



Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 1

The Upper Shire Catchment

Ministry of Water and Sanitation

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Acronyms and Abbreviations

BAWI	BAWI Consultants Lilongwe Malawi
BGS	British Geological Survey
BH	Borehole
BY	Billion Years
°C	Degree Celsius
CAPS	Convergence Ahead of Pressure Surges
DCCMS	Department of Climate change and Meteorological Services
EC	Electrical Conductivity
FB	Fractured Basement
ITCZ	Intertropical Convergence Zone
l/s	Litres per second
Km ²	Square Kilometre
Km ³	Cubic Kilometre
m	metre
m ²	Square metre
MASDAP	Malawi Spatial Data Portal
masl	Metres above sea level
mbgl	Metres below ground level
MBS	Malawi Bureau of Standards
m/d	Metre/day
m ² /d	Square metres per day
m ³ /s	Cubic metre per second
m/d	Metres per day
mm	Millimetre
mm/d	Millimetre per day
MoWS	Ministry of Water and Sanitation (current)
MoAIWD	Ministry of Agriculture, Irrigation and Water Development (pre-2022)
MS	Malawi Standard
MY	Million Years
N-S	North- south
SWS	Sustainable Water Solutions Ltd Scotland
SW-NE	Southwest-Northeast
pMC	Percent modern carbon
QA	Quaternary Alluvium
UNICEF	UNICEF
UoS	University of Strathclyde
WB	Weathered Basement
WRA	Water Resource Area
WRU	Water Resource Unit
µs/cm	Micro Siemens per centimetre

Review of Malawi Hydrogeology

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

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

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

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

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

Weathered metamorphic and igneous rocks overlying fractured rock regardless of age comprise the basement aquifers in Malawi (**Figure 1c**). It should be recognised the Fractured basement only transmits water locally and depends on storage in the overlain weathered zone of saprolite (known as

Nomenclature: Hydrogeology of Malawi

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

Weathered Basement overlying Fractured Basement

Weathered basement overlying fractured basement is ubiquitous across Malawi (**Figure 1d**) and will occur at variable depths. The areal distribution of these units will be topographically and geographically controlled, with defined “aquifers” being localised and non-contiguous. Groundwater is stored and transmitted via intergranular pore spaces in the weathered (most probable areas of high groundwater storage in the 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).

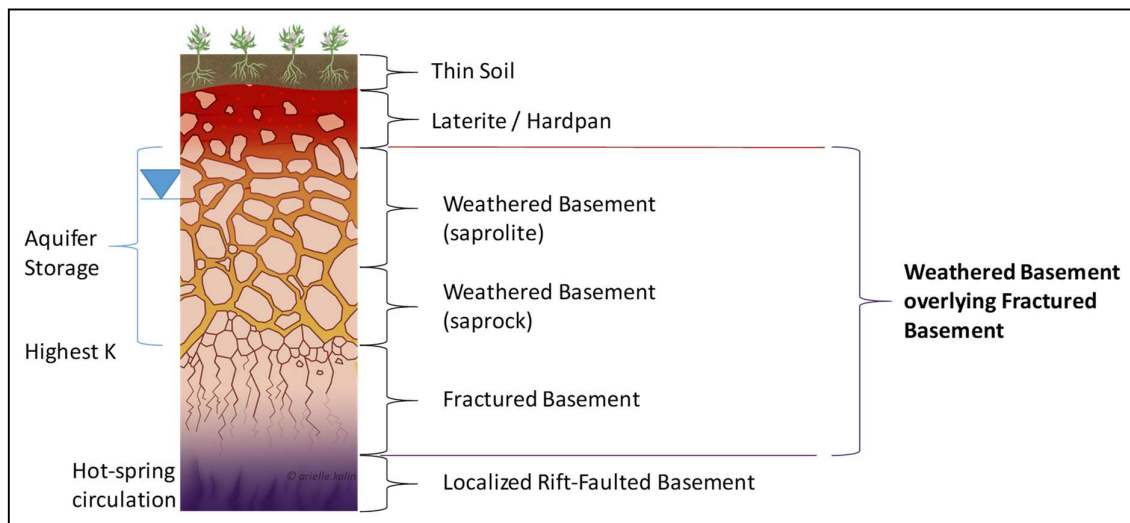


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

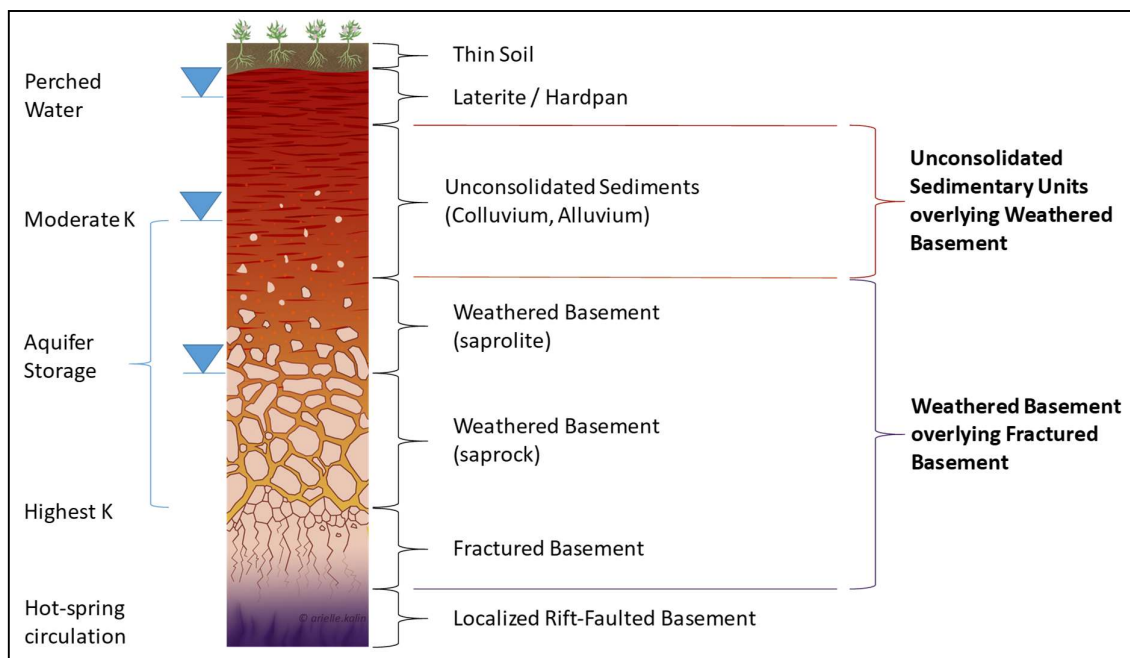


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

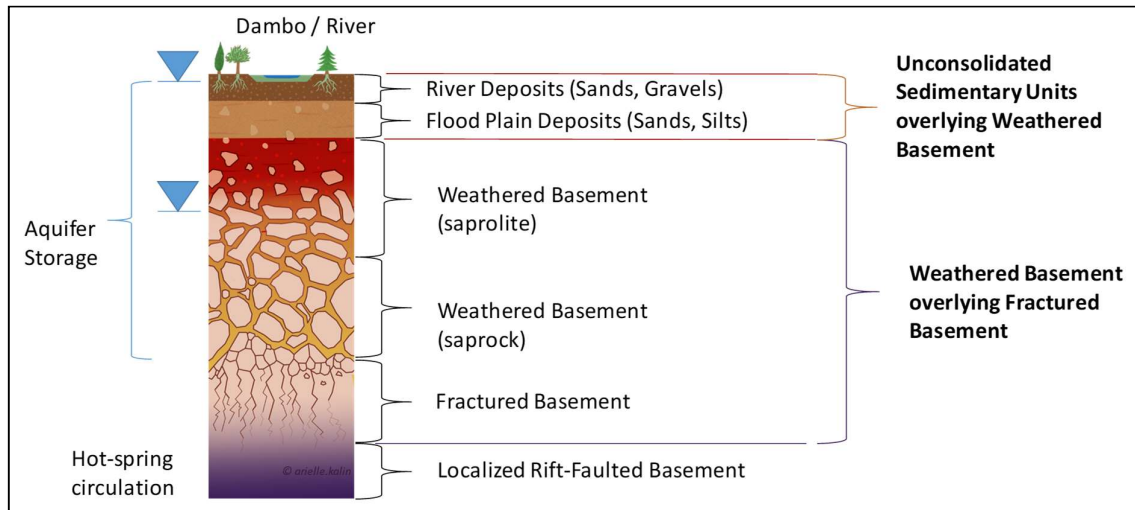


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

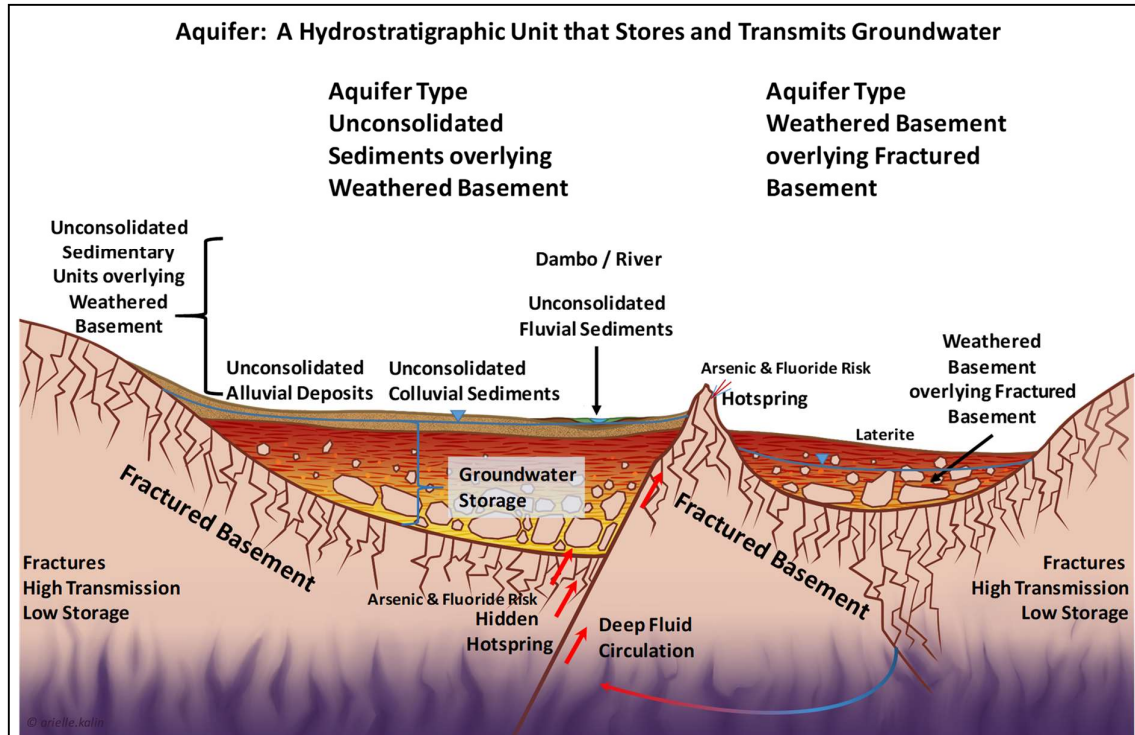


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratigraphic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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

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

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

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Water Resource Area 1 (WRA 1): The Upper Shire Catchment

Water Resource Area (WRA) 1 in southern Malawi (**Figure 2a**) is the largest WRA in Malawi covering an area of over 18,911 Km². It is largely drained by the Shire River (hence called the Shire River Catchment), the sole riverine outflow of Lake Malawi, with its major tributaries that includes Mwanza, Ruo, Lisungwe, Mkulumadzi, Likwenu and Rivi Rivers. WRA 1 covers a vast area of 18,911 Km² which, for spatial data interpretation, has been subdivided in the Hydrogeologic and Groundwater Quality Atlas into the Upper Shire and the Lower Shire. The Upper Shire Basin includes Water Resources Units (WRU) 1A, 1B, 1O, 1P, 1R, 1S and 1T (**Figure 2b**), covering an area of 8,922 Km². The Lower Shire Basin included WRU 1C, 1E, 1F, 1G, 1H, 1K, 1L, 1M and 1N, covering an area of 9,989 Km². The main river tributaries of the Upper Shire include Mwatang'ombe, Lisungwe, Nkasi, Ngande, Linjisi, Kambewe, and Massarje, and the main river tributaries of the Lower Shire include the Mkulumadzi, Ngoma, Mwambezi, Mwanza, Lalanje, and Phanga. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of adjective storms and tropical depressions from moisture carried from the Mozambique channel. The Shire Basin WRA 1 is a major tributary of the Zambezi and is heavily studied as a trans-boundary surface and groundwater bodies and as it also drains Lake Malawi Integrated Water Resources Management (IWRM) must be undertaken within Trans-boundary water sharing agreements.

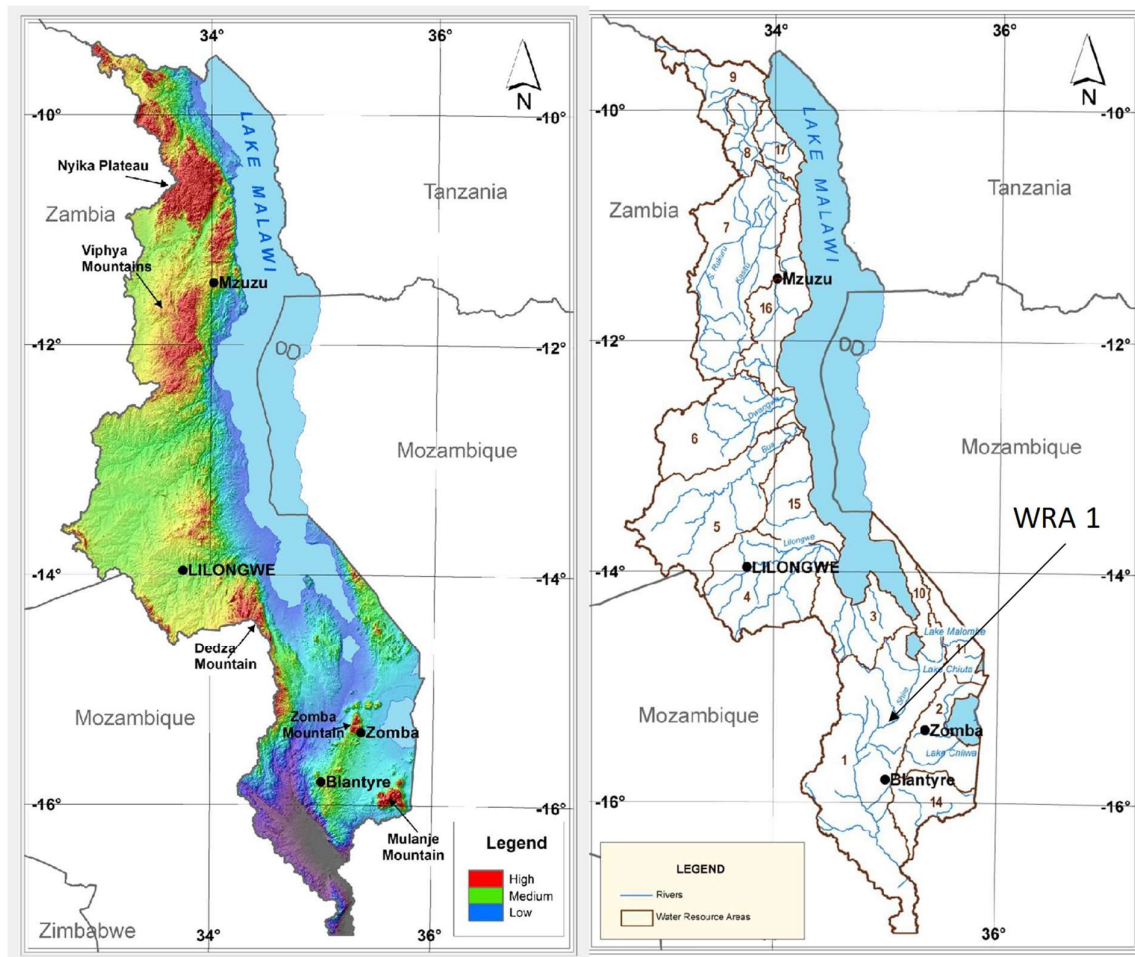


Figure 2a. Location of WRA 1 with major rivers and topography shown.

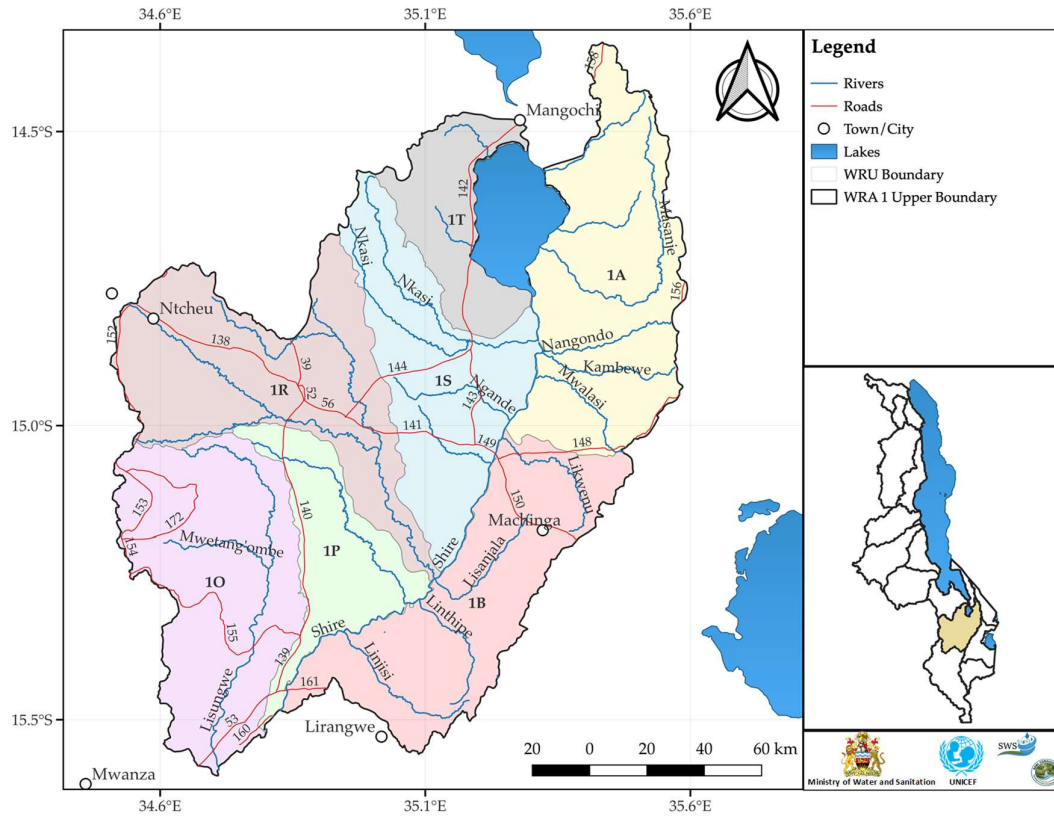


Figure 2b. Water Resource Area 1 Upper Shire and Water Resource Units

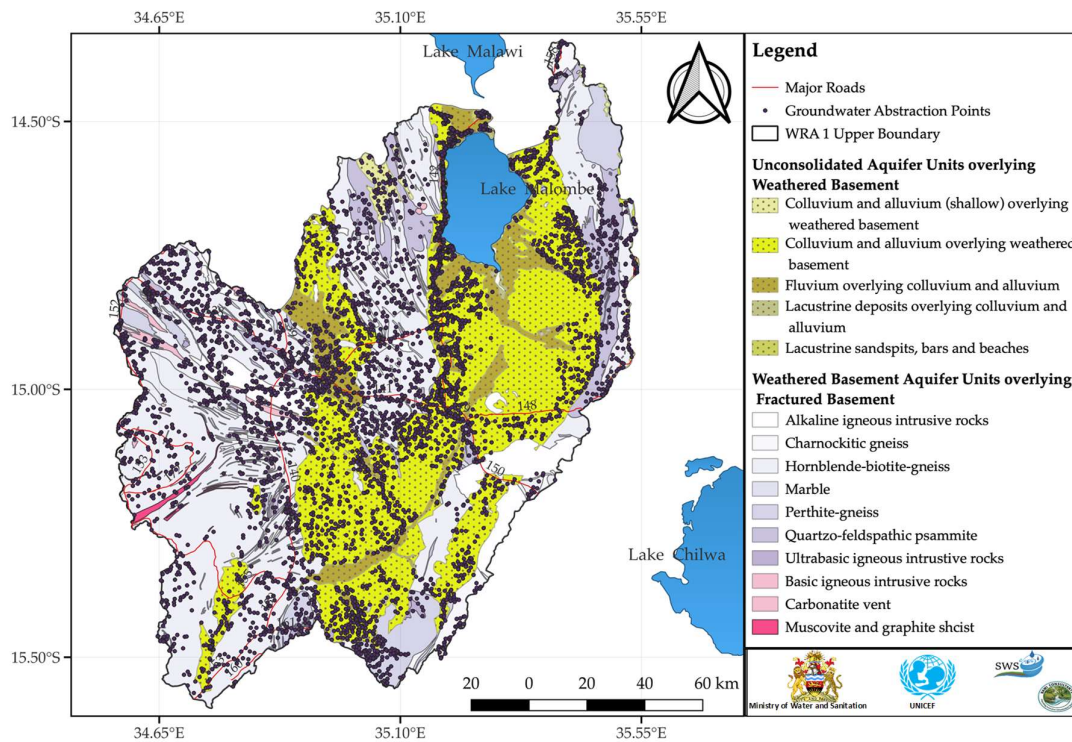


Figure 3. Distribution of groundwater abstraction points in the Upper Shire WRA 1.

Groundwater Abstraction in WRA 1 Upper Shire

Public abstraction points for groundwater are numerous in WRA 1 Upper Shire (**Figure 3, Table 2**) and it should be noted there are likely unaudited private groundwater abstraction points. Of the 8,696 known groundwater abstraction points, 83.69% are improved sources (with 598 being protected dug wells and 682 being 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 an expected range of the Afridev, Maldev, Elephant 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 1 Upper Shire, only 67.5% are fully functional (defined as providing water at design specification).

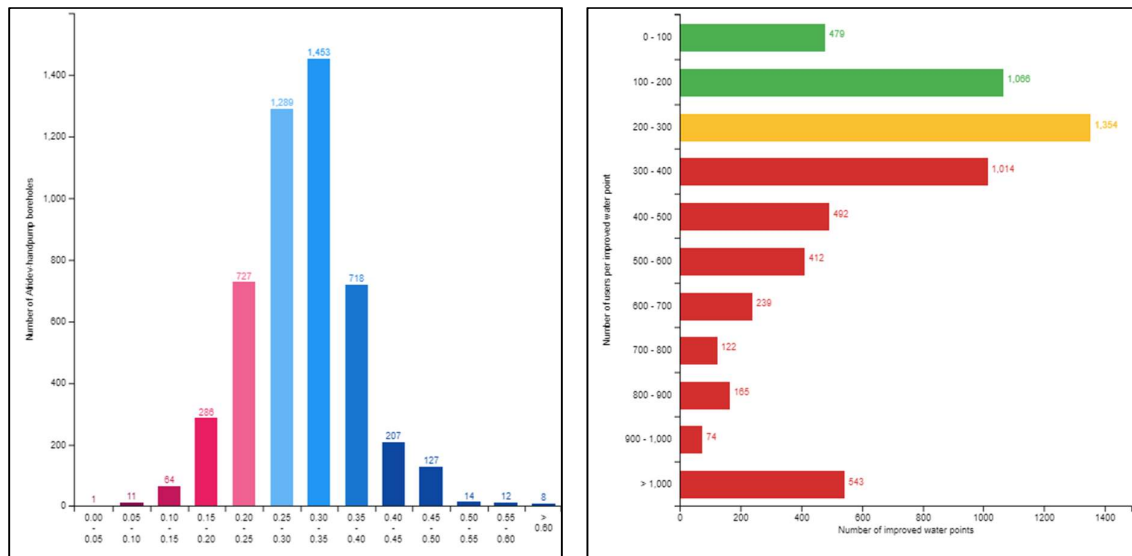


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 1 Upper Shire (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point. [Data from the 2020 National Water Point Survey]

Government guidelines recommend no more than 250 users per hand pump water point and 120 for protected shallow well, and the degree to which this is exceeded points to a need for additional investment (as new or rehabilitated groundwater abstraction points). The data in **Figure 4b** shows the guidelines are somewhat exceeded and there is an investment need in WRA 1 from a population point of view. Nearly half of the groundwater supply points provide water to 250 or more users per water point, and with the preponderance of dug wells may not meet the water quality guidelines, the WRA should be considered regulation of self-supplies and self-funded water quality monitoring within investment planning.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 10.2% 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.

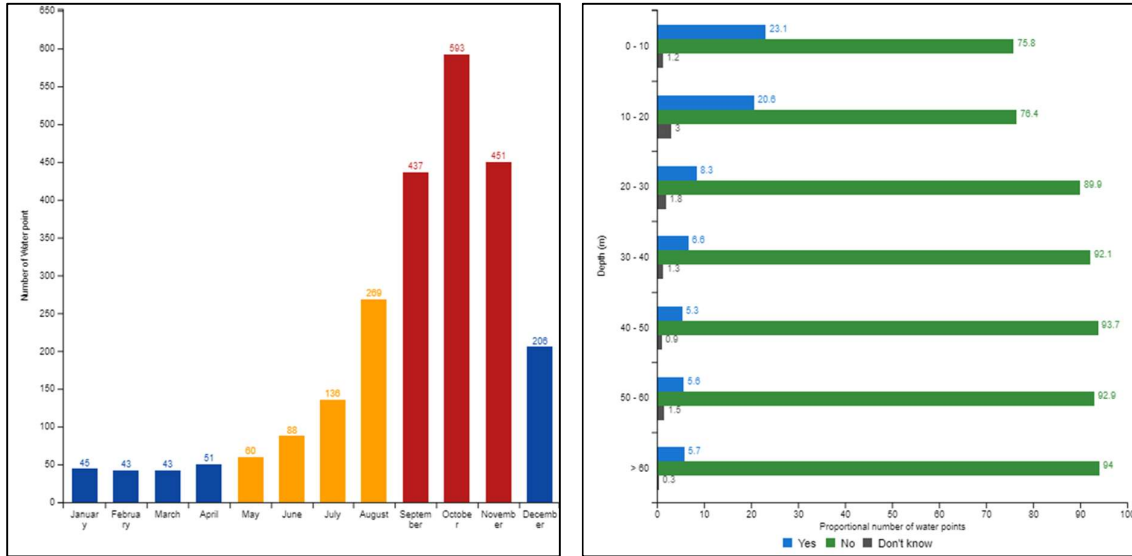


Figure 5a and 5b. Number of groundwater abstraction points in WRA 1 Upper Shire that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

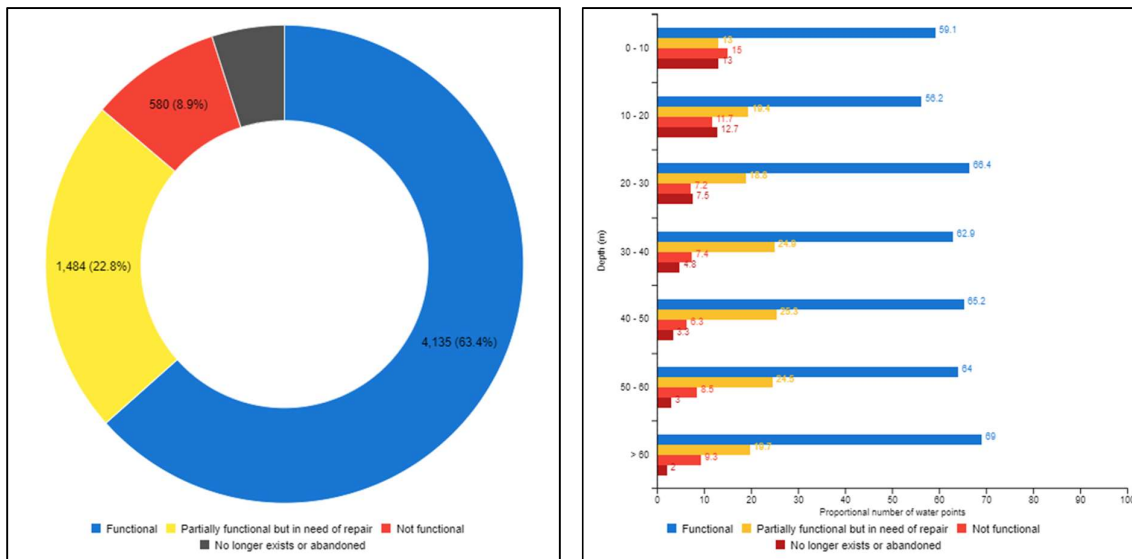


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 1 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water Point Survey]

The operational status of groundwater abstraction points in WRA 1 Upper Shire is also linked to issues of infrastructure (e.g. pump / borehole) as well as aquifer stress. There are only 63.4% of groundwater abstraction supplies which are operation at design parameters, and the distribution of functional, partly functional, non-functional and abandoned groundwater abstraction points is relatively constant with depth of abstraction point (**Figure 6a and 6b**). This indicates groundwater supply is impacted by both infrastructure quality and aquifer stress, and there is a need to undertake evaluation of stranded groundwater assets in WRA 1(after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 1[Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	7,273
Protected dug well	598
Protected spring	49
Unprotected dug well	682
Unprotected spring	94

Description of Water Resources WRA 1 Upper Shire

Water resources management according to the Water Resource Act (2013) Malawi is devolved to sub-basin Water Resource Units (WRUs), and Integrated Water Resources Management (IWRM) should be managed at this sub-basin scale. Water Resource Area (WRA) 1 in southern Malawi is the largest WRA in Malawi covering an area of about 18,911 Km². It is largely drained by the Shire River (hence called the Shire River Catchment), the sole riverine outflow of Lake Malawi, with its major tributaries that includes Mwanza, Ruo, Lisungwe, Mkulumadzi, Likwenu and Rivi Rivers. WRA 1 covers a vast area of 18,911 Km² which, for spatial data interpretation, has been subdivided in the Hydrogeologic and Groundwater Quality Atlas into the Upper Shire and the Lower Shire. The Upper Shire Basin includes Water Resources Units (WRU) 1A, 1B, 1O, 1P, 1R, 1S and 1T, covering an area of 8,922 Km². The main river tributaries of the Upper Shire include Mwatang'ombe, Lisungwe, Nkasi, Ngande, Linjisi, Kambewe, and Massarje. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of adjective storms and tropical depressions from moisture carried from the Mozambique channel. The Upper Shire Basin WRA 1 is a major tributary of the Zambezi and is heavily studied as a trans-boundary surface and groundwater bodies and as it also drains Lake Malawi Integrated Water Resources Management (IWRM) must be undertaken within Trans-boundary water sharing agreements.

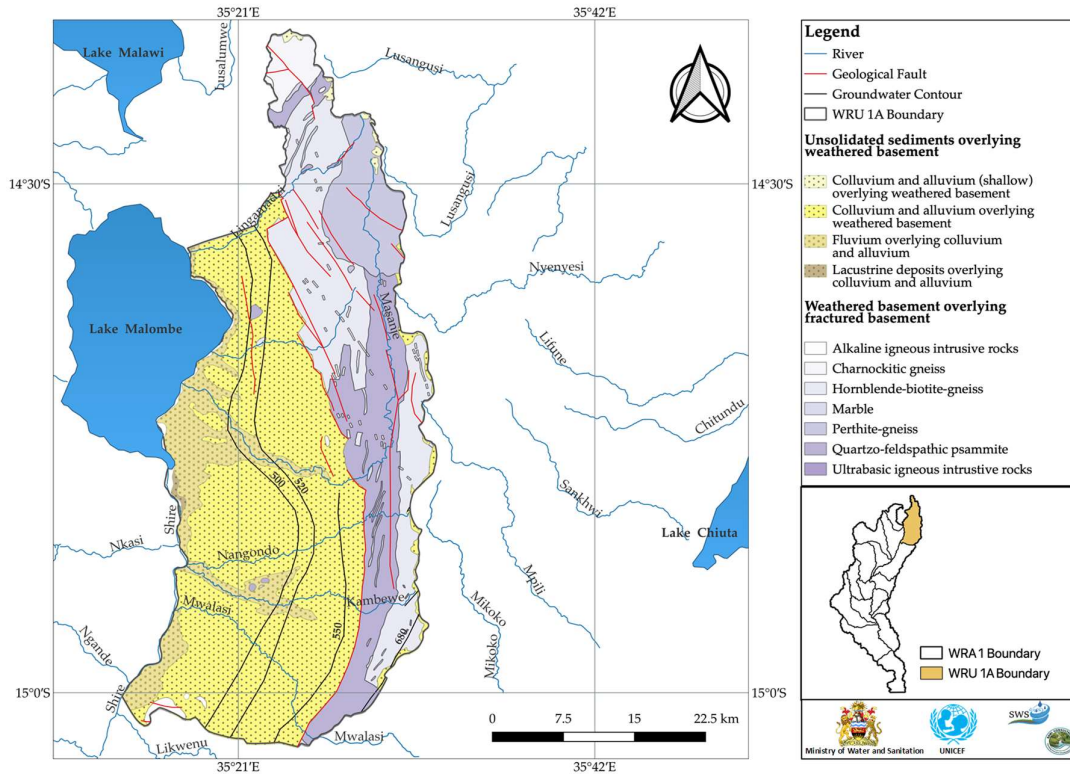


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 1A within Water Resource Area 1 (Upper Shire Catchment).

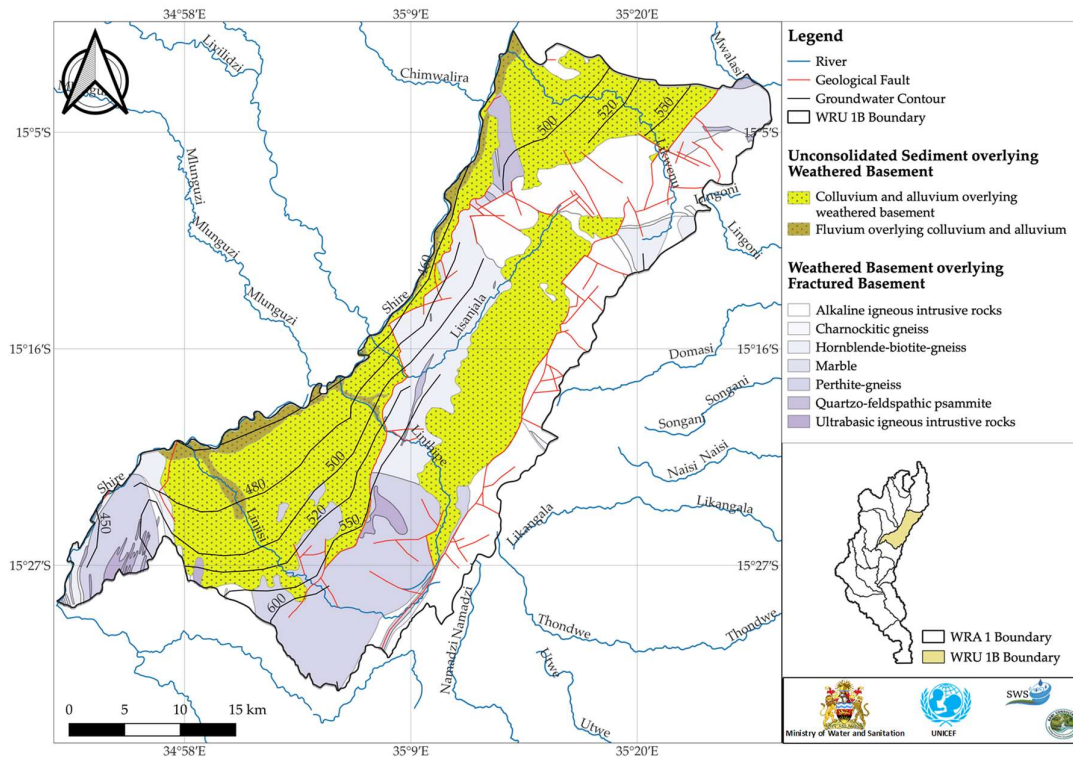


Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 1B within Water Resource Area 1 (Upper Shire Catchment).

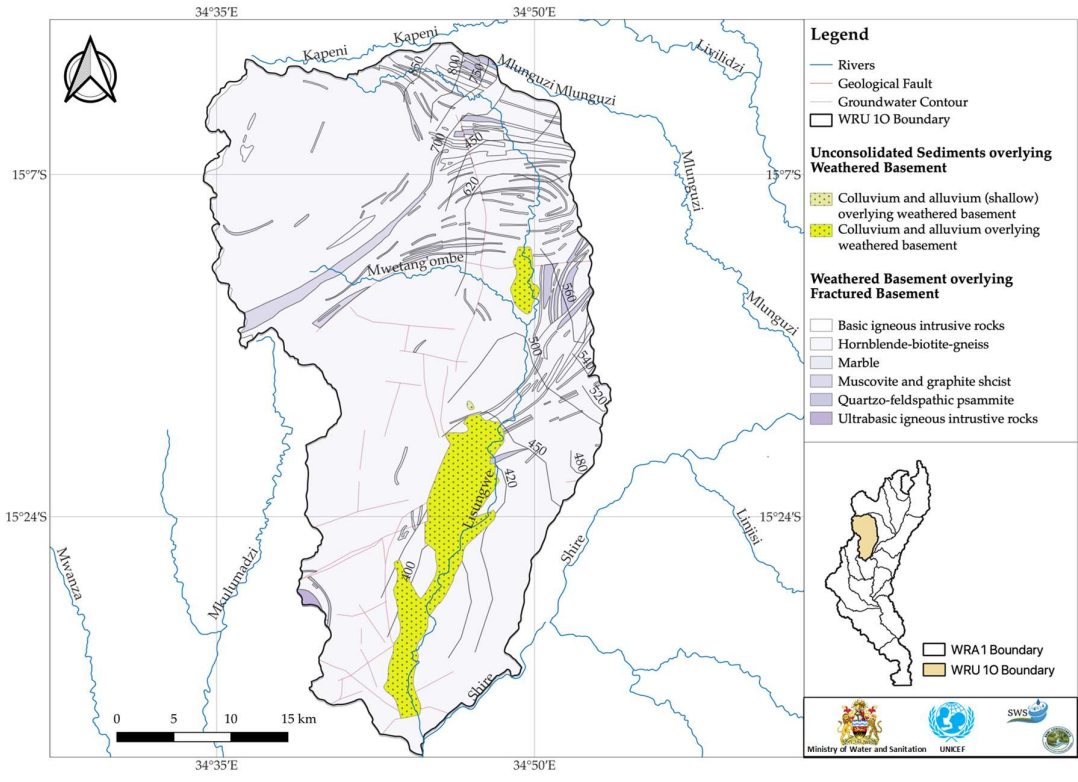


Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 1 O within Water Resource Area 1 (Upper Shire Catchment).

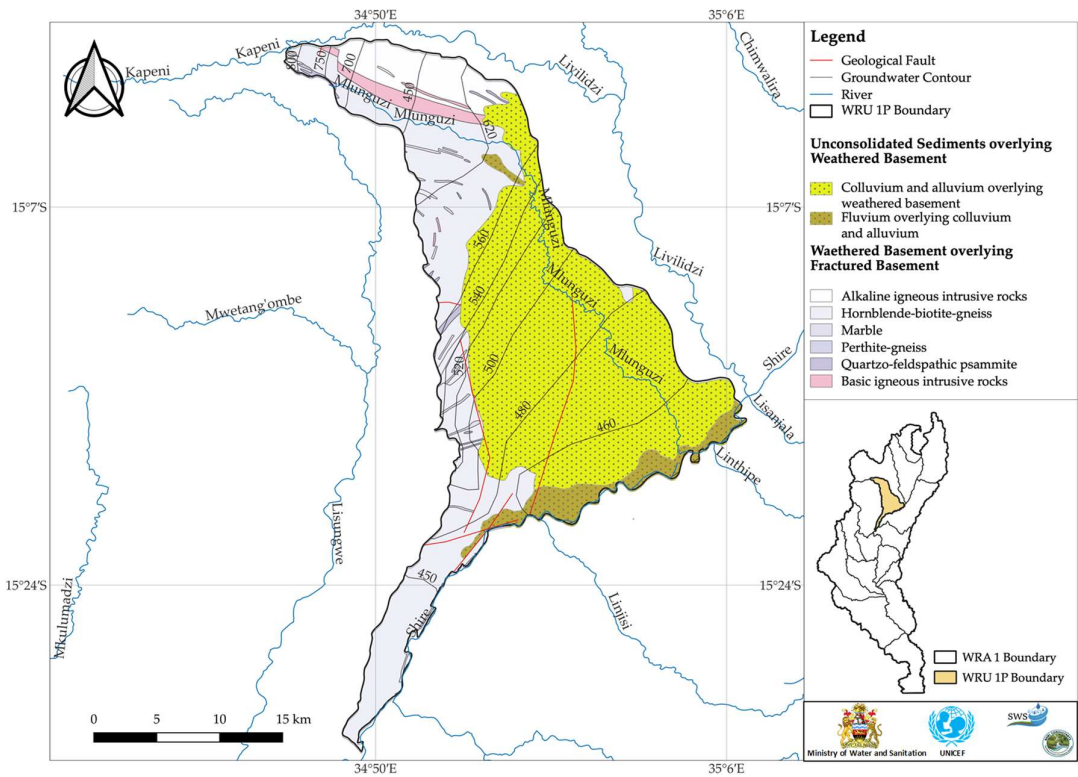


Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 1P within Water Resource Area 1 (Upper Shire Catchment).

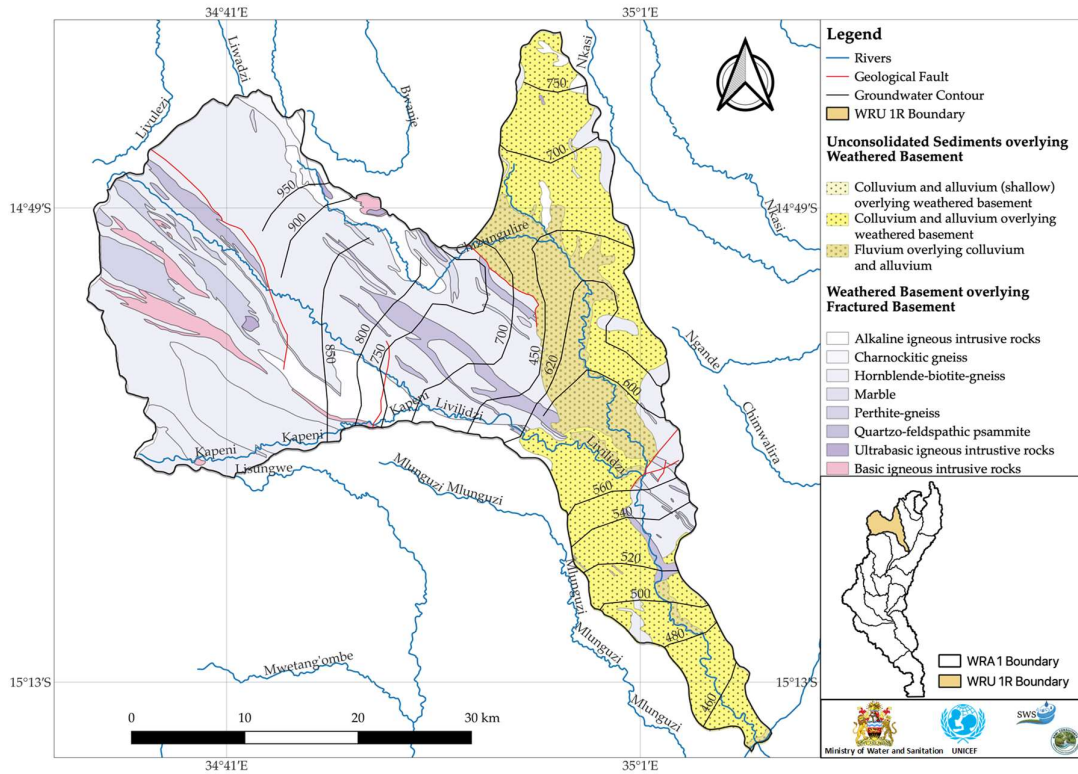


Figure 7e. Map showing the hydrogeologic units and water table for Water Resource Unit 1R within Water Resource Area 1 (Upper Shire Catchment).

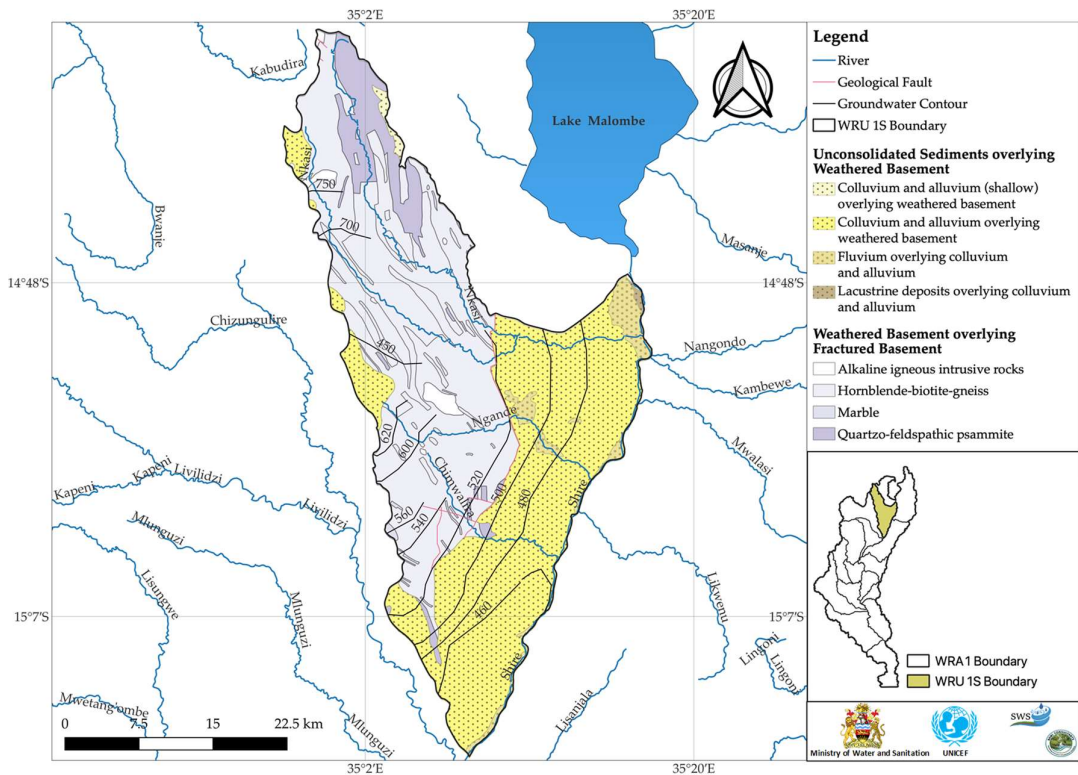


Figure 7f. Map showing the hydrogeologic units and water table for Water Resource Unit 1S within Water Resource Area 1 (Upper Shire Catchment).

