Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 5

The Bua 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 5 is interpreted within the same context as presented in the Hydrogeology and Water Quality Atlas Bulletin publication. A general description of the Hydrogeology of Malawi and its various units is provided here to remind the reader of the complexity of groundwater in Malawi and its nomenclature. The various basement geologic units have variable mineralogy, chemistry, and structural history that may be locally important for water quality parameters such as Fluoride, Arsenic and geochemical evolution. Therefore, translation of geologic units to potential hydrostratigraphic units was based on the 1:250,000-scale Geological Map of Malawi compiled by the Geological Survey Department of Malawi (Canon, 1978). Geological units were grouped into three main aquifer groups for simplicity.

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

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

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

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

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

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

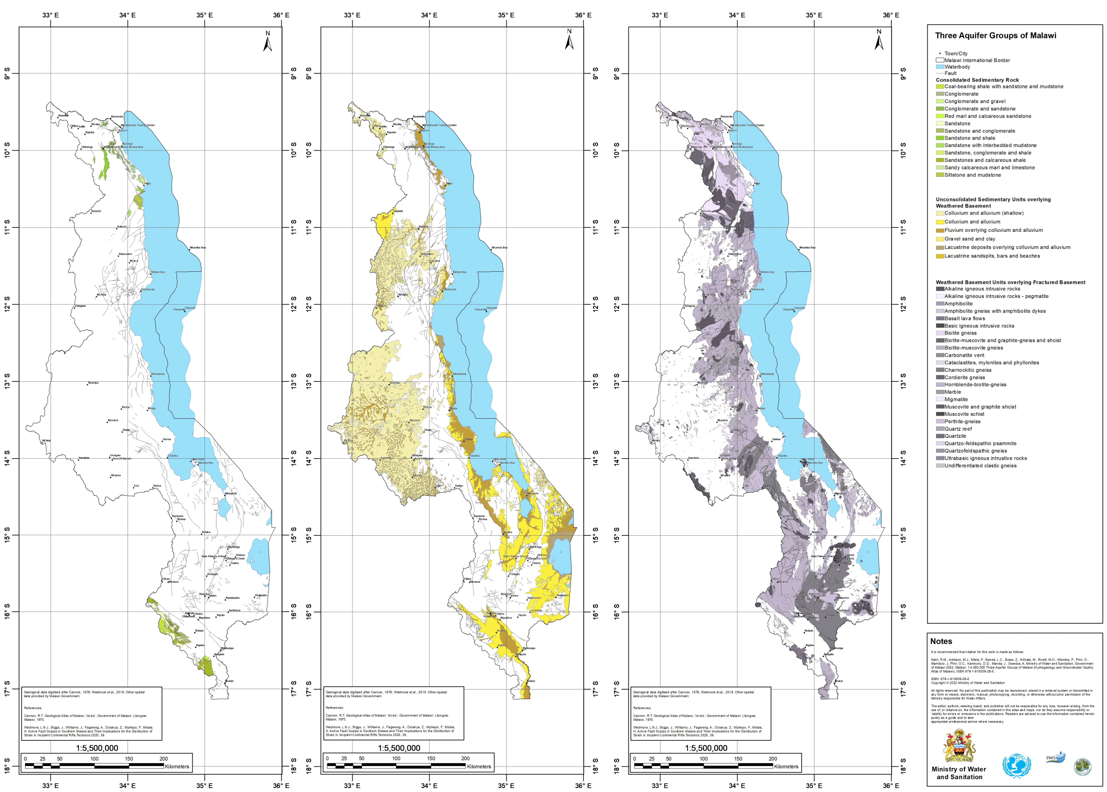

Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure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

Nomenclature: Hydrogeology of Malawi

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

Weathered Basement overlying Fractured Basement

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

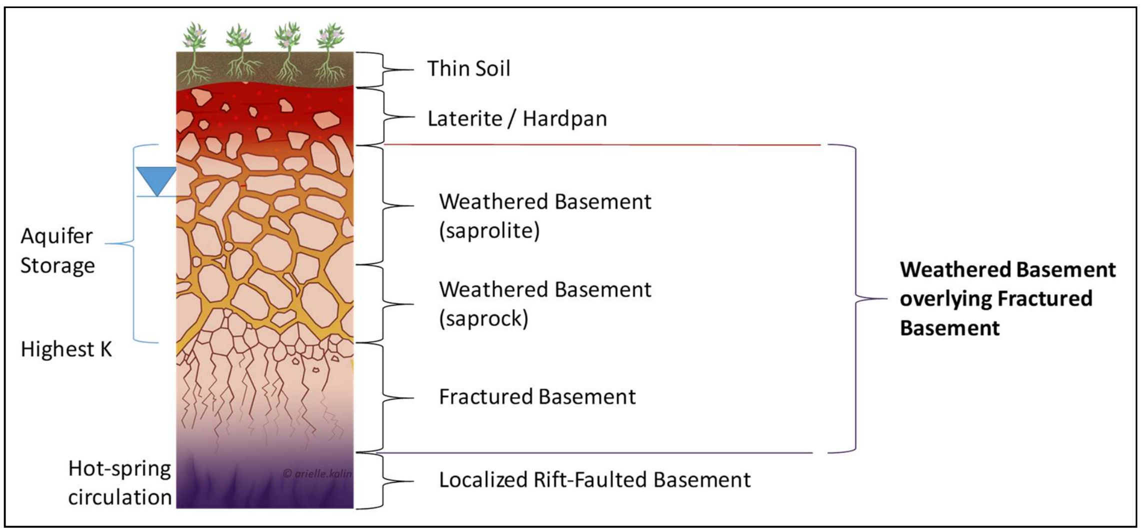

Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

Unconsolidated Colluvial and Alluvial Sedimentary Units overlying Weathered Basement

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

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

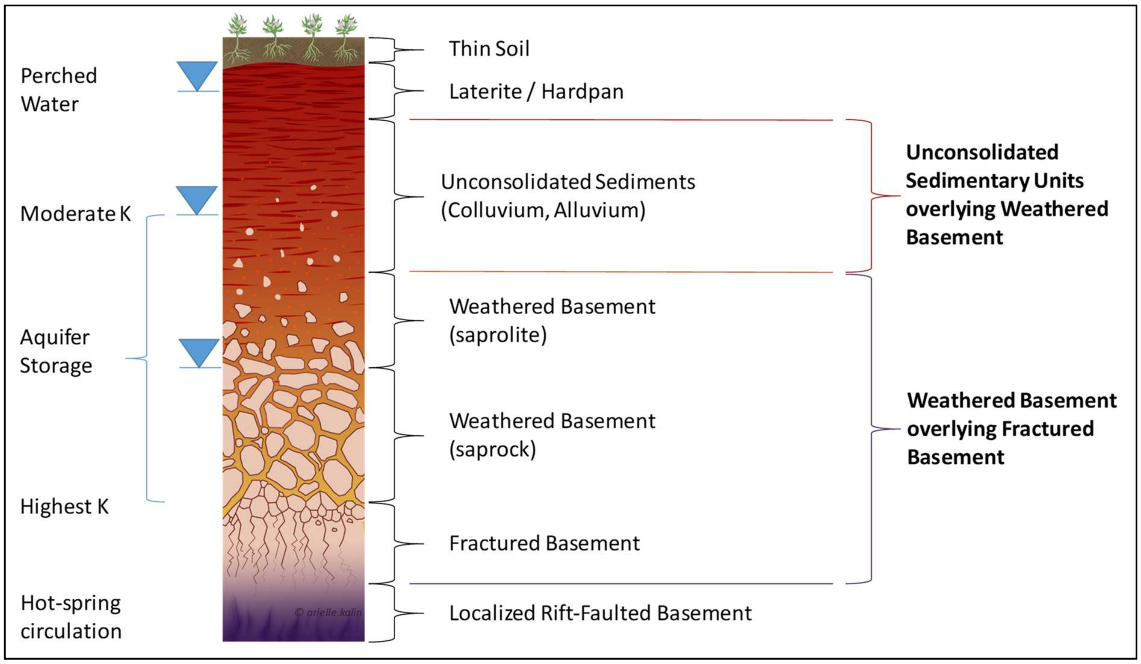

Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Unconsolidated Fluvial Sedimentary Units overlying Weathered Basement

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

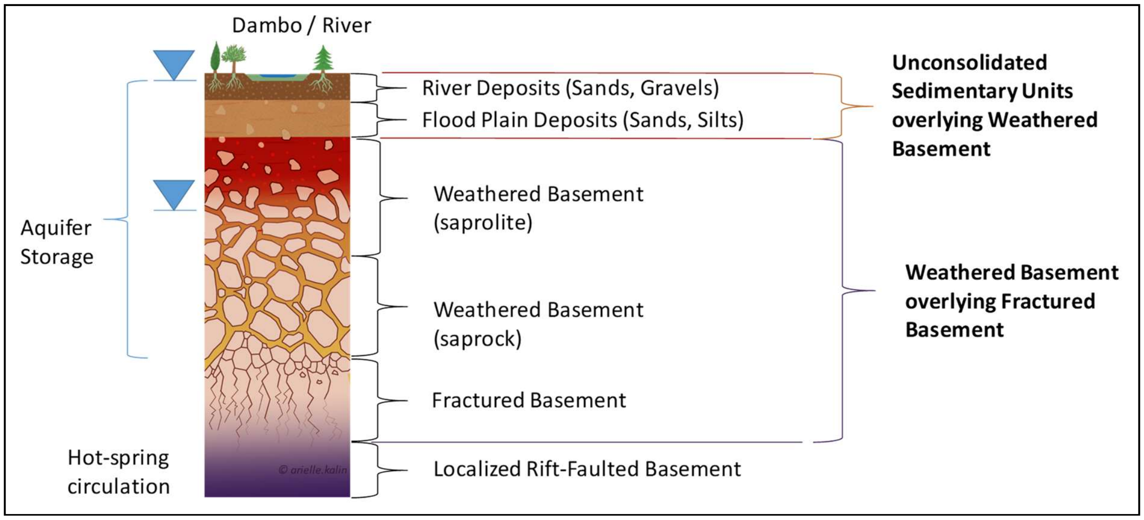

Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Idealised Cross Sectional Representation of Hydrostratigraphic Units (Aquifers)

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

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

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

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

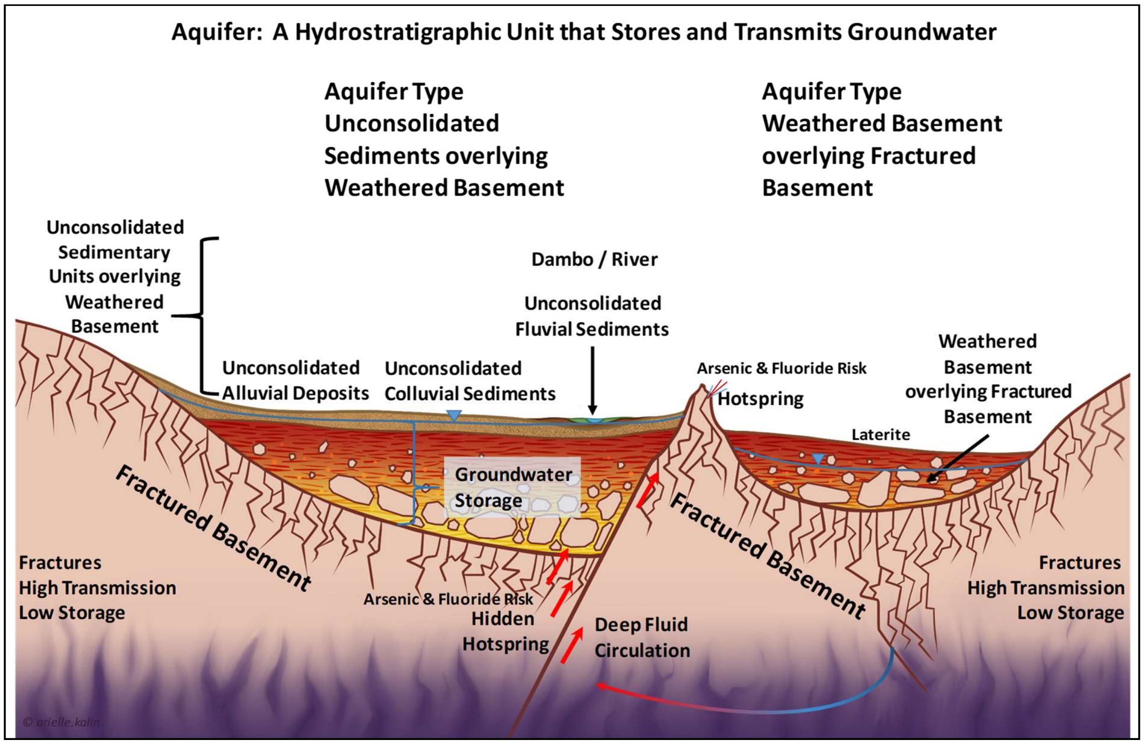

Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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

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

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

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

Water Resource Area 5 (WRA 5): The Bua River Catchment

Water Resources Area (WRA) 5 in central part of Malawi **(Figure 2a**), is mainly drained by Bua River, hence called the Bua River Catchment. The Bua River coupled with its major riverine inflows comprising of Namitete River, Rusa River and Kasangadzi River drain vast area of 10,658 Km^2 (**Figure 2b**). Much of the area lies between 1000 masl – 1300 masl covering over 90%, representing a plateau dominant topographical setting. The WRA marks an international borderline Southwest ward where the highest topographic extremity of about 1,755 m asl defines the Mchinji highlands. Elevation ranges between 472 and 1,755 m asl, with a mean of 1,111 m asl, justifies the characterisation of the plateau dominant feature. The Bua River flows eastwards through the steep slopes that defines the Rift Valley escarpment as it flows eastwards across the, after which it assumes a steady flow towards the Lake Malawi shoreline while offloading load of alluvium deposits. The WRA has distinct environmental features including the Kasungu National Park and the Mchinji Forest (covering the eastern part), the Nkhotakota Game Reserve westwards and the Ngala Forest occupying the mid-reach of the WRA. The basin is Trans-Boundary for both groundwater and surface water and therefore implementation of Integrated Water Resources Management (IWRM) requires engagement with regional transboundary water management units.

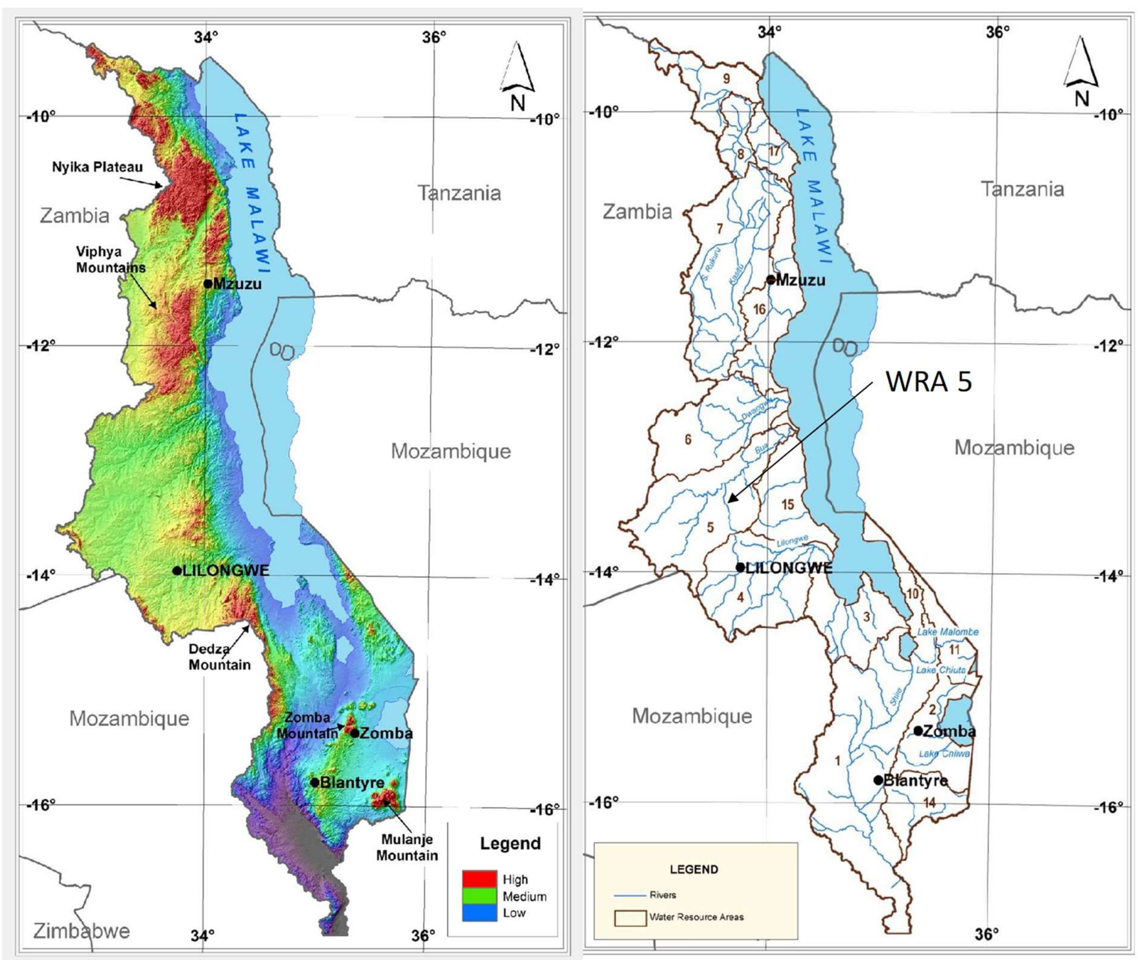

Figure 2a. Location of WRA 5 with major rivers and topography shown.

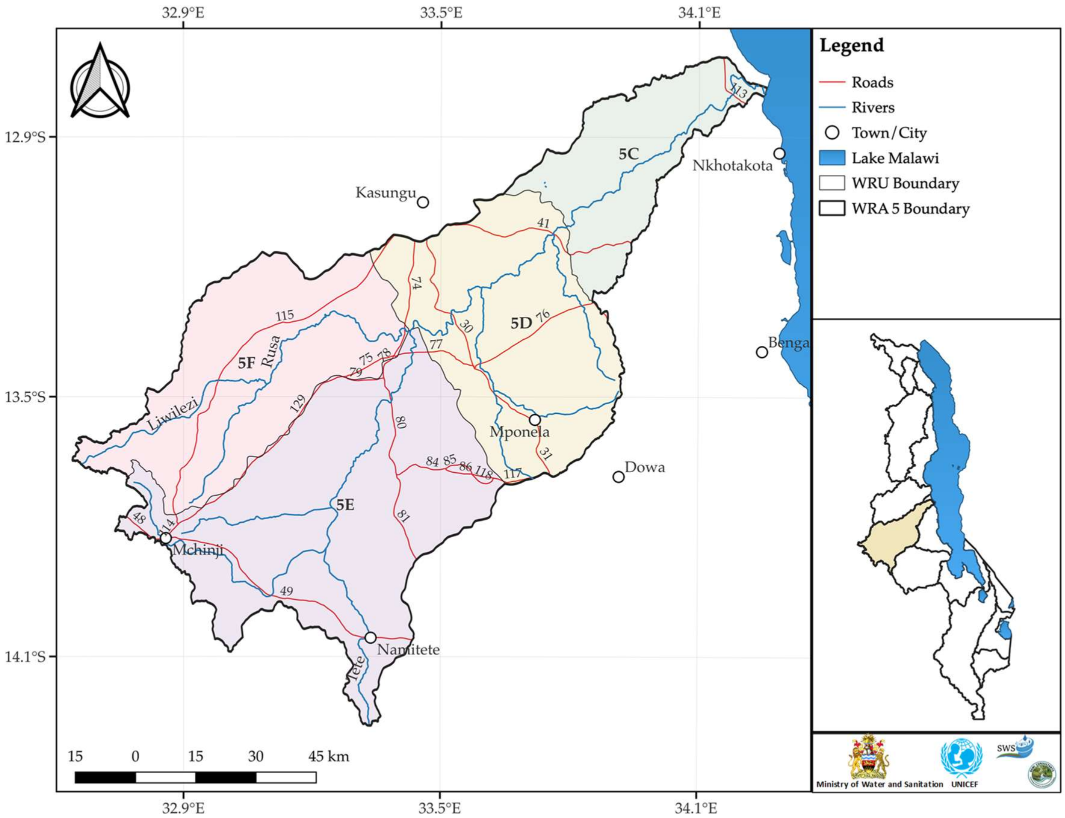

Figure 2b. Water Resource Area and Water Resource Units

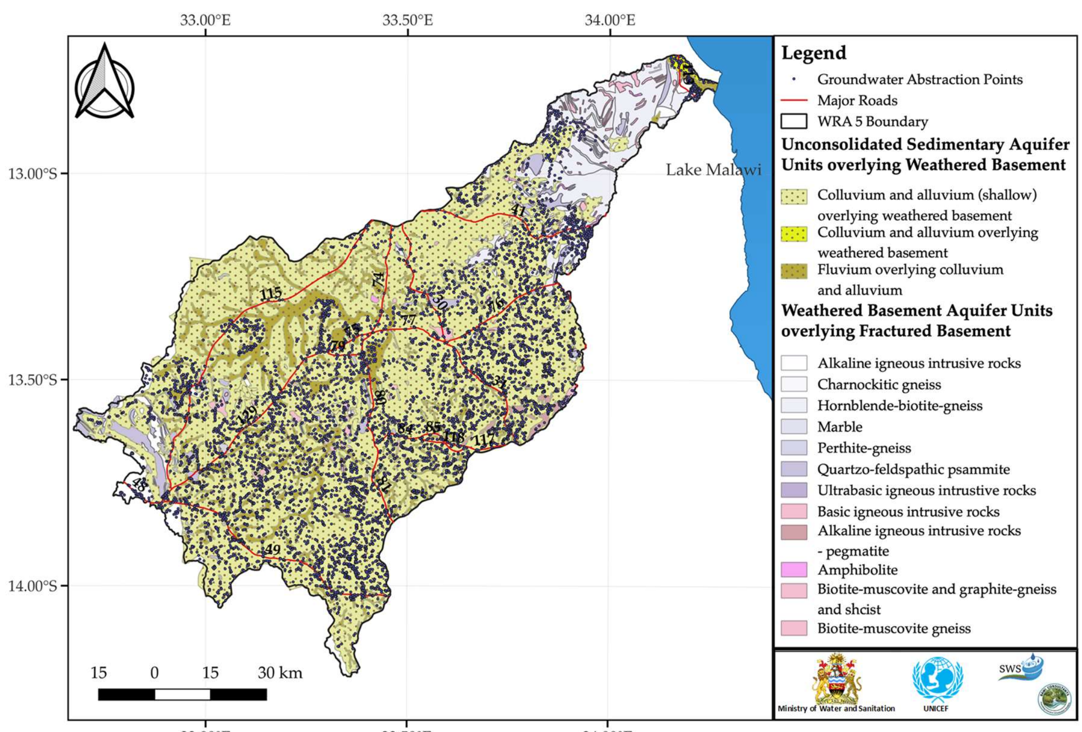

Figure 3. Distribution of groundwater abstraction points in WRA 5.

Groundwater Abstraction in WRA 5

Public abstraction points for groundwater are numerous in WRA 5 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 9,548 known groundwater abstraction points, only 80.9% are improved sources (with a high number of protected and 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 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 5, 71.3% are fully functional (defined as providing water at design specification).

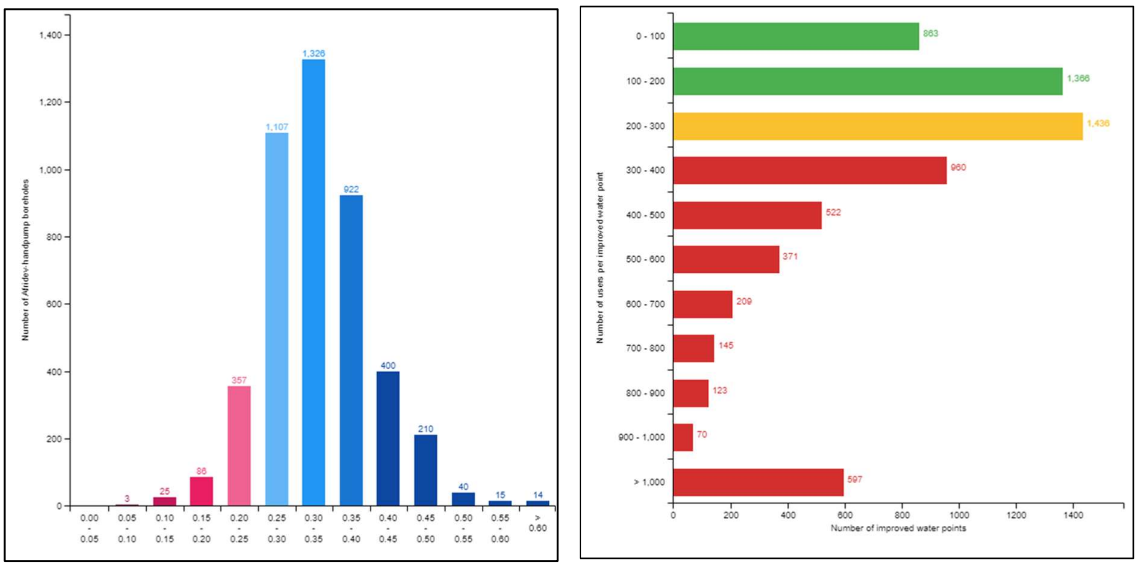

Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 5 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point. [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 exceeded and where there is an investment need in WRA 5 it should focus on a population point of view. While some of the groundwater supply points provide water to 250 or more users per water point, with the preponderance of dug wells which have a considerable contamination risk and may not meet the water quality guidelines, the WRA should be considered within investment planning to move from dug wells to a more stable groundwater supply.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 13.0% (1,240) 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.

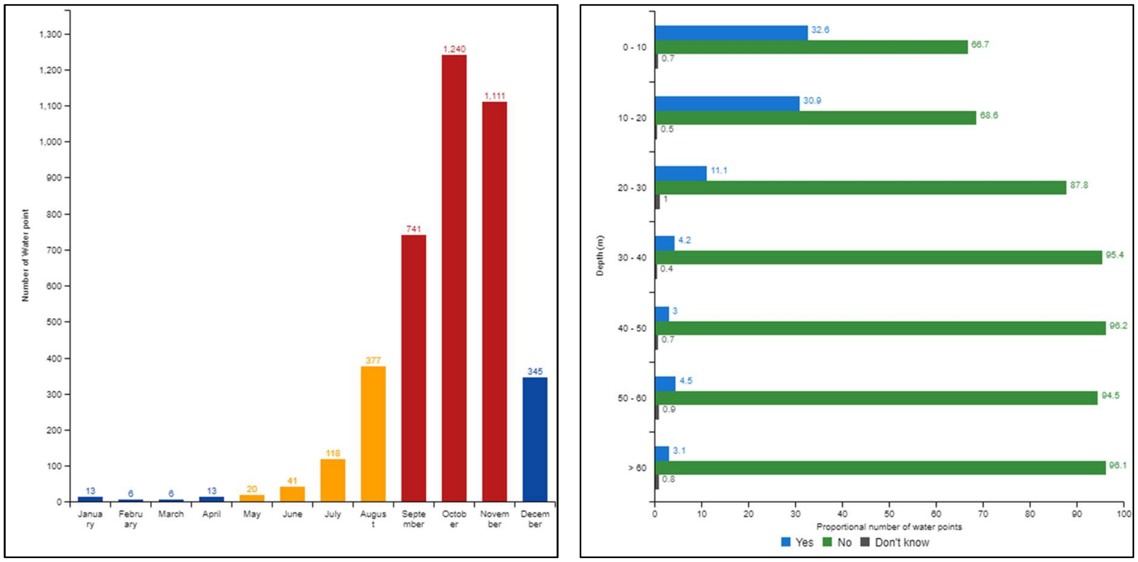

Figure 5a and 5b. Number of groundwater abstraction points in WRA 5 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated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

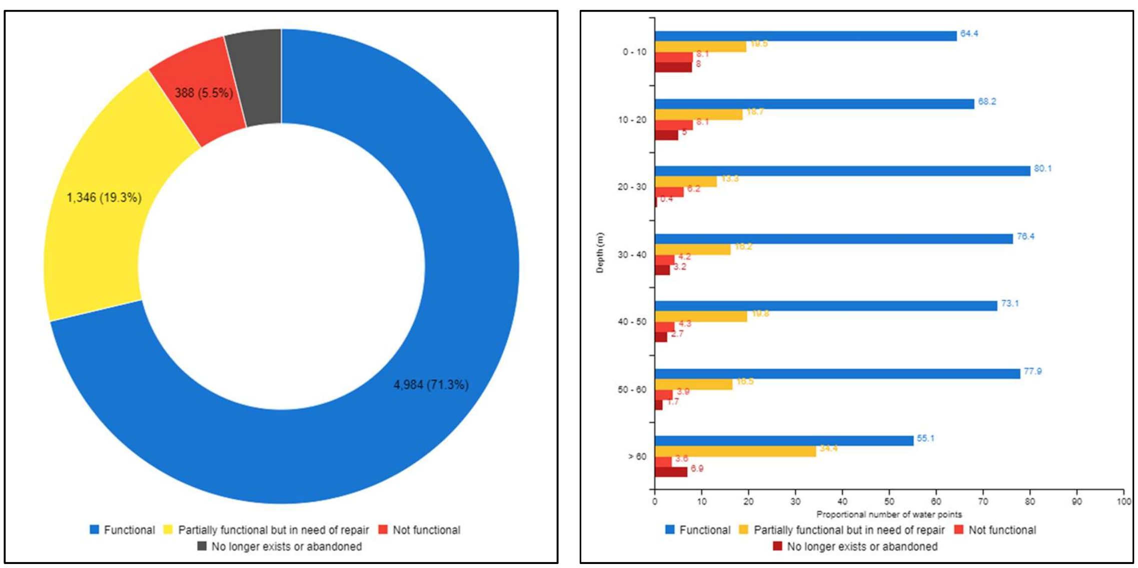

Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 5 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water 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 5 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 5 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	5,656
Protected dug well	2,064
Protected spring	10
Unprotected dug well	1,806
Unprotected spring	12

Description of Water Resources WRA 5

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. There are four sub-basins WRU 5C, 5D, 5E, and 5F (**Figures 7a – 7d**).

