Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 1

The Lower Shire 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
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	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 1 Lower 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 the weathered basement aquifer), except where basement rock forms steep topographical highs (mountains/plutons/rift escarpments). Groundwater flow regimes are highly variable in fractured basement aquifers as there is no primary porosity and secondary porosity is dominant. Weathered basement aquifers behave similarly to unconsolidated sediments hydrogeologically, but generally possess lower hydraulic conductivities and storage except locally where highly fractured and weathered. Weathered basement aquifers are generally hydraulically connected to the underlying fractured zones. The weathered zone can provide significant groundwater storage and often recharge the underlying fractured bedrock.

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

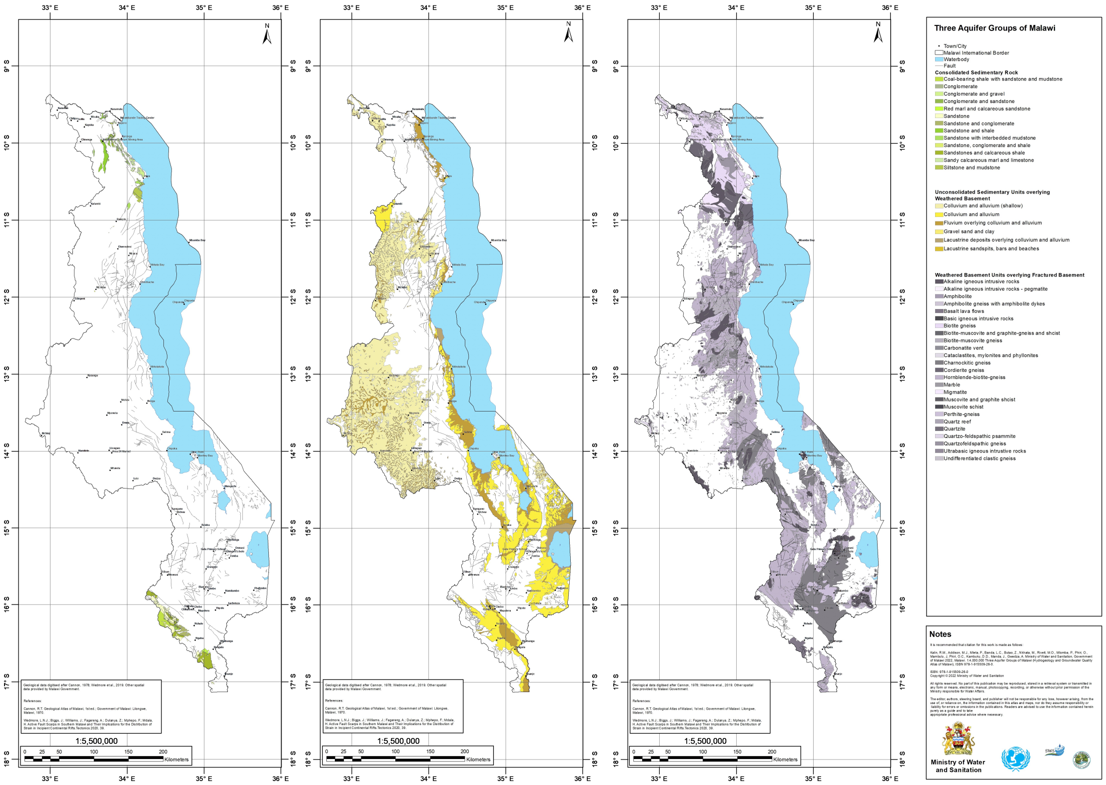

Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure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