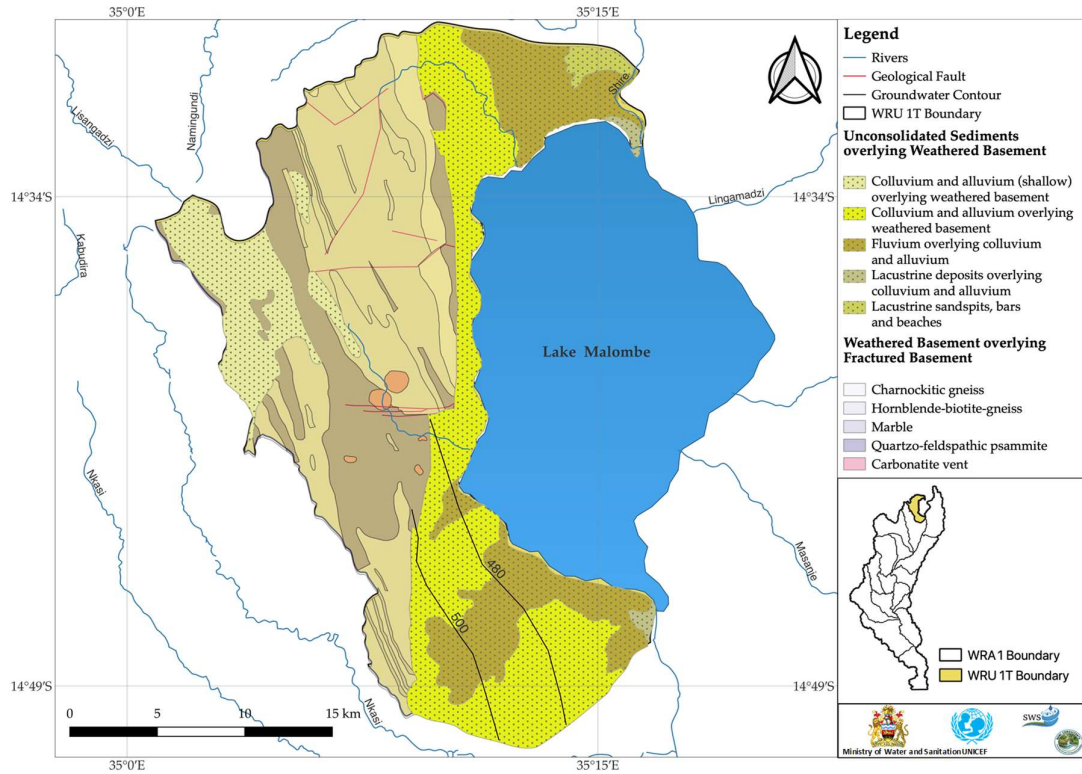


Figure 7g. Map showing the hydrogeologic units and water table for Water Resource Unit 1T within Water Resource Area 1 (Upper Shire Catchment).

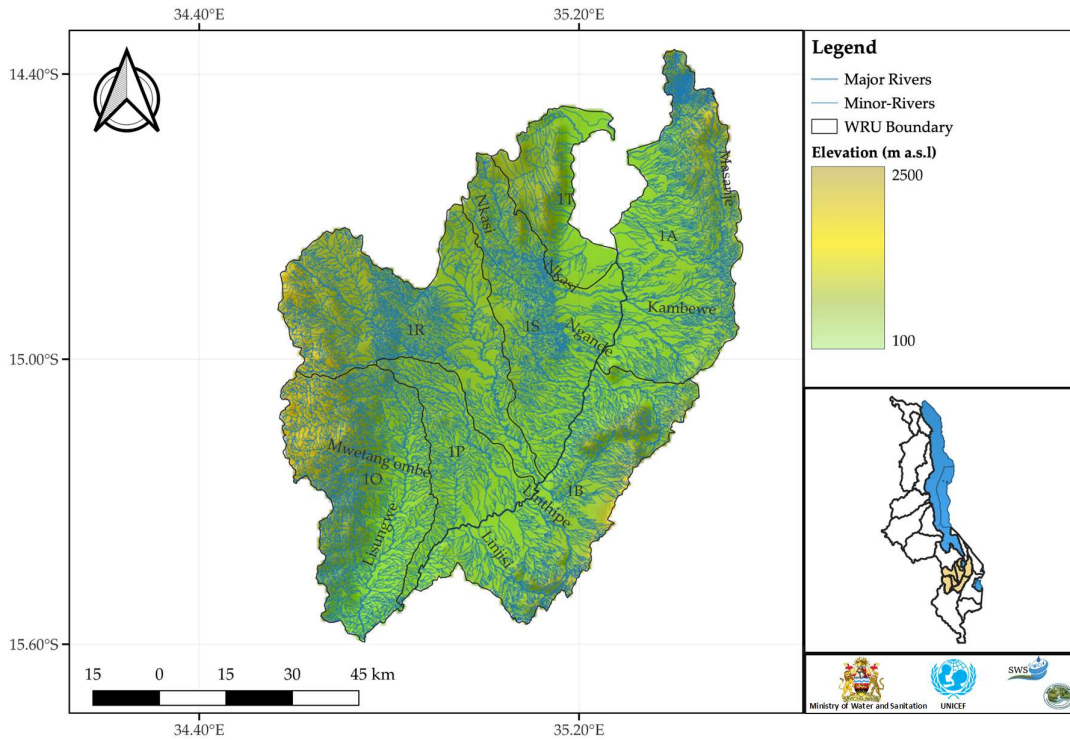


Figure 8. Drainage for the major rivers in the Upper Shire Water Resources Area 1.

Topography and Drainage

The catchment has diverse relief, dominated by the East African Rift System (EARS) valley and plains. The area is characterised by highlands in the Upper Shire to over 1,300 m asl. in the southwest of Ntcheu District where Malawi borders Mozambique and in the Mulanje District where the highest highlands occur, but is typified by hot dry lowlands below 200 m asl. in Chikwawa and Nsanje districts within the Lower Shire River Basin comprising extensive, semi-arid valley plains across the basin. The topography and major rivers in the Upper Shire WRA1 are shown in **Figure 8**.

Geology – Solid

The Upper Shire WRA 1 is dominated by the Malawi Rift Valley (**Figure 7a – 7g**). The valley floor is exposed at the Earth's surface here due to outward shallowing of the Malawi Rift. Precambrian - Lower Palaeozoic Malawi Basement Complex of metamorphic and igneous rocks dominate either side of the rift valley along rift escarpments on either side. Geological structure is controlled by the Rift Valley with a topographically steep rift escarpment along the N - S-trending 'Z-shaped' Chembe-Zomba Fault Scarps; a series of basin margin normal faults to the east of the valley which comprise the WRA's eastern boundary. Rift-parallel faulting is extensive in those rocks. West of the fault scarp is the rift basin which hosts the Shire River. The area is peppered with isolated meta-igneous intrusions of granitic and syenitic composition, and younger volcanics of the Chilwa Alkaline Igneous Province which form part of the basement complex, topographically distinct due to erosion resistance resulting in a rounded shape and a characteristically pale colour.

Geology – Unconsolidated deposits

The Unconsolidated (Superficial) deposits in the Upper Shire WRA 1 are extensively fill the rift Basin from weathering of surrounding highland and underlying Basement rock. A complex mix of Quaternary fluvial, alluvial, and lacustrine deposits occur from extensional rifting of the Malawi Rift and lacustrine deposition along the shores of Lake Malombe. Fluvial deposits dominate the basin centre, deposited by the Shire River. Colluvium foothills border the eastern rift escarpment along the Chembe-Zomba fault complex incised by small streams flowing perpendicular towards the basin centre. Isolated dambo wetlands are present in the low lying terrain.

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. Rainfall received in low lying areas spans between 650 – 700 mm, while rainfall in highlands spans between 1,200 – 1,300 mm annually (long-term data not available for modelling) (**Figure 9**), peak rainfall occurs between December and March. High rainfall in the higher elevations regions results in periodic and severe flooding in the catchment.

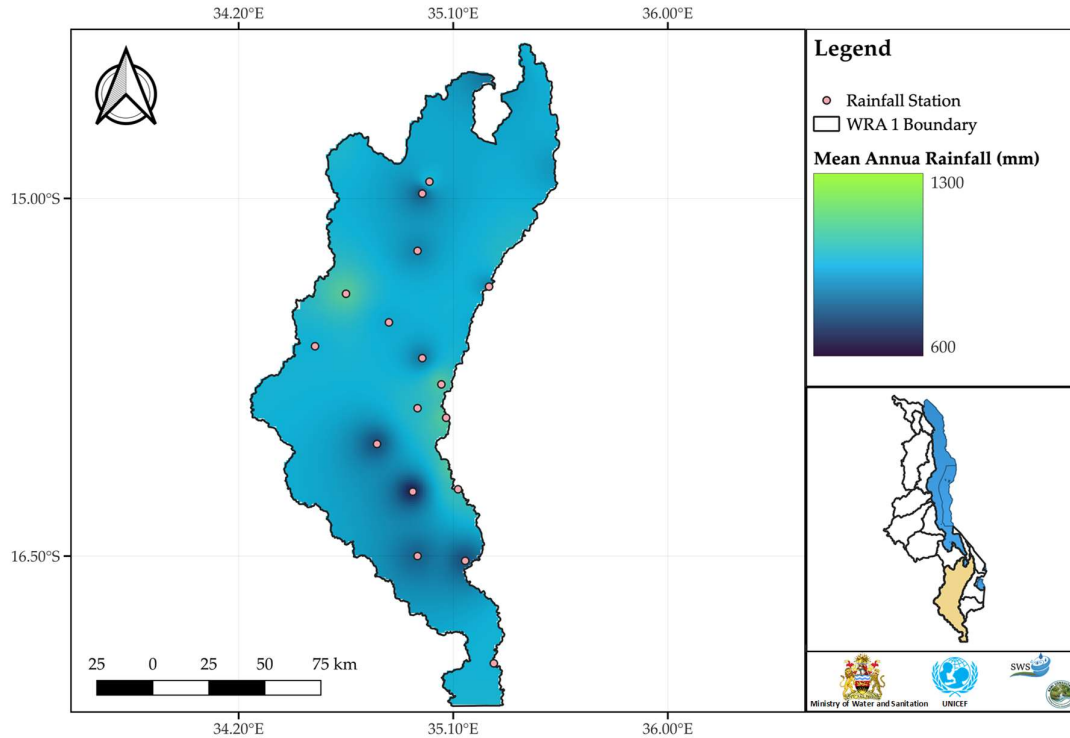


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across both Upper Shire and Lower Shire of Water Resource Area 1 with the location of weather stations. Average rainfall measured is 924mm, average rainfall modelled is 950 +/- 59mm (range 671 to 1,139mm).

Table 3. Calculated mean rainfall in each Water Resource Unit within the Upper Shire area of WRA 1. 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)
1	A	- No Station -	-	955
	B	Chingale	873	980
	O	- No Station -	-	989
	P	Phalula/Walkers Ferry	914	920
	R	Balaka/Toleza	889	943
	S	- No Station -	-	951
	T	- No Station -	-	924

Land use

Land use is largely dominated by rain fed cultivation and woodlands followed by open grasslands and marshes. The lake is of great economic significance and sustains the country's hydro-power generation by boosting Shire River flow rates, especially important during the peak of dry season when river flow rates become low as inflows from major tributaries decline, often becoming dry. Some of the basin urban centres are served by Shire River off-takes, the largest being the City of Blantyre, which abstracts close to 100 ML/d (mega-litres per day), pumped over a head of 800 m through a 48-km pipeline from the intake at Walker's Ferry to the city.

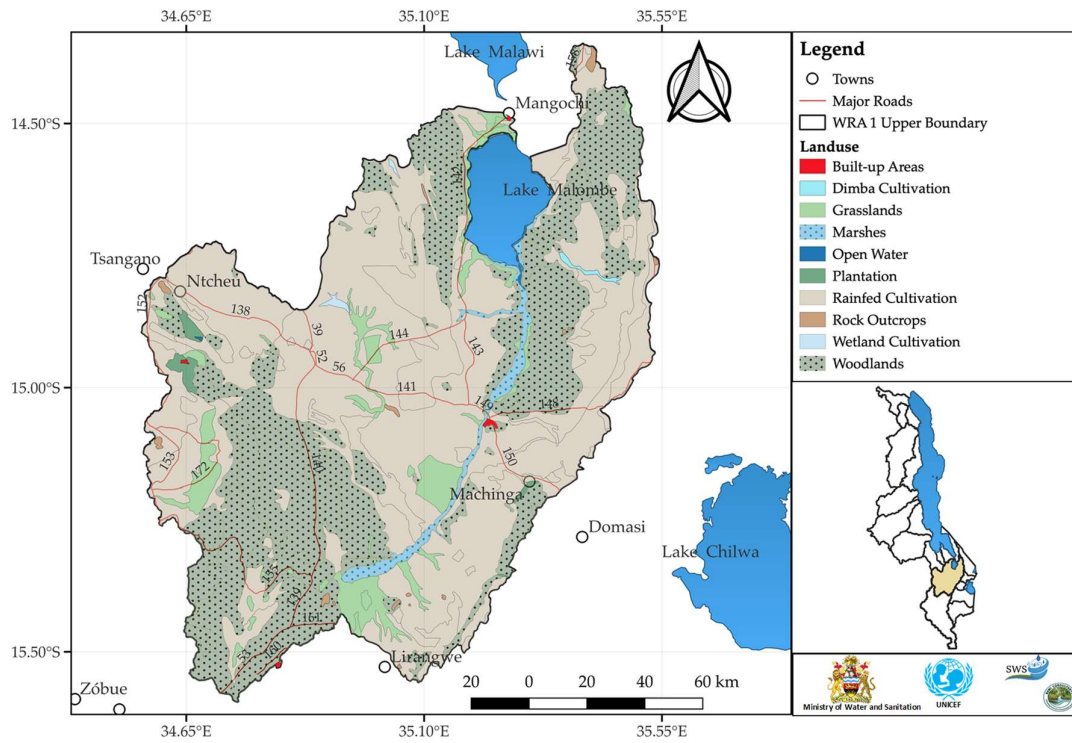


Figure 10. Land use in the Upper Shire WRA 1 is dominated by woodlands, grasslands and rain fed agriculture.

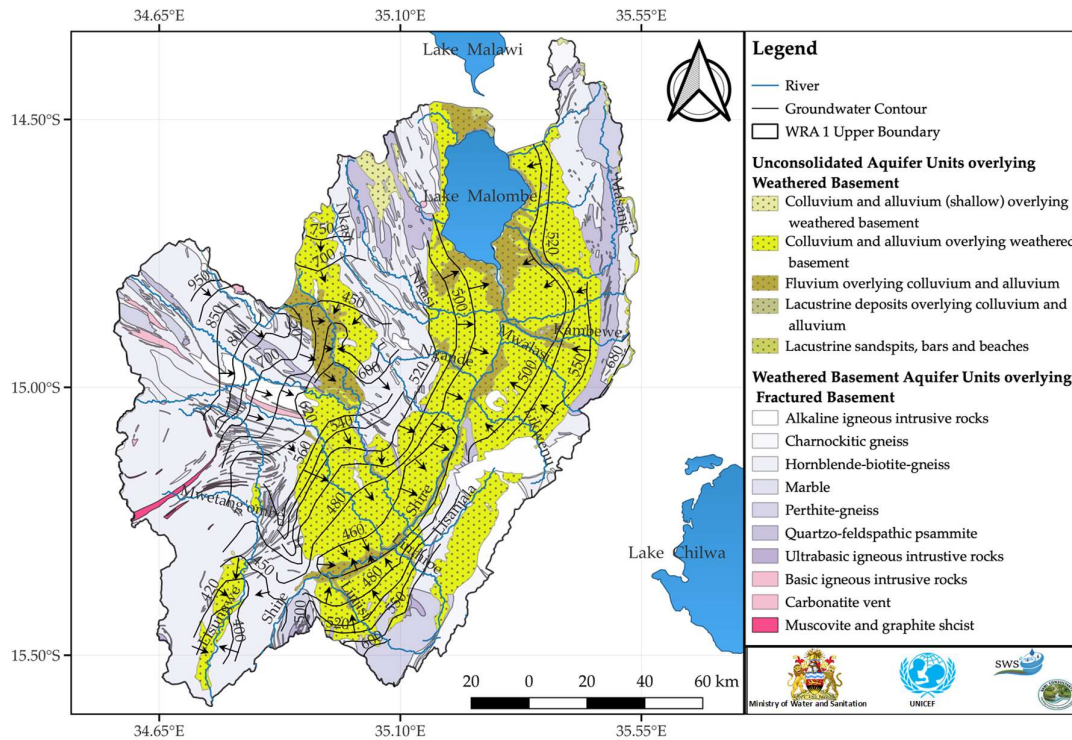


Figure 11. Groundwater level contours and flow direction in the Upper Shire WRA 1 [1987 Hydrogeological Reconnaissance data] [water level contour interval 20m]

Hydrogeology of WRA 1 Upper Shire

Aquifer Properties

The dominant aquifer type in the Upper Shire of WRA 1 is colluvium overlying weathered and fractured basement overlain by fluvial sediments in river channels. Near dambos finer flood deposits interbedded with coarser flood deposits. Groundwater abstraction is generally focused on these hydro stratigraphic units. The details of particle size distribution and detailed drilling logs were not available or were not geospatial referenced and therefore could not be assigned to specific hydro stratigraphic units and it is recommended that continued work is needed to develop the hydrogeological records of the Ministry of Water and Sanitation. WRU 1R and 1S show evidence of confined piezo metric units and flow field and should be evaluated for confined vs unconfined pumping test responses, no data was available for this work by the Ministry of Water and Sanitation Records to allow this interpretation.

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 1 is based on prior hydrogeological reconnaissance.

Groundwater head contours drawn from the 1987 Hydrogeological Reconnaissance Maps, Sheets 6, 8 and 9 (Mangochi, Blantyre and Nsanje respectively) provide comprehensive coverage of groundwater flows in the weathered Basement and extensive unconsolidated aquifer deposits in the Shire Valley. Groundwater flows throughout the lower and upper Shire Valley are generally towards the Shire River or locally towards its tributaries. Flows follow the surface water drainage with groundwater divides coincident with surface-water divides at regional and local scales.

Highest groundwater heads contoured at 950 m msl occur in the north west of the upper Shire Plateau, Nsipe River headwaters in WRU 1R. Groundwater flows south-eastwards, following topography through the widening valley to Balaka under a moderately steep hydraulic gradient averaging 0.01 (1 %). Groundwater flow directions in the Balaka area are complicated by convergence of the above flows with southerly flowing groundwater from the adjoining Liwawadzi River valley. Furthermore, a little to the east a groundwater divide occurs at the WRU 1S boundary where groundwater drains eastwards directly towards the Shire River where heads are around 480 m msl. Hydraulic gradients in the unconsolidated aquifer approaching the Shire west bank in 1S and Lake Malombe in 1T located just south of the Shire outlet from Lake Malawi are relatively low, at around 0.004 (0.4 %) steepening to around 0.008 (0.8 %) with increased weathered basement proximity to the river. Groundwater reaching the Shire from the catchment 1A to the east of the river exhibits slightly steeper gradients close to the Shire ranging from 0.005 (0.5 %) to 0.011 (1%).

Groundwater flows in 1R south of Balaka and adjoining, near parallel catchment 1P to the west drain from the surrounding weathered Basement towards the widening plain, unconsolidated aquifer convergent on the Rivi in 1R and Mlunguzi River in 1P and their tributaries flowing south-south-eastwards towards the Shire River. Highest gradients occur around the weathered Basement –

unconsolidated aquifer interface around 0.014 (1.4 %) with contour profiles convergent on the mid to upper reaches indicating the rivers are supported by base flows. However, nearing the Shire around Njerenje hydraulic gradients reduce in the lowlands approaching the Shire to as low as 0.002 (0.2 %) with head contours slightly bowing away from rivers towards the Shire indicative of perhaps losing river conditions.

Nearing the faulted escarpment, groundwater flows converge around the Thima Rapids and Kholombidzi Falls in the greatly narrowing 1 P catchment where the unconsolidated aquifer deposits give way the weathered Basement. Groundwater flows also converge to Thima Rapids point in WRU 1B to the east of the Shire where contoured groundwater heads flows and north eastwards convergent on the Linjisi River and emergence of streams and wetlands north of Mlangeni close to the Shire suggest strong base flow conditions in this relatively wide area of unconsolidated deposits east of the Shire that is driven by steep topography and high hydraulic gradients up to 0.018 (1.8 %) inland reducing to 0.004 (0.4 %) nearing the Shire. Further north in 1B hydraulic gradients of groundwater flows westwards to the Shire further upstream are steeper at around 0.012 (1.2 %) due to more typical close approach of the weathered Basement to the Shire. Such gradients are around five-fold higher than gradients found on the opposing lowlands to the west side of the Shire.

Aquifer / Borehole Yield

In most WRA's in Malawi, the borehole yield data held by the Ministry does not appear to follow the anticipated distribution based on aquifer lithology. **Figure 12** provides the distribution of the data held by the Ministry of Water and Sanitation for each WRU in the Upper Shire WRA 1, and unlike many Water Resource Areas in Malawi where it is clear the distribution is skewed toward values of < 0.25l/s, in the Upper Shire of WRA 1 has a trend towards values of ca. 1l/s. Reported yields of ca. 0.25l/s and less are 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 the Upper Shire of WRA 1 there appears to be a trend to higher borehole yields related to alluvium aquifer units (some semi- to confined), with a number of production boreholes reporting yields in excess of 2l/s. In the Upper Shire of WRA 1 (**Figures 13a to 13g**) there is some potential in the colluvium, alluvial and fluvial units for higher yielding boreholes, in particular where there are reported yields over 2l/s, and there is potential for artesian confined systems but detailed hydrogeological on-site mapping should be undertaken to confirm. The highest yielding boreholes in basement aquifers will likely be located mainly along linear structures and main streams and near contacts between different aquifers.

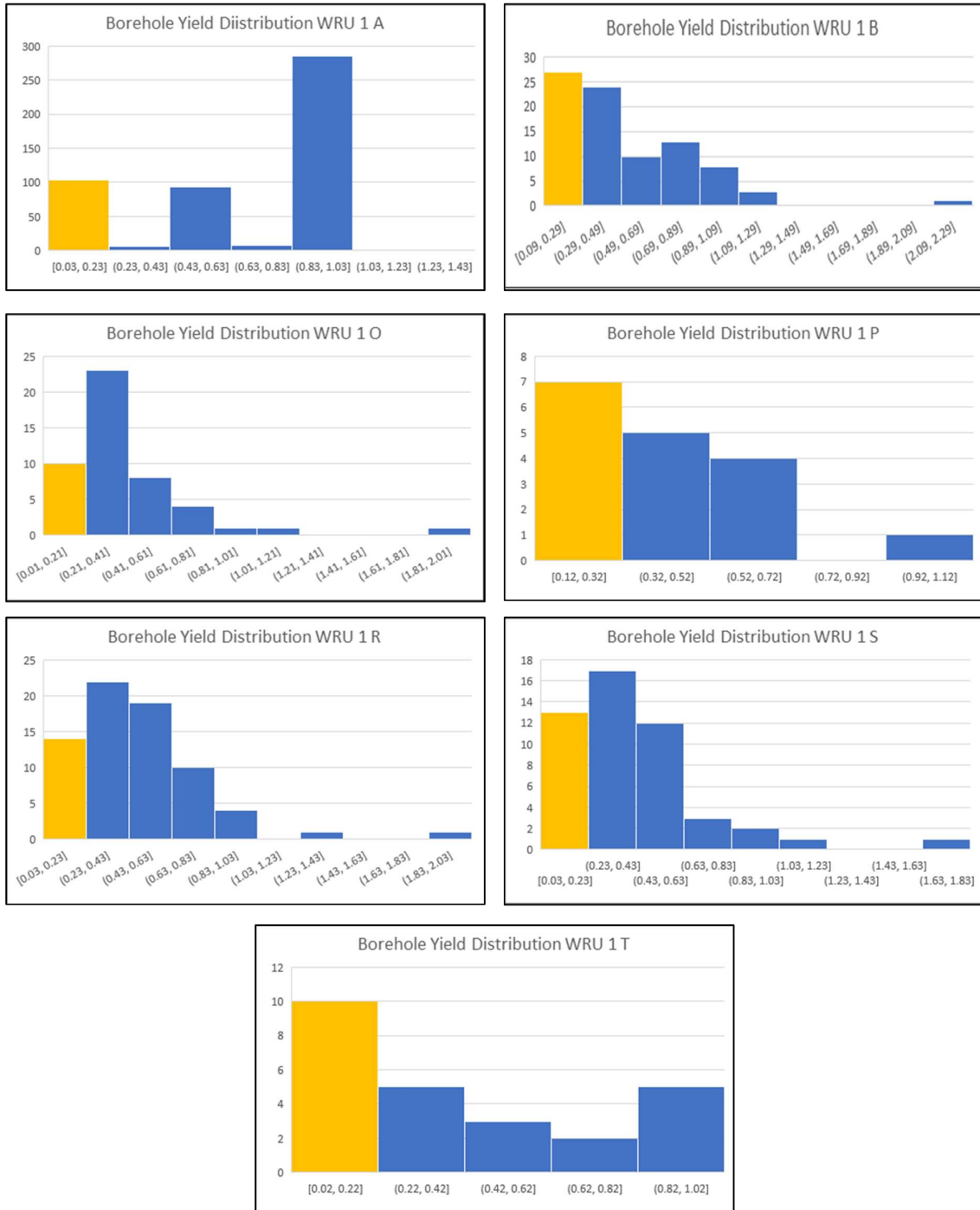


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for Water Resource Units WRU 1A, 1B, 1O, 1P, 1R, 1S, 1T within the Upper Shire Water Resource Area 1 (y axis = *n* observations)

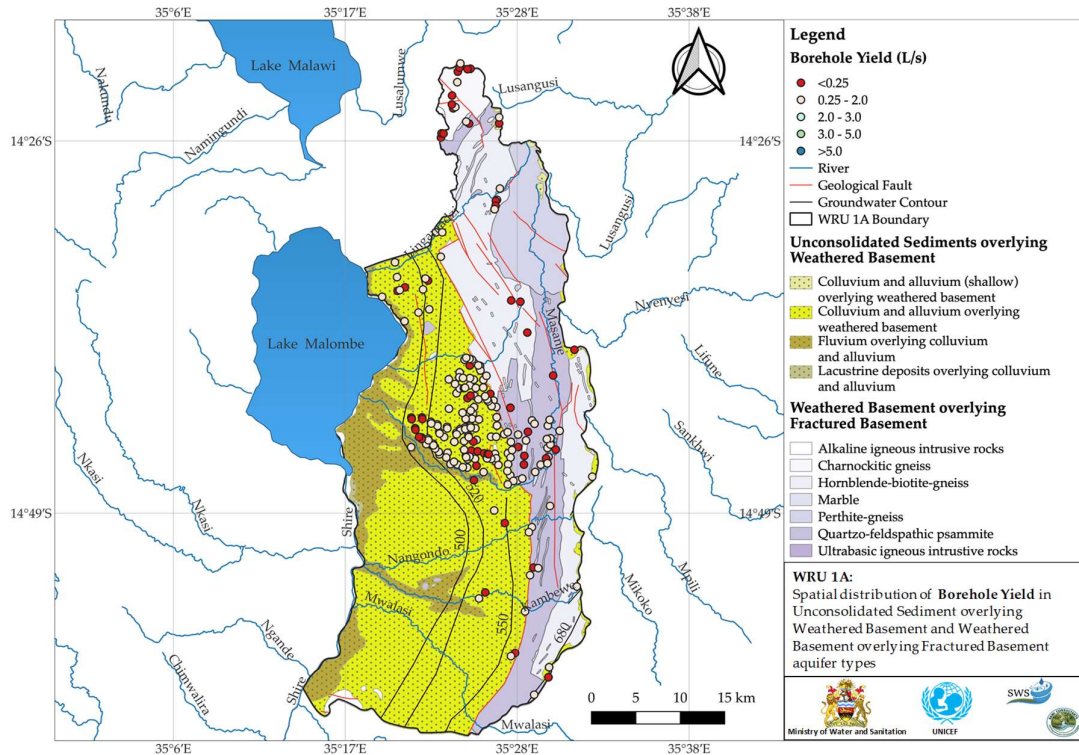


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1A.

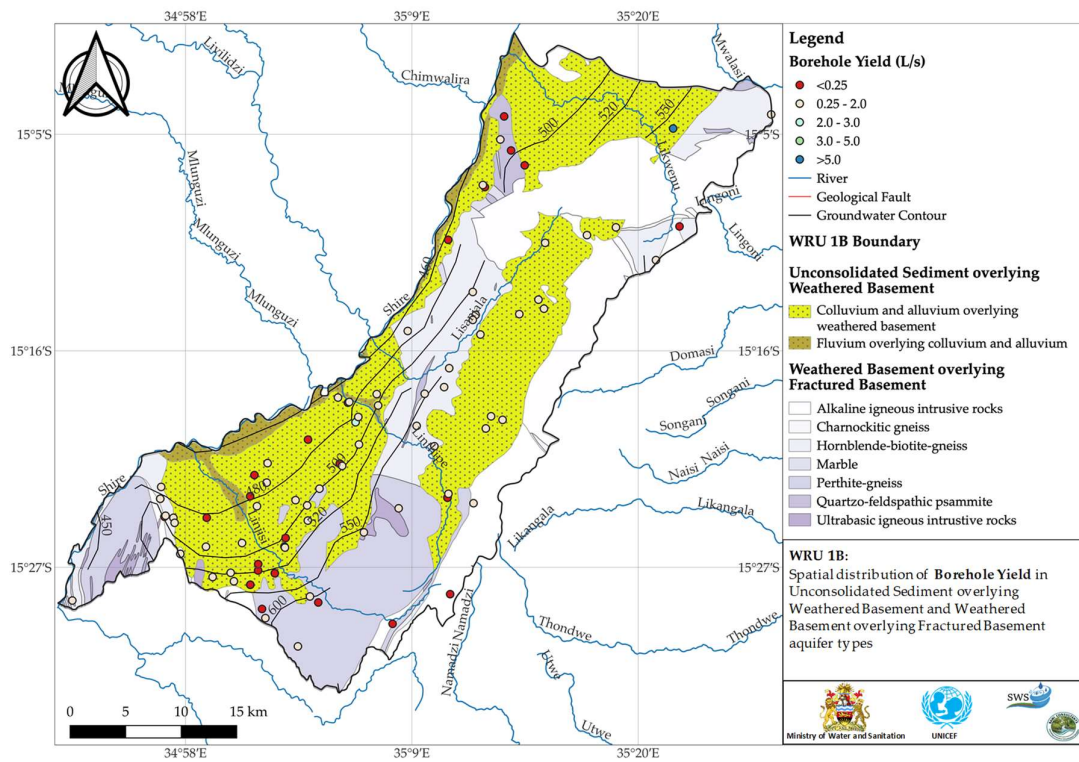


Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1B.

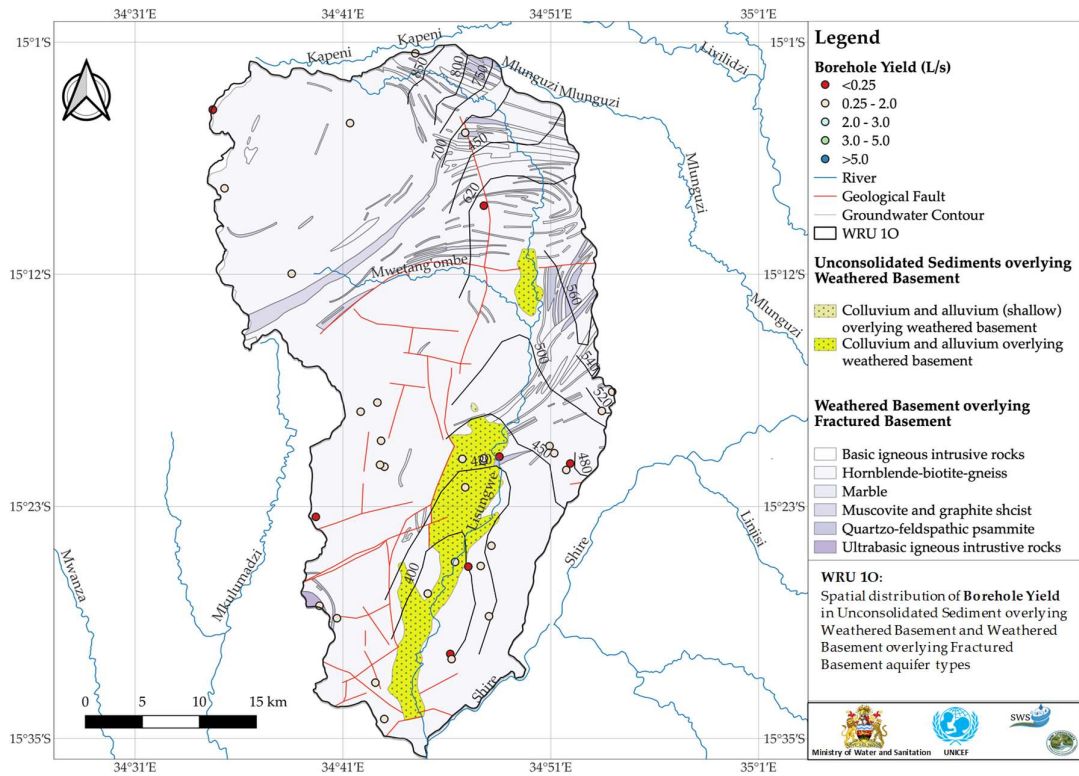


Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 10.

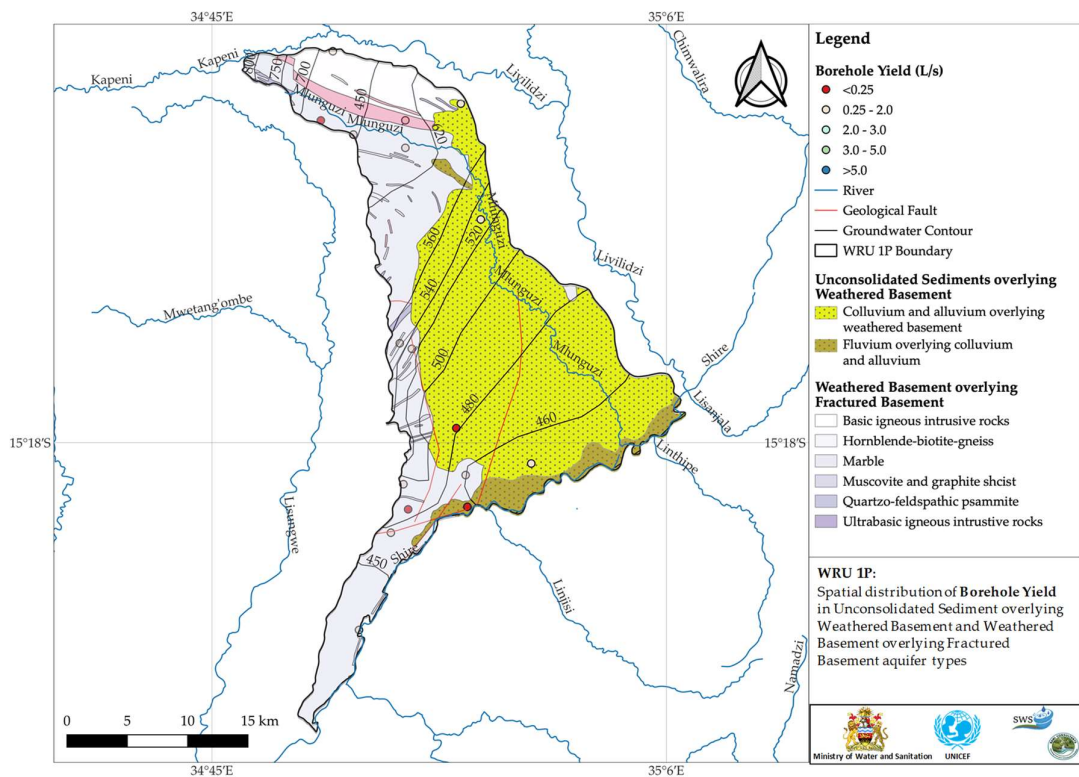


Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1P.

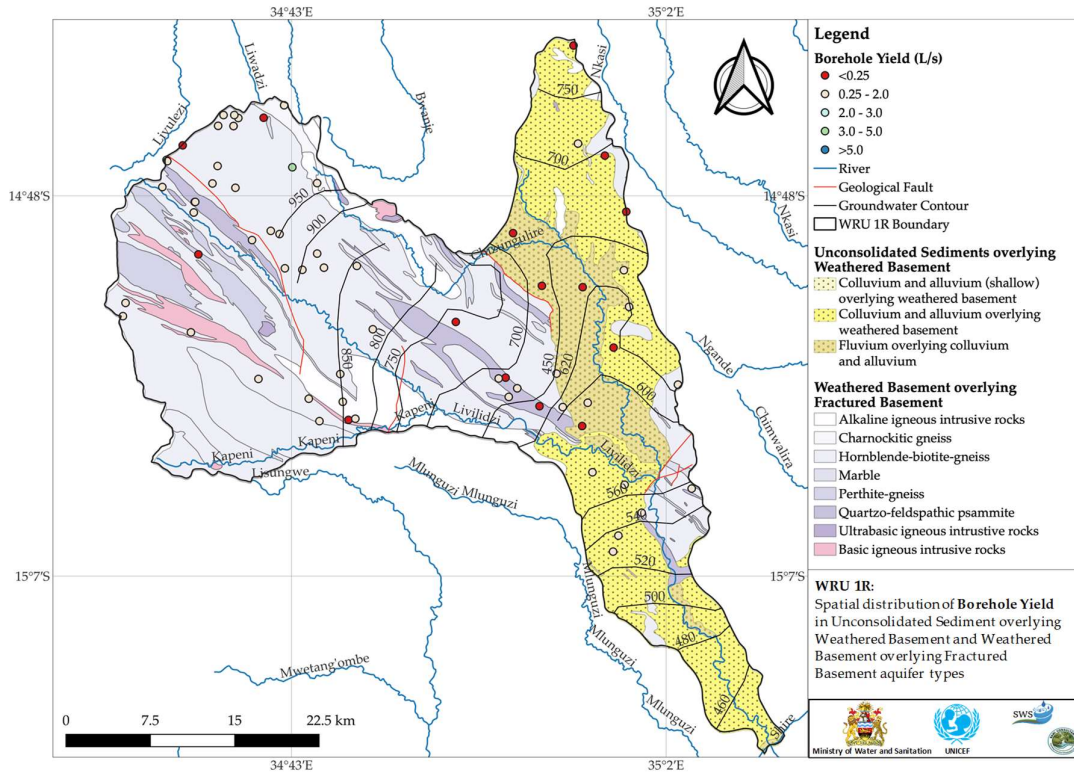


Figure 13e. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1R.

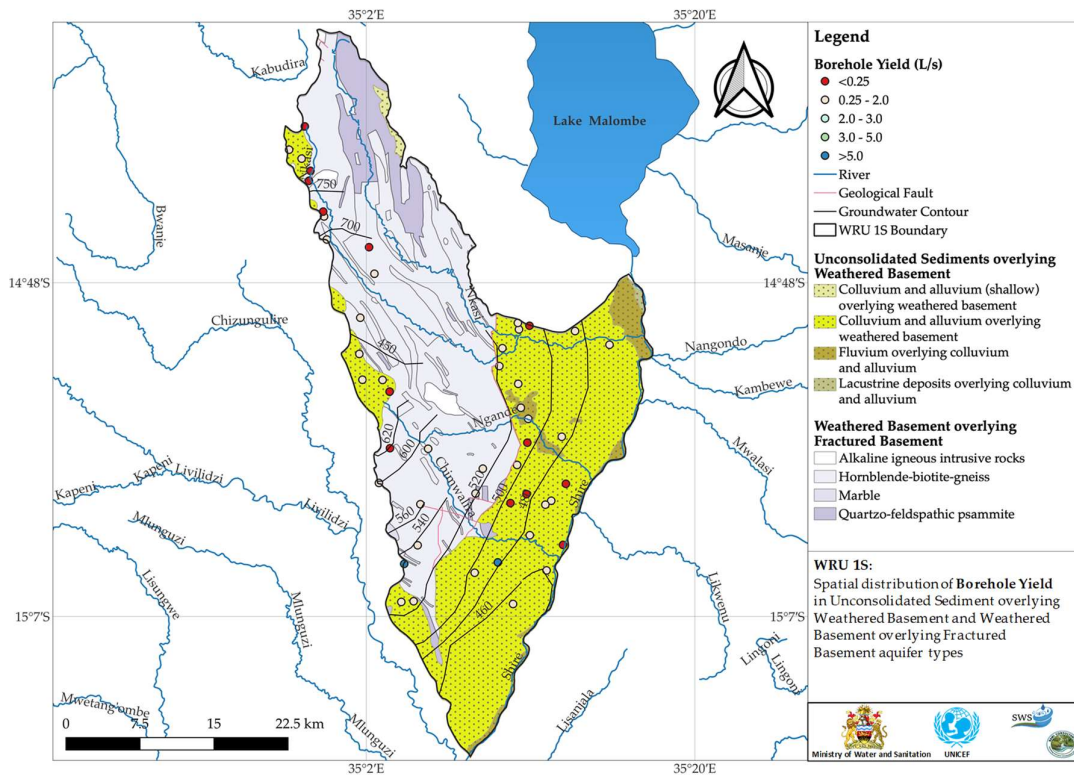


Figure 13f. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1S.

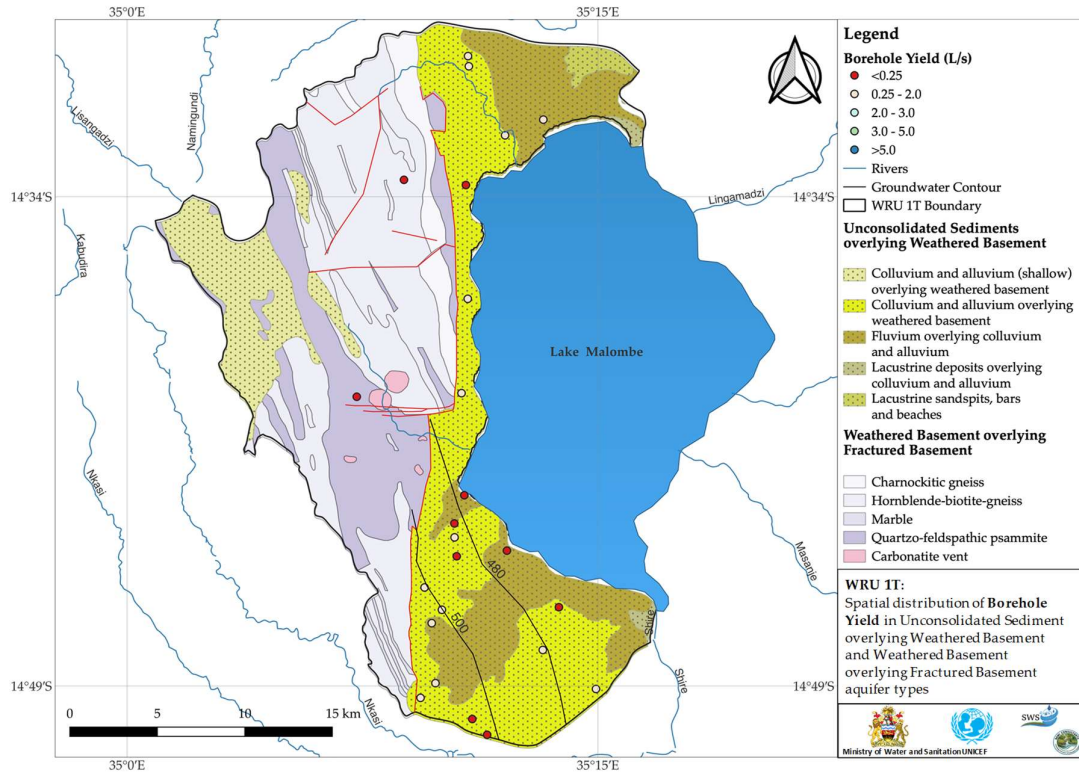


Figure 13g. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1T.

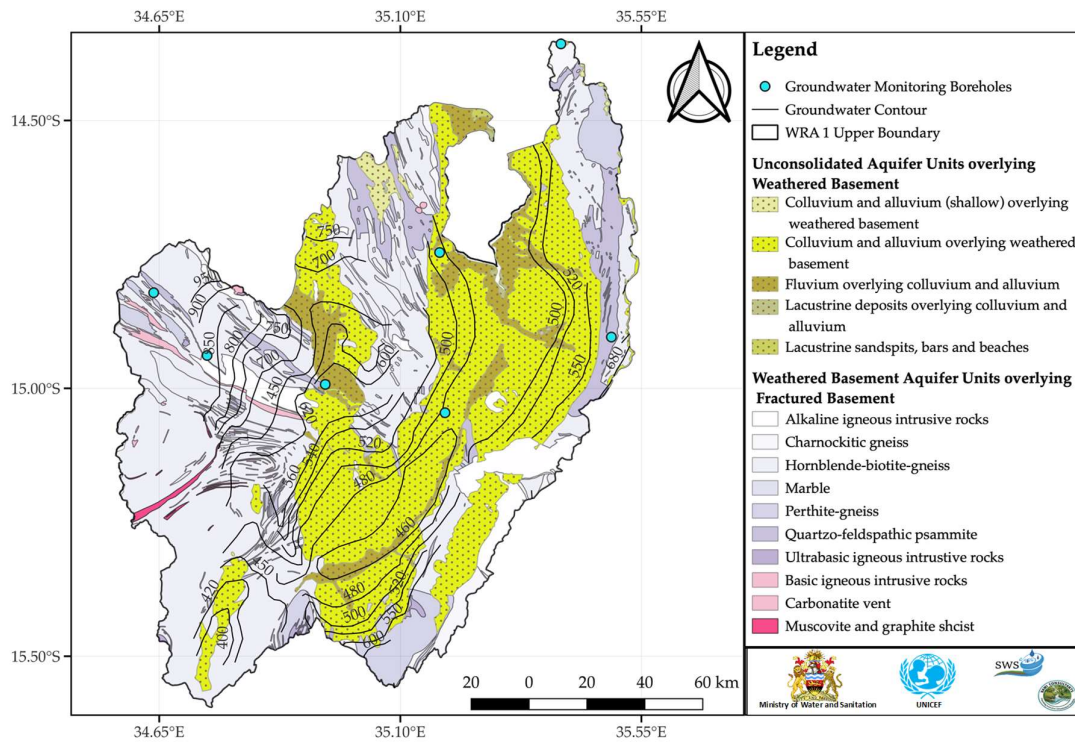


Figure 14a. Location of Groundwater Monitoring Points in the Upper Shire Water Resources Area 1.