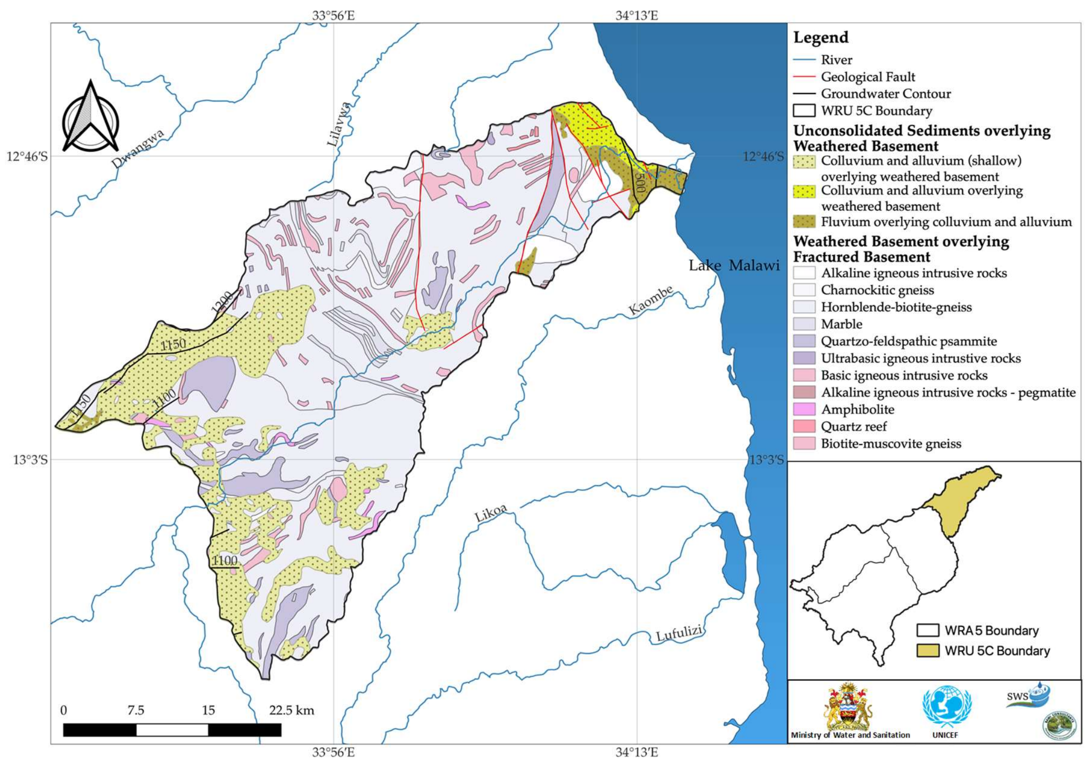

Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 5C wtihin Water Resource Area 5 (Bua River Catchment).

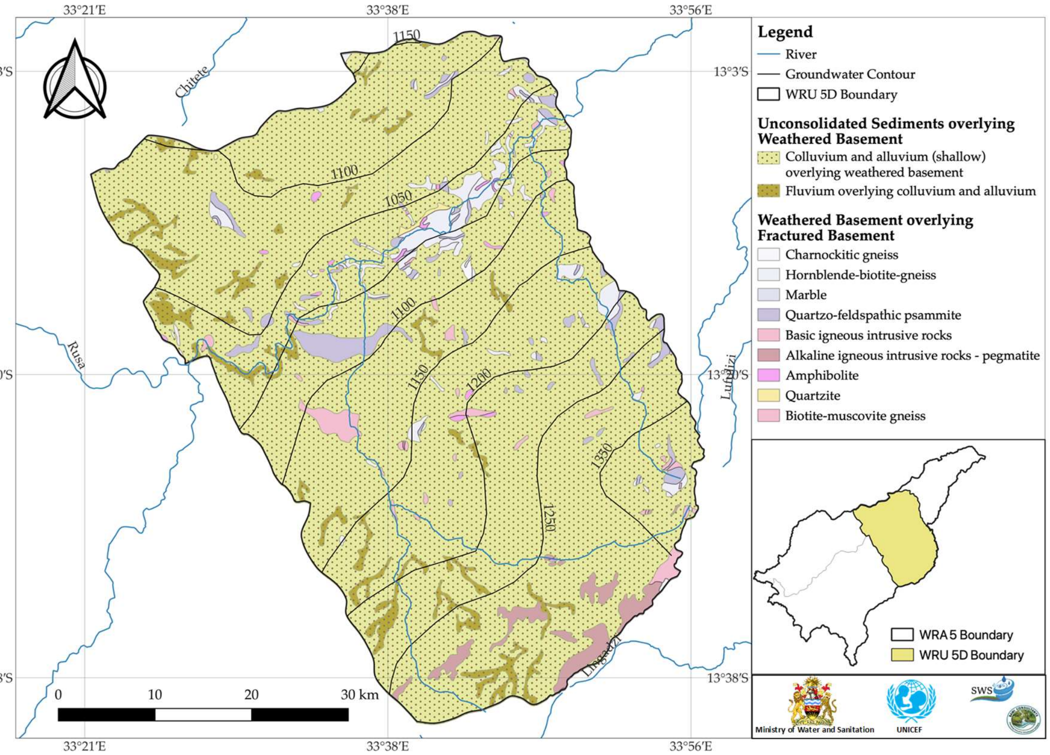

Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 5D wtihin Water Resource Area 5 (Bua River Catchment).

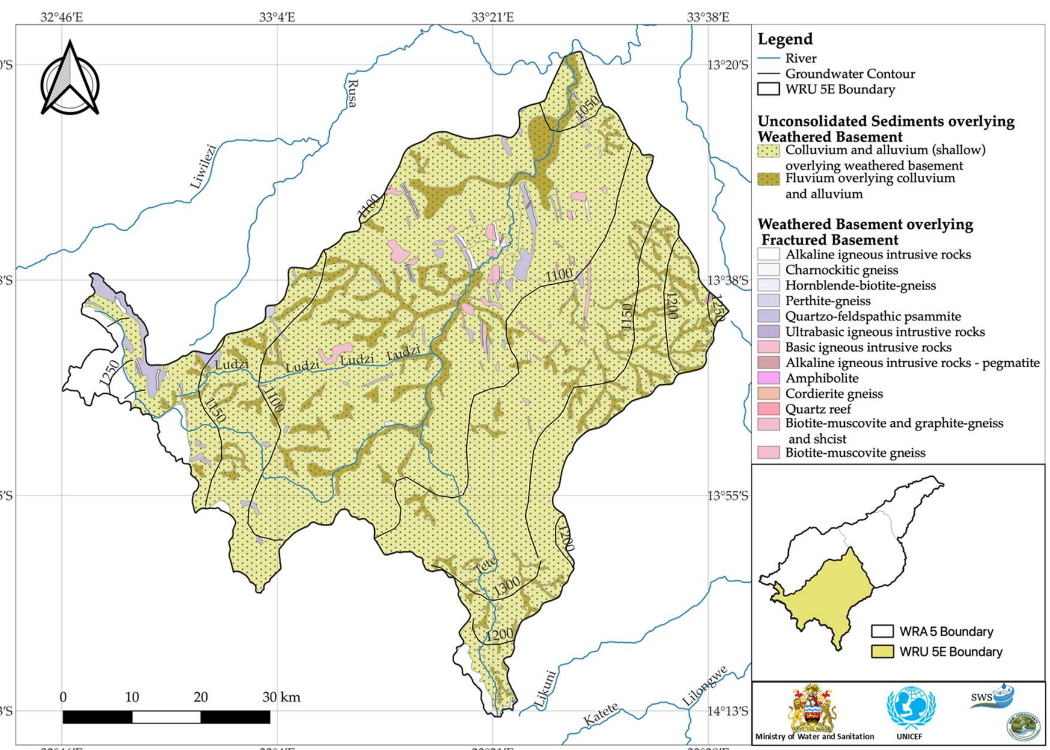

Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 5E wtihin Water Resource Area 5 (Bua River Catchment).

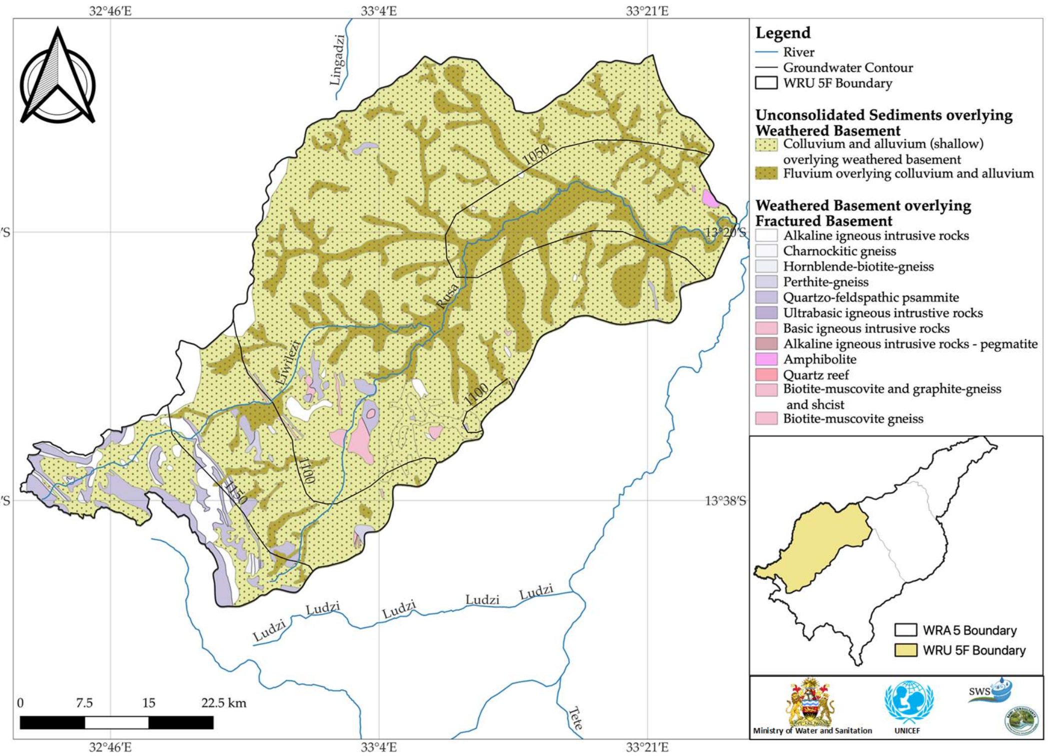

Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 5F wtihin Water Resource Area 5 (Bua River Catchment).

Topography and Drainage

The area is well known for irrigated agricultural activities dominated by rice irrigation schemes mainly along the Lake Malawi Shoreline. There is notable flooding during the peak of the rainy season, contributing to alluvium deposits along the lower reach of the WRA. A recent boom in large scale agricultural activities dominated by tobacco and maize farming has resulted in accelerated rate of deforestation due to clearing of natural vegetation in the quest to create farmlands. The WRA rainfall is largely influenced by the ITCZ, with the wet season spanning between November and April and the dry season spanning between May and October. Water resources are largely used for Irrigation and water supply, with Irrigation as a dominant water use accounting for 97% of the total surface water abstractions. Large scale irrigated agriculture of tobacco and maize under the Bua River Irrigation Initiative accounts for 65% of all surface water abstractions in the area, during the dry season and around the onset of the wet season. The other major user of water resources in the WRA is the CRWB through water supply and sanitation initiatives. It serves rural town centers in the following districts: Lilongwe, Kasungu, Mchinji, Dowa, Ntchisi and Nkhotakota.

Geology – Solid

Solid geology in WRA 5 is limited to isolated outcrops of basement lithologies, some folder exposures in the extreme west at the border with Zambia, and a small section of the rift escarpment in the east where the Bua River drains into the rift valley towards Lake Malawi (**Figure 7a – 7d**). Dominant basement lithologies are Precambrian - Lower Palaeozoic biotite and muscovite gneiss, quartzo-feldspathic granulite and gneiss, and folded syenite of unknown age.

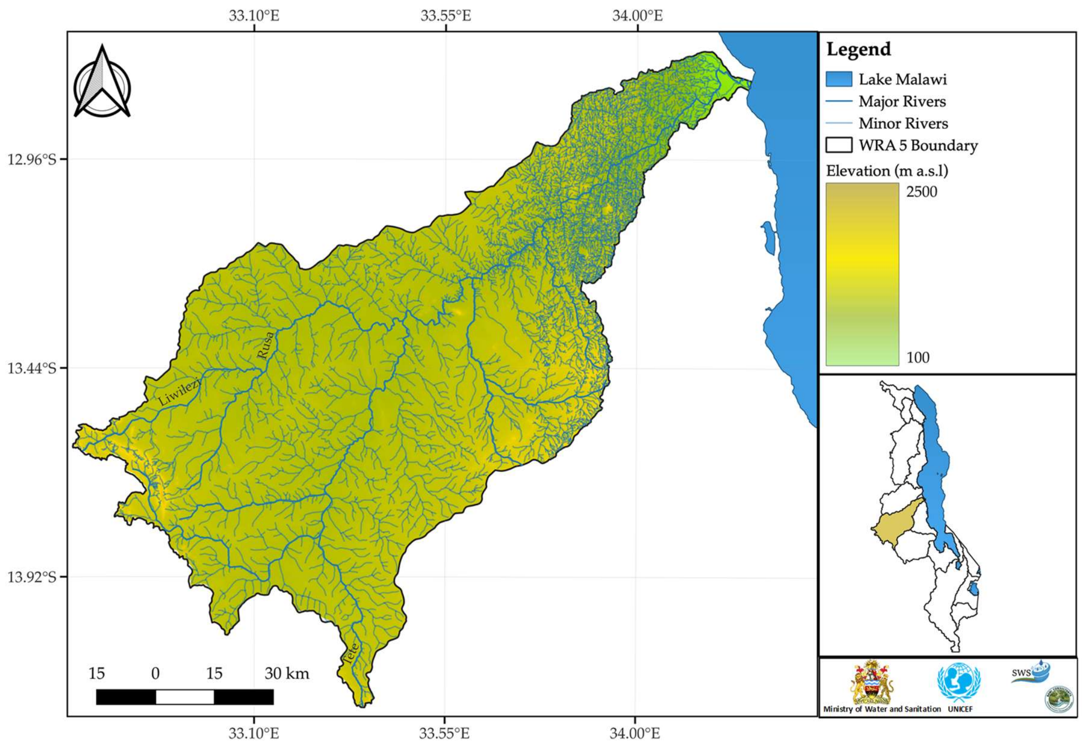

Figure 8. Drainage for the major rivers in Water Resources Area 5.

Geology – Unconsolidated deposits

WRA 5 is dominated by Tertiary - Recent unconsolidated sediments overlying fractured basement rock. This WRA constitutes the Bua river basin and is composed of colluvium, alluvium, and fluvial sediments associated with the river, and mass wasting of surrounding basement material. Isolated dambo wetlands are common in low lying areas where the river and its tributaries are present. The majority of the groundwater abstraction points likely depend on groundwater in the colluvial / fluvial sediments of the WRA.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 5. 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)
5	C	- No Station -	-	971
	D	Madisi/Mponela	779	833
	E	Kasiya/Tembwe/Mchinji	967	833
	F	- No Station -	-	833

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 measured at rainfall stations is 982mm (**Figure 9**) but is higher along the lake and in the mountains near the Zambia border, peak rainfall occurs between December and March. High rainfall in the rainy results in periodic flooding in the catchment.

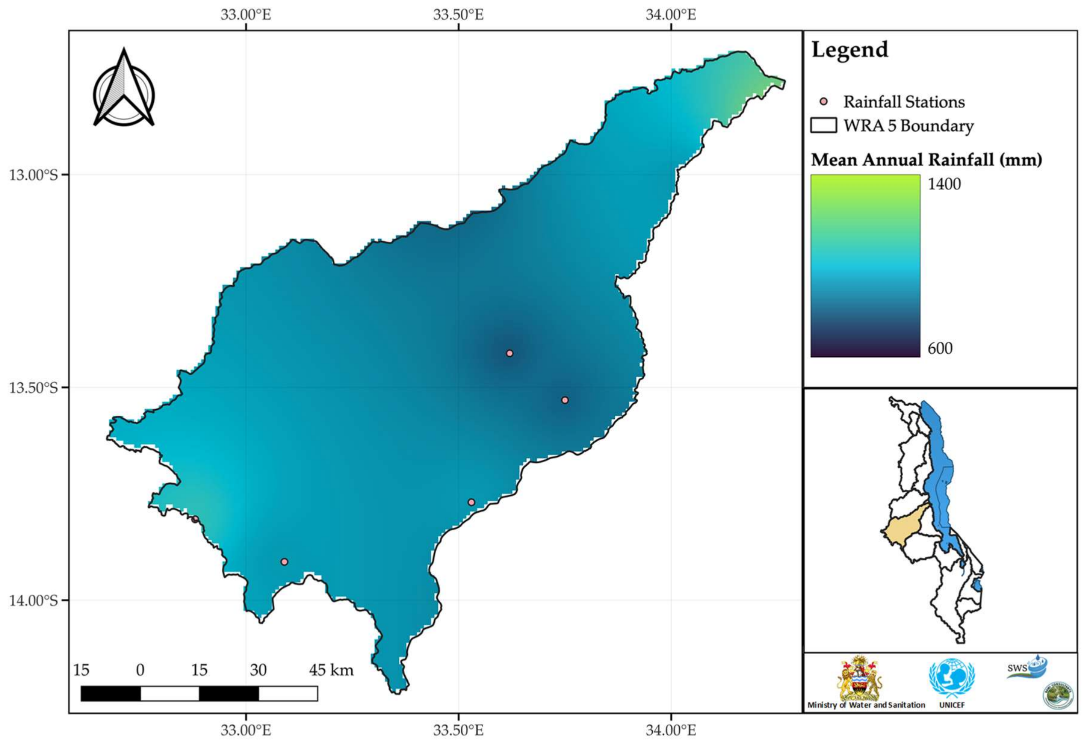

Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 5 with the location of weather stations. Average rainfall measured is 892mm, average rainfall modelled is 898 +/- 63mm (range 770 to 1,228mm).

Land use

The area is well known for irrigated agricultural activities dominated by rice irrigation schemes mainly along the Lake Malawi Shoreline. There is notable flooding during the peak of the rainy season, contributing to alluvium deposits along the lower reach of the WRA. A recent boom in large scale agricultural activities dominated by tobacco and maize farming has resulted in accelerated rate of deforestation due to clearing of natural vegetation in the quest to create farmlands. Large scale irrigated agriculture of tobacco and maize under the Bua River Irrigation Initiative accounts for 65% of all surface water abstractions in the area, during the dry season and around the onset of the wet season. The other major user of water resources in the WRA is the Central Region Water Board through water supply and sanitation initiatives.

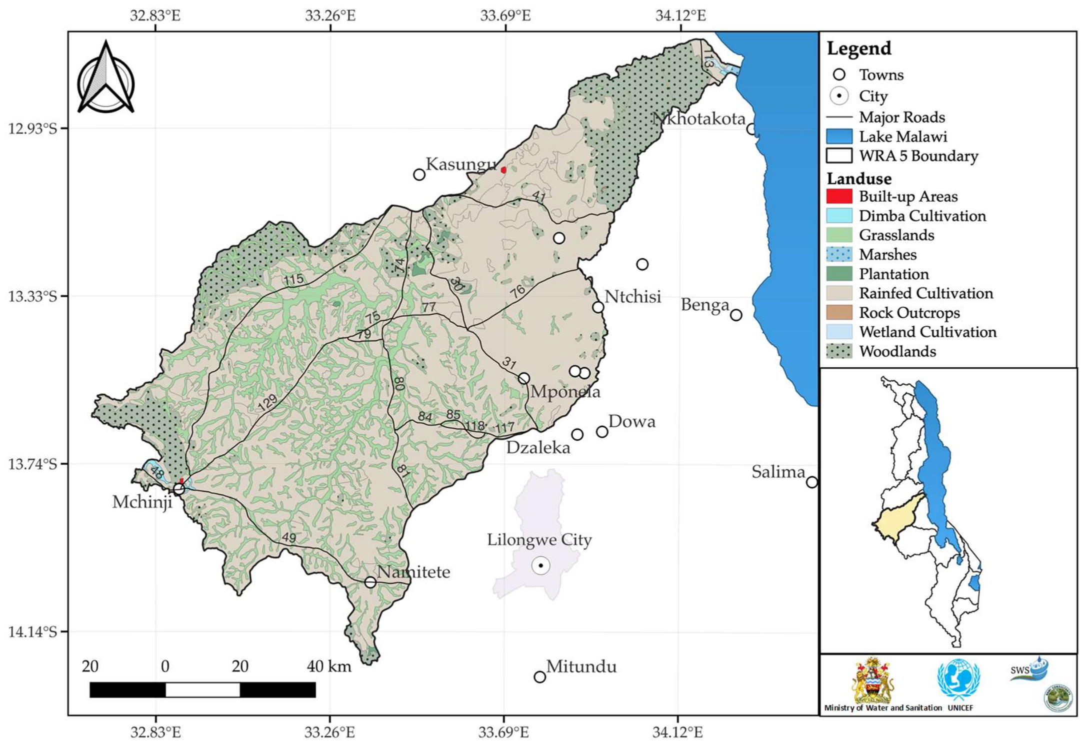

Figure 10. Land use in WRA 5 is dominated by cultivation with woodlands and grasslands.

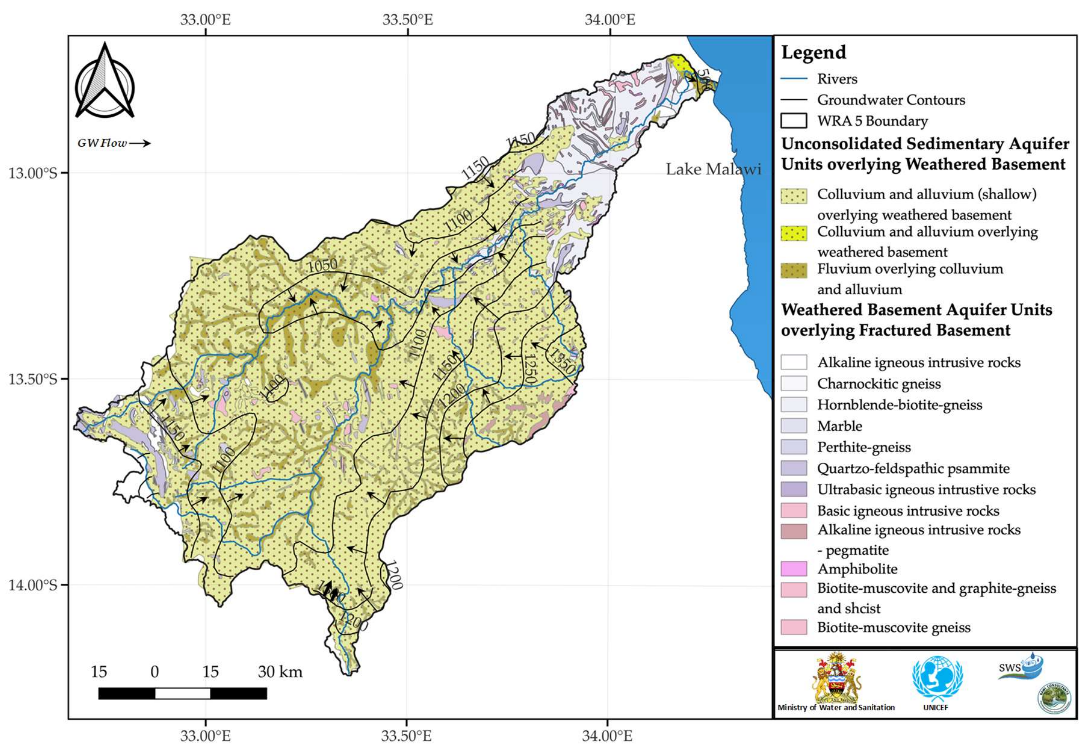

Figure 11. Groundwater level contours and flow direction in WRA 5 [1987 Hydrogeological Reconnaissance data] [water level contour interval 50m]

Hydrogeology of WRA 5

Aquifer properties

Most of Water Resources Area 5 has colluvium units overlain by ubiquitous fluvial river deposits underlain by weathered and fractured basement. It is anticipated these deposits contain various secondary clay minerals interspersed with saprolitic sediments resulting is moderate to low transmissivities except in areas of faulting. Detailed geospatial analysis of the stratigraphy of these units is challenging as records with sediment size distributions and drilling logs were not geospatially tagged, and further work is required in the Ministry of Water and Sanitation to harmonise all drilling records with location records from the 2020 National Asset register. Weathered basement overlying fractured basement dominates the western rift valley interspersed with riverine deposits. The approach to Lake Malawi has lacustrine and fluvial deposits, likely in hydraulic connection with Lake Malawi and moderately productive transmissivities.

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 5 is based on prior hydrogeological reconnaissance.

Groundwater level data for WRA 5 based on prior hydrogeological reconnaissance confirm a system flow regime following topographic drainage (**Figure 11**). Whilst groundwater hydraulic heads up to 1300 m asl have been locally measured in the WRU 5F far west higher ground, lower heads at 1150 and 1100 m heads in the weathered basement highlands continuously encircle the headwaters catchment – dambo wetlands of the Bua River in south west of 5E and Rusa River in the west of 5F. Groundwater flows follow the shallow topography, towards the Bua in 5E and towards the Rusa in 5F, gravitating regionally towards the confluence of these rivers in the central plateau. Groundwater head contours in WRU 5D in the eastern plateau approximately parallel the north-east flowing Bua with hence flows from the north and south converge on the river indicating significant wet-season base flows to the river, especially from the more extensive 5D catchment to the south.

Hydraulic gradients are generally moderate to low, or very low across 5D, 5E and 5F. For instance, gradients driving flows north-westwards in 5D towards the Bua amongst the higher gradients regionally are around 0.01 compared to gradients in 5F towards the Rusa of only 0.002 ascribed to the low-relief, flood-vulnerable, plateau topography. For a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2, respective groundwater velocities for these gradients would be 18 m/yr and 3.7 m/yr. Hydraulic head data to the east in WRU 5C are not available in the Basement Rift Valley escarpment, incised by the rivers, but only in the narrow Lake Malawi shoreline unconsolidated deposits where the hydraulic gradient towards the lake is around 0.007.

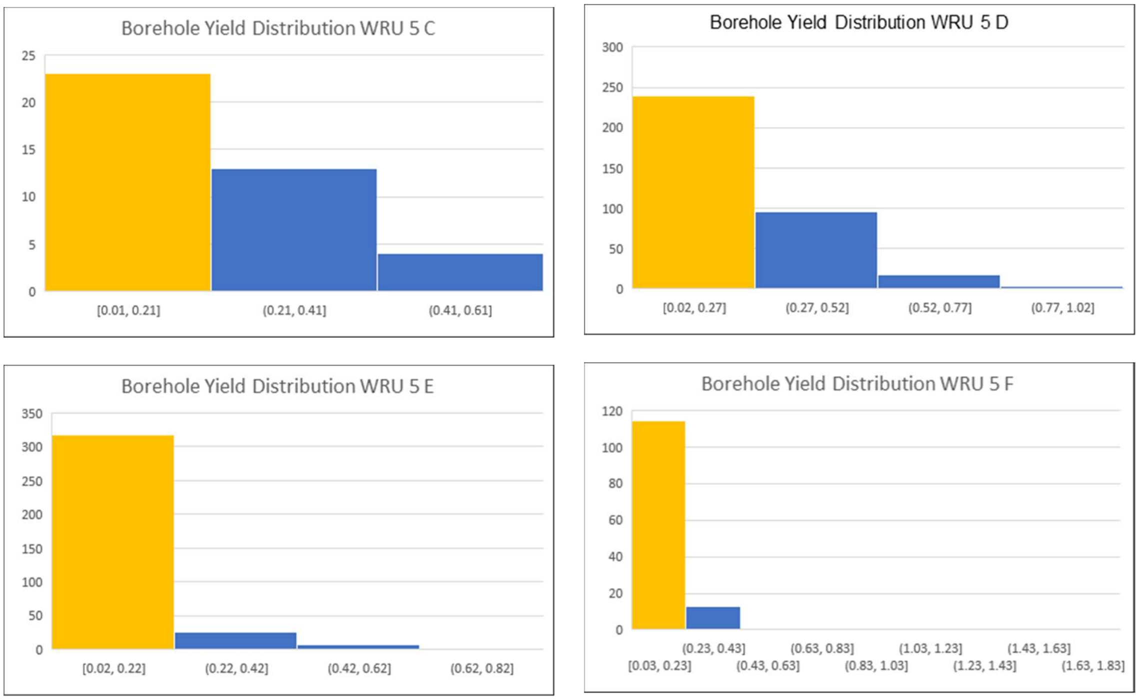

Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 5 (note: limited data in WRU 5C) (y axis = *n* observations)

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 WRA6 there appears to be a trend to higher borehole yields in the lower reaches of WRU 5D with a number of production boreholes reporting yields in excess of 2l/s. In WRA 5 (**Figures 13a, 13b, 13c and 13d**) there is generally lower yields and the piezo metric surface suggest strong surface water and groundwater interaction and there is a need to enhance monitoring and evaluation of aquifer properties in WRA 5. The highest yielding boreholes in basement aquifers will likely be located mainly along linear structures, fluvial channels and main streams, and near contacts between different units.

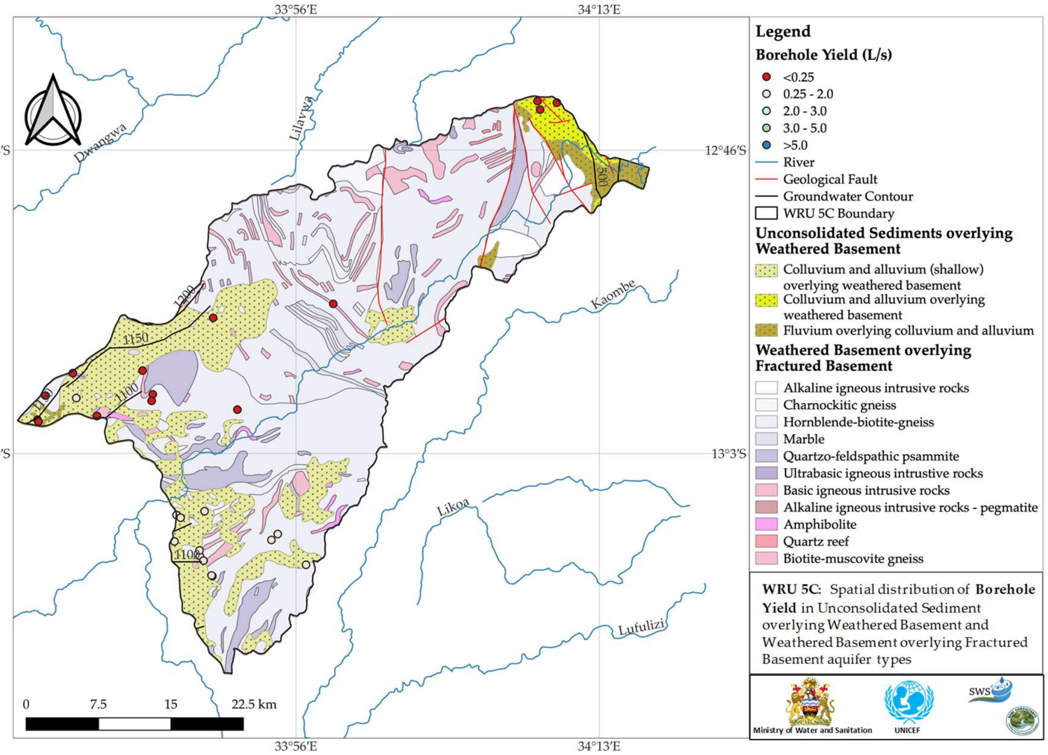

Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 5C.

