley draining northwards towards Lake Chilwa. Heads mapped in the weathered Basement nearing the WRA 14 western boundary Shire Highlands in WRU 14A reach 1150 m asl with a very steep hydraulic gradient decline into the valley of 0.024 driving groundwater flows and base flows to the Luchenza tributary at 750 m asl and then Thuchila River at 600 – 650 m asl. Groundwater velocities are calculated over 40 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2. Groundwater flows likewise converge to the same Thuchila reach from the less extensive eastern valley flank draining the Mulanje Mountains with lower, but still moderate gradients of 0.01. Groundwater flows here are influenced by a close-by groundwater (and surface water) divide in the Mulanje foothills resulting in more southward flows from the mountain draining into WRU 14C and providing base flow to the Ruo River headwaters. The confluence of the much larger Thuchila River with the Ruo (becoming the named river downstream) occurs at the southern intersection of WRUs 14A, 14B and 14 C where hydraulic heads are around 500 m a msl with the Ruo downstream following the national boundary. Whilst groundwater head data are not available for the eastern basin bordering Mozambique, including the north-east; if groundwater flows follow the surface water drainage and topography, most natural groundwater flow would be expected to drain from Mozambique into Malawi.

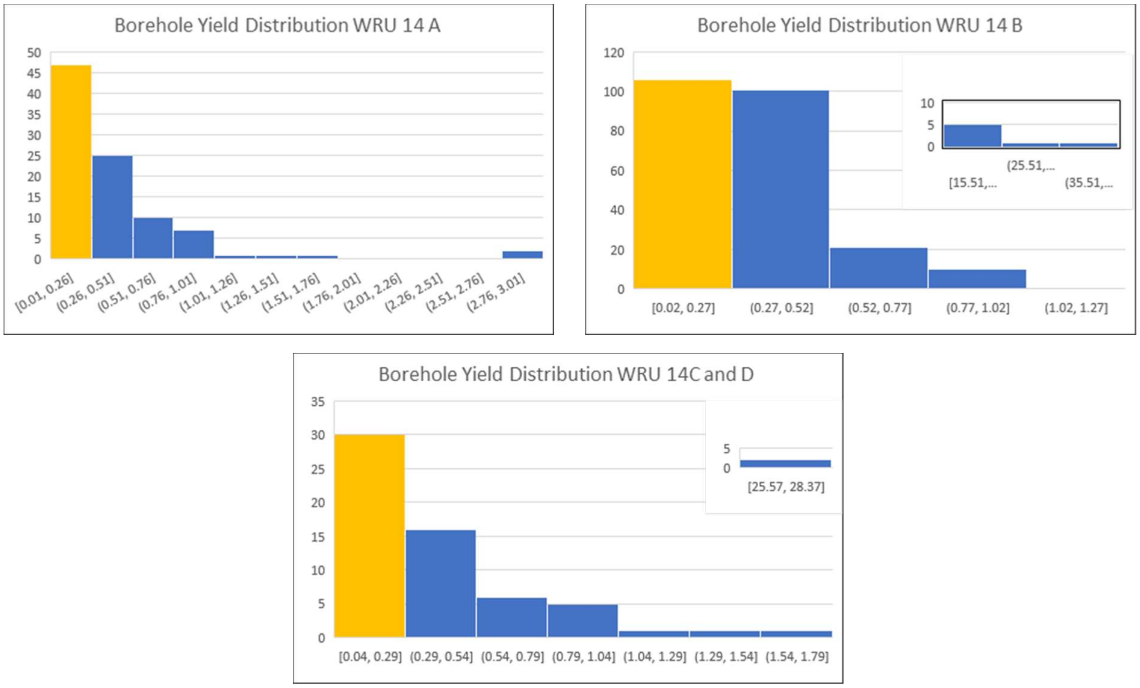


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 14 (note: limited data in WRU 14C) (y axis = *n* observations).

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, 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 WRA14 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 20l/s. In WRA 14 (**Figures 13a, 13b, 13c and 13d**) the high average rainfall and potential for recharge suggests there is some potential in the lower elevations for higher yielding boreholes, in particular where there are reported yields over 5l/s, and there is potential for artesian confined systems along the escarpment but detailed hydrogeological on-site mapping should be undertaken to confirm.

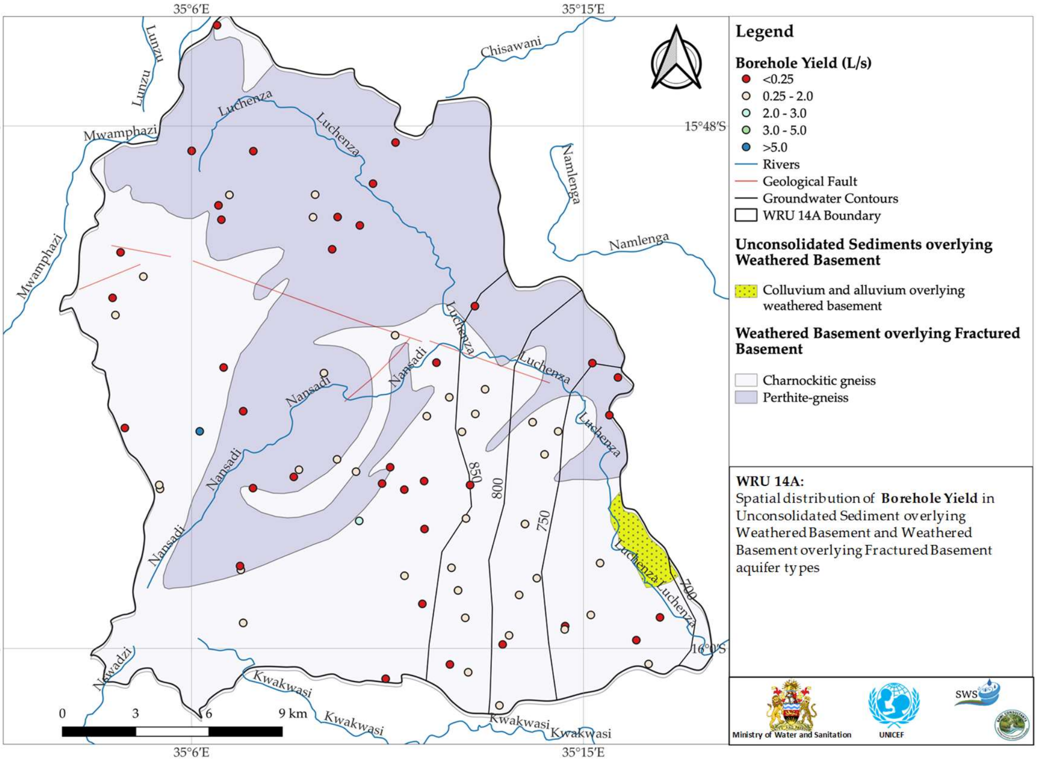


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 14A.

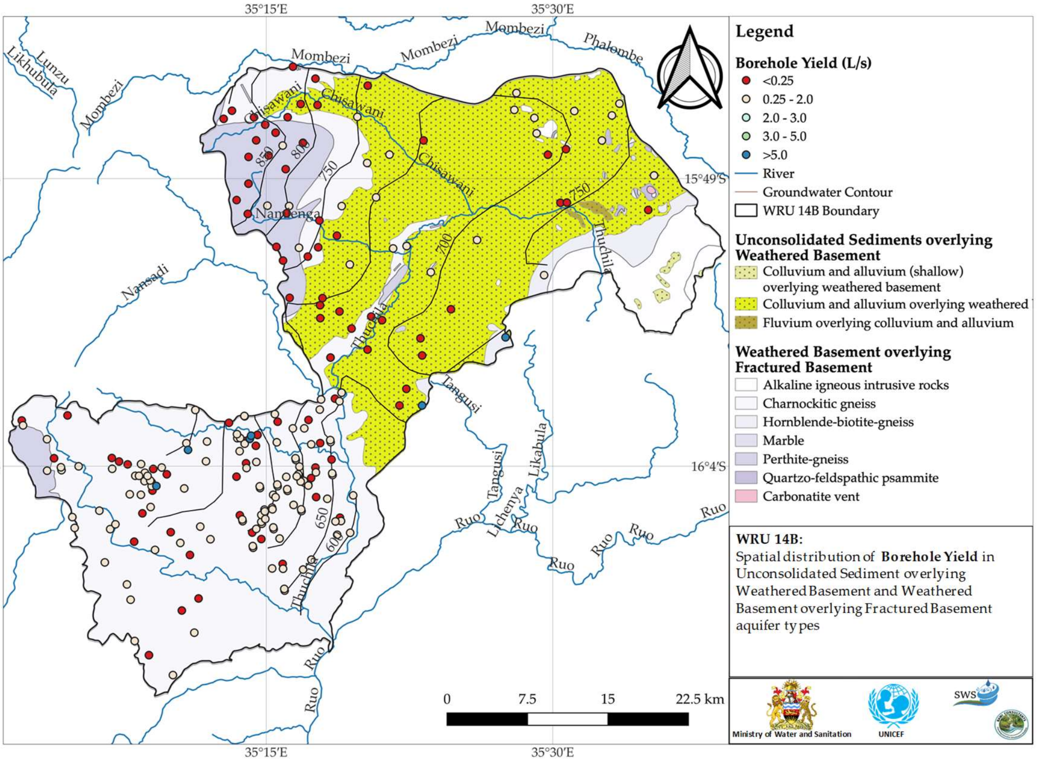


Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 14B.

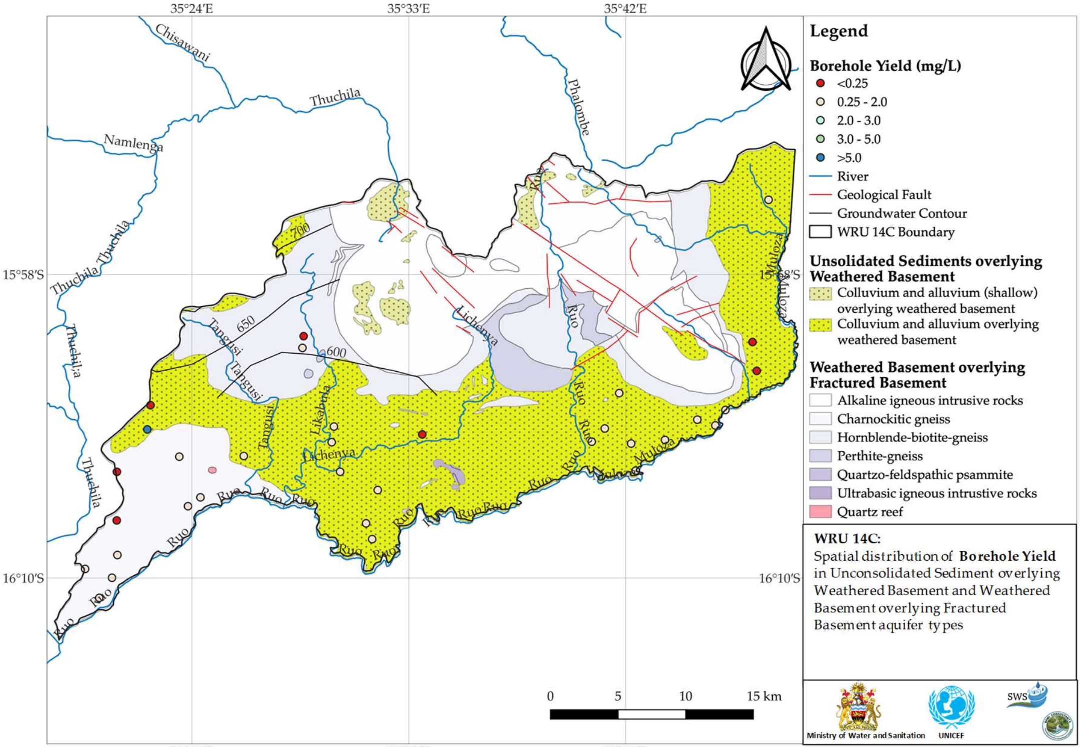


Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 14C.

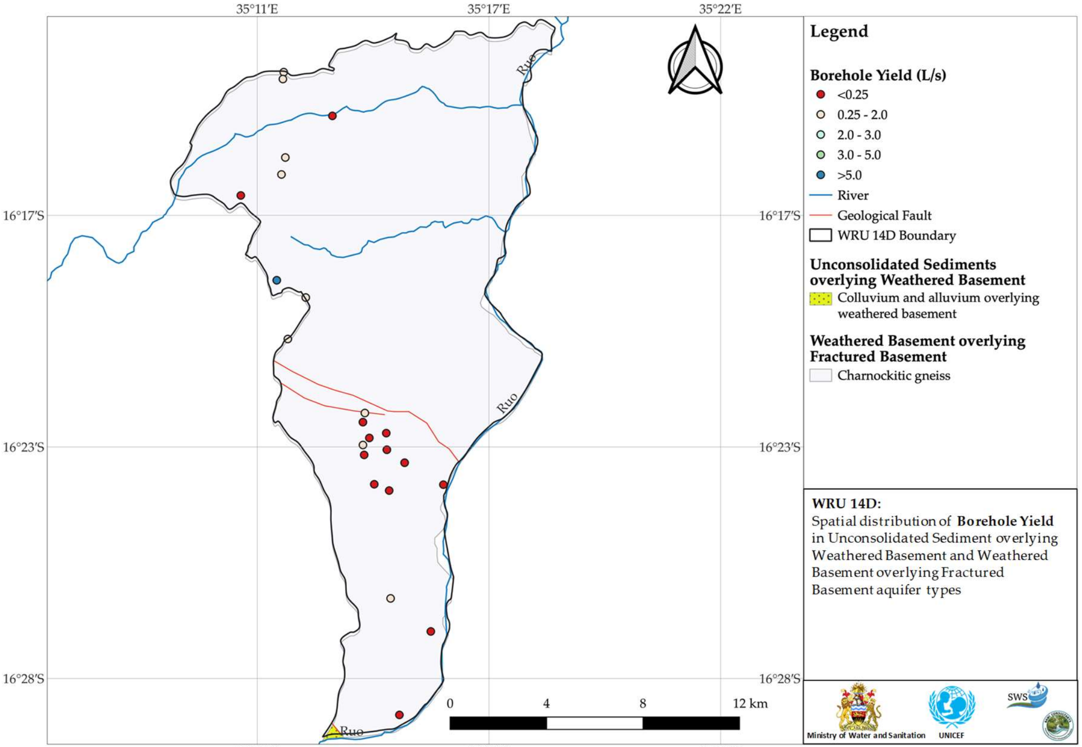


Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 14D.

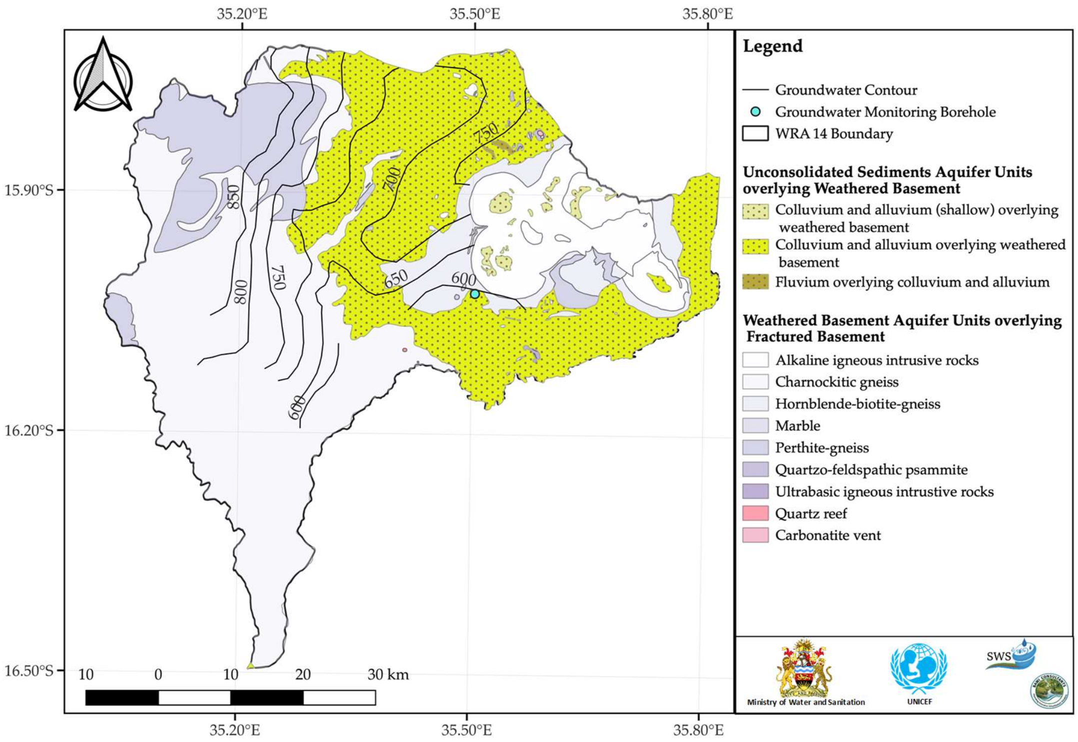


Figure 14a. Location of groundwater monitoring point in WRA 14.

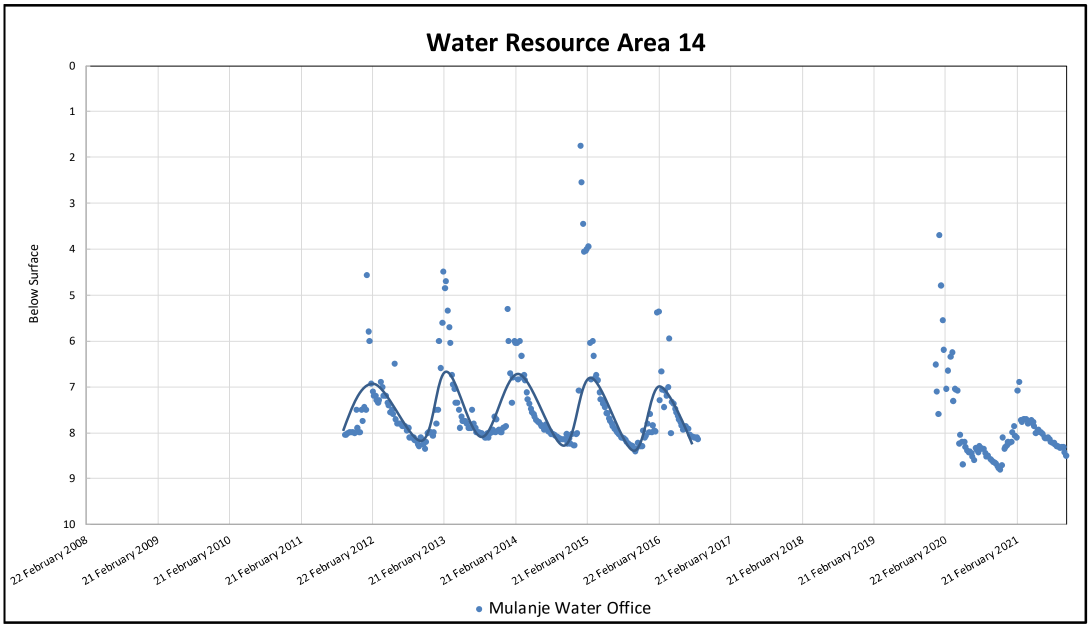


Figure 14. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 14. (units not assumed to be meters below ground level).

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

Groundwater Table Variations

There is only one operational groundwater monitoring stations within WRA 14 at the Mulanje Water Office, the data is not complete but it does show a 5 years of continuous (annual) readings (**Figure 14a** shows locations of groundwater monitoring points and **Figure 14b** monitoring data). There is a low amplitude (ca 1m per annum) variation in the water table that is overlain by short amplitude rises of up to 5 meters. It is likely the installation intersects two aquifer units, and the upper unit responds to annual flooding cycles. However detailed drilling logs are not available to confirm this hypothesis. 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 not possibly to determine any long-term trends that may relate to climate variability (rainfall and recharge relationships). The magnitude of the seasonal variation suggests the aquifers these monitoring points intersect are unconfined (though the lower unit may be semi-confined) and receive annual seasonal recharge. However, given here are no borehole logs or multi-level installations that separate different hydro-stratigraphic units and it is recommended that multi-level installations are placed into each hydrostratigraphic unit is an area for future investment.

Groundwater recharge

The groundwater volume in each WRU was calculated using the estimated range of porosities published by McDonald et al. (2021) and the range of saturated thickness for each aquifer type (based on the depth of boreholes and water strikes per agreement with the Ministry of Water and Sanitation).

Table 4a. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 14A, 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.	4.5	10%	30%	0.02	0.06	8.9	80.3	
W & F Basement	502.1	1%	10%	0.02	0.03	100.4	1,506.3	
	Area of WRU (km^2)	14A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*109.3*	*1,586.6*	*Total Volume Groundwater*
	506.6	1088	Average Rainfall in WRU	10.88	81.6	5.5	41.3	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]						20	38	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 14B, 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	3.5	10%	35%	0.02	0.10	6.9	121.6	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	692.0	10%	30%	0.02	0.06	1,383.9	12,455.1	
W & F Basement	1,026.5	1%	10%	0.02	0.03	205.3	3,079.5	
	Area of WRU (km^2)	14B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,596.1*	*15,656.2*	*Total Volume Groundwater*
	1,721.9	1146	Average Rainfall in WRU	11.46	85.95	19.7	148.0	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]						81	106	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 14C, 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.	450.2	10%	30%	0.02	0.06	900.5	8,104.3	
W & F Basement	592.9	1%	10%	0.02	0.03	118.6	1,778.6	
	Area of WRU (km^2)	14C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,019.1*	*9,882.9*	*Total Volume Groundwater*
	1,043.1	1549	Average Rainfall in WRU	15.49	116.175	16.2	121.2	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]						63	82	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 14D, 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.	0.2	10%	30%	0.02	0.06	0.5	4.4	
W & F Basement	242.9	1%	10%	0.02	0.03	48.6	728.8	
	Area of WRU (km^2)	14D	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*49.1*	*733.2*	*Total Volume Groundwater*
	243.2	1035	Average Rainfall in WRU	10.35	77.625	2.5	18.9	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						19	39	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 14 ranges between 43.9 Million Cubic Meters (MCM) and 329.4 MCM per year, with a mean age of groundwater of 56 years across the Water Resource Area (**Tables 4a, 4b, 4c, 4d**). 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.

Table 5. Distribution of dissolved species in groundwater WRA 14. 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 14	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	7.1	542	55.7	43.0	4.8	0.6	56.7	2.3	46.0	16.8	1.4
Std Dev	0.9	892	175	125	23.2	0.5	165	2.1	63.5	20.5	2.8
Median	7.2	278	10.0	5.9	0.4	0.5	16.0	1.8	28.0	11.2	0.4
Max	8.7	7,340	1,692	974	282	2.0	1,720	16	518	152	11.0
Min	5.0	8.0	0.0	0.1	0.0	0.0	0.2	0.2	0.2	0.2	0.0
n	247	217	180	198	162	112	168	166	176	146	40

Groundwater quality WRA 14

Groundwater major-ion water quality in WRA 14 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**).

Piper plots of the WRA 14 water quality data suggest most water has expected major geochemical changes from water-rock interactions dominated by Ca-HCO_3 trending to Ca-Mg-HCO_3 type waters with a number of samples from weathered basement overlying fractured basement aquifers having an increasing Na-Cl-SO_4 likely due to evaporative enrichment with possible ion exchange effects especially notable in the trend from Ca to Na (**Figure 15a and 15b**). The average groundwater age, precipitation rate and calculated recharge rates together with the relatively low electrical conductivity points to recent meteoric recharge of much of the groundwater dominated by water-rock interactions, however in low-lying areas there are zones of high EC groundwater likely related to evaporative enrichment.

The distribution of key dissolved water quality species in groundwater of WRA 14 is provided in **Figure 16** however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routinely distributed in WRA 14, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements. It should be noted there are a number of water points with considerable Nitrate and Iron indicating sources of contamination that may result in lower redox conditions from either latrine loading or agricultural activities. A study of the sources of low redox water and nitrogen species distribution is recommended for WRA 14, potentially using stable isotope geochemical species.