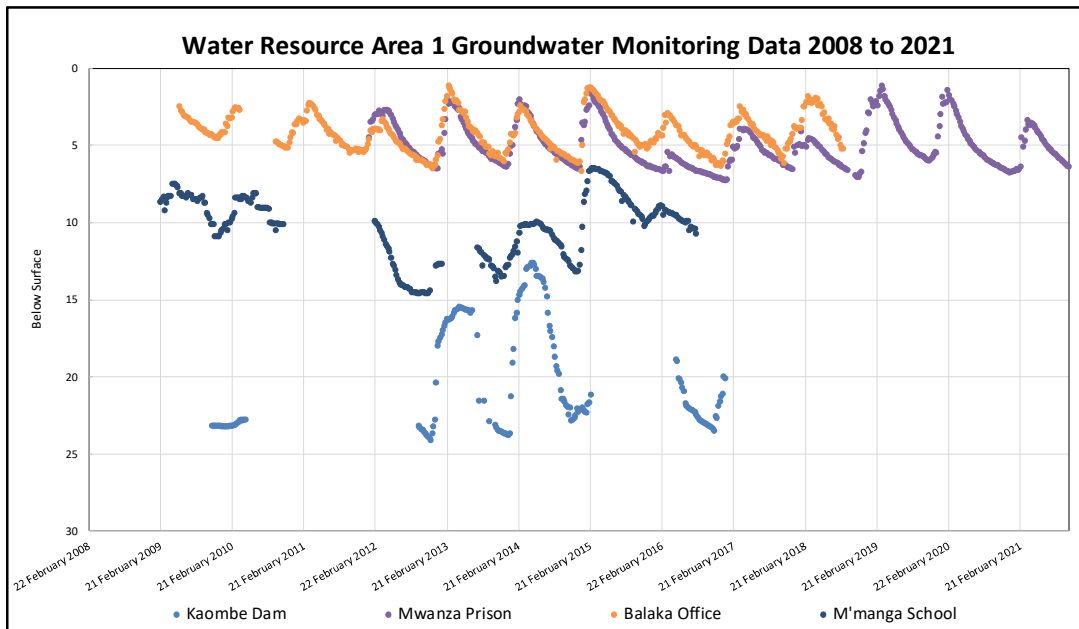


Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in the Upper Shire Water Resources Area 1 (units assumed to be meters below ground level).

Groundwater Table Variations

There are a number of operational groundwater monitoring stations within the Upper Shire WRA 1 (Figure 14a for location and Figure 14b for data), some of which have been vandalised or have had challenges with continuous data. The Balaka water office and Mwanza Prison records are those of the most complete for the period 2008 to 2021. Data from the 2020 National Survey suggested seasonal water table declines, supported by the data in Figure 14. From the data that is held by the Ministry of Water and Sanitation, there is between a 5- and 7 -meter annual change in groundwater table, with long-term trends of over 10 meters that may relate to climate variability (rainfall and recharge relationships) and over abstraction. The magnitude of the seasonal variation suggests the aquifers these monitoring points intersect are unconfined and receive annual seasonal recharge. However, there are no detailed borehole logs providing specific zones for monitoring nor multi-level installations that separate different hydro-stratigraphic units, this highly limits the usefulness of the data and it is recommended that multi-level installations into each 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 1A, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness High Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	149.4	10%	35%	0.02	0.10	298.7	5,227.4	
Lacustrine units	2.9	10%	35%	0.02	0.03	5.8	30.4	
Colluvial etc.	750.7	10%	30%	0.02	0.06	1,501.5	13,513.5	
W & F Basement	632.5	1%	10%	0.02	0.03	126.5	1,897.4	
	Area of WRU (km ²)	1A WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	1,932.5	20,668.6	Total Volume Groundwater
	1,535.4	955 Average Rainfall in WRU		9.55	71.625	14.7	110.0	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]						132	188	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 1B, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness High Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	41.0	10%	35%	0.02	0.10	82.0	1,435.6	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	576.8	10%	30%	0.02	0.06	1,153.6	10,382.6	
W & F Basement	664.5	1%	10%	0.02	0.03	132.9	1,993.4	
	Area of WRU (km ²)	1B WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	1,368.5	13,811.5	Total Volume Groundwater
	1,282.3	980 Average Rainfall in WRU		9.8	73.5	12.6	94.2	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]						109	147	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 1O, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness High Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	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.	104.3	10%	30%	0.02	0.06	208.6	1,877.2	
W & F Basement	1,374.5	1%	10%	0.02	0.03	274.9	4,123.4	
	Area of WRU (km ²)	1O WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	483.5	6,000.6	Total Volume Groundwater
	1,478.8	989 Average Rainfall in WRU		9.89	74.175	14.6	109.7	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						33	55	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 1P, 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	37.6	10%	35%	0.02	0.10	75.2	1,315.5	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	340.0	10%	30%	0.02	0.06	680.0	6,119.7	
W & F Basement	279.8	1%	10%	0.02	0.03	56.0	839.5	
	Area of WRU (km ²)	1P	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	811.1	8,274.7	Total Volume Groundwater
	657.4	920	Average Rainfall in WRU	9.2	69	6.0	45.4	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						134	182	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4e. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 1R, 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	155.7	10%	35%	0.02	0.10	311.3	5,448.5	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	344.9	10%	30%	0.02	0.06	689.8	6,208.5	
W & F Basement	997.9	1%	10%	0.02	0.03	199.6	2,993.7	
	Area of WRU (km ²)	1R	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	1,200.8	14,650.7	Total Volume Groundwater
	1,498.5	943	Average Rainfall in WRU	9.43	70.725	14.1	106.0	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]						85	138	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4f. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 1S, 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	41.5	10%	35%	0.02	0.10	82.9	1,451.6	
Lacustrine units	1.6	10%	35%	0.02	0.03	3.3	17.2	
Colluvial etc.	499.1	10%	30%	0.02	0.06	998.3	8,984.3	
W & F Basement	635.8	1%	10%	0.02	0.03	127.2	1,907.3	
	Area of WRU (km ²)	1S	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	1,211.6	12,360.4	Total Volume Groundwater
	1,178.0	951	Average Rainfall in WRU	9.51	71.325	11.2	84.0	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]						108	147	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4g. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 1T, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km ²)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness High Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	88.7	10%	35%	0.02	0.10	177.4	3,103.8	
Lacustrine units	8.7	10%	35%	0.02	0.03	17.4	91.4	
Colluvial etc.	195.5	10%	30%	0.02	0.06	391.0	3,519.3	
W & F Basement	273.7	1%	10%	0.02	0.03	54.7	821.1	
	Area of WRU (km ²)	1T WRU		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	640.5	7,535.5	Total Volume Groundwater
	566.6	924 Average Rainfall in WRU		9.24	69.3	5.2	39.3	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]						122	192	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 1 ranges between 78.4 Million Cubic Meters (MCM) and 588.6 MCM per year, with a mean age of groundwater of 127 years across the Water Resource Area (**Tables 4a to 4g**). There is a need to better constrain water volume/balance aspects of the basin and to expand the use of Isotope Hydrology and properly modelled and measured groundwater age constraints.

Groundwater quality WRA 1 Upper Shire

Groundwater major-ion water quality in WRA 1 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**).

Table 5. Distribution of dissolved species in all groundwater from WRA 1 (the distribution of various parameters for each WRU are provide at the end of this annex). 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 1	pH	EC	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	7.5	1,033	120	93	5.6	1.8	127	4.0	77	30	3.7
StdDev	0.8	1,463	393	343	11	6.3	301	7.8	83	49	11
Median	7.8	650	20	14	1.0	0.8	40	2.0	58	19	0.3
Max	9.8	17,500	5,840	4,900	95	108	3,900	95	980	730	91
Min	4.1	10.0	0.0	0.1	0.1	0.1	0.2	0.1	10	0.1	0.0
n	4,384	4,422	3,951	4,016	2,154	2,852	3,995	3,857	3,831	3,766	2,318

Piper plots of the WRA 1 water quality data suggest most water has expected geochemical changes from water-rock interactions dominated by Ca-Mg-HCO₃ type waters with a trend for increasing Na-Cl-SO₄ likely due to fault zone fluids or evaporative enrichment, but given the increases in sulphate

and high fluoride measurements, geologic sources are more likely (Figure 14a, 14b and 14c). The average groundwater age, precipitation rate and calculated recharge rates together with the moderate electrical conductivity points to recent meteoric recharge of much of the groundwater with water-rock interactions and fault-zone water movements, however in low-lying areas there are zones of high EC groundwater that most likely are only related to evaporative enrichment. Further isotope hydrology study is needed at local scale to elucidate mechanisms.

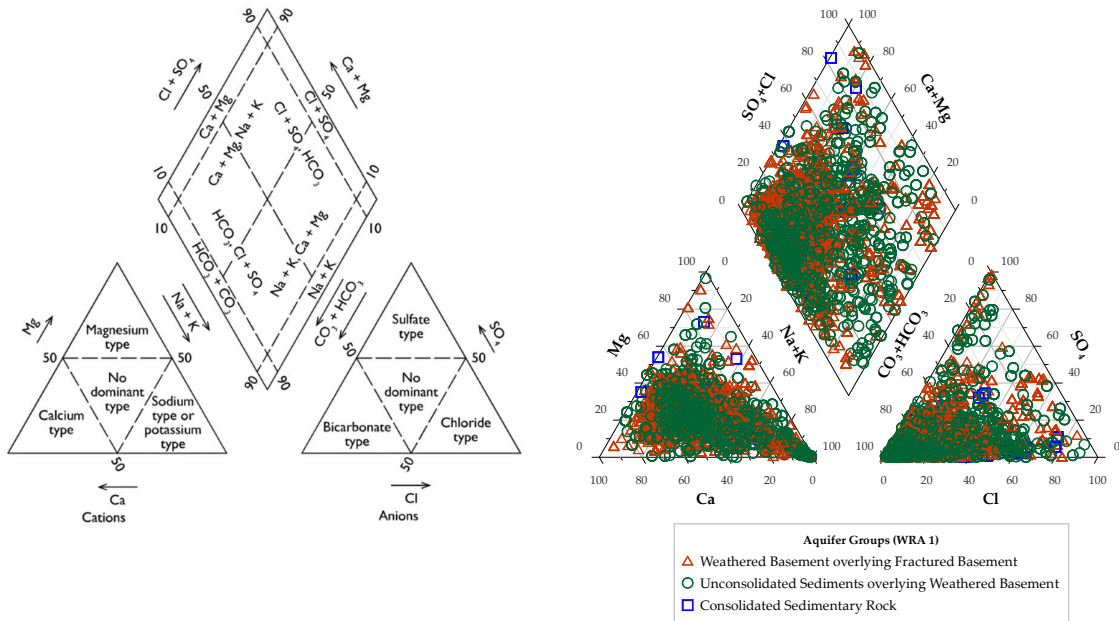


Figure 14a, 14b. Piper Diagrammes of Groundwater Samples in WRA 1 and for each Aquifer Type in WRA 1.

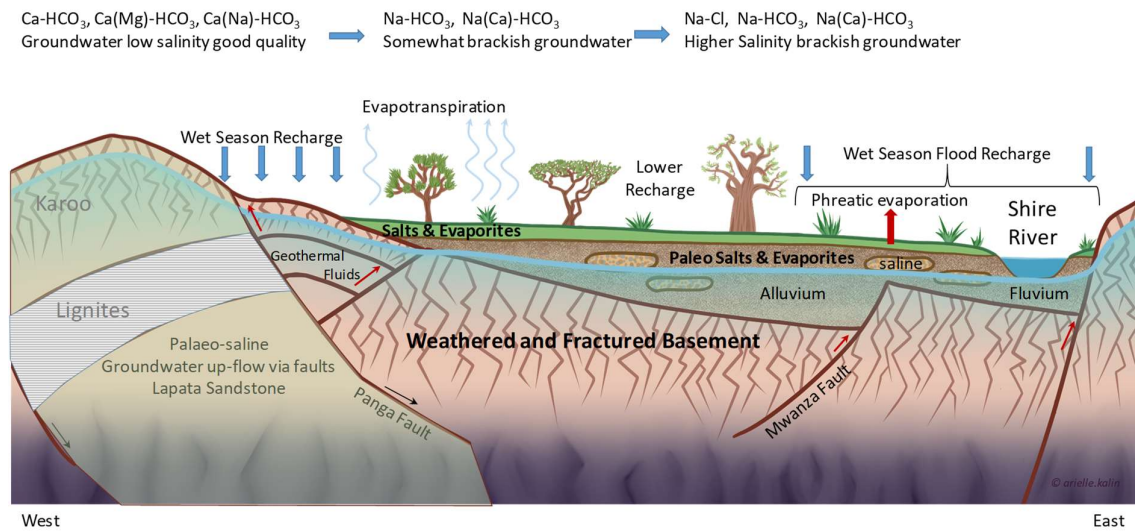


Figure 14c. Idealised cross section of WRA 1 showing the likely influences of evaporative enrichment of groundwater salinity coupled with fluid flow along rift faults.

The distribution of key dissolved water quality species in groundwater of WRA 1 is provided however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine in WRA 1, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

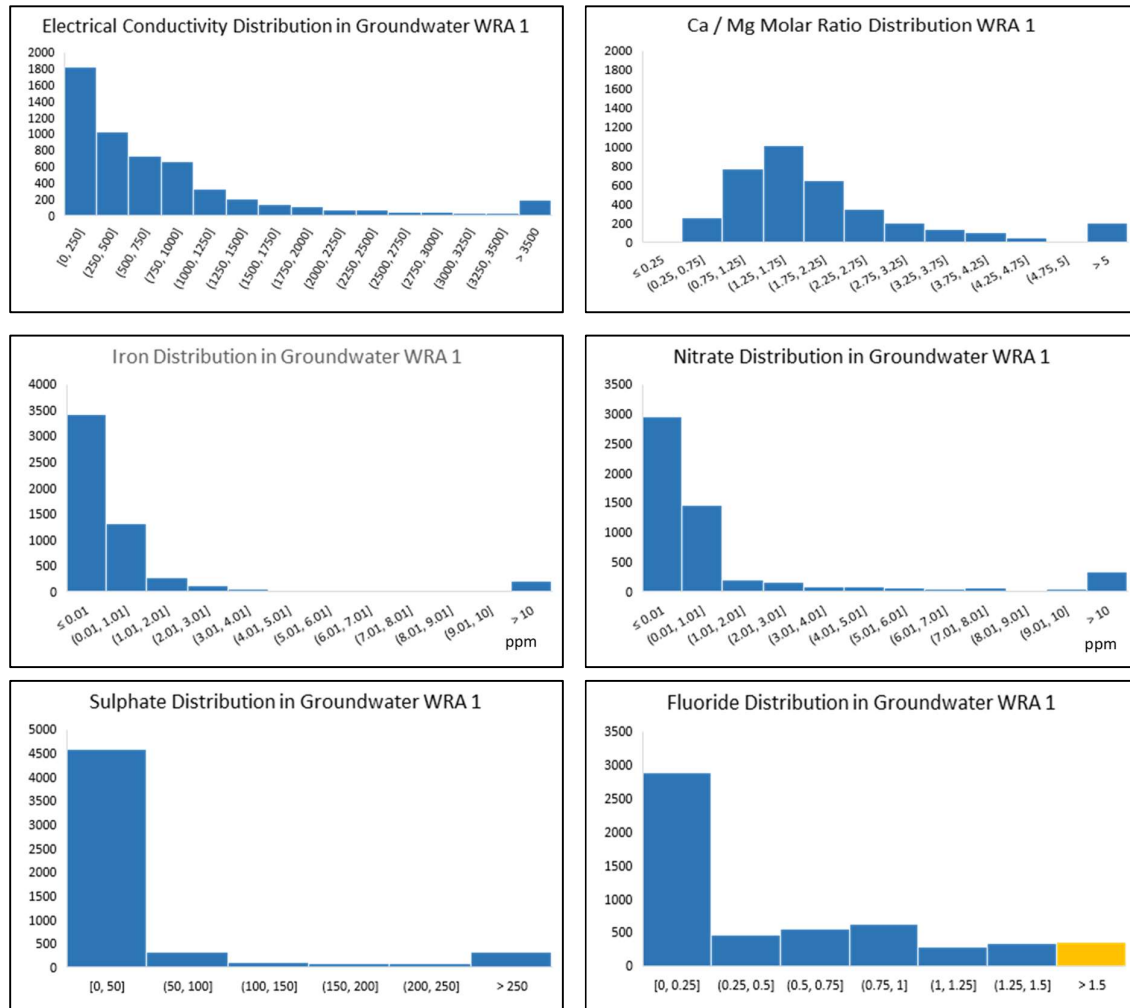


Figure 15 Distribution of chemical species in groundwater within WRA 1 (y axis = n observations).

Stable Isotope Results

Stable isotopes are unique for evaluating the complexities associated with groundwater–surface-water interactions which are diverse occurrence in WRA 1 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 in the Shire Basin (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 1 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.

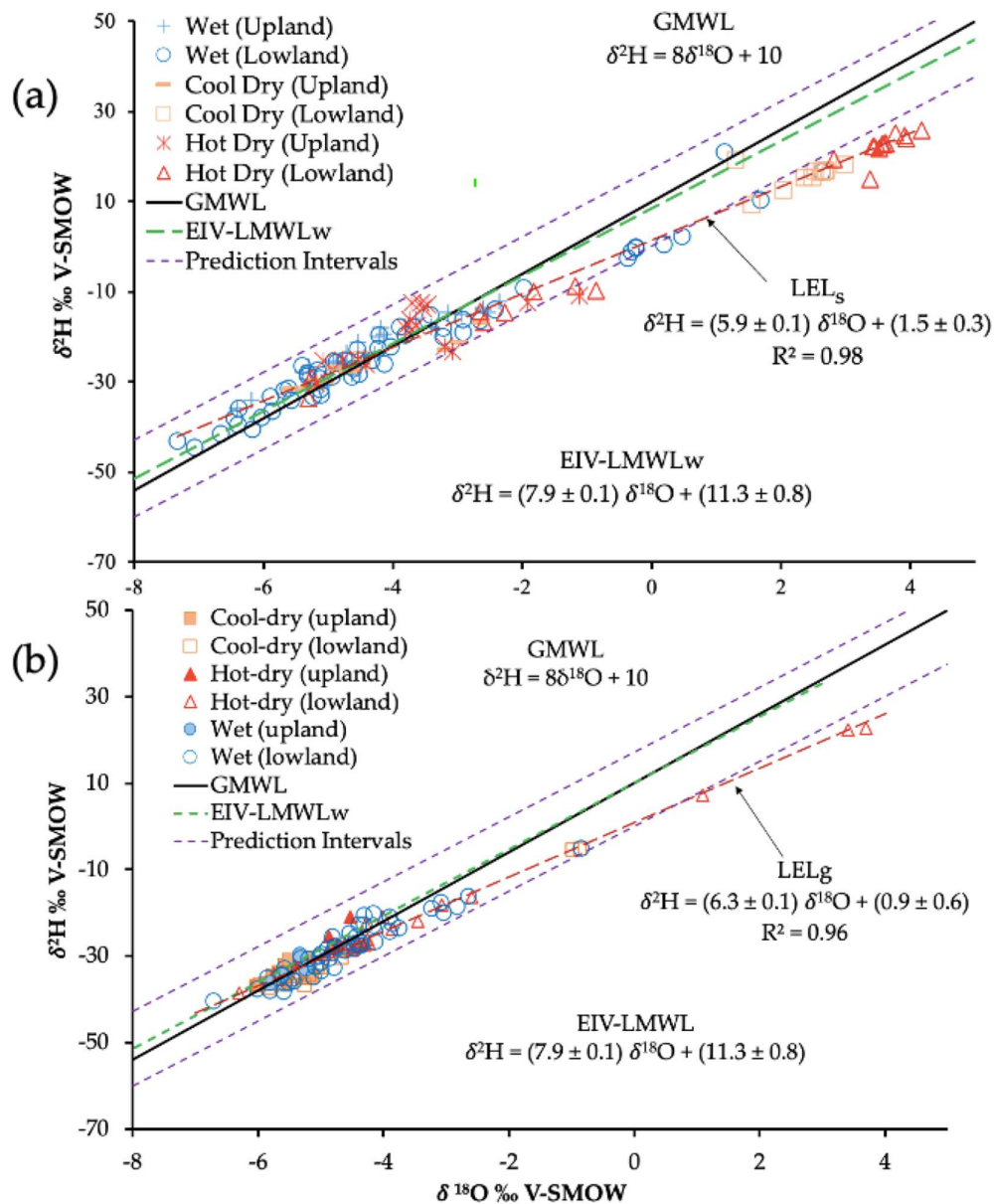


Figure 16a and 16b. Stable isotope measurements of groundwater in WRA showing the effects of evaporation on (a) surface water and (b) groundwater samples for the 3 seasons Cool-Dry, Hot-Dry and Wed (after Banda et al 2019).

The variation spatially of isotope results support highly enriched isotopic values of surface water were observed in lowland sites of the Lower Shire WRA 1 with highly depleted isotopic values more apparent in upland sites of the Upper Shire WRA 1 (Figure 16c). Highly enriched isotopic values are distributed along the Shire River bankside area from upper to lower reaches of the Basin. Groundwater exhibits a similar pattern of enriched isotopic signatures in lowland sites and depleted isotopic signatures in upland sites. Highly enriched isotopic values in groundwater are more

pronounced in superficial aquifer systems compared to the basement aquifer systems, as the former mostly occurred in lowlands characteristic of high evaporation effects, while the latter were largely found in uplands associated with cool temperatures, less evaporative effects and probably deeper water tables or possible confined groundwater systems. The spatial distribution of isotopic content of groundwater appears more influenced by evaporative fractionation in near-river in the Lower Shire WRA 1 such as wetland vicinities (e.g., the Elephant Marsh) where water tables are shallower and groundwater is slow moving.

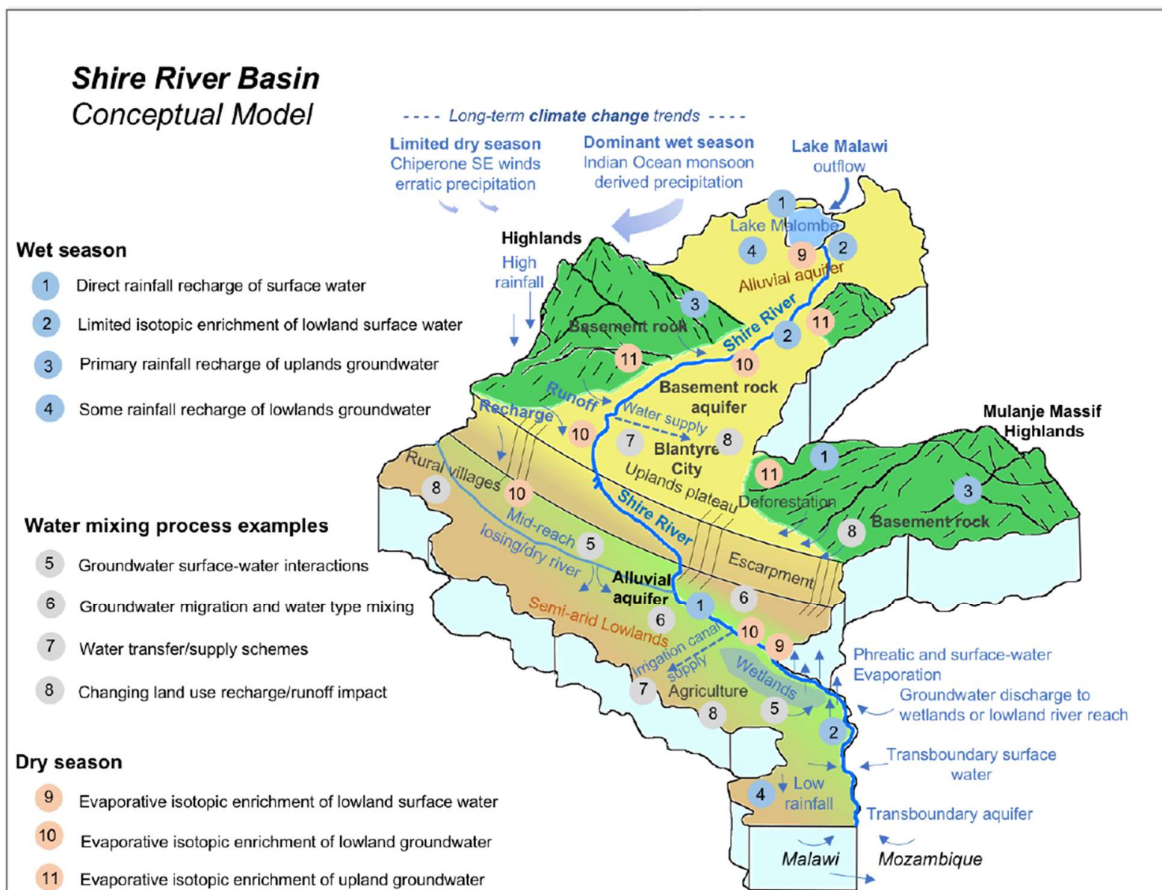


Figure 16c. Conceptual model of isotope hydrology for the Shire Basin WRA 1 (after Banda et al 2019).

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 1 (**Table 5** and **Figure 15**) is low but there are areas where salinity is above both WHO and Malawi standards, exceeding 3,500mg/l. The lack of routine and widespread water quality analyses held by the Ministry of Water and Sanitation does not allow for interpretation with respect to hydrogeologic units but a review of data by Rivett et al (2019) provided interpretation of the dominant processes that result in high salinity (**Figure 14c**). It is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation.

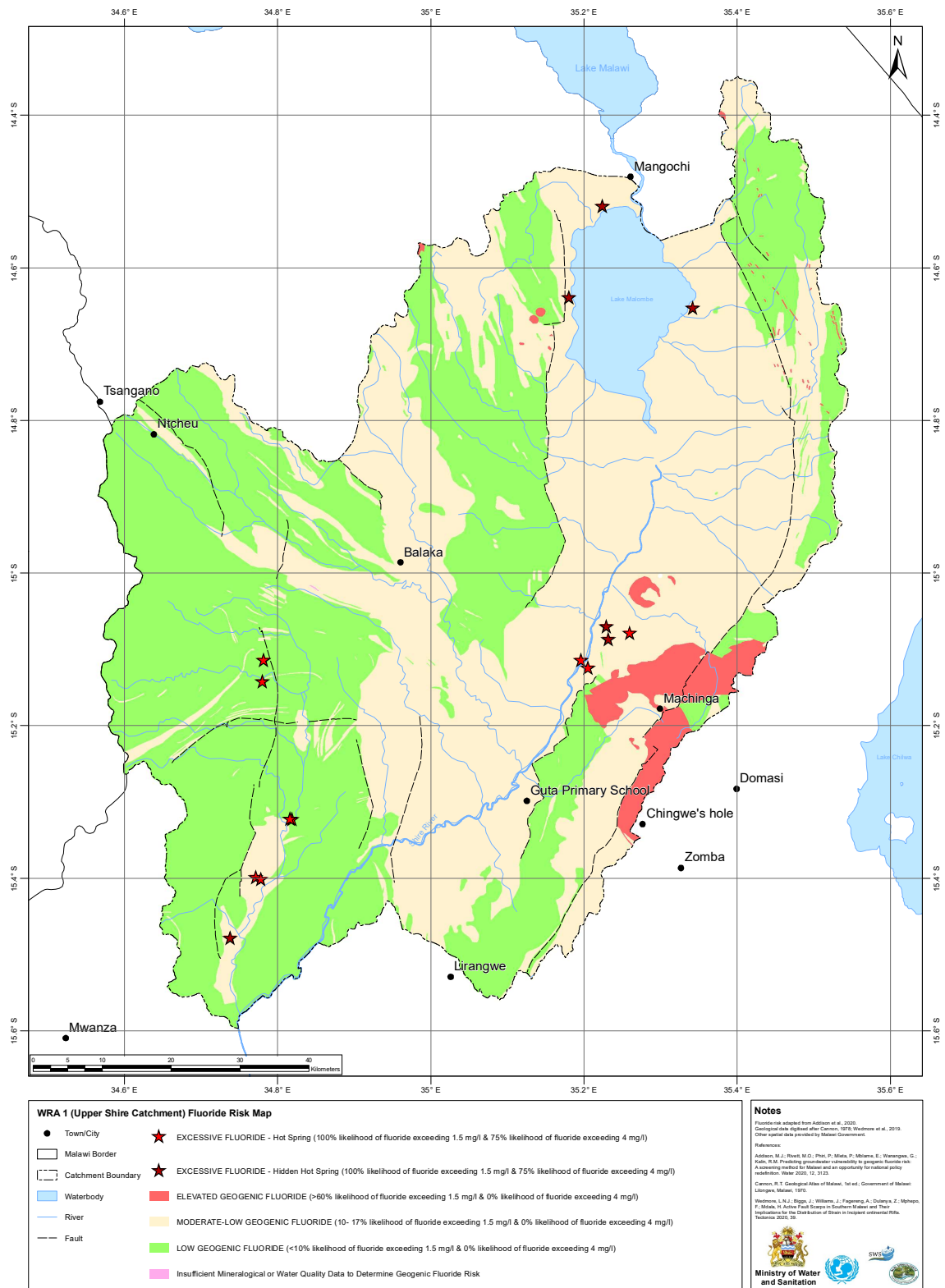


Figure 17. Groundwater Fluoride Risk Map WRA 1 Upper Shire (after Addison et. al. 2021).

Fluoride

There are a considerable number of hot springs in WRA 1 but the mineralogy of much of the geology placing WRA 1 in a **Lower Risk** category for fluoride in groundwater except for areas around the numerous fault zones which are **High Risk (Figure 17)**. Groundwater data drawn from the recent national-scale assessments (**Figure 15**) reveal a large number of analyses are above 1.5mg/l, known hot springs or areas where fault zones underlie aquifers should be targeted for re-analysis as given the co-location with major faults, those water points in proximity to the faults have an increased risk of $F > 1.5$ mg/l. Additionally, surface water supplies from the areas where basement geology contains fluoride bearing minerals should be monitored for groundwater and any spring runoff that may contain fluoride. The current water quality monitoring data held by the Ministry of Water and Sanitation is insufficient to manage this risk and it is recommended that a detailed and systematic survey of groundwater quality in WRA 1 is planned and implemented.

Arsenic

A recent national collation of arsenic groundwater survey data (Rivett et al 2018) found widespread low concentrations but with only a few above the WHO 10 µg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. This national dataset did sample WRA 1 with no levels above the WHO limit, however arsenic risks may exist due to the presence of hot springs on the western rift zone, this remain unproven due to a lack of routine, geospatially managed WQ analyses. It is recommended that a detailed and systematic survey of groundwater quality in WRA 1 is planned and implemented

E-Coli and Pit Latrine Loading to Groundwater

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

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

Table 6. Calculated pit latrine loading 2012 to 2022 within WRA 1.

Water Resource Unit	Population (Worldpop online)						Projection	Latrine fecal sludge	Cumulative Sludge loading
	Calculated Number of Latrine users								
	Year 2011 - 2012	Year 2013 - 2014	Year 2015 - 2016	Year 2017 - 2018	Year 2019 - 2020	Year 2021 - 2022	Total Volume over 10 year period (Liters)	Estimated Total Loading (metric tonnes fecal sludge 2012 - 2022)	
1A	150,786	161,941	175,782	189,095	203,025	192,190	579,321,996	695,186	
1Ba	416,005	399,101	379,069	433,234	330,287	369,390	1,256,626,552	1,507,952	
1Bb	194,799	203,715	210,869	218,216	225,658	227,168	691,428,726	829,714	
1C	235,171	235,613	235,129	253,223	228,543	241,303	771,650,718	925,981	
"1E2"	160,152	161,489	162,836	172,797	161,187	174,538	536,219,159	643,463	
1F	228,447	236,015	244,505	252,008	258,697	259,662	798,840,287	958,608	
1G	115,018	117,324	120,975	123,335	124,840	126,187	392,946,641	471,536	
1H	205,488	211,854	217,168	222,228	226,895	229,654	709,174,961	851,010	
1K	171,881	181,668	191,533	202,181	212,605	203,688	628,319,694	753,984	
1L	46,912	48,790	50,438	52,079	53,659	55,066	165,749,417	198,899	
1M	62,173	67,281	72,456	77,659	83,207	77,569	237,786,173	285,343	
1N	21,426	22,949	23,964	25,247	26,576	26,030	78,943,854	94,733	
1O	107,303	115,439	124,091	132,540	141,468	132,254	406,671,012	488,005	
1P	68,363	71,616	76,408	80,682	84,356	82,311	250,417,254	300,501	
1R	279,491	297,263	315,133	332,746	350,663	381,246	1,056,532,568	1,267,839	
1S	173,810	185,405	197,281	209,735	222,325	222,339	653,883,113	784,660	
1T	106,045	113,565	122,323	130,398	138,773	152,181	412,174,380	494,609	
WRA 1	2,743,269	2,831,027	2,919,960	3,107,402	3,072,765	3,152,775	9,626,686,505	11,552,024	

A recent publication by Rivett et al (2022) provided strong evidence of pit-latrines induced e-coli contamination of groundwater supplies regardless of season (wet / dry). Water resource Area 1 has a modelled calculated total of 11,552,024 metric tonnes of faecal matter loading over the 10-year period (2012-2022) (Table 6). Over the same 10-year period the modelled number of pit latrine users in the region increased by 409,506. WRA 1 covers roughly 15.3% 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, 30,983 metric tonnes of fertiliser would be used in WRA 1 per year which is 37 less than faecal matter was added to this WRA this 10-year period. The prevalence of Iron and Nitrate in groundwater suggests there is a growing impact of pit latrines on groundwater quality but there is no systematic study of this impact and it is recommended that routine water quality monitoring that focuses on the impact of pit latrines is implemented.

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Detailed Maps

Water Resource Unit (WRA) 1 Figures

Figure WRA 1.0: Aquifer Units and Groundwater Level Contours Water Resources Area 1

Figure WRA 1.1: Aquifer Units and Groundwater Level Contours Upper Shire WRA 1

Figure WRA 1.0: Aquifer Units and Groundwater Level Contours WRA 1

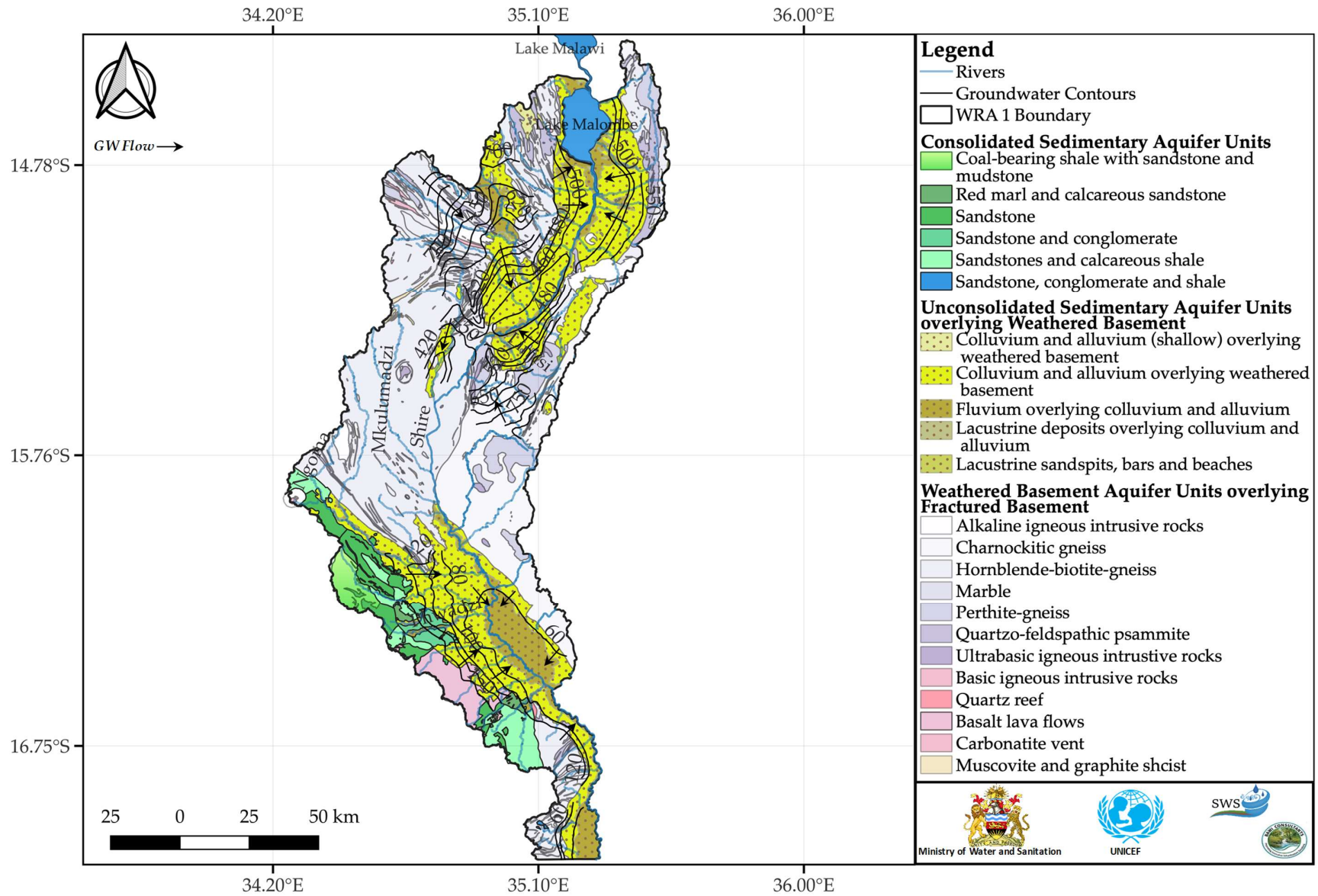
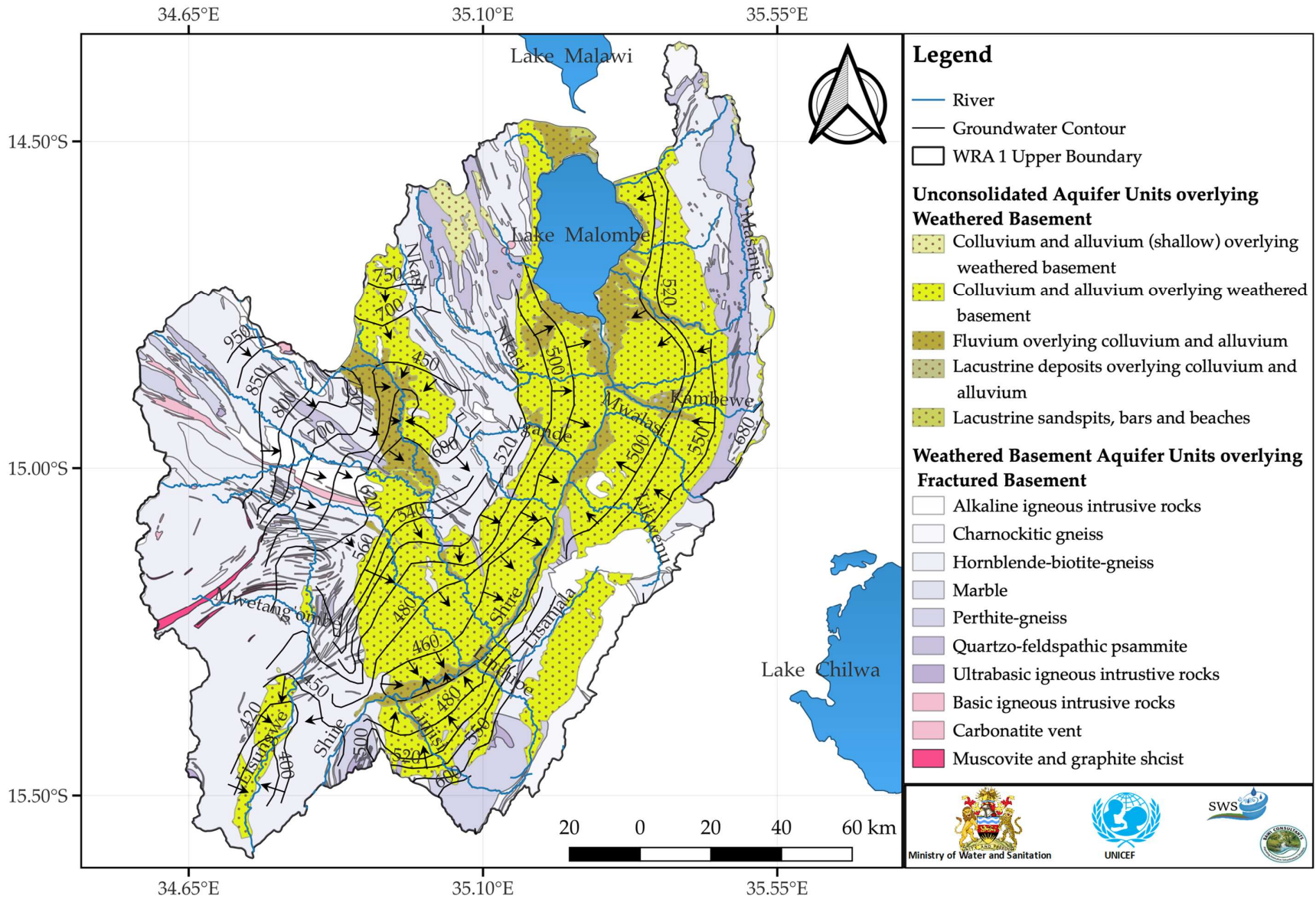


Figure WRA 1.1: Aquifer Units and Groundwater Level Contours Upper Shire WRA 1



WRU 1A Figures

Figure WRU 1A.1 Land Use and Major Roads

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Figure WRU 1A.10 Borehole Yield Map for data held by the Ministry