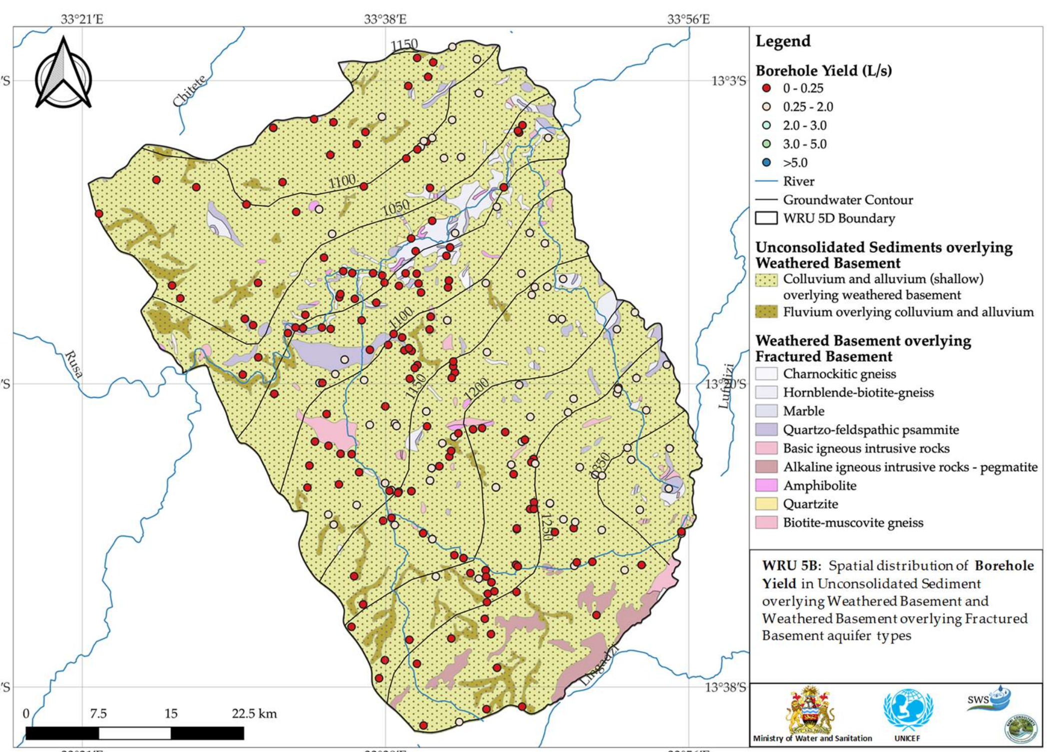

Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 5D.

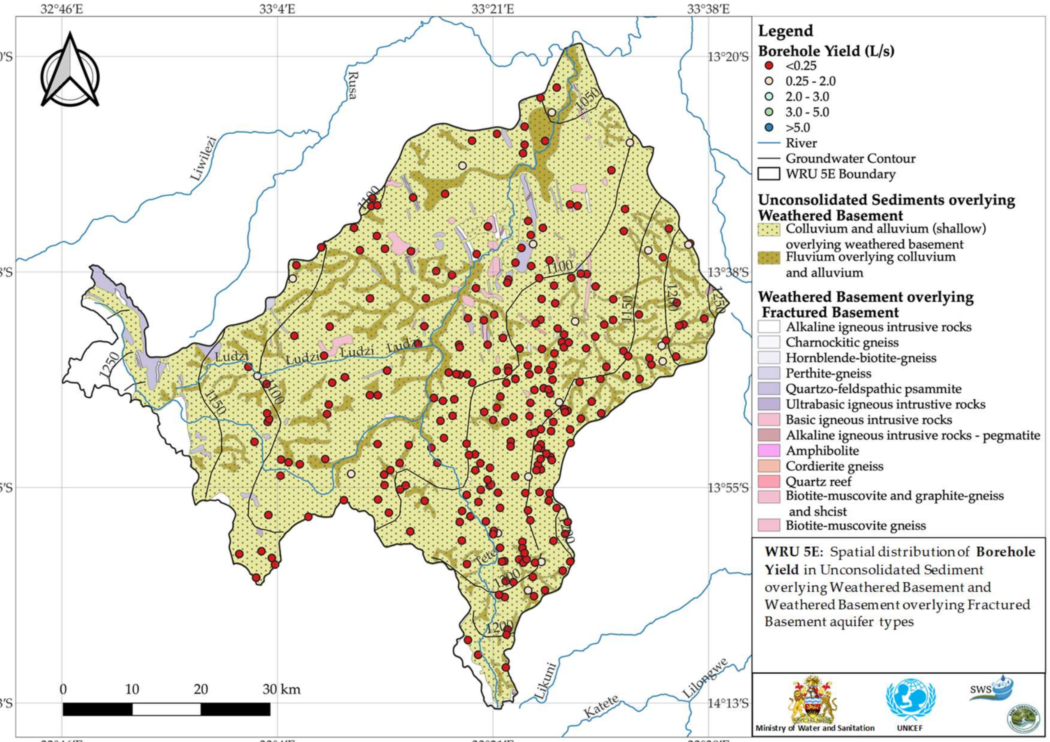

Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 5E.

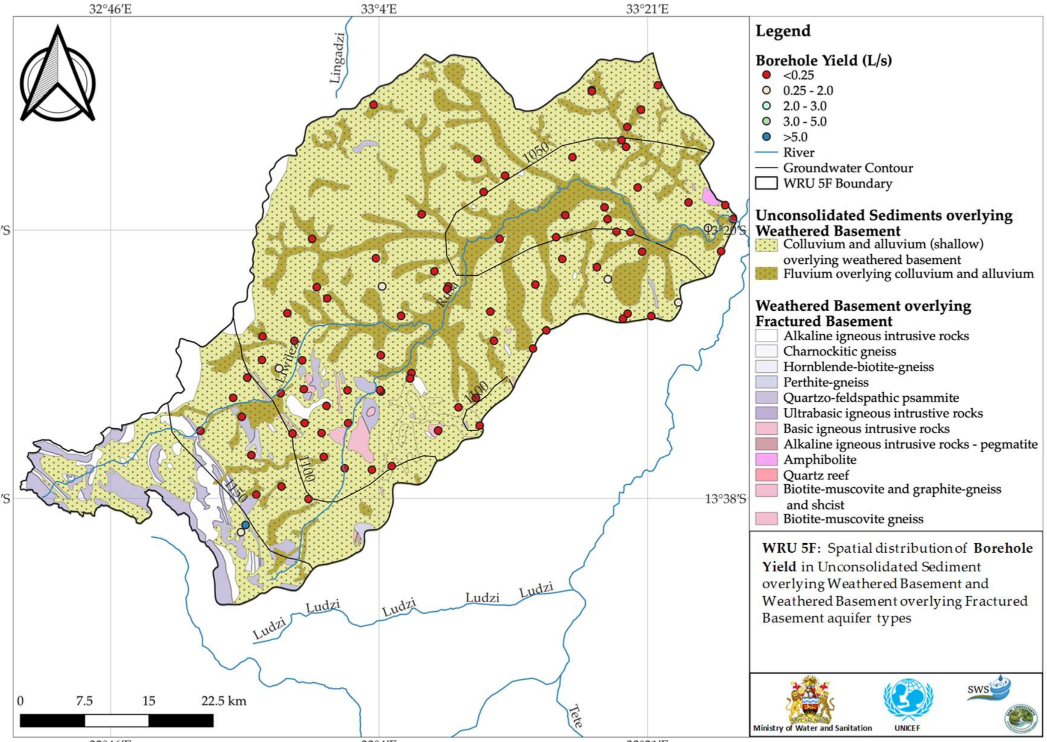

Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 5F.

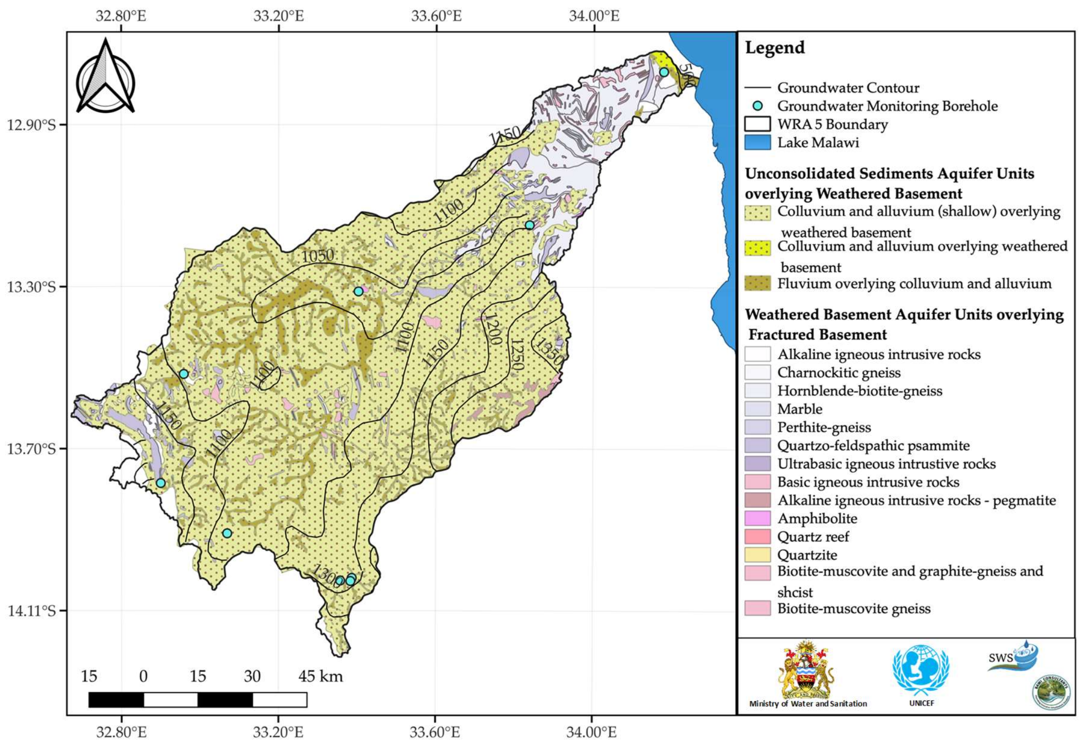

Figure 14a. Location of groundwater monitoring points in WRA 5.

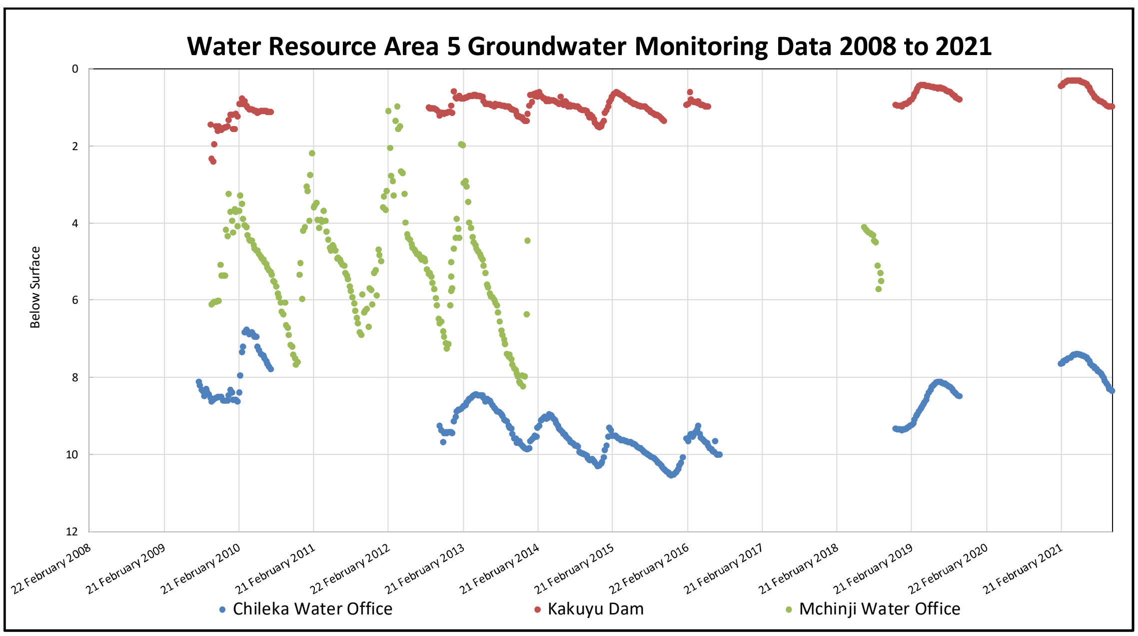

Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 5. (units assumed to be meters below ground level).

Groundwater Table Variations

There are three semi-operational groundwater monitoring stations (**Figure 14a**) within WRA 5 that has any data (**Figure 14b)** with no data was available for other sites. The data is not complete and perhaps there is a possible low amplitude (ca 1m per annum) variation in the water table but there is also a short amplitude change of up to 8 meters per year at the Mchinji Water Office site, annual variations within 1 meter at the Kakuyu Dam site and approximately 2 meter per year variation at the Chileka Water Office (with a potential long-term climate related trend). Data from the 2020 National Survey suggested seasonal water table declines in shallow groundwater supplies and this may be supported by the data in **Figure 14b**. It is not possibly to uniquely determine any long-term trends that may relate to climate variability (rainfall and recharge relationships). 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. Given the relationship of the water table and the rivers, monitoring of the surface water and groundwater tables is strongly advised where interaction likely occurs, especially if solar boreholes are used.

Table 4a. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 5C, 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	33.3	10%	35%	0.02	0.10	66.6	1,165.5	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	298.0	10%	30%	0.02	0.06	595.9	5,363.5	
W & F Basement	1,109.1	1%	10%	0.02	0.03	221.8	3,327.3	
	Area of WRU (km^2)	5C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*884.4*	*9,856.4*	*Total Volume Groundwater*
	1,440.4	971	Average Rainfall in WRU	9.71	72.825	14.0	104.9	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]						63	94	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 5D, 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	113.1	10%	35%	0.02	0.10	226.3	3,959.8	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	2,364.4	10%	30%	0.02	0.06	4,728.9	42,559.9	
W & F Basement	262.7	1%	10%	0.02	0.03	52.5	788.1	
	Area of WRU (km^2)	5D	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*5,007.7*	*47,307.8*	*Total Volume Groundwater*
	2,740.3	833	Average Rainfall in WRU	8.33	62.475	22.8	171.2	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]						219	276	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 5E, 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	469.8	10%	35%	0.02	0.10	939.6	16,443.4	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	3,173.7	10%	30%	0.02	0.06	6,347.5	57,127.5	
W & F Basement	186.7	1%	10%	0.02	0.03	37.3	560.1	
	Area of WRU (km^2)	5E	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*7,324.5*	*74,131.0*	*Total Volume Groundwater*
	3,830.3	833	Average Rainfall in WRU	8.33	62.475	31.9	239.3	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]						230	310	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 5F, 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	485.9	10%	35%	0.02	0.10	971.9	17,007.7	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	1,799.2	10%	30%	0.02	0.06	3,598.4	32,385.2	
W & F Basement	225.9	1%	10%	0.02	0.03	45.2	677.7	
	Area of WRU (km^2)	5F	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*4,615.4*	*50,070.6*	*Total Volume Groundwater*
	2,511.0	833	Average Rainfall in WRU	8.33	62.475	20.9	156.9	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]						221	319	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Groundwater recharge

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

The calculated volume of groundwater recharge in WRA 5 ranges between 89.6 Million Cubic Meters (MCM) and 672.3 MCM per year, with a mean age of groundwater of 216 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 5. 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 5

Groundwater major-ion water quality in WRA 5 for data available within the Ministry of Water and Sanitation is available and data presented here is limited to those analyses which have geospatial information. Data which was reported as 'zero' or below reported minimum detection limits were ignored (**Table 5**).

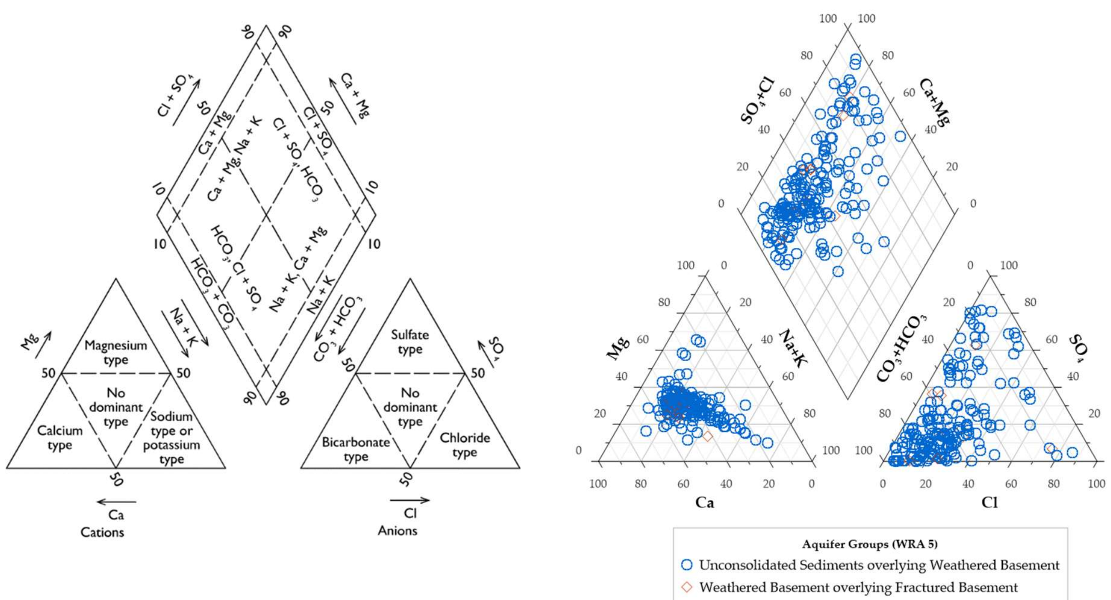

Figure 15a, 15b. Piper Diagramme of Groundwater Samples in WRA 5 and for each Aquifer Type in WRA 5.

Piper plots of the WRA 5 water quality data suggest most water has expected major geochemical changes from water-rock interactions dominated by Ca-Mg-HCO_3 type waters with a clear trend for increasing Na-Cl-SO_4 likely due to evaporative enrichment (**Figure 15a and 15b**). The average groundwater age, the high precipitation rate and calculated recharge rates together with the relatively low electrical conductivity points to recent meteoric recharge of much of the groundwater with limited 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 5 is provided however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine in WRA 5, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

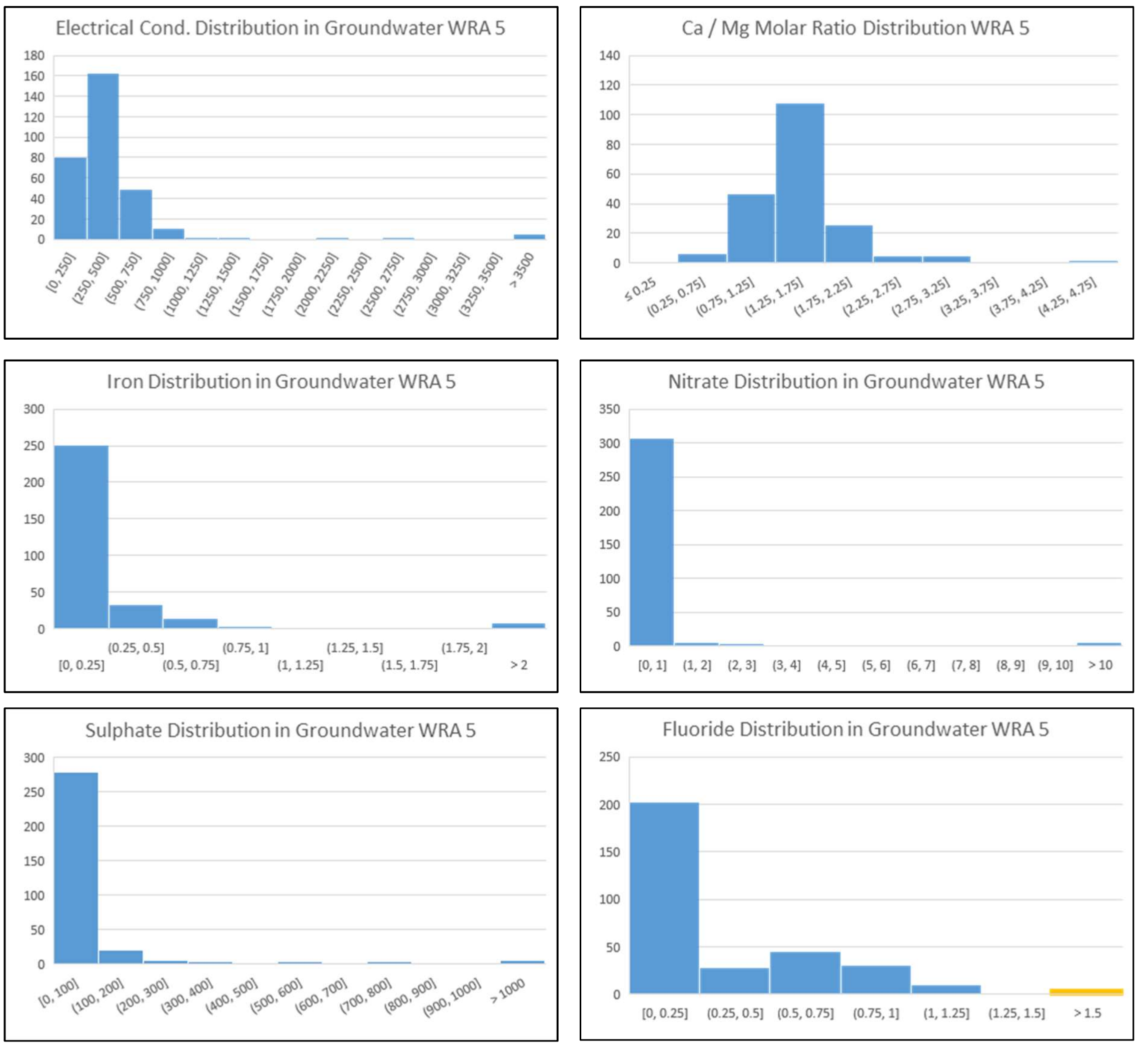

Figure 16 Distribution of chemical species in groundwater within WRA (y axis = *n* observations) .

Stable Isotope Results

Stable isotopes are unique for evaluating the complexities associated with groundwater–surface-water interactions which are diverse occurrence in WRA 5 including delayed, slow-release of water from dambos that sustain system flows in the dry season; influent and eluent river reaches in various parts of the plateau and lakeshore plains; and complex groundwater processes occurring at the Lake

Malawi–foreshore (Banda et al 2019). Resolving the detail of groundwater processes will require focused, higher spatial/temporal resolution studies including bespoke multi-level monitoring of groundwater levels and water quality for which isotope tools may be significant. This approach should be required by the Ministry of Water and Sanitation at all sites where 'solar pump' or distributed groundwater supply networks are installed. In Malawi and WRA 5 widened application of isotopes could be used to assess fault-assisted flows to the surface of deep-sourced groundwater suspected to influence groundwater salinity, fluoride and arsenic risks. In WRA 5 hydraulic gradients towards Lake Malawi in the low-relief lakeshore plains are minimal at 0.001–0.01, transmissivity estimates from pumping tests in the Salima area of 100–300 m^2/d support the hypothesis that groundwater flow in the alluvium discharges to the lake (calculated by Smith and Carrington (1983) at around 0.13–0.38 x 10^6 m^3 annually per kilometre of shoreline for a gradient of 0.0035). Stable isotopes of local groundwater (**Figure 17**) are similar to Lake Malawi evaporated water supporting some reversal of flow (lake to land) in the vicinity of the lake shoreline when levels become 1–2 m higher than the groundwater, resulting in temporary storage of lake water in the alluvial aquifer. It is likely this trend reverses as Lake Malawi levels fall during the year. The isotope signatures of groundwater at the lakeshore suggest evaporation and groundwater-surface water occur for aquifers in hydraulic connection with Lake Malawi.

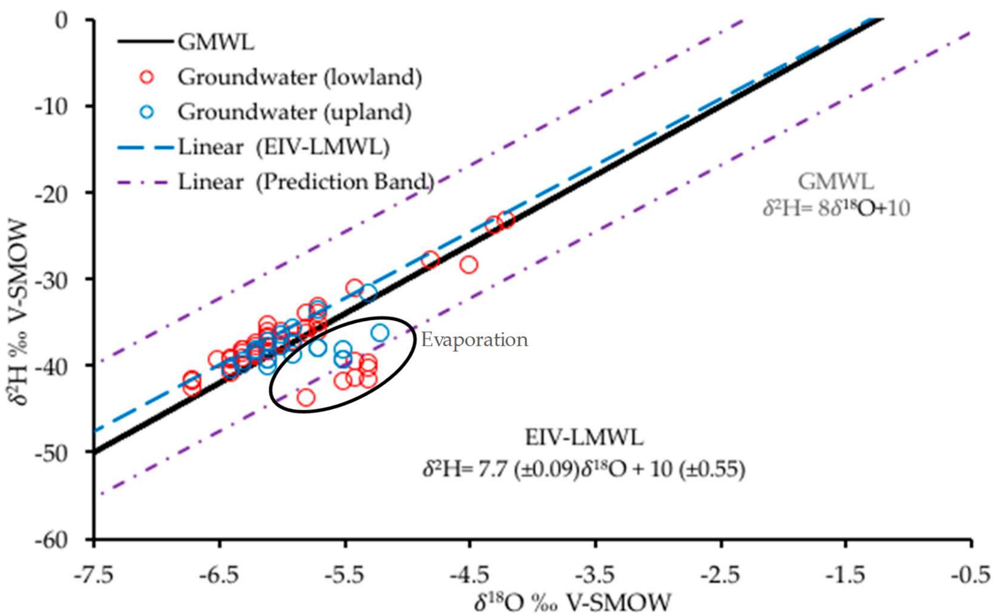

Figure 17. Stable isotope measurements of groundwater in WRA showing evaporation of near lake groundwater (after Banda et al 2019)

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 5 is moderate (**Figure 16**) however along the approach to Lake Malawi evaporation or influence of hidden fault zone water groundwater results in excess of 3,500μS electrical conductivity.

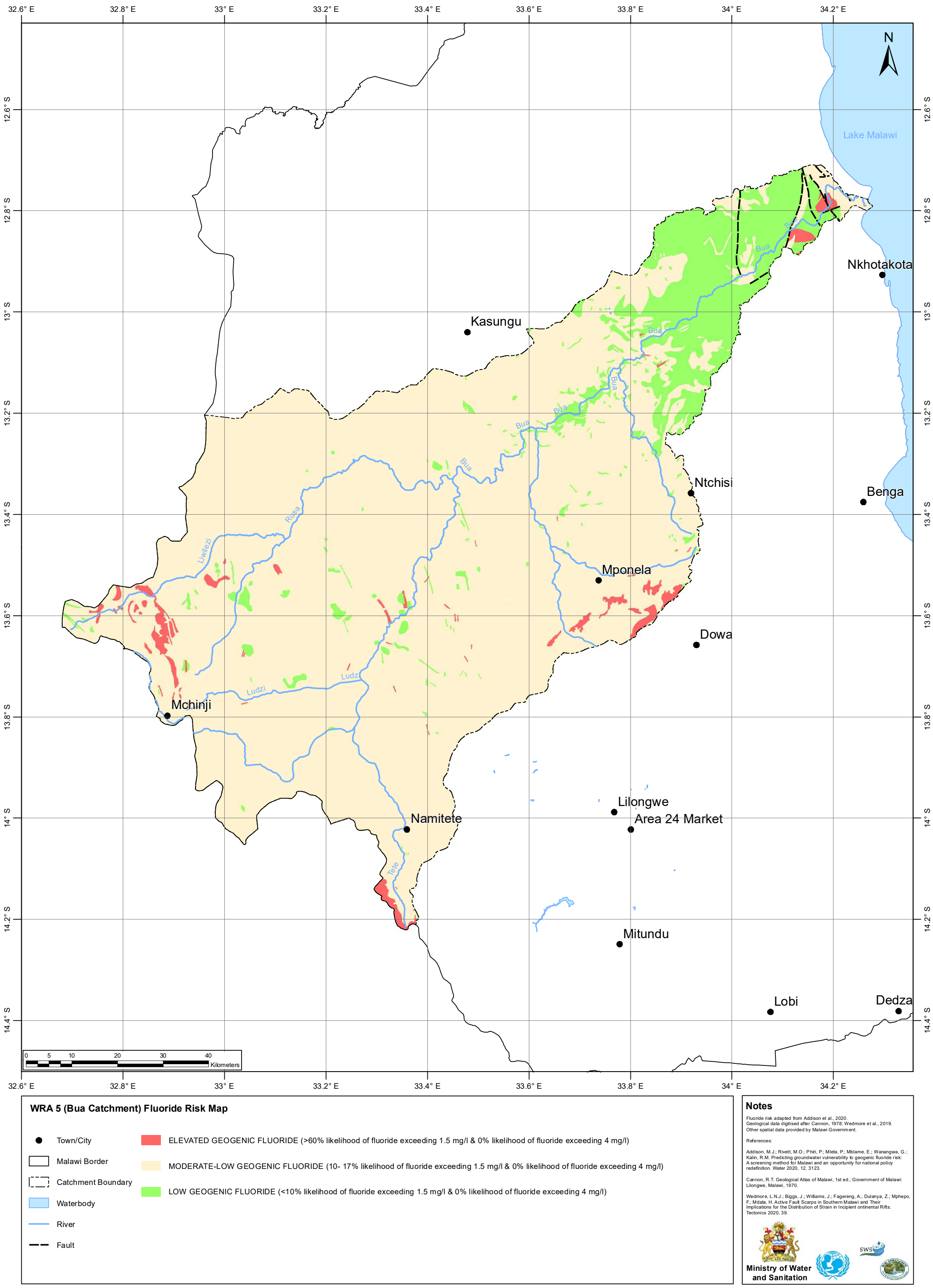

Figure 18. Groundwater Fluoride Risk Map WRA 5 (after Addison et. al. 2021).

The lack of routine and wide-spread georeferenced water quality analyses from known aquifer units does not allow for detailed interpretation. It is recommended that investment in routine monitoring of public water supplies is planned and implemented as part of any planning for enhanced groundwater resource utilisation, especially solar pumped boreholes.

Fluoride

There is little prevalence of hot springs in WRA 5 but several geologic units that have potential to result in higher Fluoride. WRA 5 should therefore be considered a **Lower Risk** category for fluoride in groundwater. Groundwater data drawn from the recent national-scale assessments (**Figure 18**) a limited number of analyses above 1.5mg/l, any newly located fault-zone discharges to shallow aquifers should be targeted for 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. 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 5 is planned and implemented.

Arsenic

A recent national collation of arsenic groundwater survey data (Rivett et al 2018) found widespread low concentrations but with only a few above the WHO 10 µg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. This national dataset did not sample in WRA 5 and arsenic may be low, 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 5 is planned and implemented

E-Coli and Pit Latrine Loading to Groundwater

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

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

Table 6. Calculated pit latrine loading 2012 to 2022 within WRA 5.