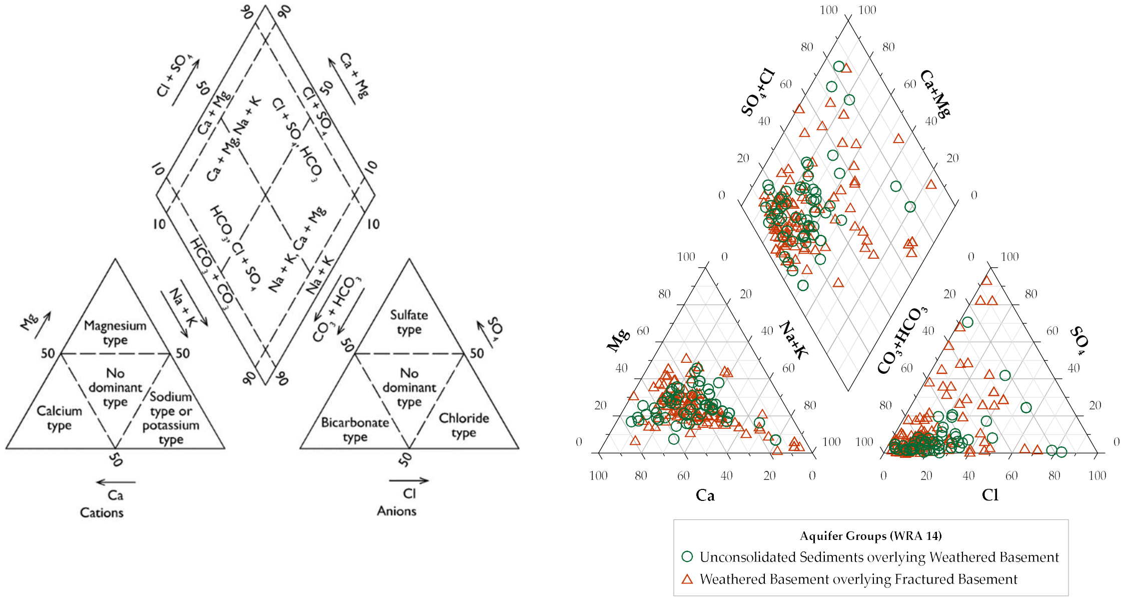


Figure 15a, 15b. Piper Diagrammes of Groundwater Samples in WRA 14 and for each Aquifer Type in WRA 14.

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 14 is low however the lack of routine and wide-spread water quality analyses held by the Ministry of Water and Sanitation does not allow for interpretation with respect to hydrogeologic units (**Figure 16**). It is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation, especially where 'solar pump' boreholes or reticulated systems are placed.

Fluoride

There is limited prevalence of hot springs in WRA 14, placing **Lower Risk** category for fluoride in groundwater. Groundwater data drawn from the recent national-scale assessments (**Figure 16 and Figure 17**) reveals though only 2 existing analyses are above 1.5mg/l, known hot springs 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 Mulaje Massif should be monitored for groundwater-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 14 is planned and implemented.

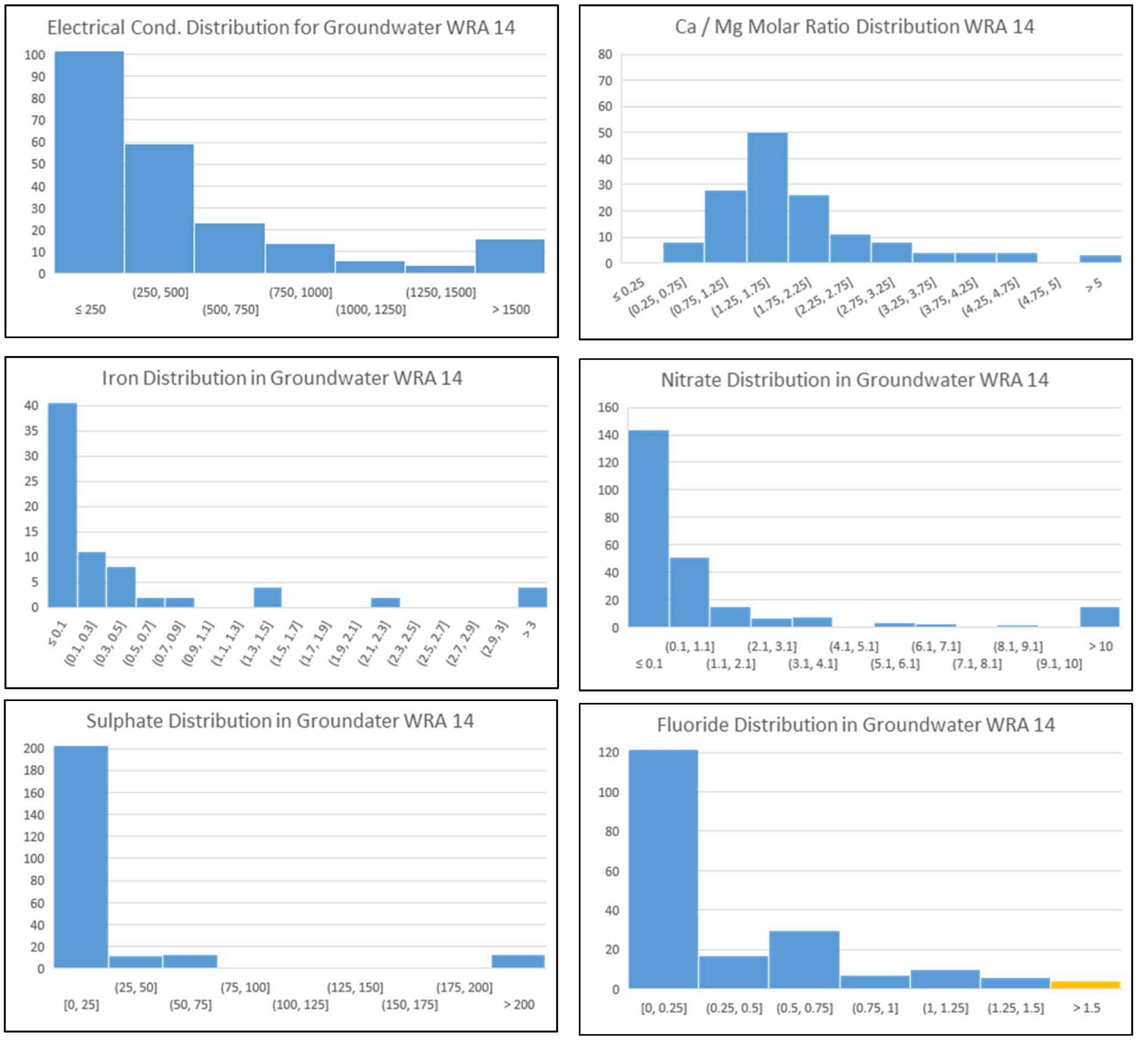
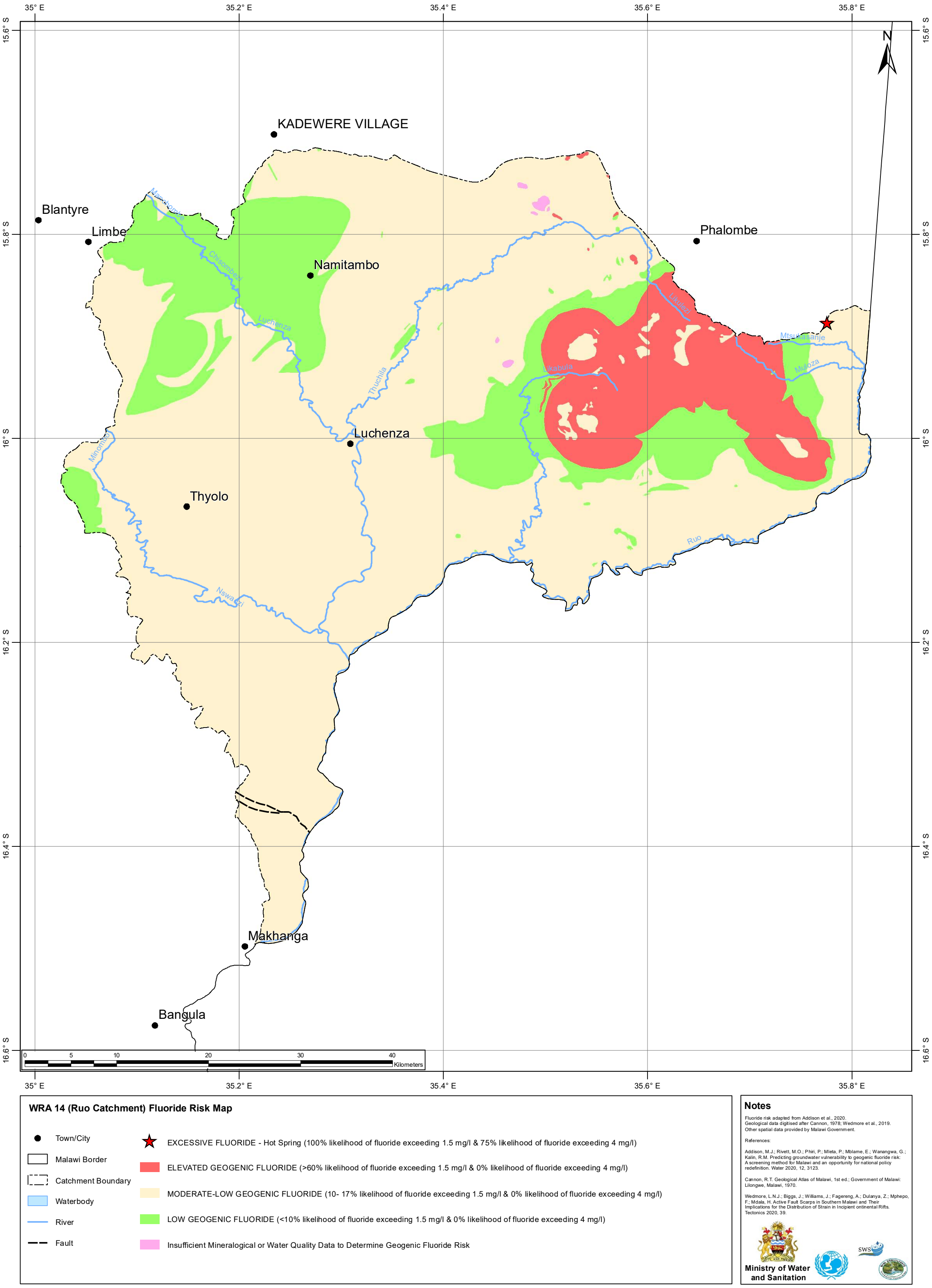


Figure 16 Distribution of chemical species in groundwater within WRA 14 (y axis = *n* observations).

Arsenic

A recent national collation of arsenic groundwater survey data (Rivett et al 2018) found widespread low concentrations but with only a few above the WHO 10 µg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. This national dataset did sample the Phalombe area of WRA 14 with no elevated levels round, however arsenic risks may exist due to the presence of hot springs on the east of Mulanje Massif, 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 14 is planned and implemented



Notes

Fluoride risk adapted from Addison et al., 2020.
Geological data digitised after Cannon, 1978; Wedmore et al., 2019.
Other spatial data provided by Malawi Government.

References:

Addison, M.J.; Rivett, M.O.; Phiri, P.; Mleta, P.; Mblame, E.; Wanangwa, G.; Kalin, R.M. Predicting groundwater vulnerability to geogenic fluoride risk: A screening method for Malawi and an opportunity for national policy redefinition. Water 2020, 12, 3123.

Cannon, R.T. Geological Atlas of Malawi, 1st ed.; Government of Malawi: Lilongwe, Malawi, 1970.

Wedmore, L.N.J.; Biggs, J.; Williams, J.; Fagereng, A.; Dulanya, Z.; Mphepo, F.; Mdala, H. Active Fault Scarps in Southern Malawi and Their Implications for the Distribution of Strain in Incipient ontinental Rifts. Tectonics 2020, 39.

Figure 17. Groundwater Fluoride Risk Map WRA 14 (after Addison et. al. 2021).

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 14.

	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**
14A	291,599	295,638	297,757	320,847	300,895	317,804	985,251,848	1,182,302
14B	505,520	531,196	552,791	574,698	595,963	588,558	1,808,312,004	2,169,974
14C	298,997	307,749	316,839	325,065	332,939	304,364	1,018,414,083	1,222,097
14D	65,160	68,689	71,284	74,439	77,718	71,359	231,470,315	277,764
WRA 14	**1,161,276**	**1,203,272**	**1,238,670**	**1,295,048**	**1,307,515**	**1,282,085**	**4,043,448,250**	**4,852,138**

A recent publication by Rivett et al (2022) provided strong evidence of pit-latrine induced e-coli contamination of groundwater supplies in WRA 14 regardless of season (wet / dry). Modelling for water resource area 14 resulted (**Table 6**) in a calculated total of 4,852,138 metric tonnes of faecal matter loading over the 10-year period (2012-2022). Over the 10-year period the modelled number of pit latrine users in the region increased by 120,809.

WRA14 covers roughly 2.84% 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, 5,766 metric tonnes of fertiliser would be used in WRA1 per year; the modelled loading indicates 84 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

References

Geological Bulletins

Garson MS, Walshaw RD, 1969. The Geology of the Mlanje area, Bulletin No. 21

Habgood F, Holt DN, Walshaw RD, 1973. The Geology of the Thyolo area, Bulletin No. 22

Hydrogeological Reconnaissance Maps

Kafundu RD, Basali G, 1987. Hydrogeological Reconnaissance Map: Sheet 8 - Blantyre

Mainala SM, Magulu W, 1987. Hydrogeological Reconnaissance Map: Sheet 9 - Nsanje

Bibliography WRA 14

Boke-Olén, N., Abdi, A., Hall, O. et al. High-resolution African population projections from radiative forcing and socio-economic models, 2000 to 2100. Sci Data 4, 160130 (2017). https://doi.org/10.1038/sdata.2016.130

Bradford RB. The Hydrogeochemistry of the Lower Shire Area between Chikwawa and Chiromo; Geological Survey Department, Zomba, Malawi; 1973. https://resources.bgs.ac.uk/sadcreports/malawi1973bradfordhydrochemlshire.pdf

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren, D. P., and Zhang, X.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geosci. Model Dev., 13, 5425–5464, https://doi.org/10.5194/gmd-13-5425-2020

Kalin, R.M.; Mwanamveka, J.; Coulson, A.B.; Robertson, D.J.C.; Clark, H.; Rathjen, J.; Rivett, M.O. Stranded Assets as a Key Concept to Guide Investment Strategies for Sustainable Development Goal 6. Water 2019, 11, 702. https://doi.org/10.3390/w11040702

Kambwiri AM, Changadeya W, Chimphamba J, Tandwe T. Land use impacts on water quality of rivers draining from Mulanje Mountain: a case of Ruo river in the Southern Malawi. Malawi J. Sci. Technol. 2014; 10(1), 15-31. https://www.ajol.info/index.php/mjst/article/view/105866

Alan M MacDonald *et al* 2021 *Environ. Res. Lett.* **16** 034012 https://doi.org/10.5285/45d2b71c-d413-44d4-8b4b-6190527912ff.

Pritchard M, Mkandawire T, O'Neil JG. Biological, chemical and physical drinking water quality from shallow wells in Malawi: Case study of Blantyre, Chiradzulu and Mulanje. Phys. Chem. Earth 2007; 27, 845-850. https://doi.org/10.1016/j.pce.2007.07.013

Rivett, MO; HL Robinson, LM Wild, J Melville, L McGrath, P Phiri, J Flink, GJ Wanangwa, P Mlwta, SSP MacLeod, AVM Miller, RM Kalin (2018), Arsenic occurrence in Malawi groundwater, Journal of Applied Sciences and Environmental Management, Vol 22, No 11, http://dx.doi.org/10.4314/jasem.v22i11.16

Rivett, Micheal O., Laurent-Charles Tremblay-Levesque, Ruth Carter, Rudi C.H. Thetard, Morris Tengatenga, Ann Phoya, Emma Mbalame, Edwin Mchilikizo, Steven Kumwenda, Prince Mleta, Marc J. Addison, Robert M. Kalin, Acute health risks to community hand-pumped groundwater supplies following Cyclone Idai flooding, Science of The Total Environment, Volume 806, Part 2, 2022, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.150598

Stevens FR, Gaughan AE, Linard C, Tatem AJ (2015) Disaggregating Census Data for Population Mapping Using Random Forests with Remotely-Sensed and Ancillary Data. PLoS ONE 10(2): e0107042. https://doi.org/10.1371/journal.pone.0107042

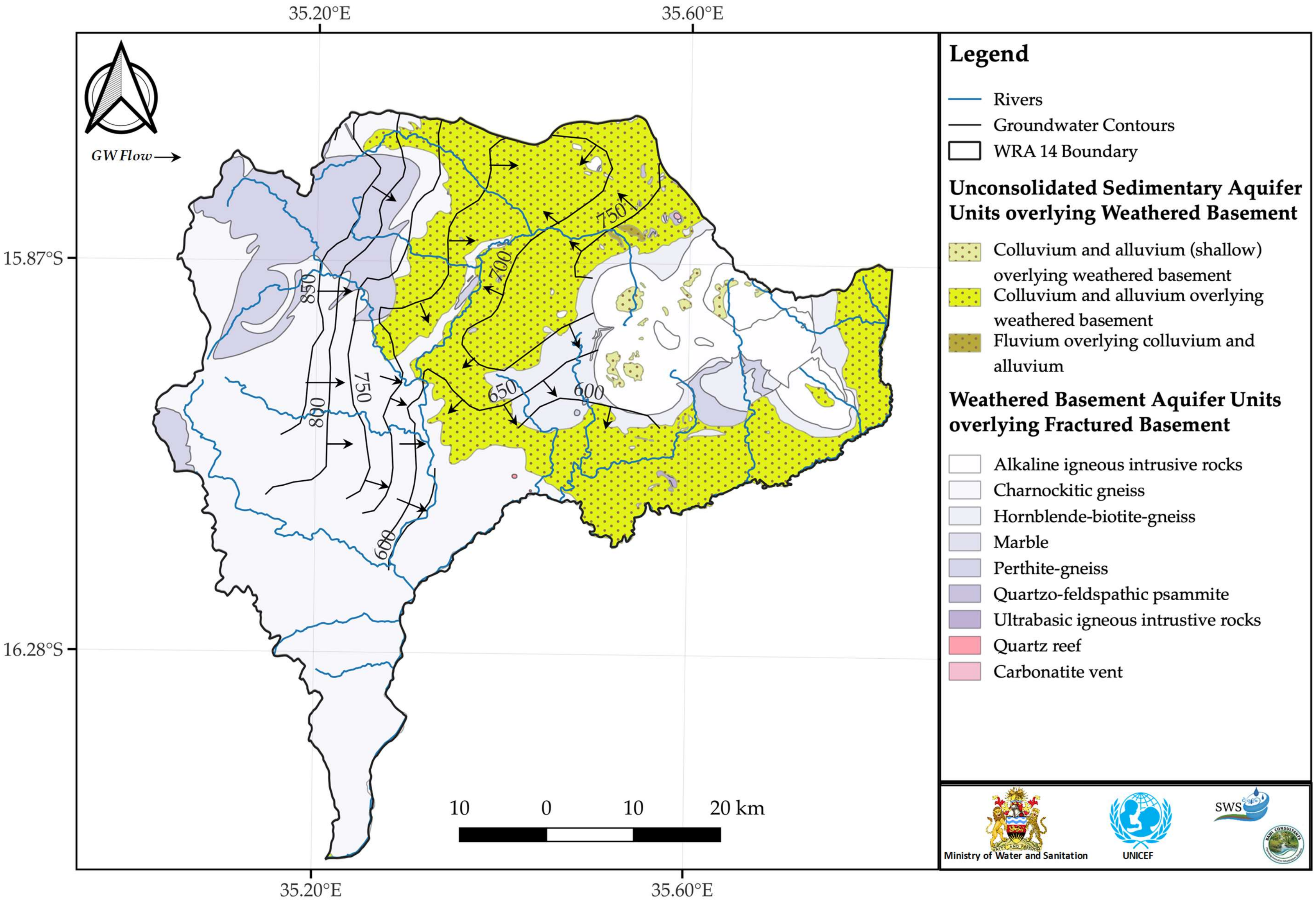
World bank 2022. https://data.worldbank.org/indicator/AG.CON.FERT.ZS?locations=MW. Accessed 28/02/2022

WorldPop. Malawi 100m Population, Version 2. University of Southampton. www.worldpop.org. Accessed 28/02/2022

Water Resource Unit (WRA) 14 Figures

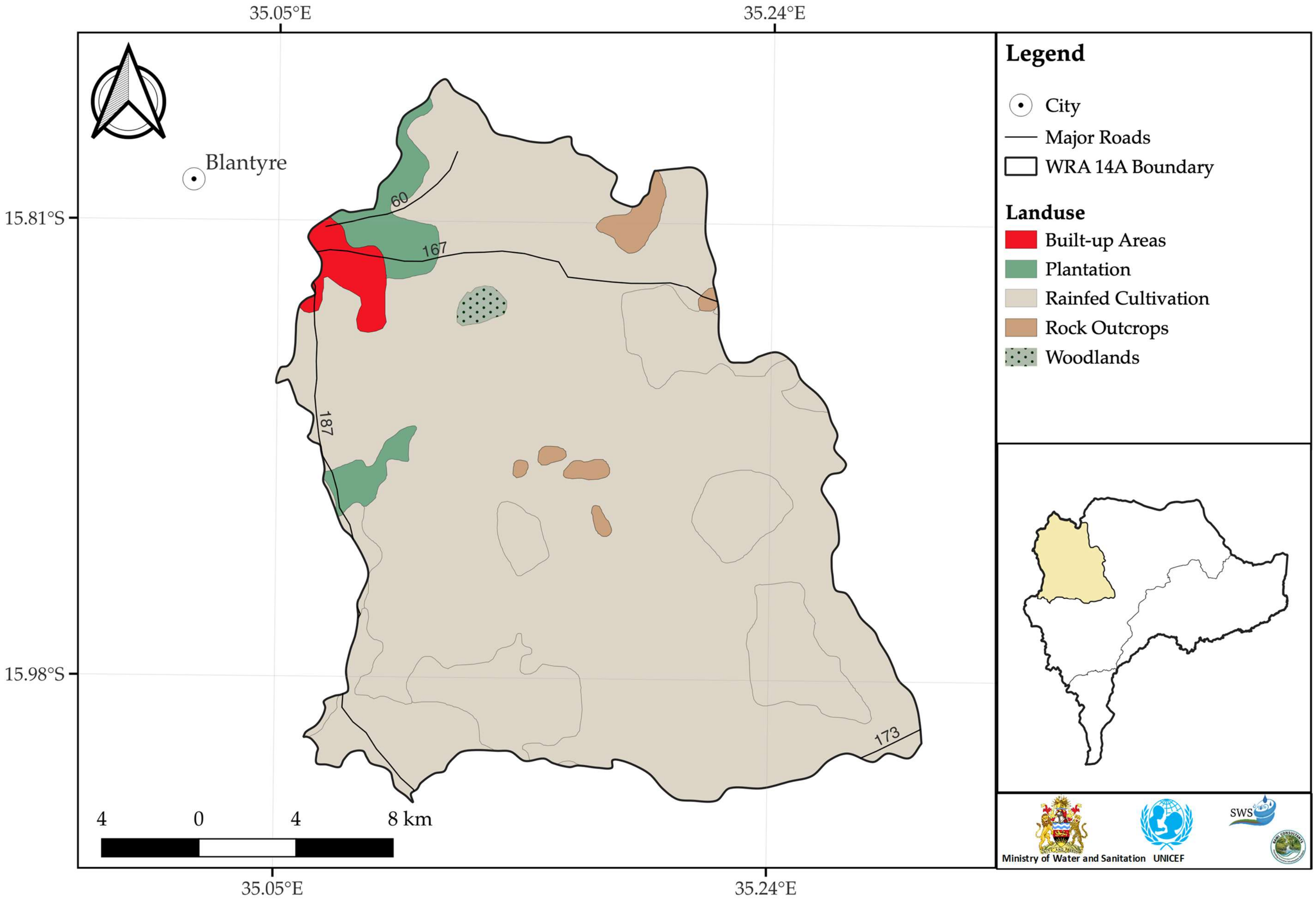
Figure WRA 14.0: Aquifer Units and Groundwater Level Contours Water Resources Area 14