Figure WRU 1A.1 Land Use and Major Roads

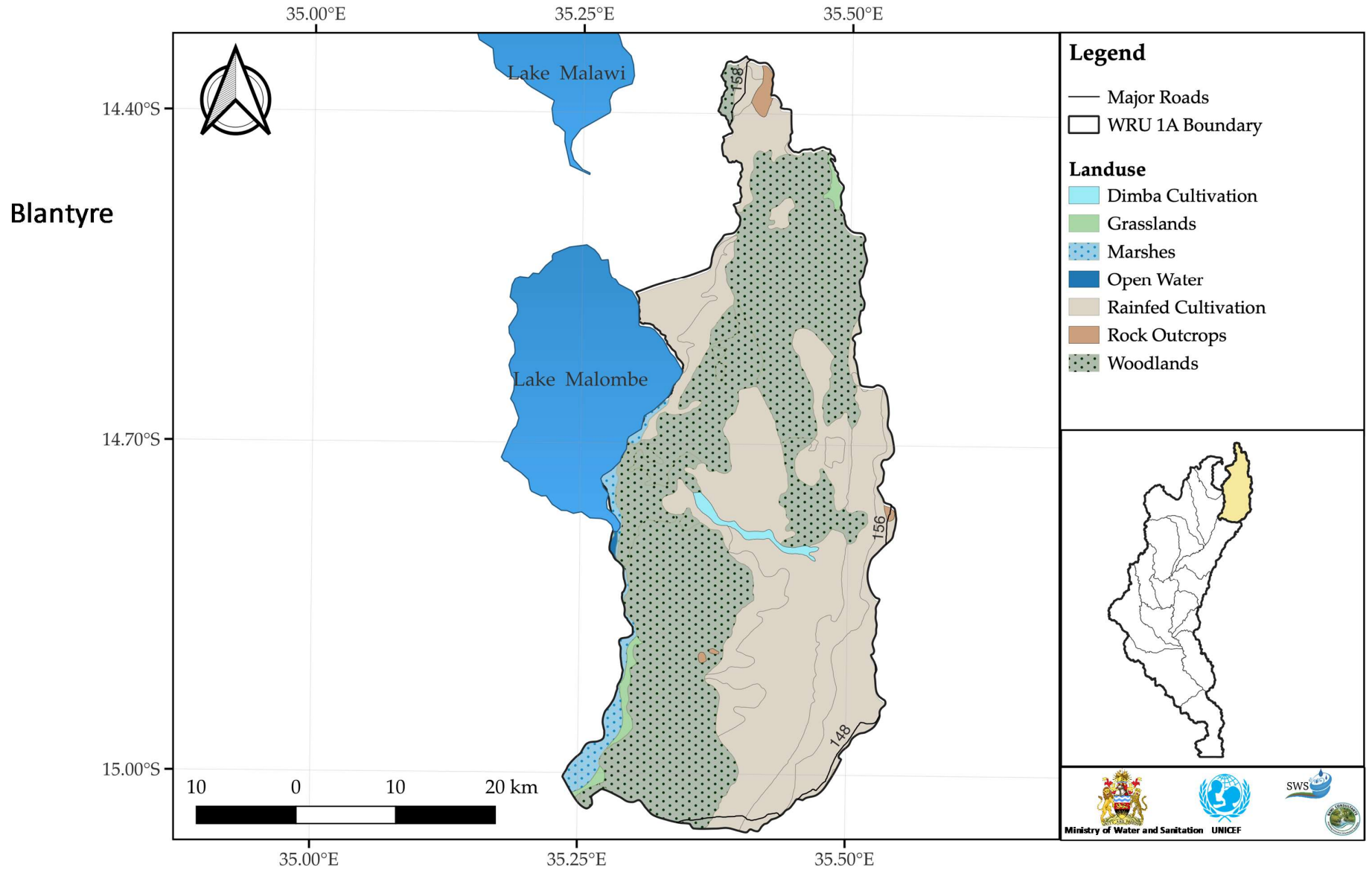


Figure WRU 1A.2 Rivers and Wetlands

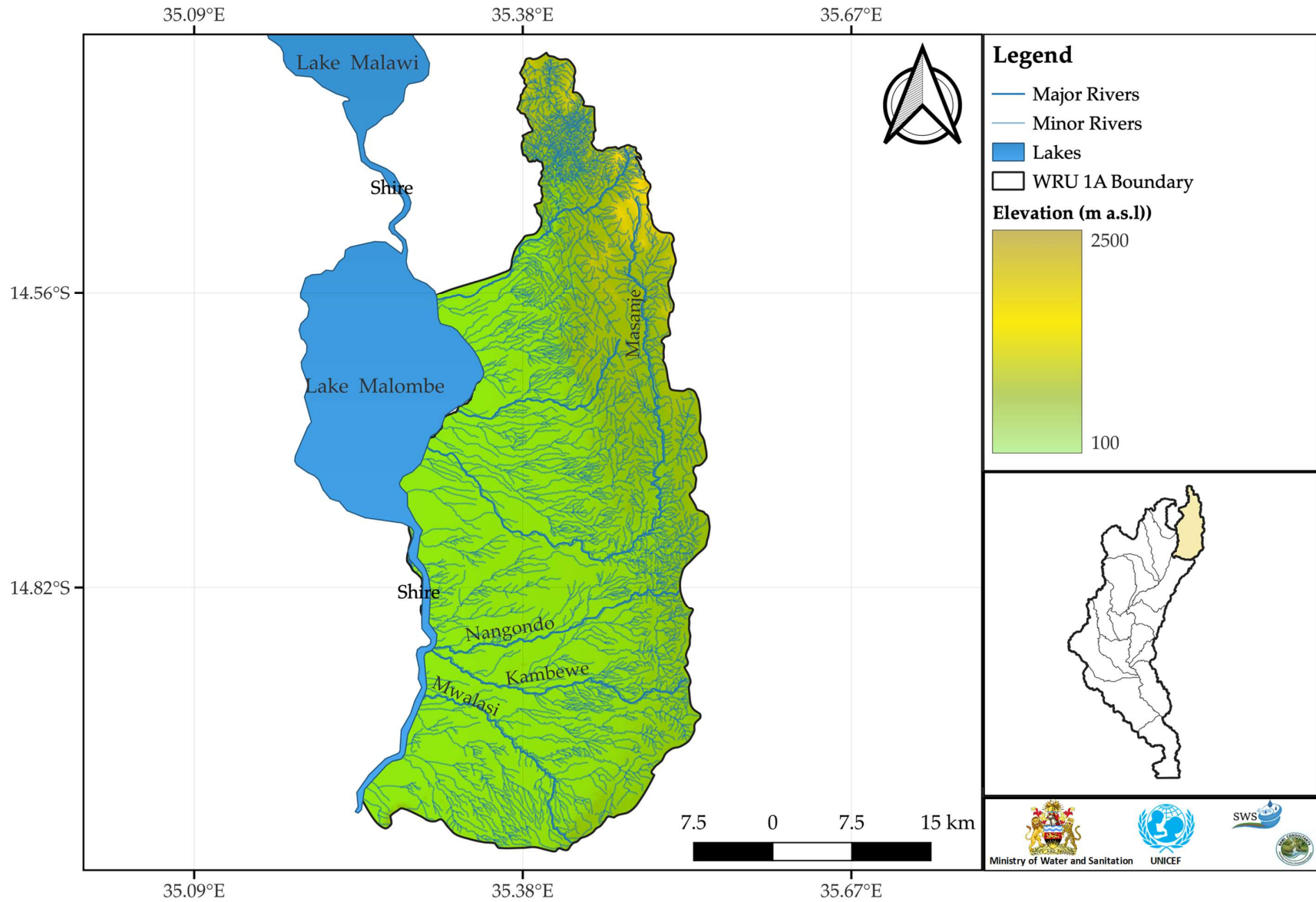


Figure WRU 1A.3 Hydrogeology Units and Water Table

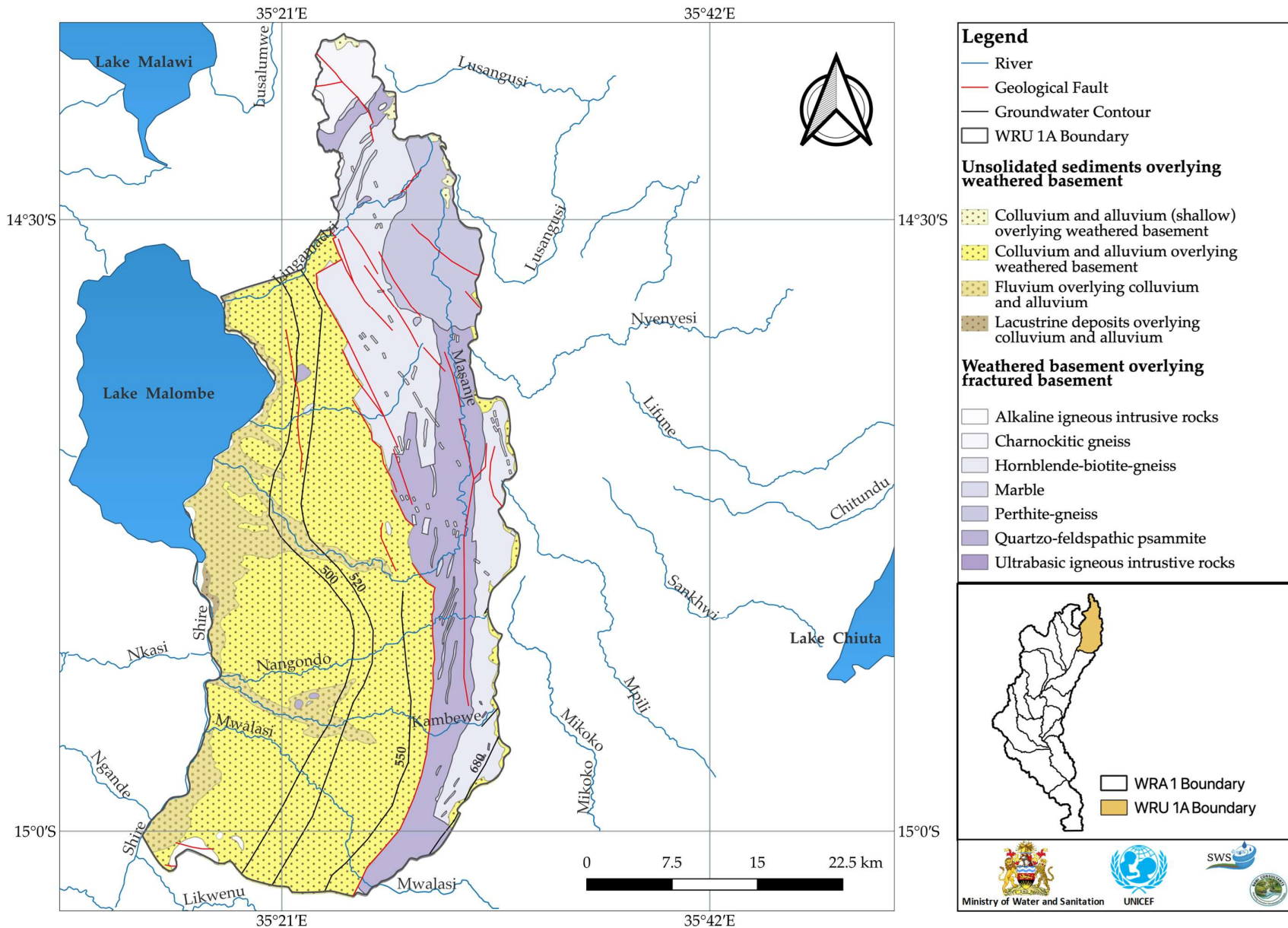


Figure WRU 1A.4 Groundwater Chemistry Distribution Electrical Conductivity

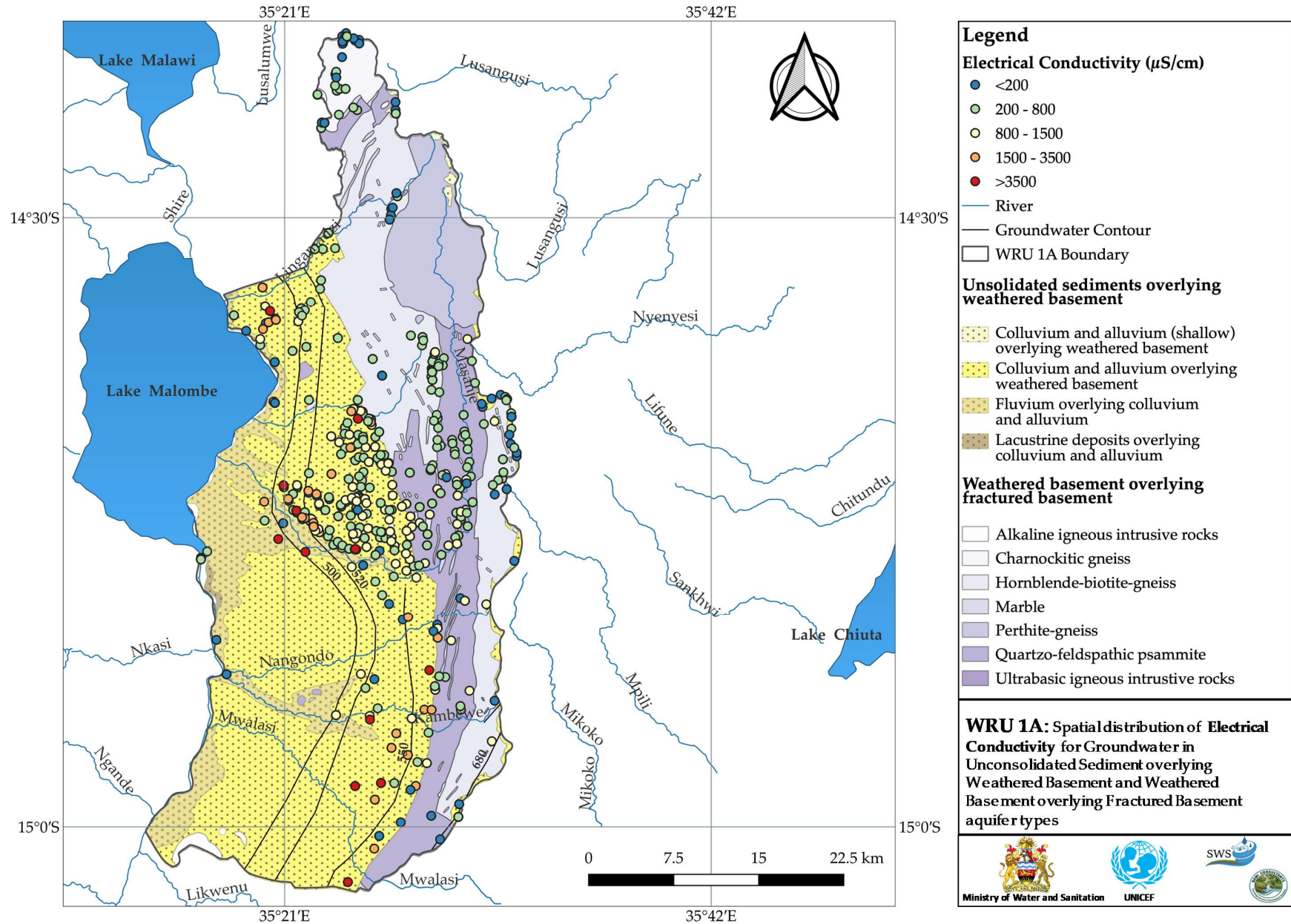


Figure WRU 1A.5 Groundwater Chemistry Distribution Sulphate

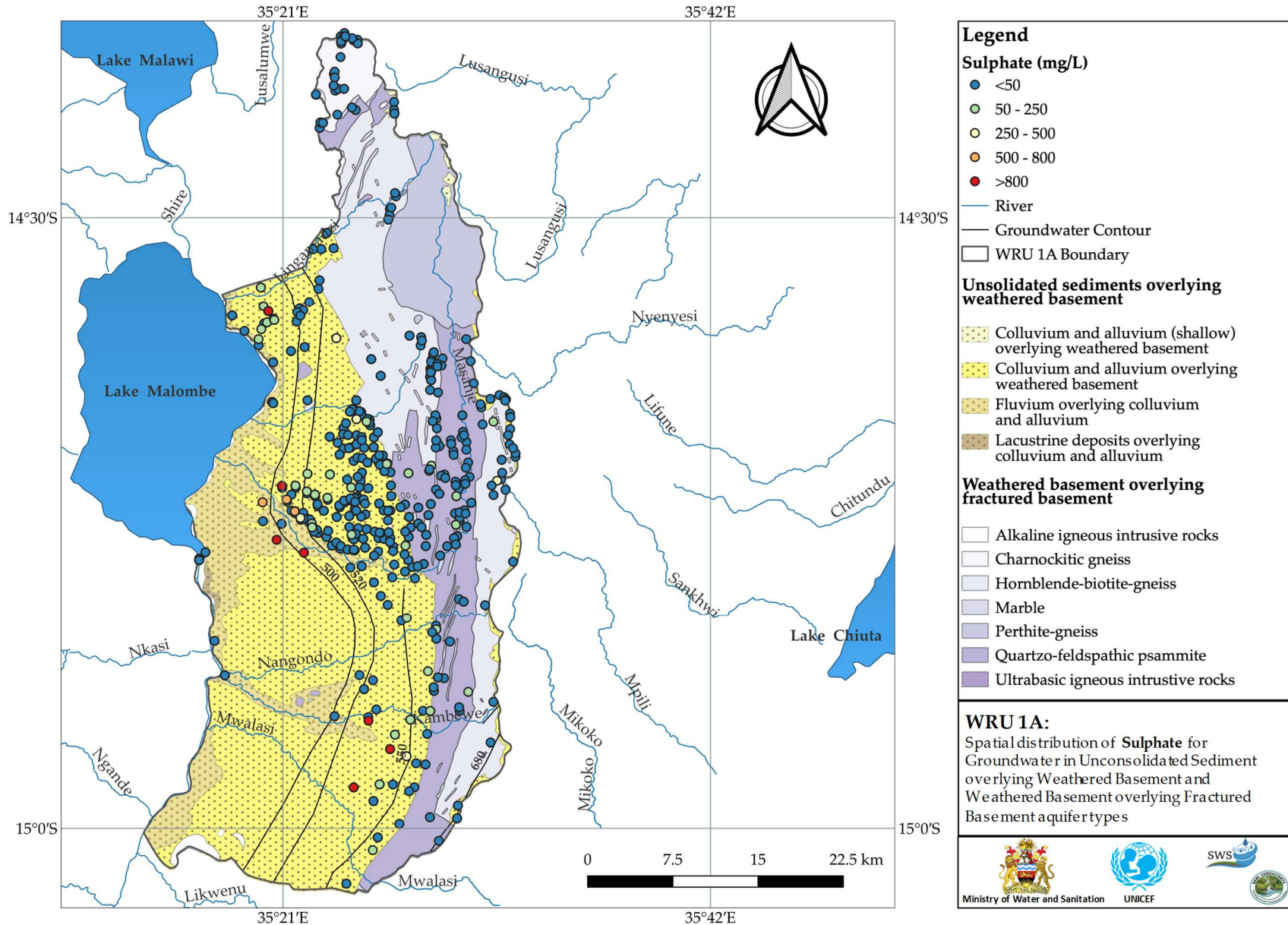


Figure WRU 1A.6 Groundwater Chemistry Distribution Chloride

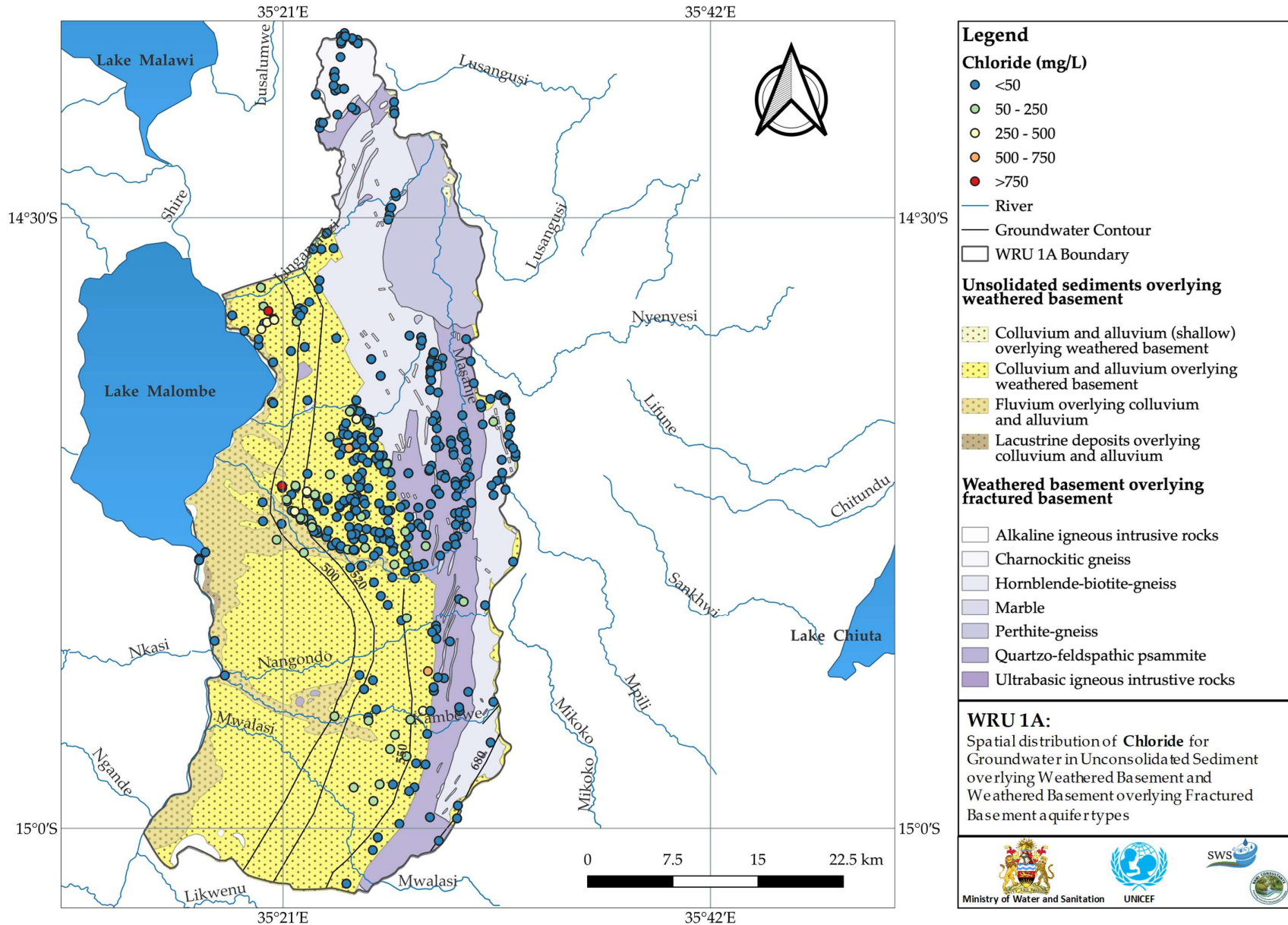


Figure WRU 1A.7 Groundwater Chemistry Distribution Sodium

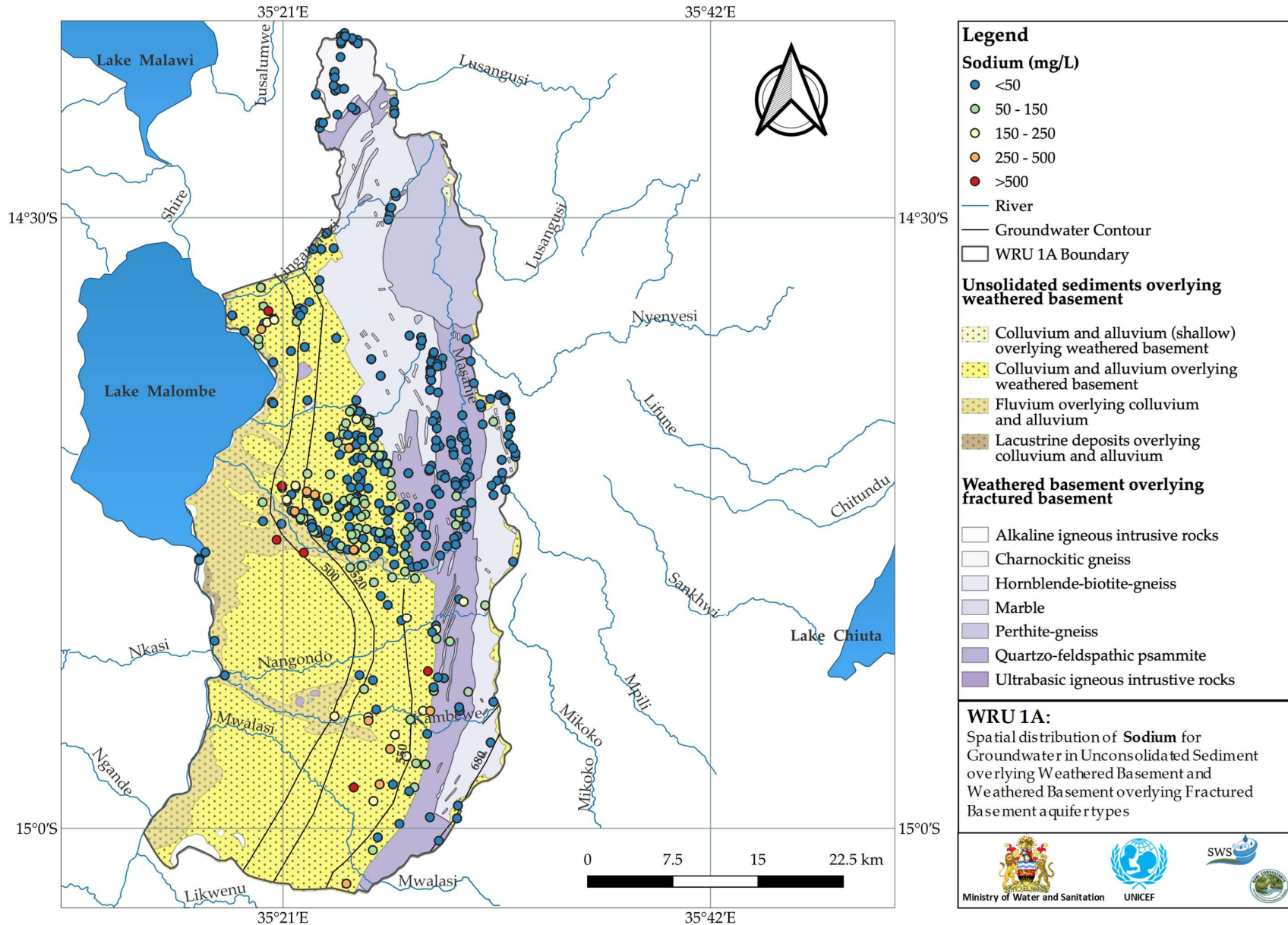


Figure WRU 1A.8 Groundwater Chemistry Distribution Calcium

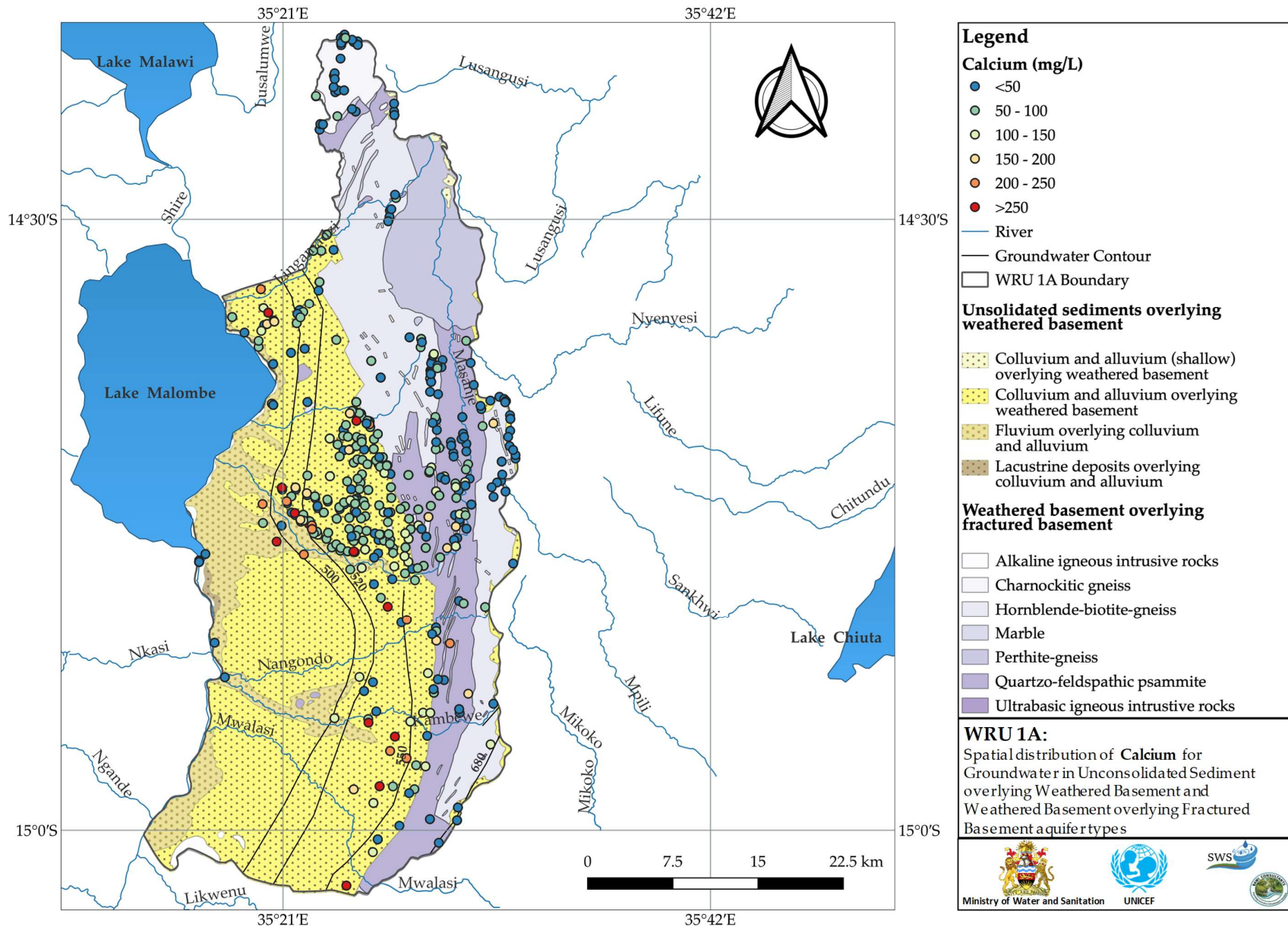


Figure WRU 1A.9 Piper Diagram of water quality results with respect to the major aquifer type

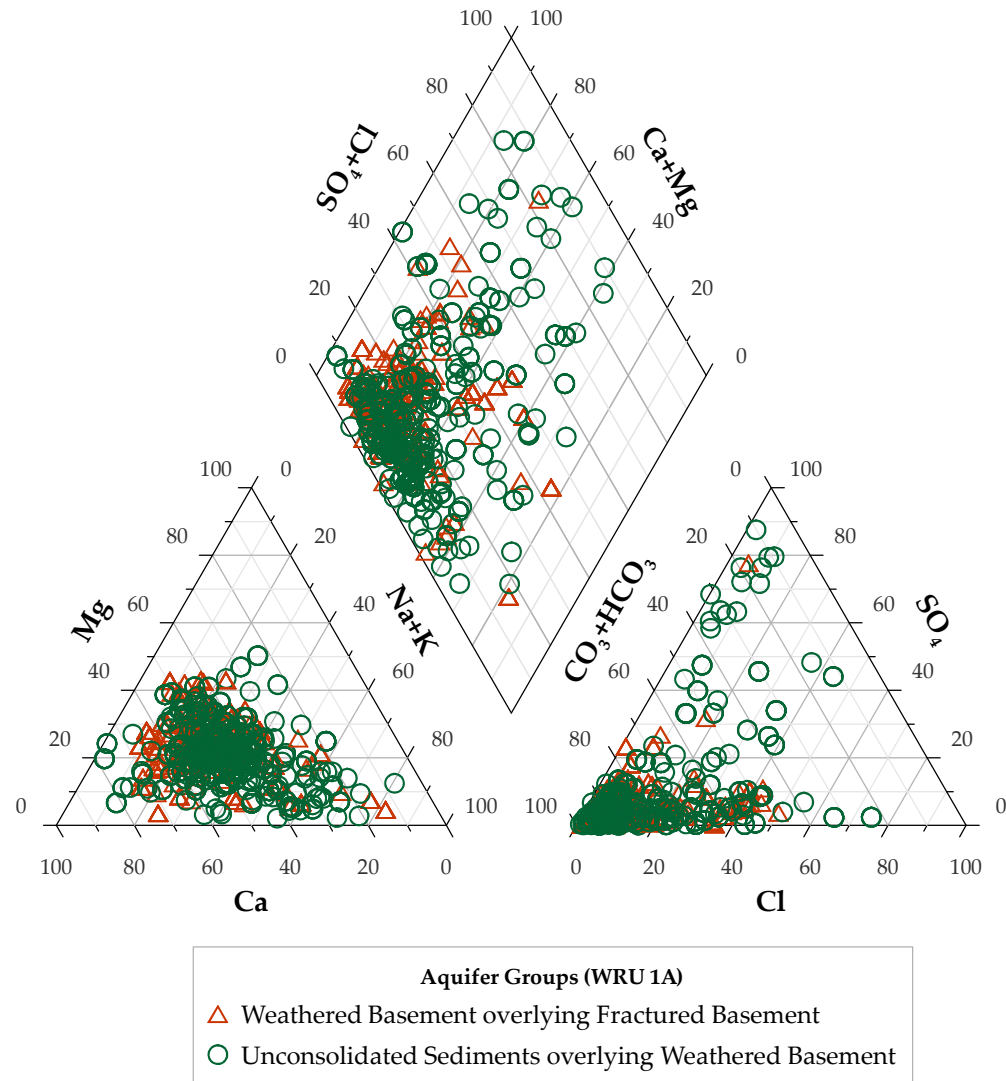
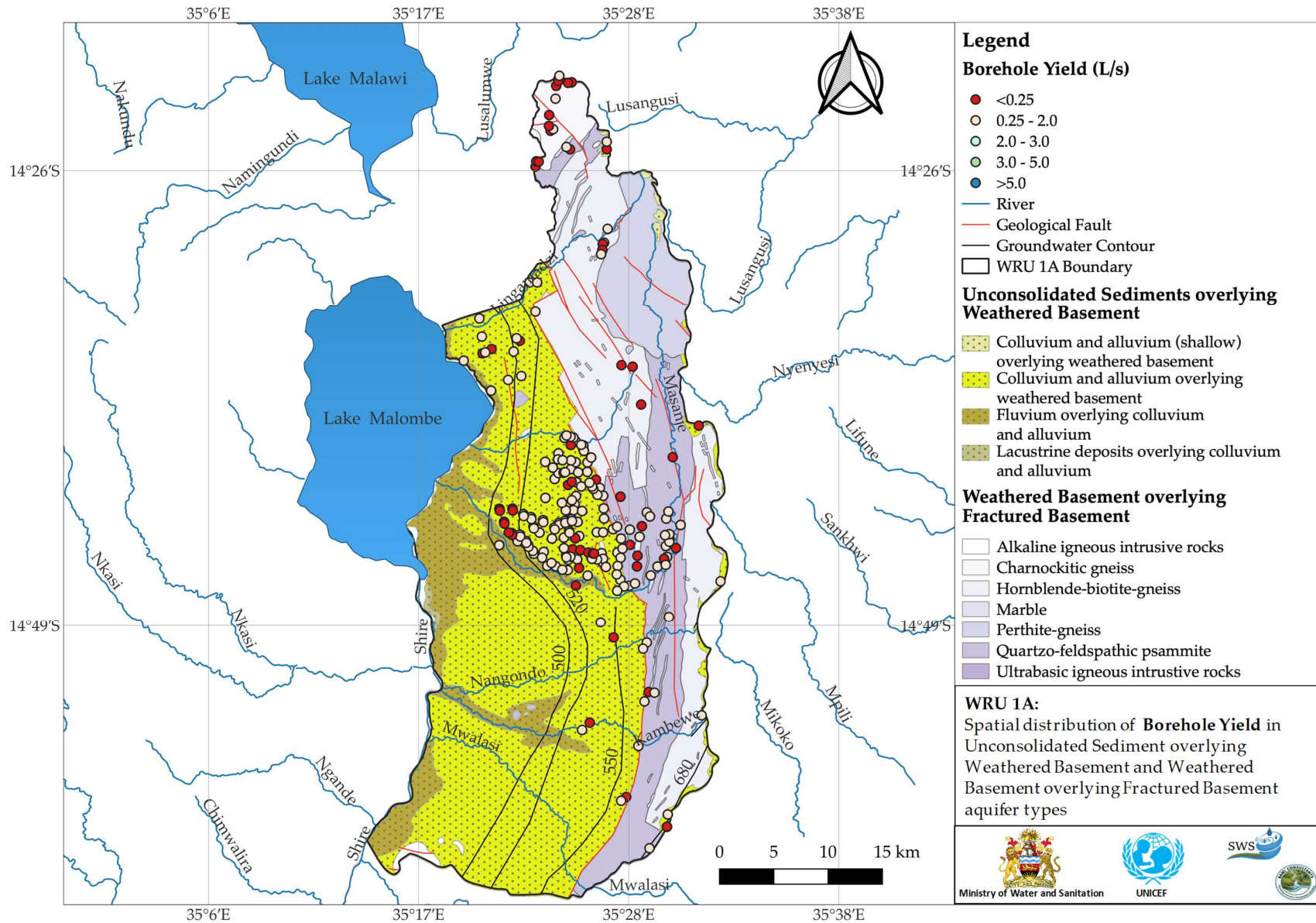


Figure WRU 1A.10 Borehole Yield Map for data held by the Ministry



WRU 1B Figures

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Figure WRU 1B.6 Groundwater Chemistry Distribution Chloride

Figure WRU 1B.7 Groundwater Chemistry Distribution Sodium

Figure WRU 1B.8 Groundwater Chemistry Distribution Calcium

Figure WRU 1B.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 1B.10 Borehole Yield Map for data held by the Ministry