	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**
5C	103,181	109,978	119,150	128,582	137,997	129,611	393,389,802	472,068
5D	462,212	498,185	533,852	569,545	606,144	598,462	1,764,936,002	2,117,923
5E	705,183	744,230	783,218	821,341	858,993	788,960	2,539,039,846	3,046,848
5F	196,674	205,272	213,290	220,391	227,359	204,909	684,663,575	821,596
WRA 5	**1,467,250**	**1,557,666**	**1,649,511**	**1,739,860**	**1,830,493**	**1,721,941**	**5,382,029,224**	**6,458,435**

The model results shown in **Table 6** indicate WRA 5 has a calculated total of 6,458,435metric 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 254,691. WRA 5 covers roughly 8.61% 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. 17,463 metric tonnes of fertiliser would be used in WRA 5 per year, the modelled latrine loading suggests 37 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

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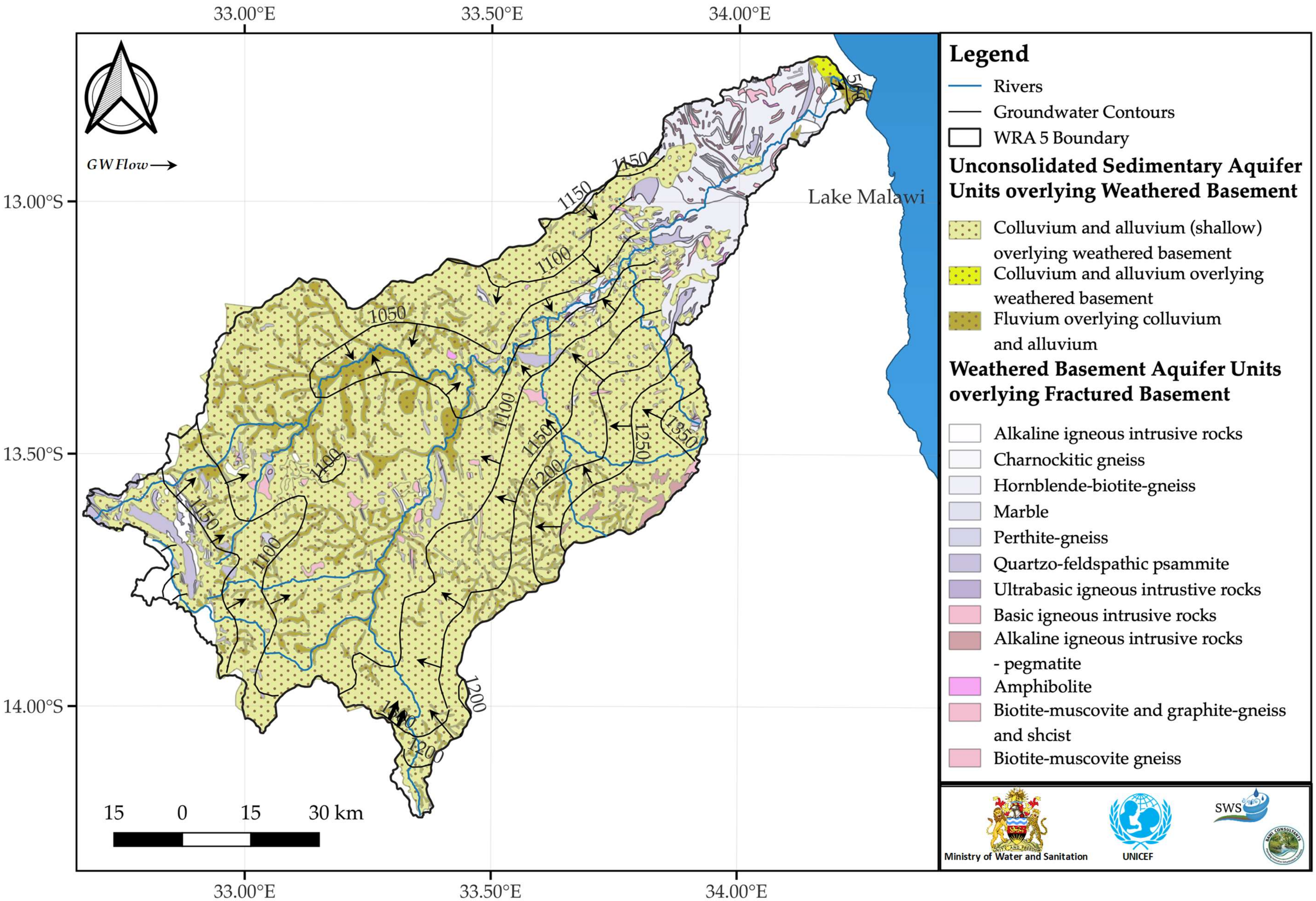
Water Resource Unit (WRA) 5 Figures

Figure WRA 5.0: Aquifer Units and Groundwater Level Contours Water Resources Area 5

Figure WRA 5.0: Aquifer Units and Groundwater Level Contours WRA 5



WRU 5C Figures

Figure WRU 5C.1 Land Use and Major Roads

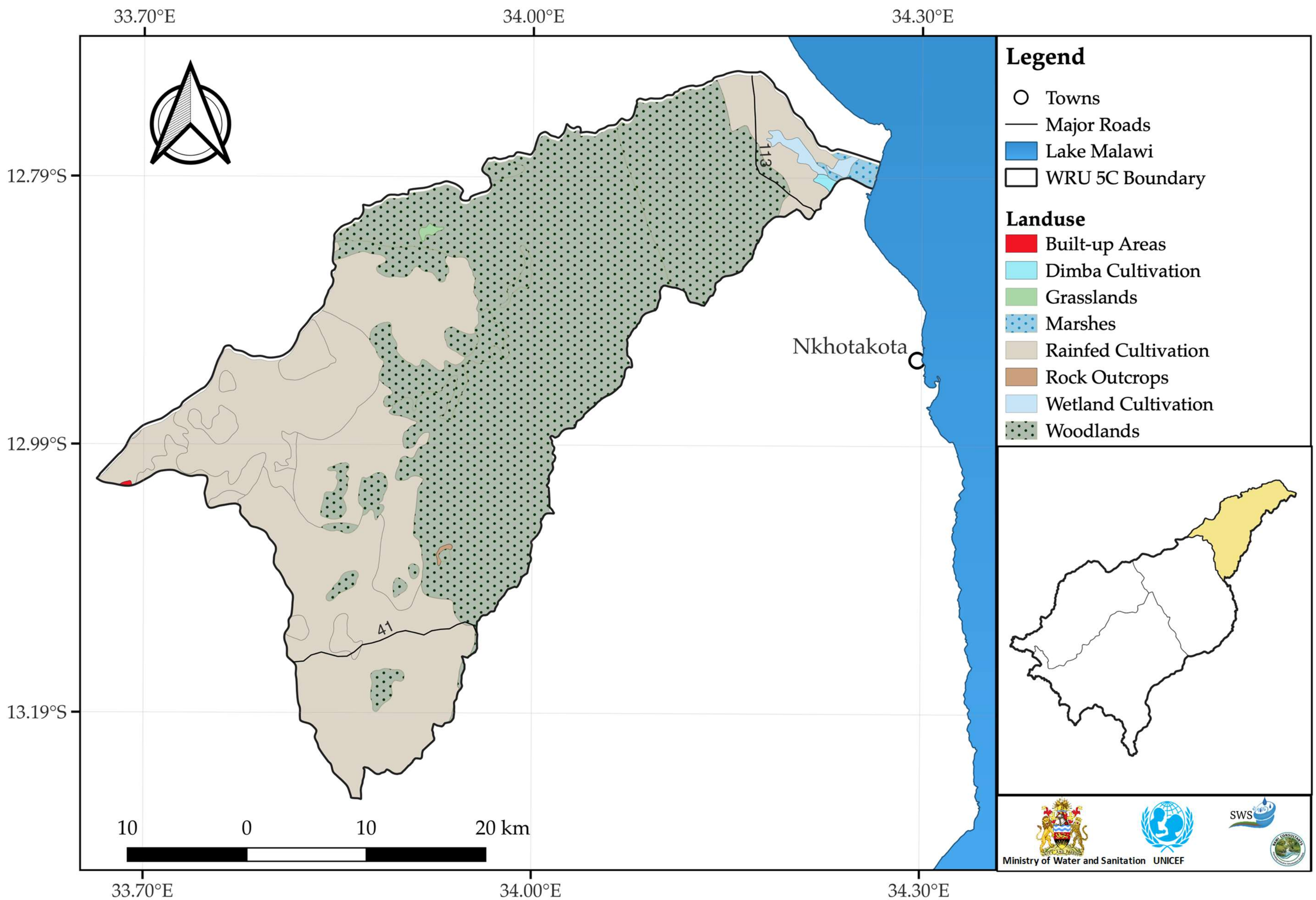


Figure WRU 5C.2 Rivers and Wetlands

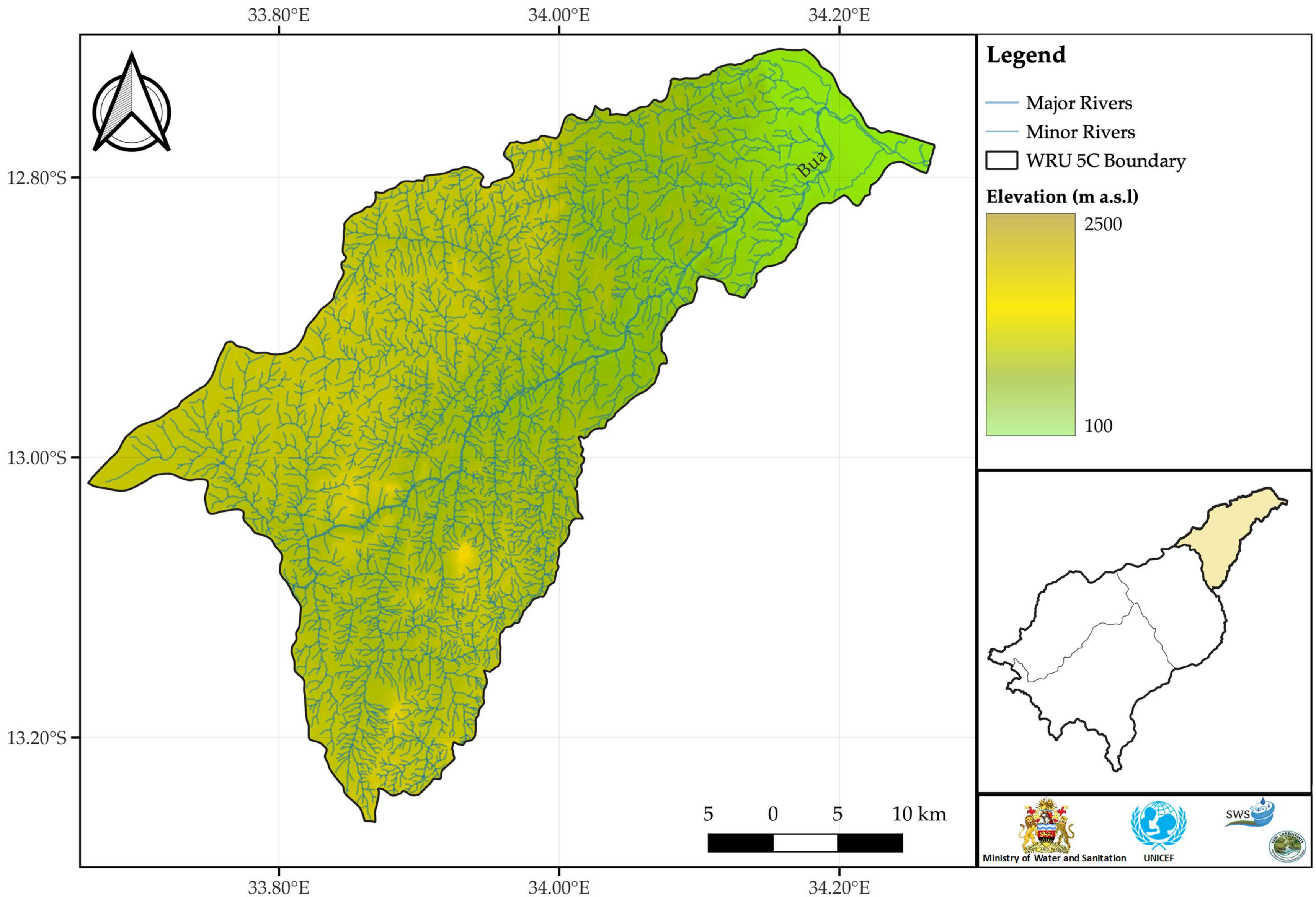


Figure WRU 5C.3 Hydrogeology Units and Water Table

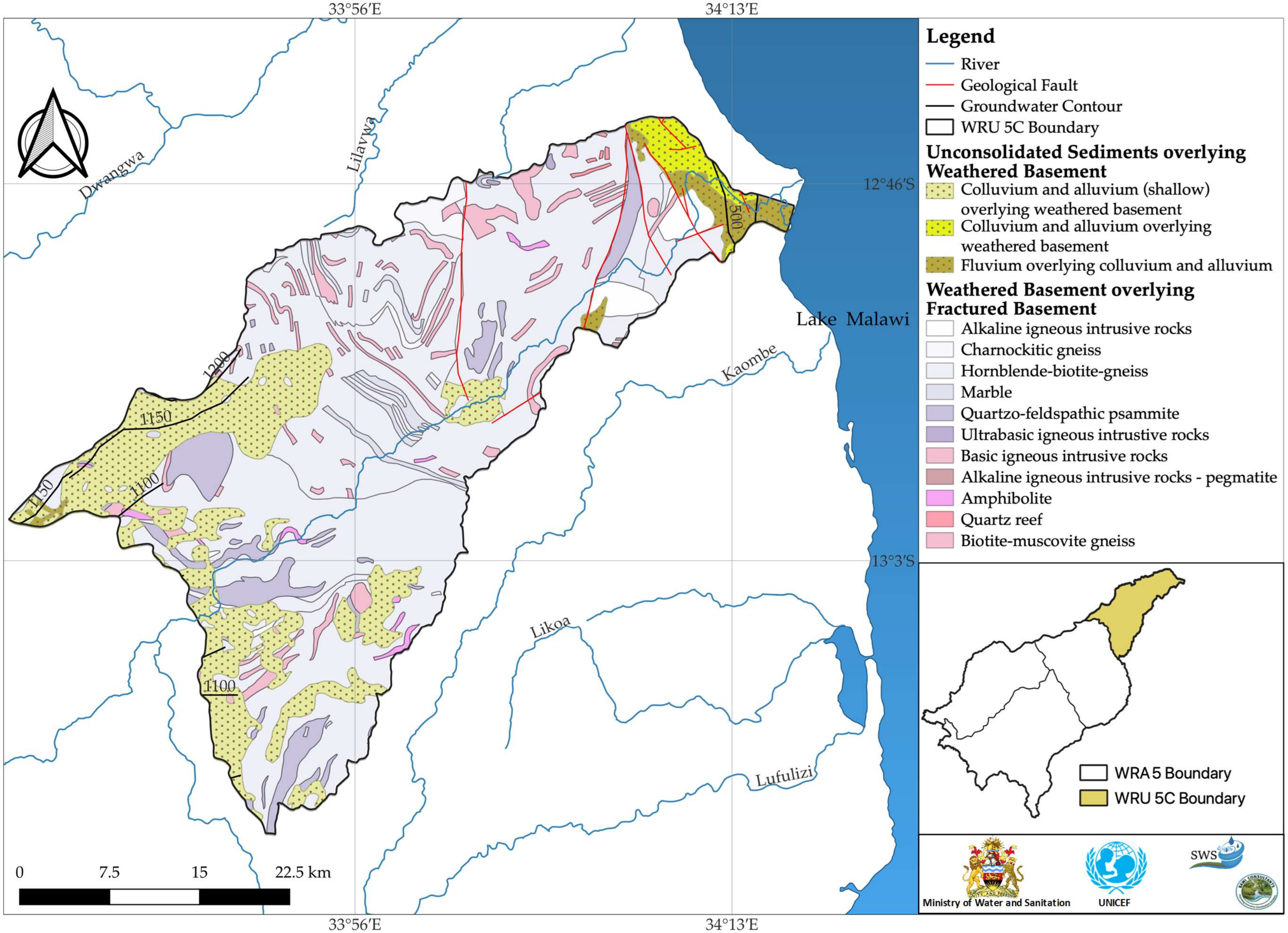


Figure WRU 5C.4 Groundwater Chemistry Distribution Electrical Conductivity

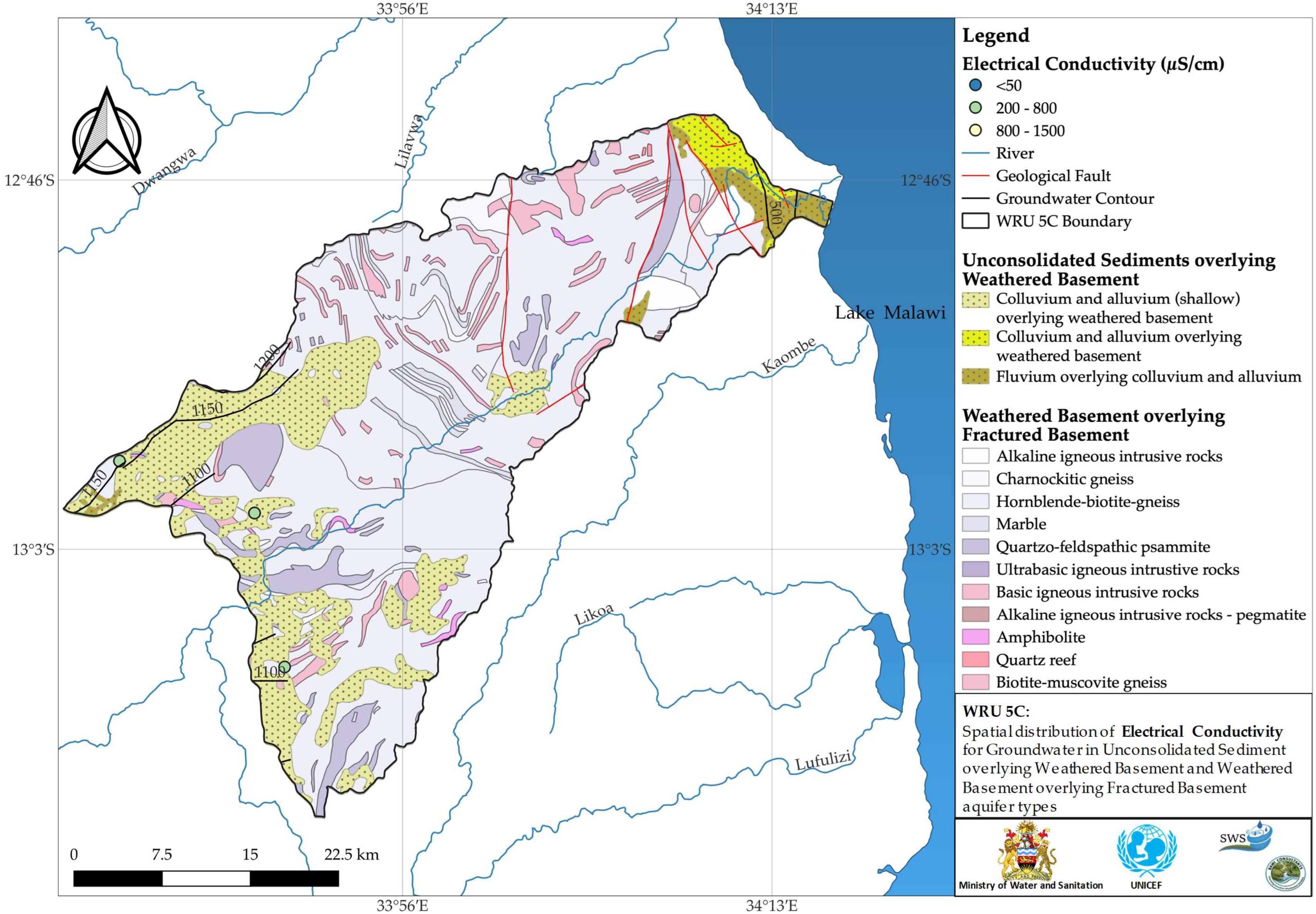


Figure WRU 5C.5 Groundwater Chemistry Distribution Sulphate

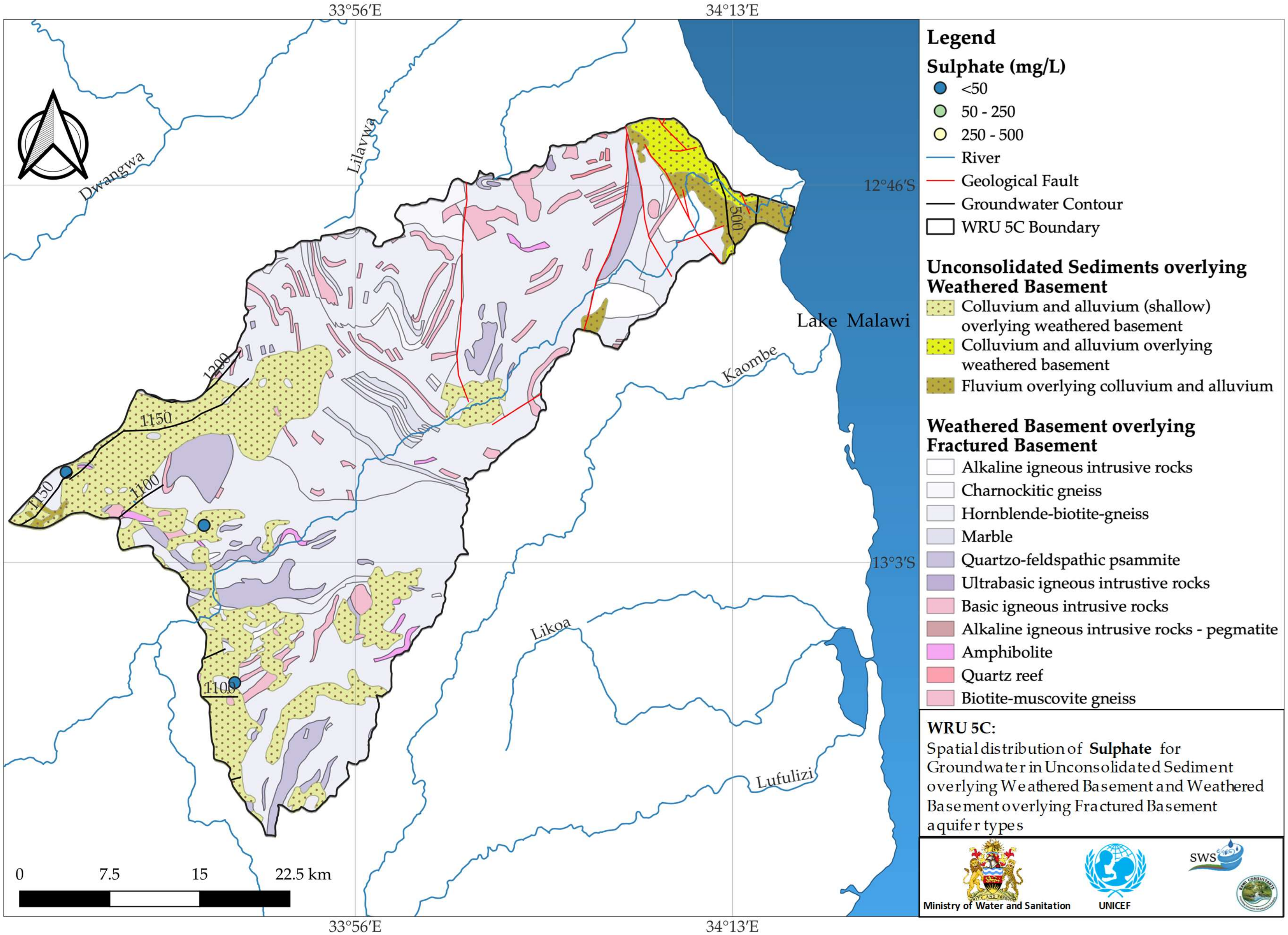


Figure WRU 5C.6 Groundwater Chemistry Distribution Chloride

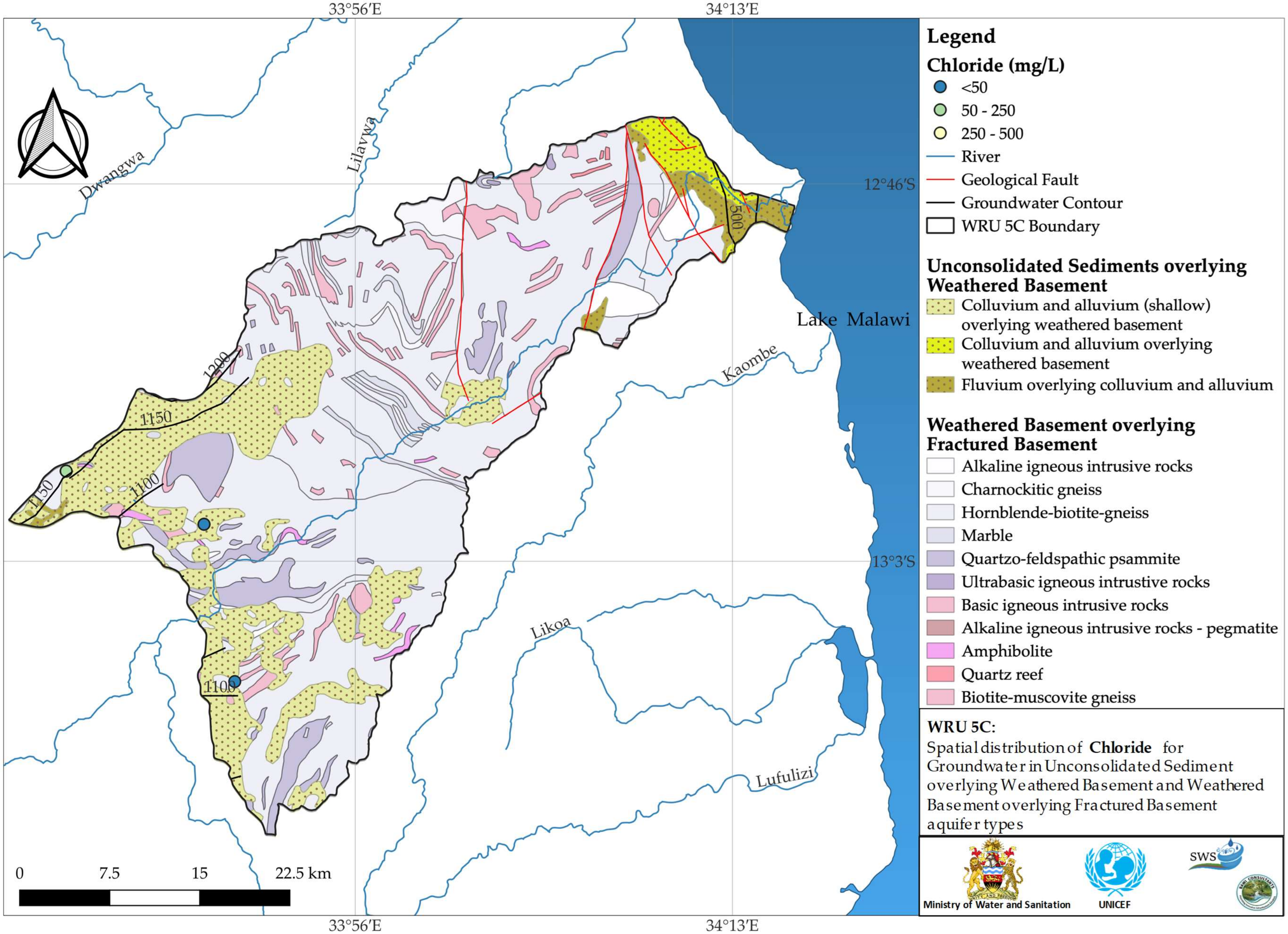


Figure WRU 5C.7 Groundwater Chemistry Distribution Sodium

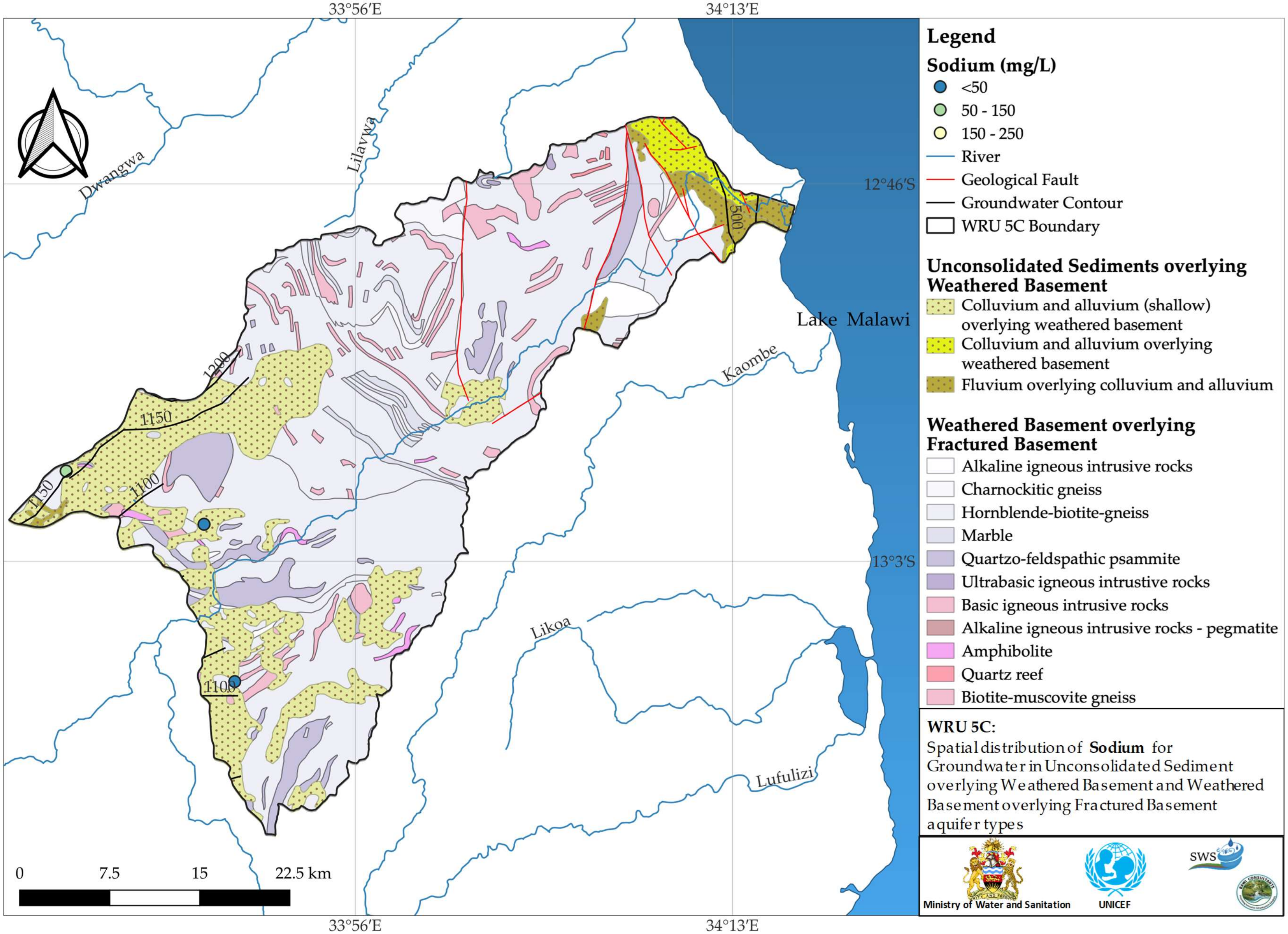


Figure WRU 5C.8 Groundwater Chemistry Distribution Calcium

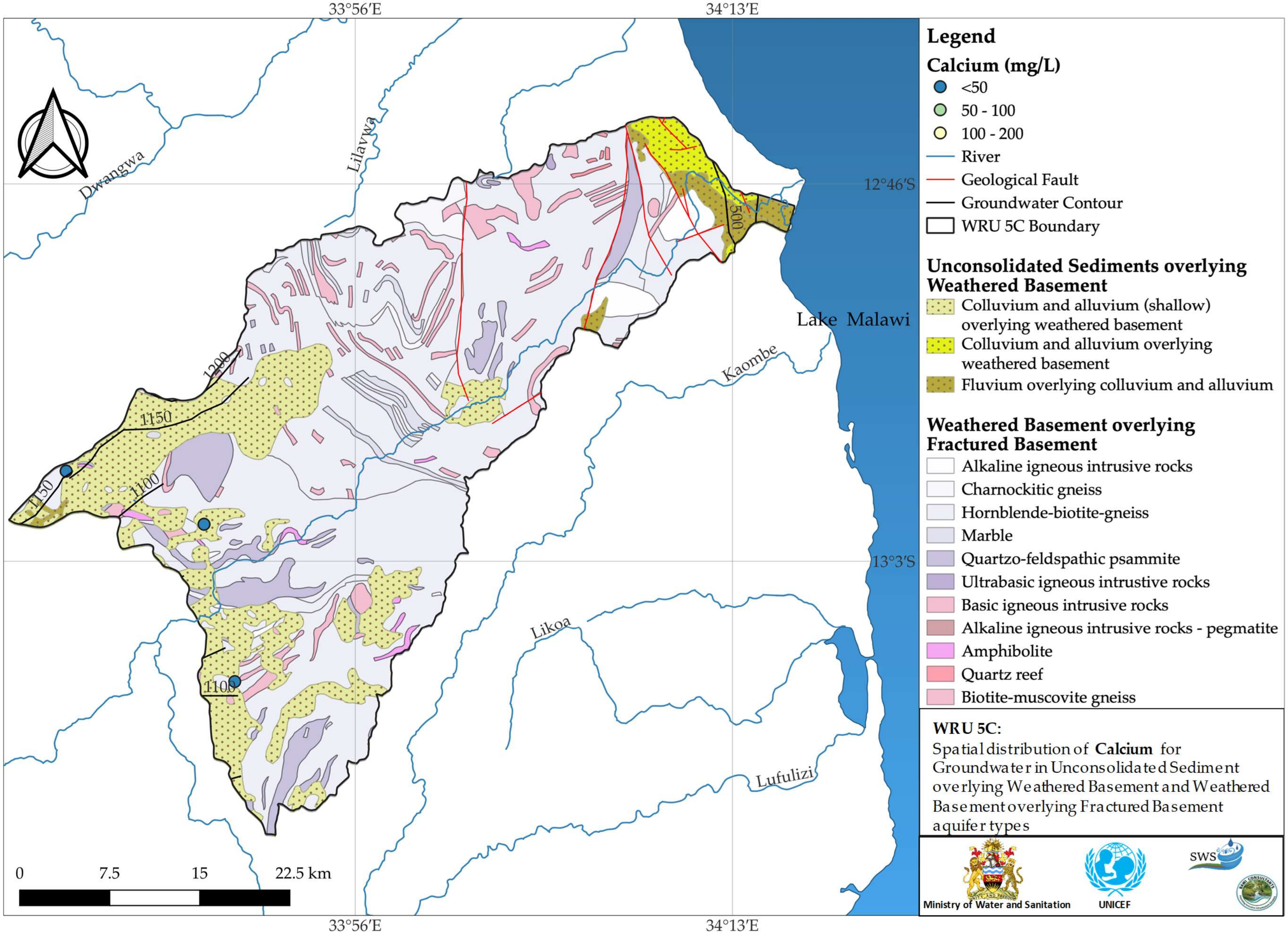


Figure WRU 5C.9 Piper Diagram of water quality results with respect to the major aquifer type