Figure WRA 14.0: Aquifer Units and Groundwater Level Contours WRA 14



WRU 14A Figures

Figure WRU 14A.1 Land Use and Major Roads



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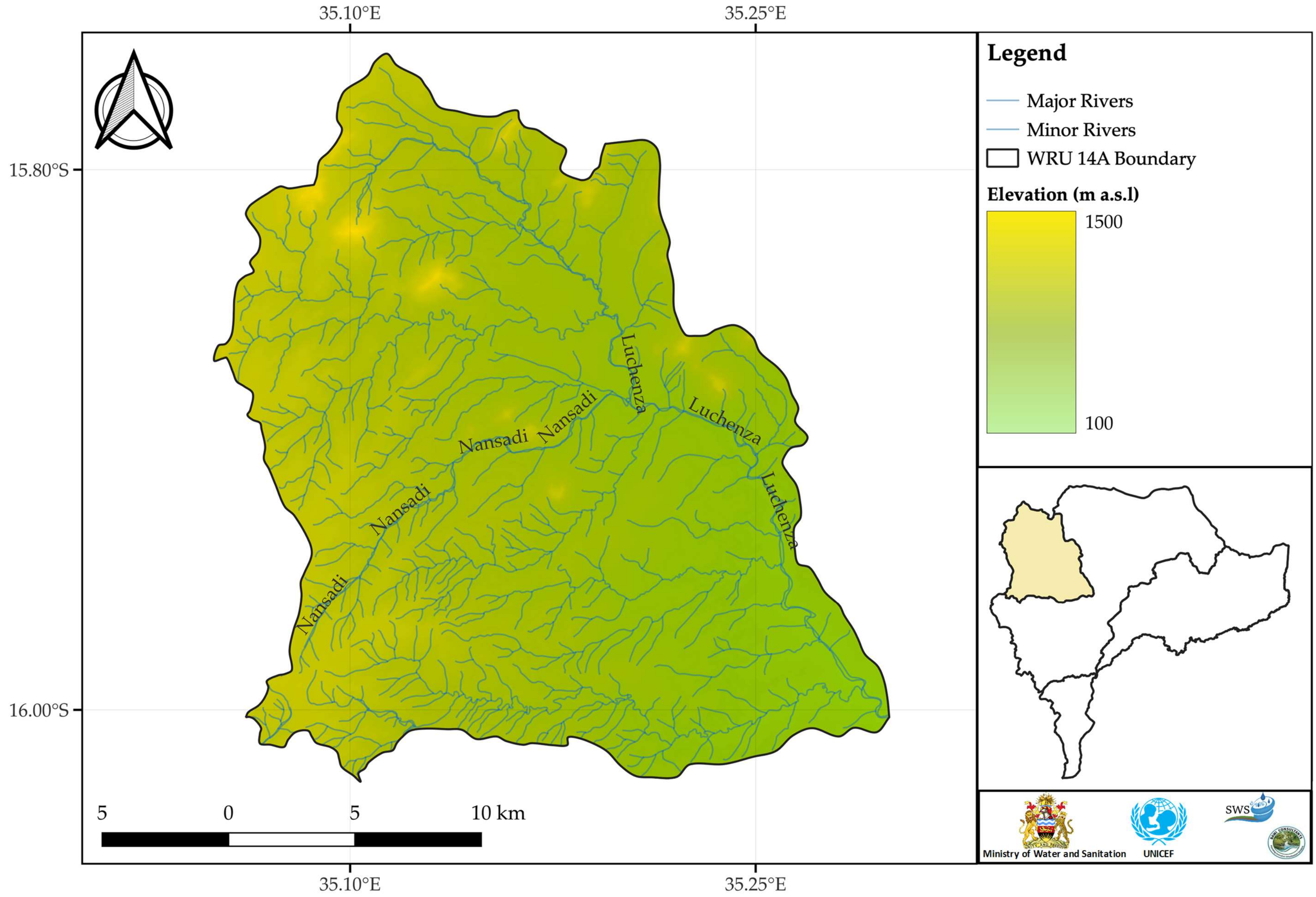


Figure WRU 14A.3 Hydrogeology Units and Water Table

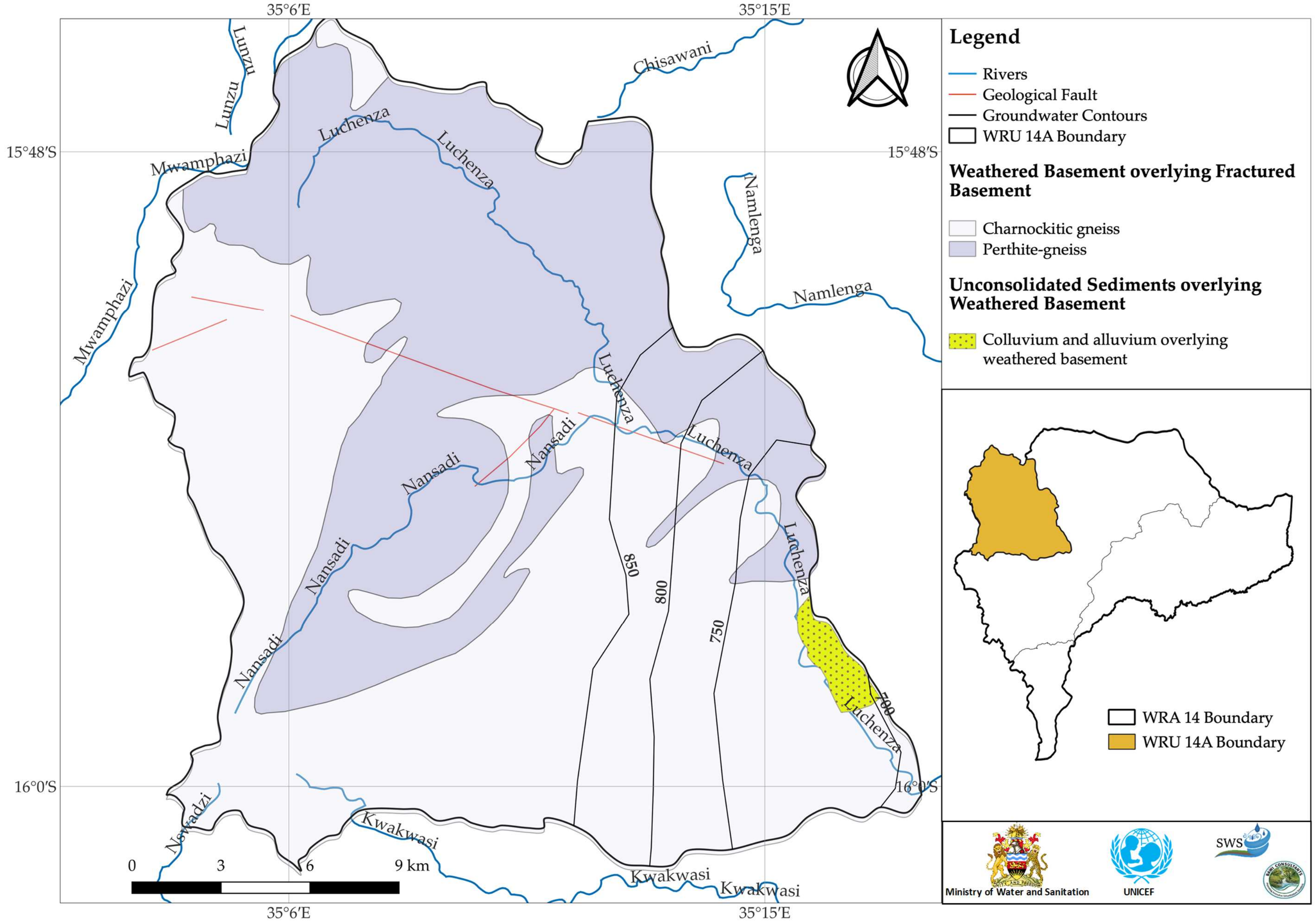
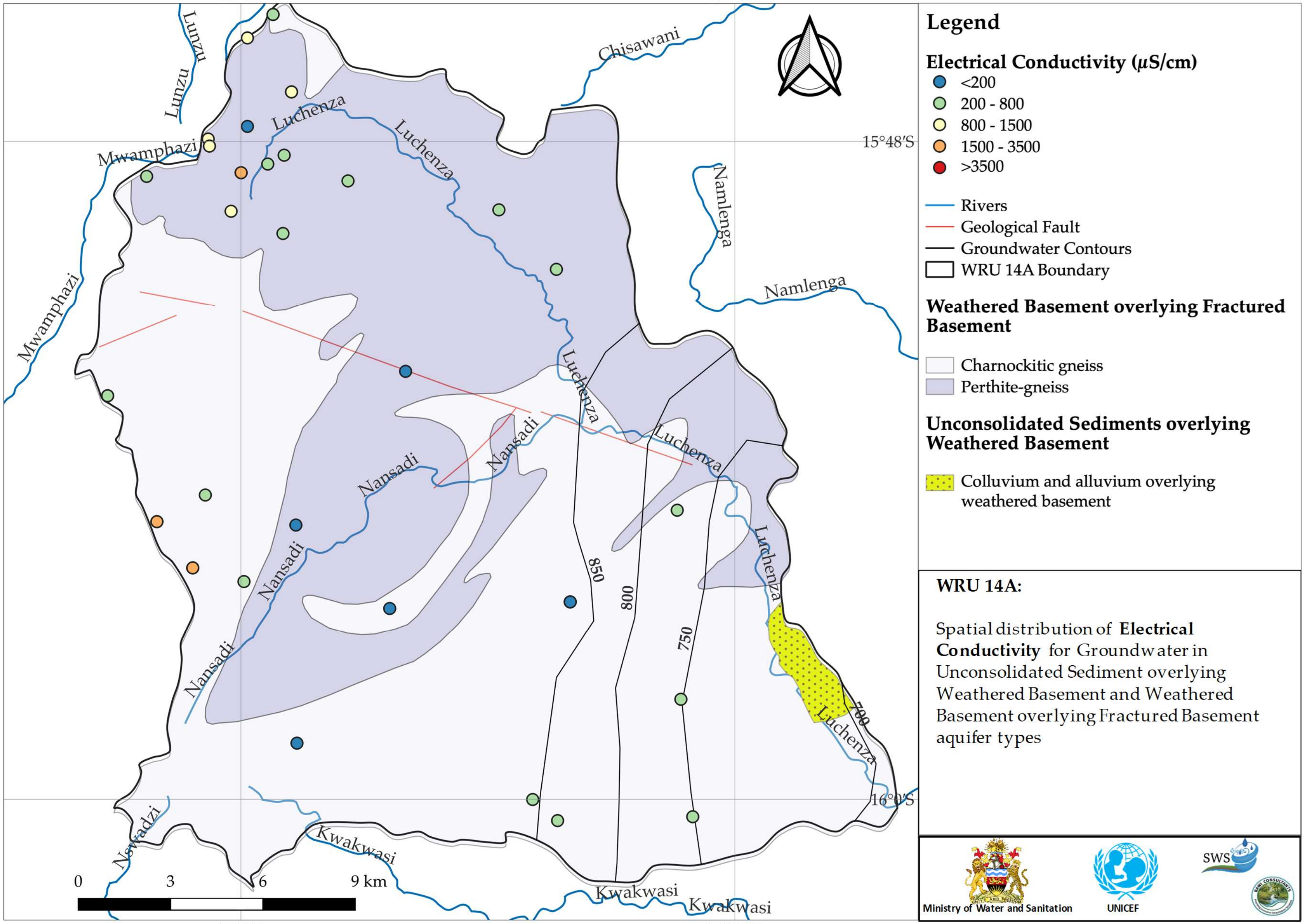


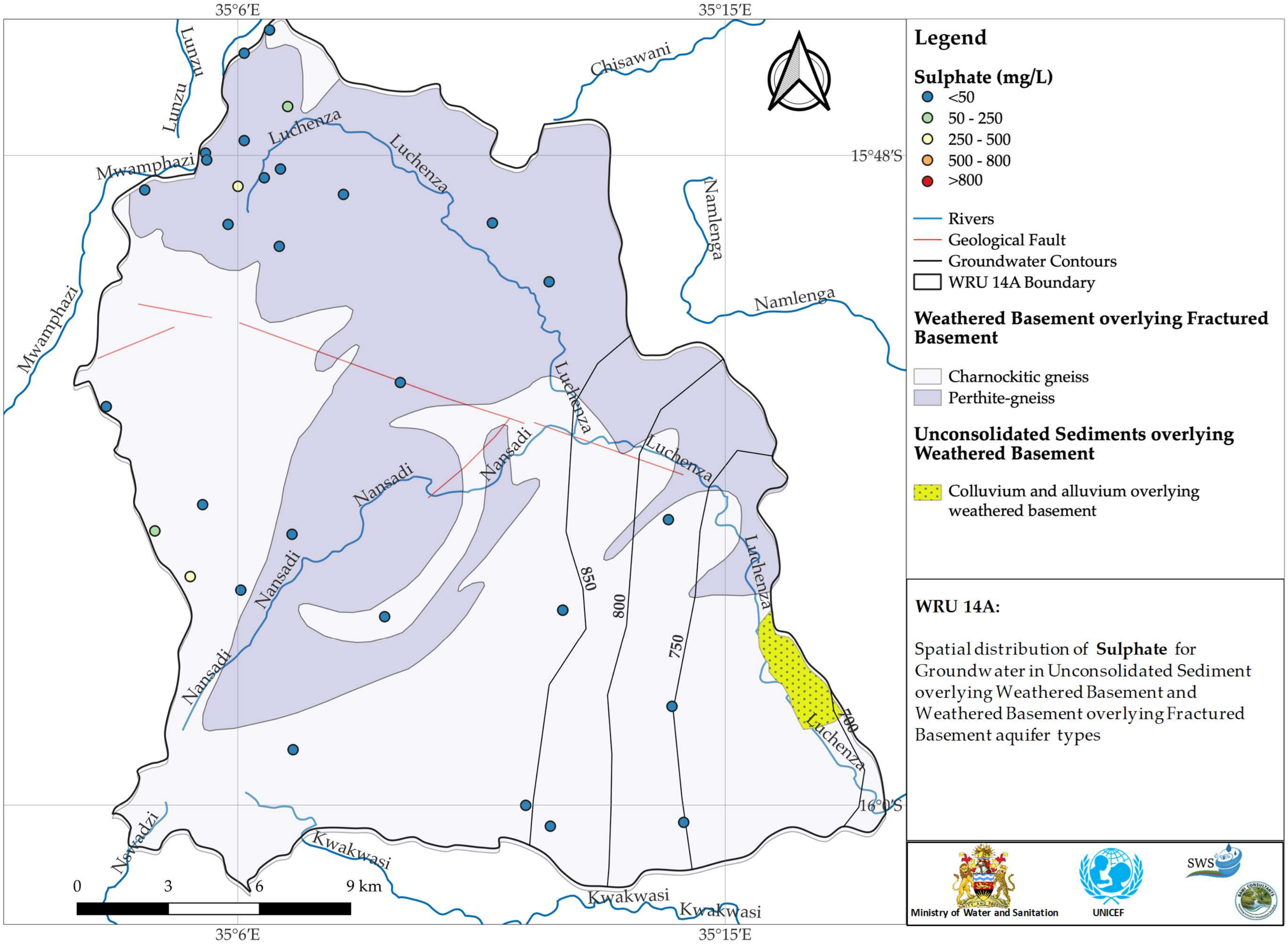
Figure WRU 14A.4 Groundwater Chemistry Distribution Electrical Conductivity



WRU 14A:

Spatial distribution of **Electrical Conductivity** for Groundwater in Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 14A.5 Groundwater Chemistry Distribution Sulphate



WRU 14A:

Spatial distribution of **Sulphate** for Groundwater in Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 14A.6 Groundwater Chemistry Distribution Chloride

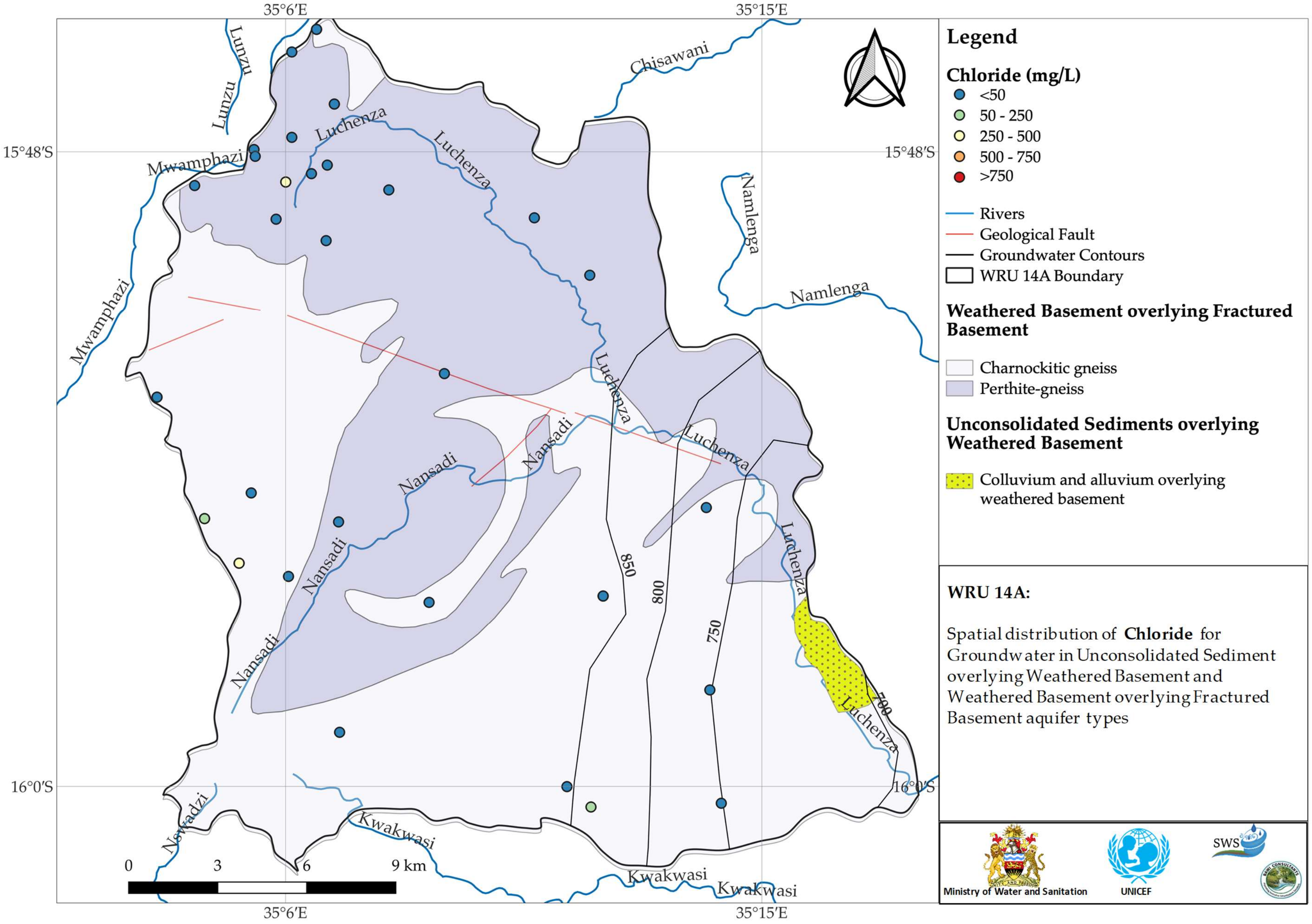
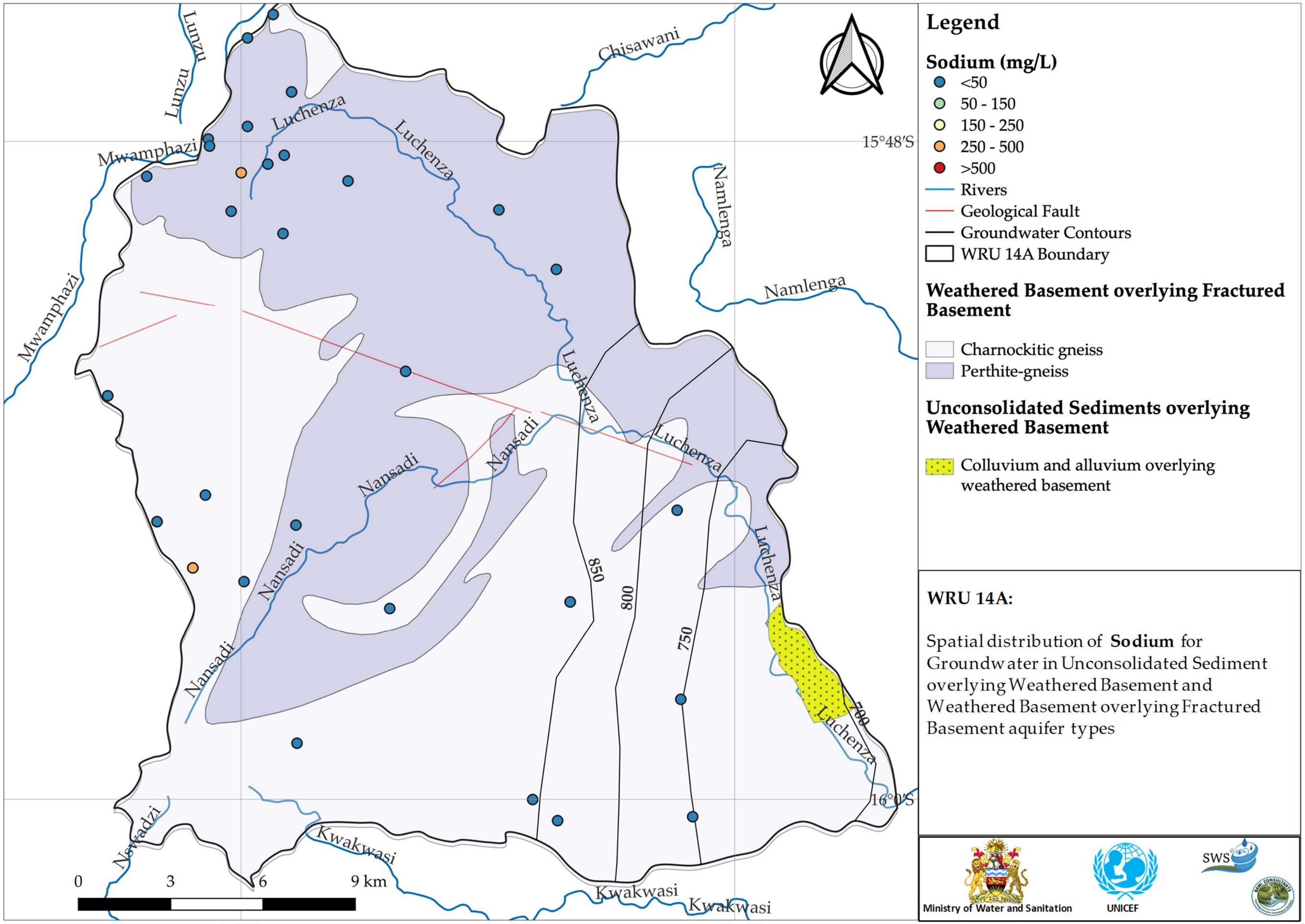


Figure WRU 14A.7 Groundwater Chemistry Distribution Sodium



WRU 14A:

Spatial distribution of **Sodium** for Groundwater in Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 14A.8 Groundwater Chemistry Distribution Calcium

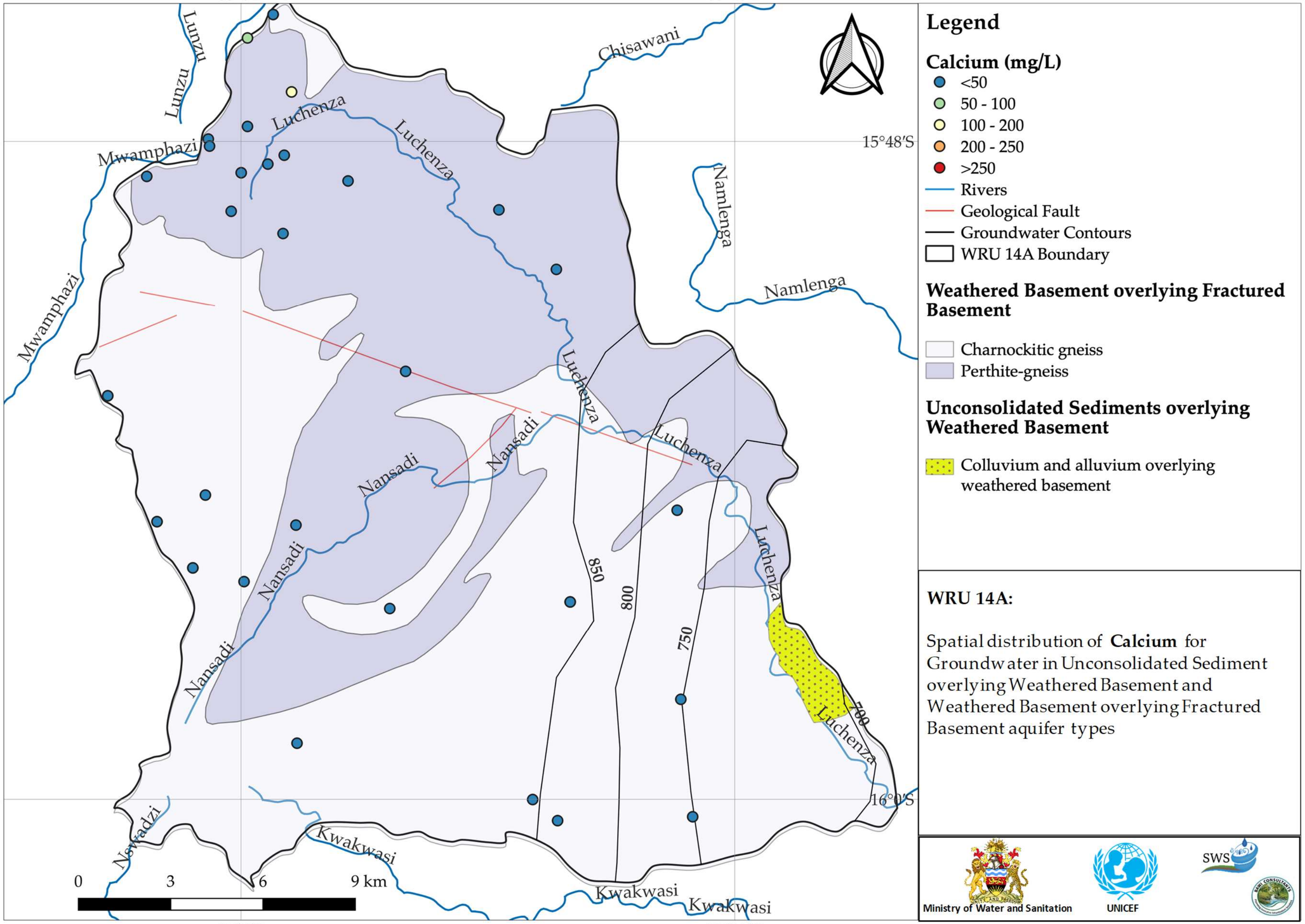


Figure WRU 14A.9 Piper Diagram of water quality results with respect to the major aquifer type