Figure WRU 1B.1 Land Use and Major Roads

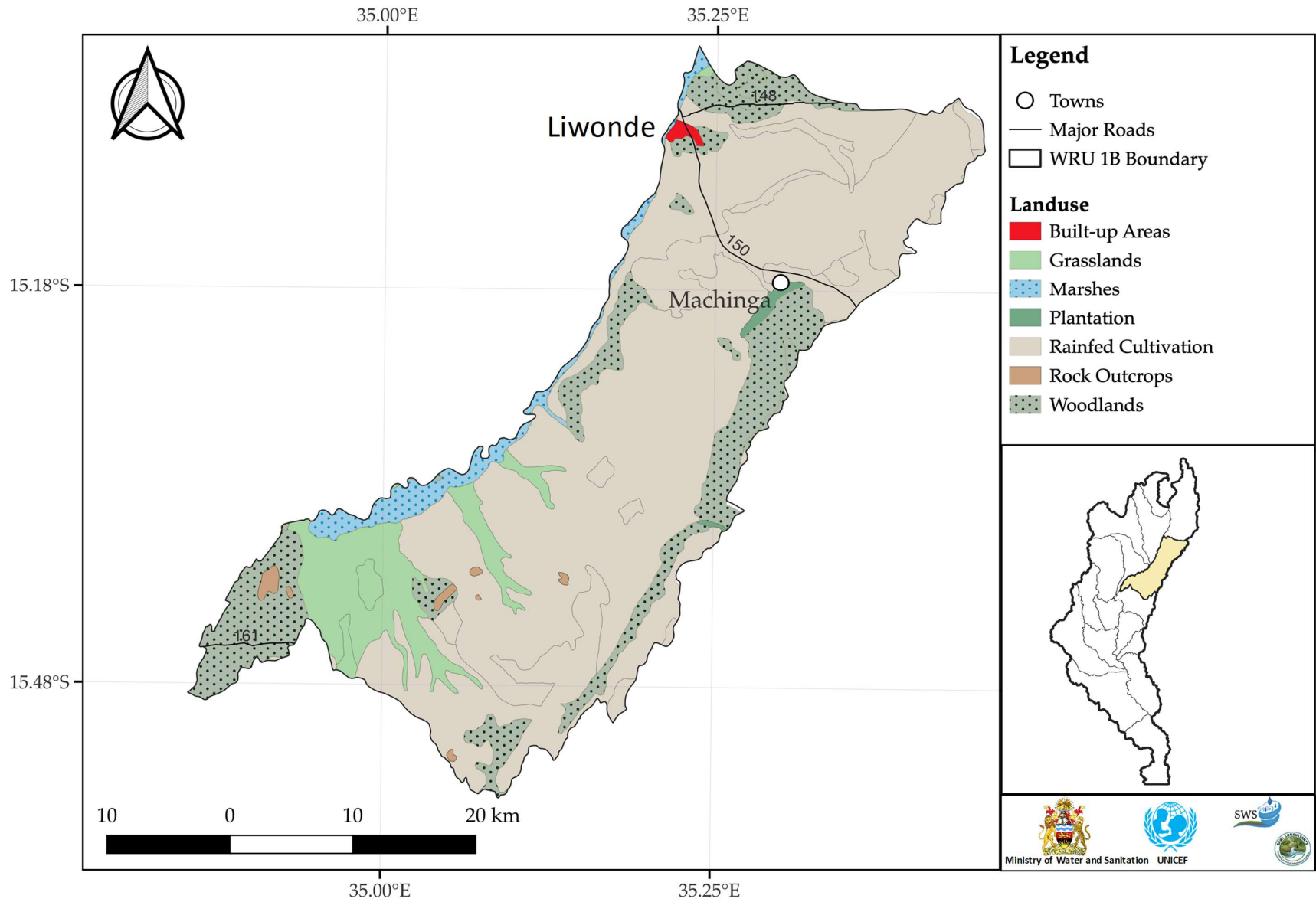


Figure WRU 1B.2 Rivers and Wetlands

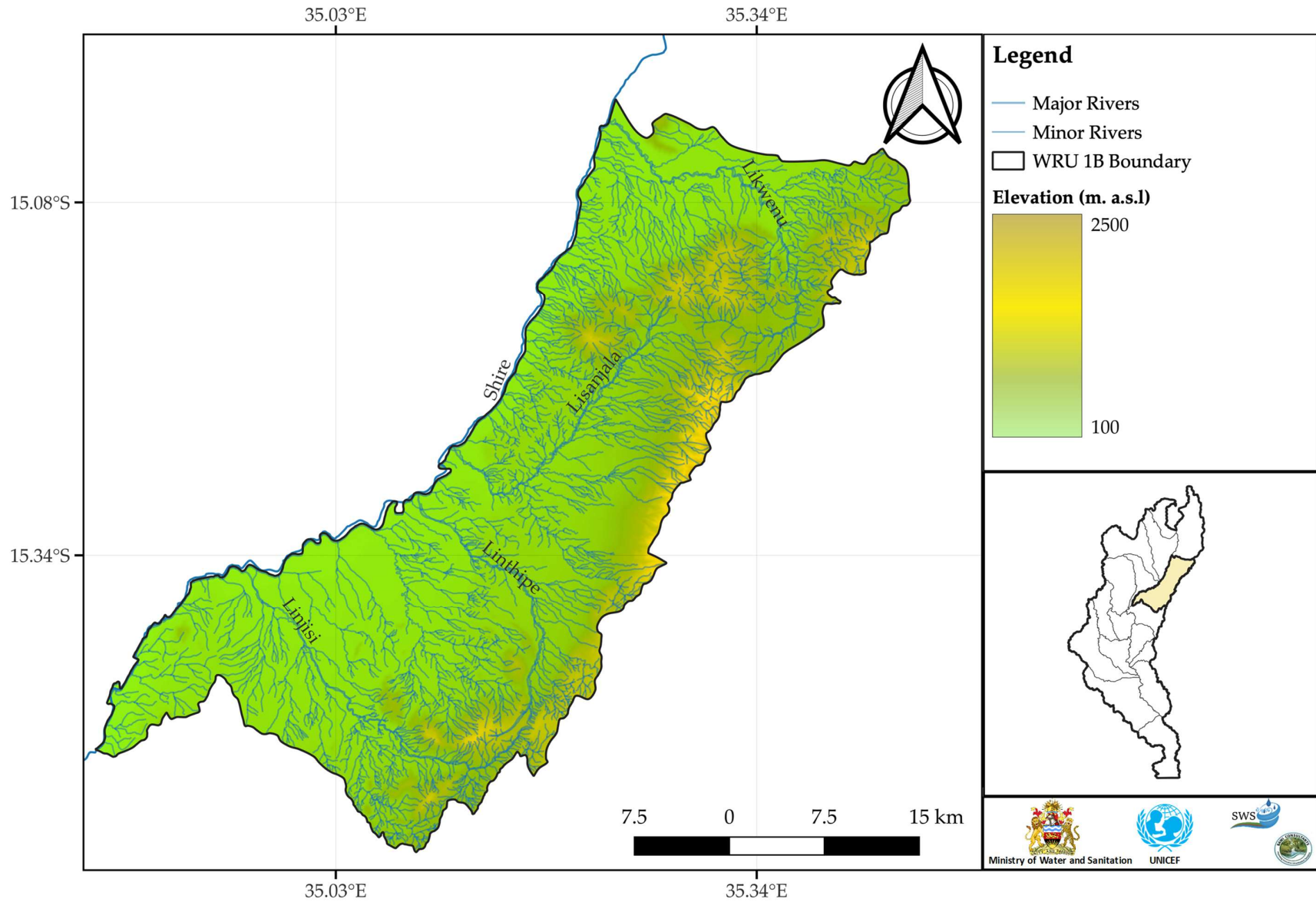


Figure WRU 1B.3 Hydrogeology Units and Water Table

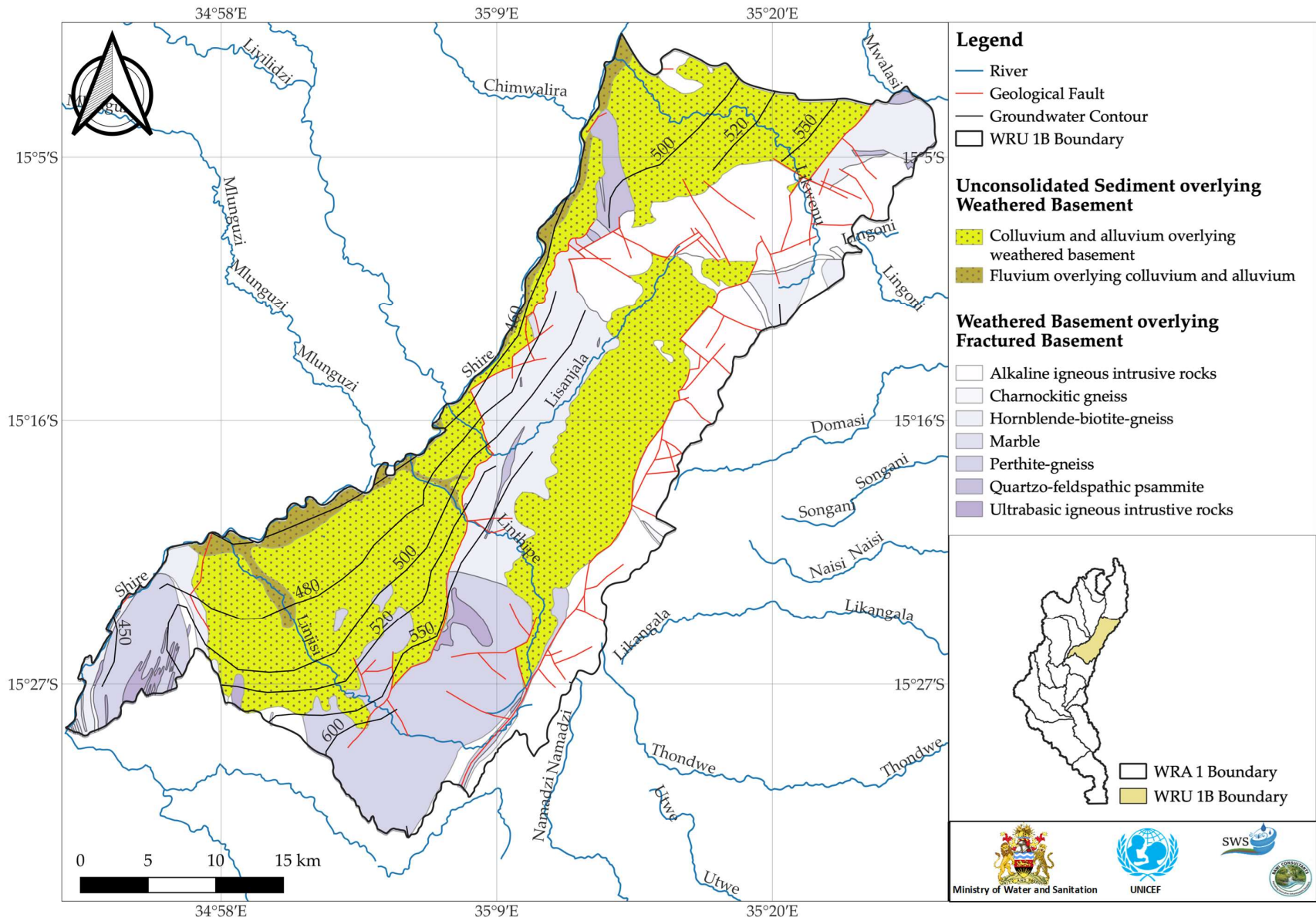


Figure WRU 1B.4 Groundwater Chemistry Distribution Electrical Conductivity

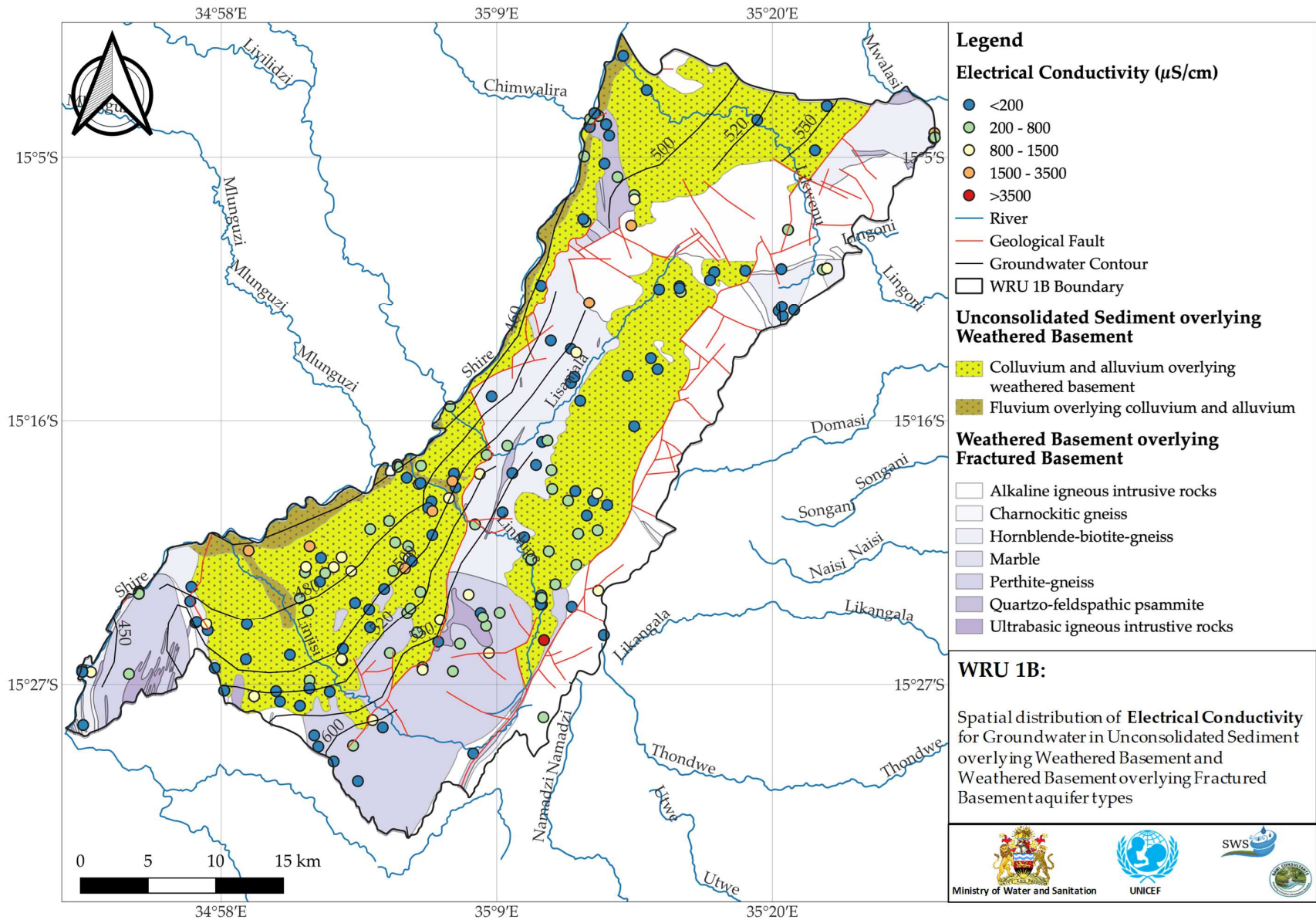


Figure WRU 1B.5 Groundwater Chemistry Distribution of Sulphate

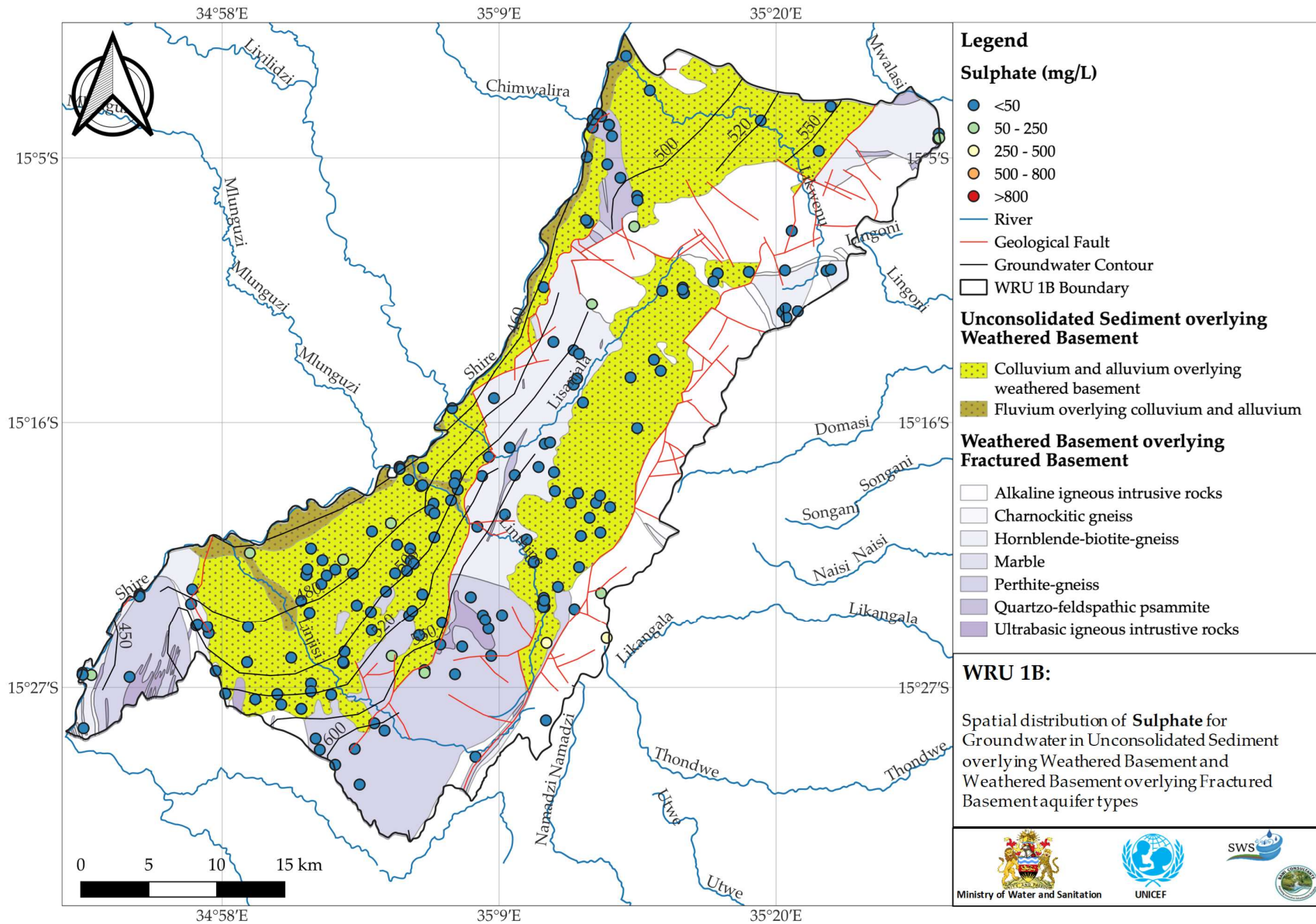


Figure WRU 1B.6 Groundwater Chemistry Distribution Chloride

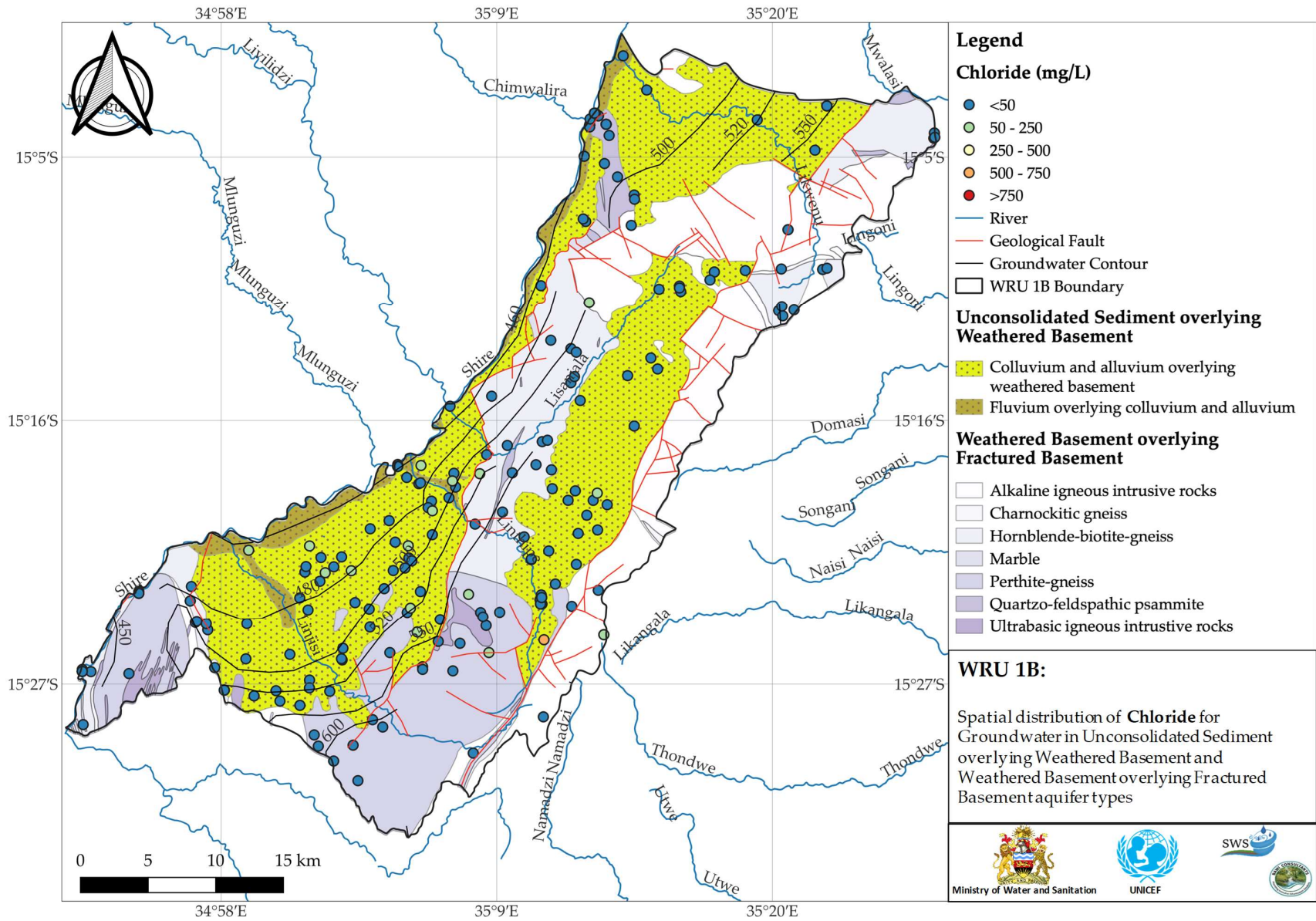


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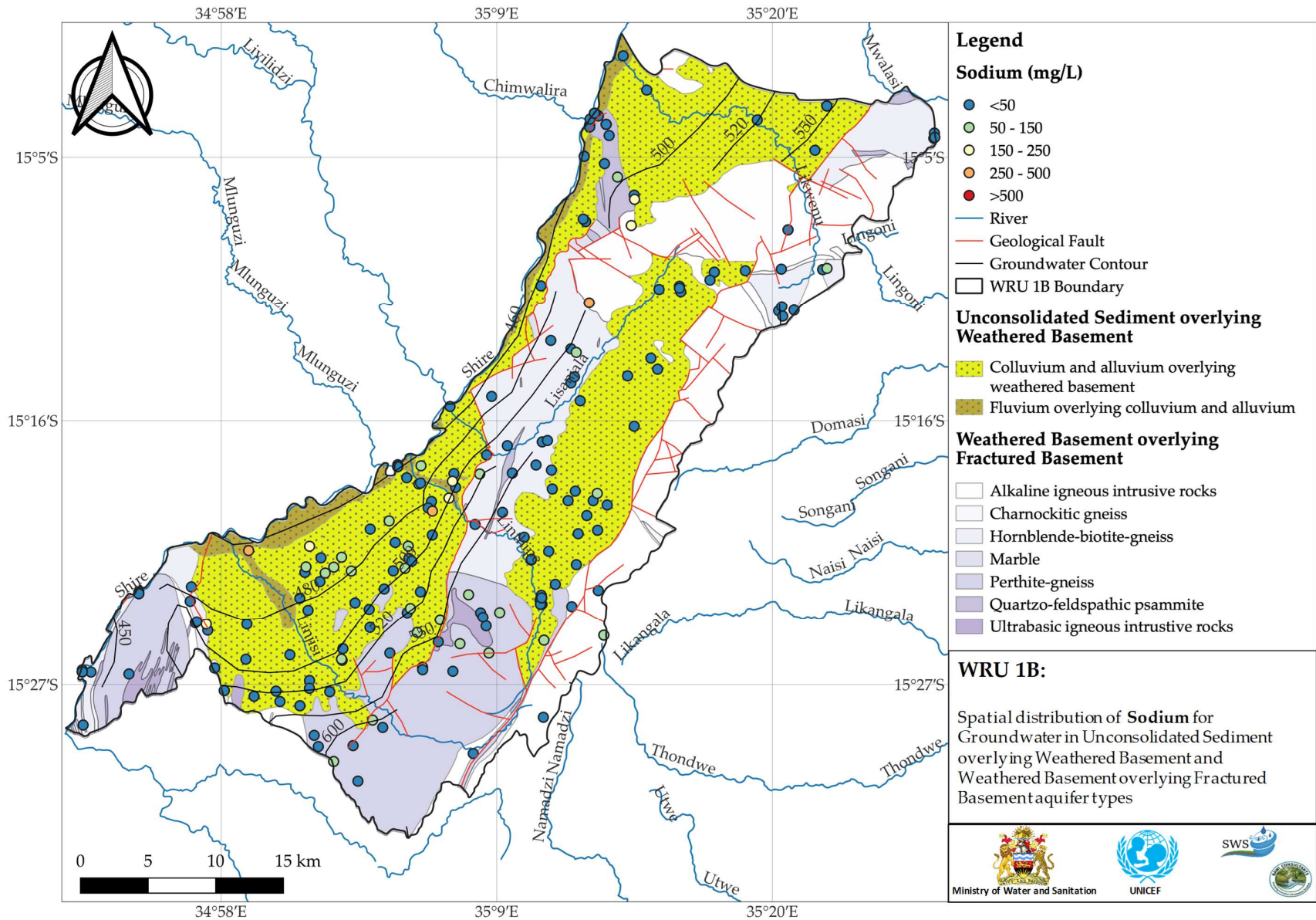


Figure WRU 1B.8 Groundwater Chemistry Distribution Calcium

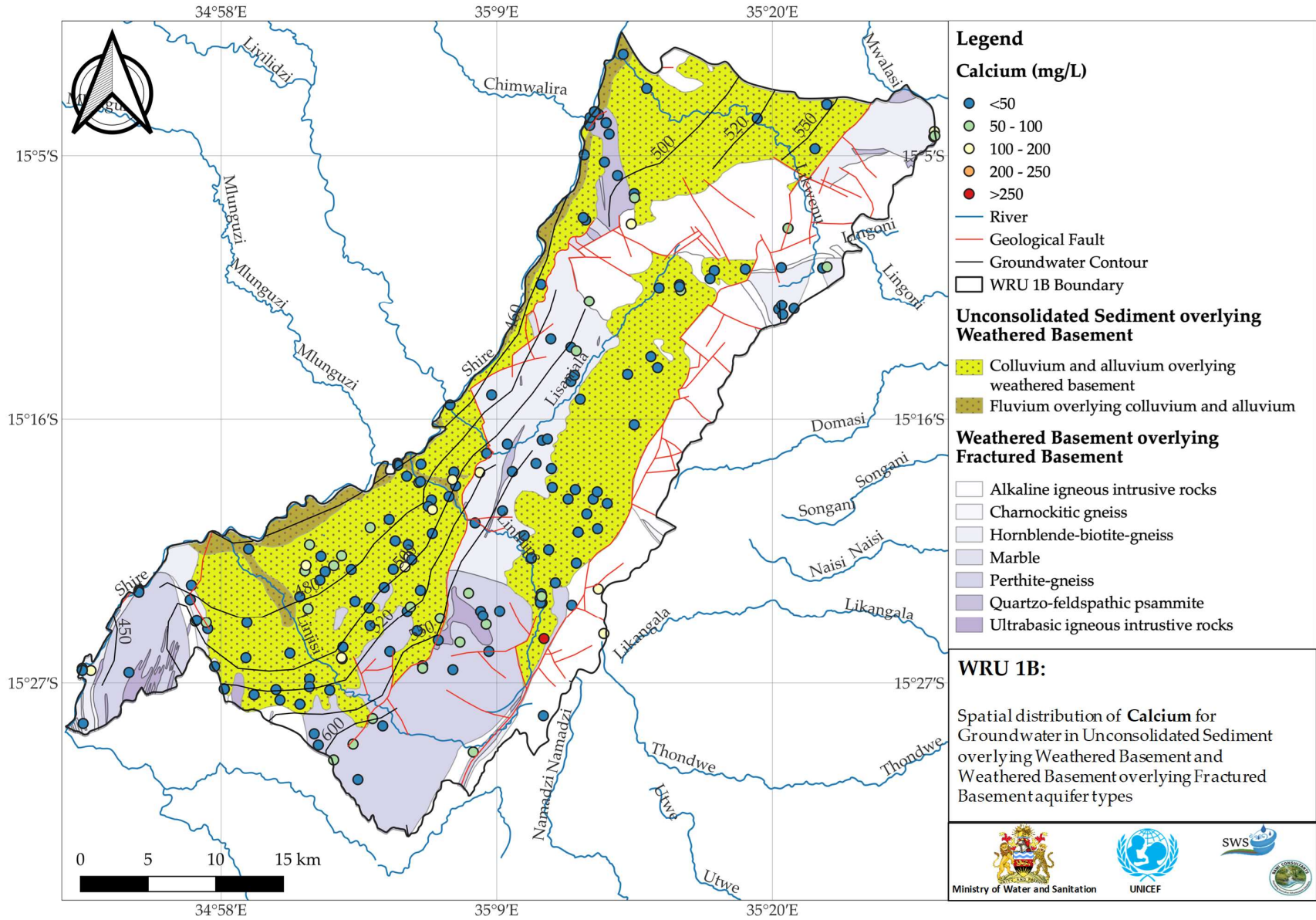


Figure WRU 1B.9 Piper Diagram of water quality results with respect to the major aquifer type

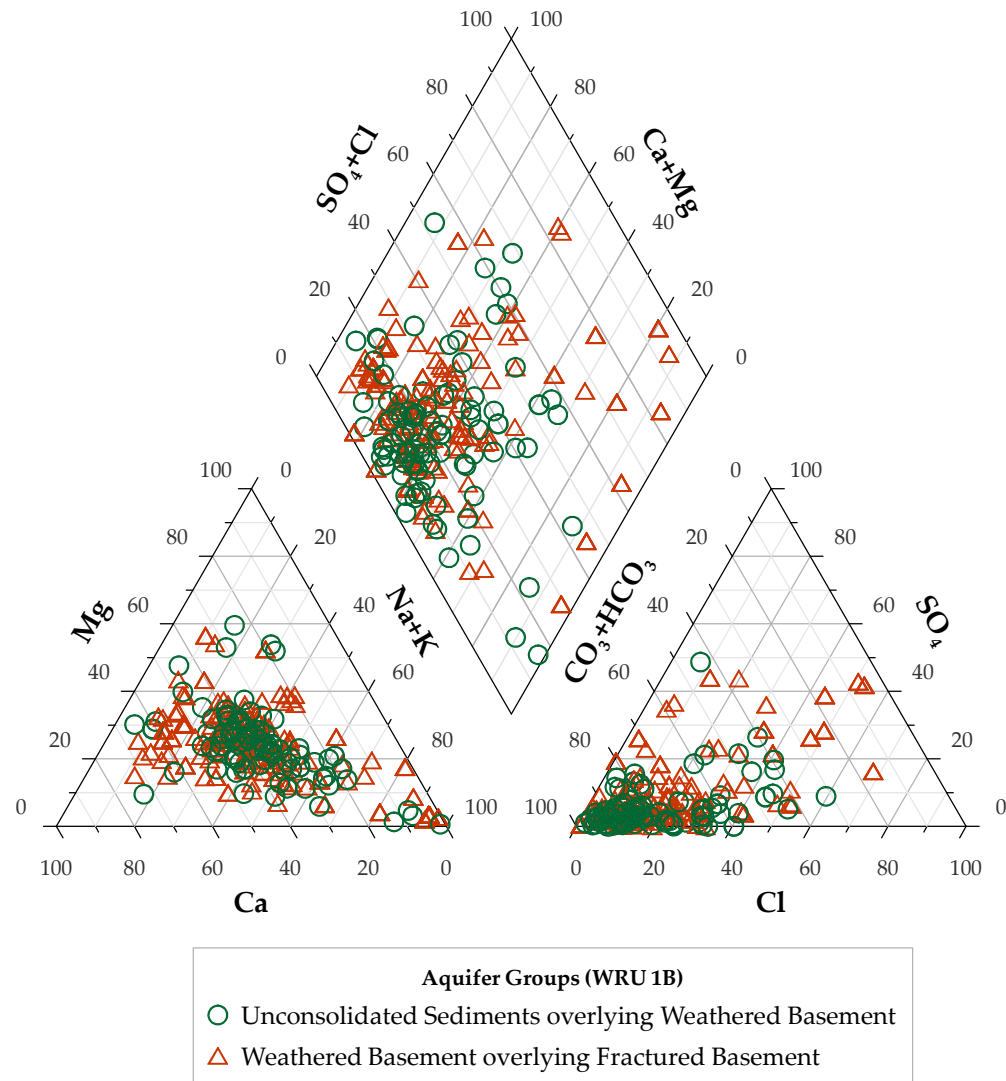
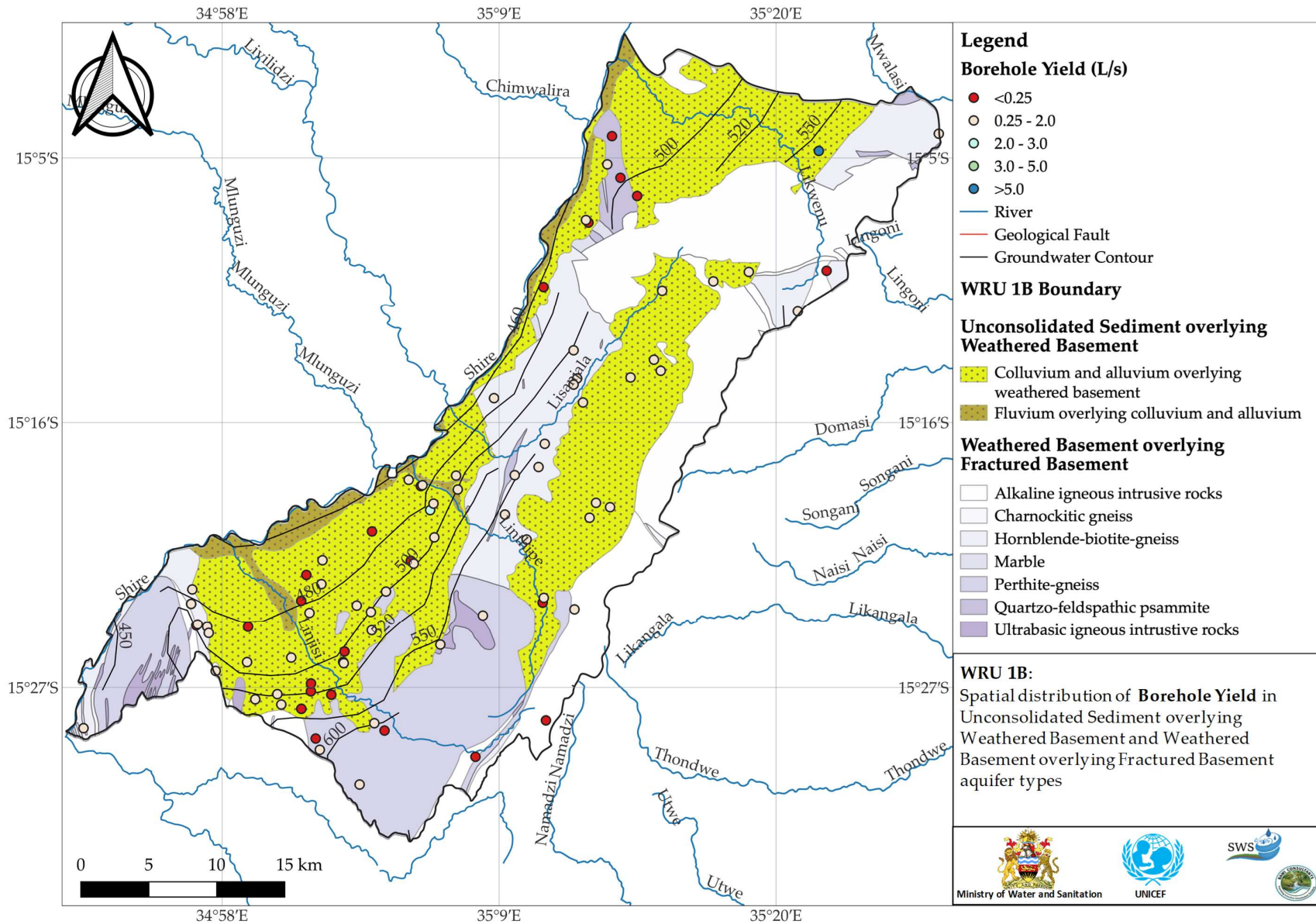


Figure WRU 1B.10 Borehole Yield Map for data held by the Ministry



WRU 10 Figures

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Figure WRU 10.10 Borehole Yield Map for data held by the Ministry

Figure WRU 10.1 Land Use and Major Roads

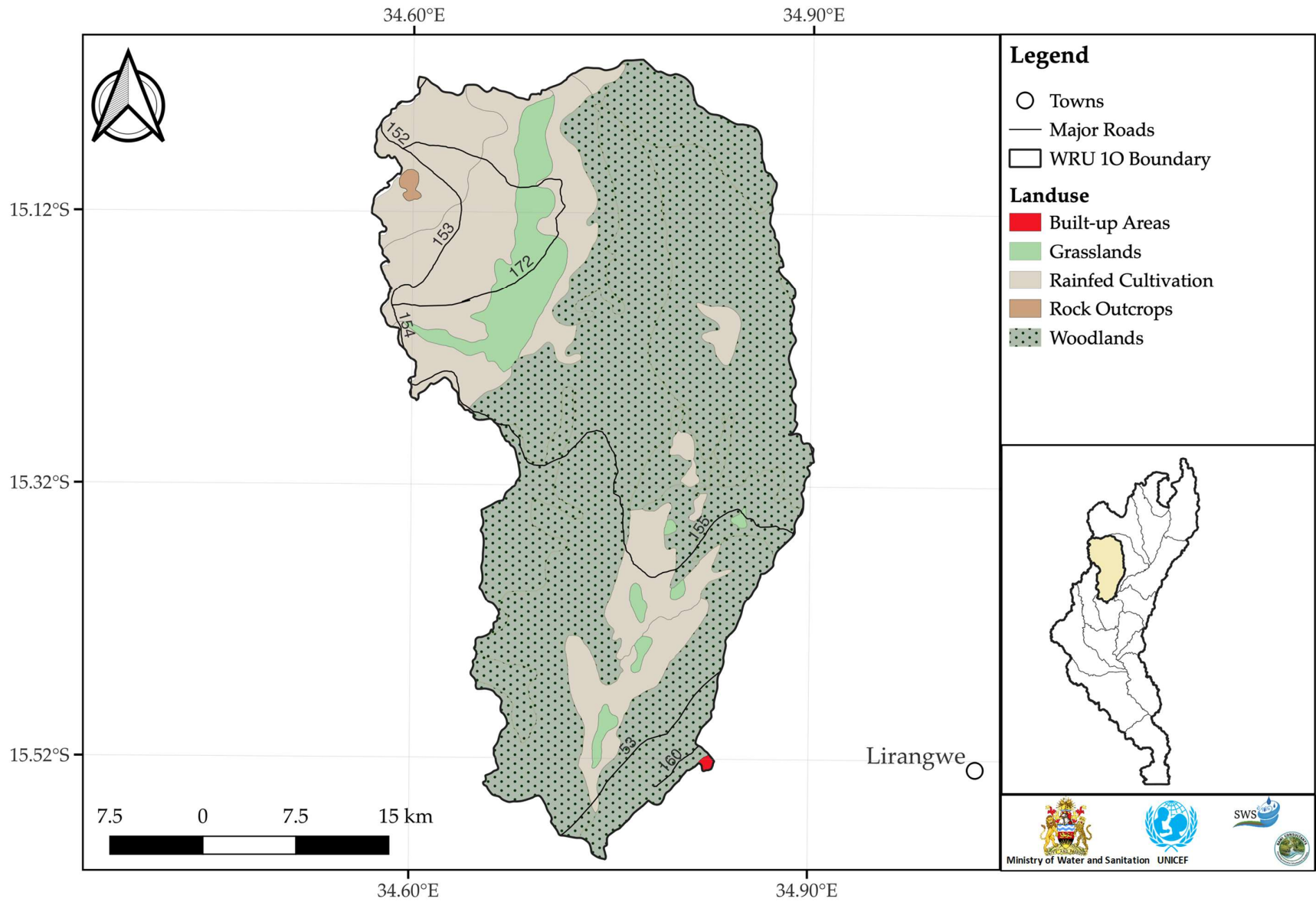


Figure WRU 10.2 Rivers and Wetlands

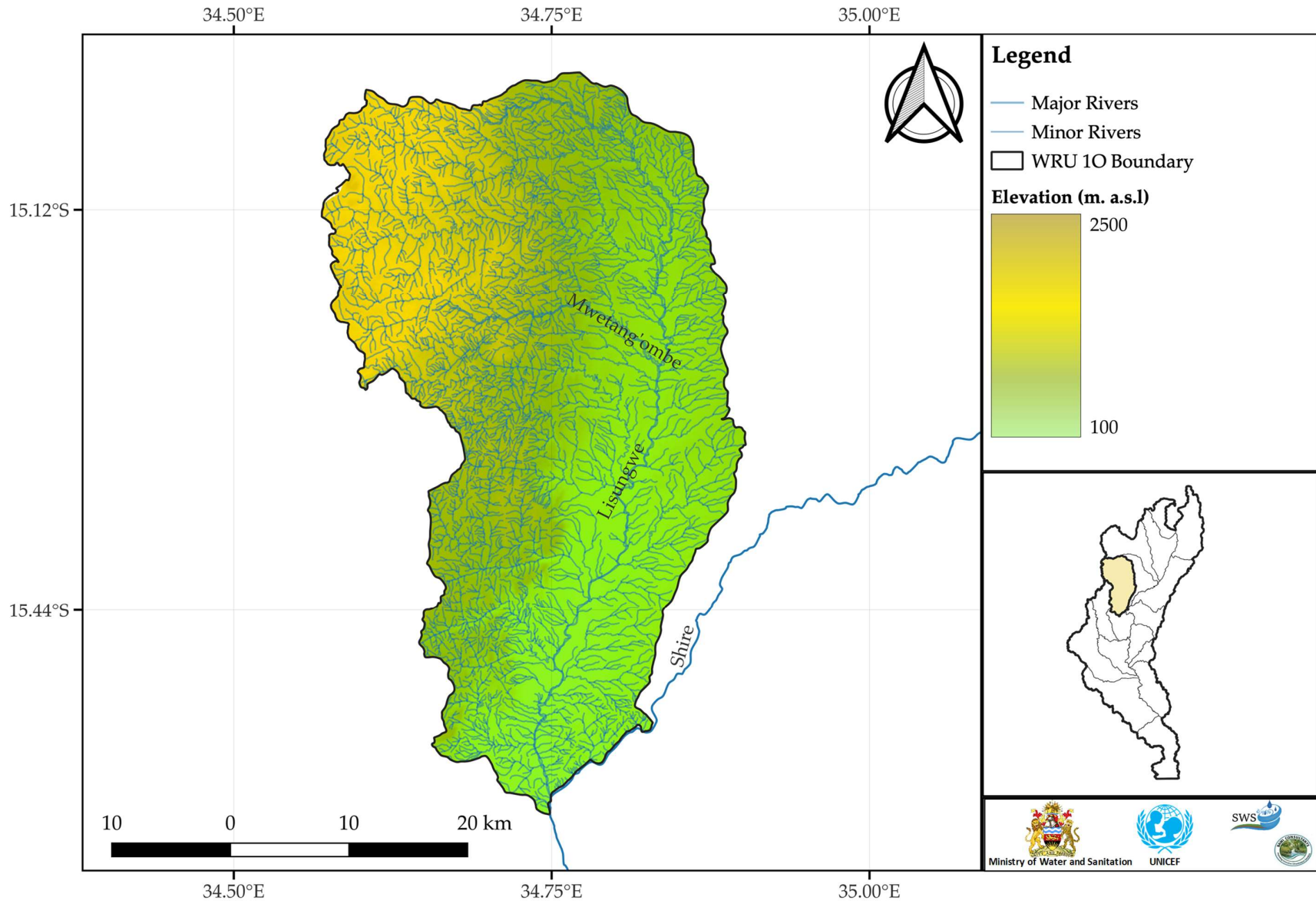


Figure WRU 10.3 Hydrogeology Units and Water Table

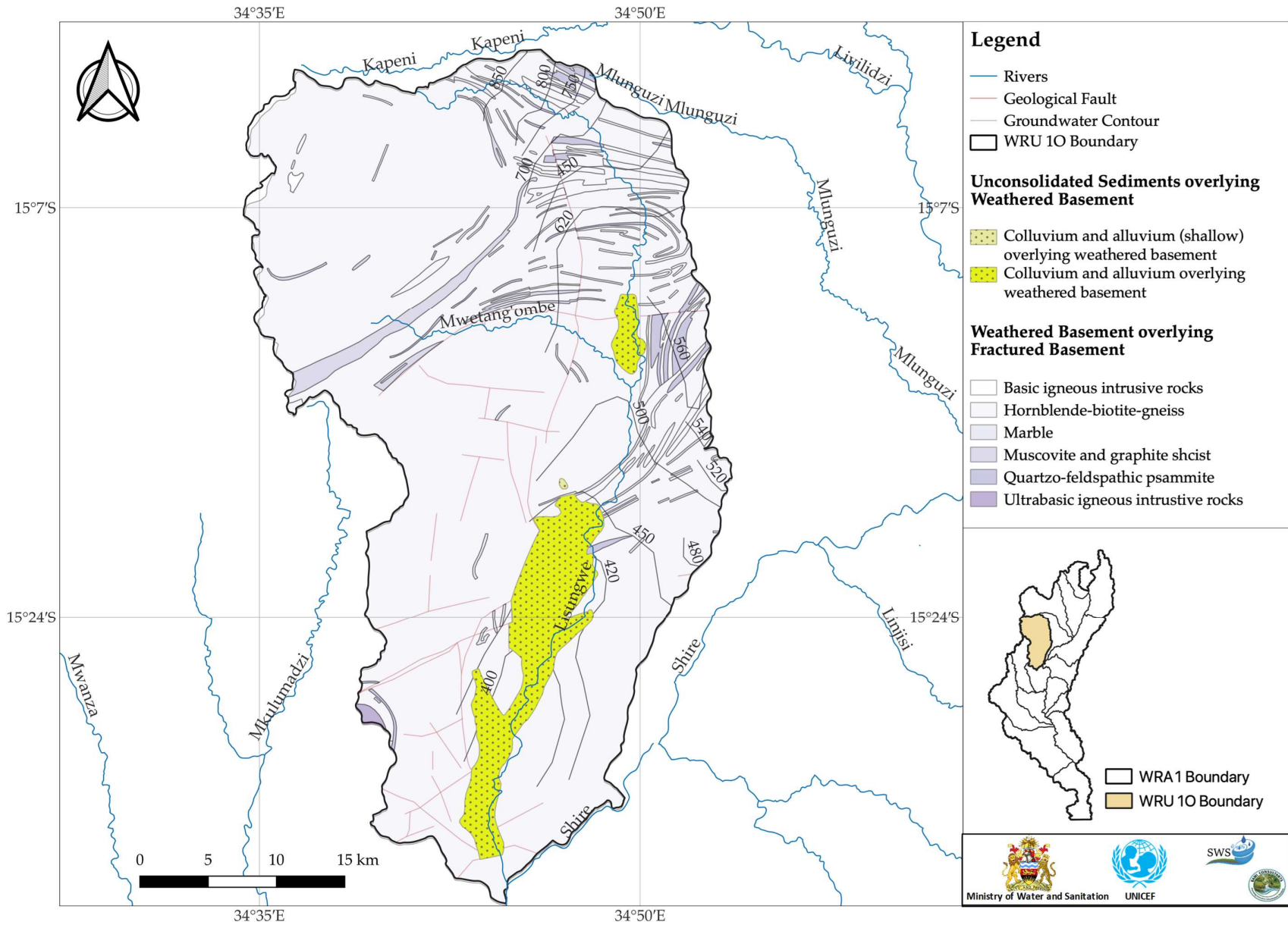


Figure WRU 10.4 Groundwater Chemistry Distribution Electrical Conductivity

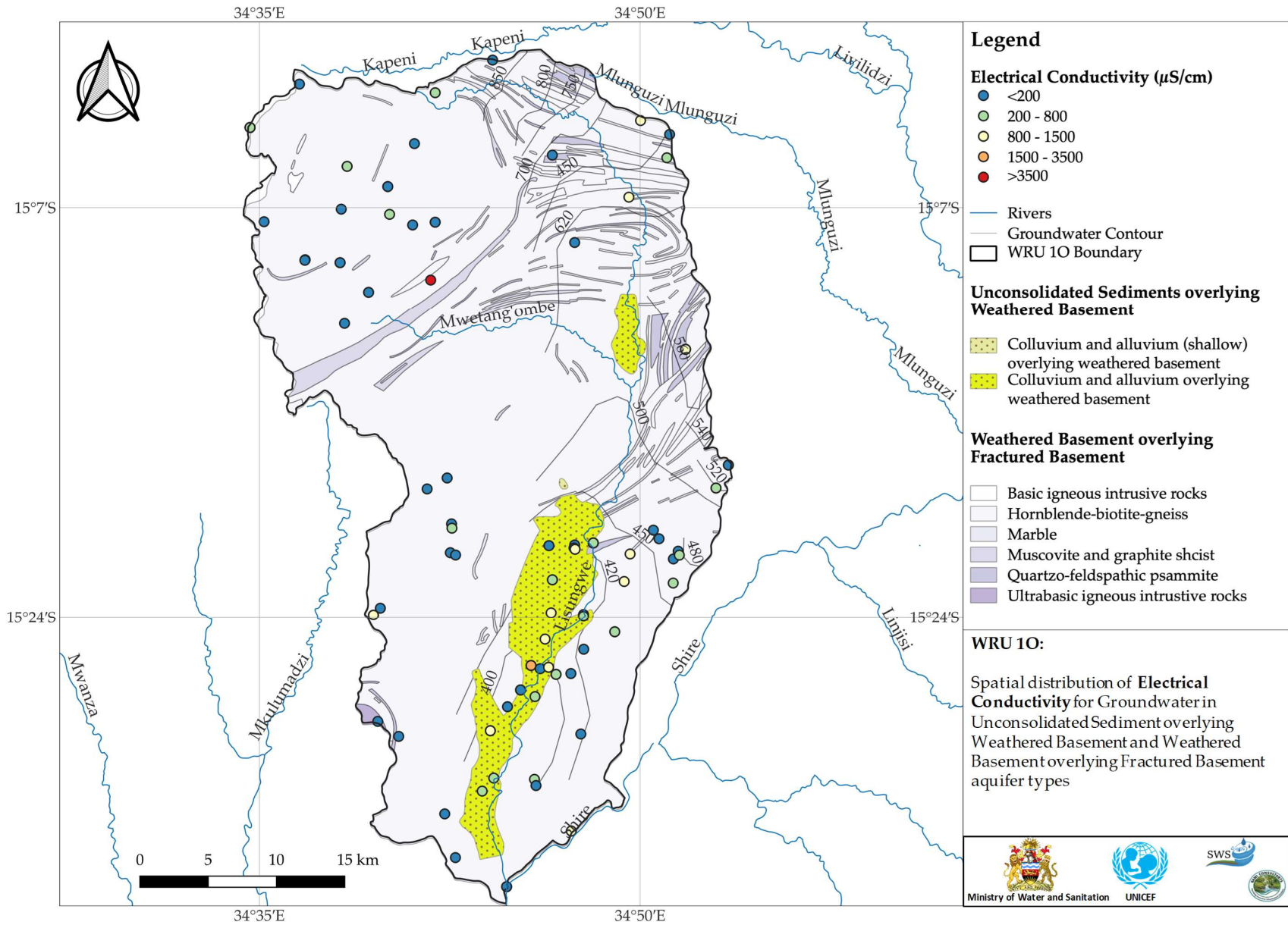


Figure WRU 10.5 Groundwater Chemistry Distribution of Sulphate

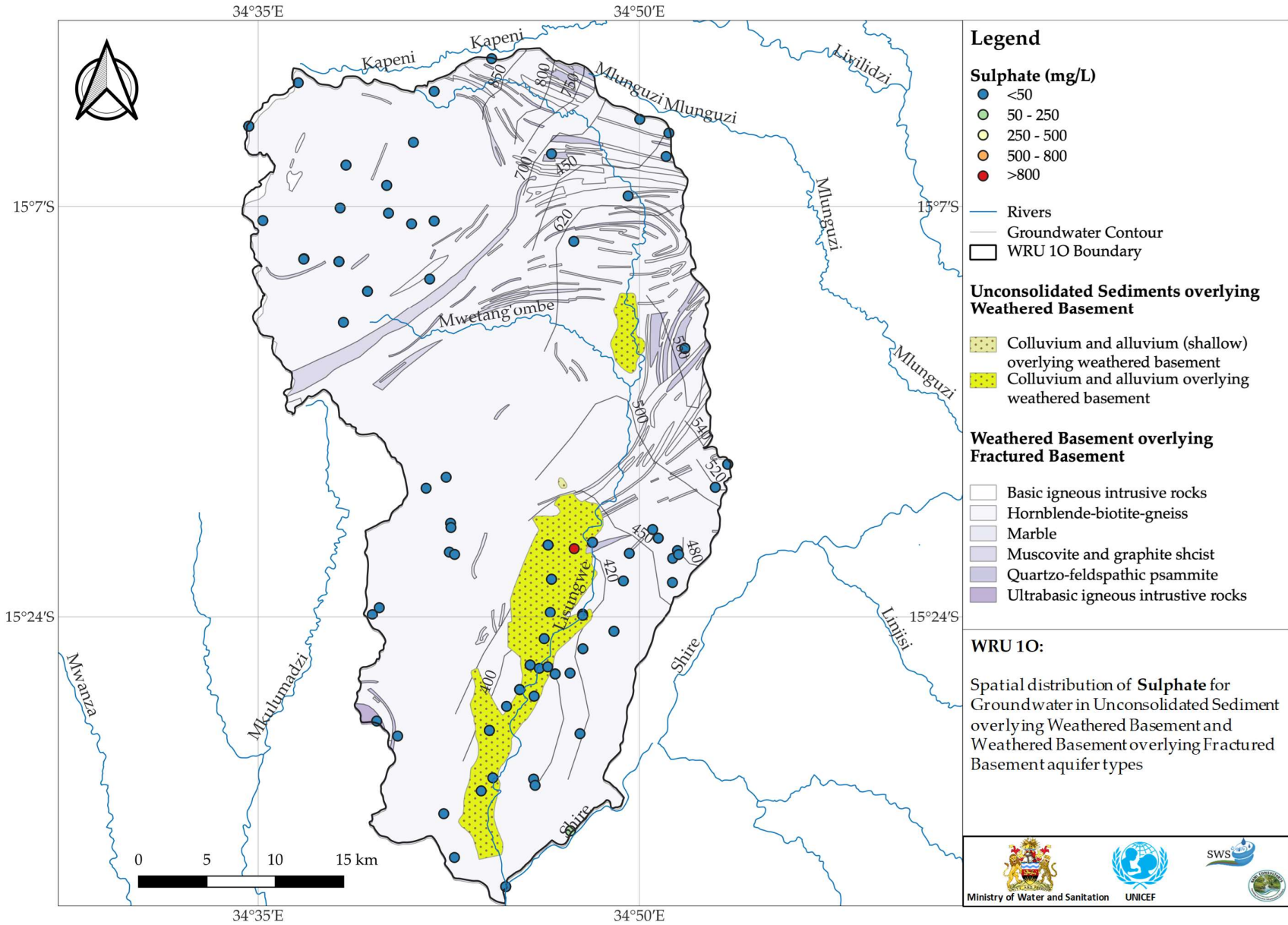


Figure WRU 10.6 Groundwater Chemistry Distribution Chloride

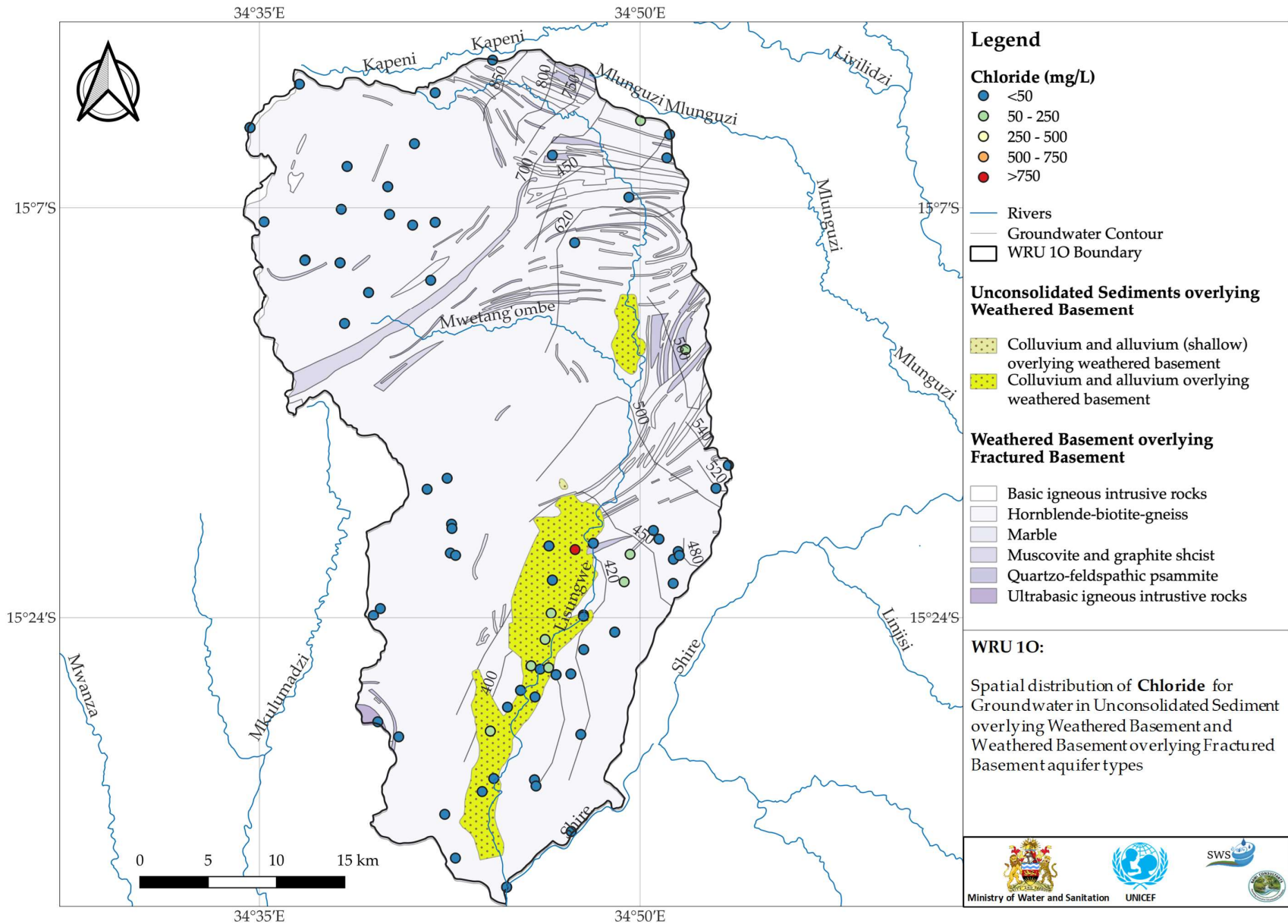


Figure WRU 10.7 Groundwater Chemistry Distribution Sodium

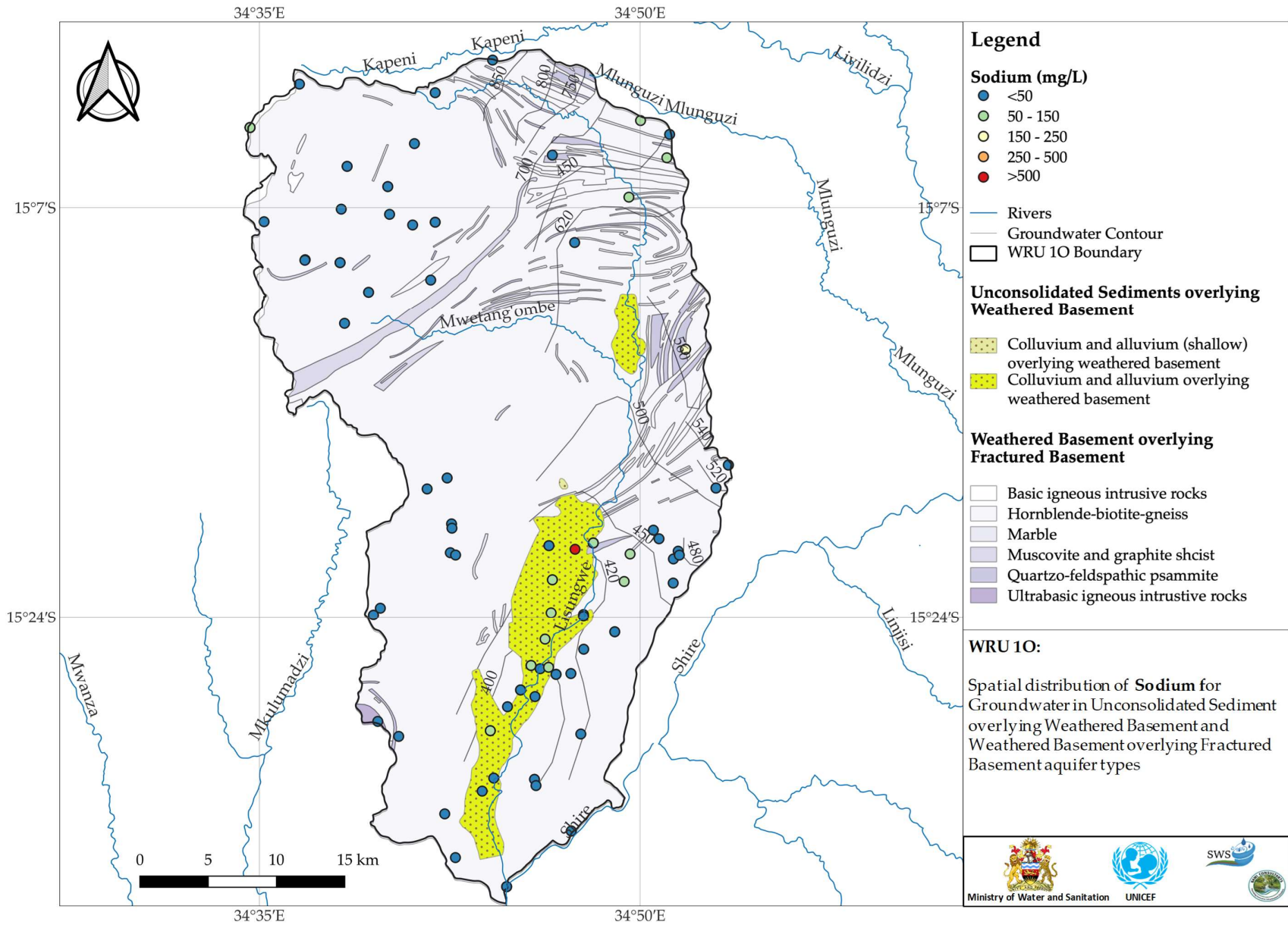


Figure WRU 10.8 Groundwater Chemistry Distribution Calcium

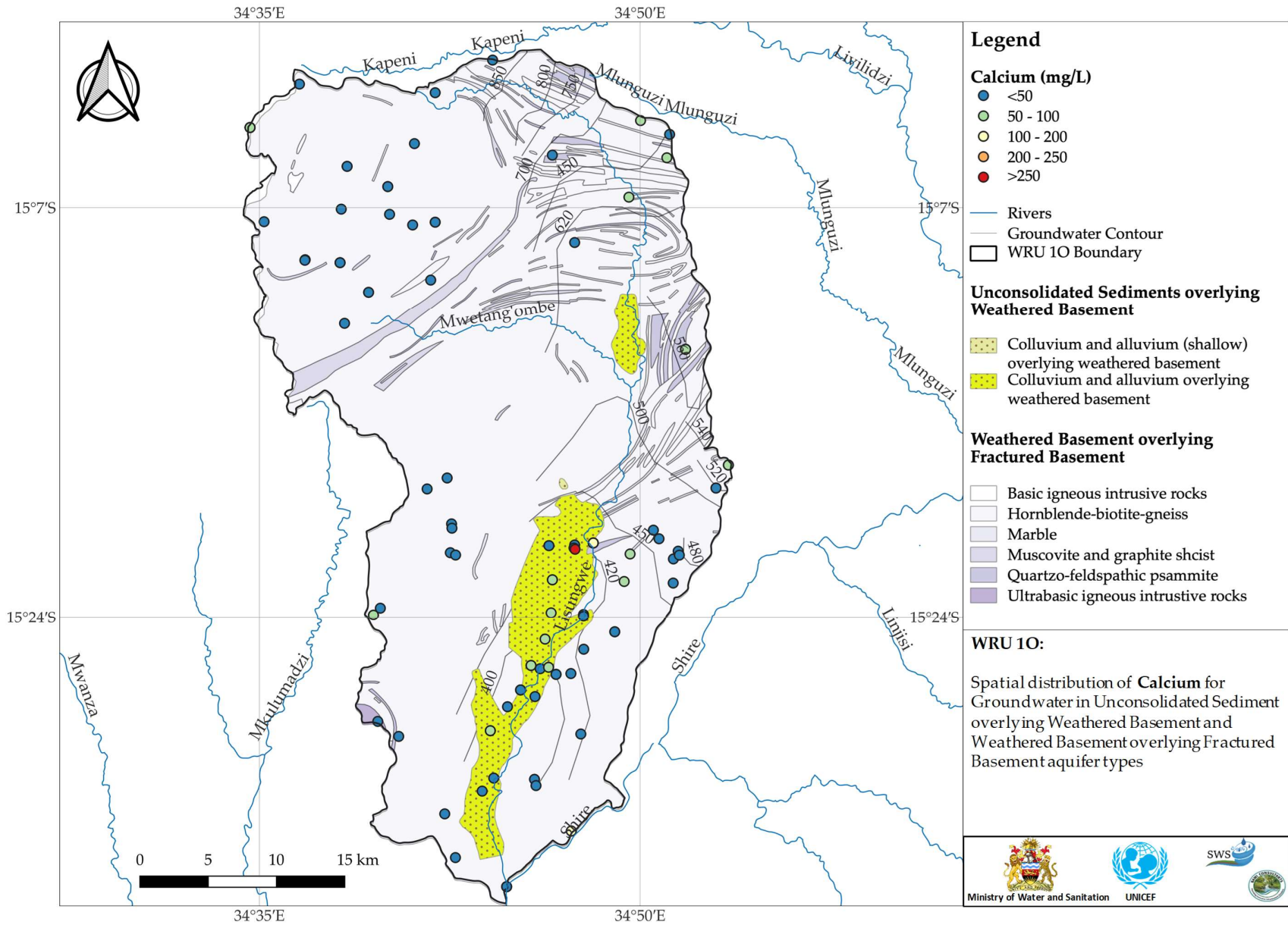


Figure WRU 10.9 Piper Diagram of water quality results with respect to the major aquifer type