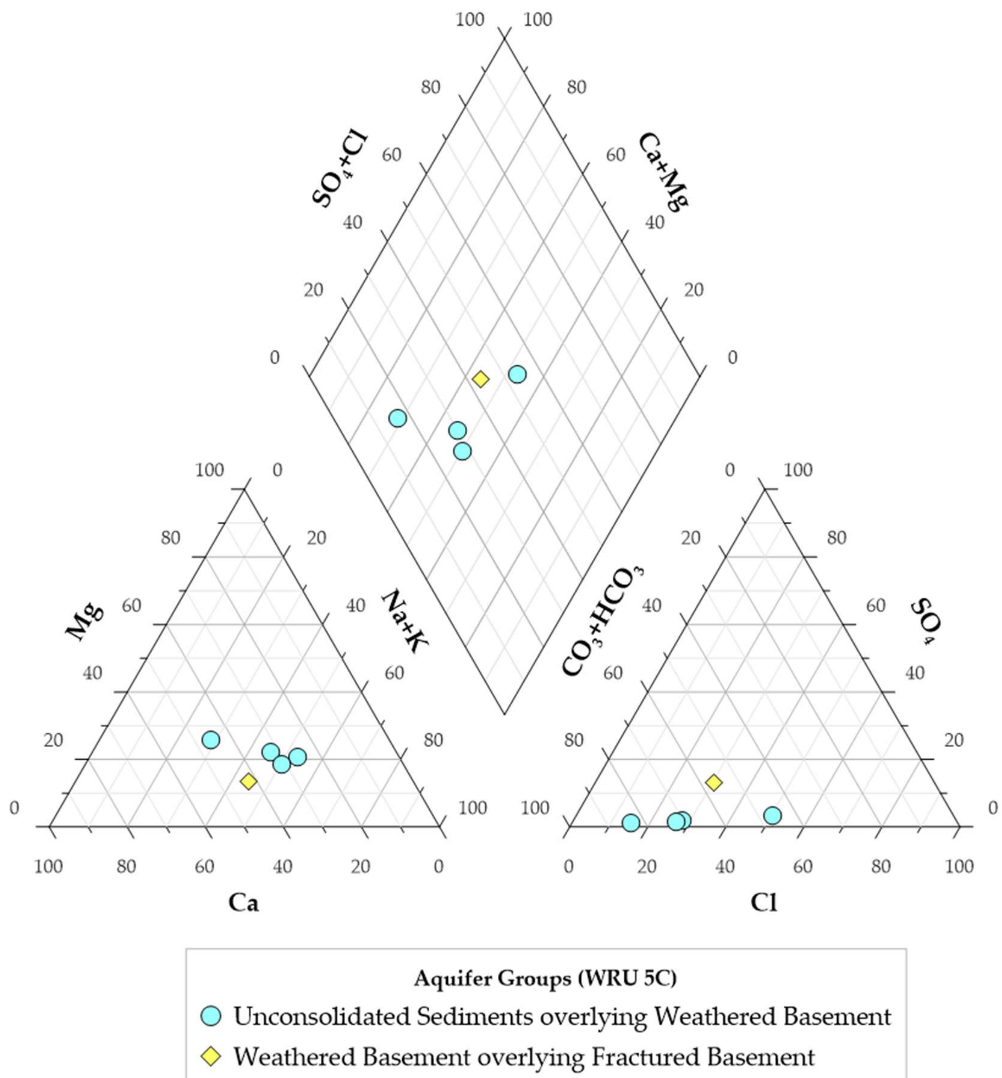
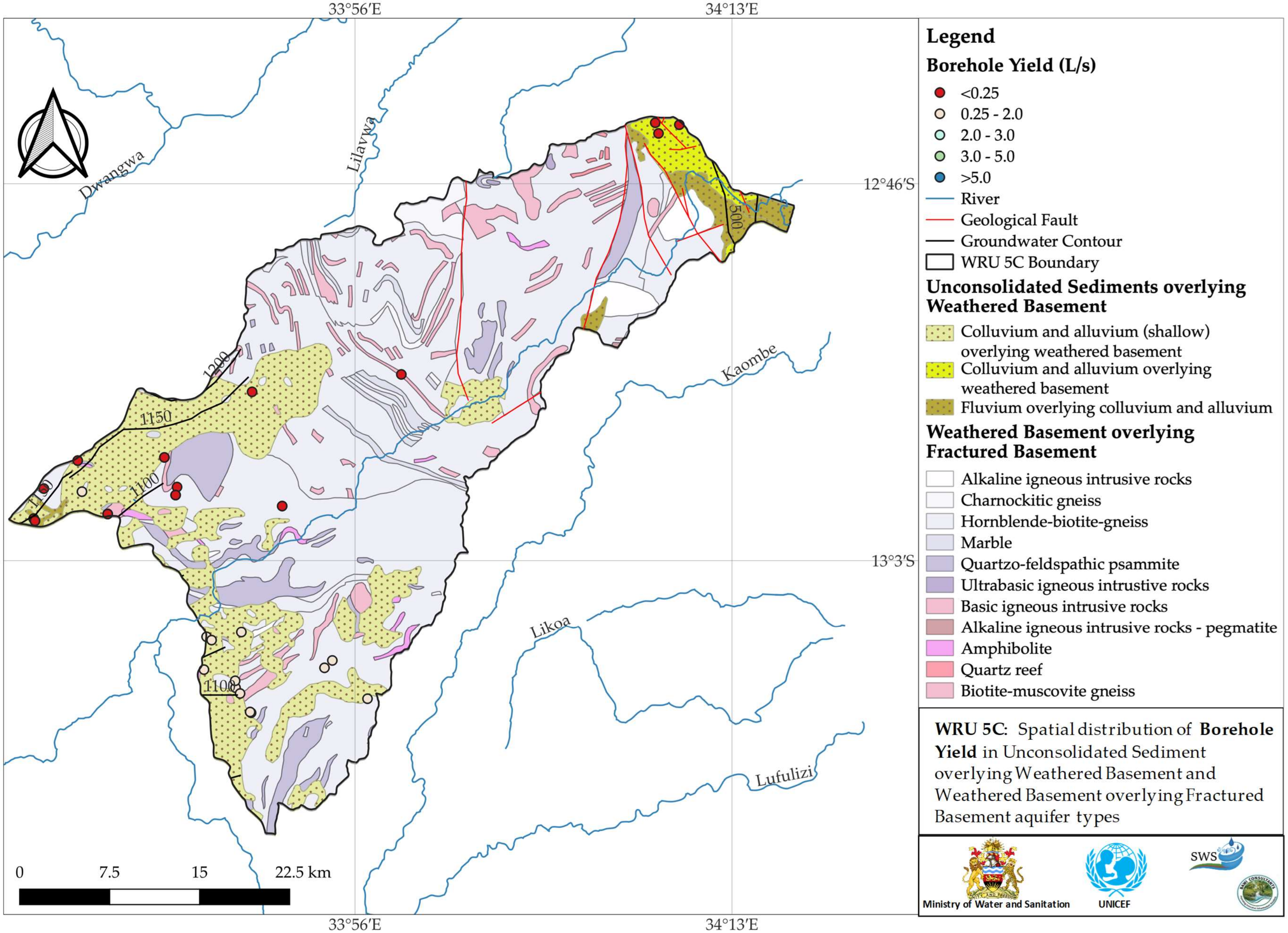


Figure WRU 5C.10 Borehole Yield Map for data held by the Ministry



WRU 5D Figures

Figure WRU 5D.1 Land Use and Major Roads

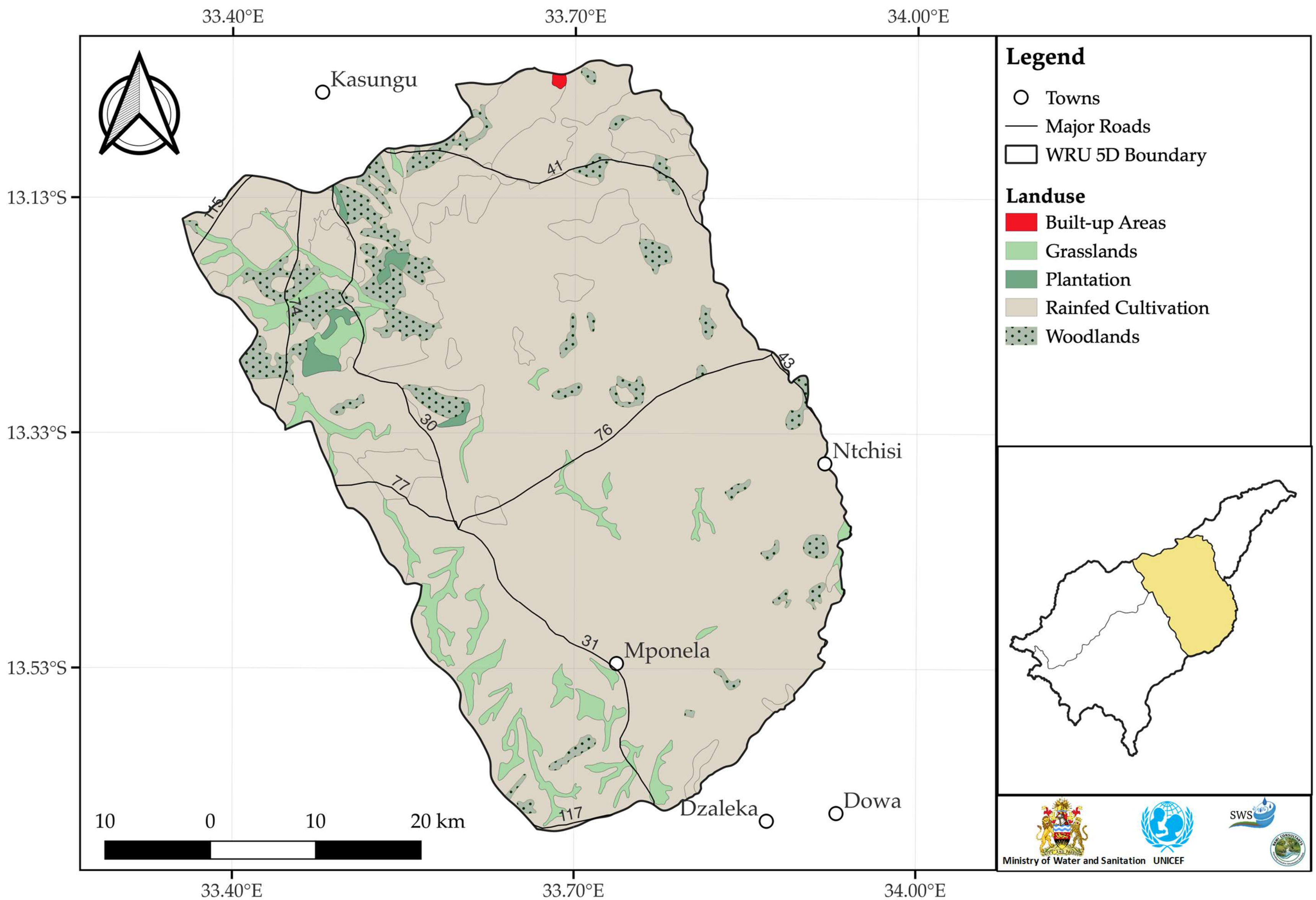


Figure WRU 5D.2 Rivers and Wetlands

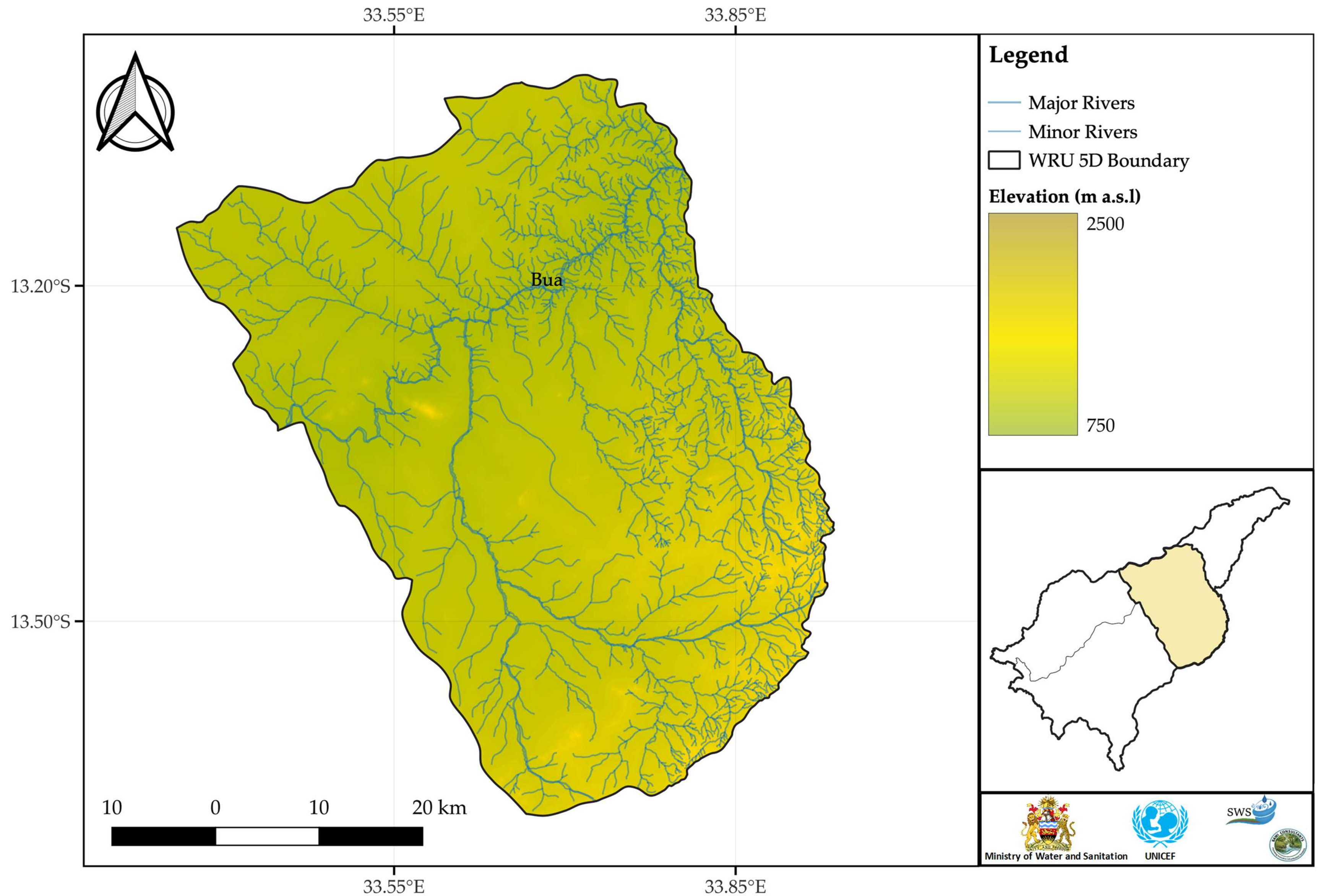


Figure WRU 5D.3 Hydrogeology Units and Water Table

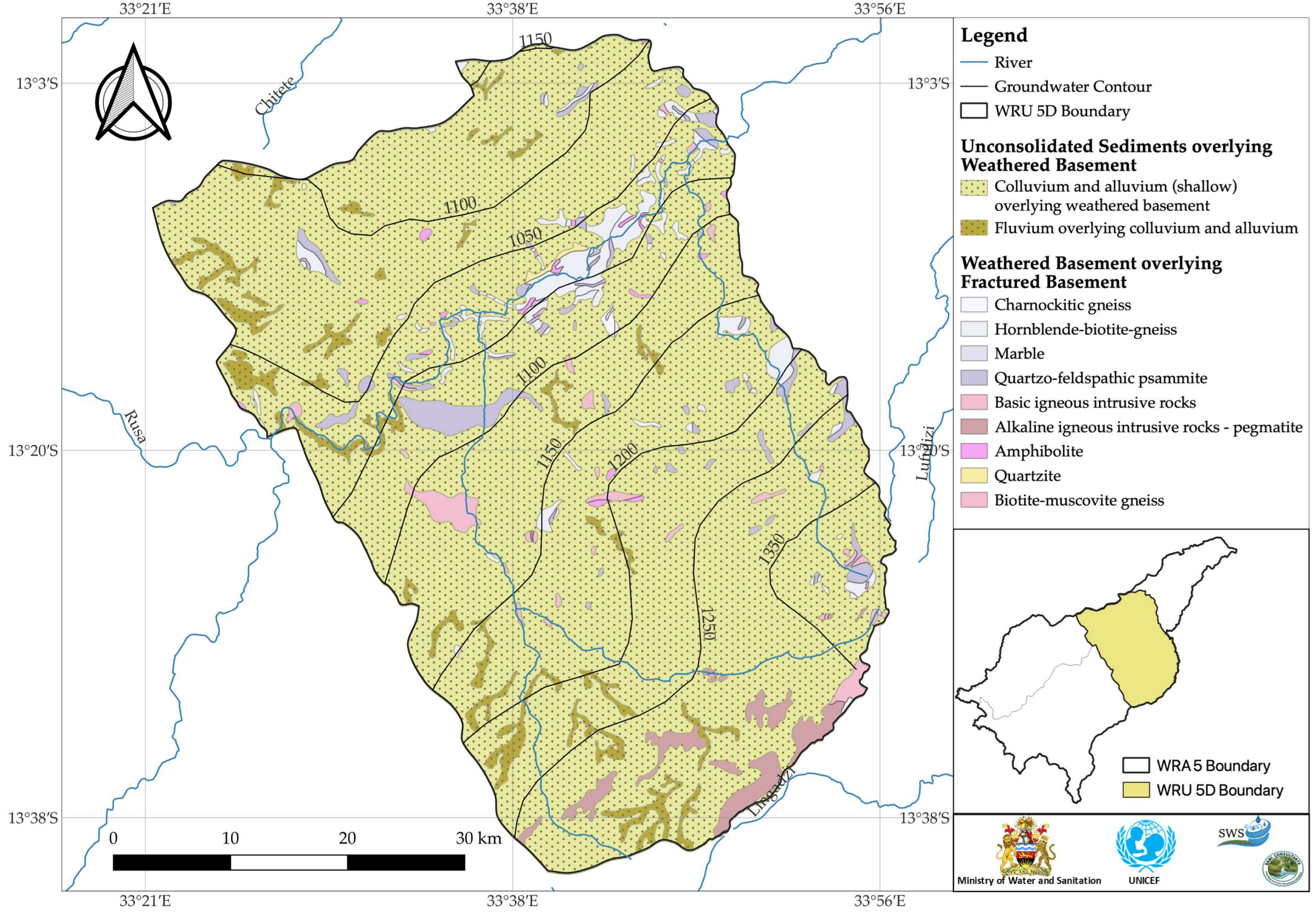


Figure WRU 5D.4 Groundwater Chemistry Distribution Electrical Conductivity

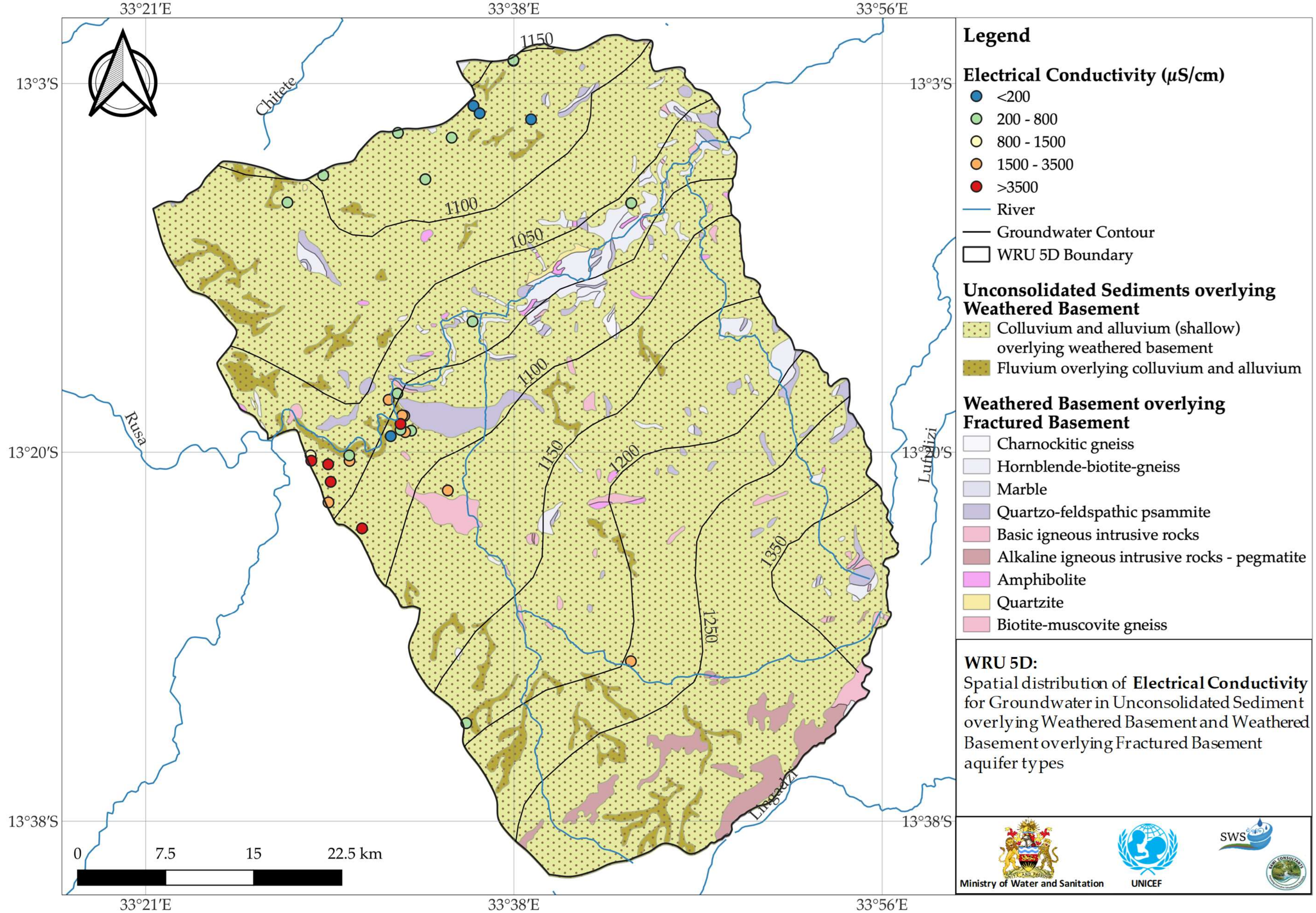
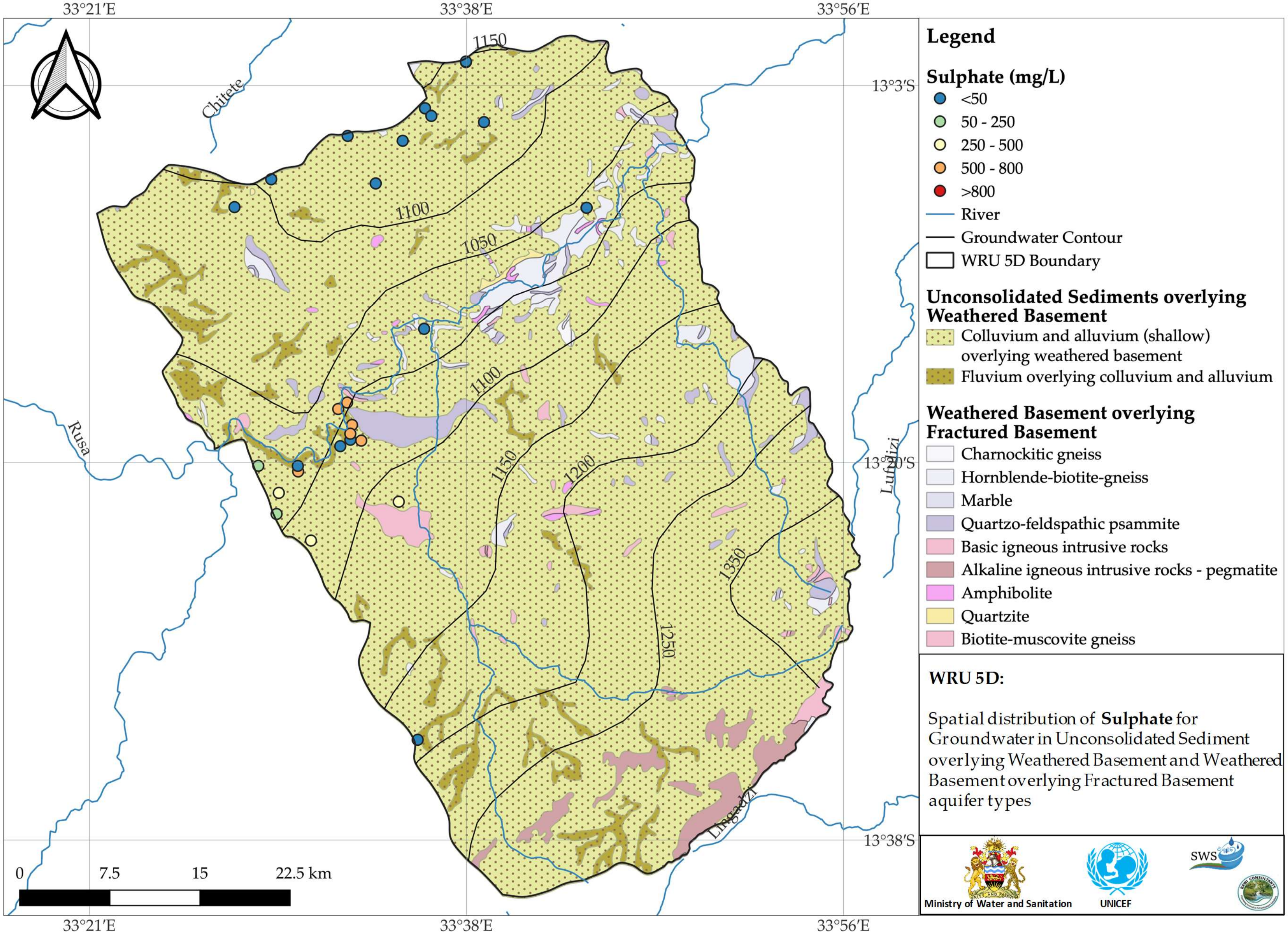