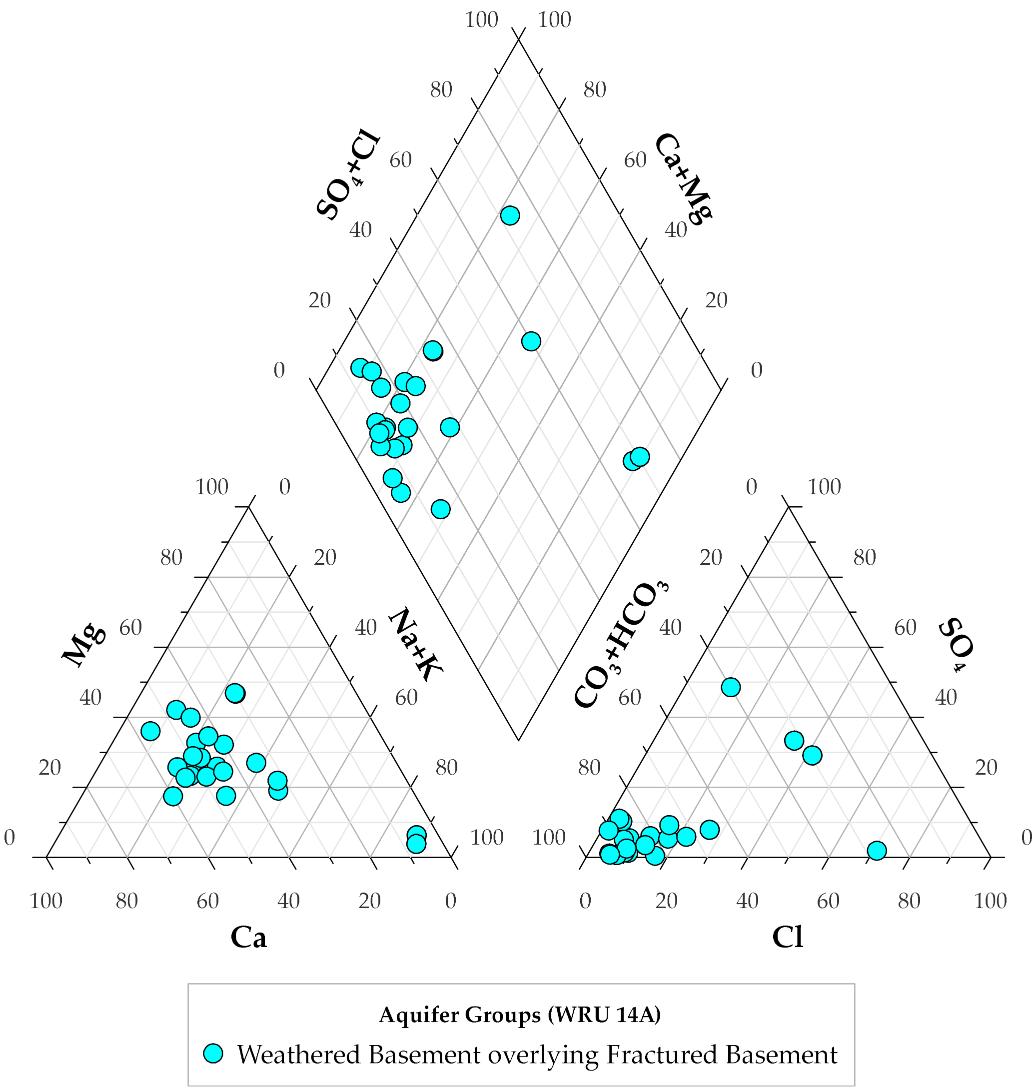
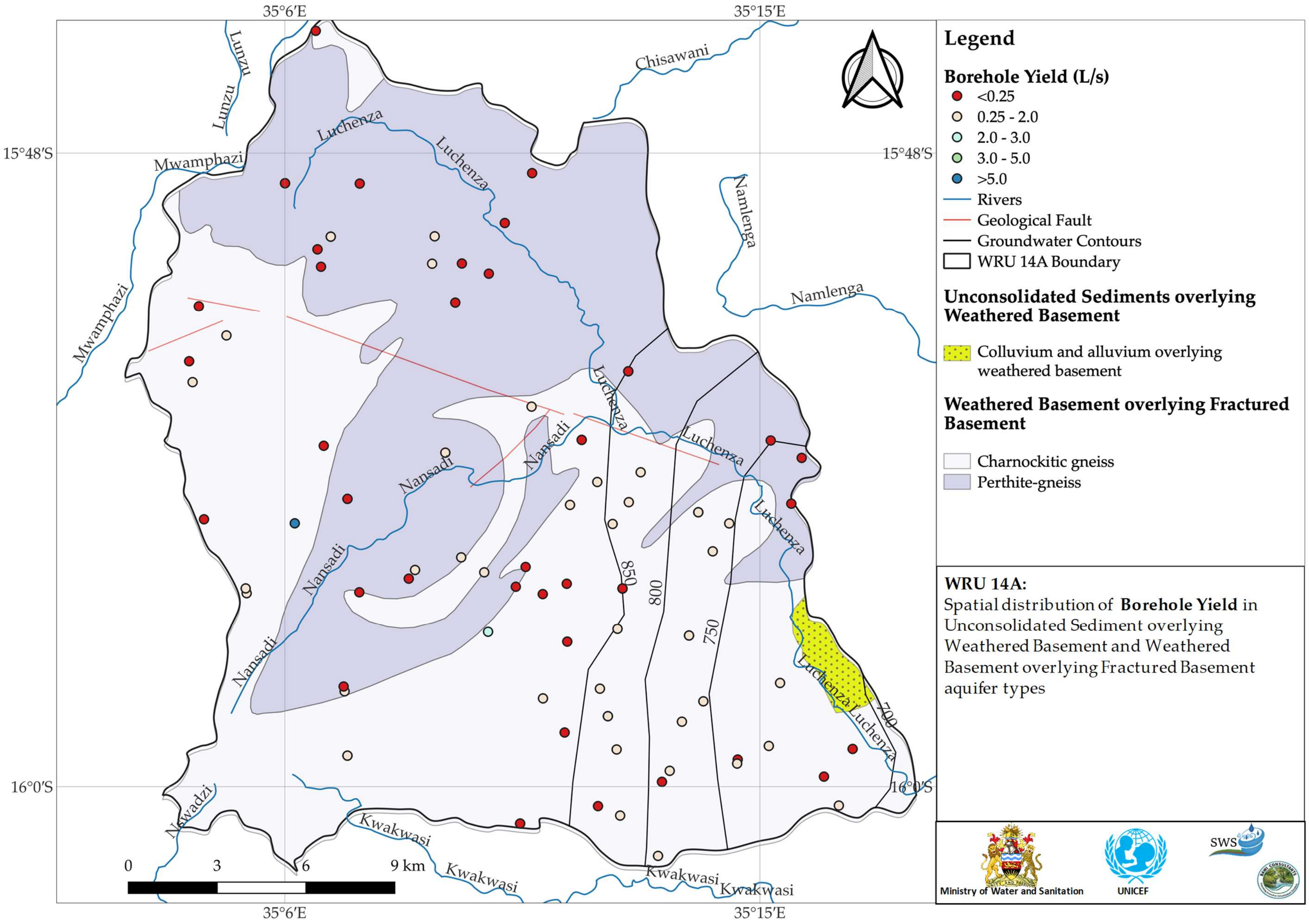