Nomenclature: Hydrogeology of Malawi

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

Weathered Basement overlying Fractured Basement

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

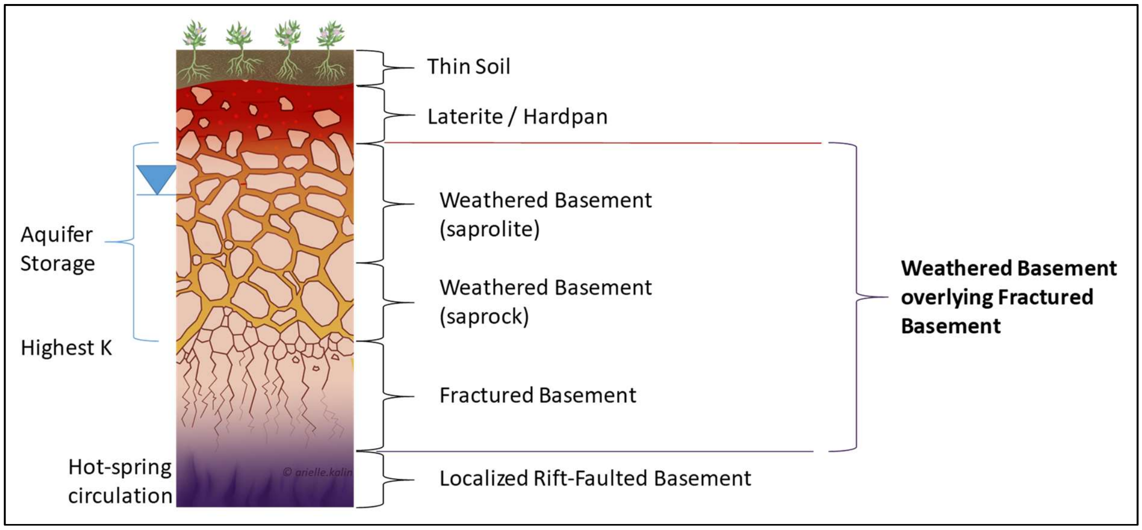

Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

Unconsolidated Colluvial and Alluvial Sedimentary Units overlying Weathered Basement

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

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

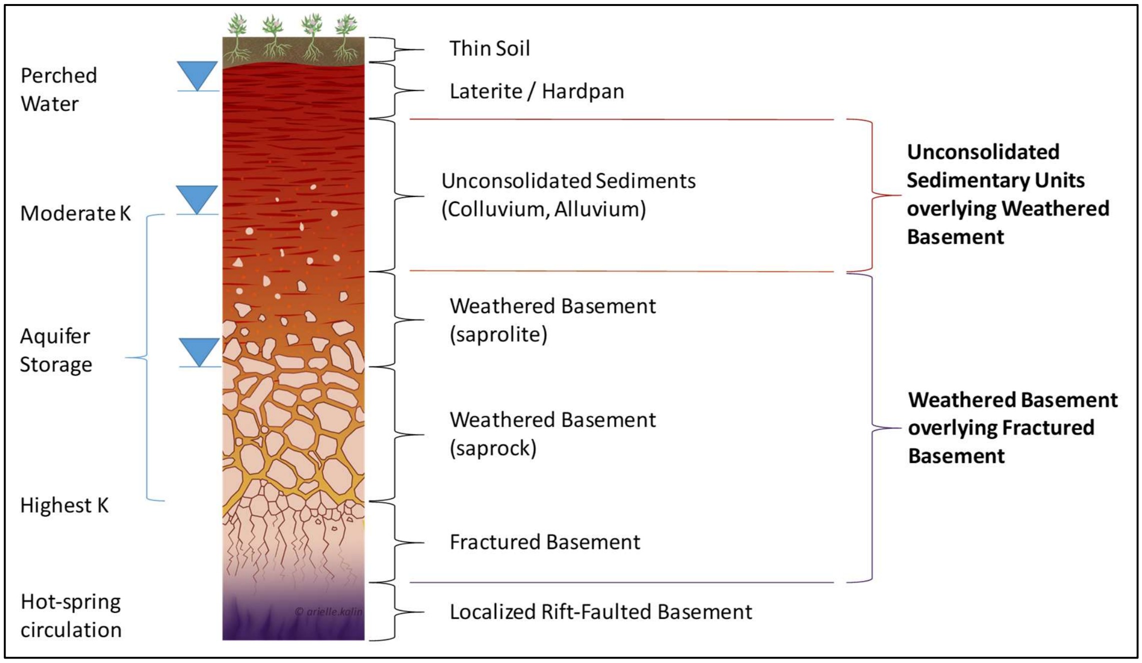

Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Unconsolidated Fluvial Sedimentary Units overlying Weathered Basement