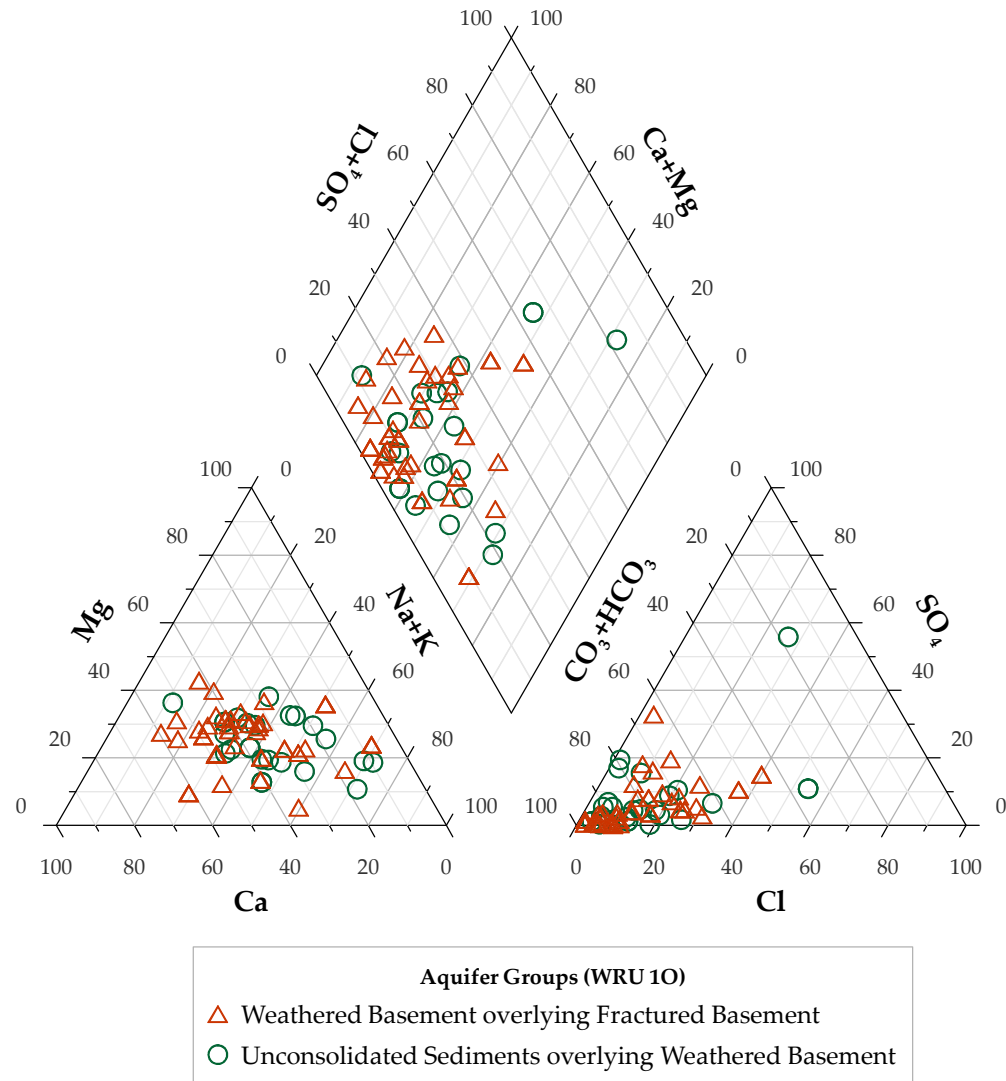
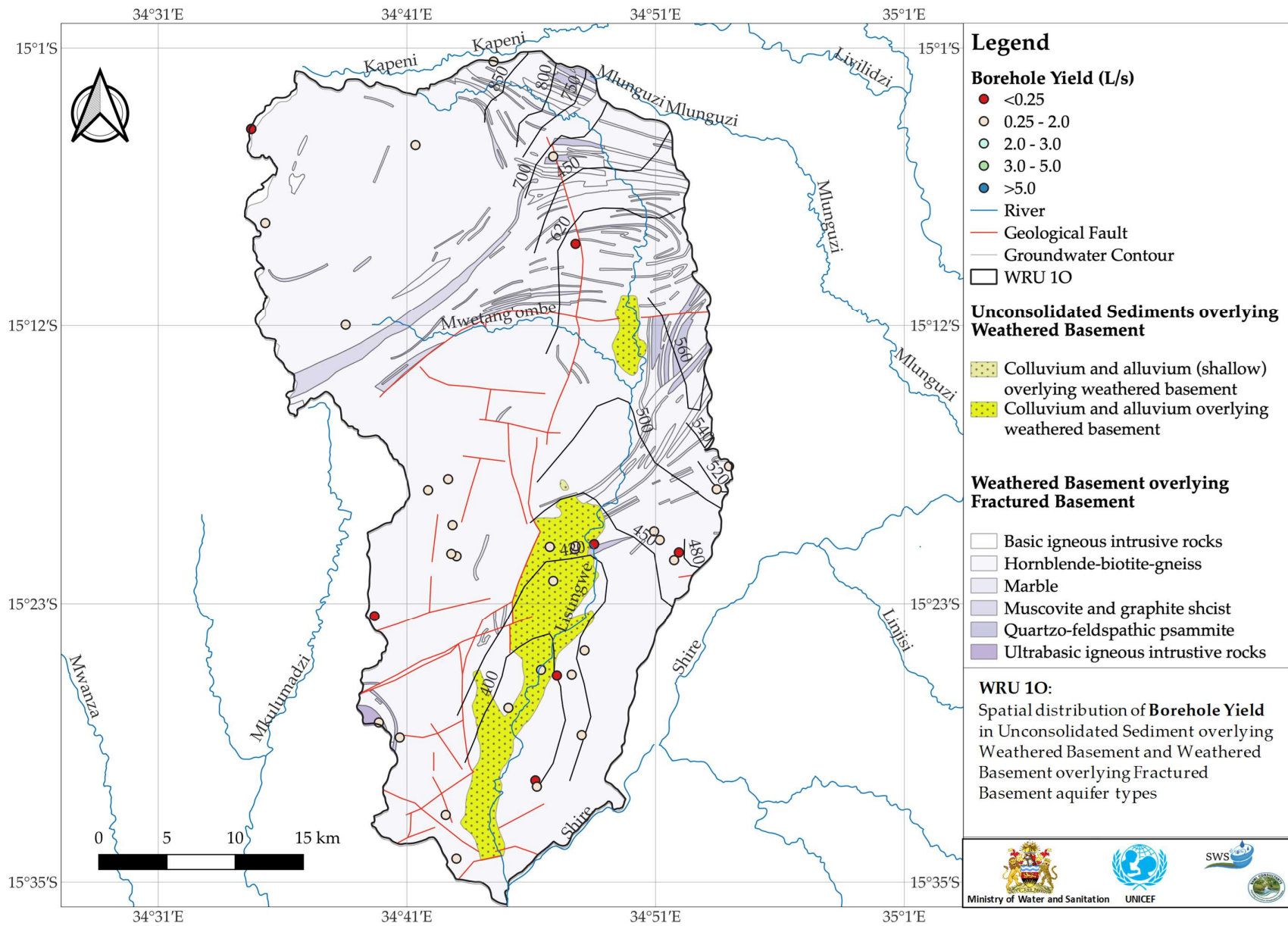


Figure WRU 10.10 Borehole Yield Map for data held by the Ministry



WRU 1P Figures

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Figure WRU 1P.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 1P.10 Borehole Yield Map for data held by the Ministry

Figure WRU 1P.1 Land Use and Major Roads

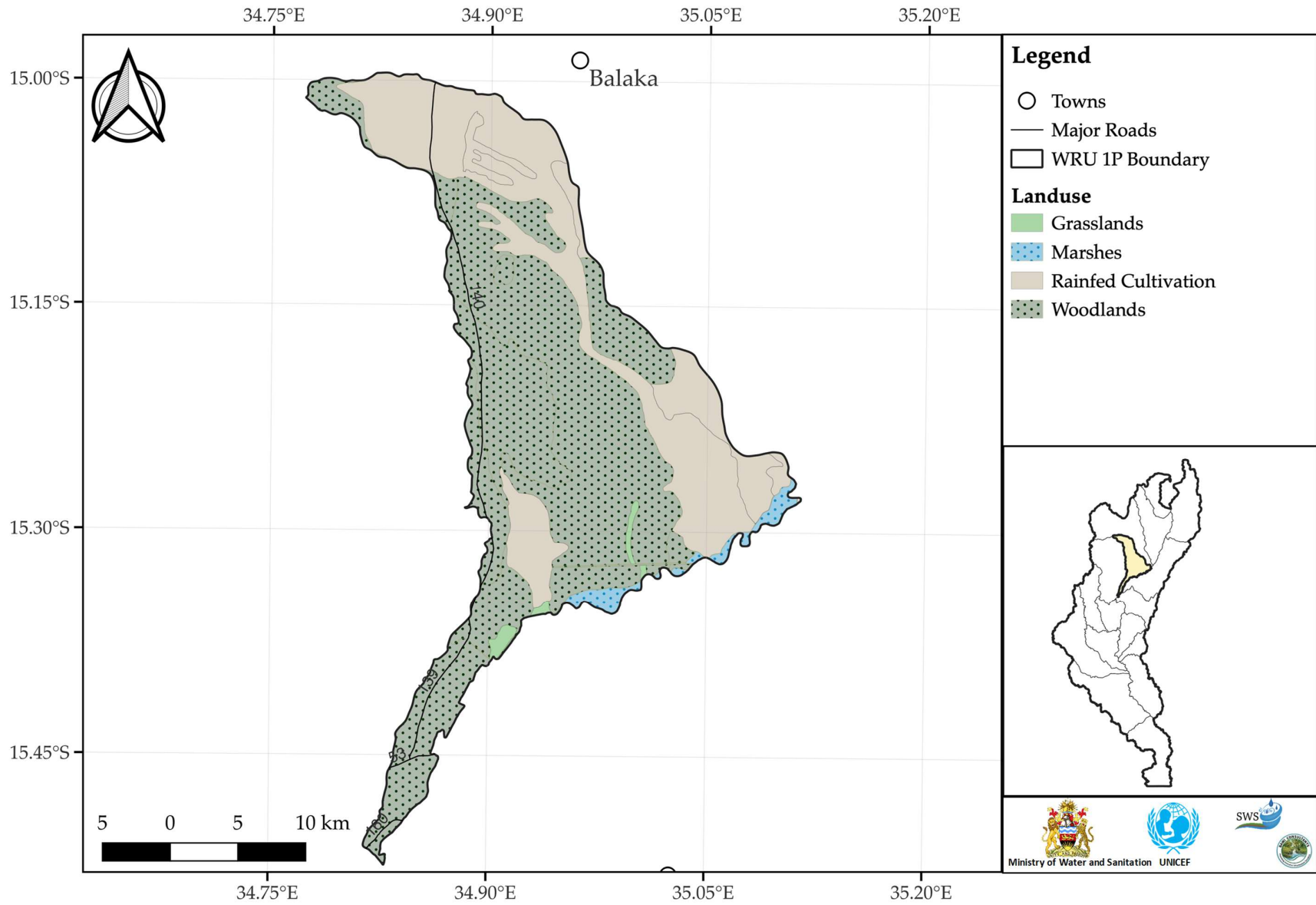


Figure WRU 1P.2 Rivers and Wetlands

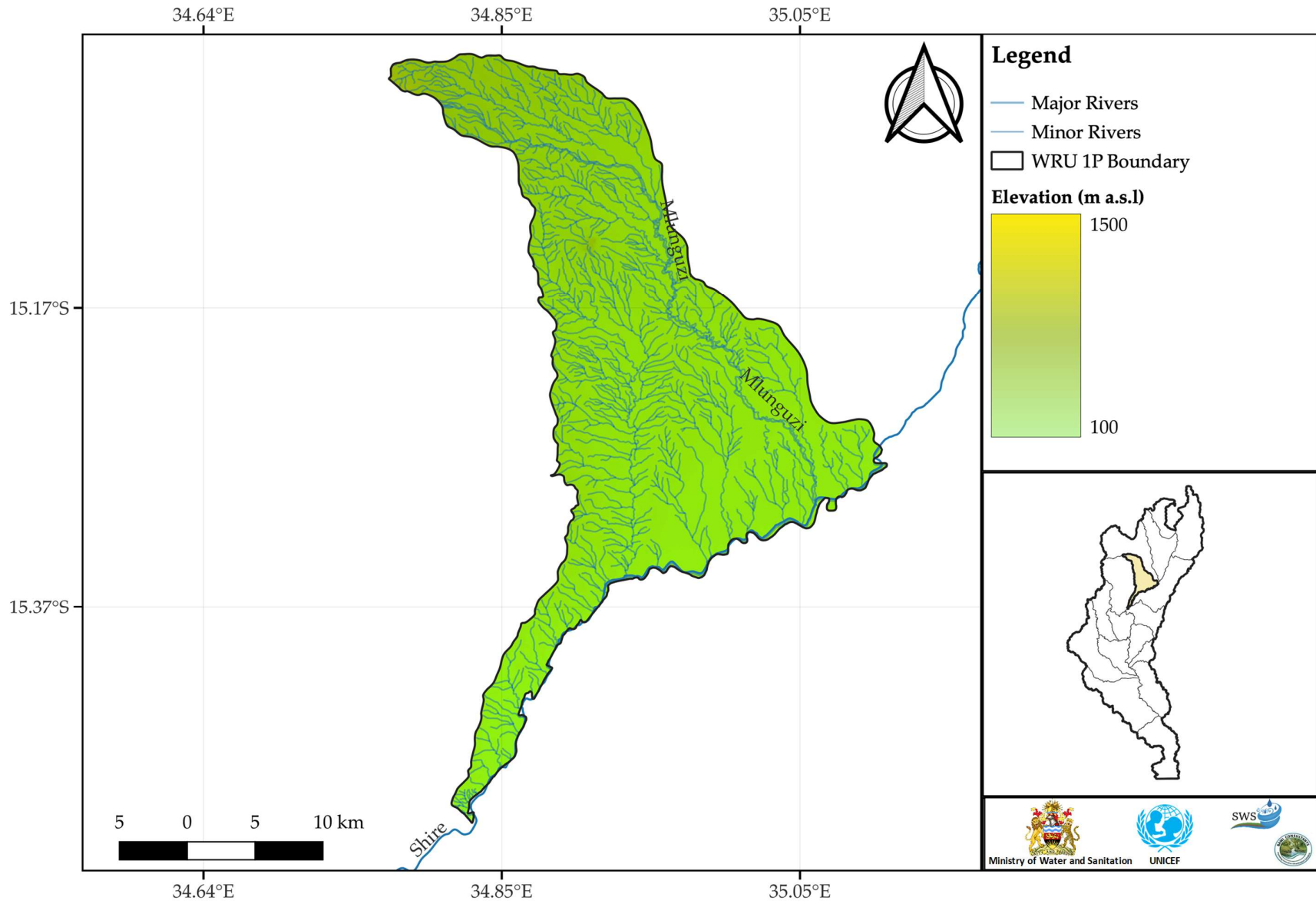


Figure WRU 1P.3 Hydrogeology Units and Water Table

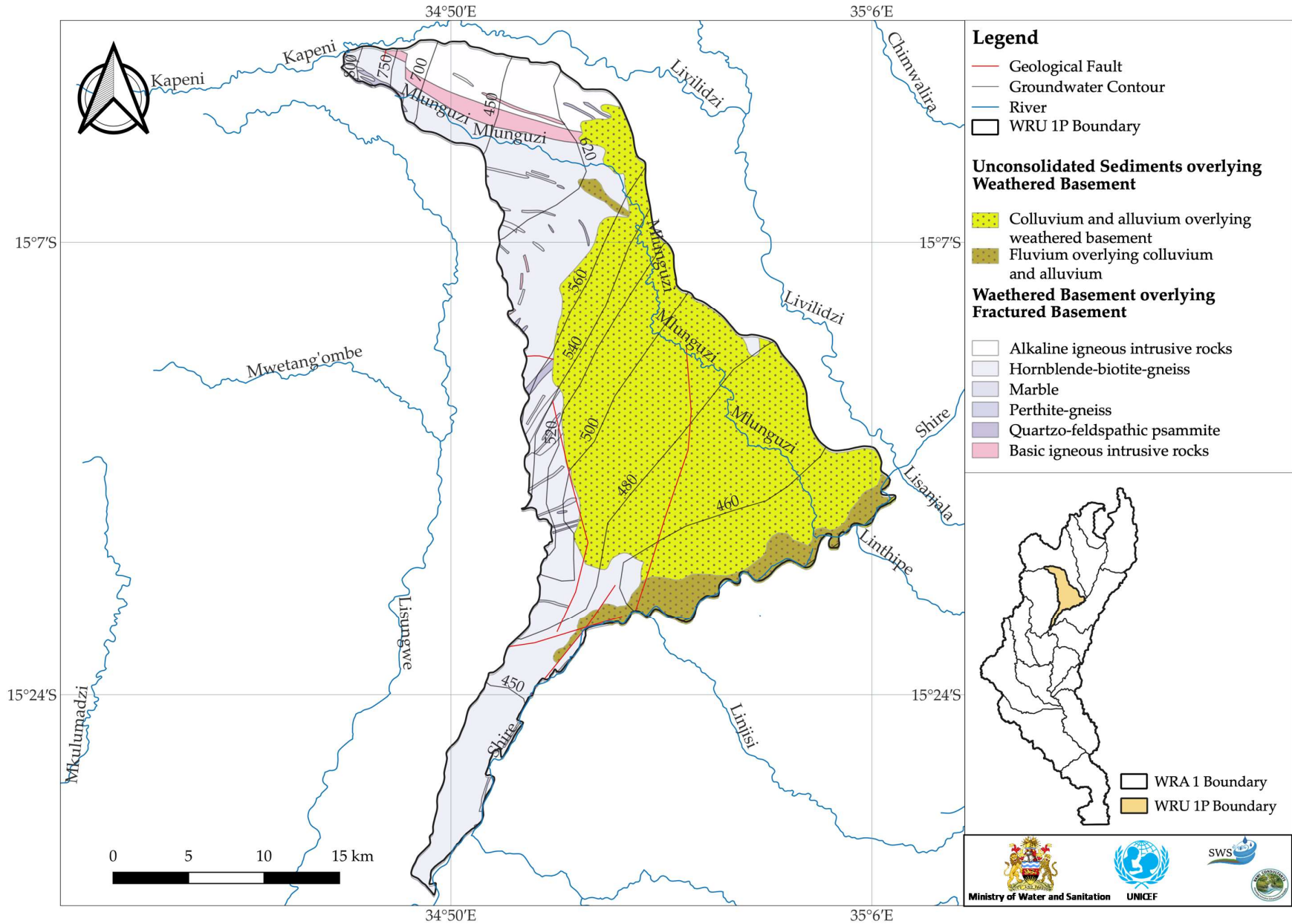


Figure WRU 1P.4 Groundwater Chemistry Distribution Electrical Conductivity

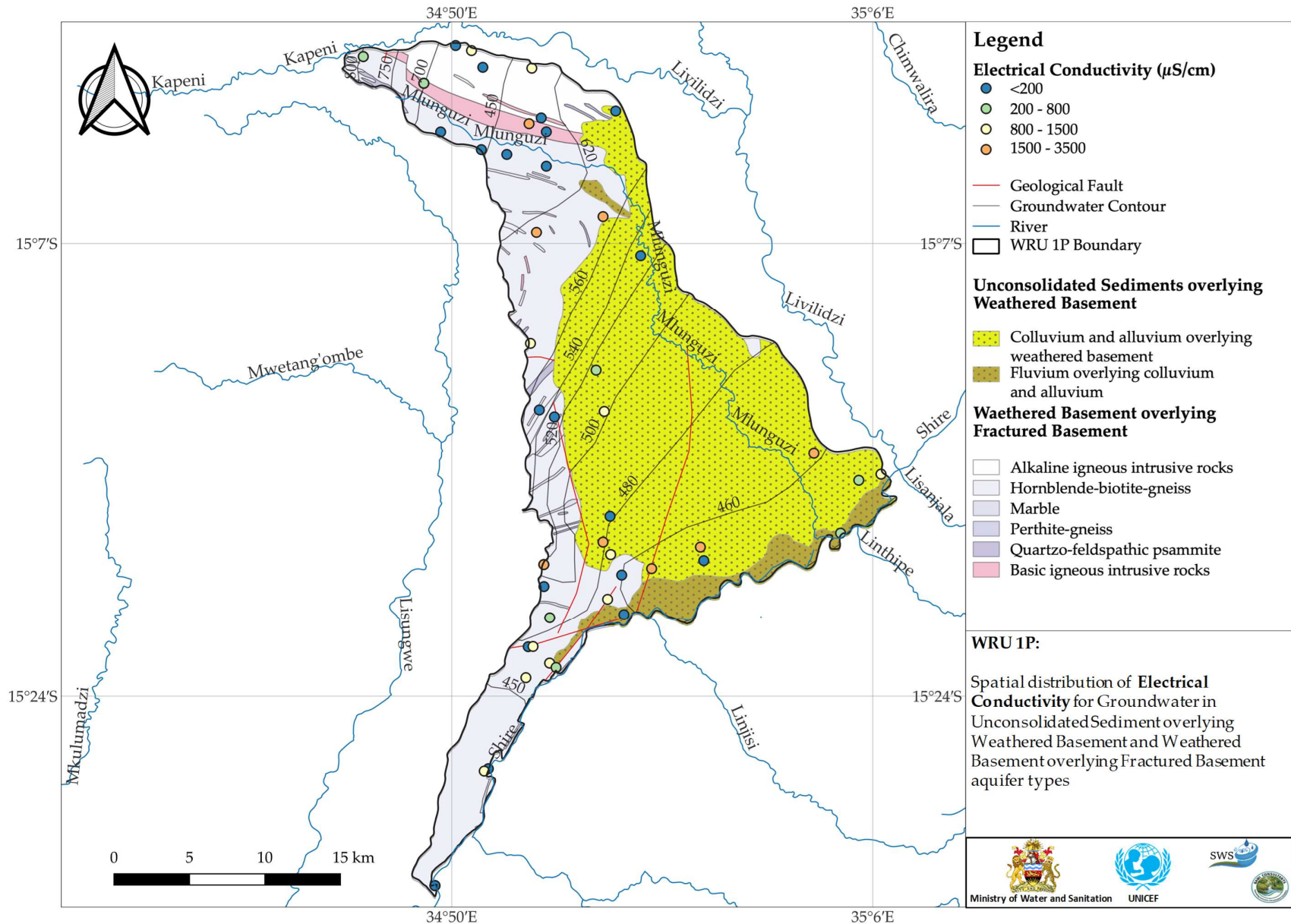


Figure WRU 1P.5 Groundwater Chemistry Distribution of Sulphate

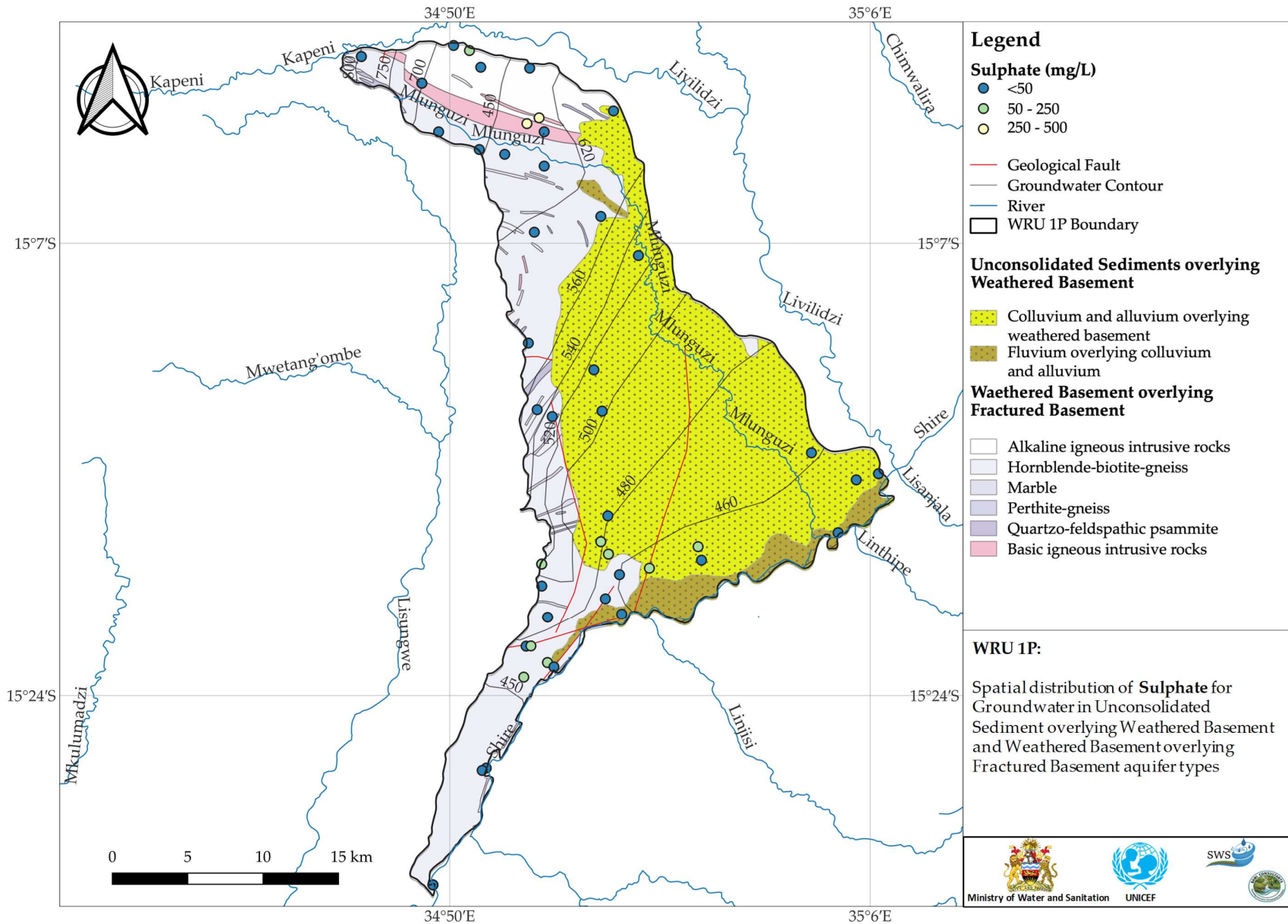


Figure WRU 1P.6 Groundwater Chemistry Distribution Chloride

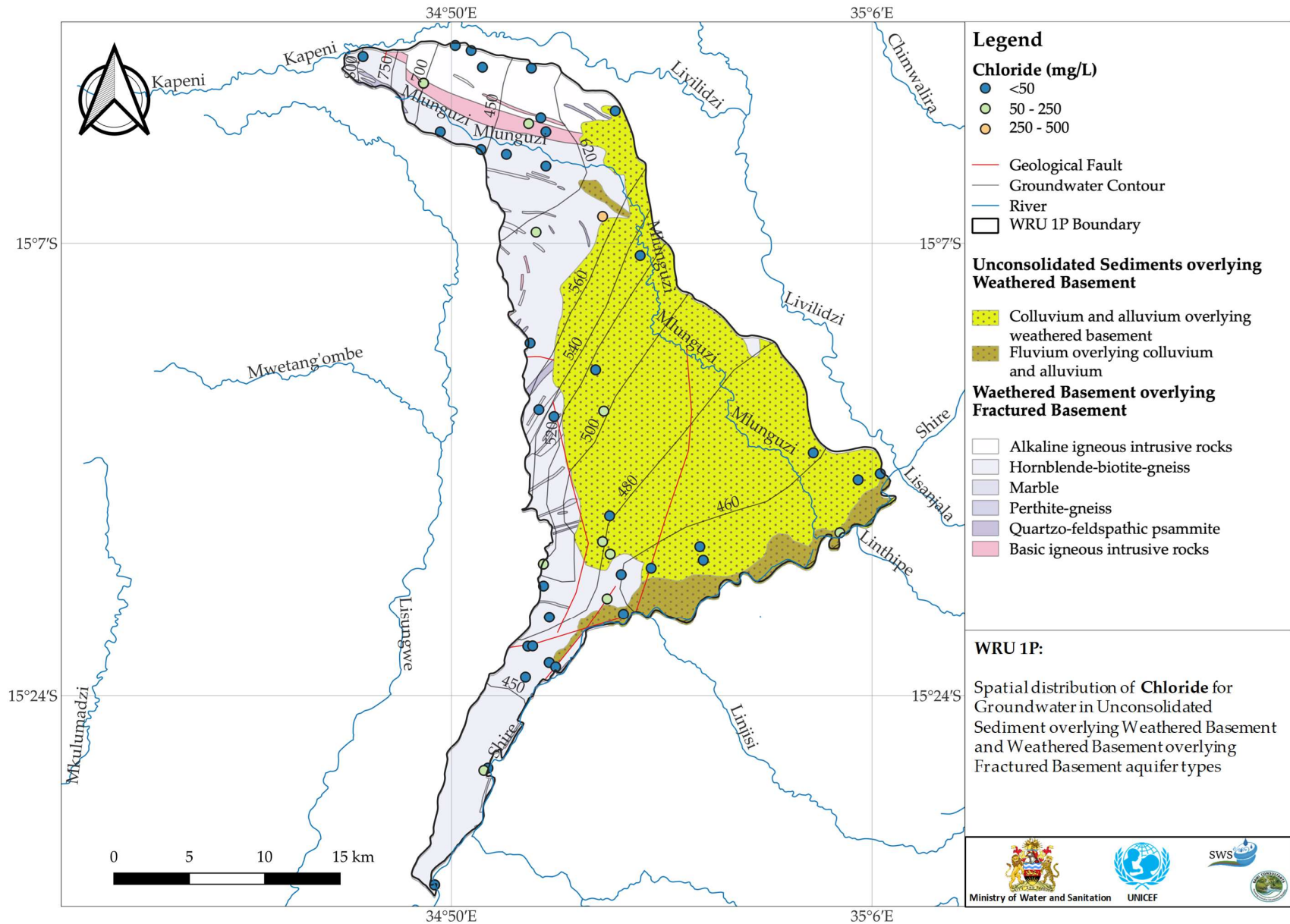


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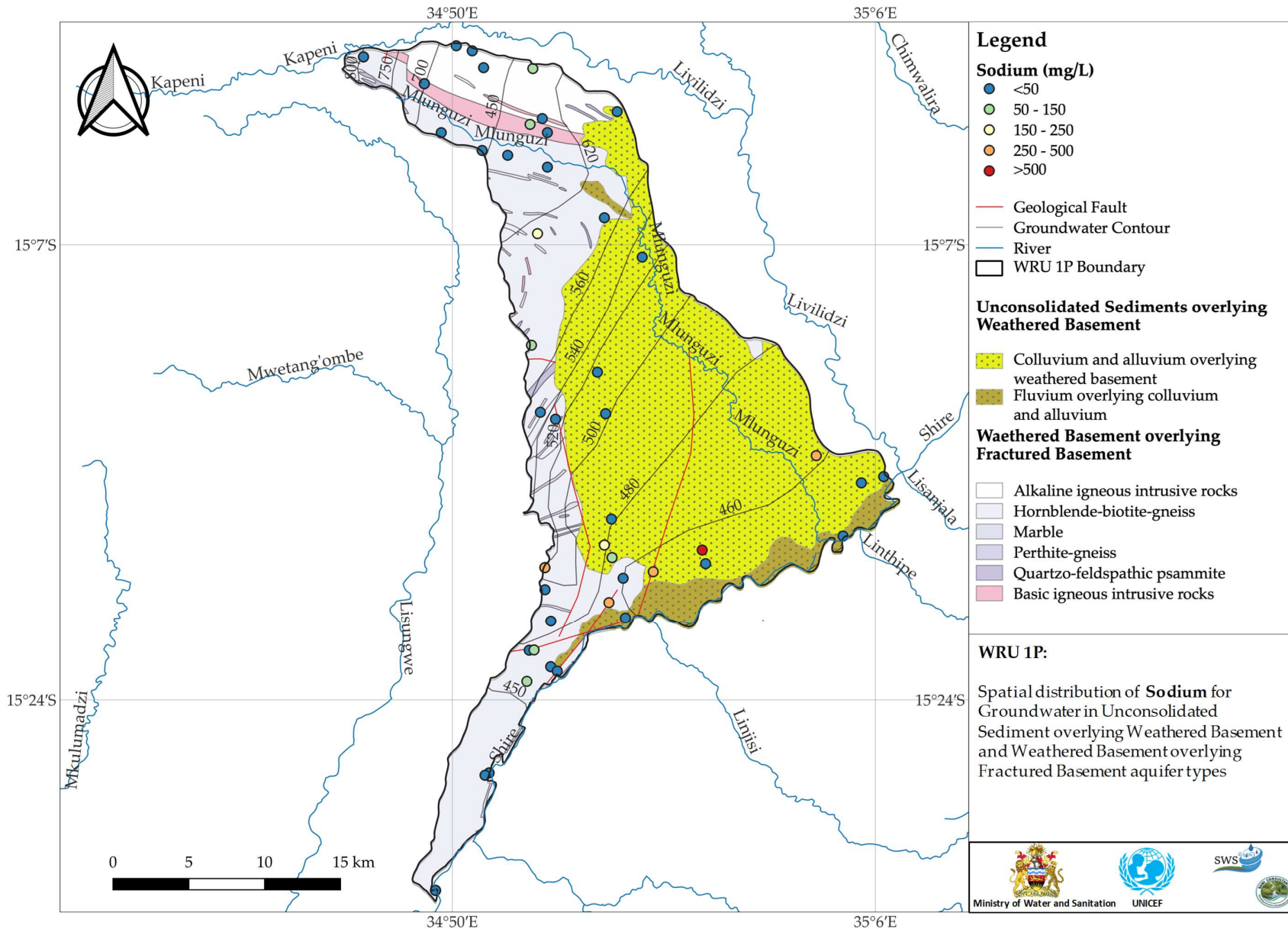


Figure WRU 1P.8 Groundwater Chemistry Distribution Calcium

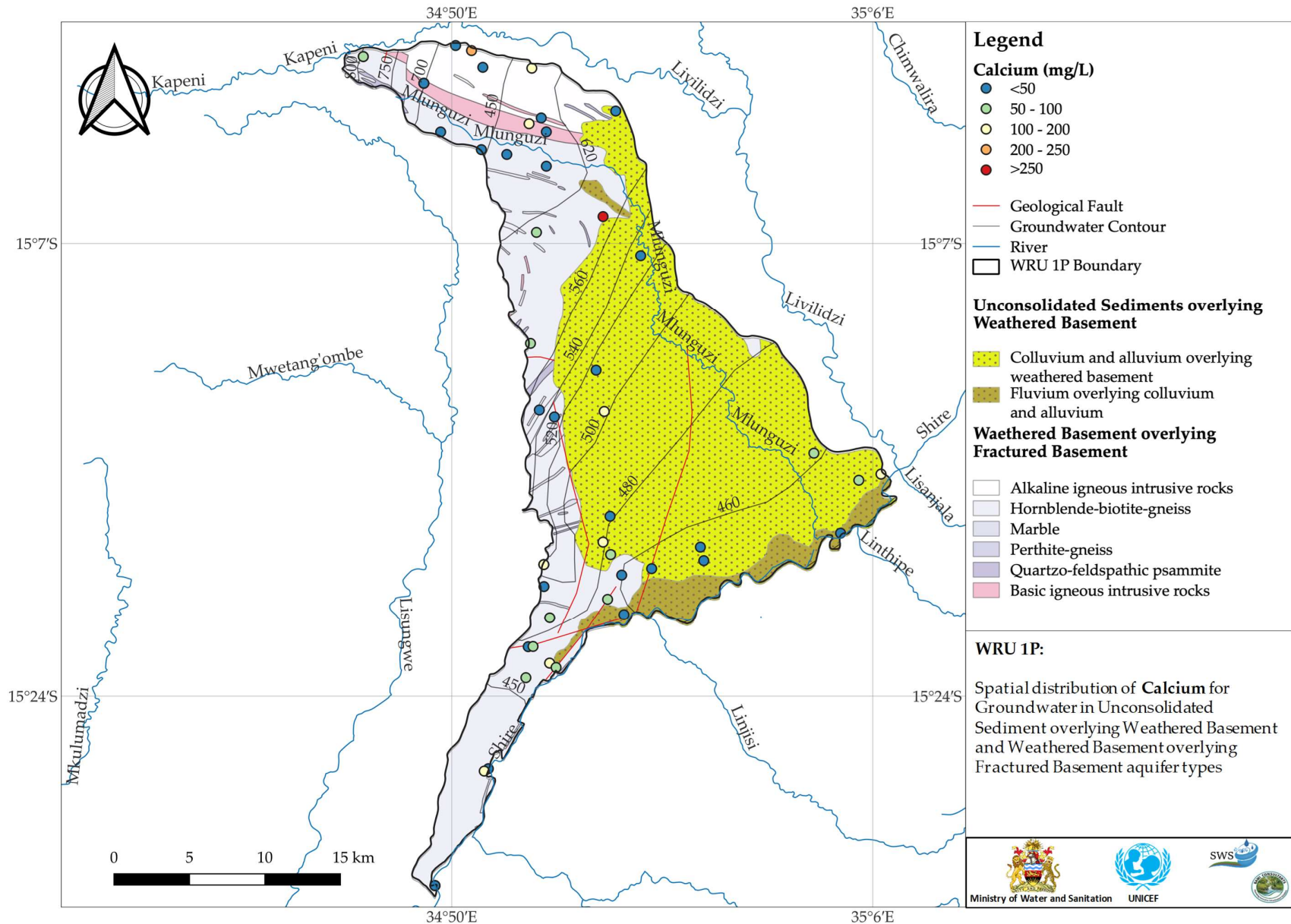
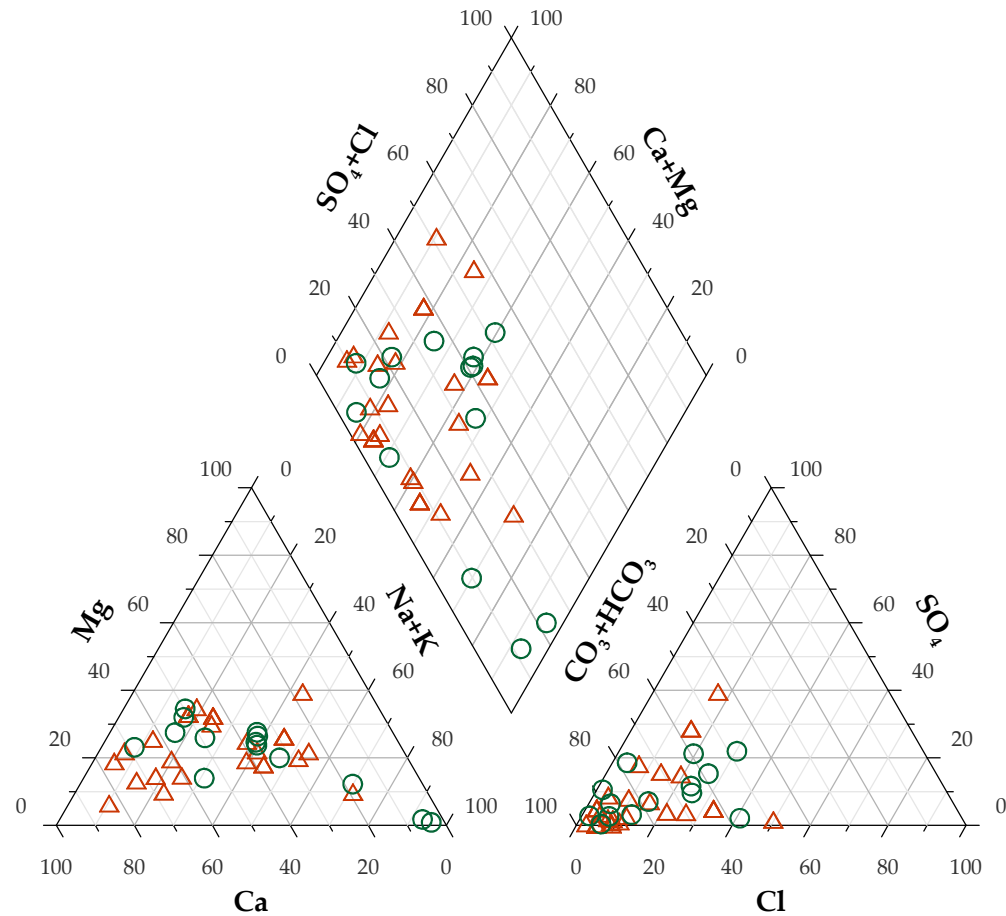