Figure WRU 14A.10 Borehole Yield Map for data held by the Ministry



WRU 14B Figures

Figure WRU 14B.1 Land Use and Major Roads

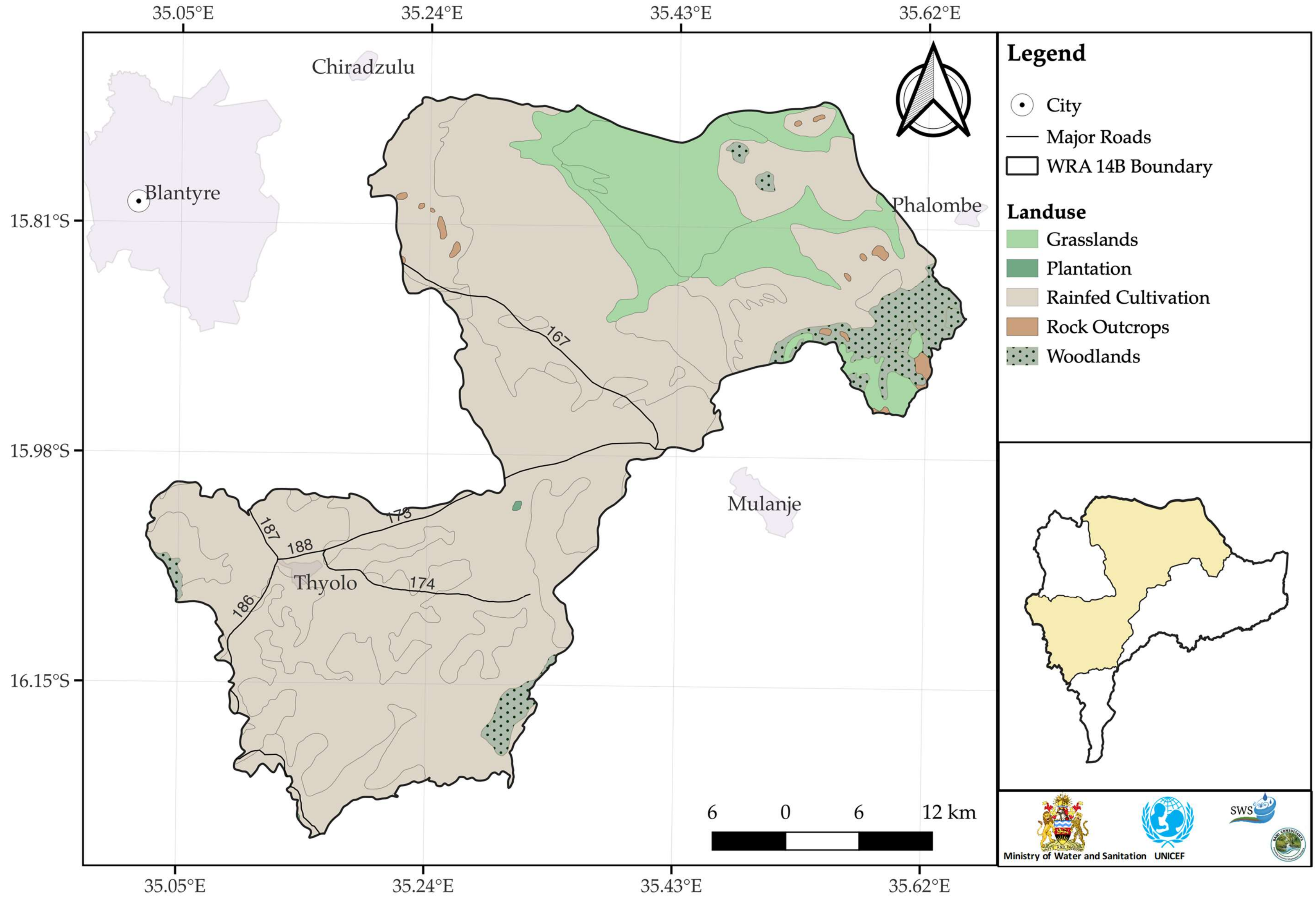


Figure WRU 14B.2 Rivers and Wetlands

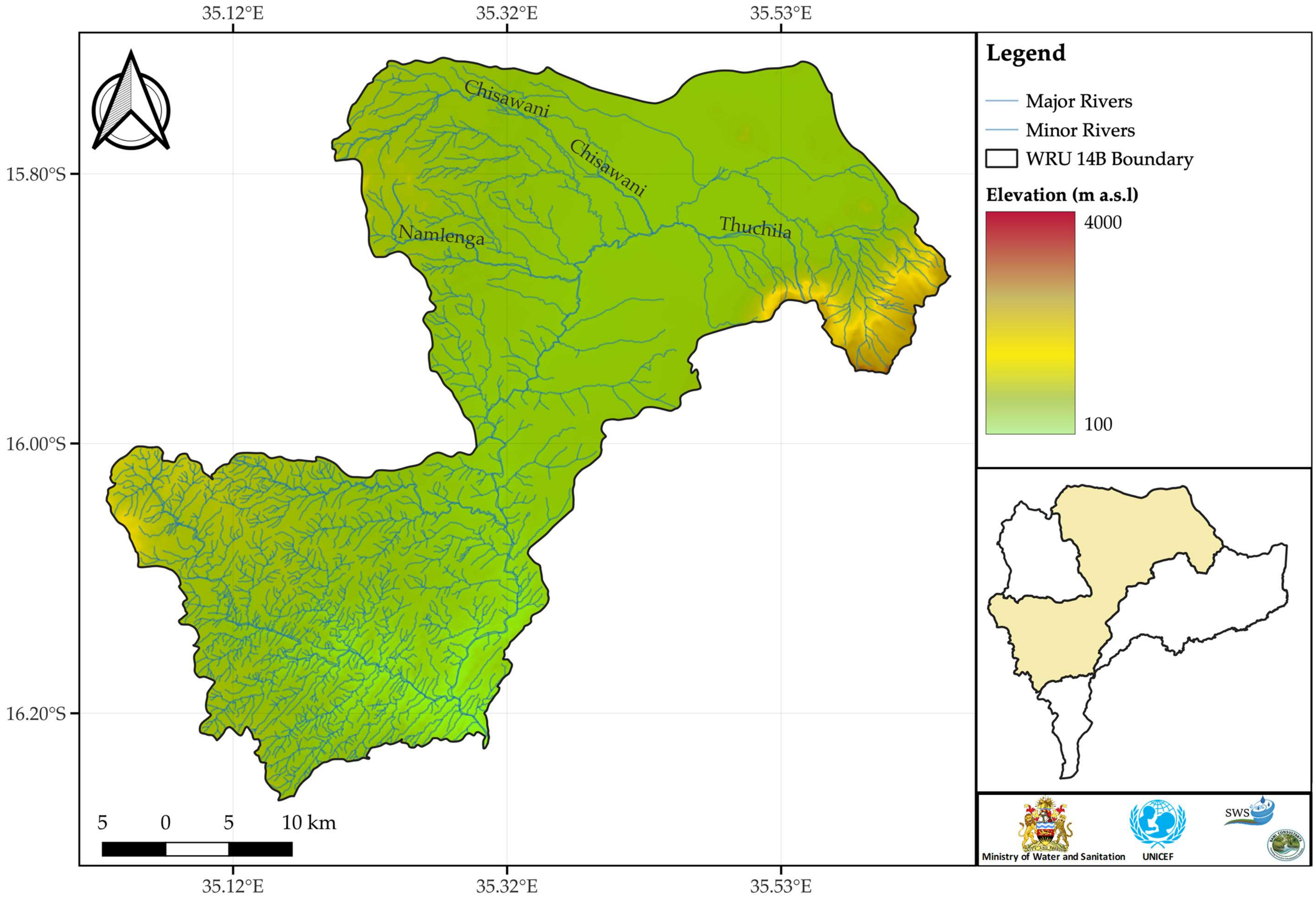


Figure WRU 14B.3 Hydrogeology Units and Water Table

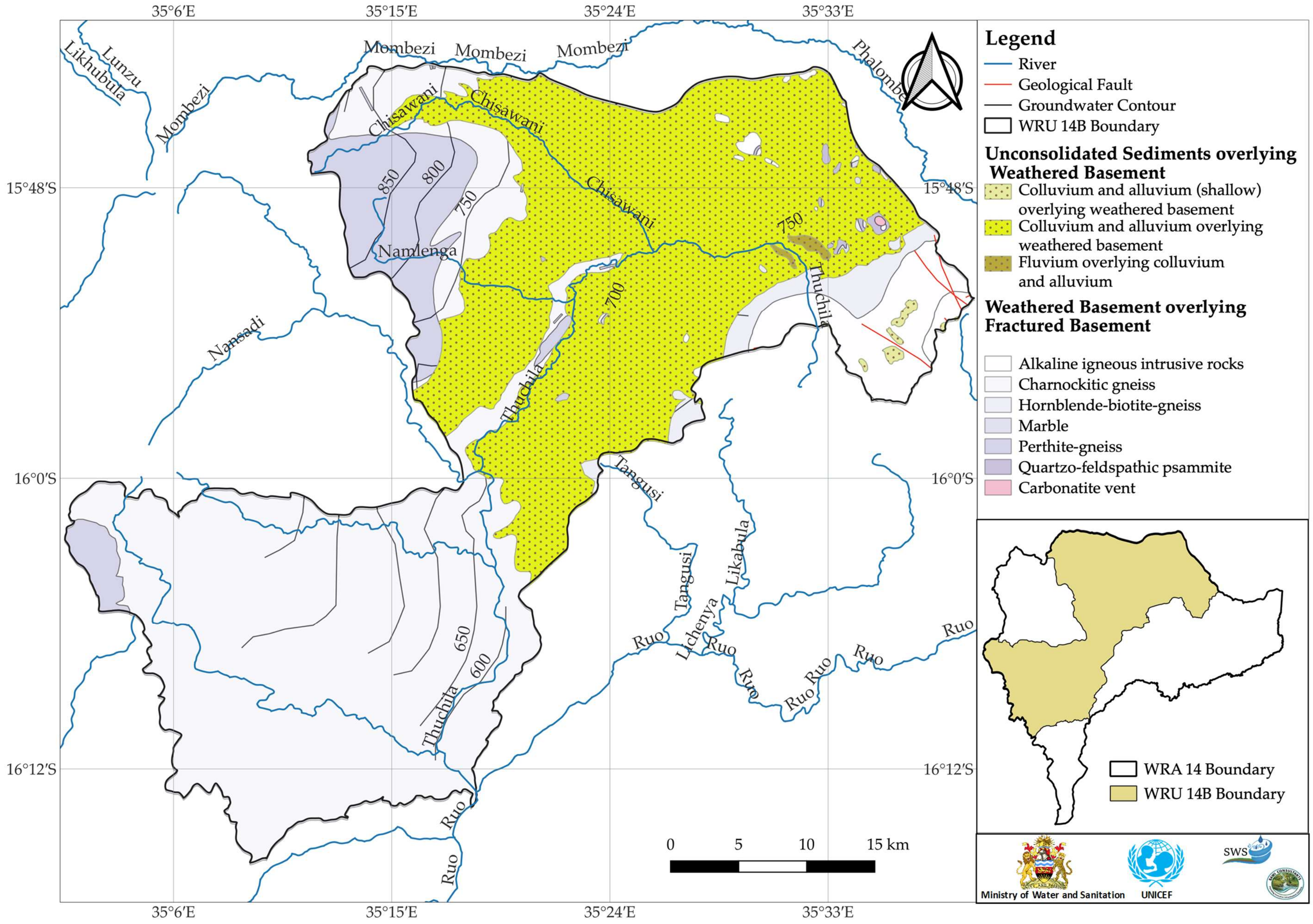


Figure WRU 14B.4 Groundwater Chemistry Distribution Electrical Conductivity

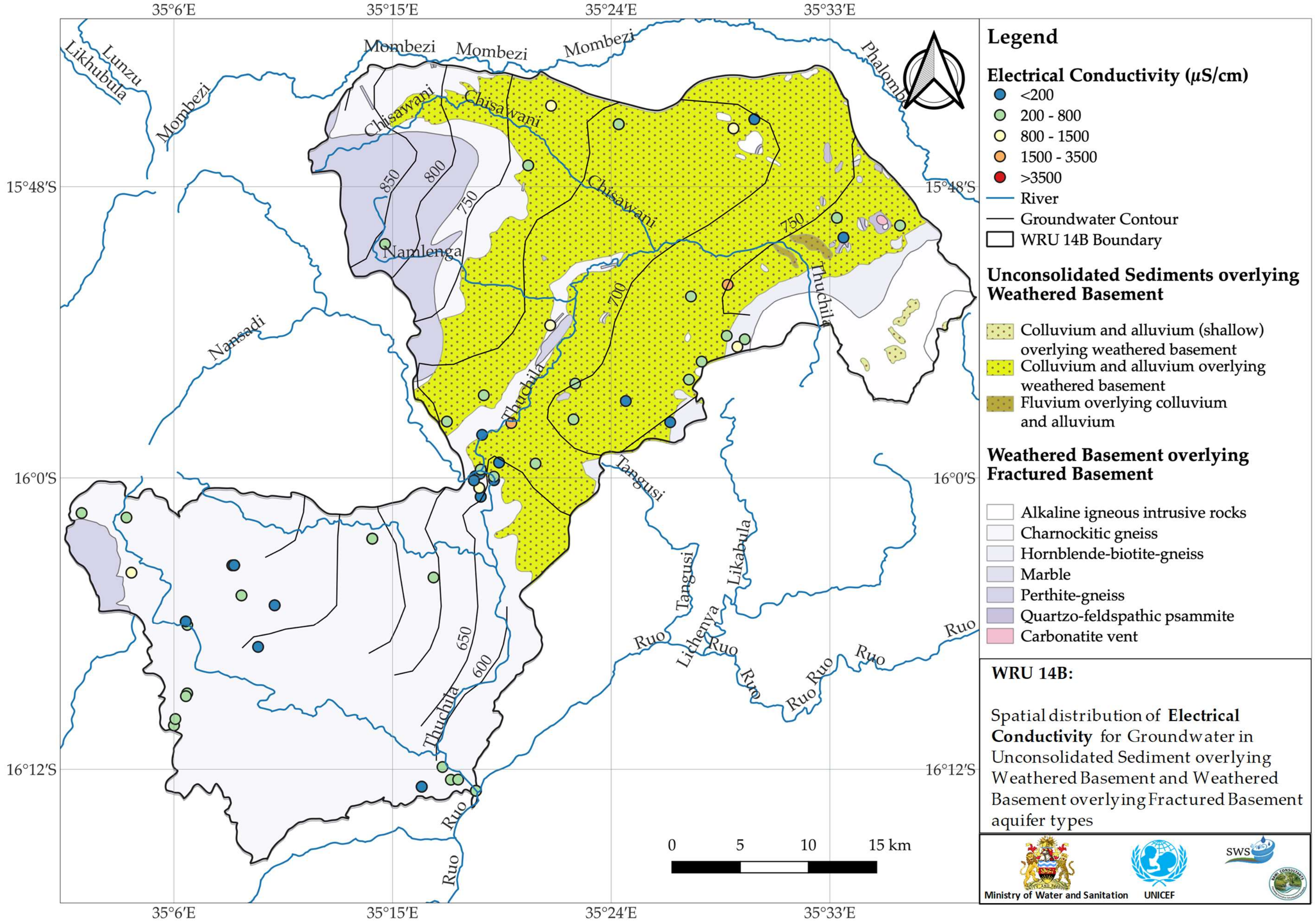


Figure WRU 14B.5 Groundwater Chemistry Distribution of Sulphate

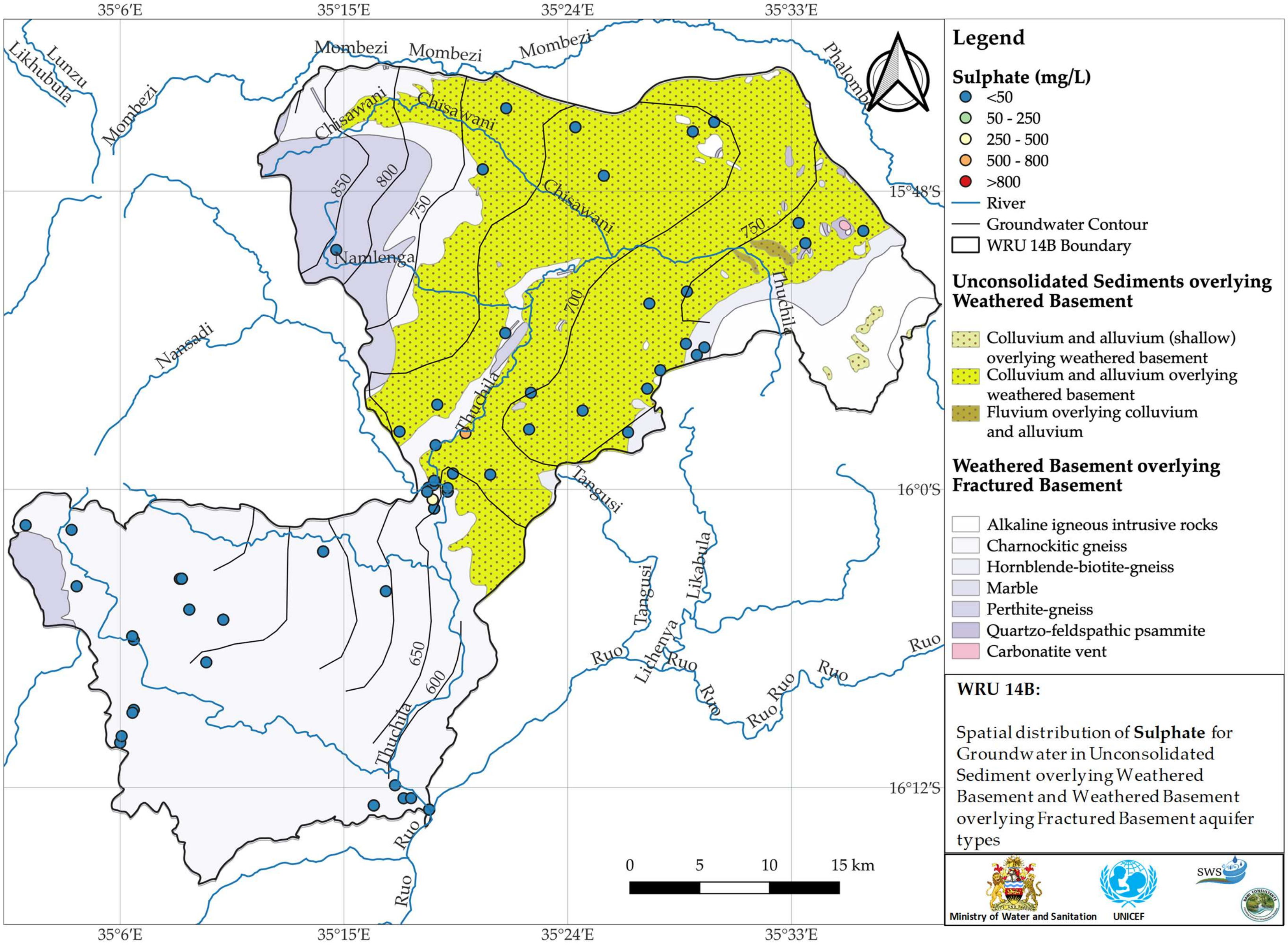


Figure WRU 14B.6 Groundwater Chemistry Distribution Chloride

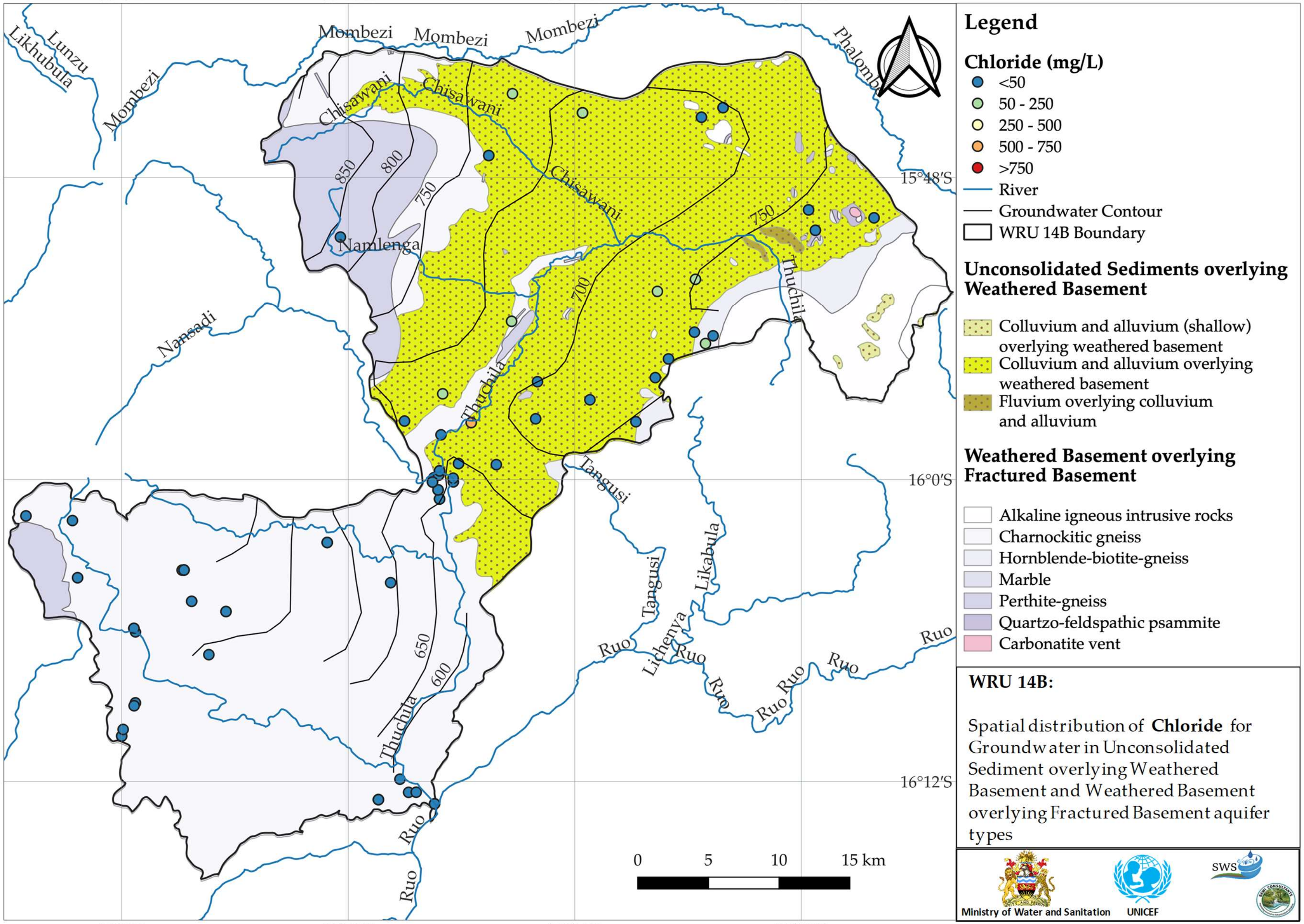


Figure WRU 14B.7 Groundwater Chemistry Distribution Sodium

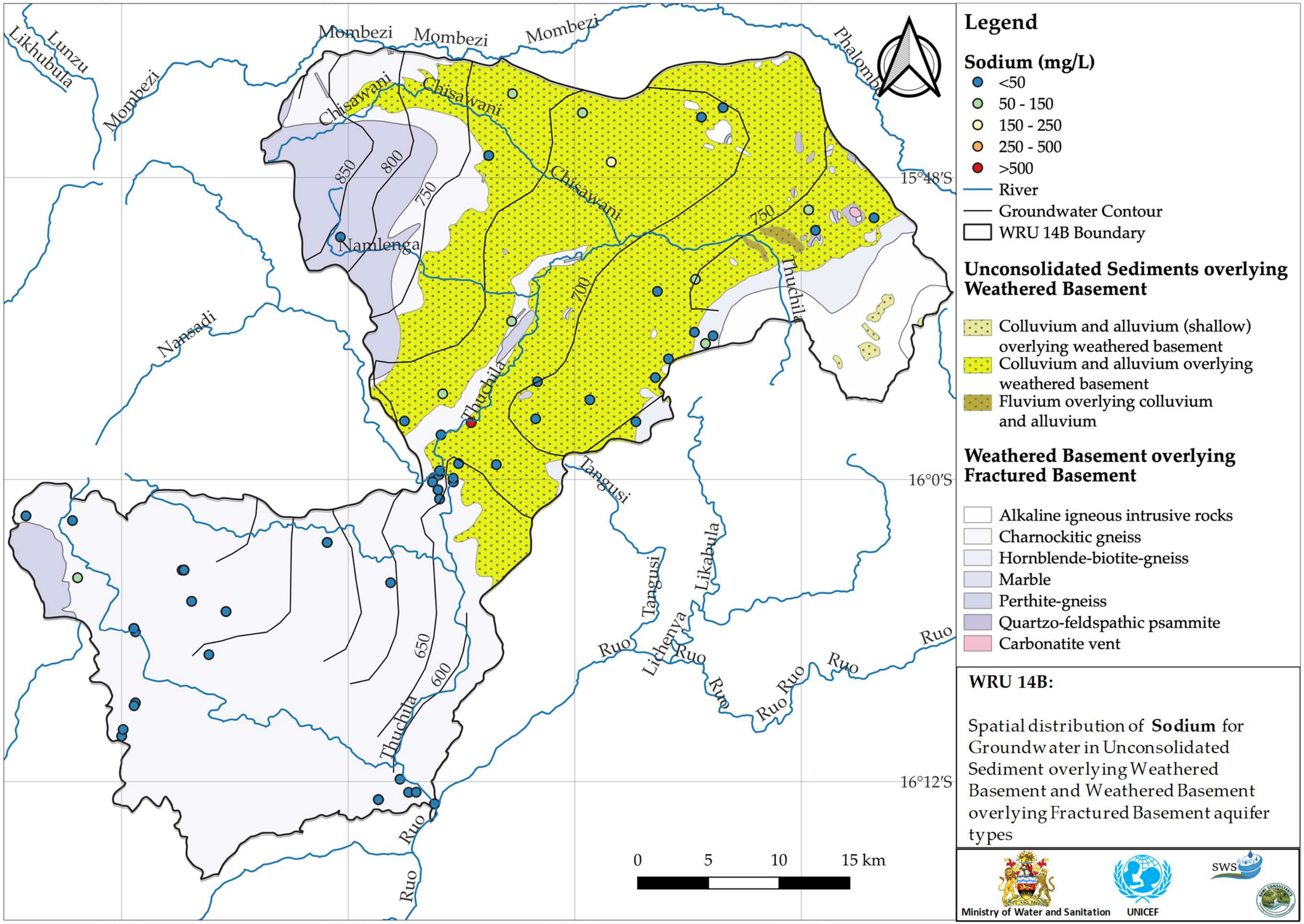


Figure WRU 14B.8 Groundwater Chemistry Distribution Calcium

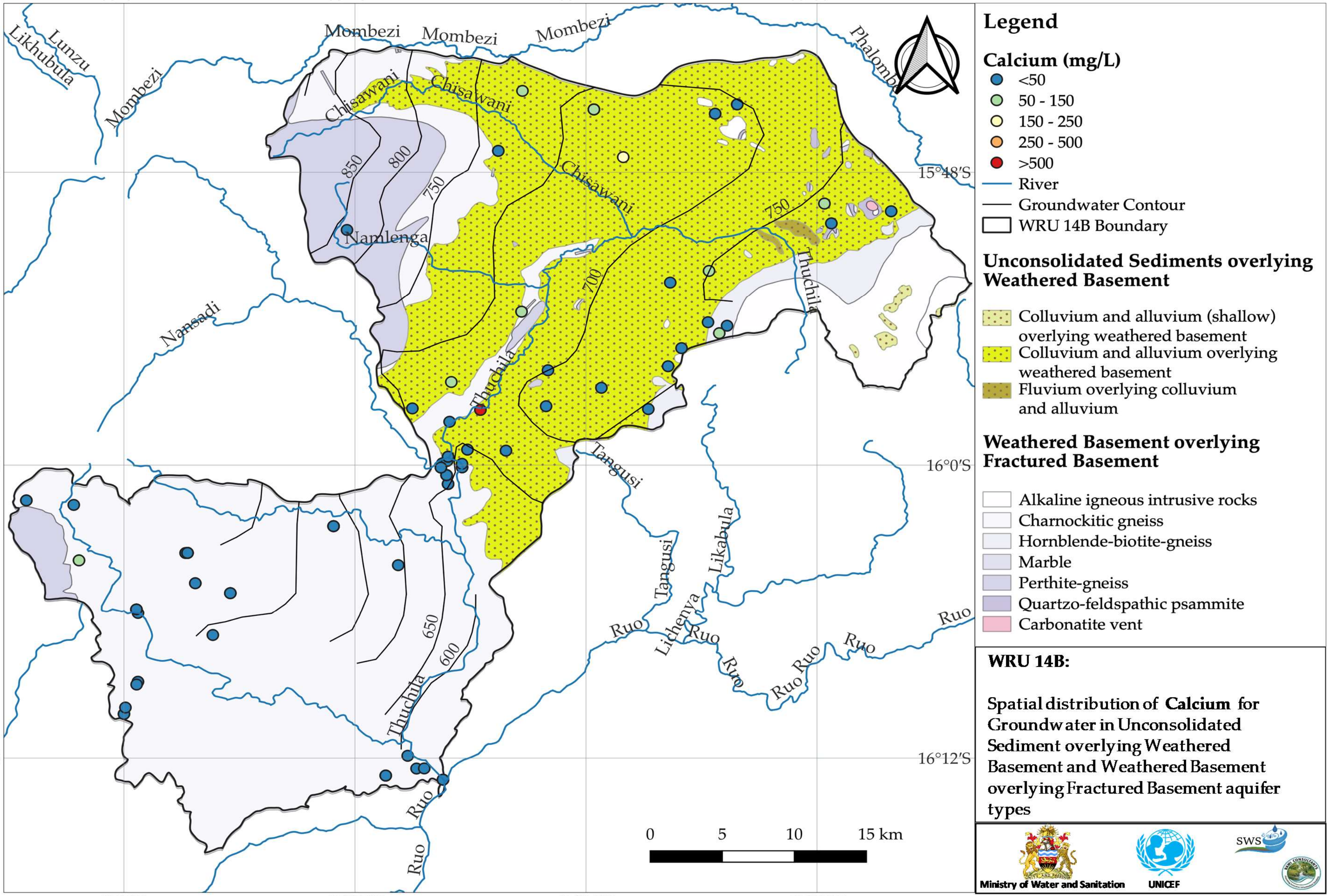


Figure WRU 14B.9 Piper Diagram of water quality results with respect to the major aquifer type

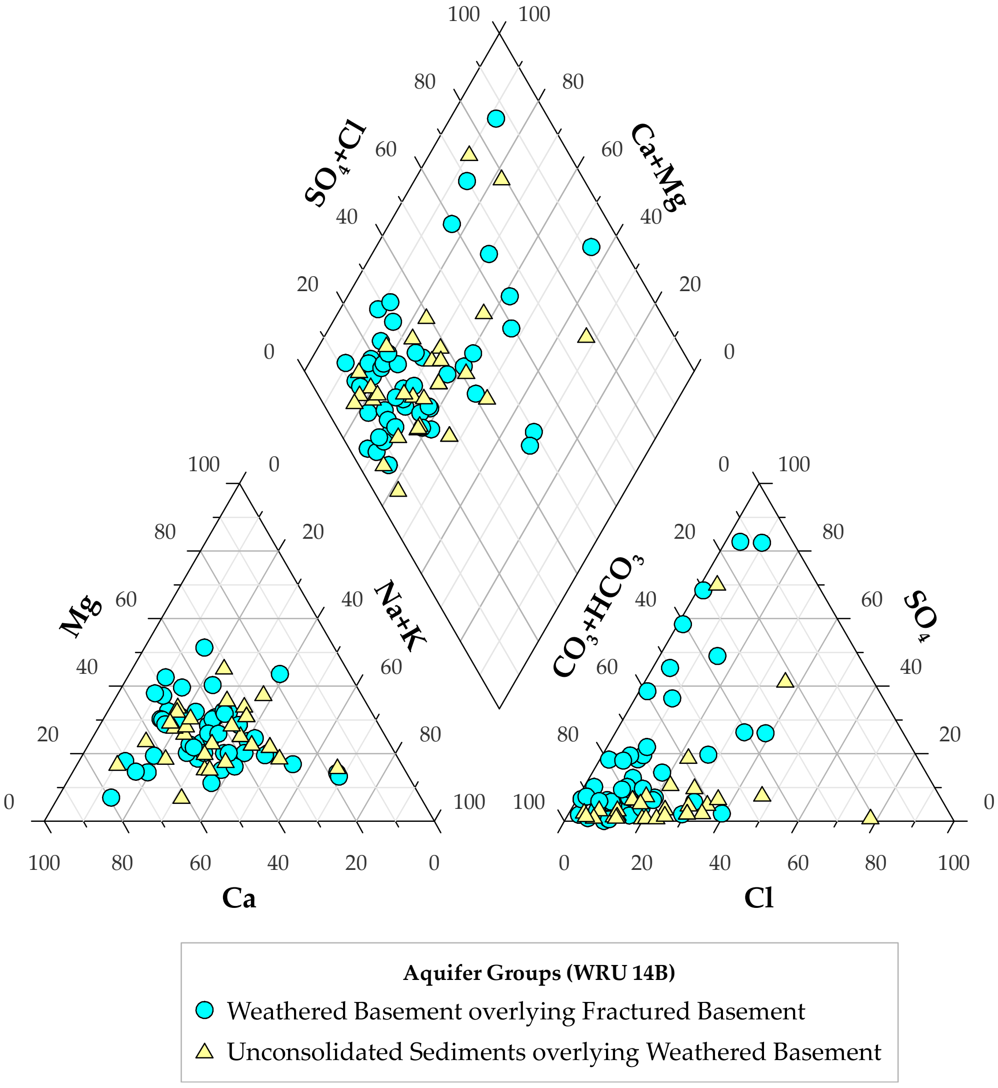
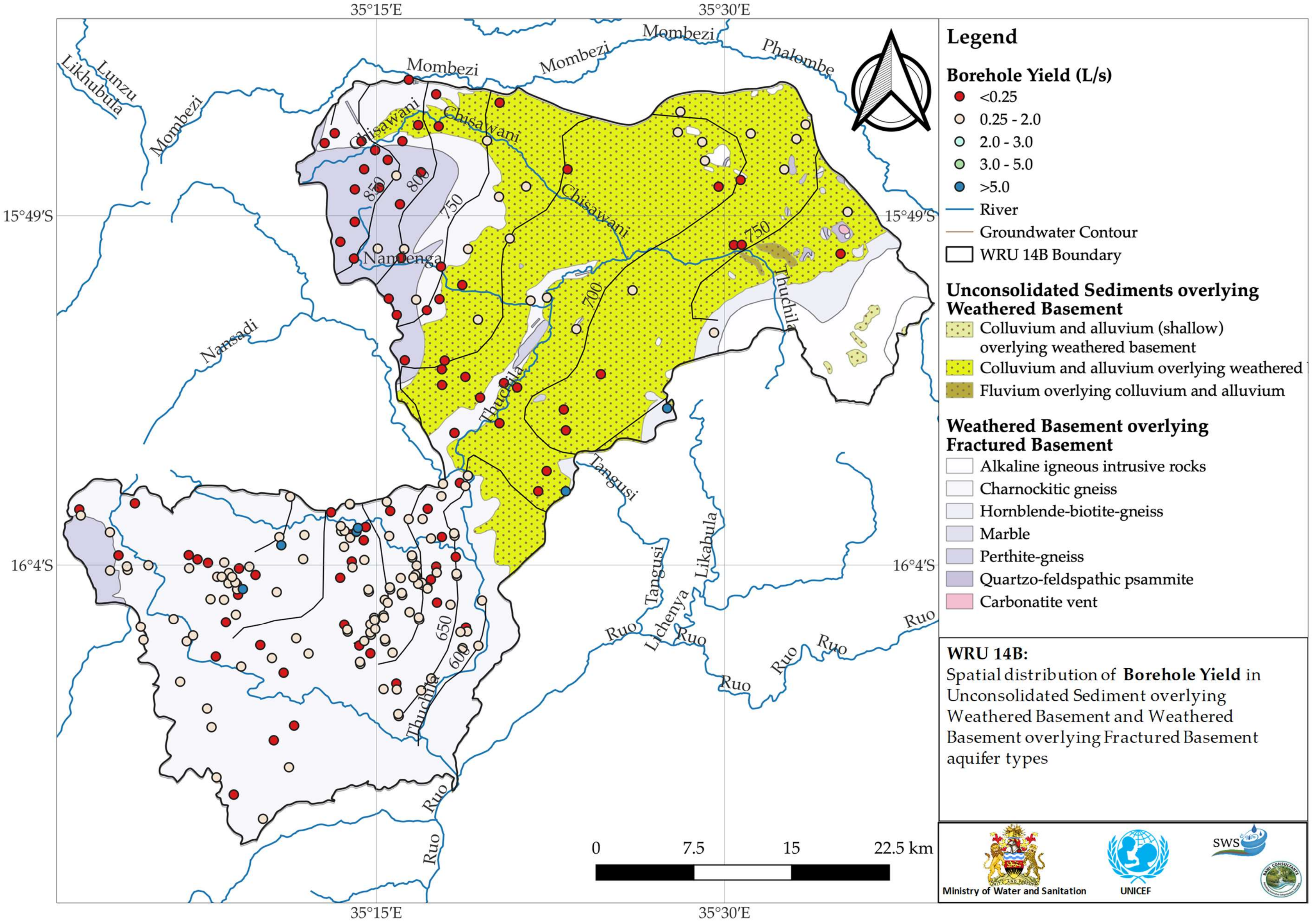