Figure WRU 5D.5 Groundwater Chemistry Distribution of Sulphate



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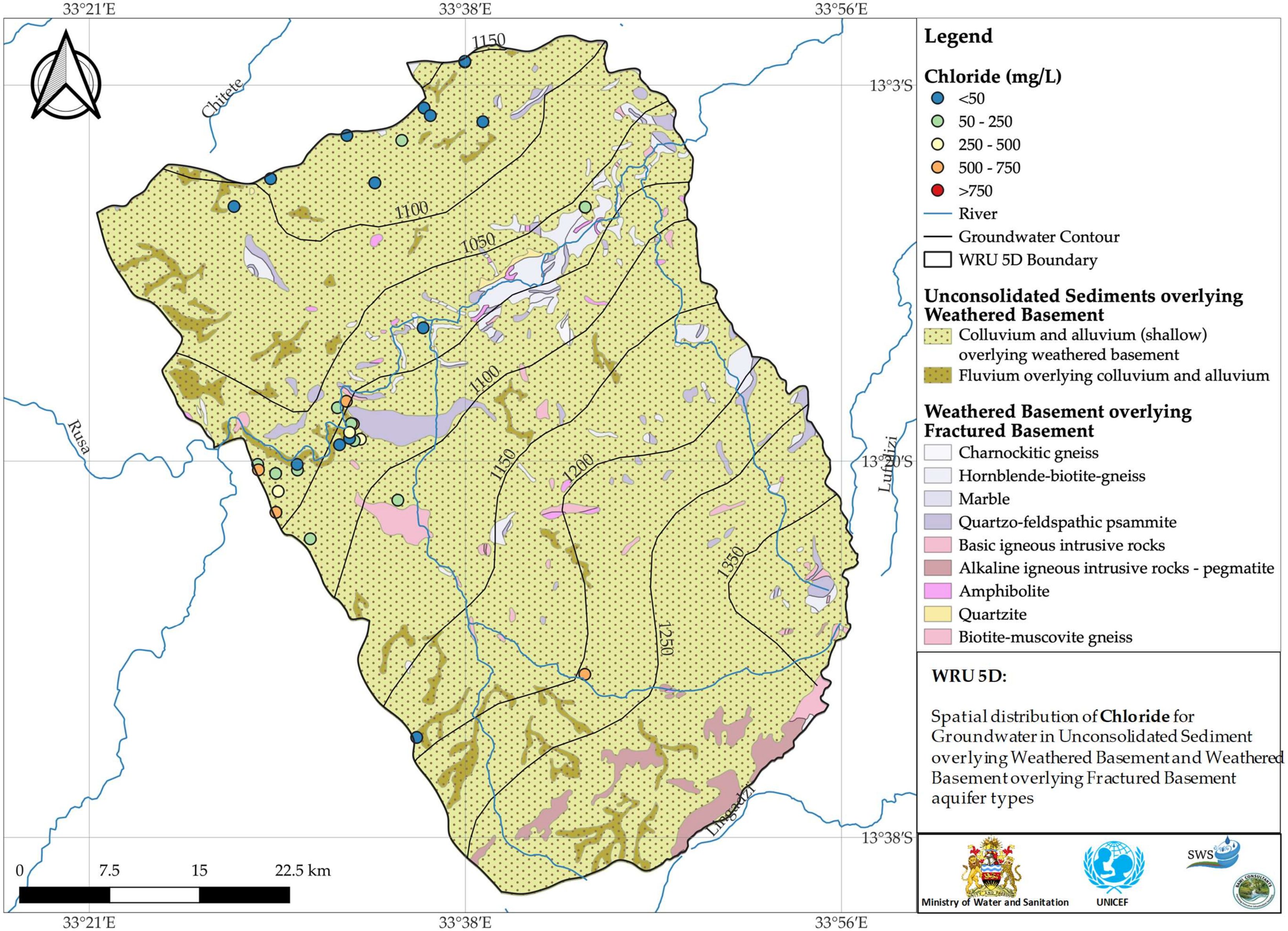

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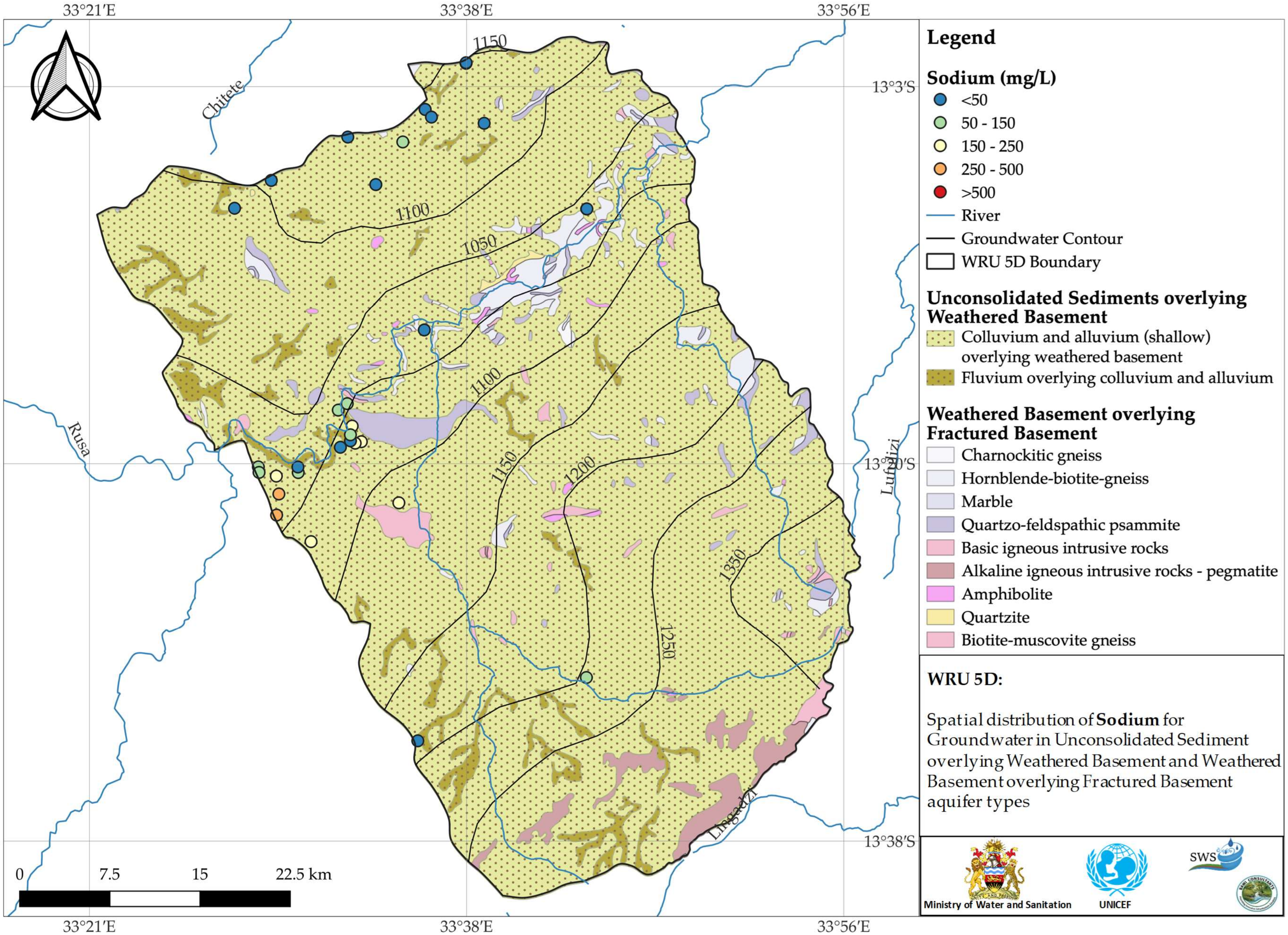


Figure WRU 5D.8 Groundwater Chemistry Distribution Calcium

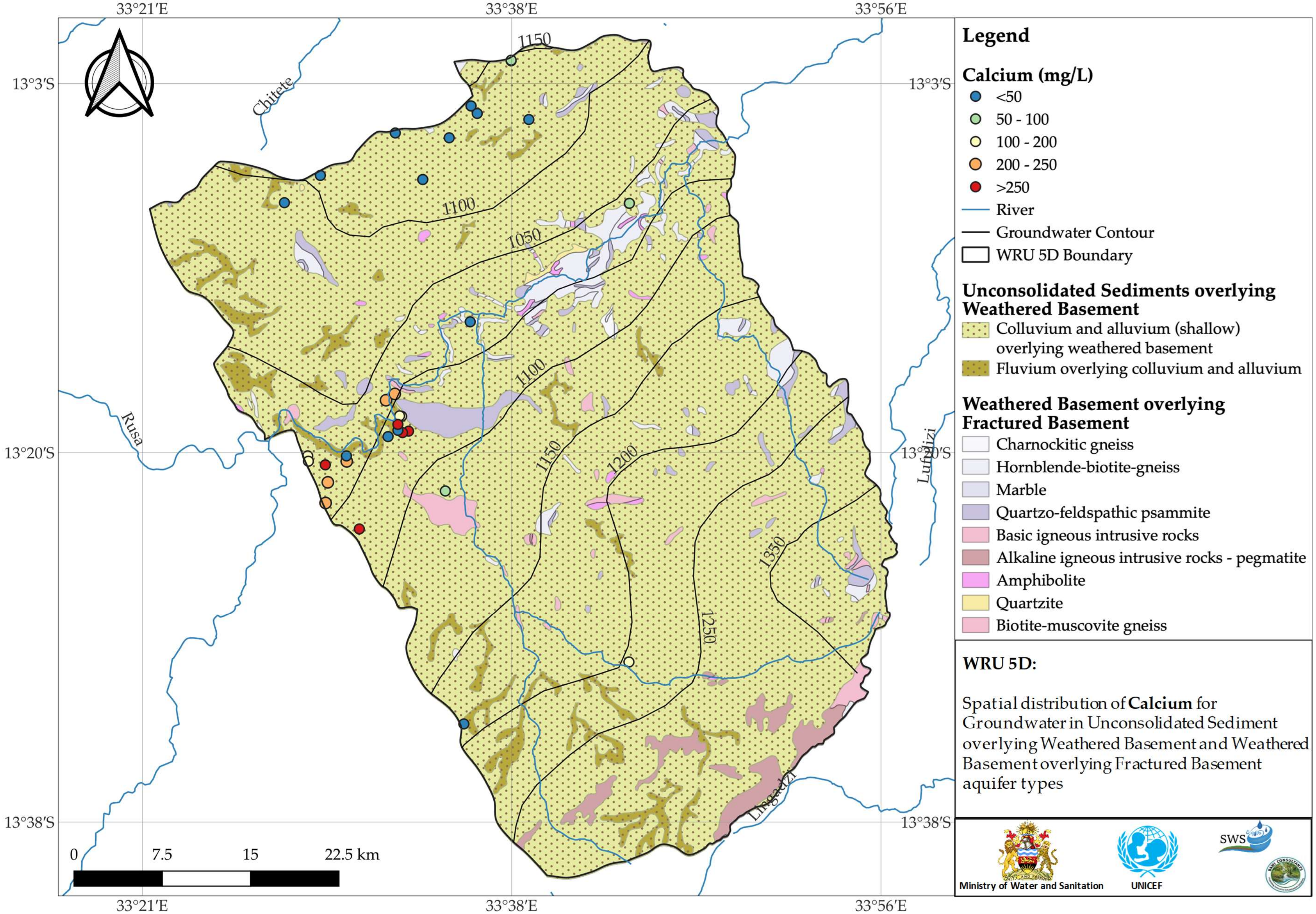


Figure WRU 5D.9 Piper Diagram of water quality results with respect to the major aquifer type

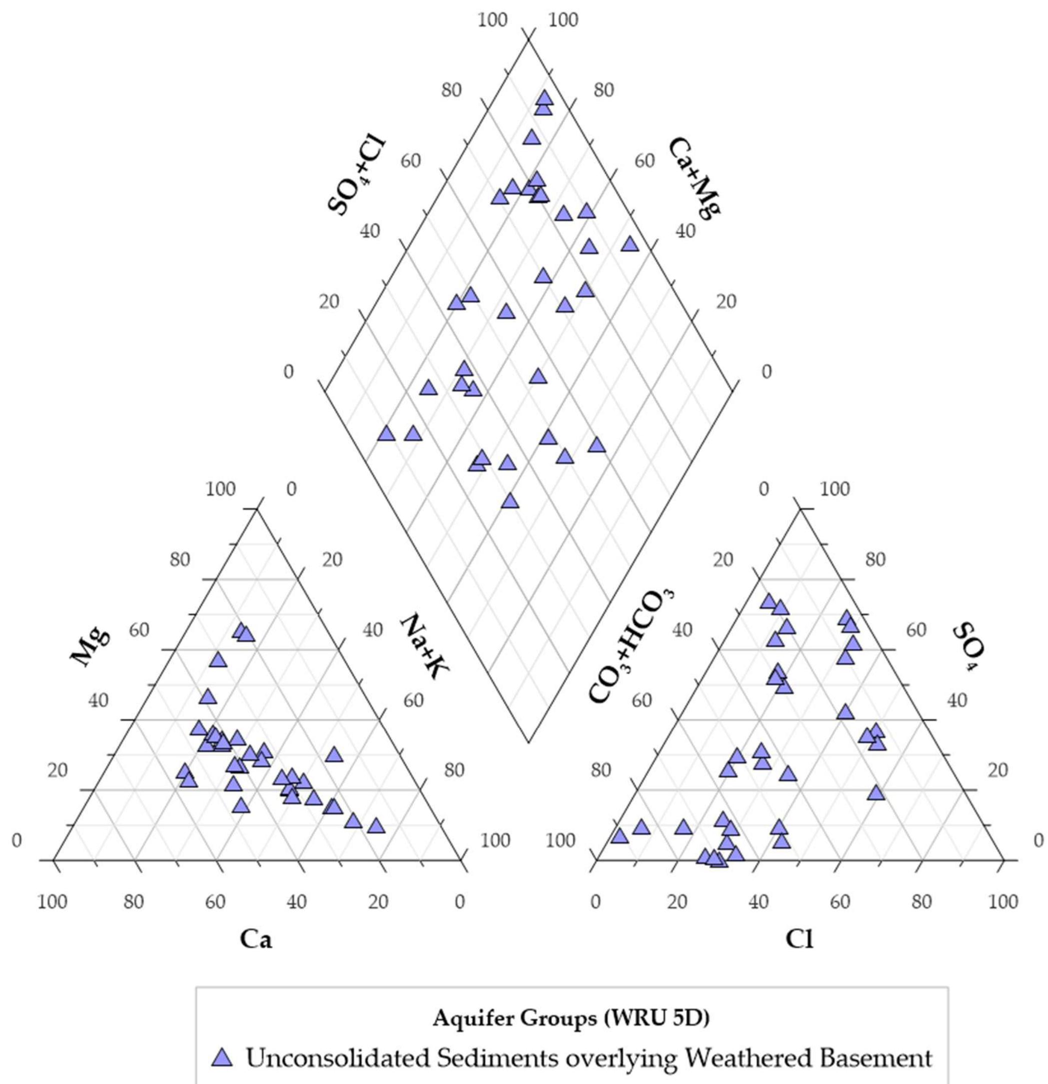
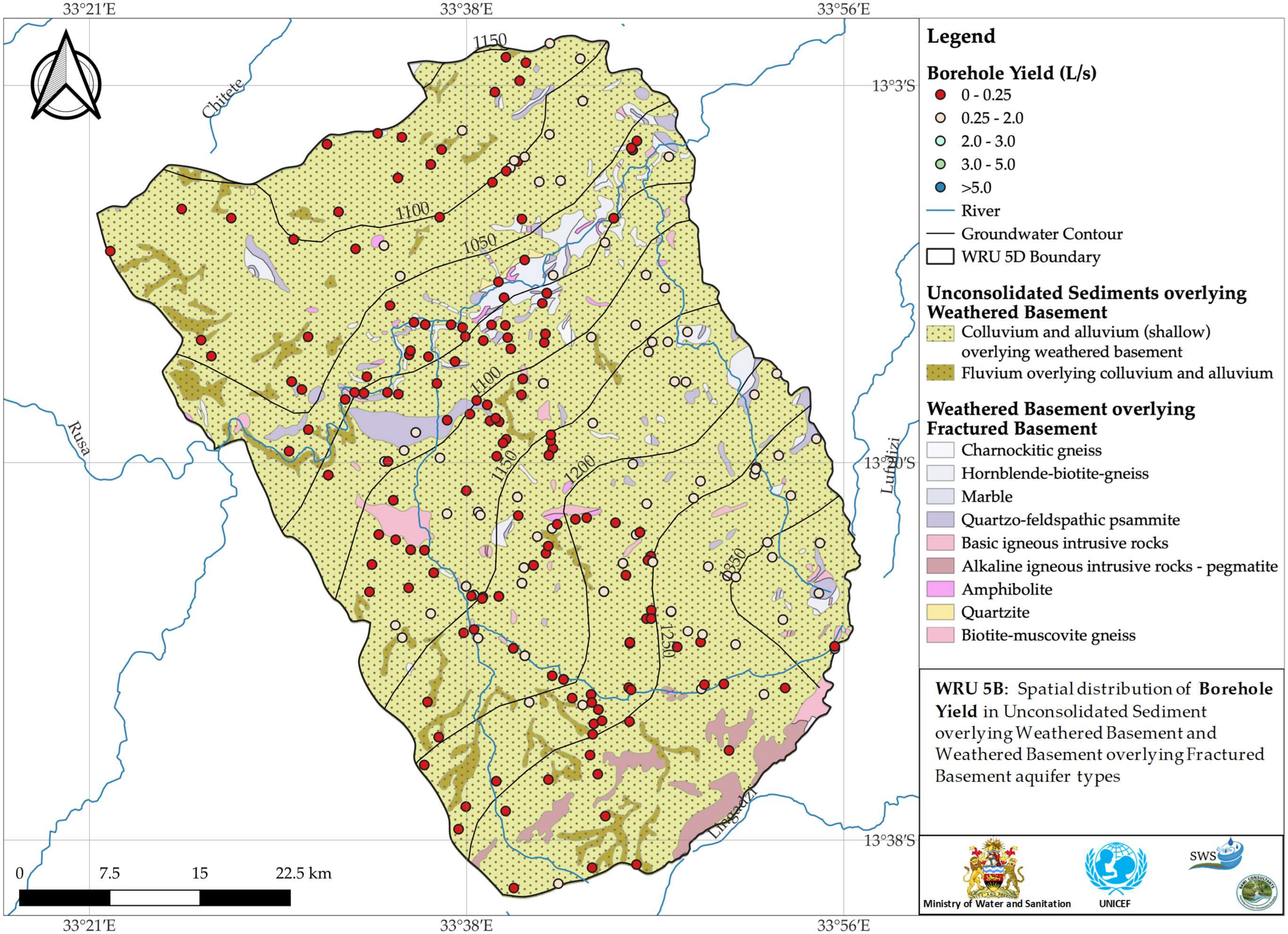