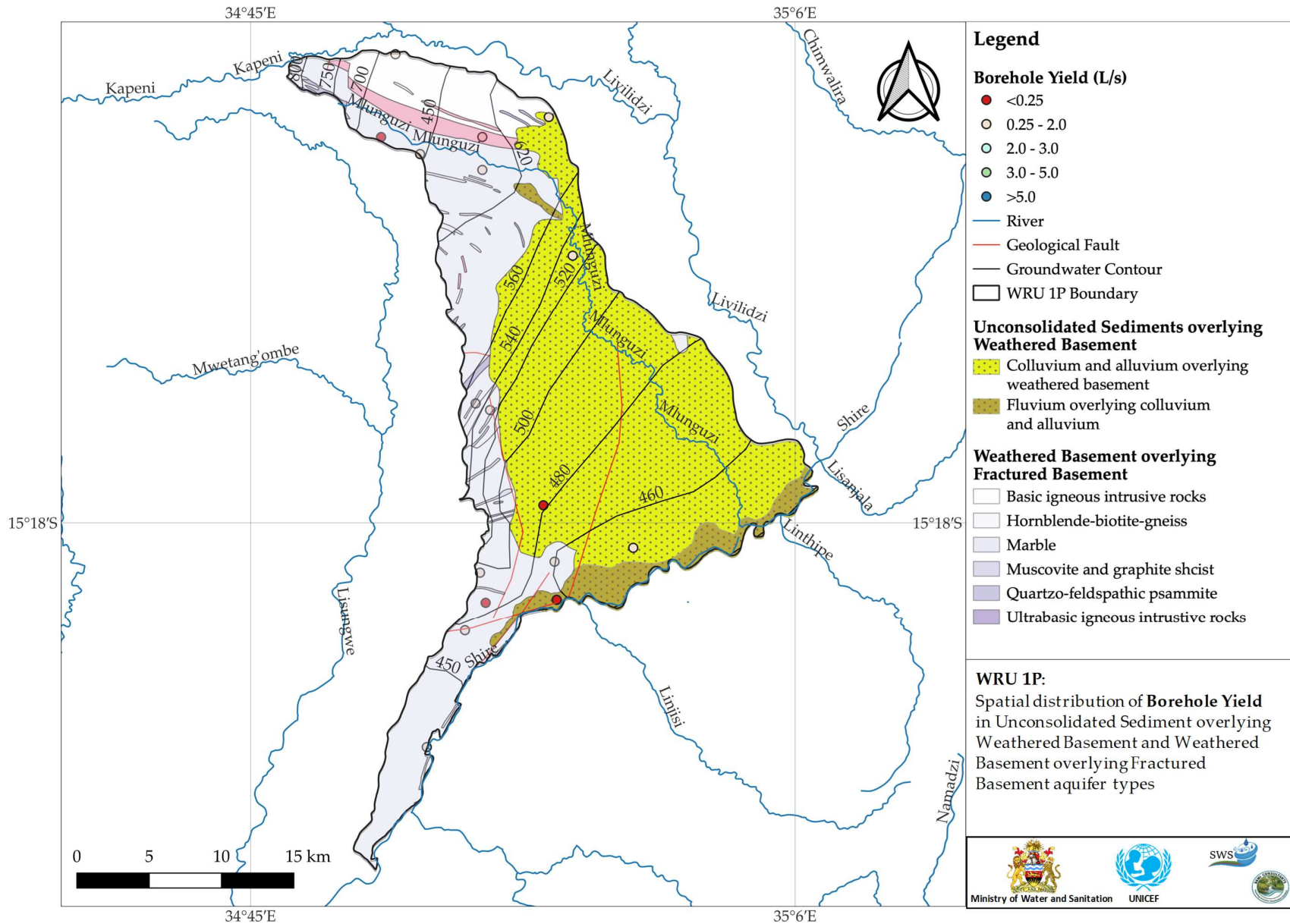
Figure WRU 1P.9 Piper Diagram of water quality results with respect to the major aquifer type



Aquifer Groups (WRU 1P)

- △ Weathered Basement overlying Fractured Basement
- Unconsolidated Sediments overlying Weathered Basement

Figure WRU 1P.10 Borehole Yield Map for data held by the Ministry



WRU 1R Figures

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Figure WRU 1R.6 Groundwater Chemistry Distribution Chloride

Figure WRU 1R.7 Groundwater Chemistry Distribution Sodium

Figure WRU 1R.8 Groundwater Chemistry Distribution Calcium

Figure WRU 1R.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 1R.10 Borehole Yield Map for data held by the Ministry

Figure WRU 1R.1 Land Use and Major Roads

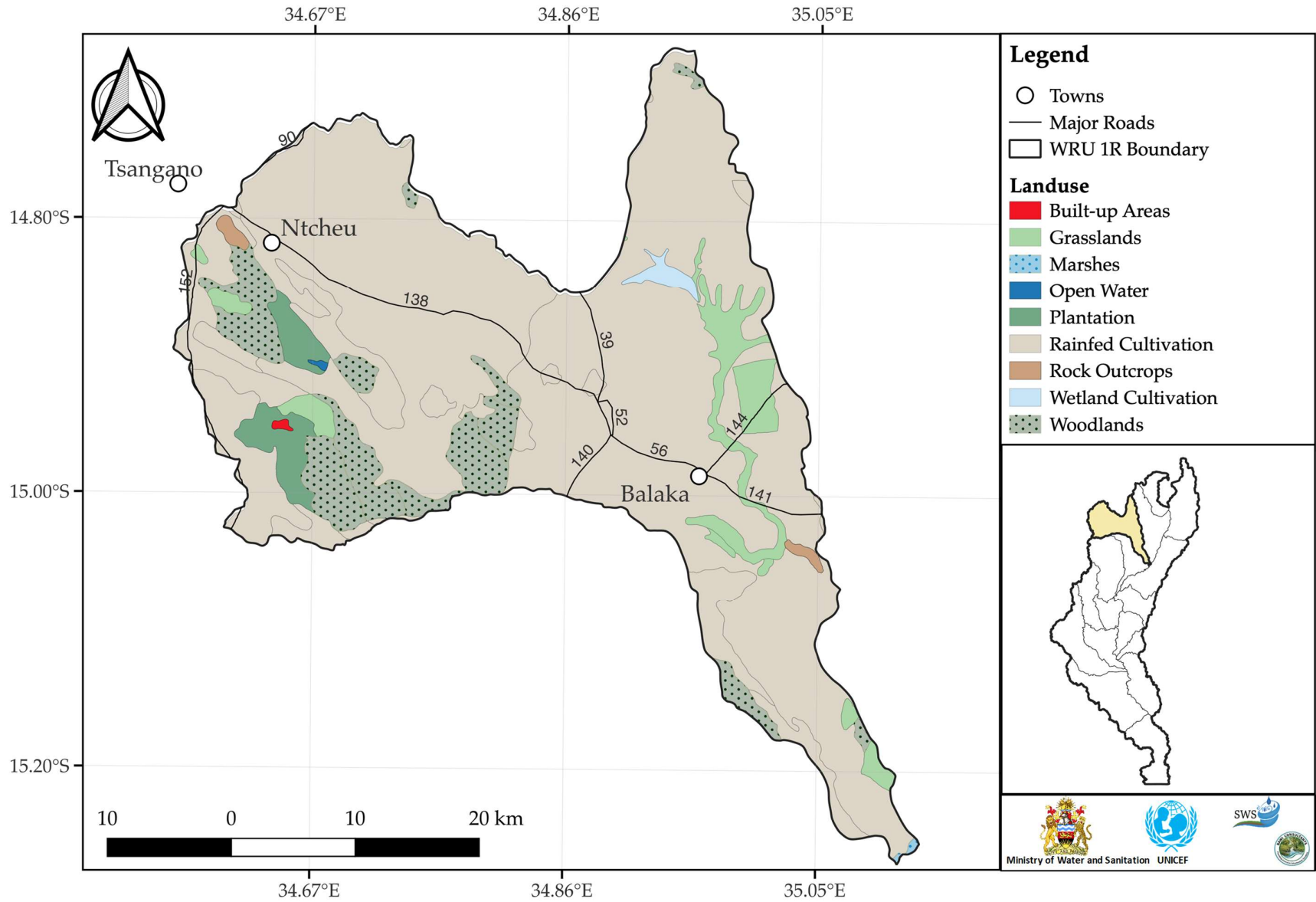


Figure WRU 1R.2 Rivers and Wetlands

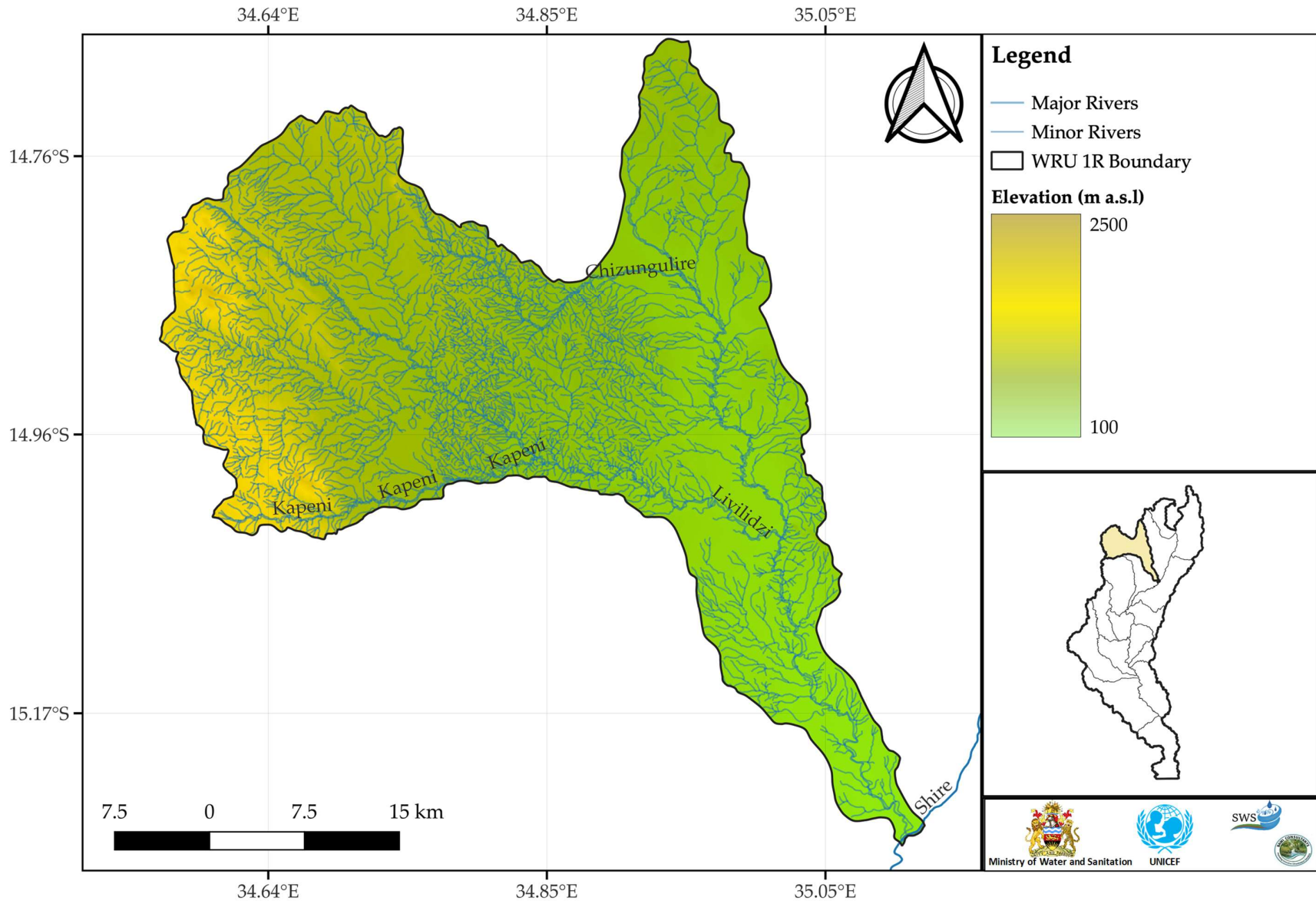


Figure WRU 1R.3 Hydrogeology Units and Water Table

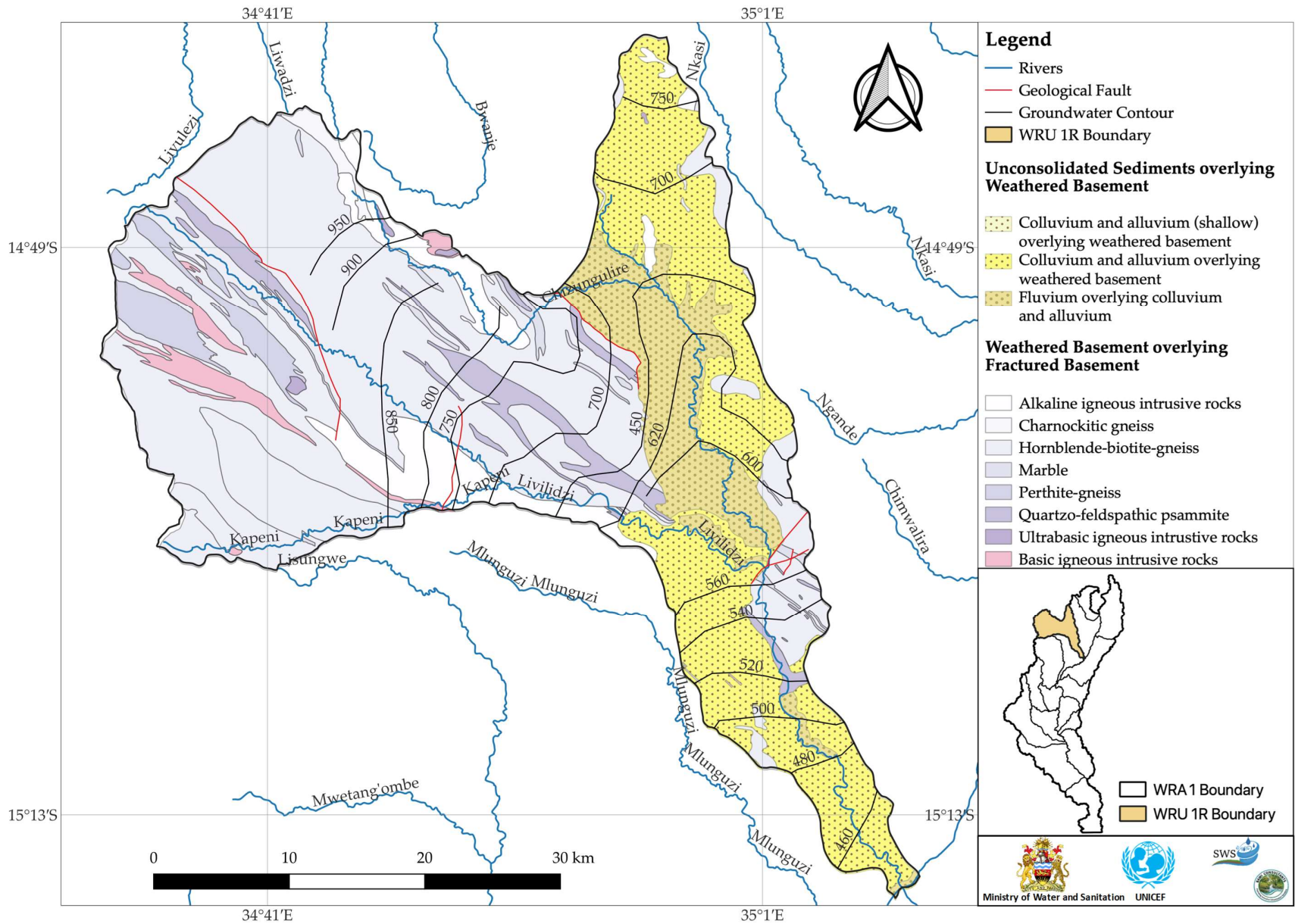


Figure WRU 1R.4 Groundwater Chemistry Distribution Electrical Conductivity

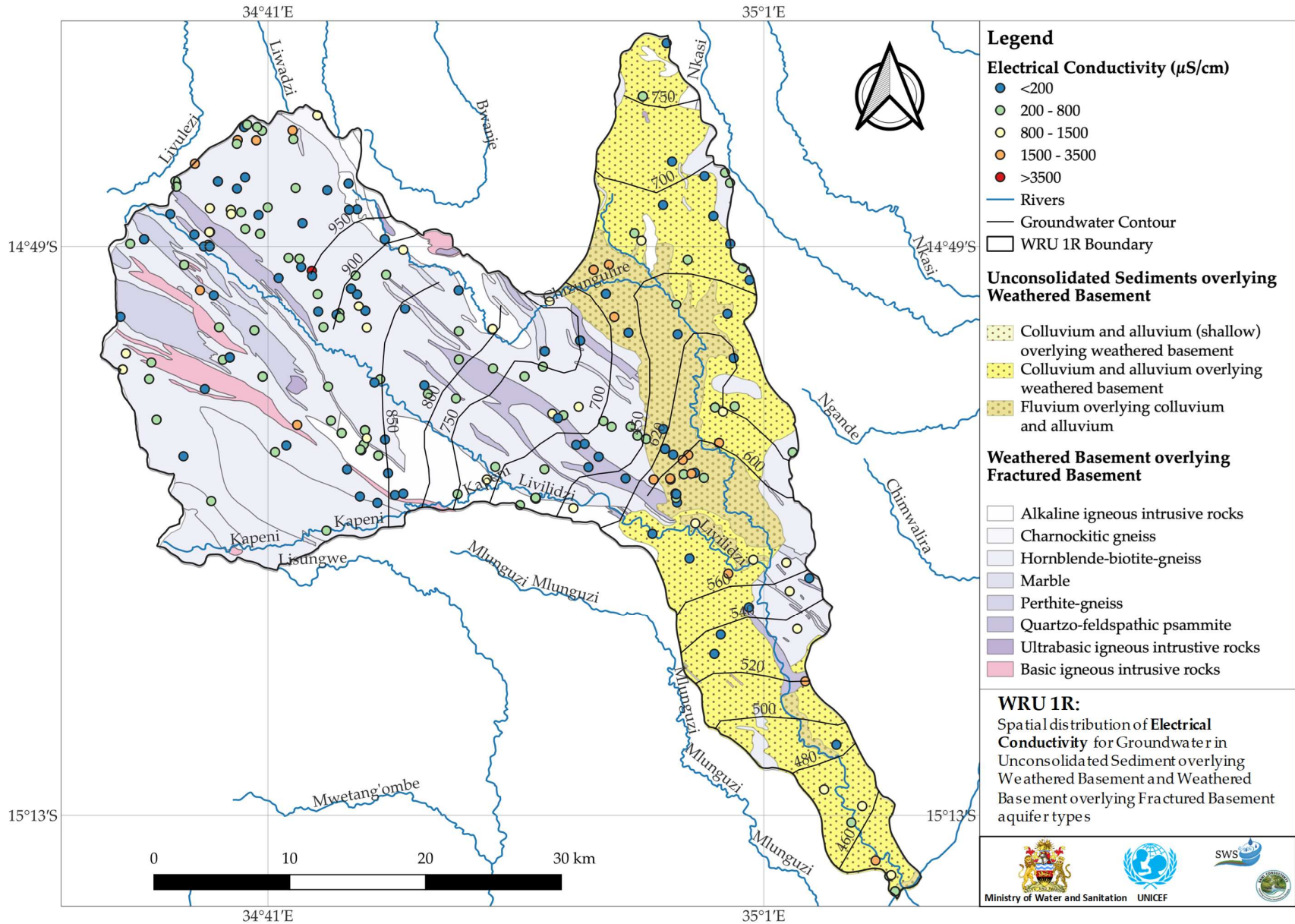
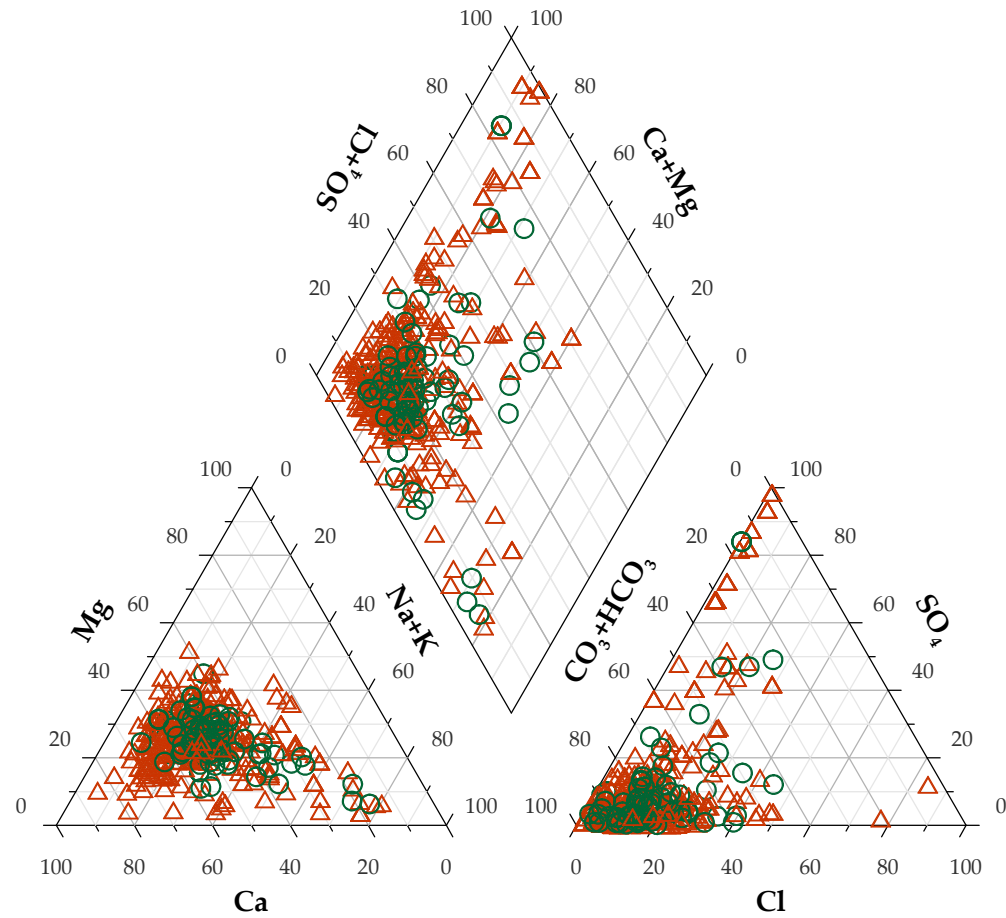


Figure WRU 1R.9 Piper Diagram of water quality results with respect to the major aquifer type



Aquifer Groups (WRU 1R)

- △ Weathered Basement overlying Fractured Basement
- Unconsolidated Sediments overlying Weathered Basement

WRU 1S Figures

Figure WRU 1S.1 Land Use and Major Roads

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Figure WRU 1S.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 1S.6 Groundwater Chemistry Distribution Chloride

Figure WRU 1S.7 Groundwater Chemistry Distribution Sodium

Figure WRU 1S.8 Groundwater Chemistry Distribution Calcium

Figure WRU 1S.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 1S.10 Borehole Yield Map for data held by the Ministry

Figure WRU 1S.1 Land Use and Major Roads

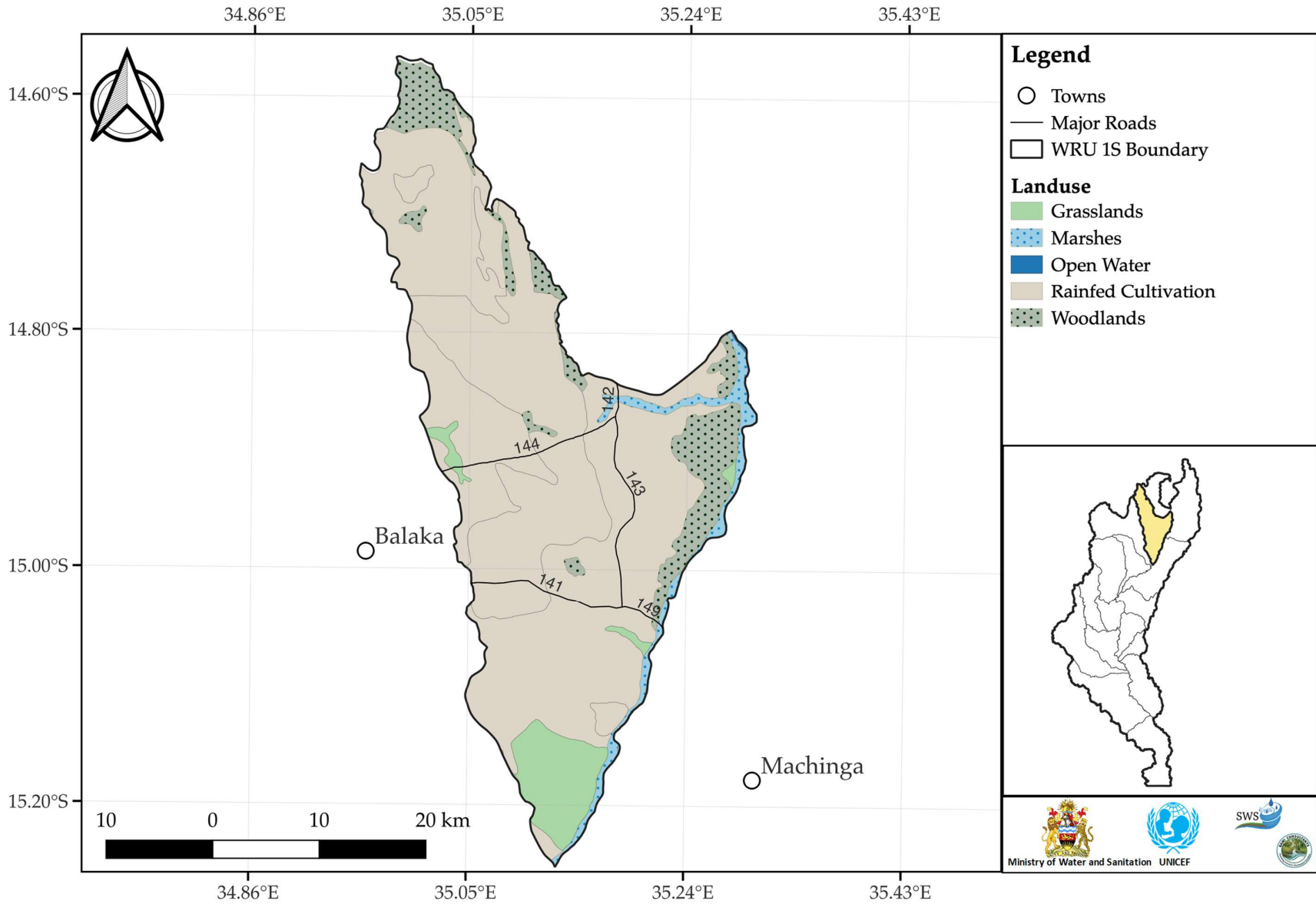


Figure WRU 1S.2 Rivers and Wetlands

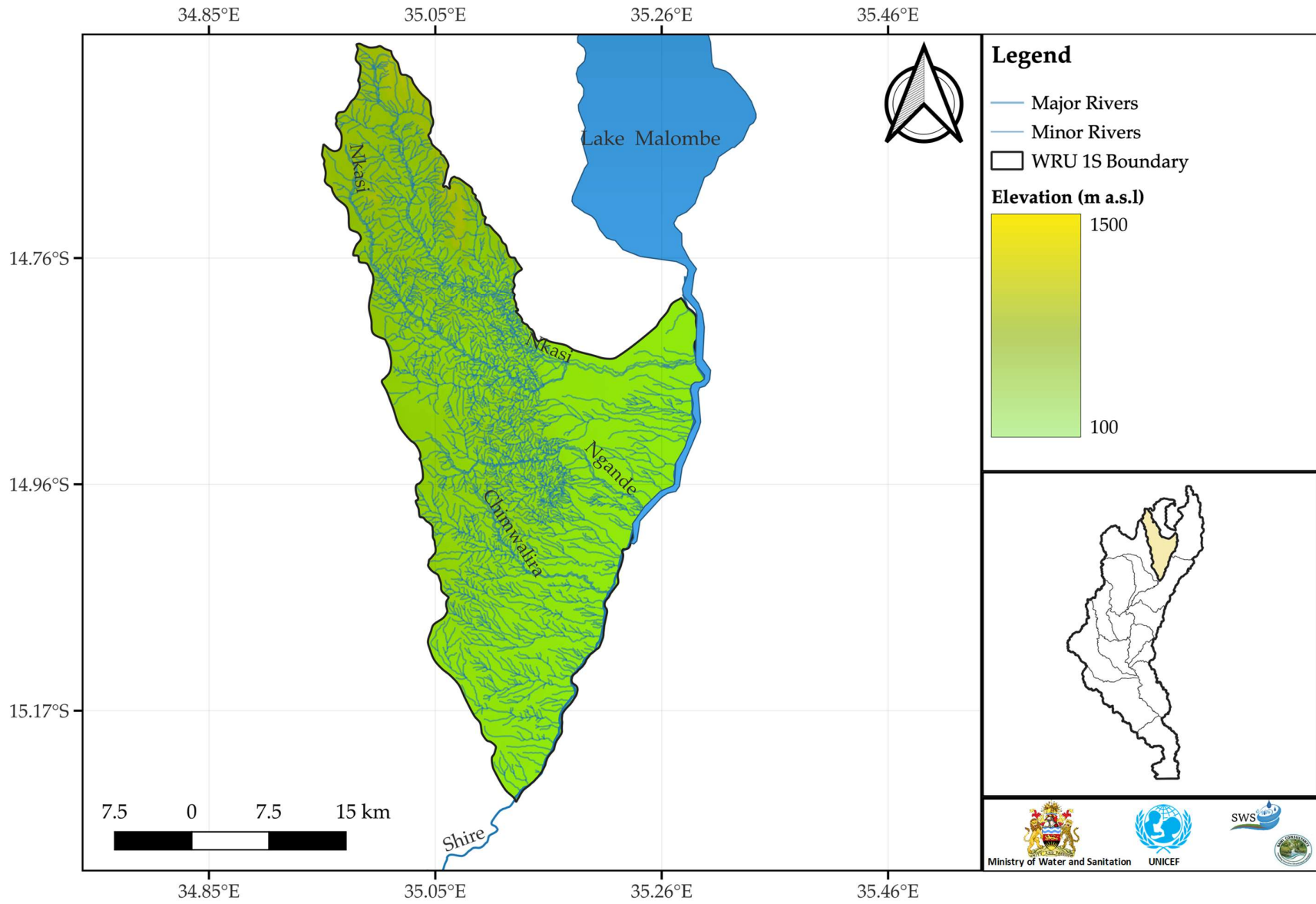


Figure WRU 1S.3 Hydrogeology Units and Water Table

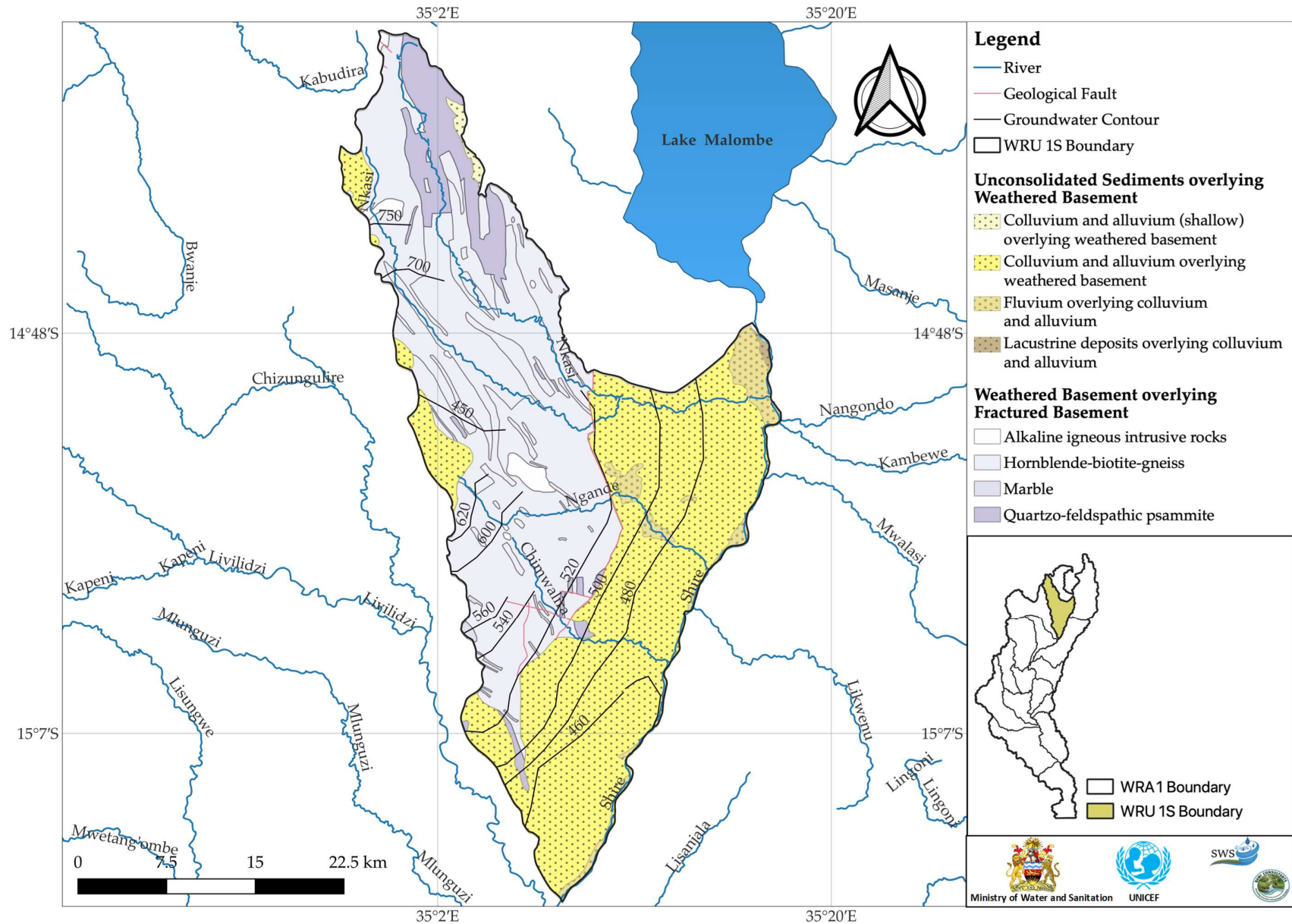


Figure WRU 1P.4 Groundwater Chemistry Distribution Electrical Conductivity

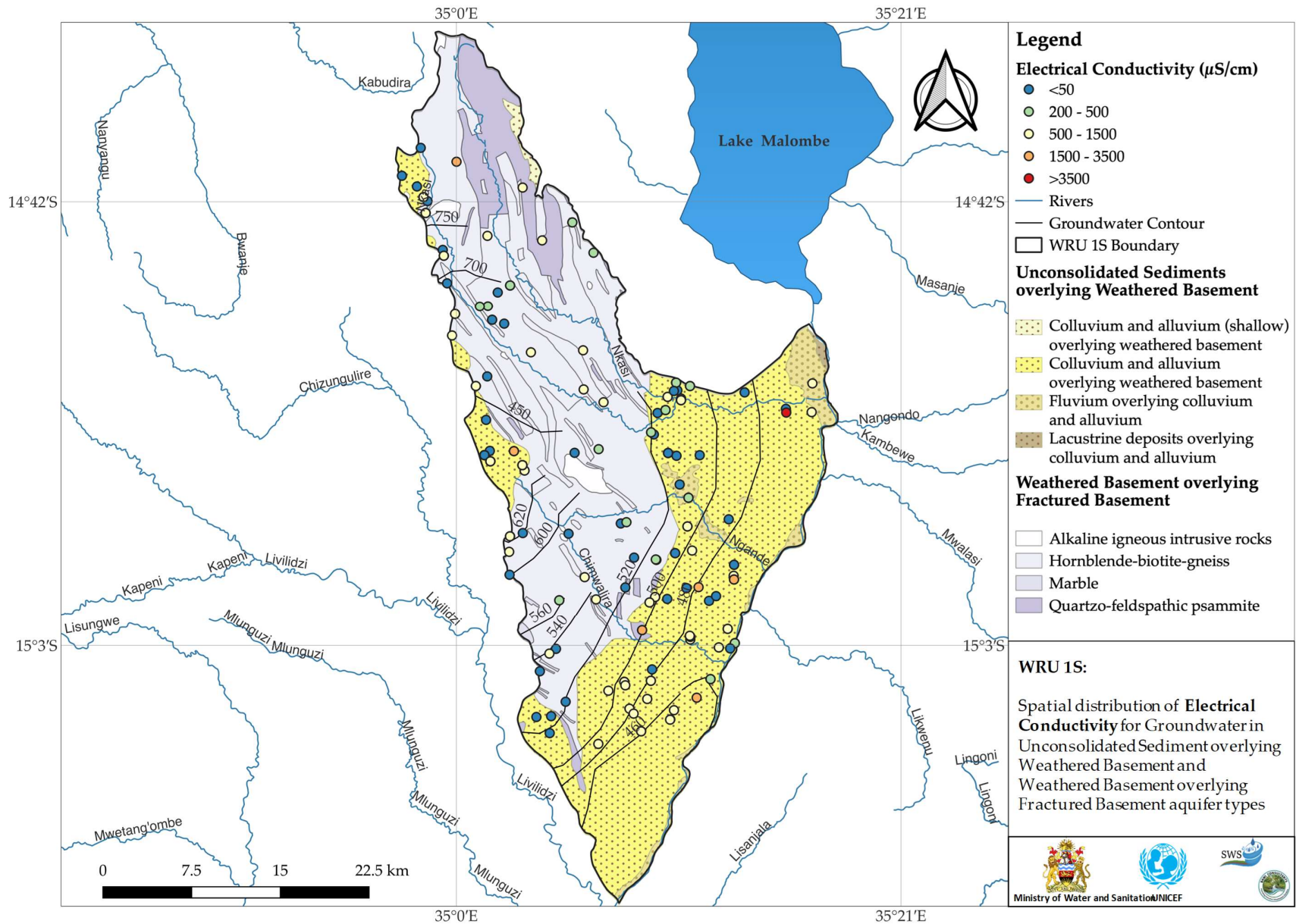


Figure WRU 1S.6 Groundwater Chemistry Distribution Chloride

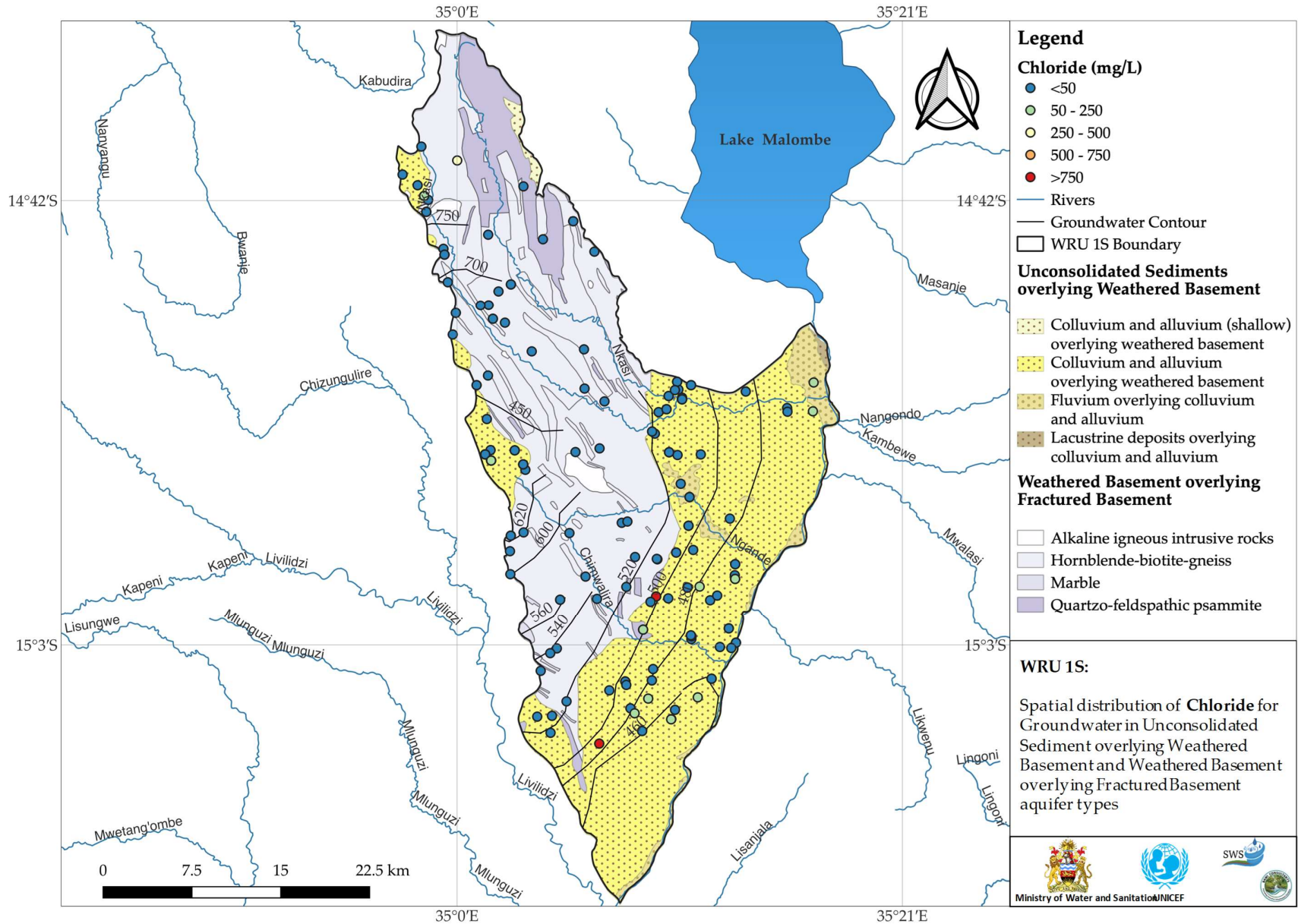


Figure WRU 1S.7 Groundwater Chemistry Distribution Sodium

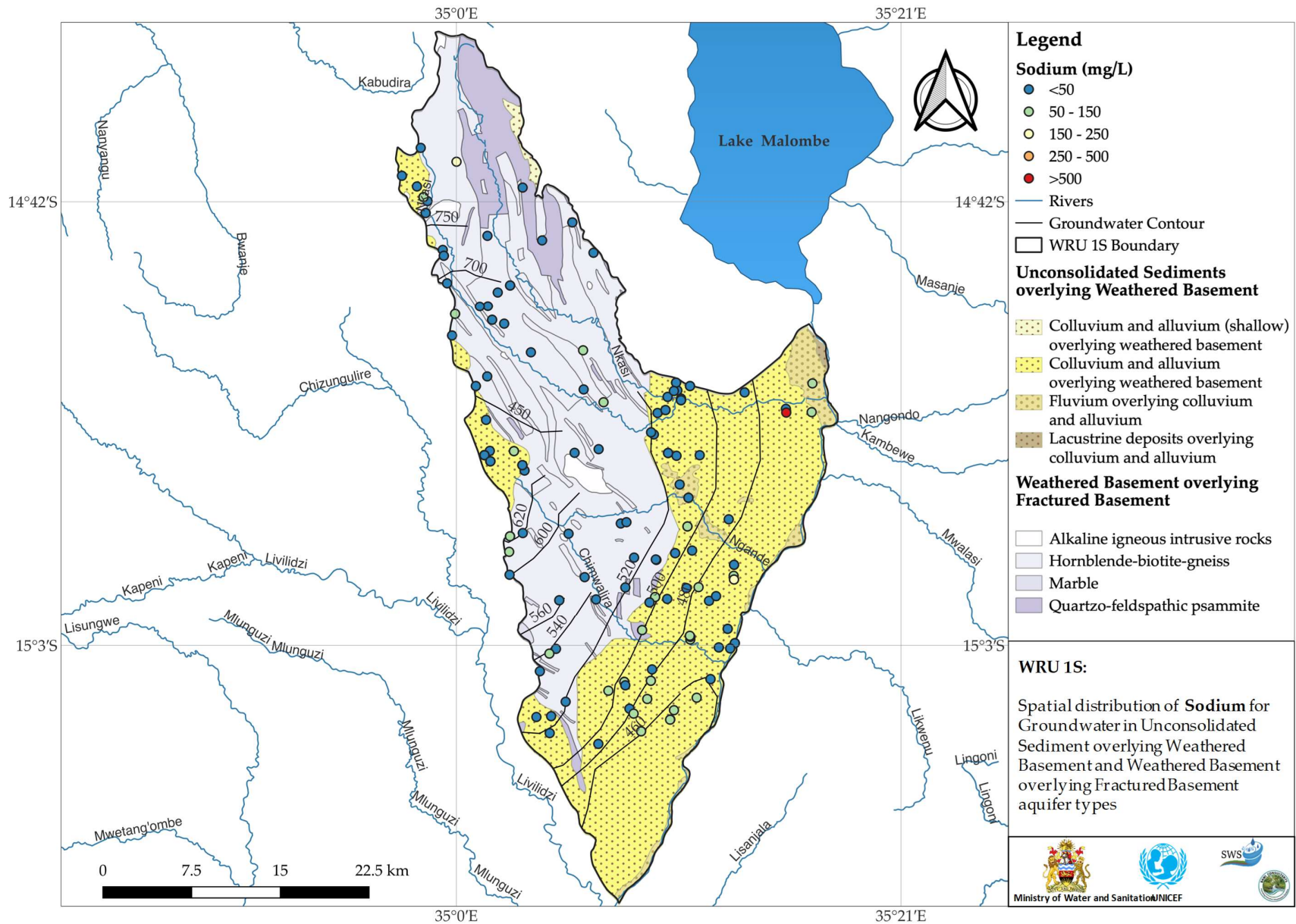


Figure WRU 1S.8 Groundwater Chemistry Distribution Calcium

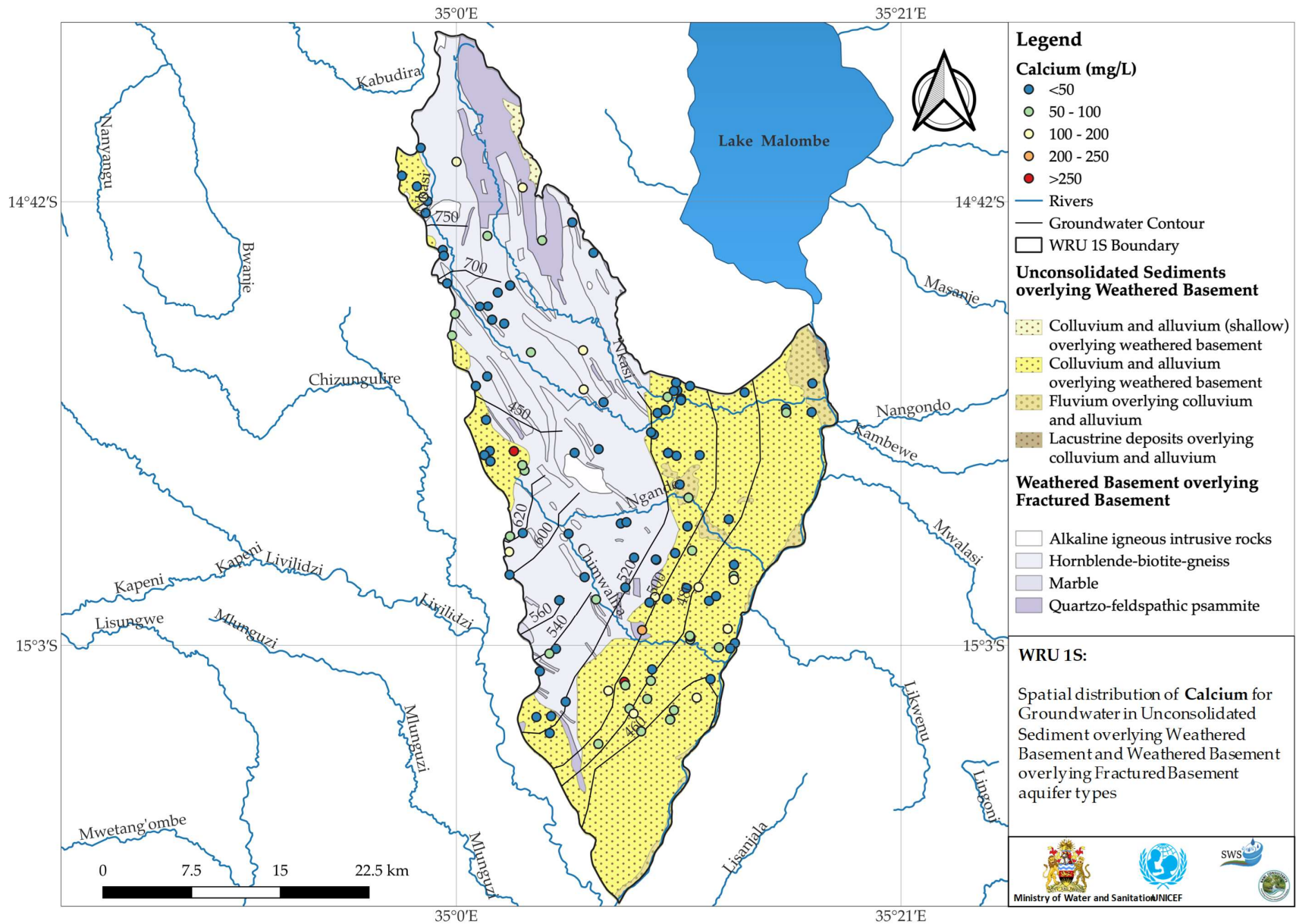
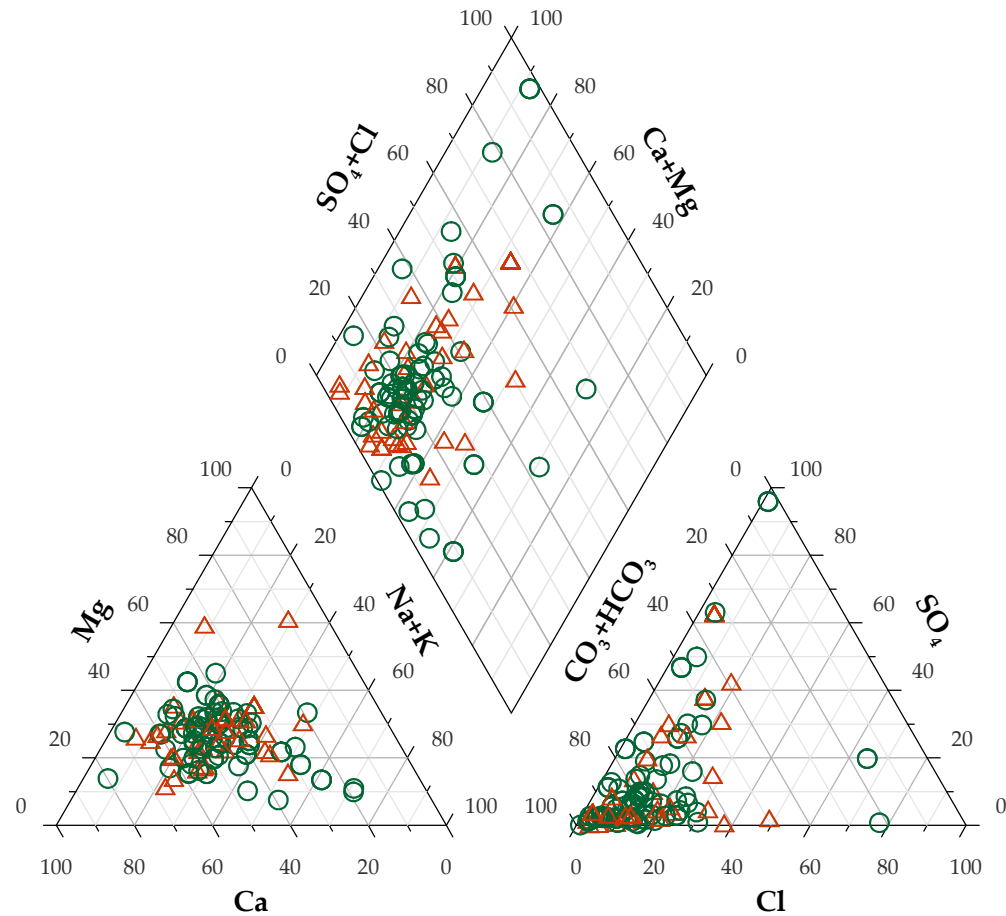