Figure WRU 14B.10 Borehole Yield Map for data held by the Ministry



WRU 14C Figures

Figure WRU 14C.1 Land Use and Major Roads

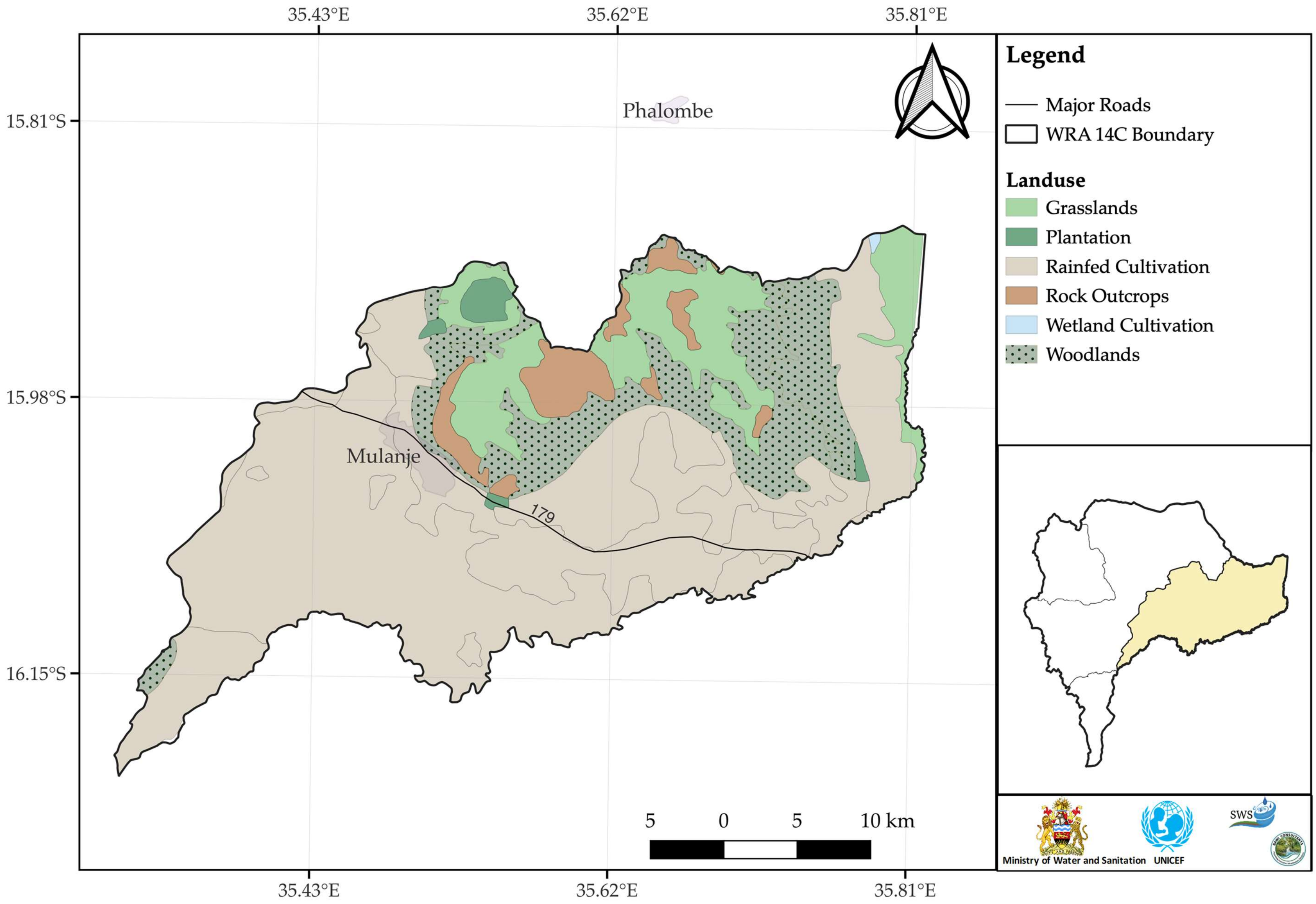


Figure WRU 14C.2 Rivers and Wetlands

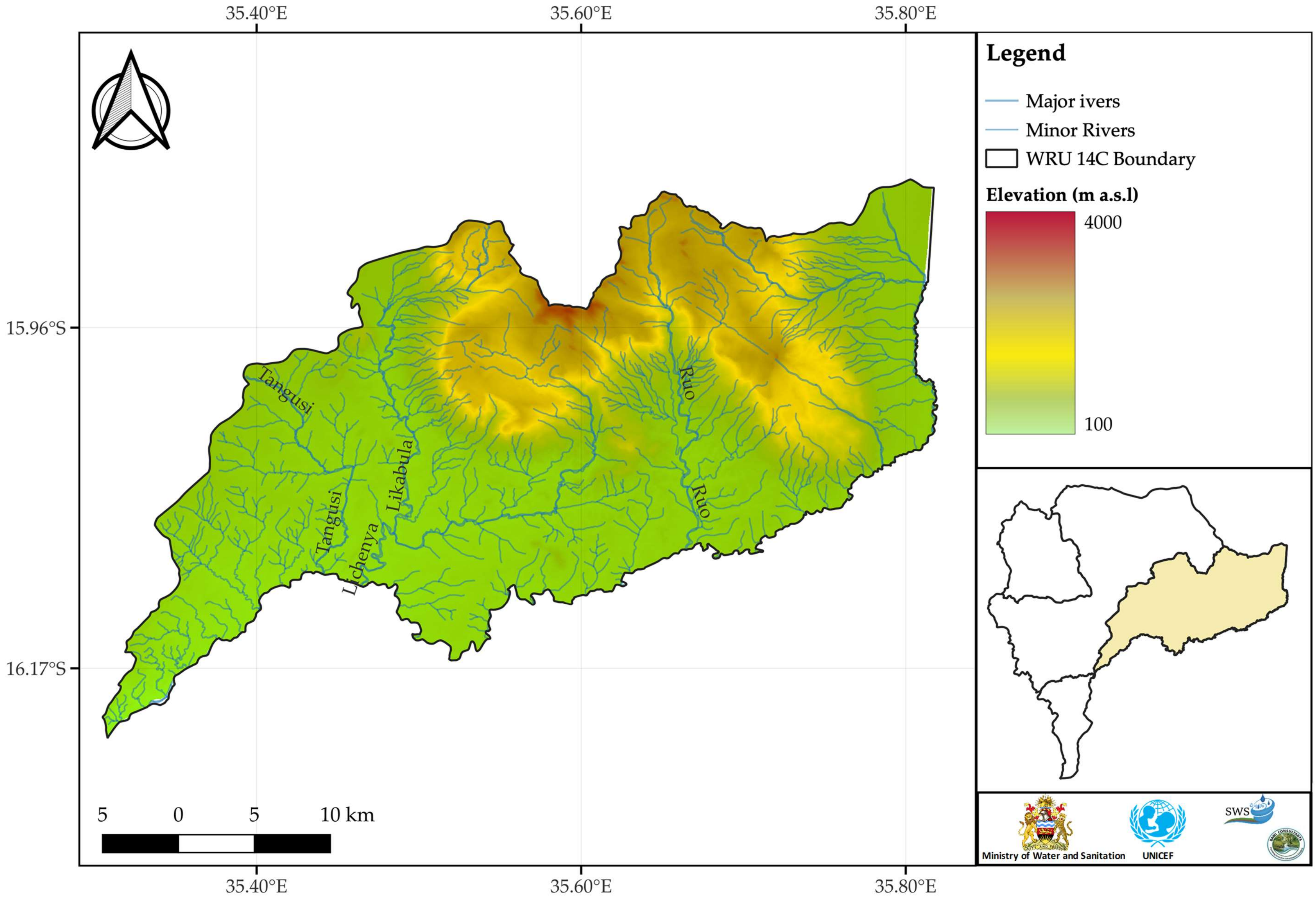


Figure WRU 14C.3 Hydrogeology Units and Water Table

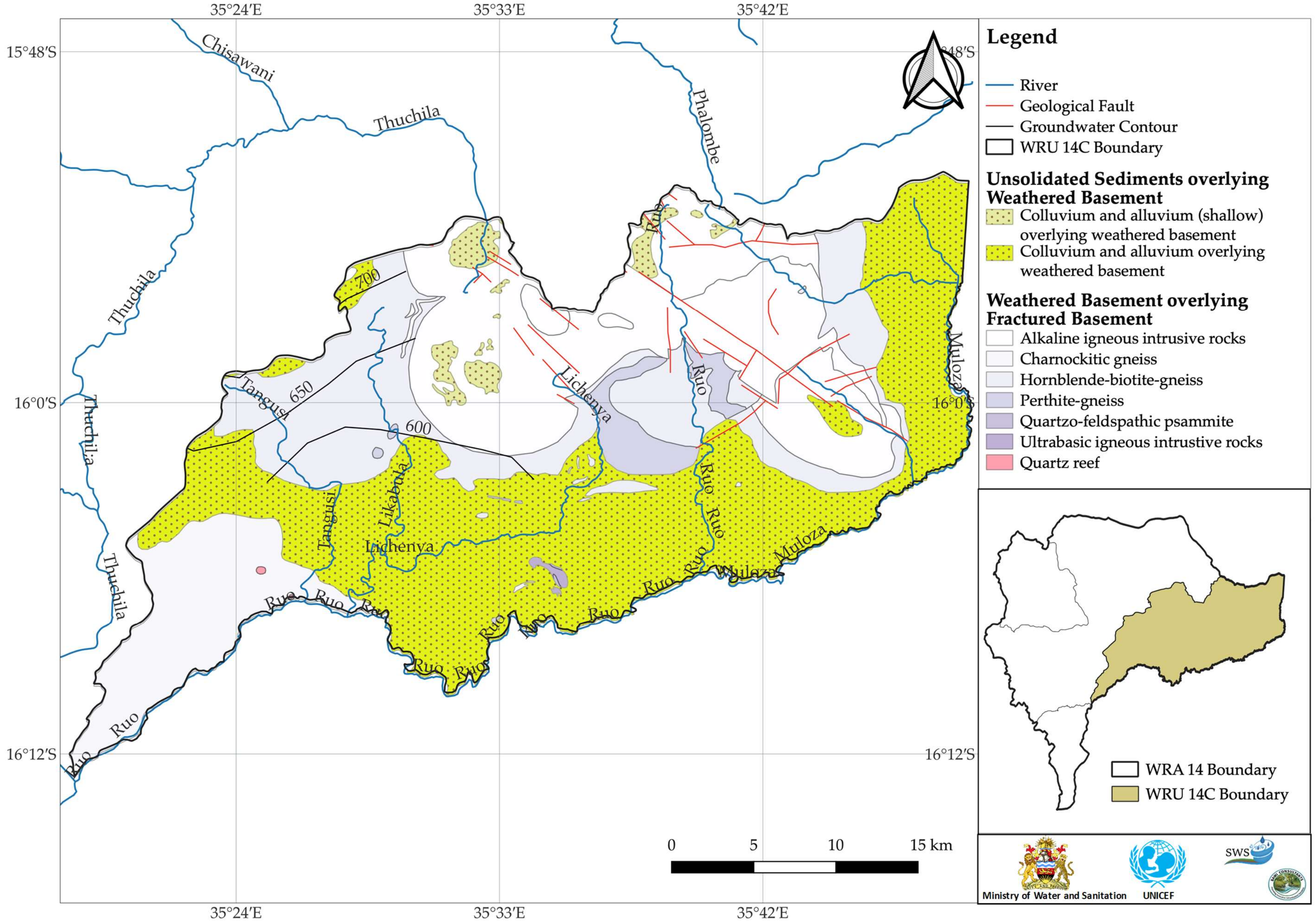


Figure WRU 14C.4 Groundwater Chemistry Distribution Electrical Conductivity

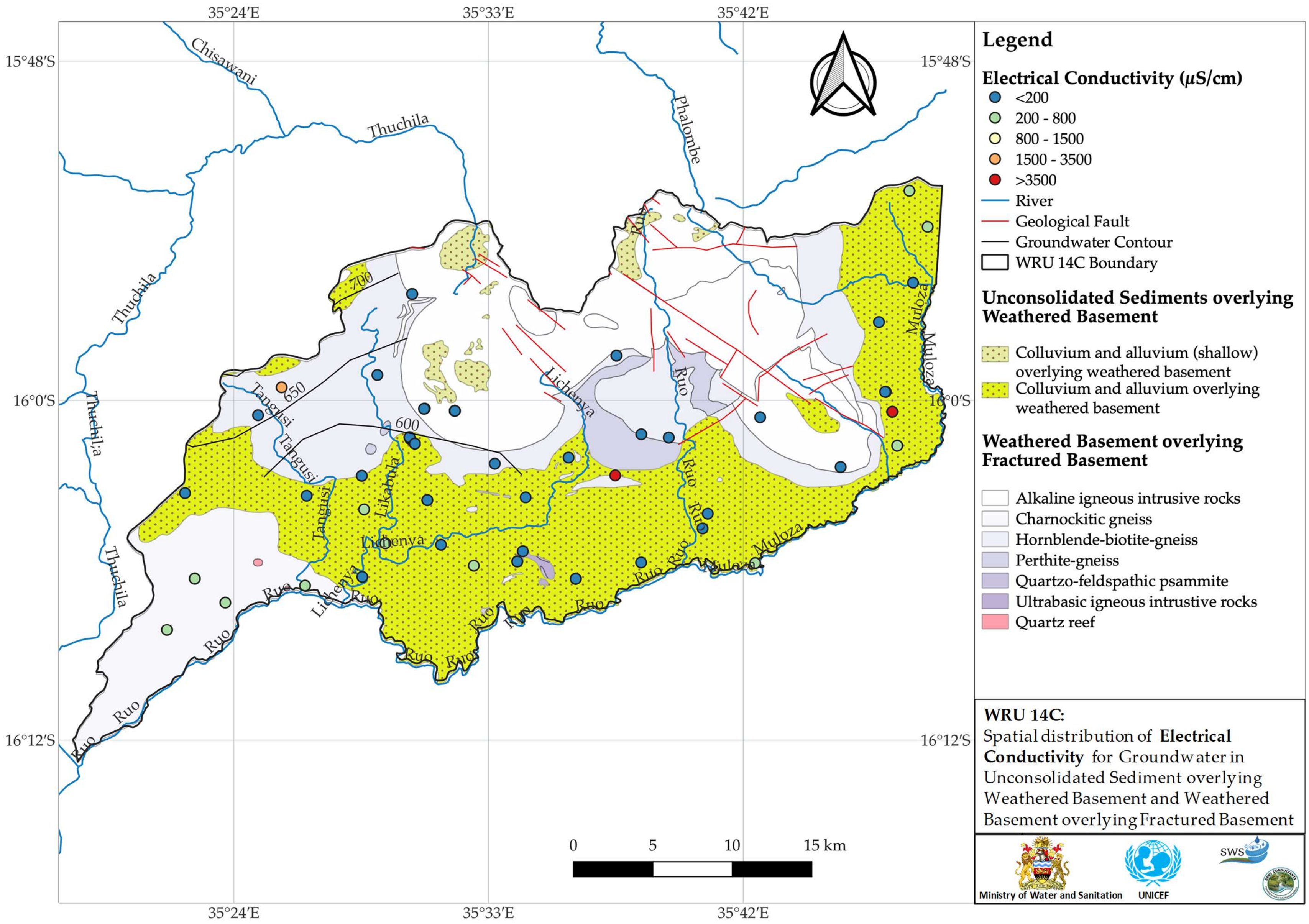


Figure WRU 14C.5 Groundwater Chemistry Distribution of Sulphate

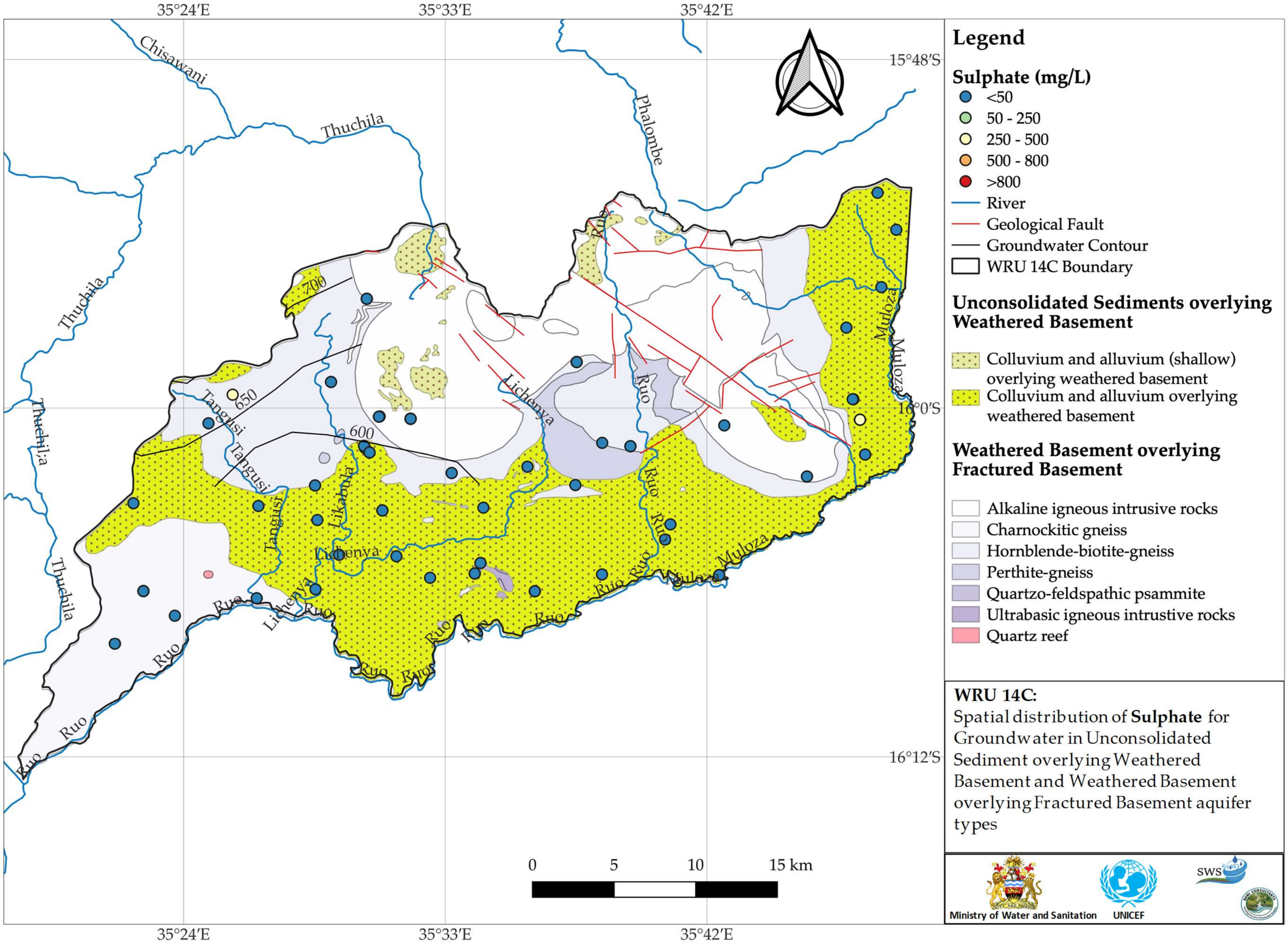


Figure WRU 14C.6 Groundwater Chemistry Distribution Chloride

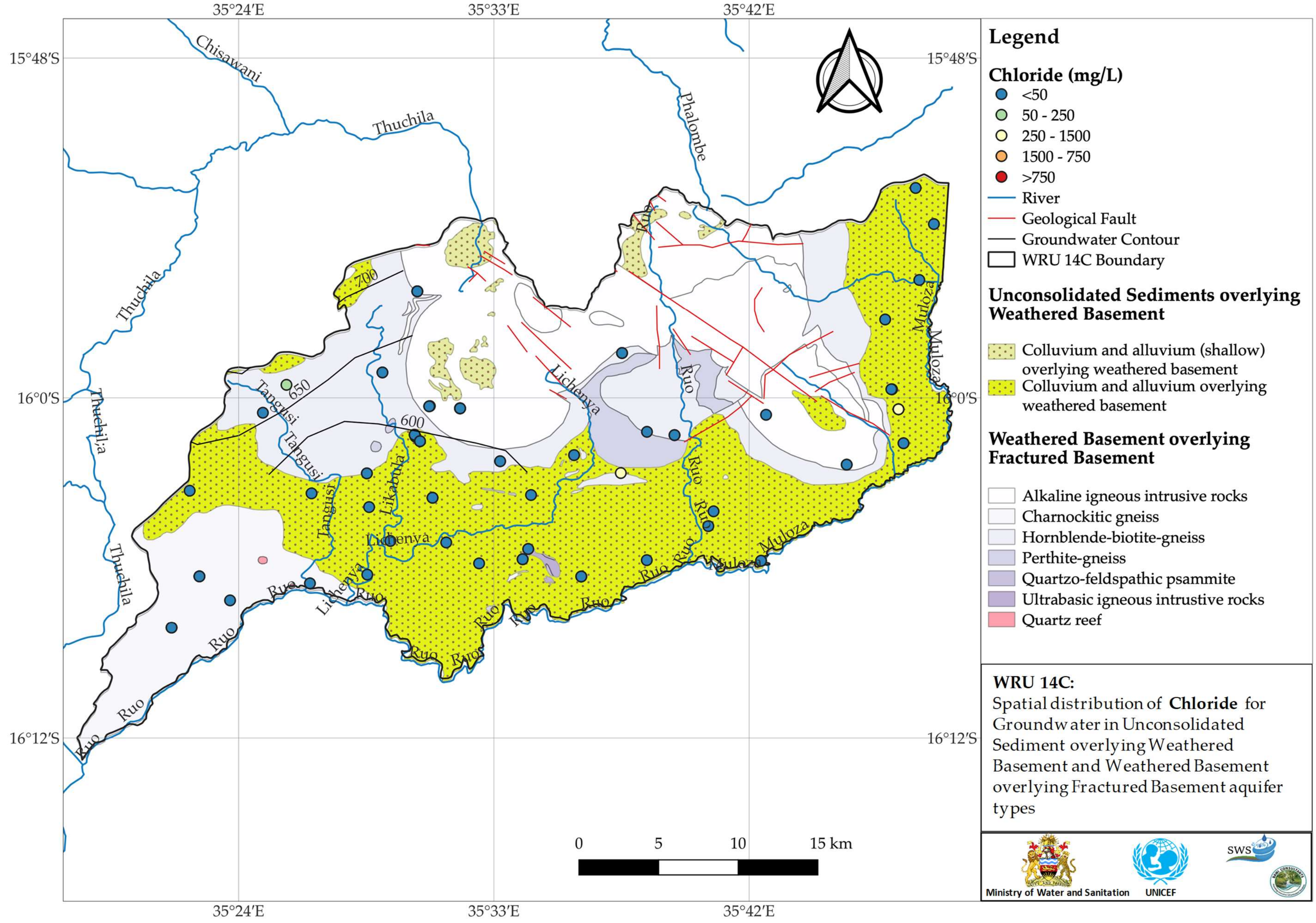


Figure WRU 14C.7 Groundwater Chemistry Distribution Sodium

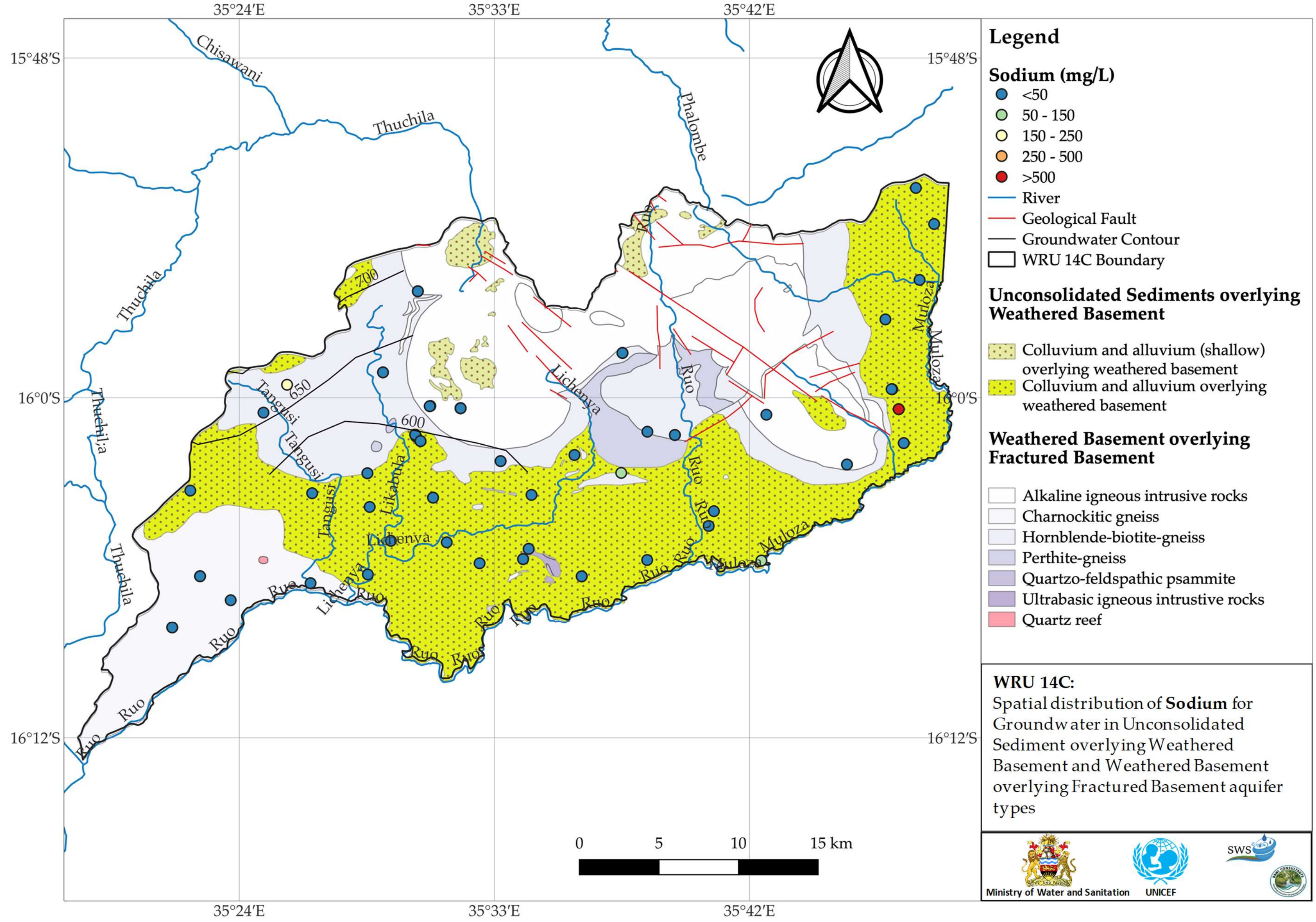


Figure WRU 14C.8 Groundwater Chemistry Distribution Calcium

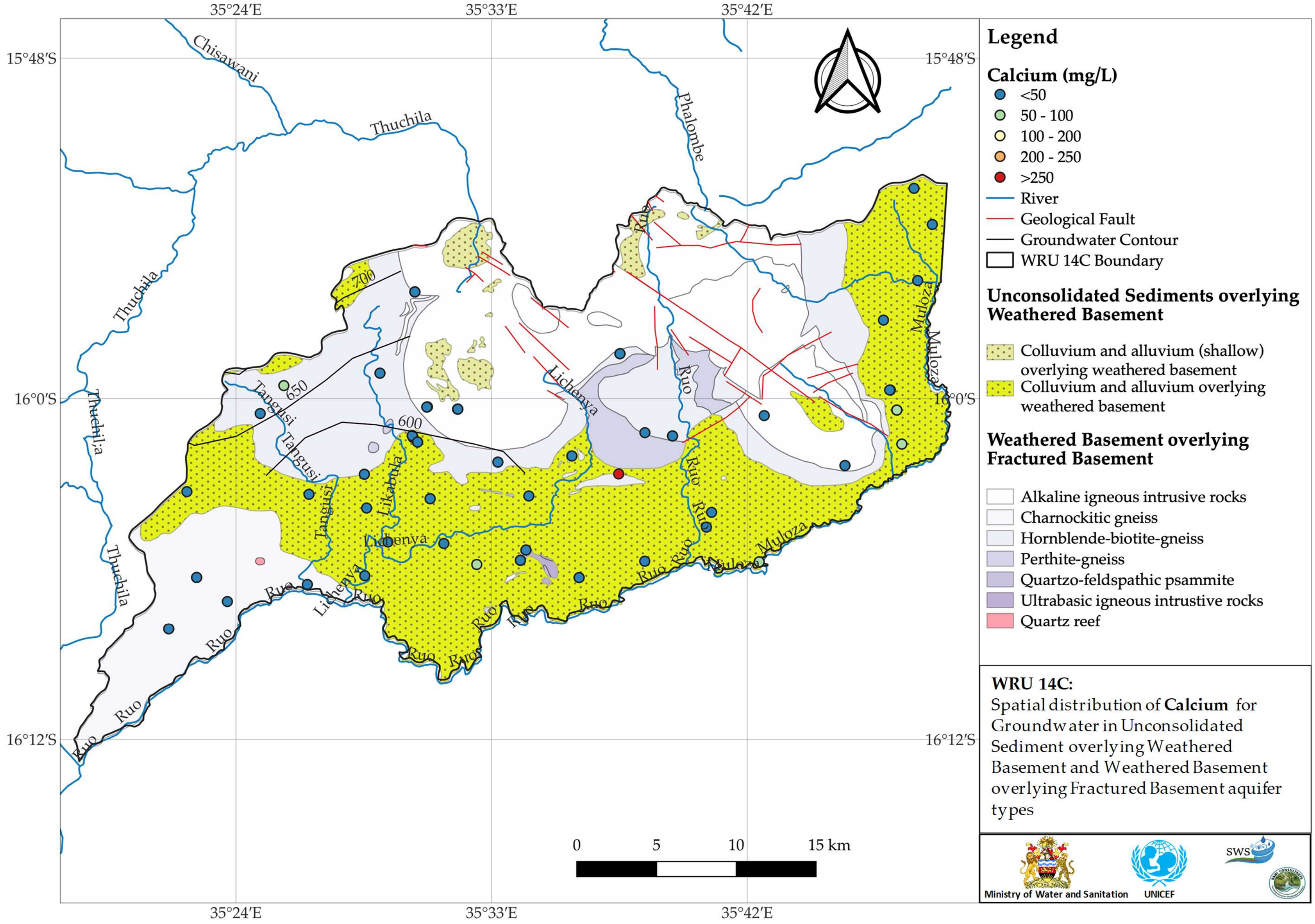


Figure WRU 14C.9 Piper Diagram of water quality results with respect to the major aquifer type