Figure WRU 5D.10 Borehole Yield Map for data held by the Ministry



WRU 5E Figures

Figure WRU 5E.1 Land Use and Major Roads

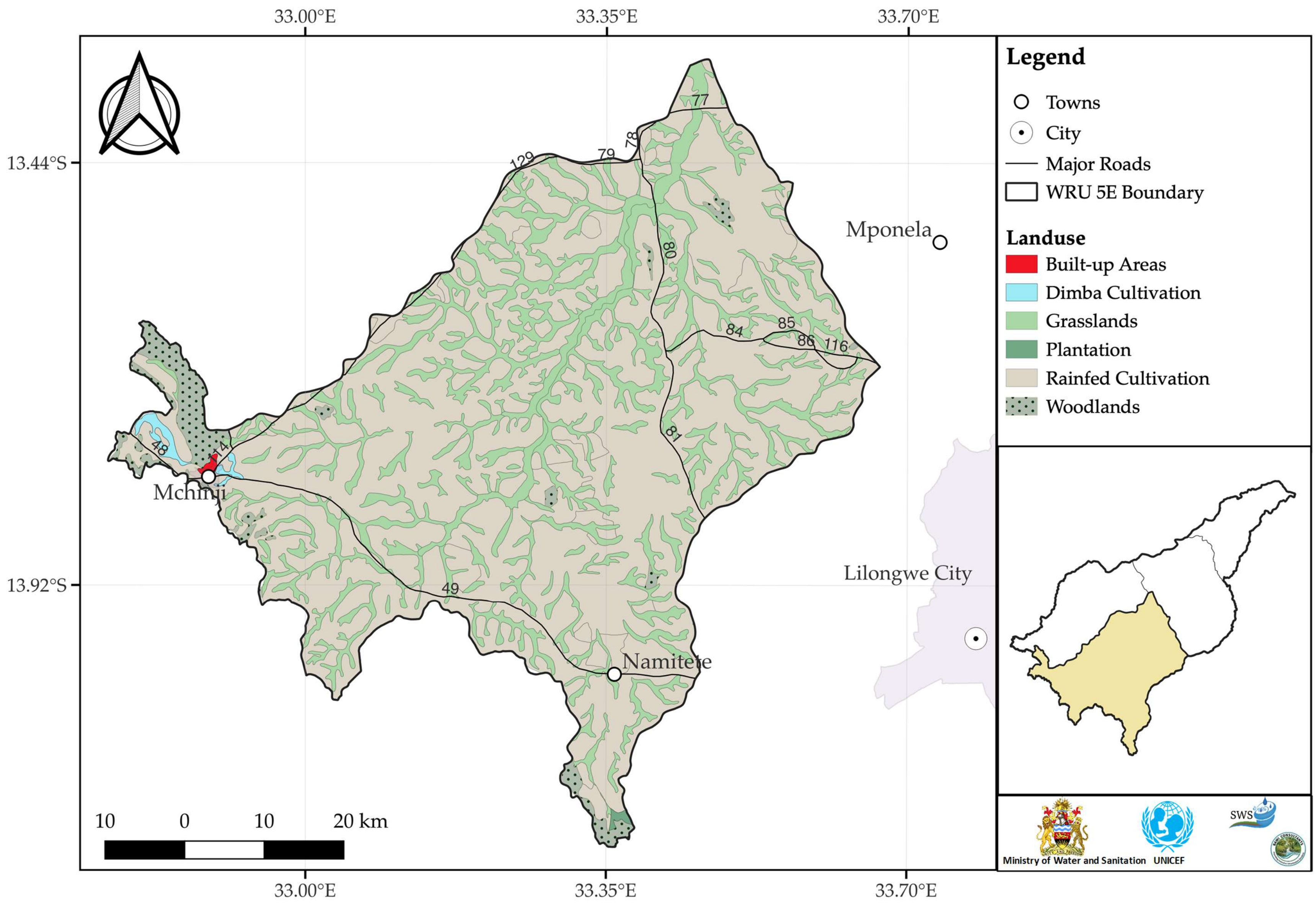


Figure WRU 5E.2 Rivers and Wetlands

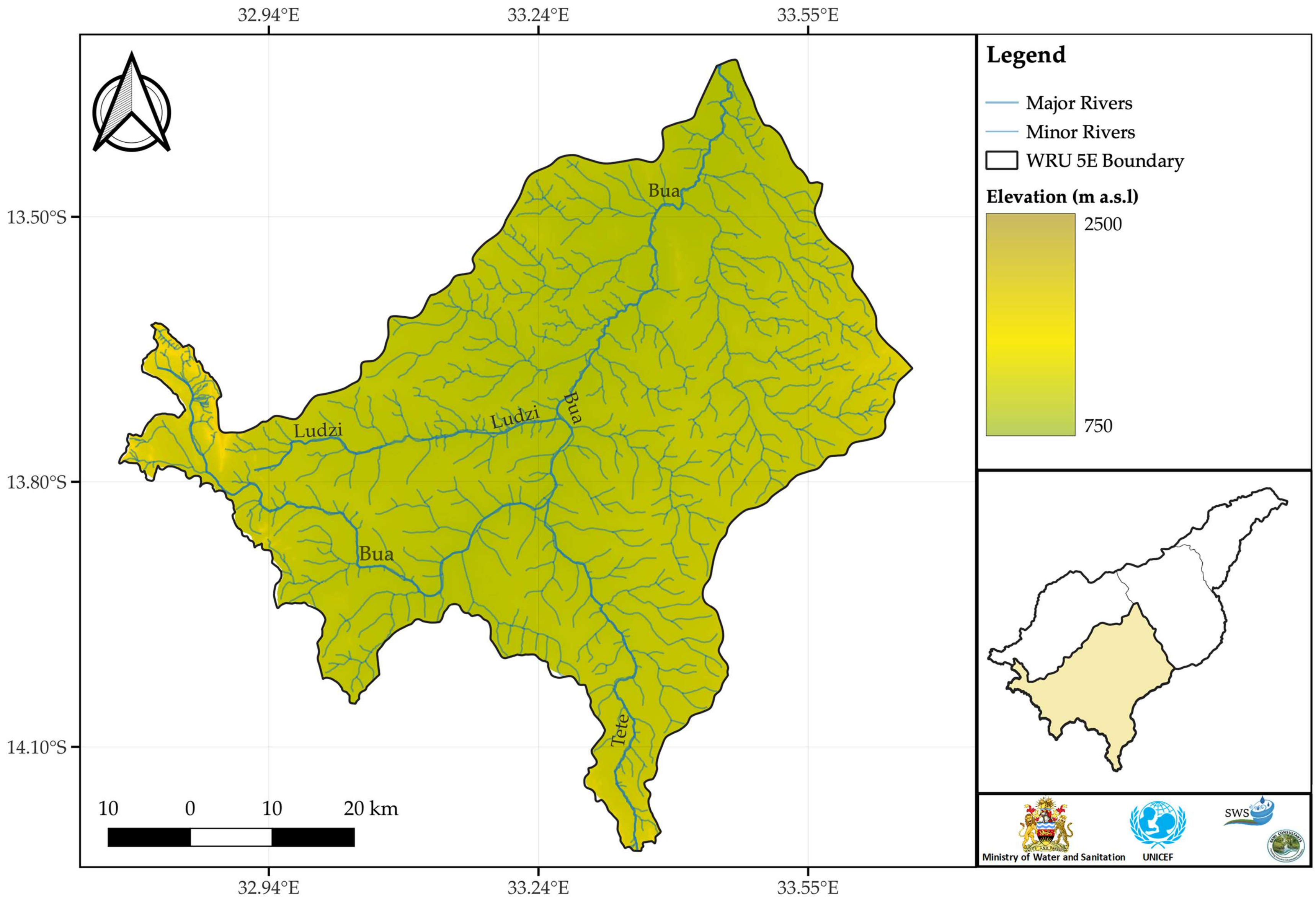


Figure WRU 5E.3 Hydrogeology Units and Water Table

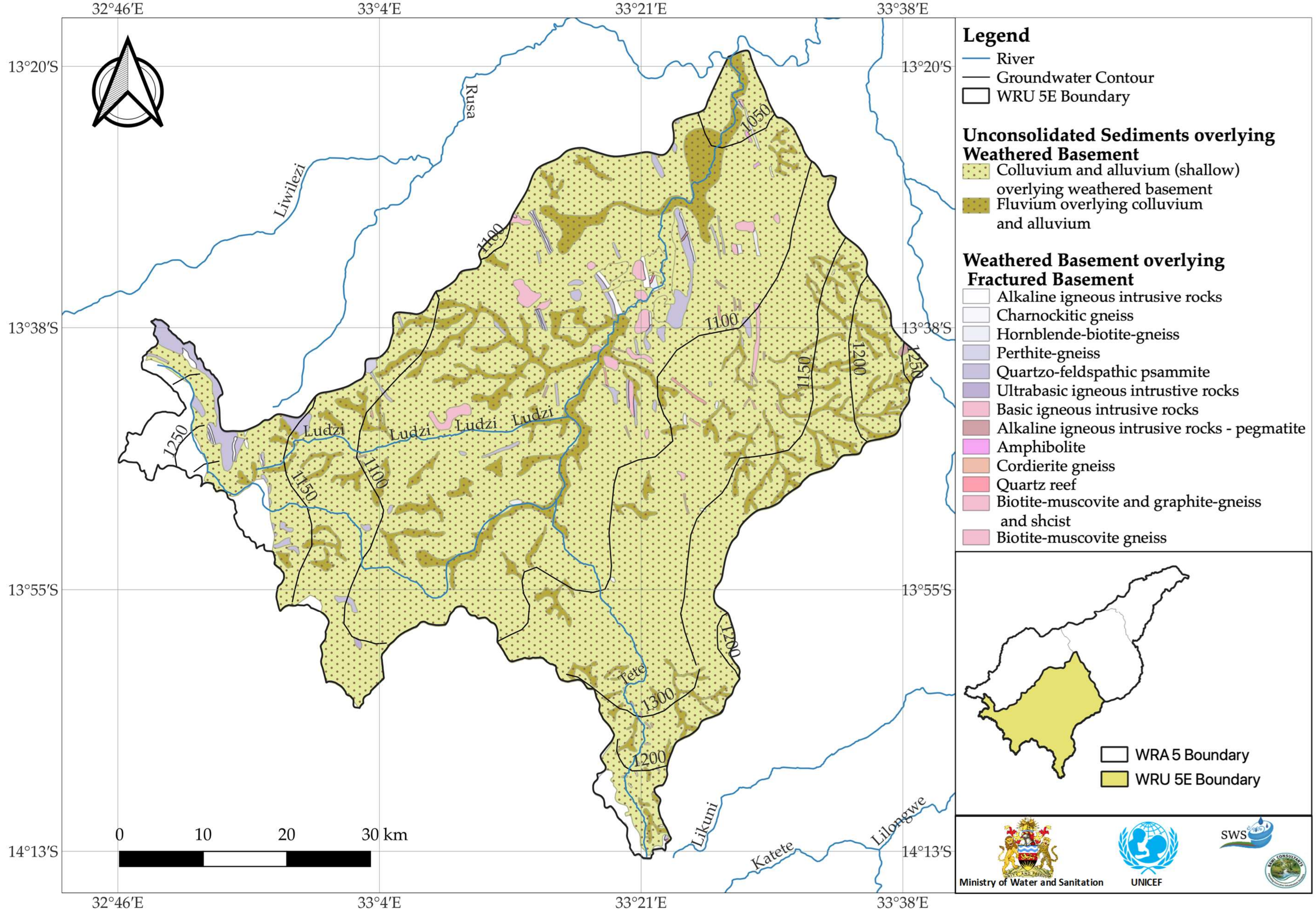


Figure WRU 5E.4 Groundwater Chemistry Distribution Electrical Conductivity

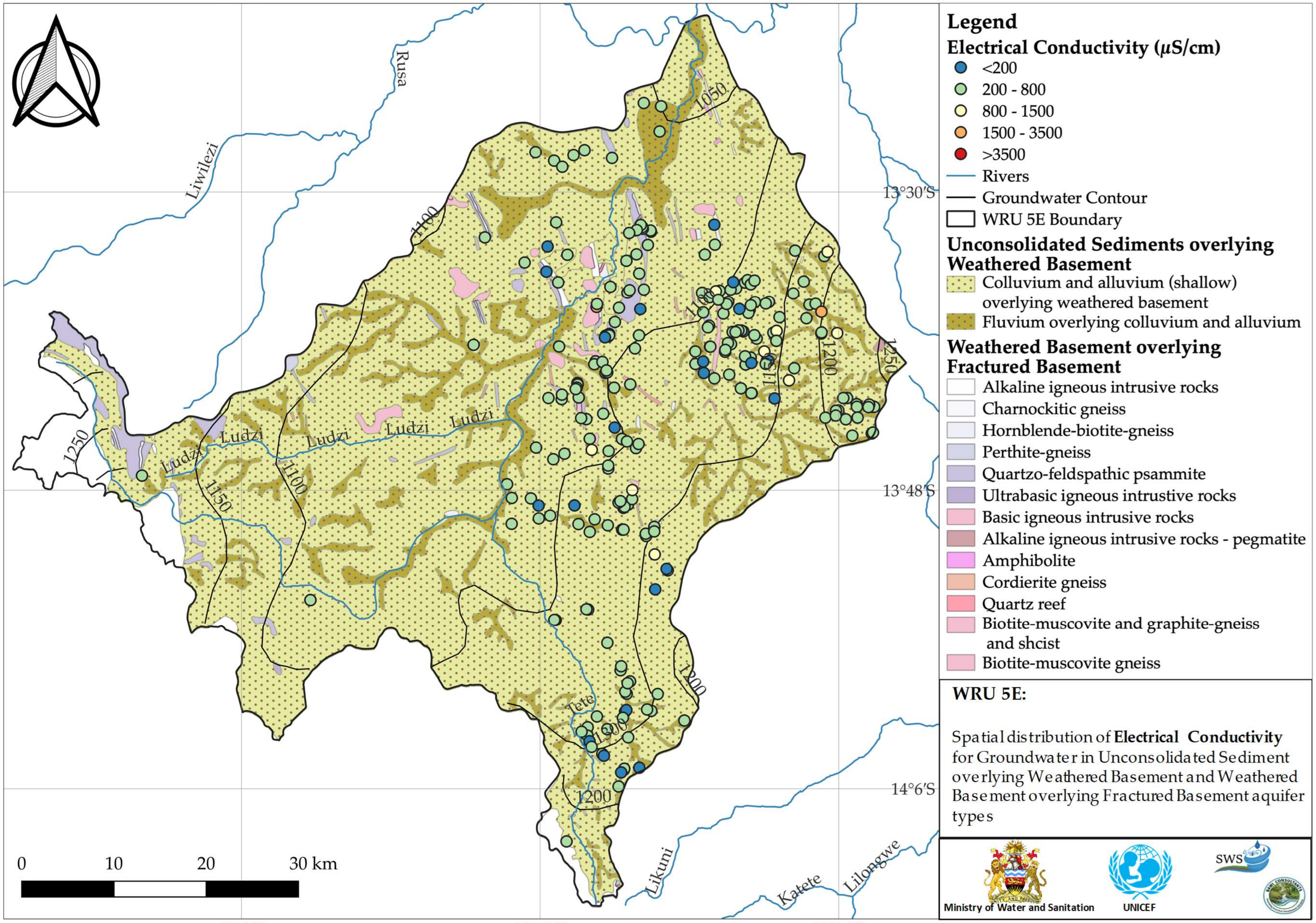


Figure WRU 5E.5 Groundwater Chemistry Distribution of Sulphate

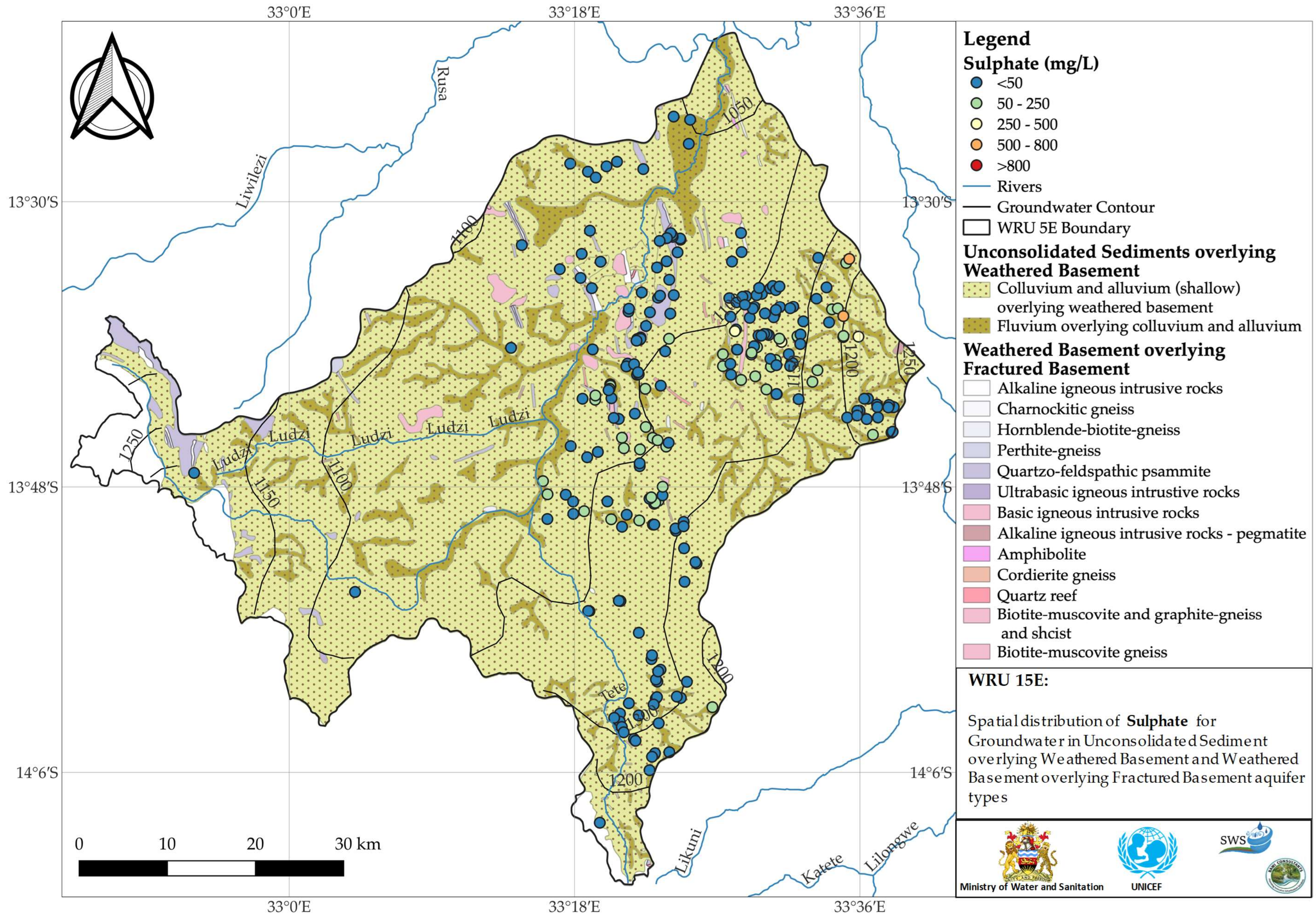


Figure WRU 5E.6 Groundwater Chemistry Distribution Chloride

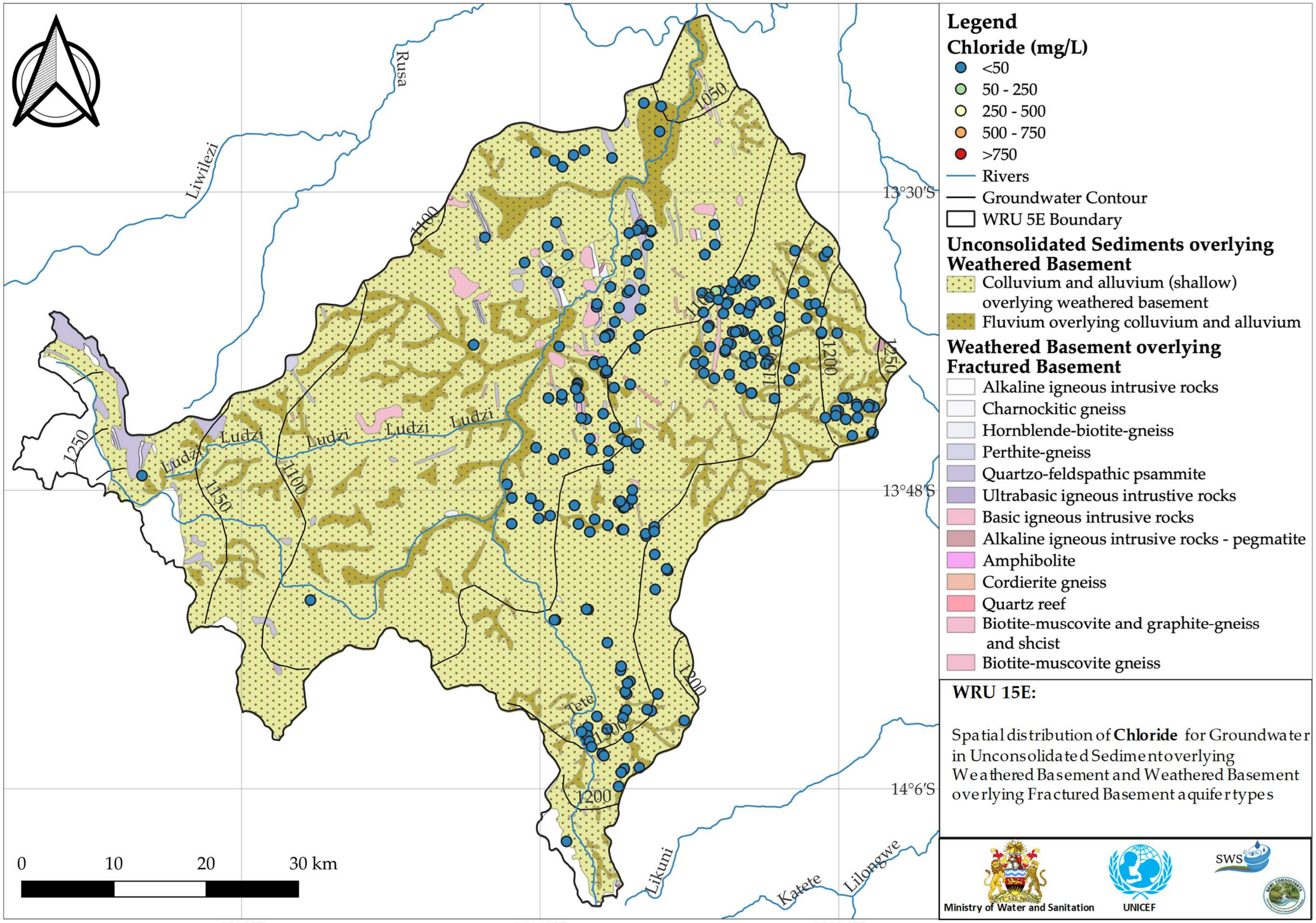


Figure WRU 5E.7 Groundwater Chemistry Distribution Sodium

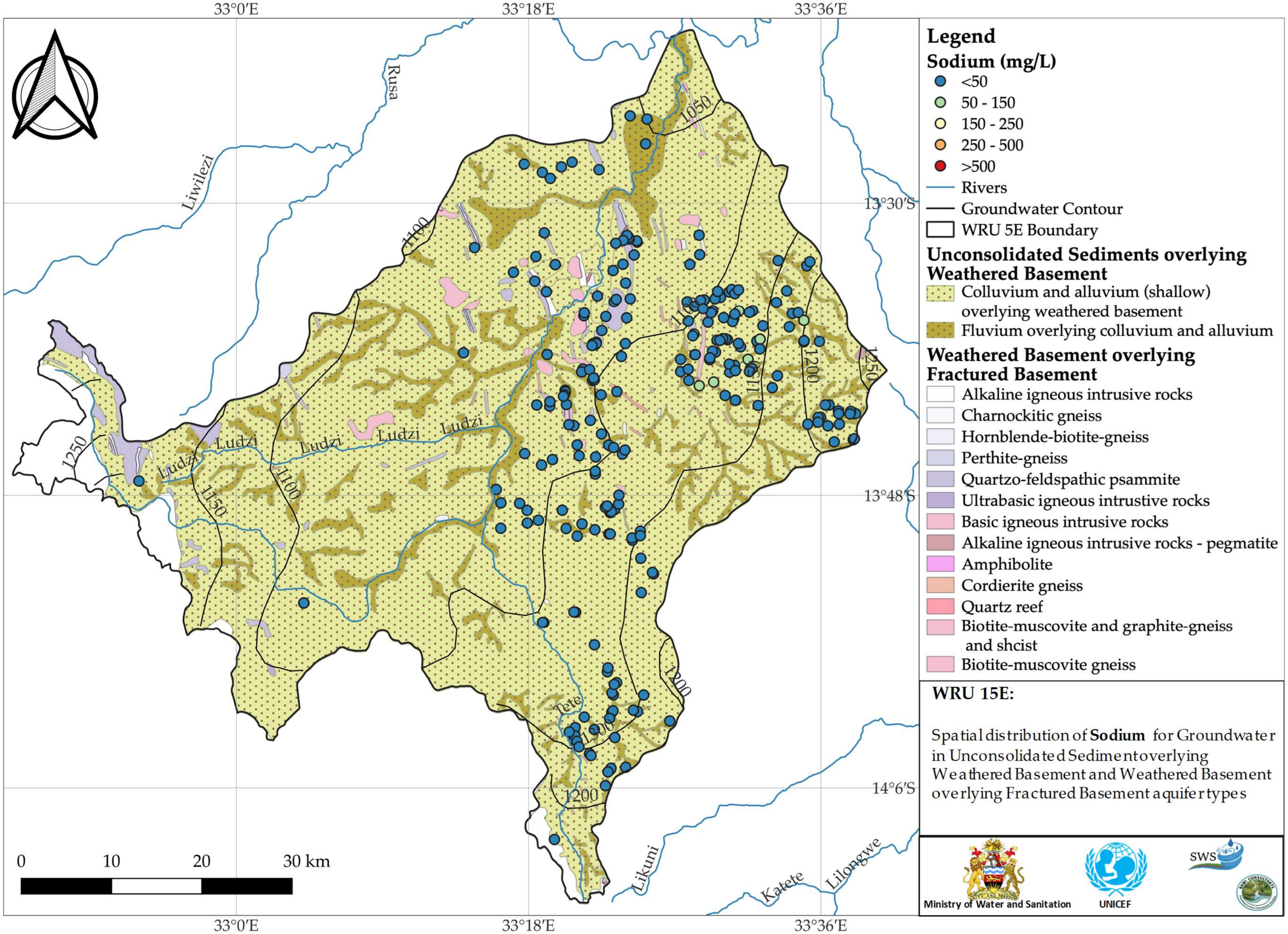


Figure WRU 5E.8 Groundwater Chemistry Distribution Calcium

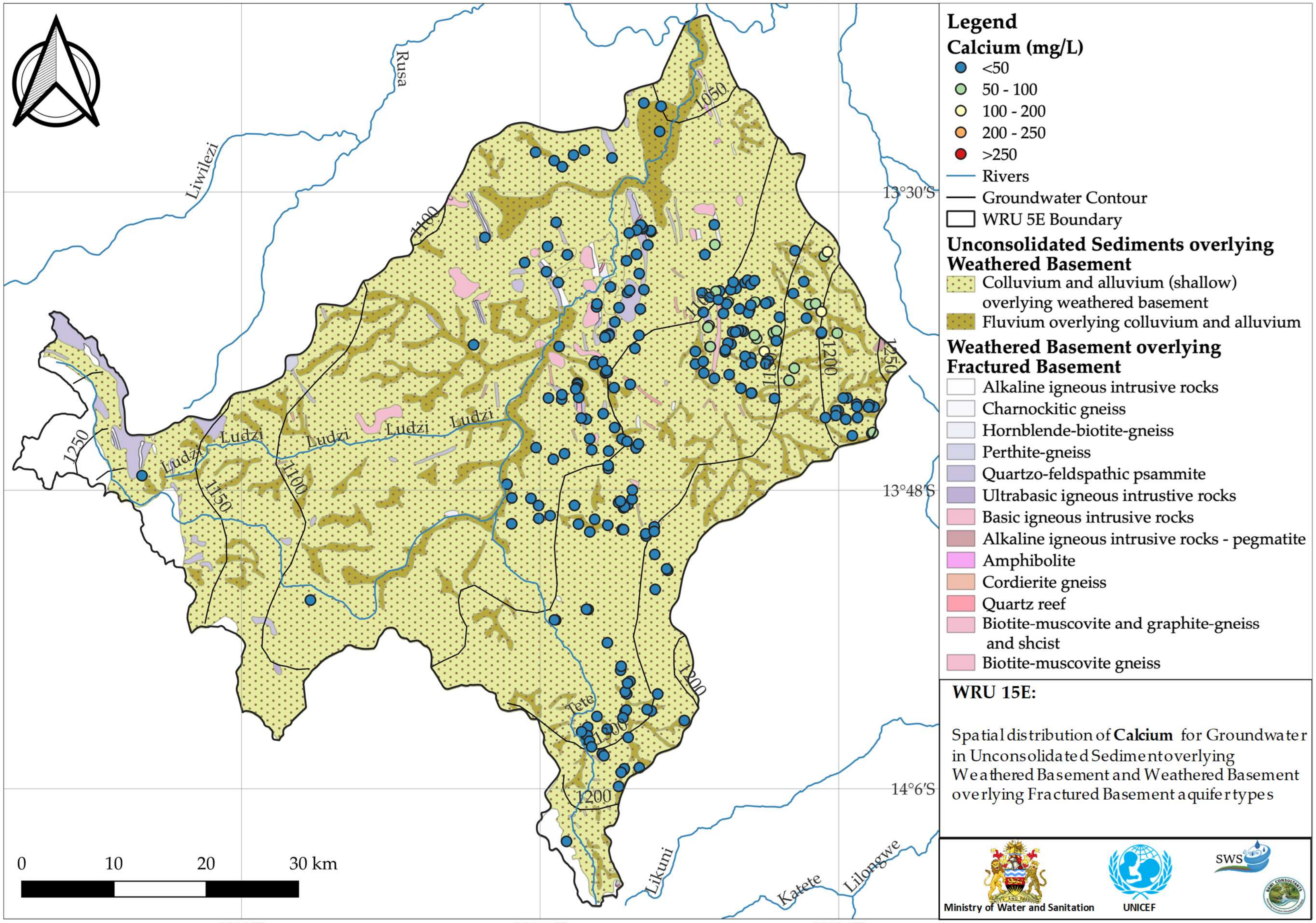


Figure WRU 5E.9 Piper Diagram of water quality results with respect to the major aquifer type

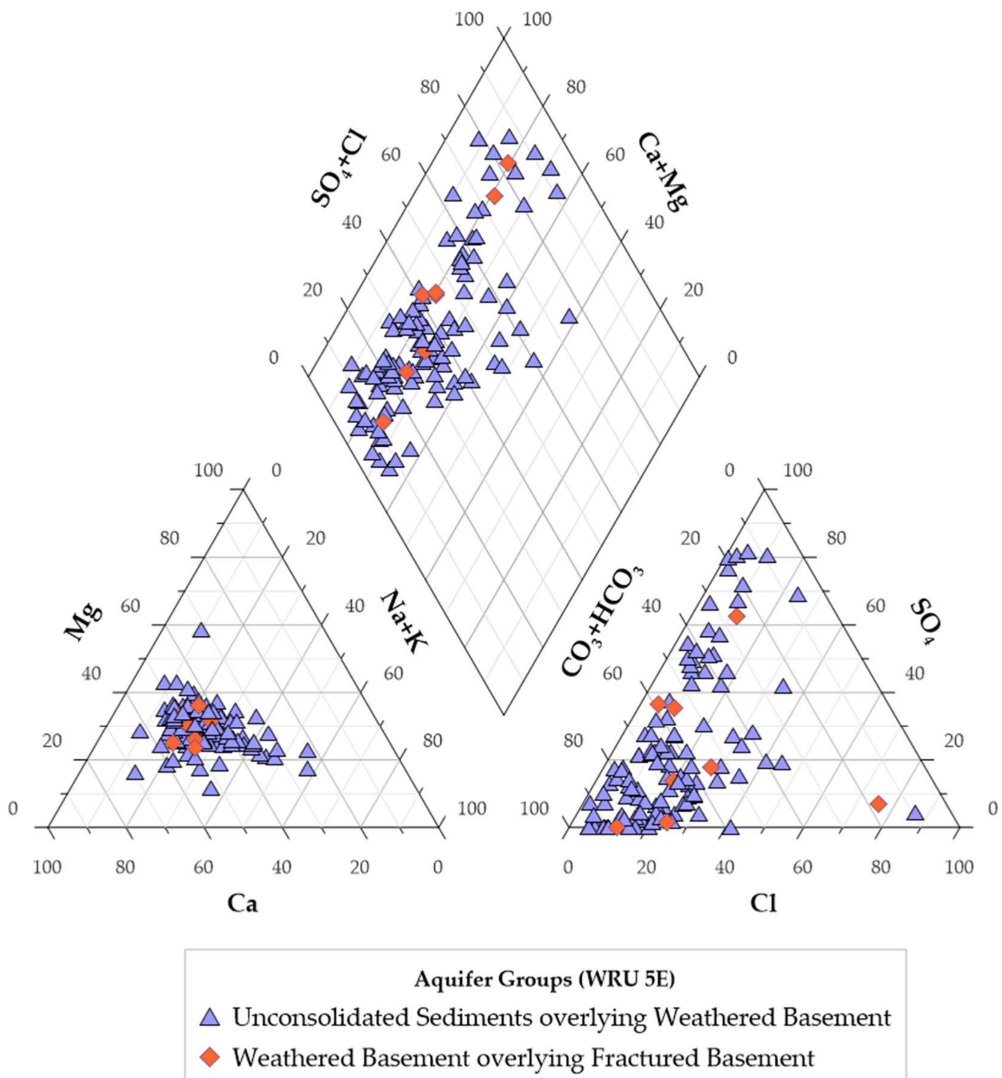
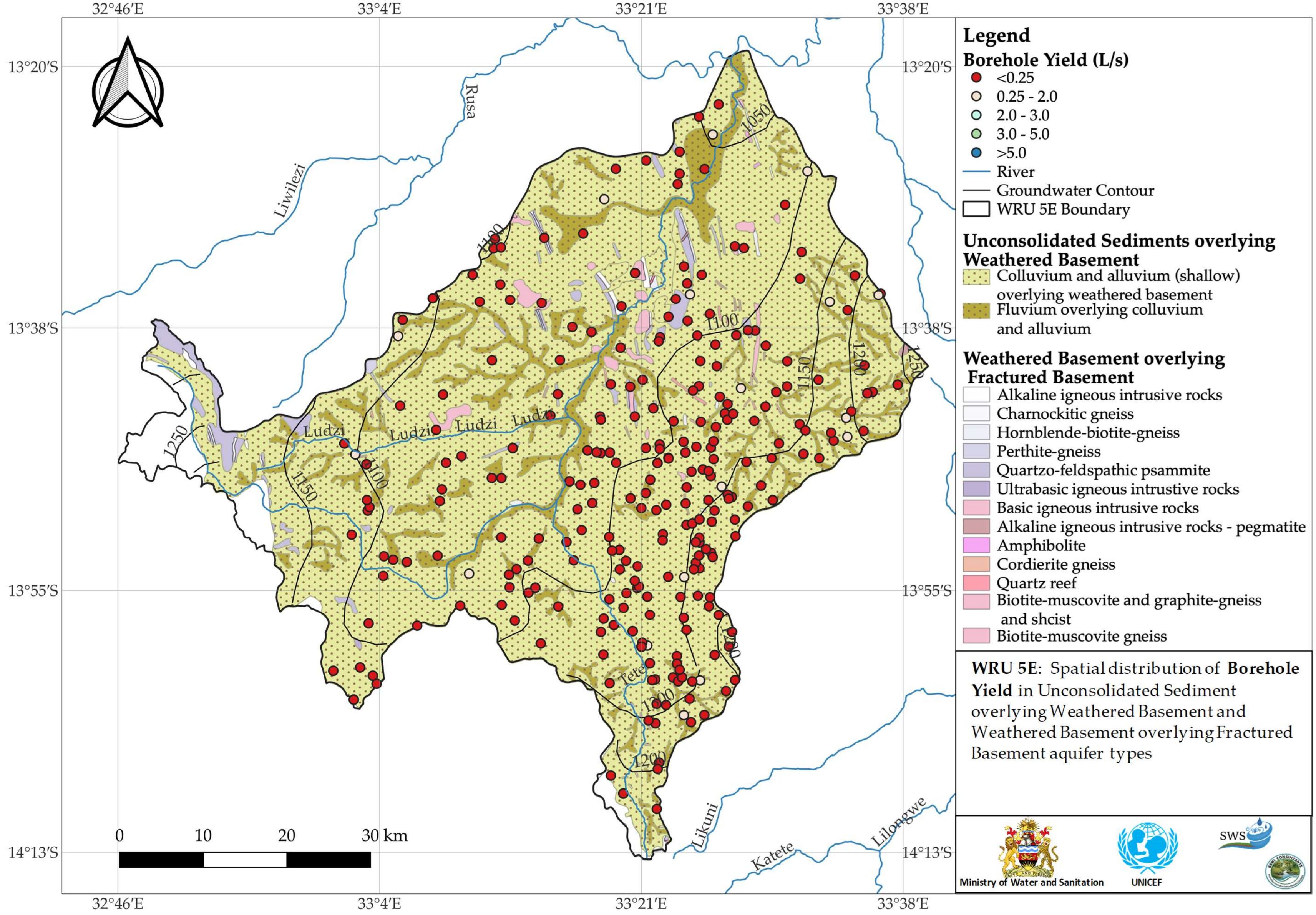