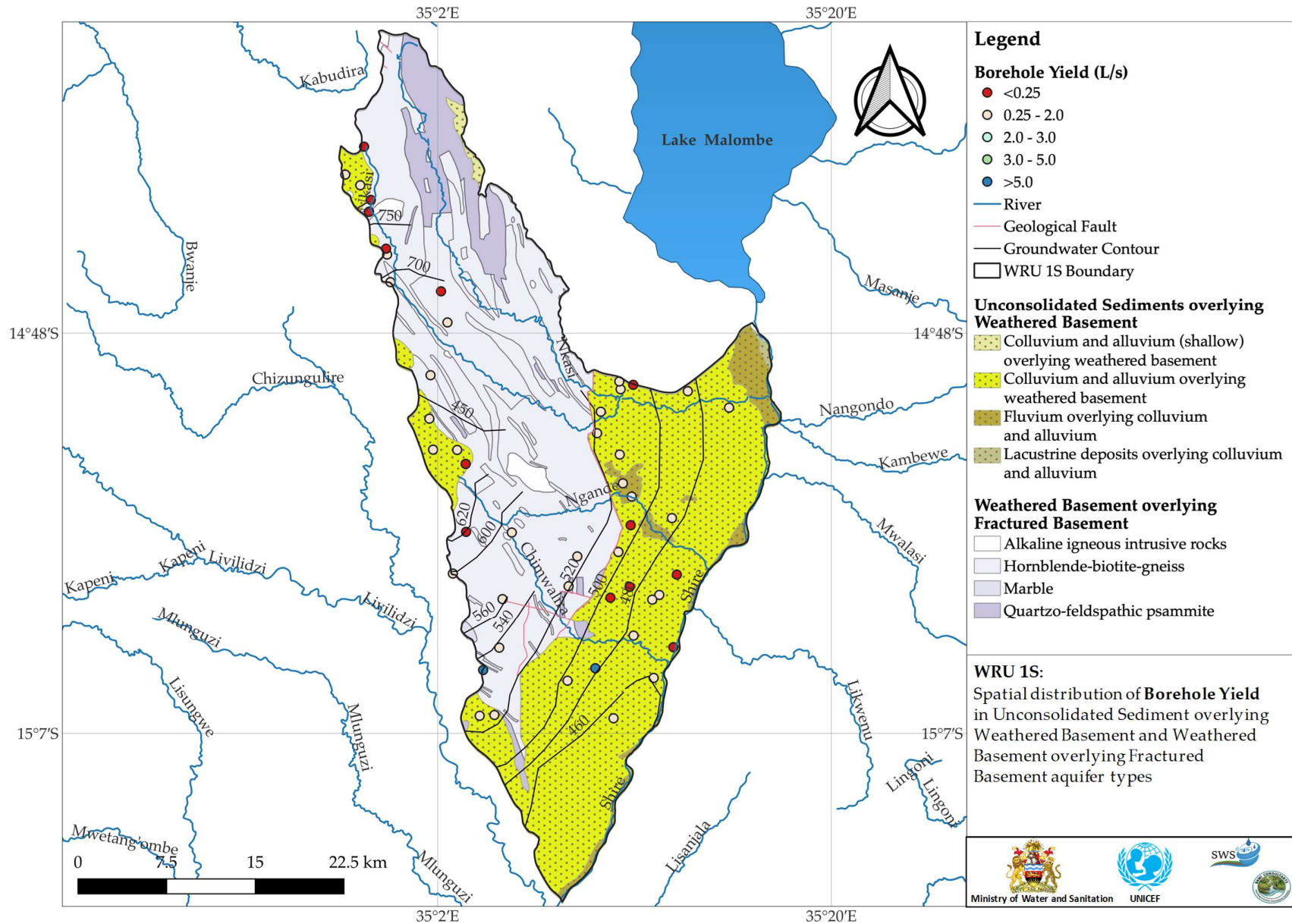
Figure WRU 15.10 Piper Diagram of water quality results with respect to the major aquifer type



Aquifer Groups (WRU 15)

- △ Weathered Basement overlying Fractured Basement
- Unconsolidated Sediments overlying Weathered Basement

Figure WRU 1S.11 Borehole Yield Map for data held by the Ministry



WRU 1T Figures

Figure WRU 1T.1 Land Use and Major Roads

Figure WRU 1T.2 Rivers and Wetlands

Figure WRU 1T.3 Hydrogeology Units and Water Table

Figure WRU 1P.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 1T.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 1T.6 Groundwater Chemistry Distribution Chloride

Figure WRU 1T.7 Groundwater Chemistry Distribution Sodium

Figure WRU 1T.8 Groundwater Chemistry Distribution Calcium

Figure WRU 1T.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 1T.10 Borehole Yield Map for data held by the Ministry

Figure WRU 1T.1 Land Use and Major Roads

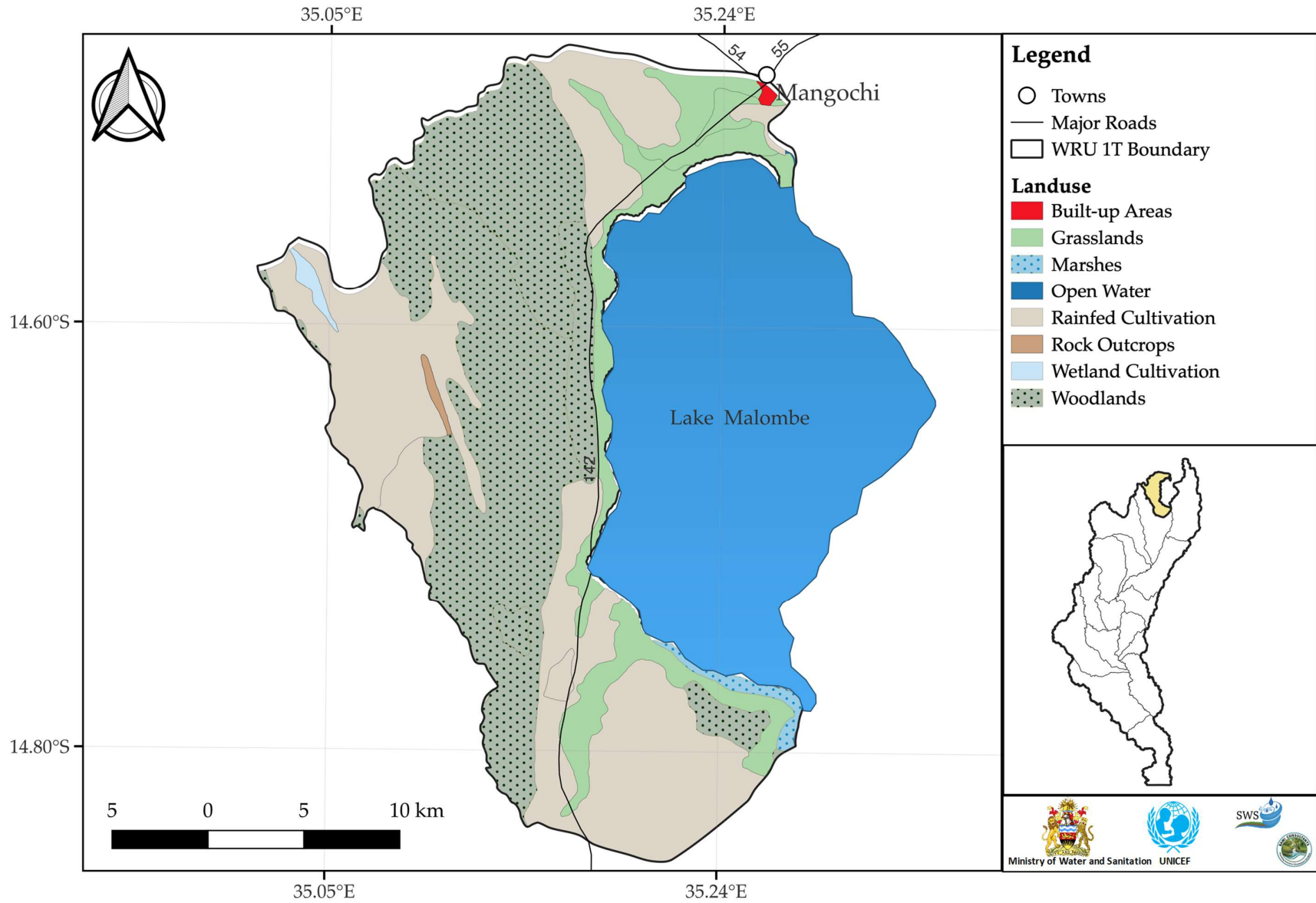


Figure WRU 1T.2 Rivers and Wetlands

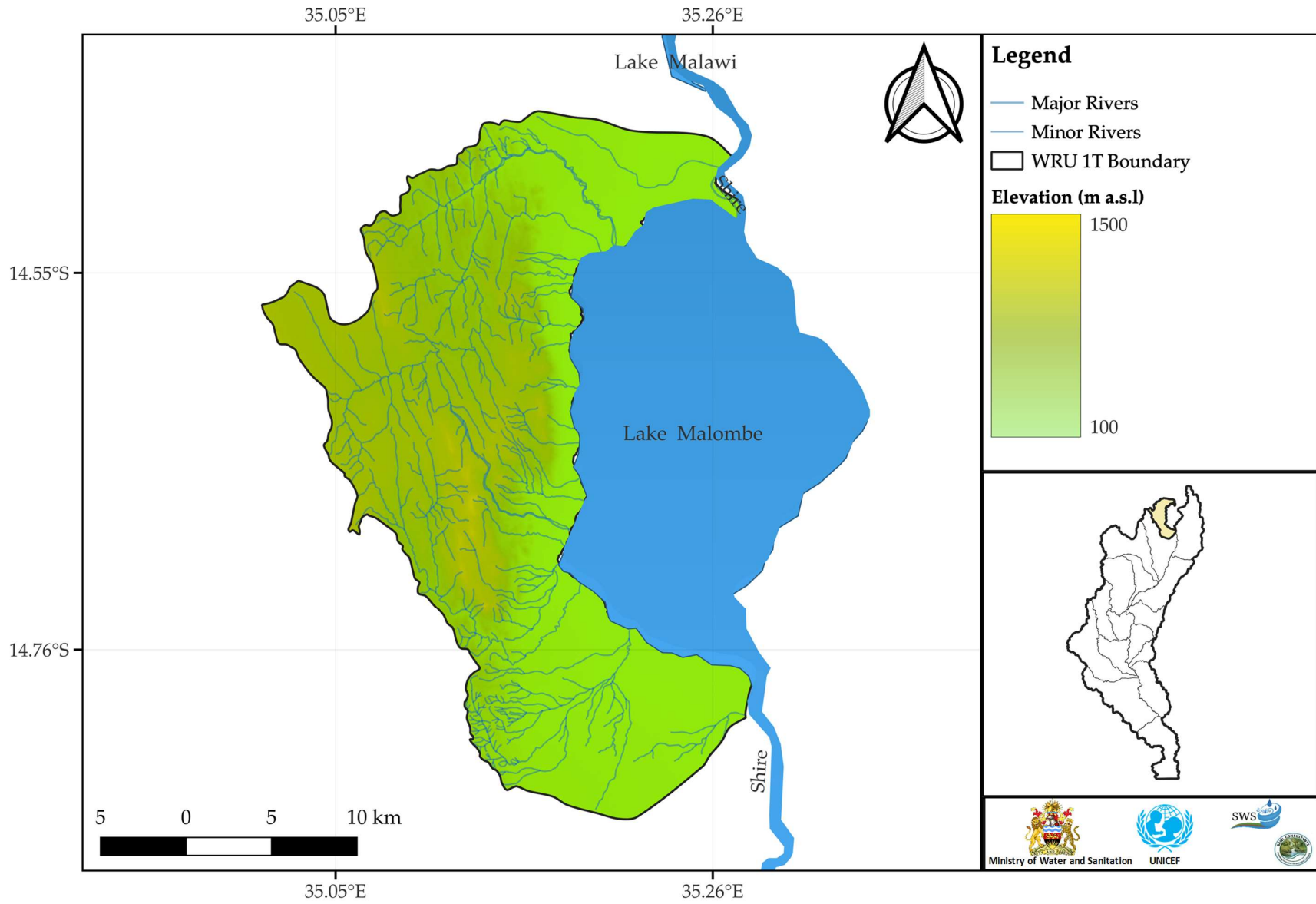


Figure WRU 1T.3 Hydrogeology Units and Water Table

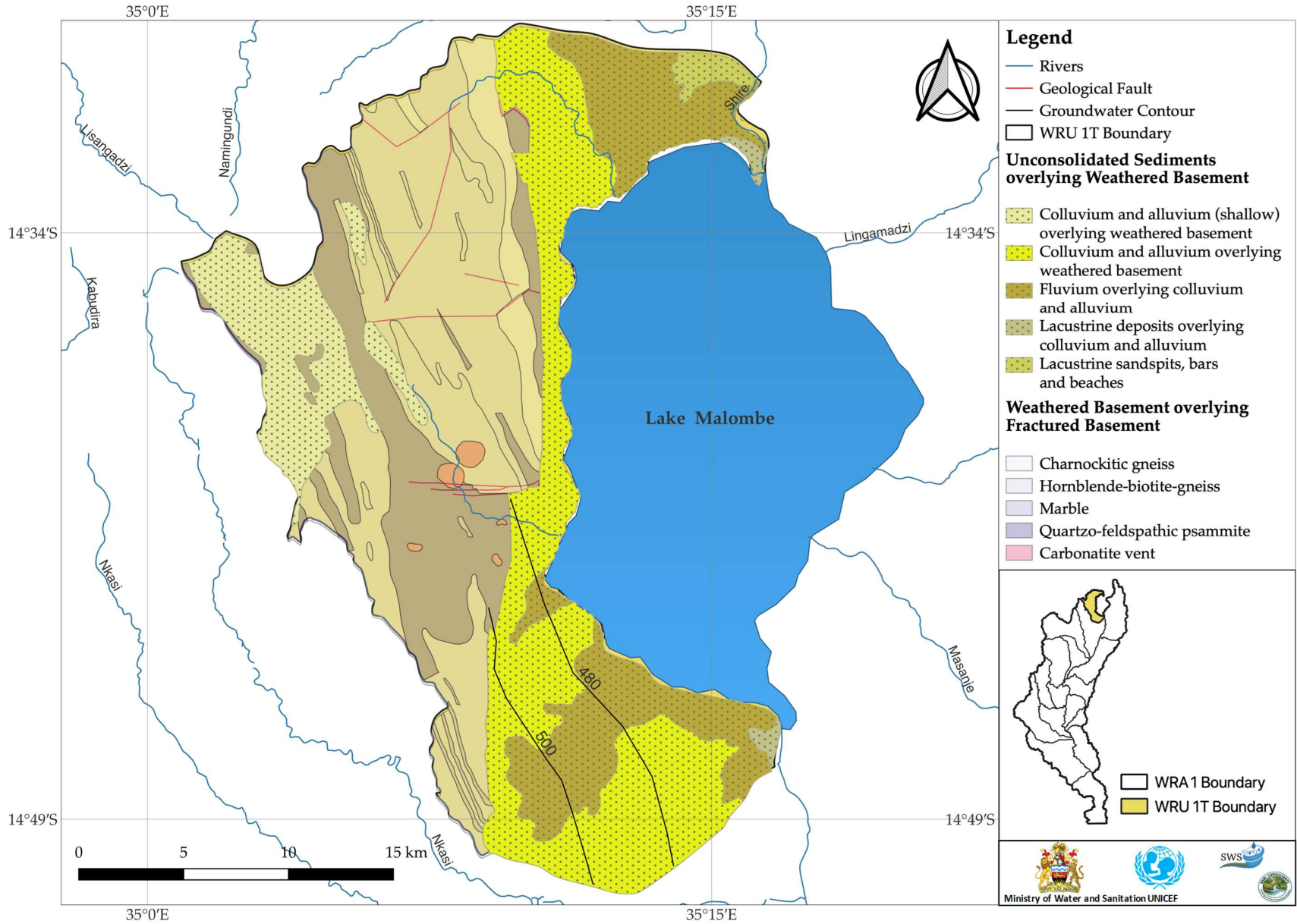


Figure WRU 1T.4 Groundwater Chemistry Distribution of Electrical Conductivity

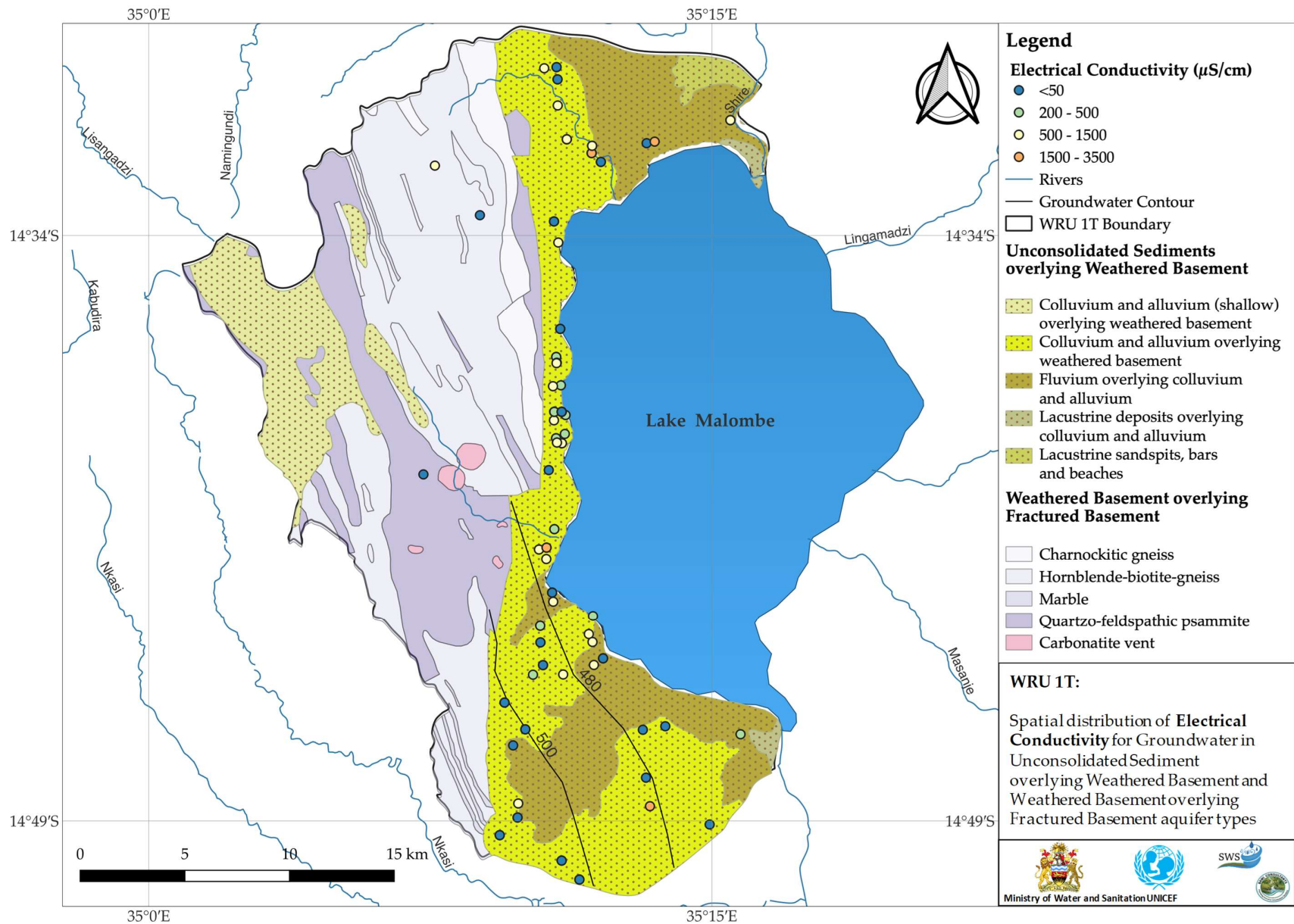


Figure WRU 1T.5 Groundwater Chemistry Distribution of Sulphate

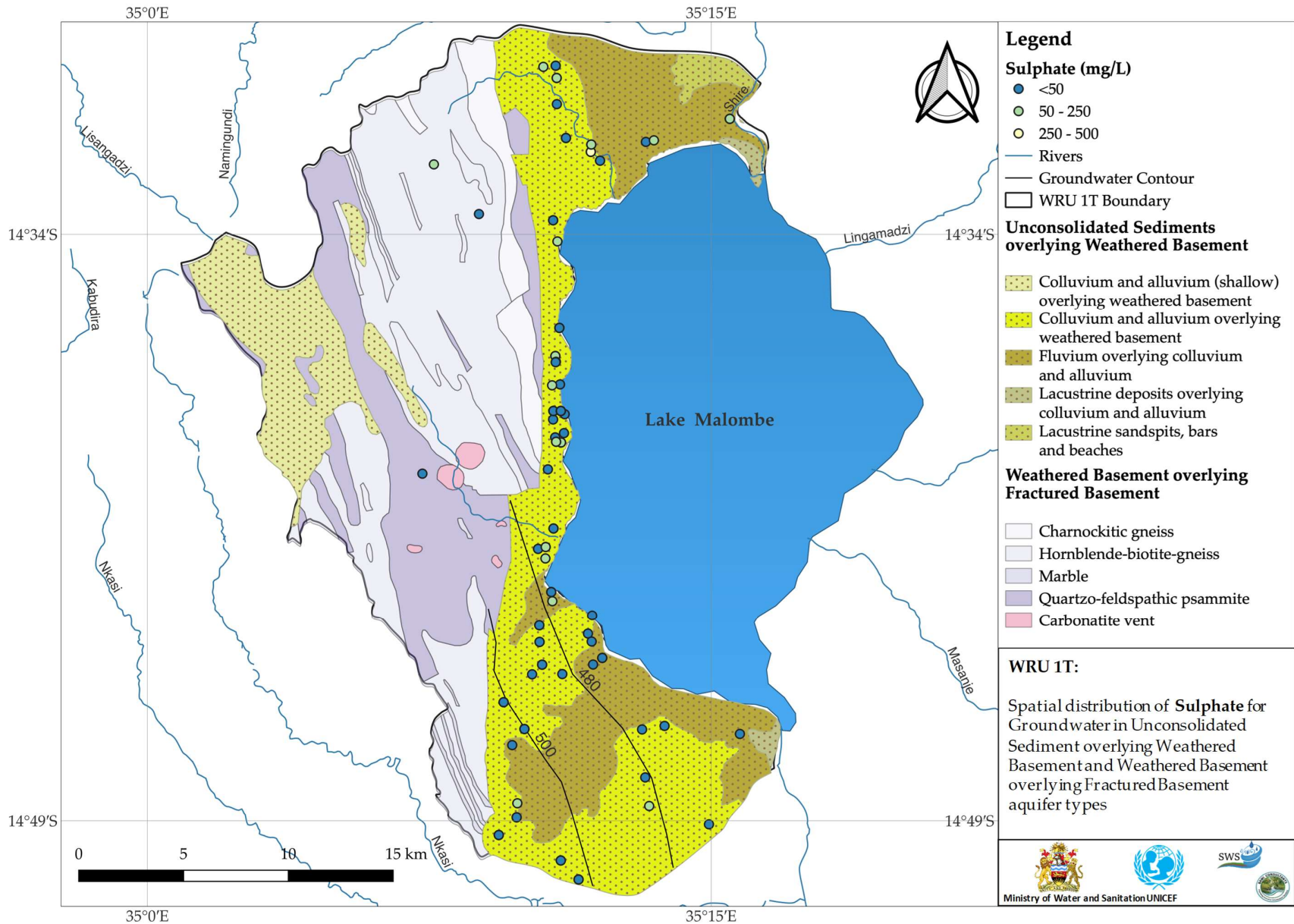


Figure WRU 1T.6 Groundwater Chemistry Distribution Chloride

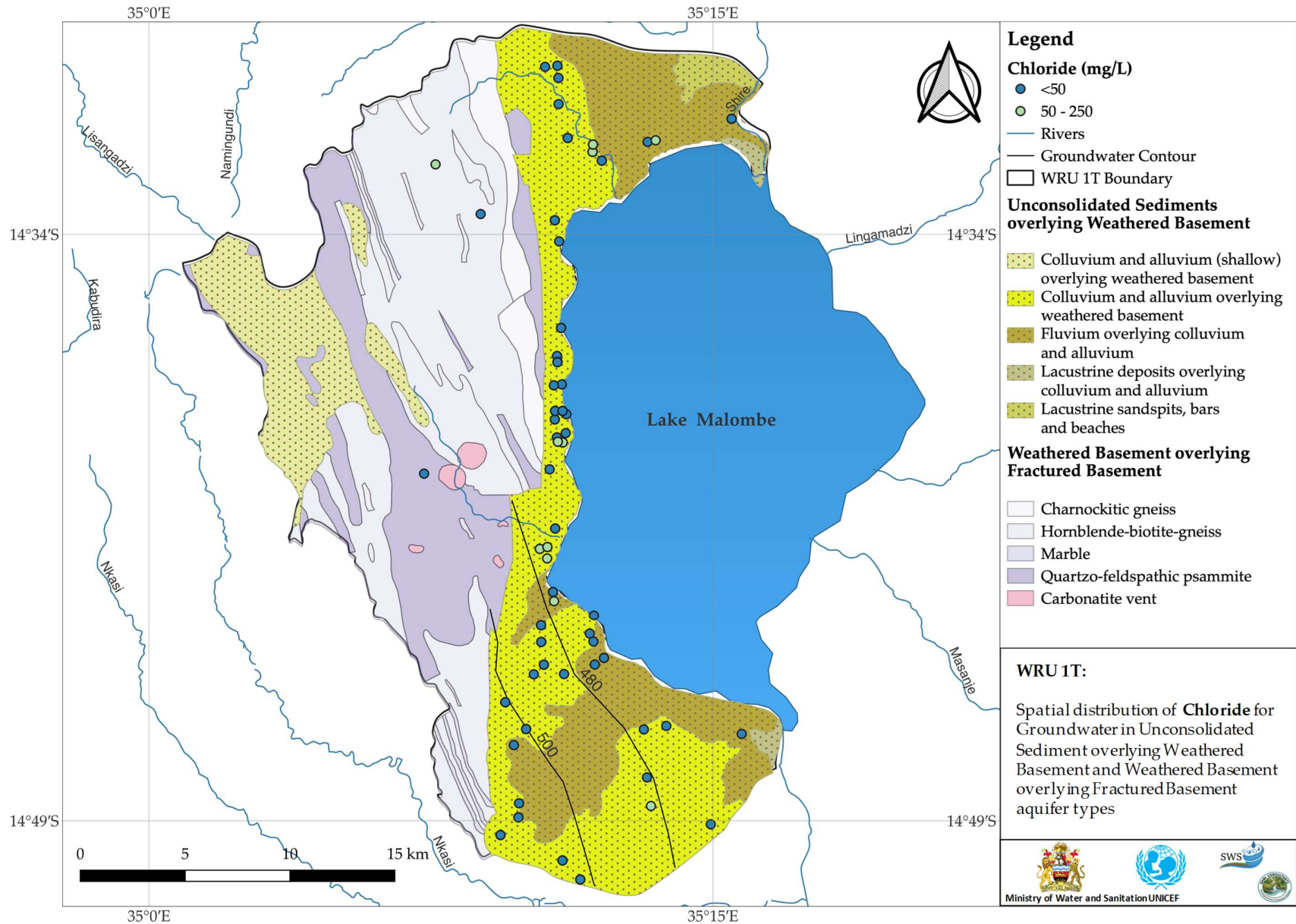


Figure WRU 1T.7 Groundwater Chemistry Distribution Sodium

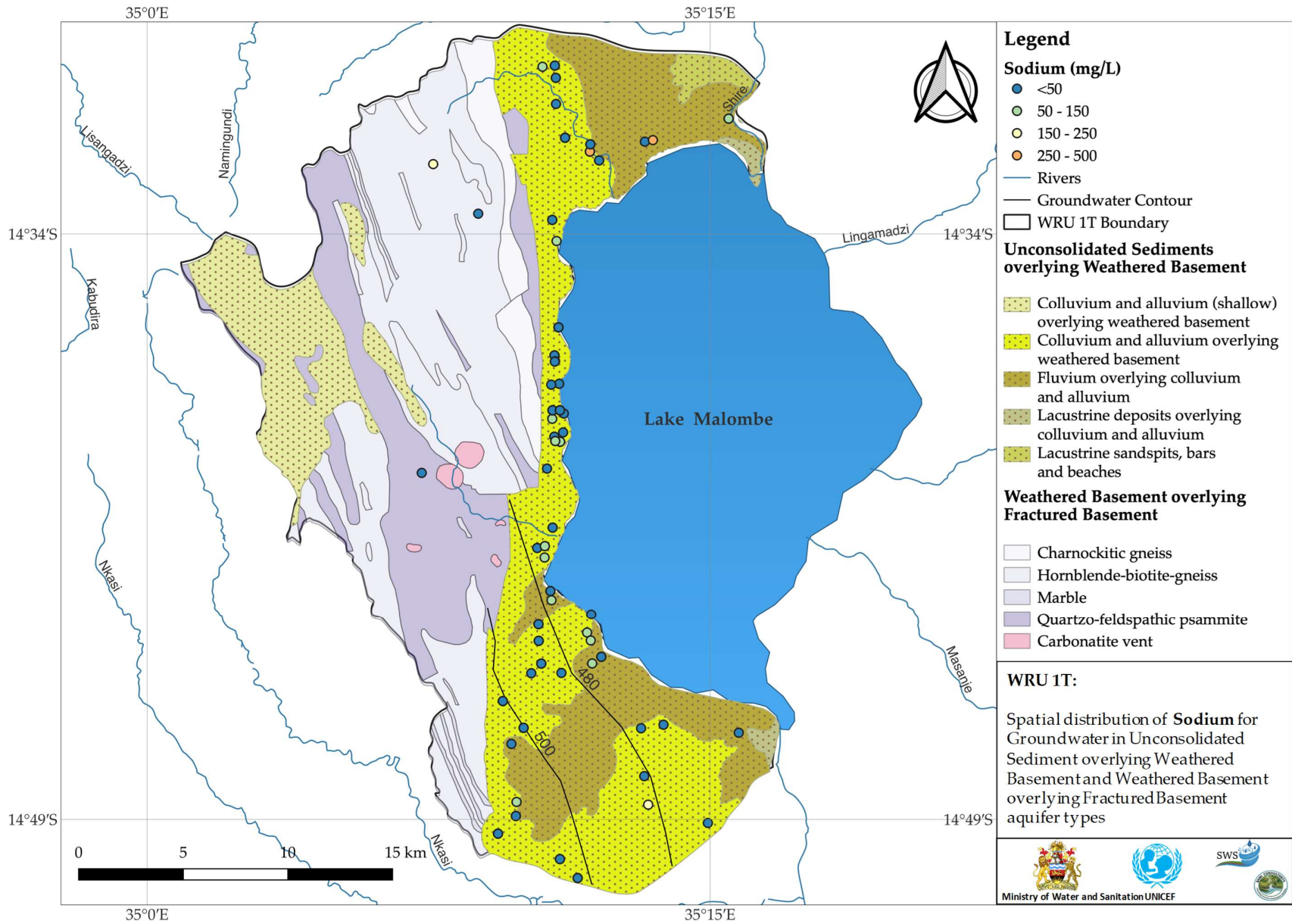


Figure WRU 1T.8 Groundwater Chemistry Distribution Calcium

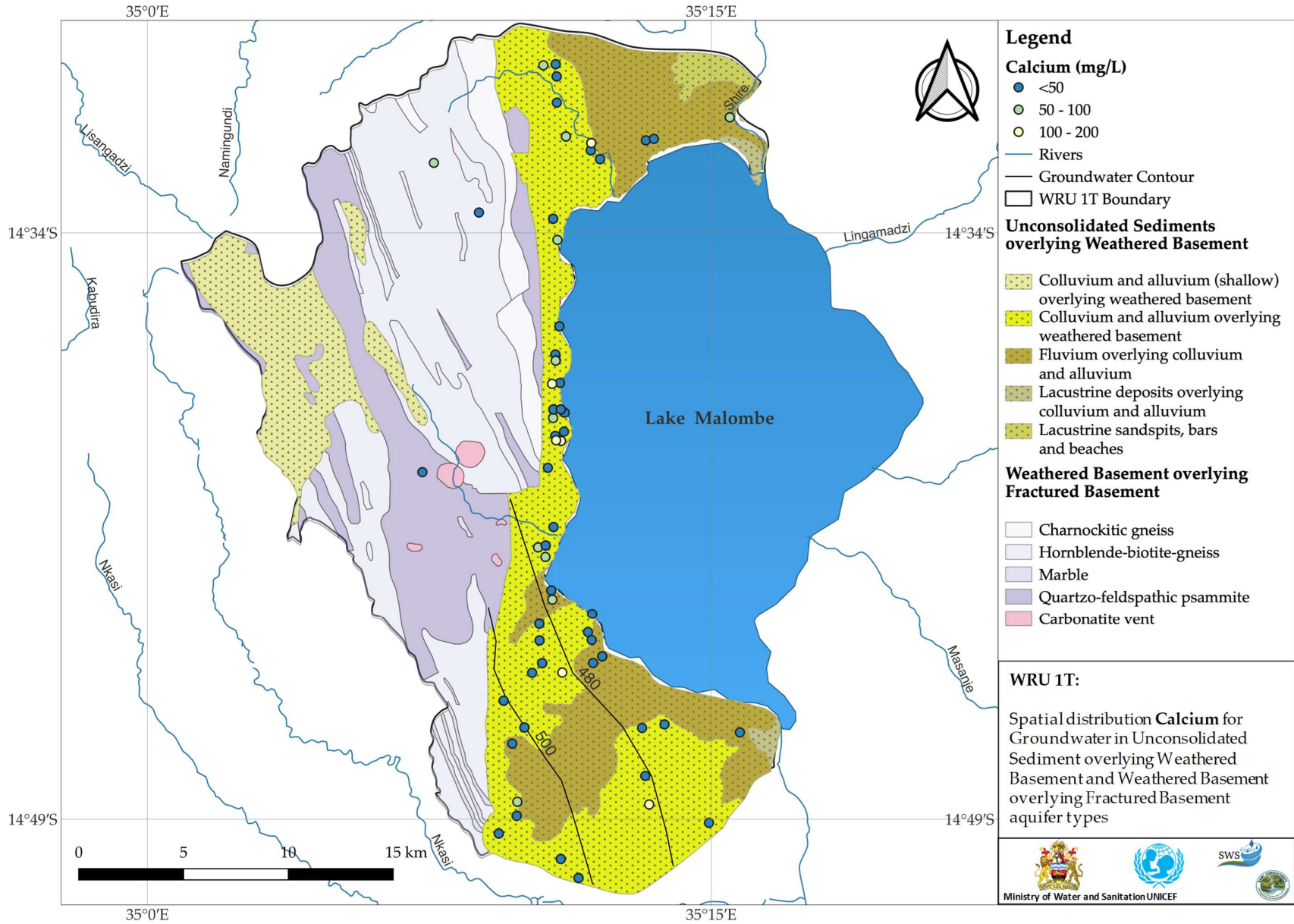
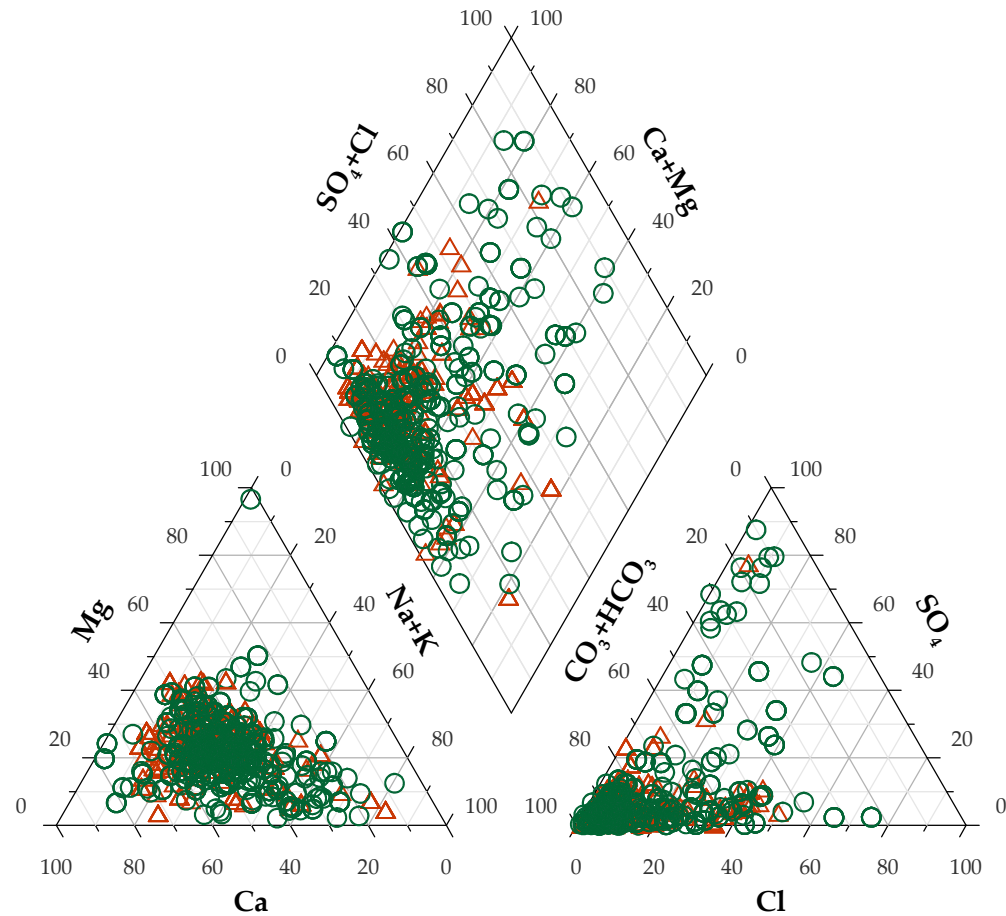


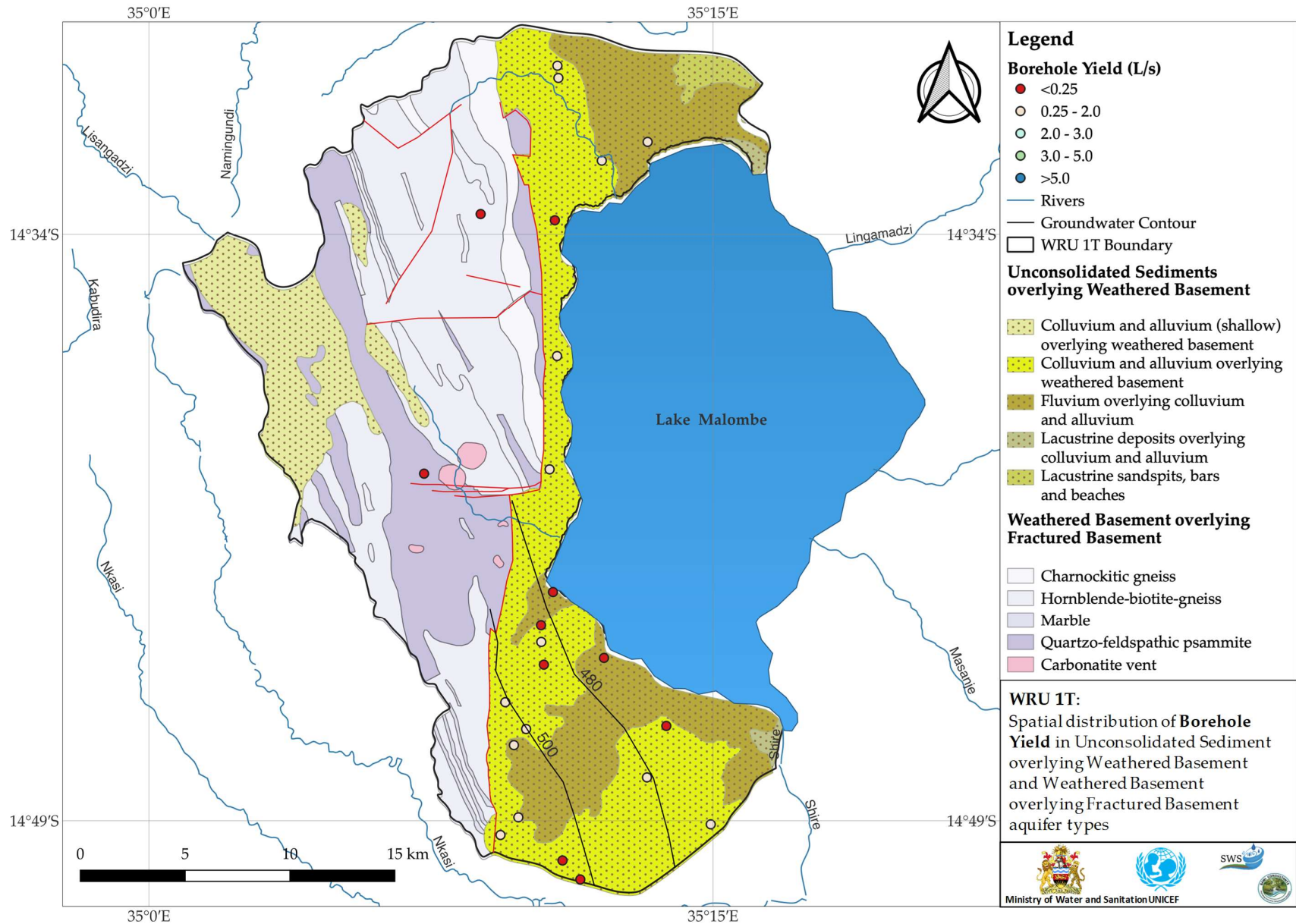
Figure WRU 1T.9 Piper Diagram of water quality results with respect to the major aquifer type



Aquifer Groups (WRU 1T)

- △ Weathered Basement overlying Fractured Basement
- Unconsolidated Sediments overlying Weathered Basement

Figure WRU 1T.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., Mambul, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A. (2022) Hydrogeology and Groundwater Quality Atlas of Malawi Water Resource Area 1 Upper Shire Catchment, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-01-7 129pp