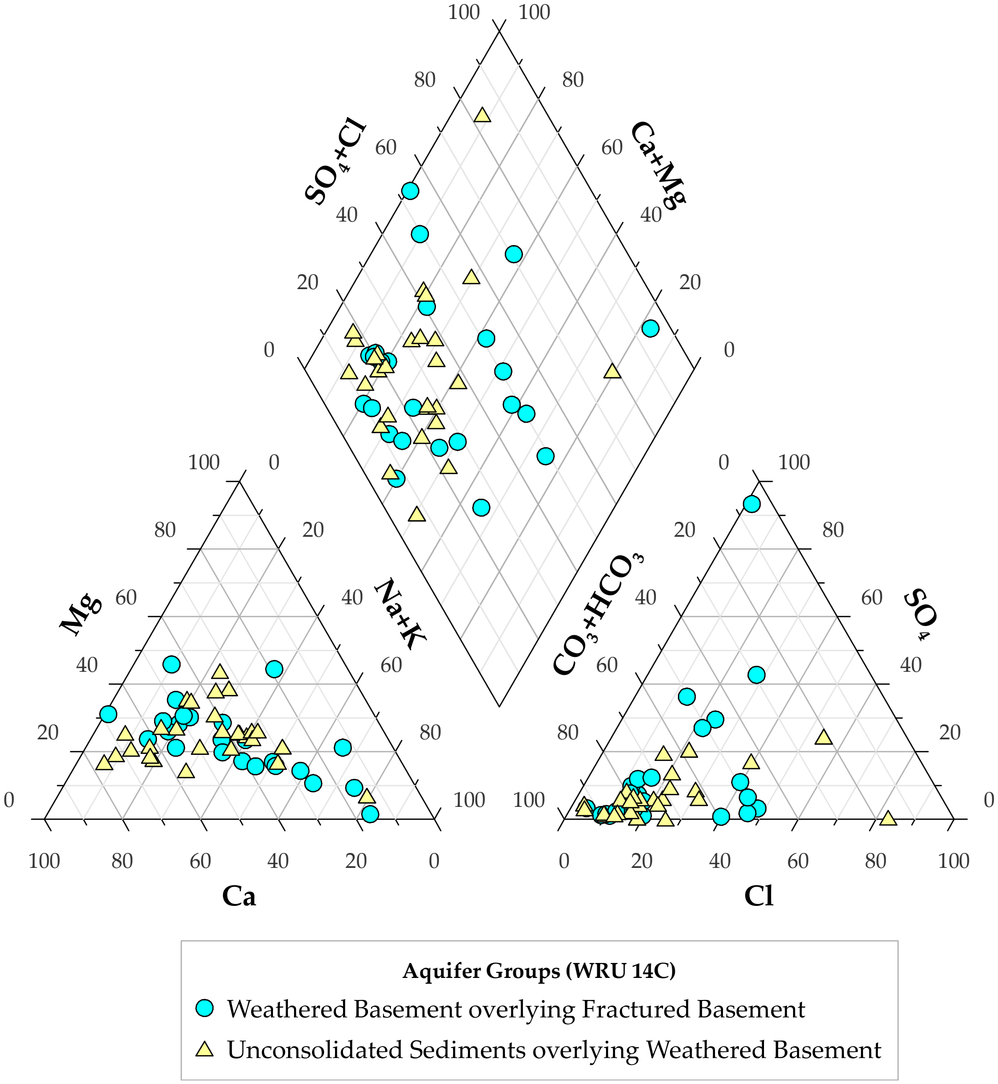
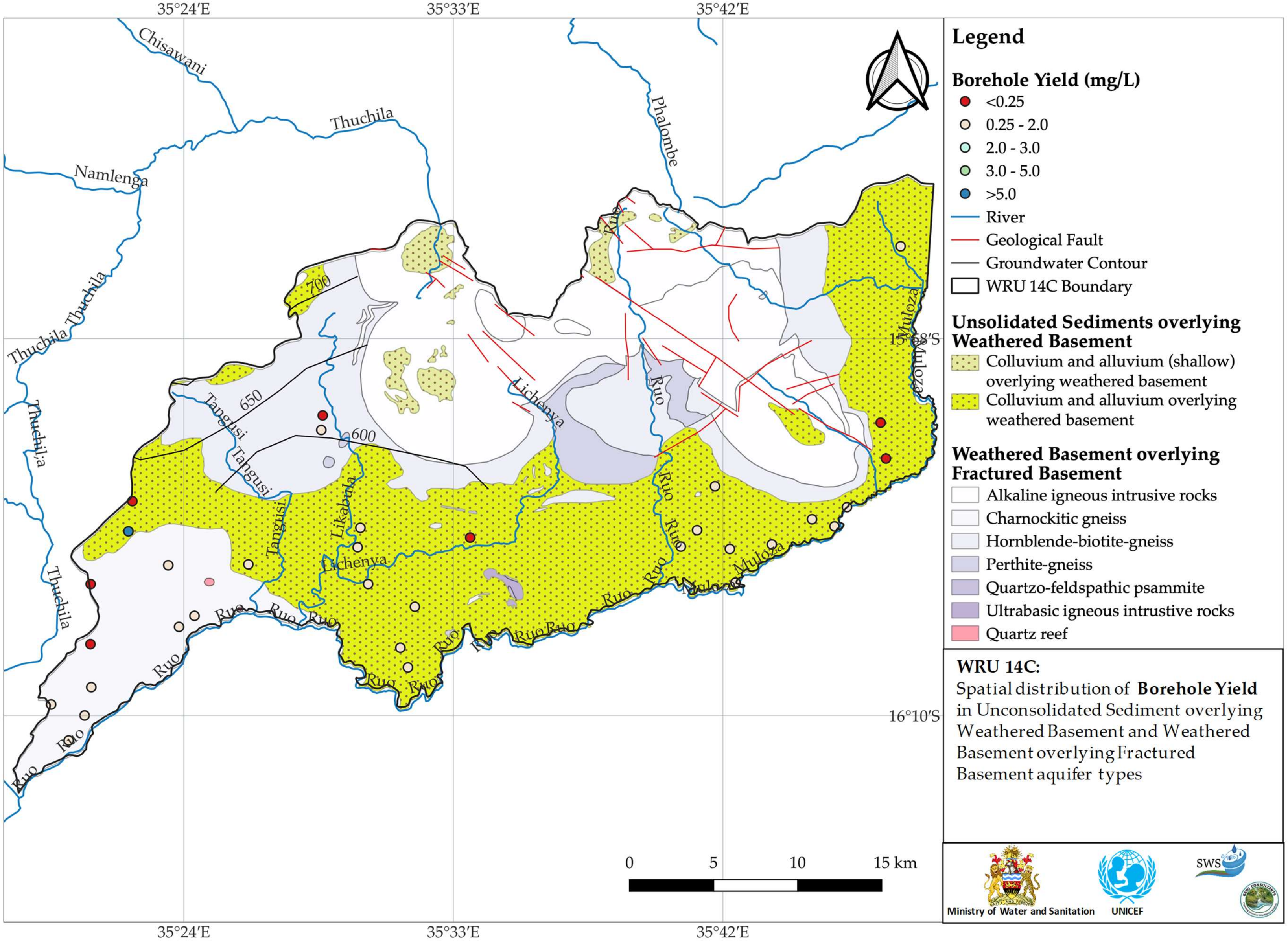