Figure WRU 5E.10 Borehole Yield Map for data held by the Ministry



WRU 5F Figures

Figure WRU 5F.1 Land Use and Major Roads

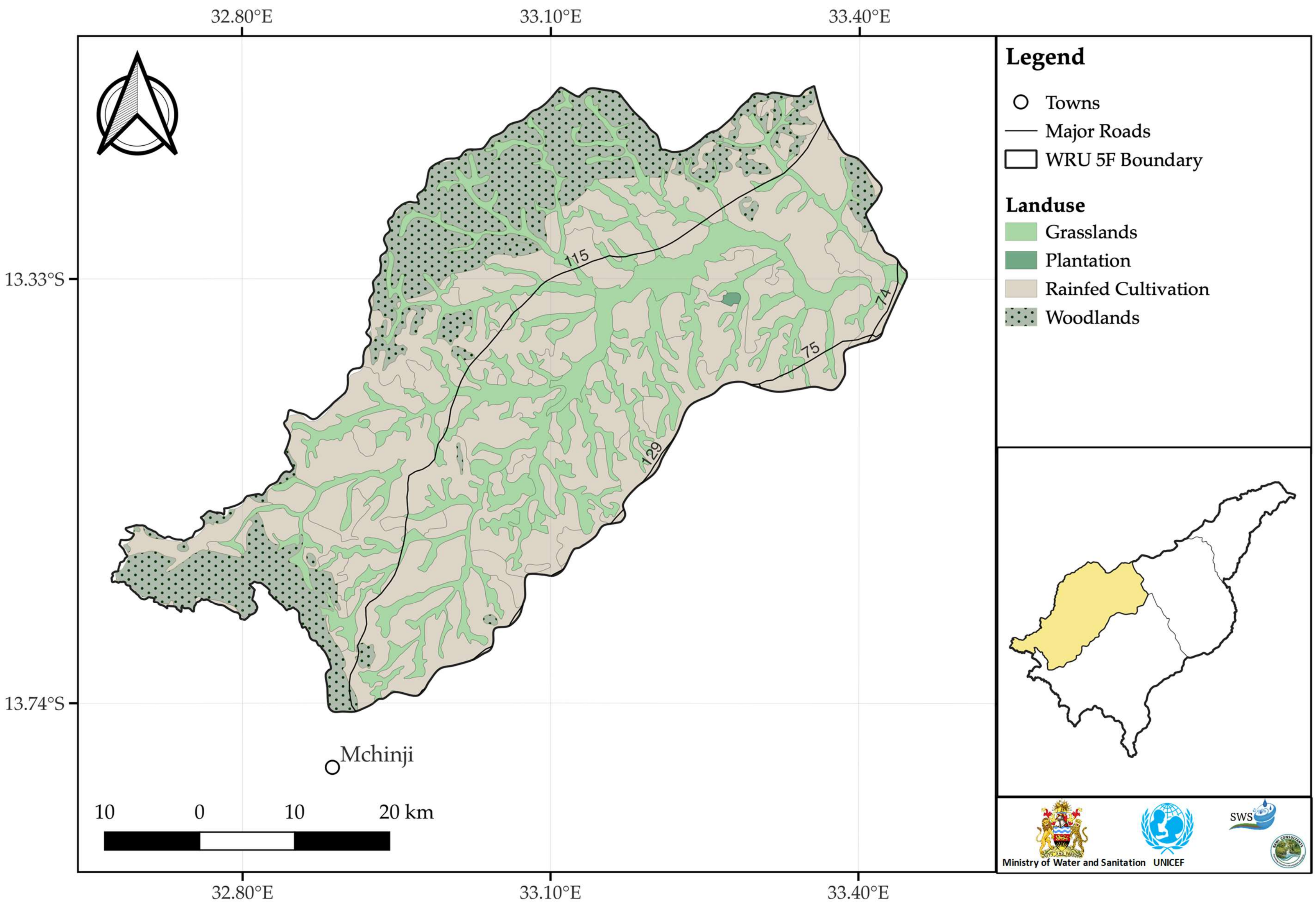


Figure WRU 5F.2 Rivers and Wetlands

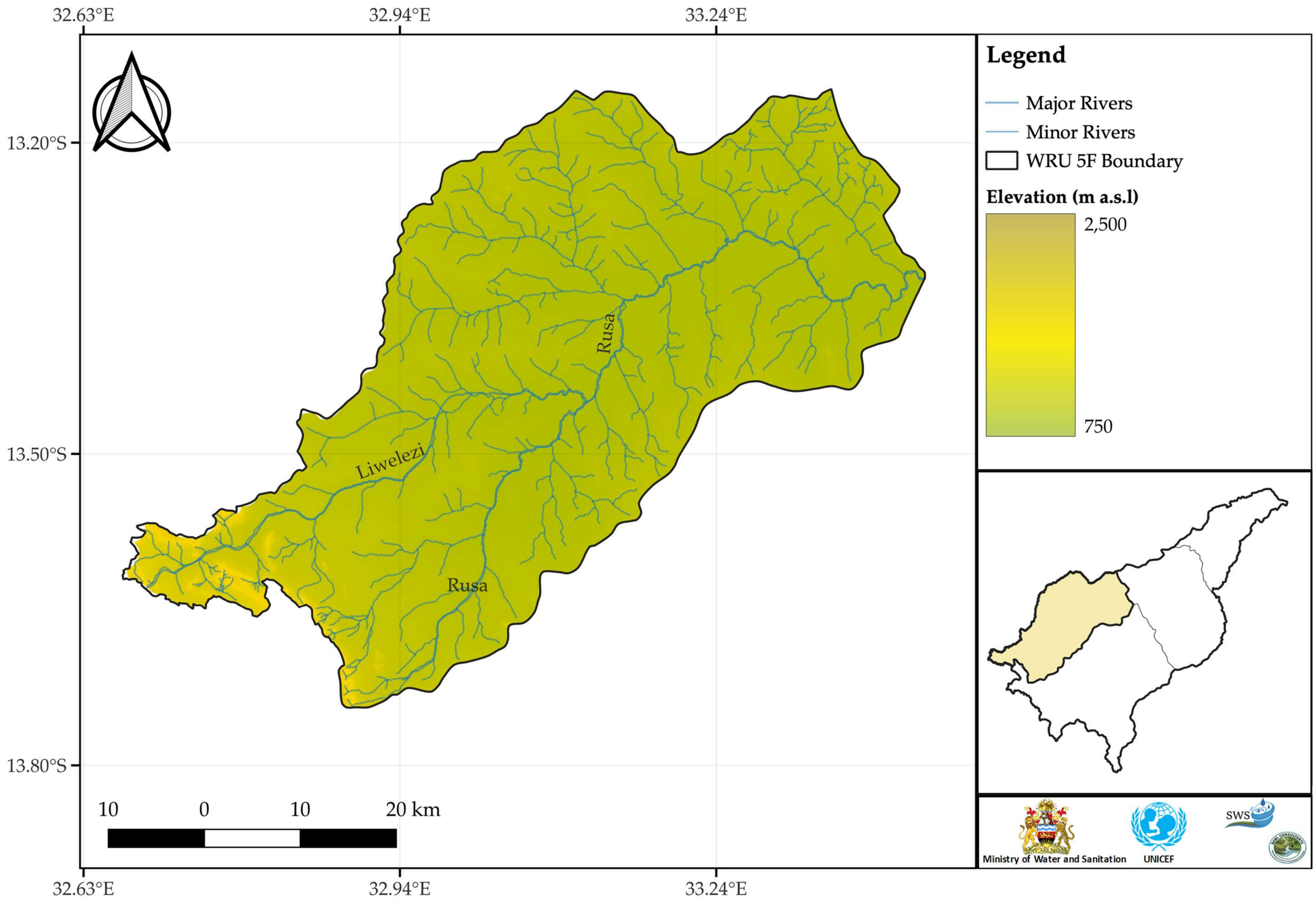


Figure WRU 5F.3 Hydrogeology Units and Water Table

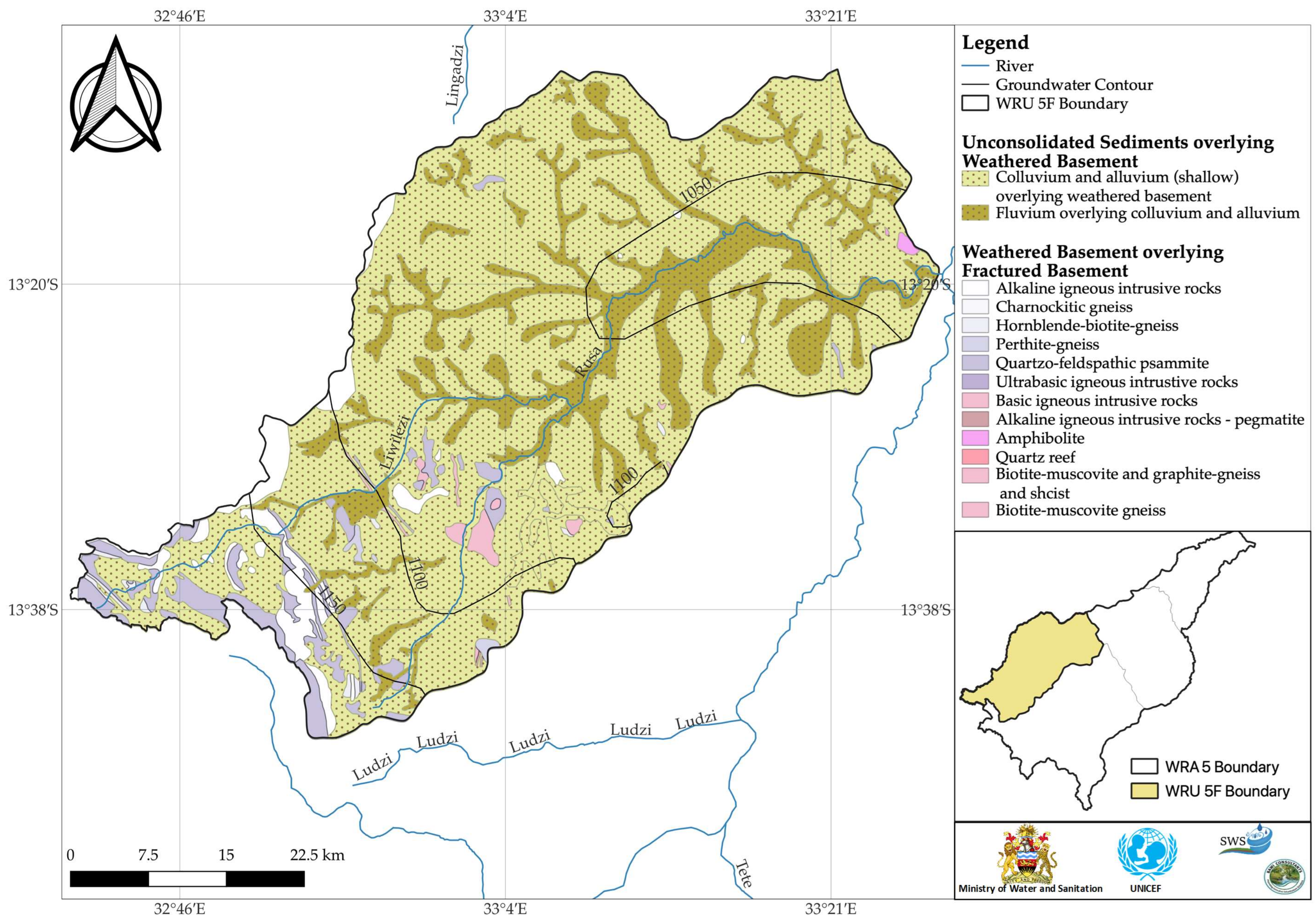


Figure WRU 5F.4 Groundwater Chemistry Distribution Electrical Conductivity

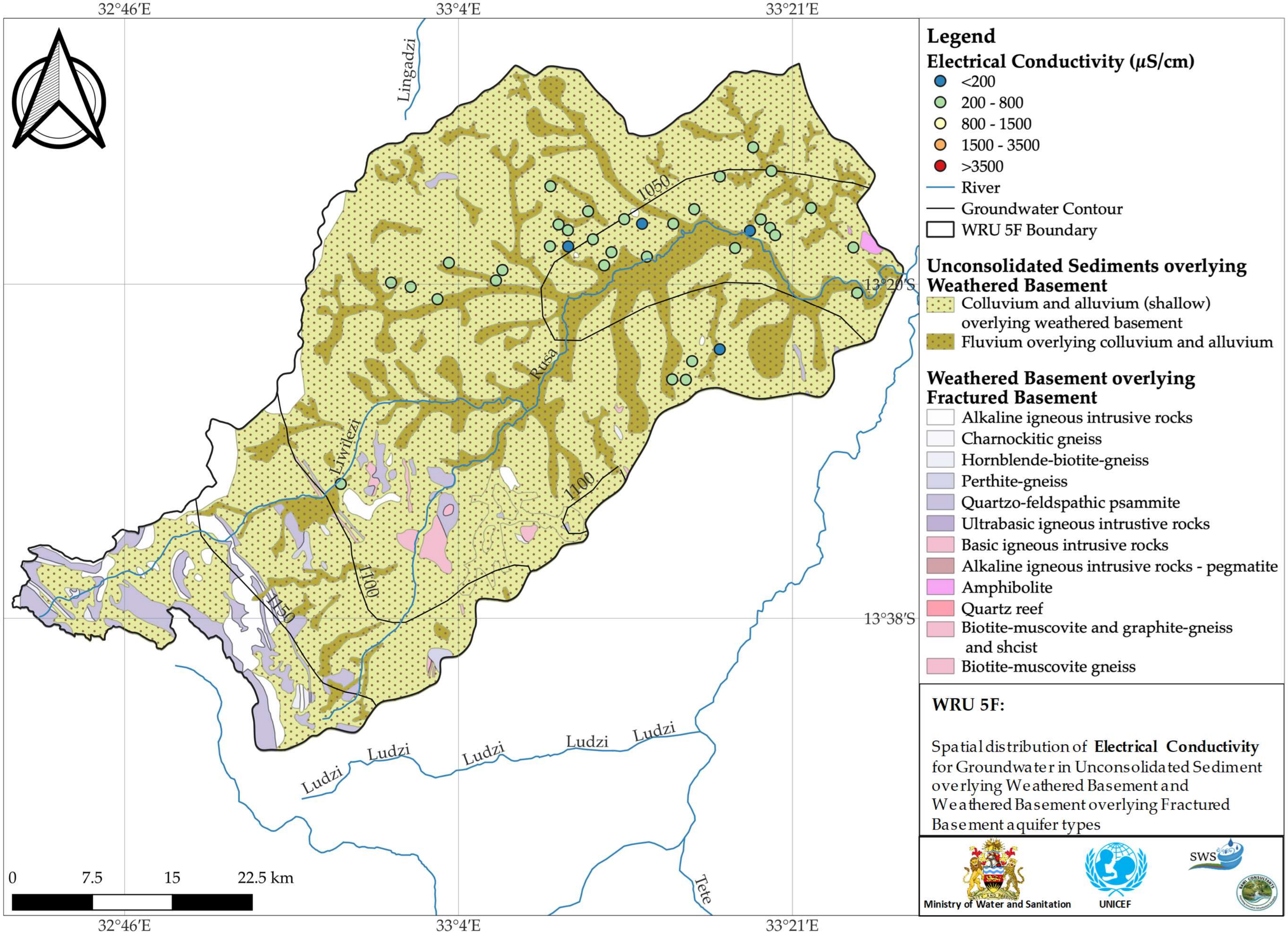


Figure WRU 5F.5 Groundwater Chemistry Distribution of Sulphate

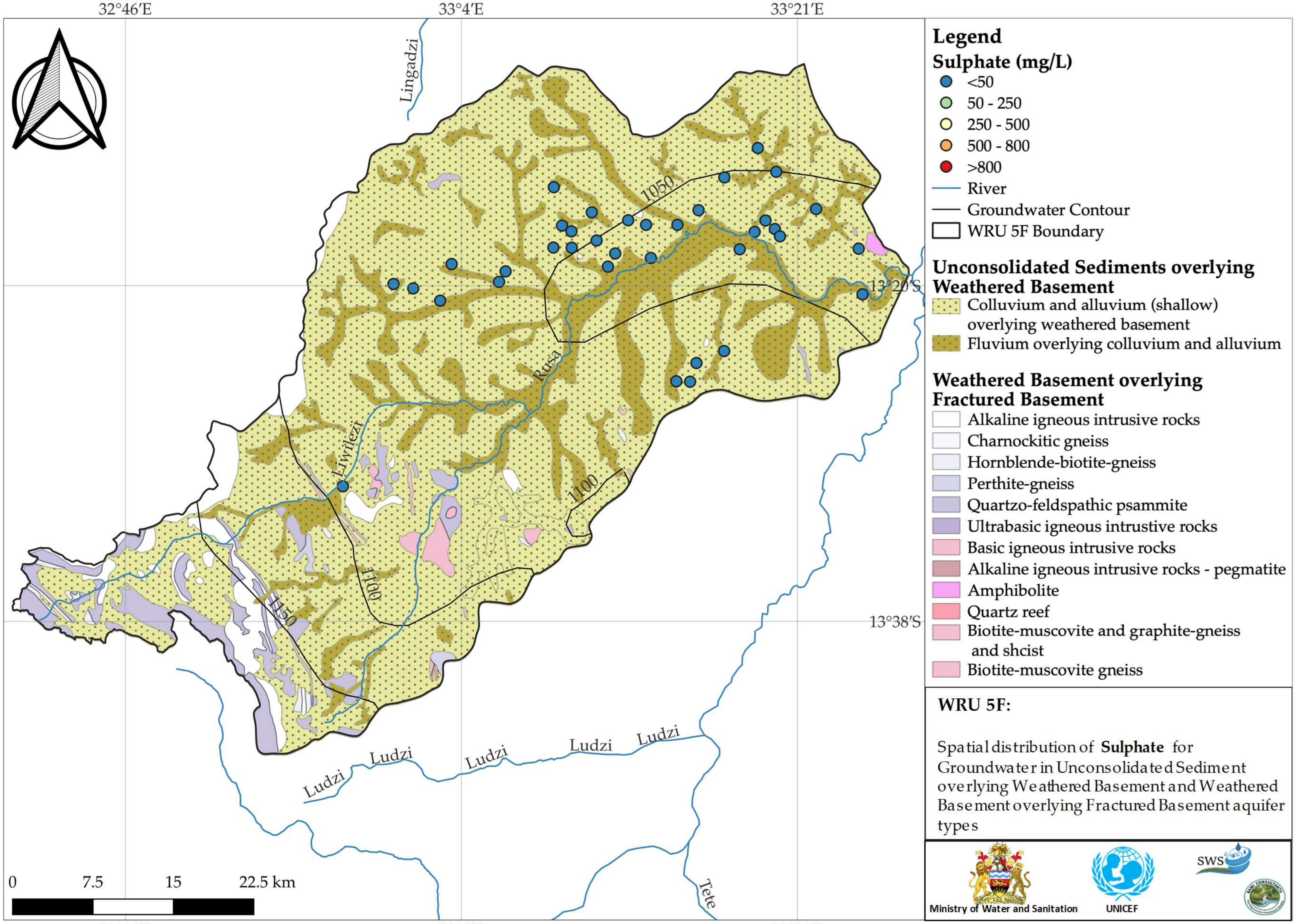


Figure WRU 5F.6 Groundwater Chemistry Distribution Chloride

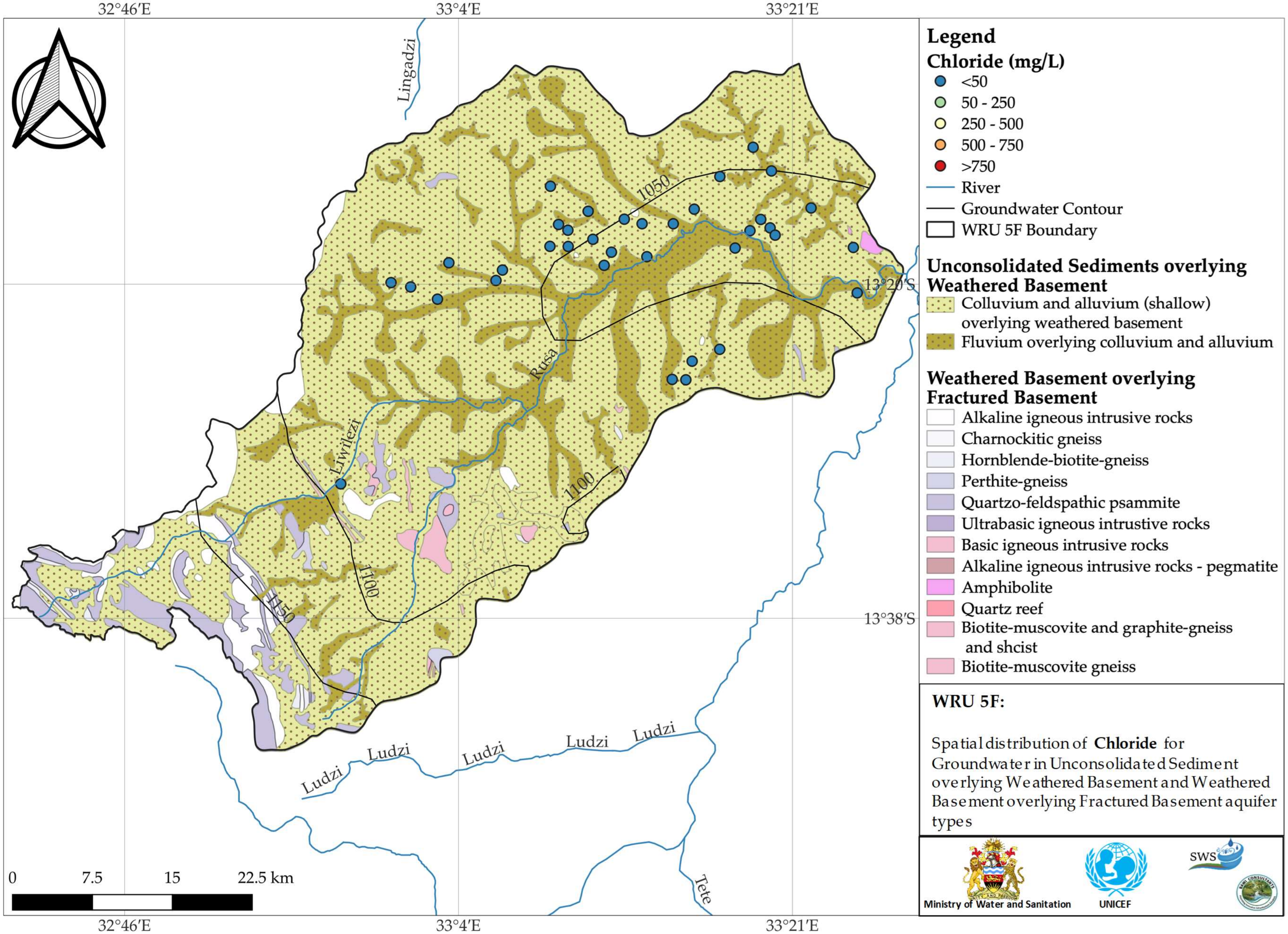


Figure WRU 5F.7 Groundwater Chemistry Distribution Sodium

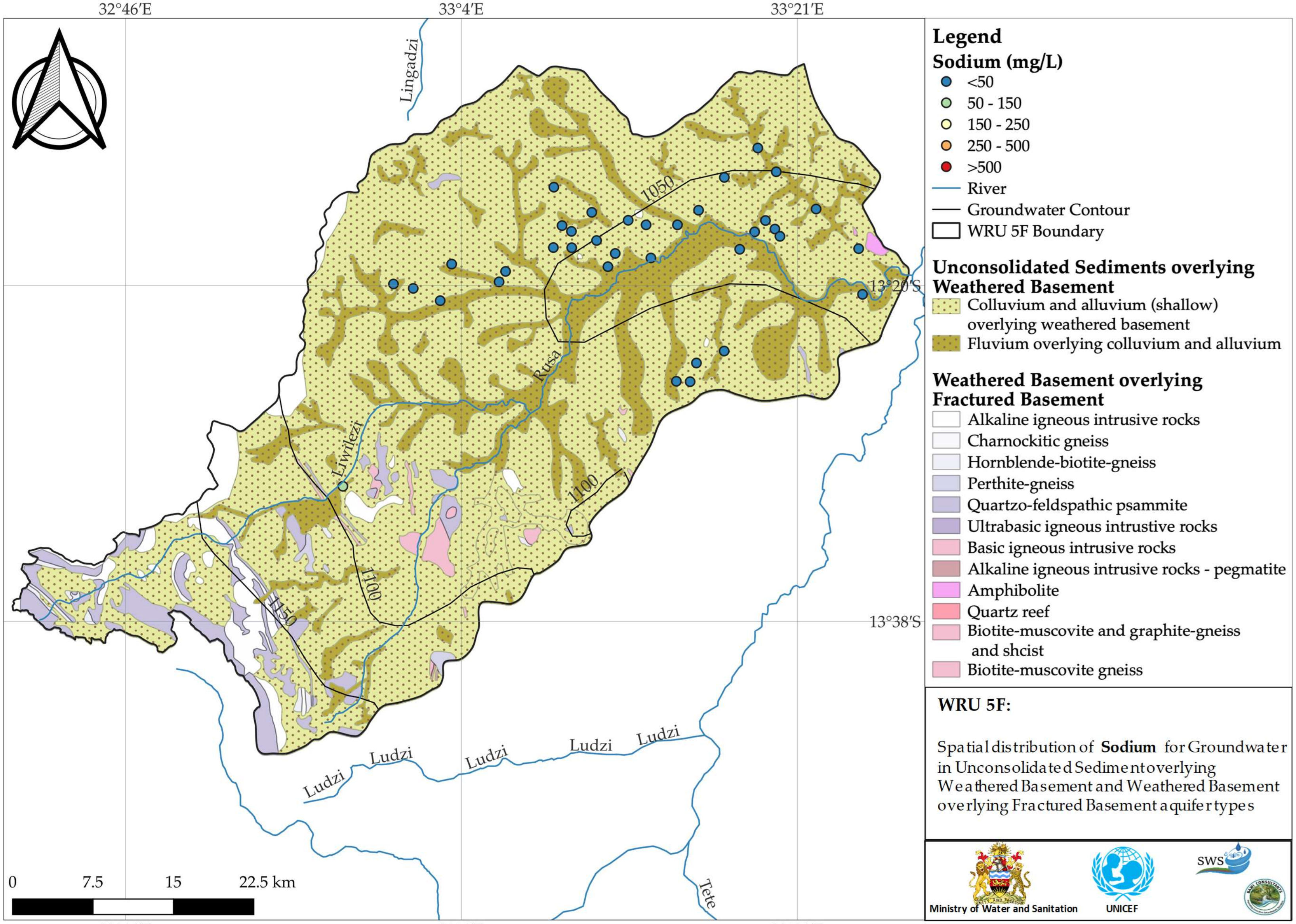


Figure WRU 5F.8 Groundwater Chemistry Distribution Calcium

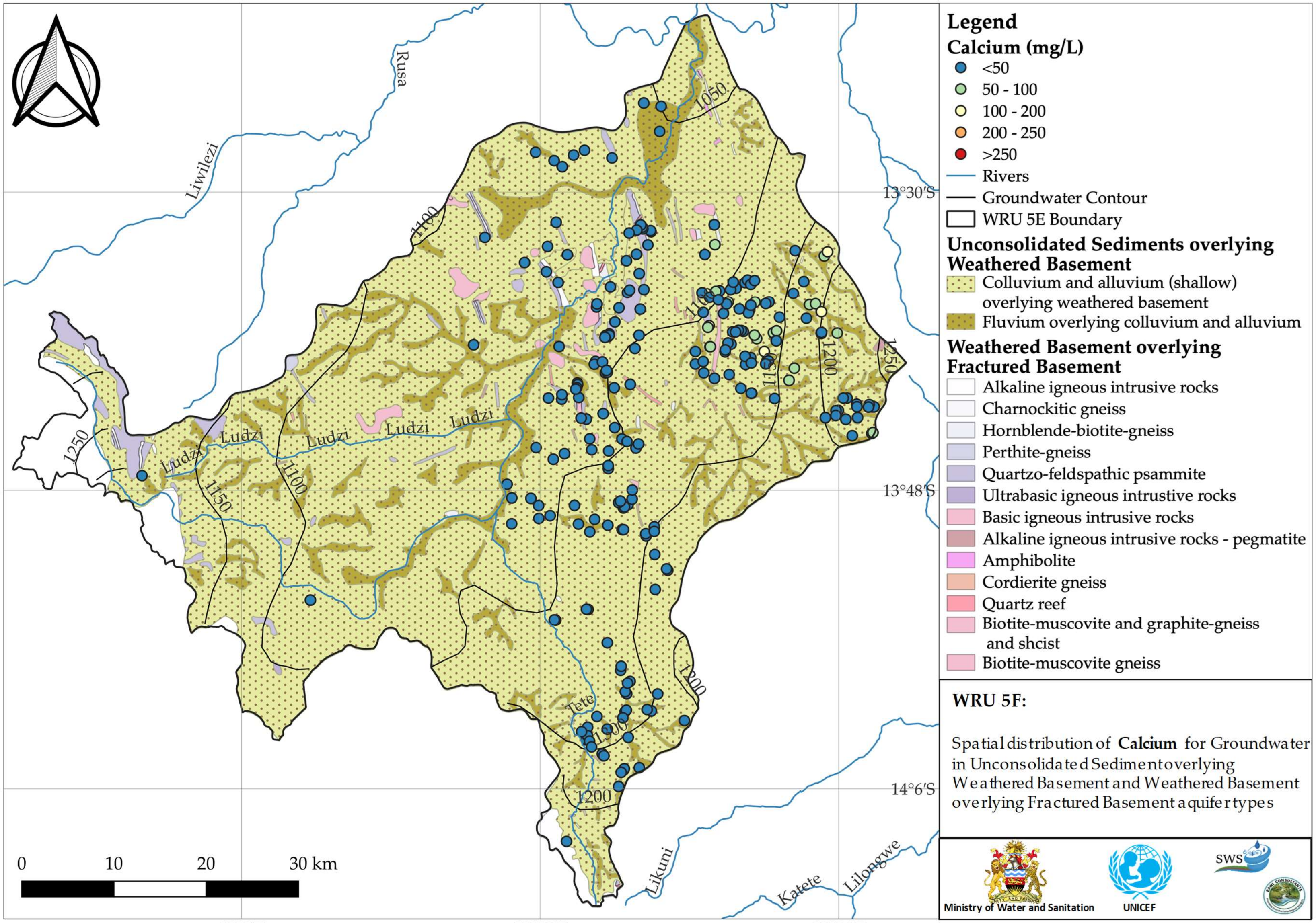


Figure WRU 5F.9 Piper Diagram of water quality results with respect to the major aquifer type

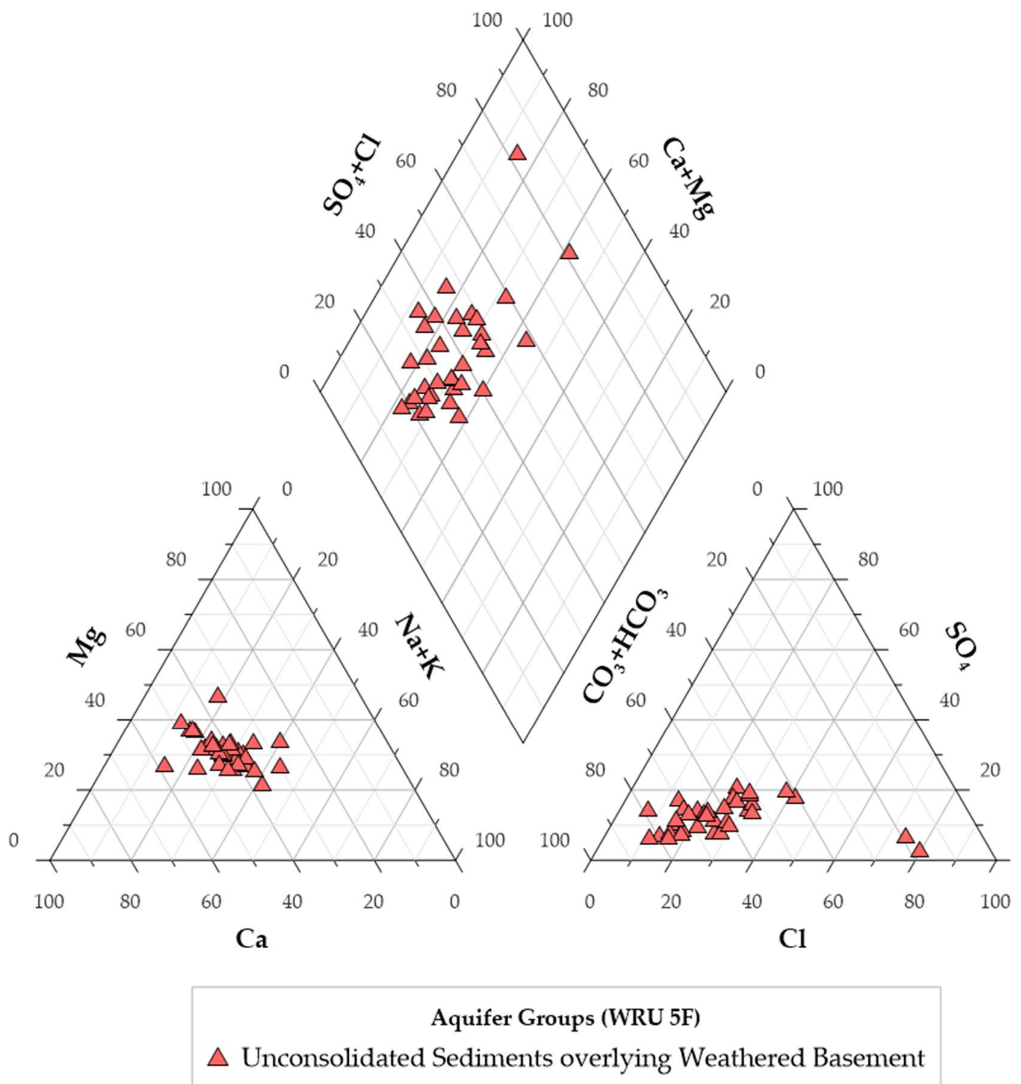
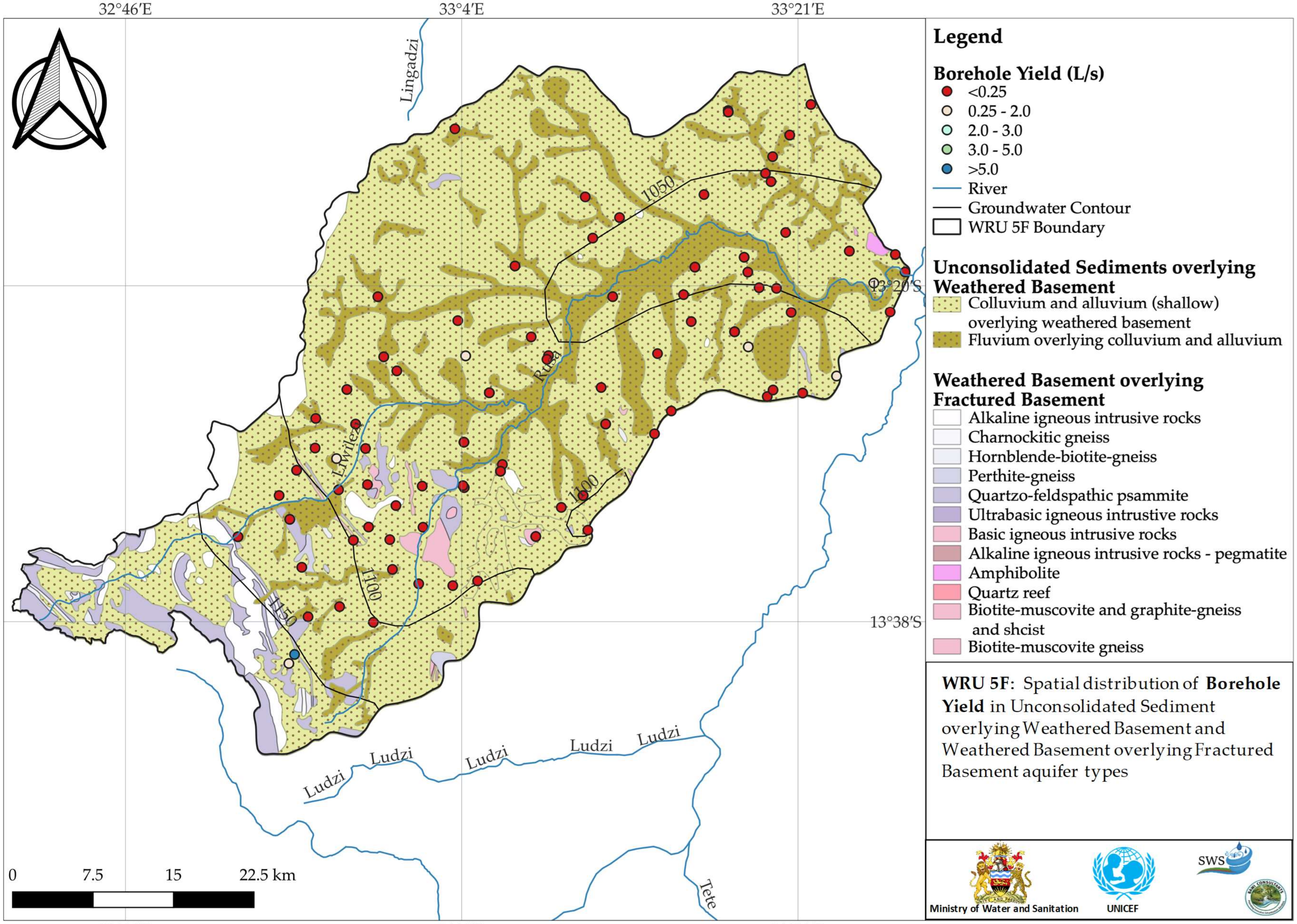


Figure WRU 5F.10 Borehole Yield Map for data held by the Ministry



Ministry of Water and Sanitation

Hydrogeology and Groundwater Quality Atlas of Malawi

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