Figure WRU 14C.10 Borehole Yield Map for data held by the Ministry



WRU 14D Figures

Figure WRU 14D.1 Land Use and Major Roads

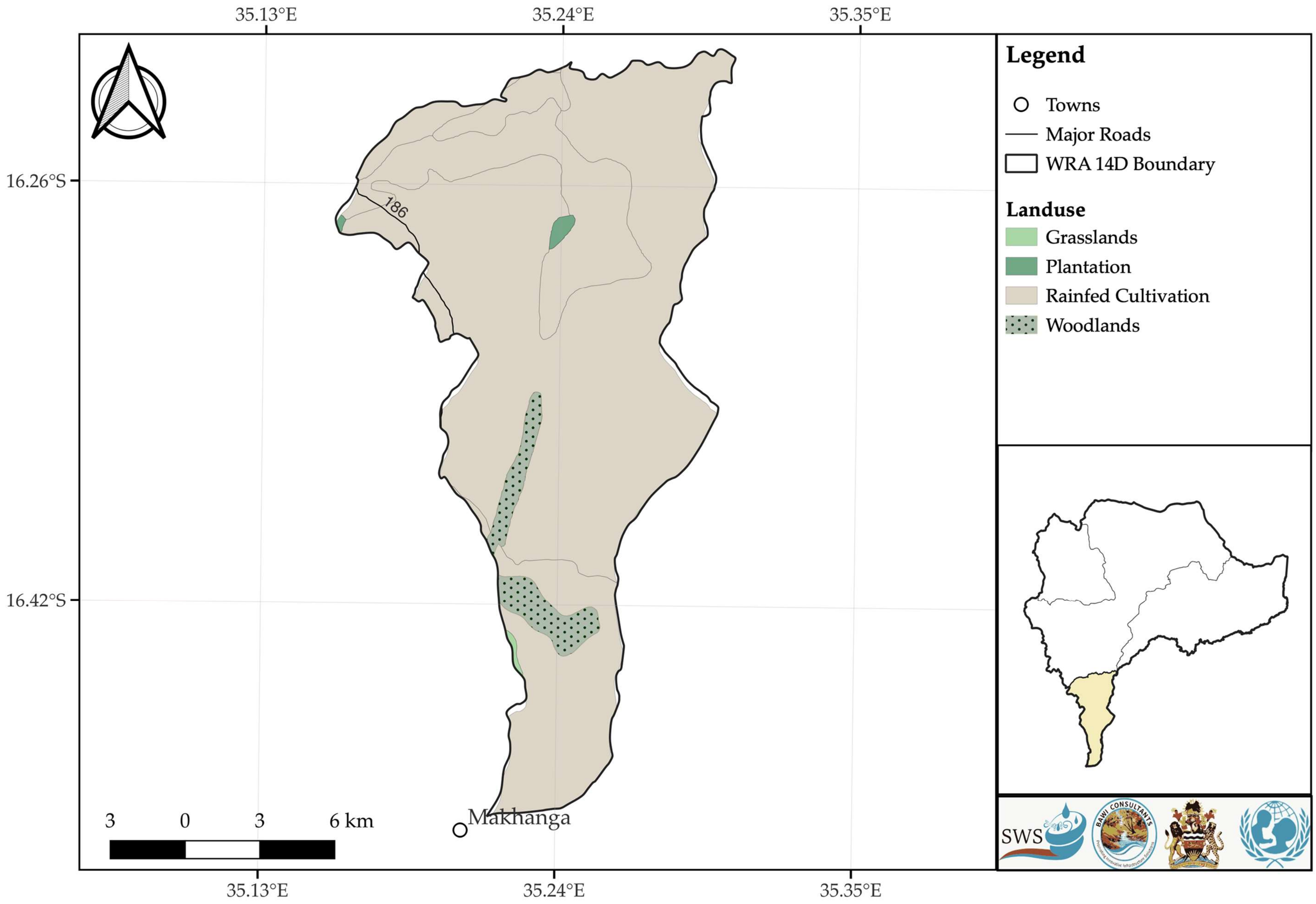


Figure WRU 14D.2 Rivers and Wetlands

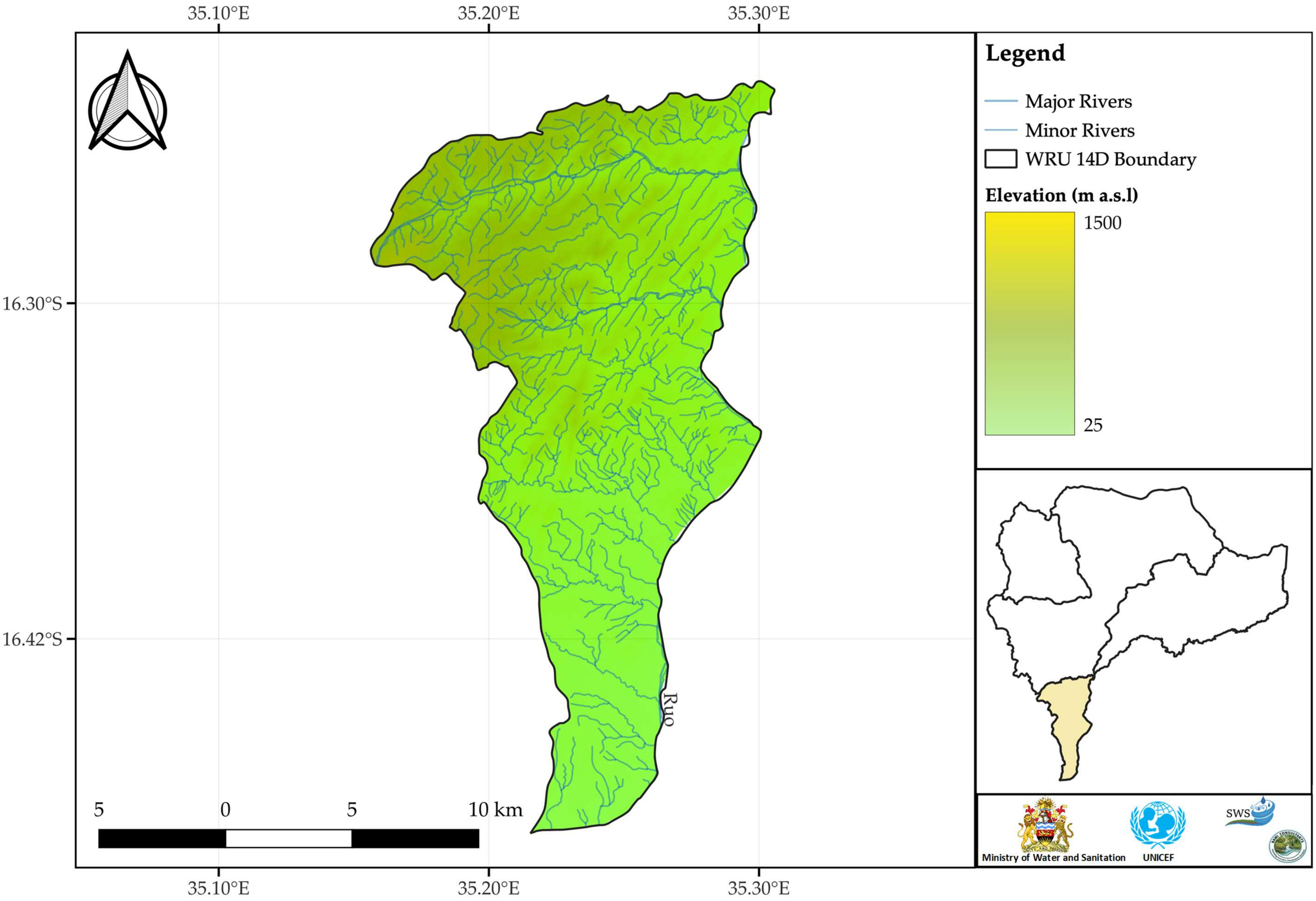


Figure WRU 14D.3 Hydrogeology Units and Water Table

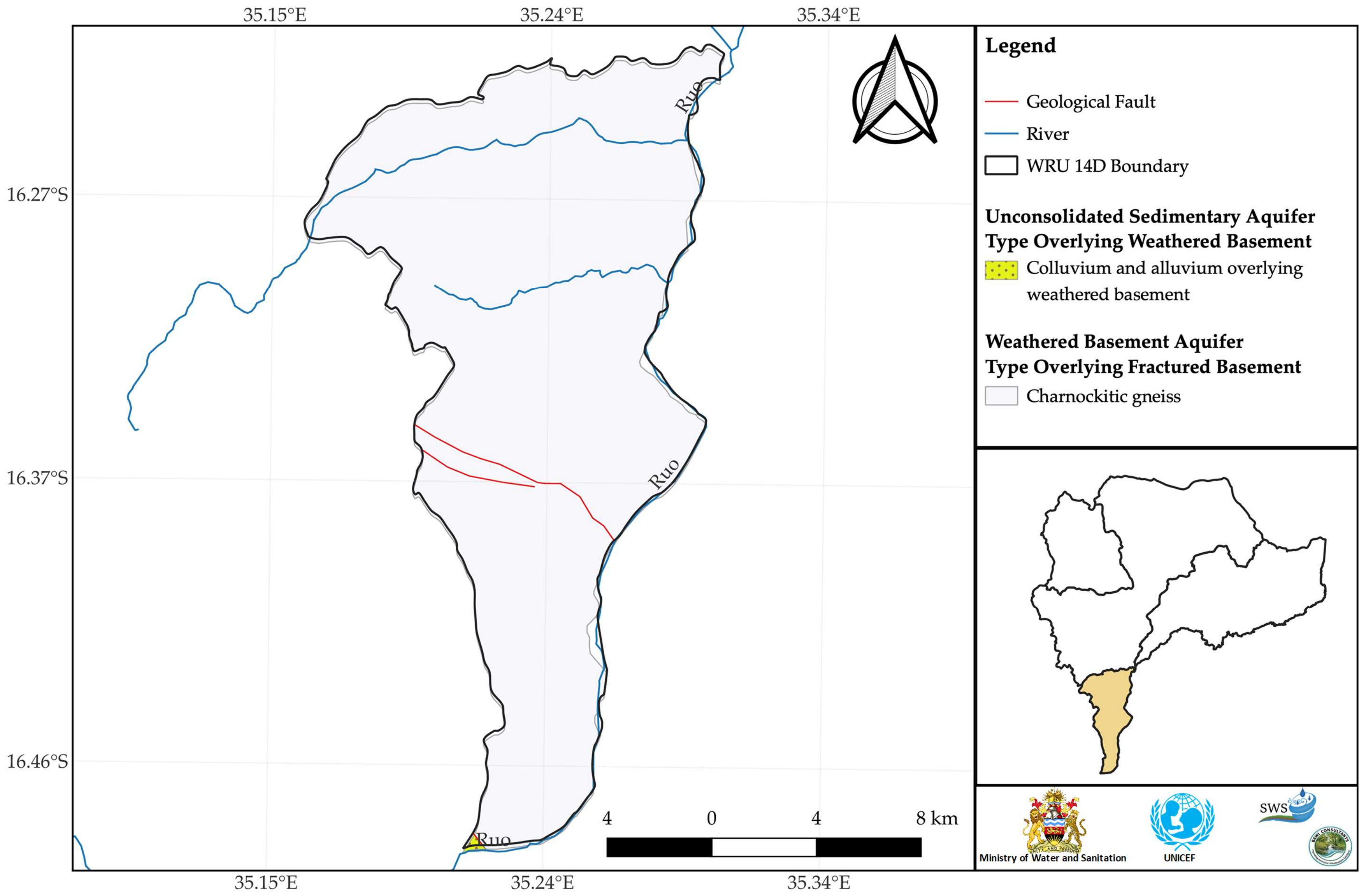


Figure WRU 14D.4 Groundwater Chemistry Distribution Electrical Conductivity

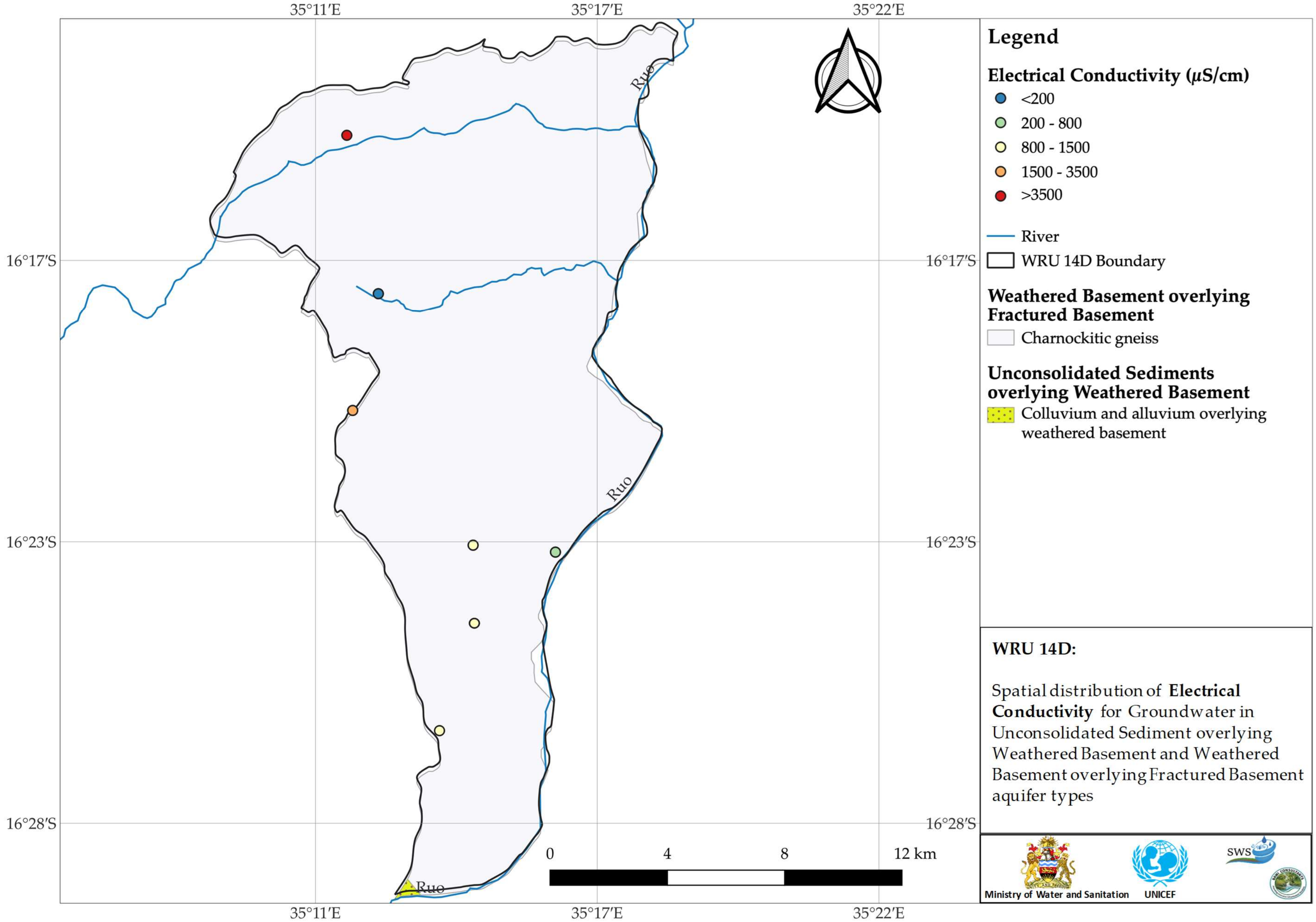


Figure WRU 14D.5 Groundwater Chemistry Distribution of Sulphate

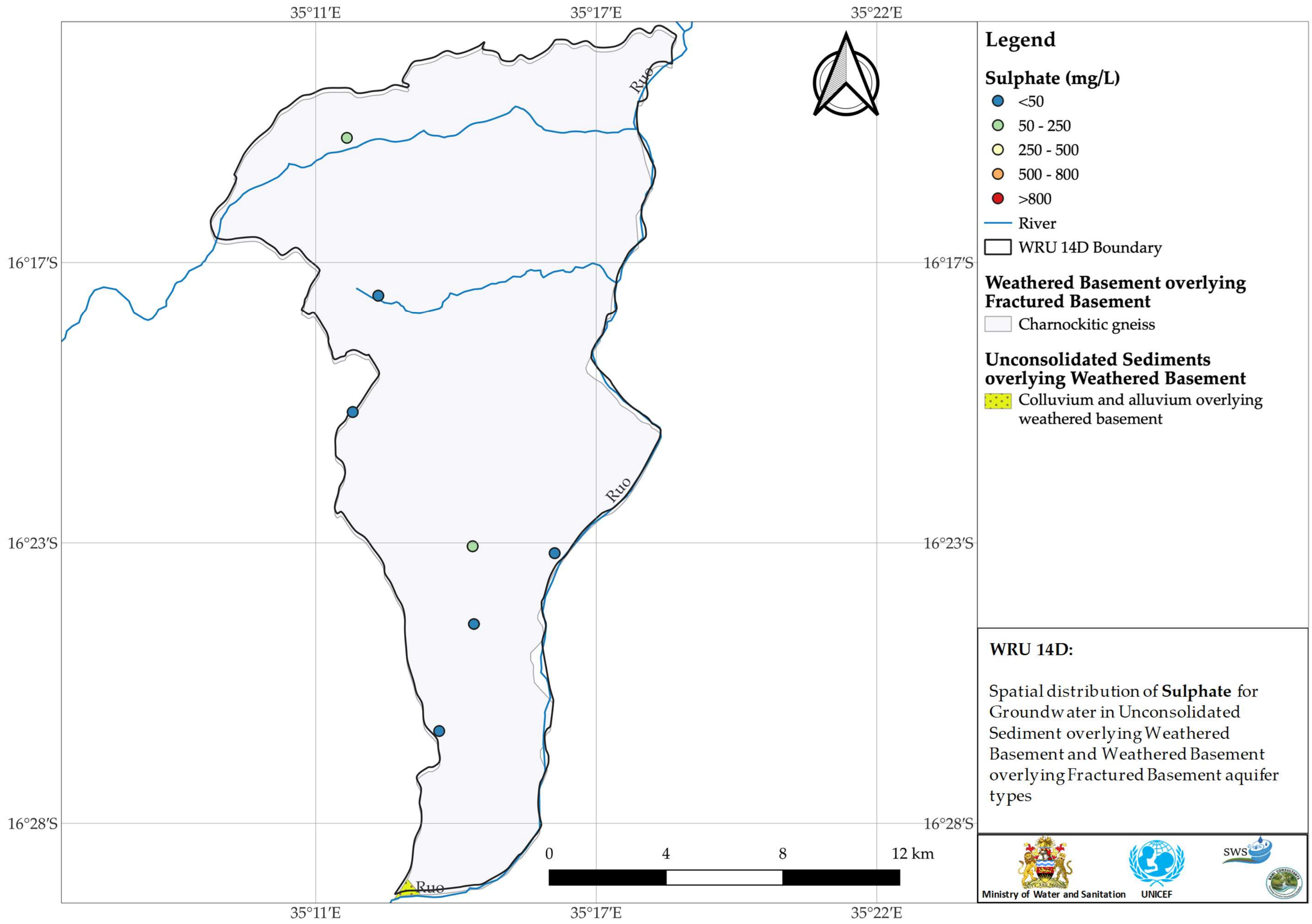


Figure WRU 14D.6 Groundwater Chemistry Distribution Chloride

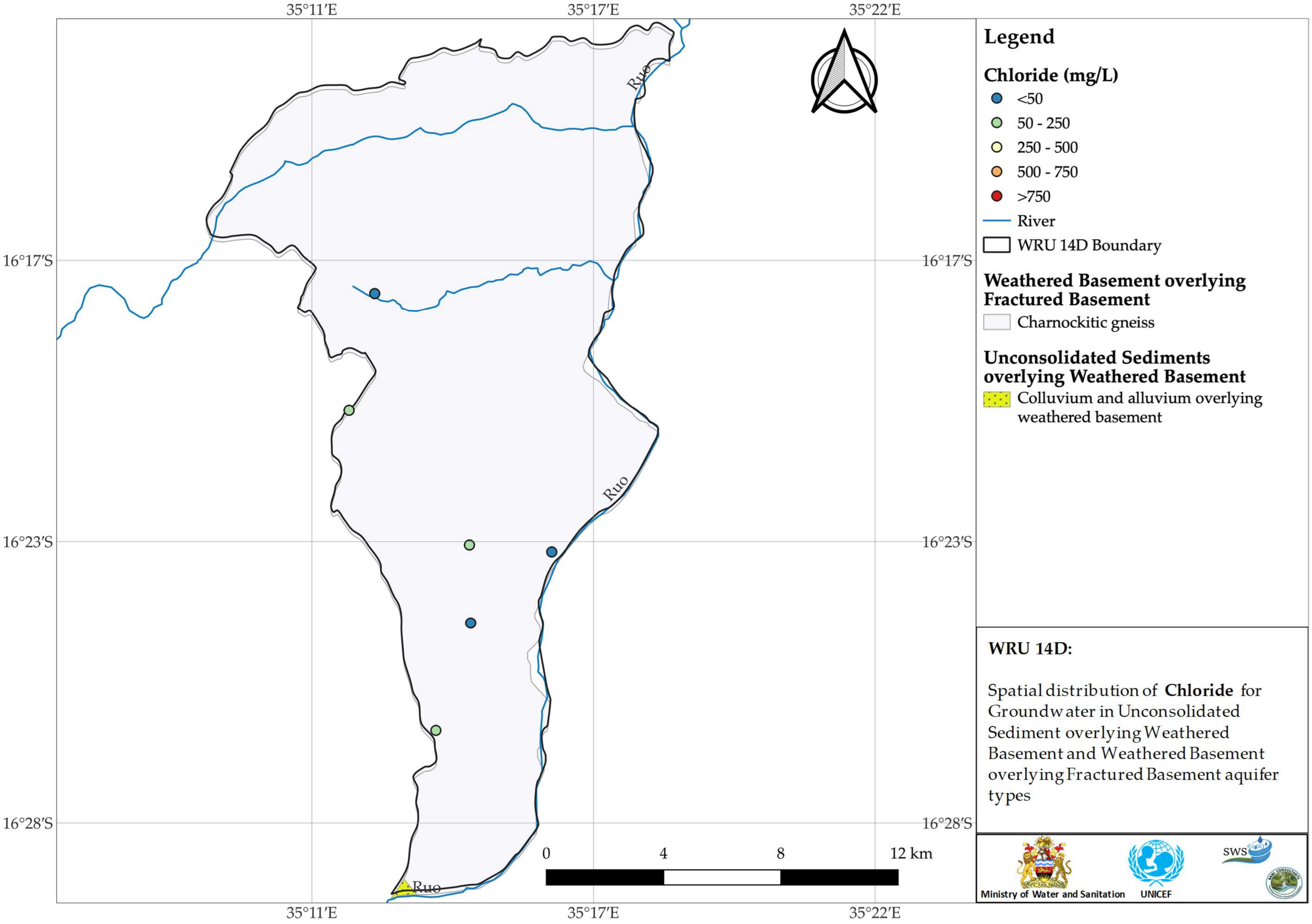
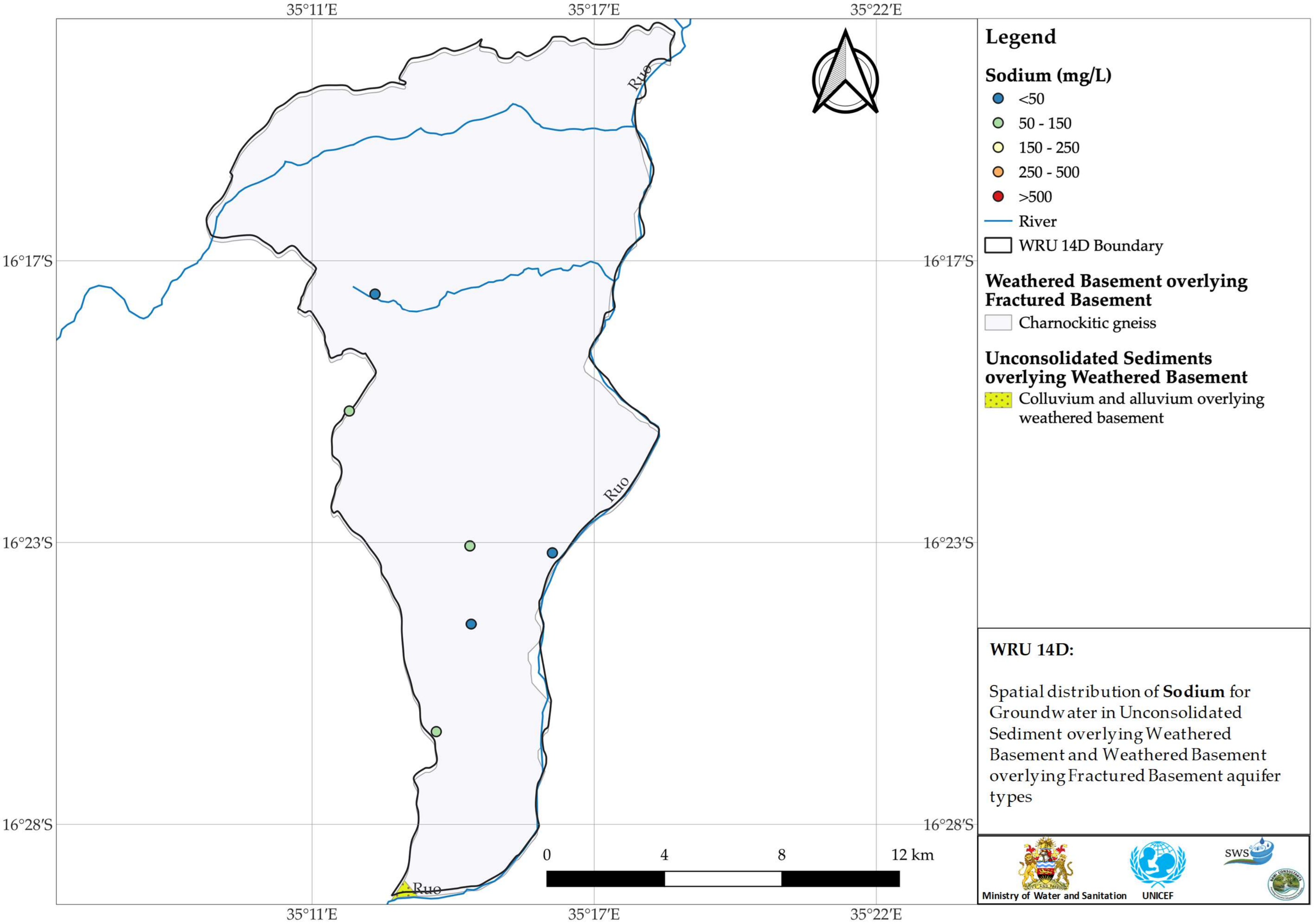
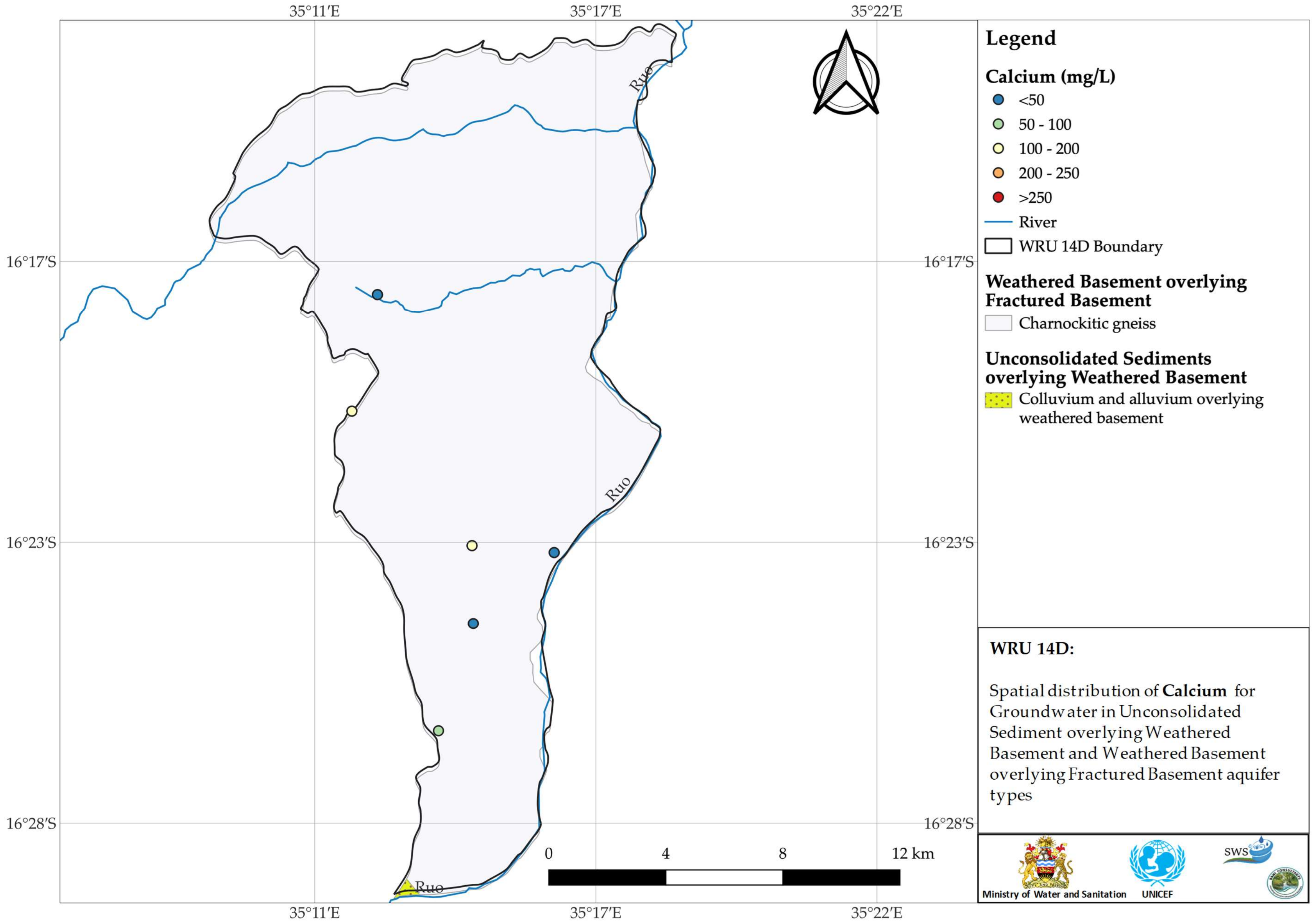


Figure WRU 14D.7 Groundwater Chemistry Distribution Sodium



Spatial distribution of **Sodium** for Groundwater in Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 14D.8 Groundwater Chemistry Distribution Calcium



WRU 14D:

Spatial distribution of **Calcium** for Groundwater in Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 14D.9 Piper Diagram of water quality results with respect to the major aquifer type

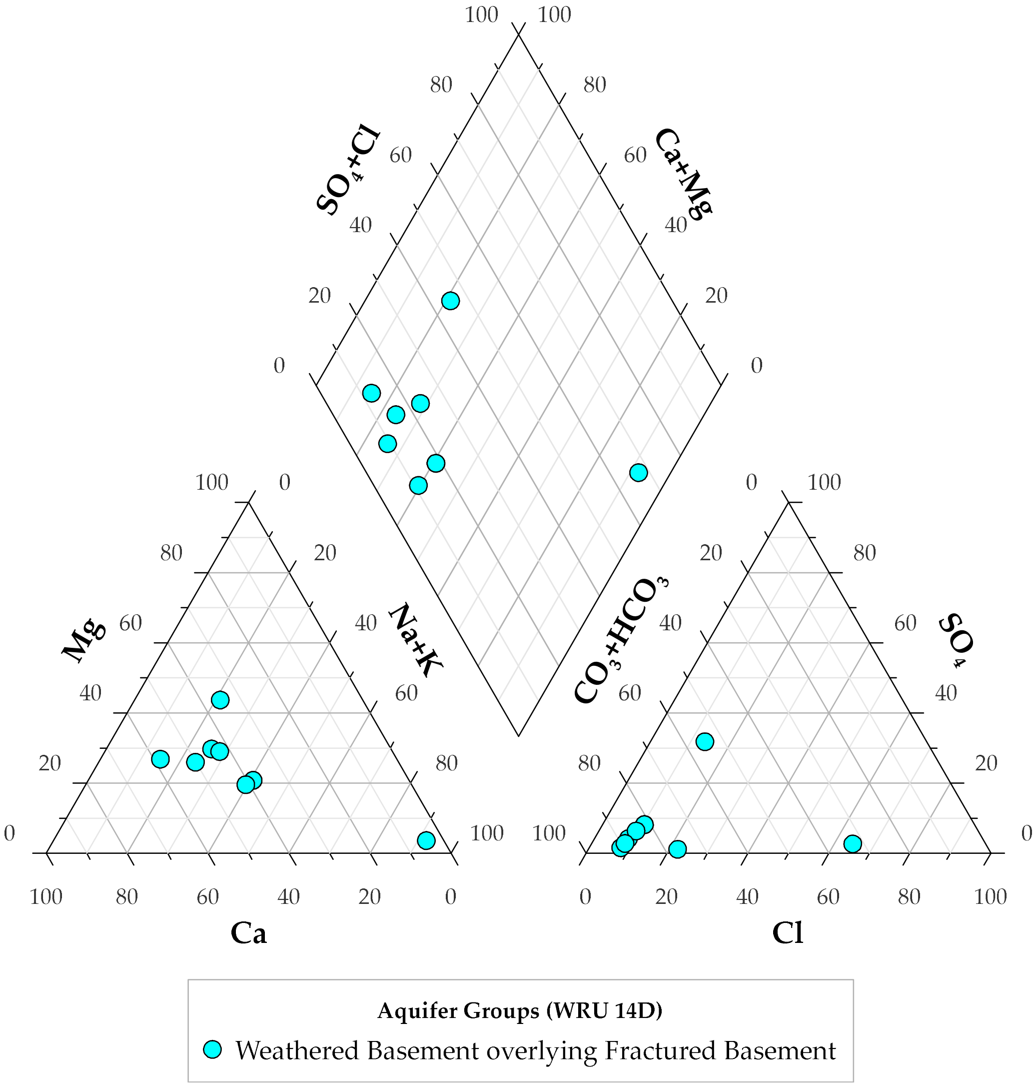
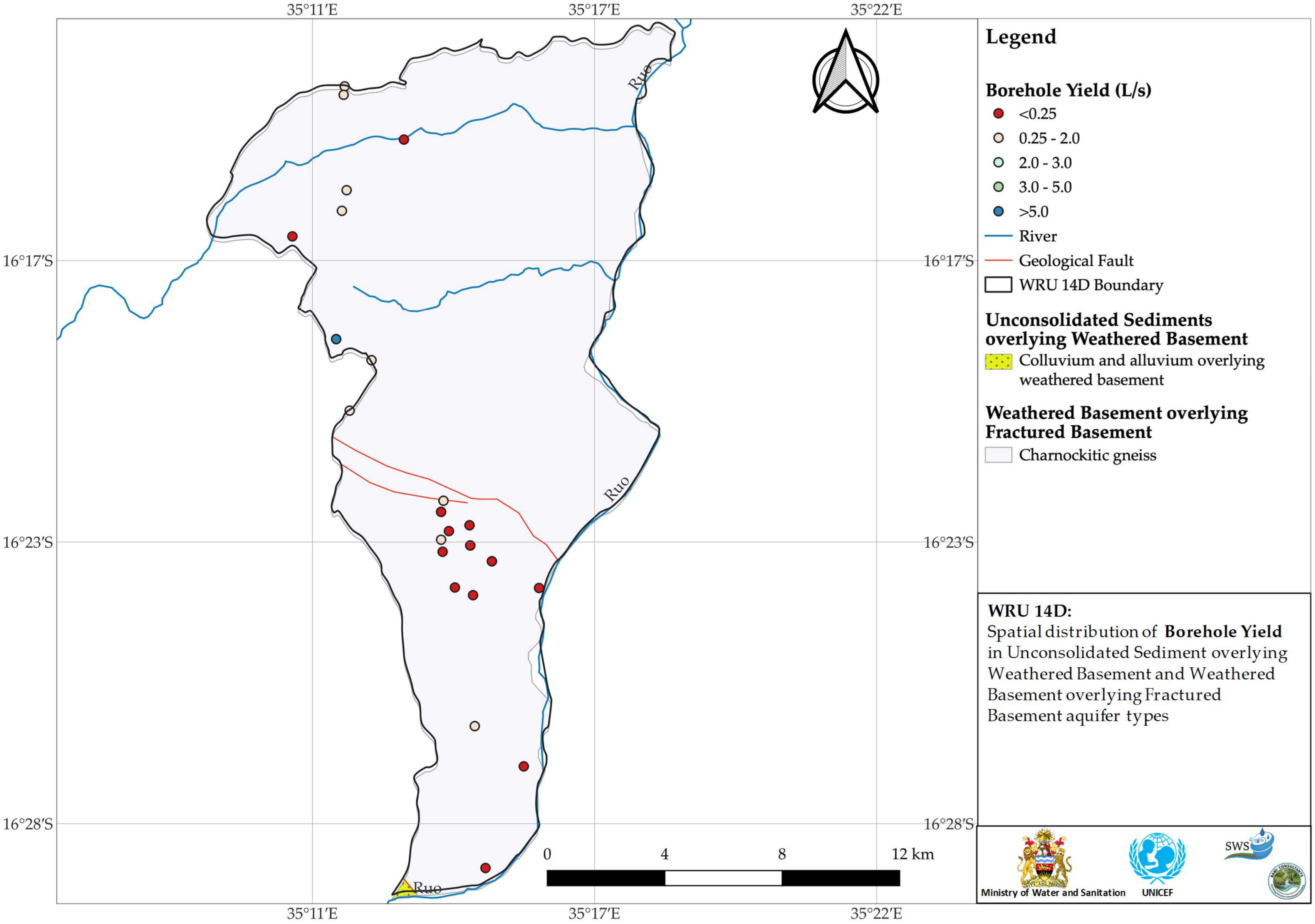


Figure WRU 14D.10 Borehole Yield Map for data held by the Ministry



Ministry of Water and Sanitation

Hydrogeology and Groundwater Quality Atlas of Malawi

Reference: Kalin, R.M., Mleta, P., Addison, M.J., Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A., Hinton, R. (2022) *Hydrogeology and Groundwater Quality Atlas of Malawi, Ruo River Catchment, Water Resource Area 14, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-13-0 82pp*