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

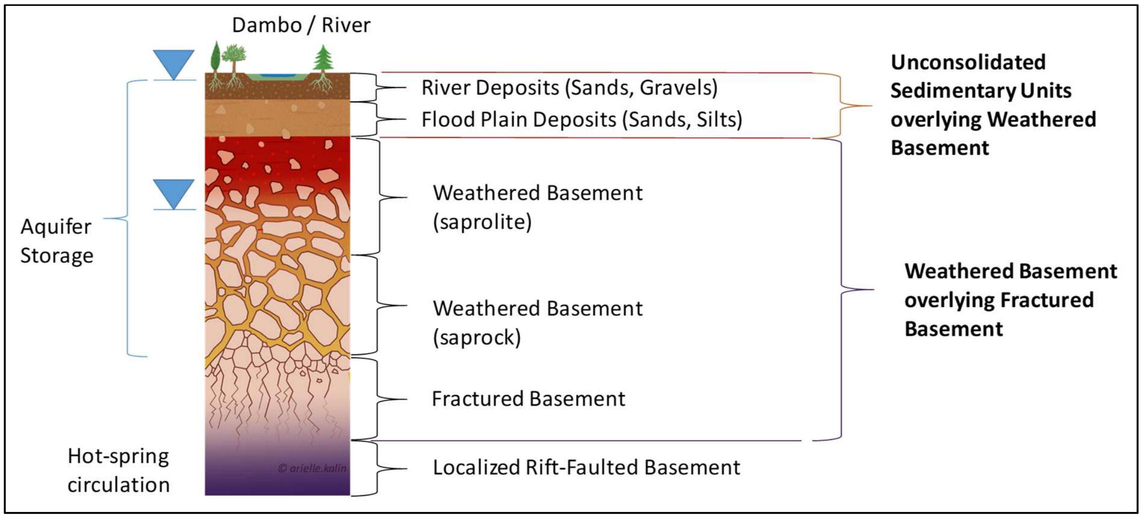

Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Idealised Cross Sectional Representation of Hydrostratigraphic Units (Aquifers)

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

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

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

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

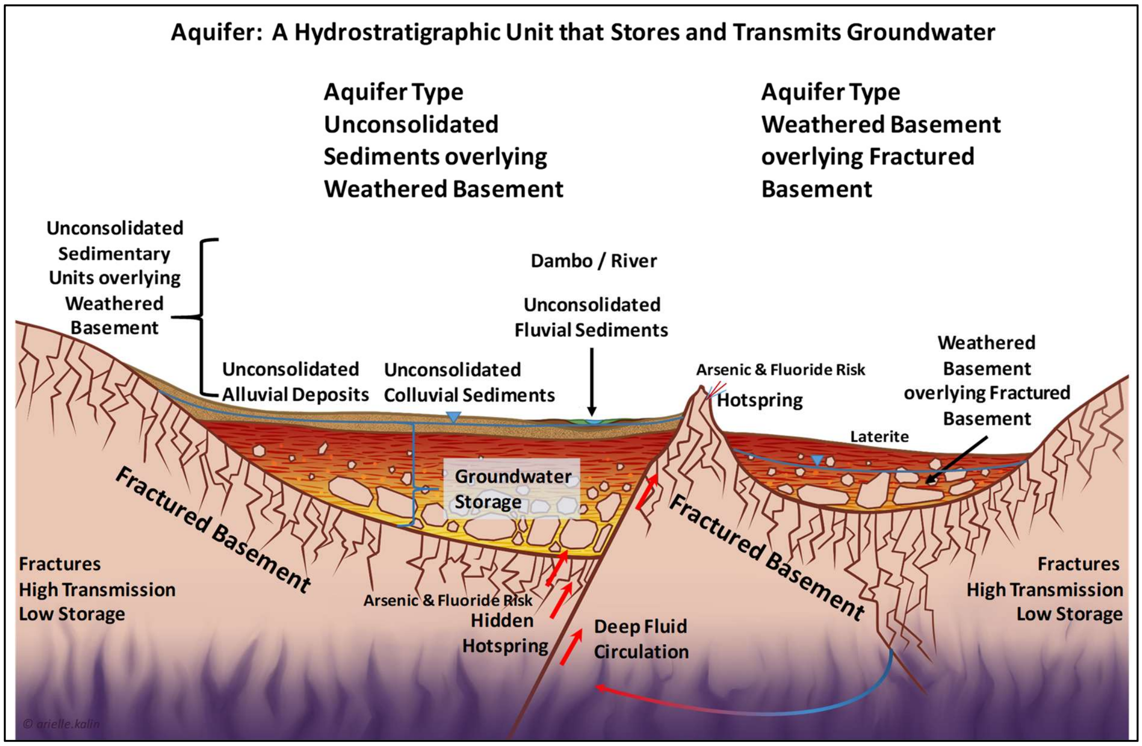

Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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

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

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

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

Water Resource Area (WRA) 1 (**Figure 2a**) in southern Malawi is the largest WRA in Malawi covering an area of over 18,911 Km^2. 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 Km^2 which, for spatial data interpretation, has been subdivided in the Hydrogeologic and Groundwater Quality Atlas into the Lower Shire and the Upper Shire. The Upper Shire Basin (**Figure 2b**) includes Water Resources Units (WRU) 1A, 1B, 1O, 1P, 1R, 1S and 1T, covering an area of 8,922 Km^2. The Lower Shire Basin includes WRU 1C, 1D, 1E, 1F, 1G, 1H, 1K, 1L, 1M and 1N, covering an area of 9,989 Km^2. 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.

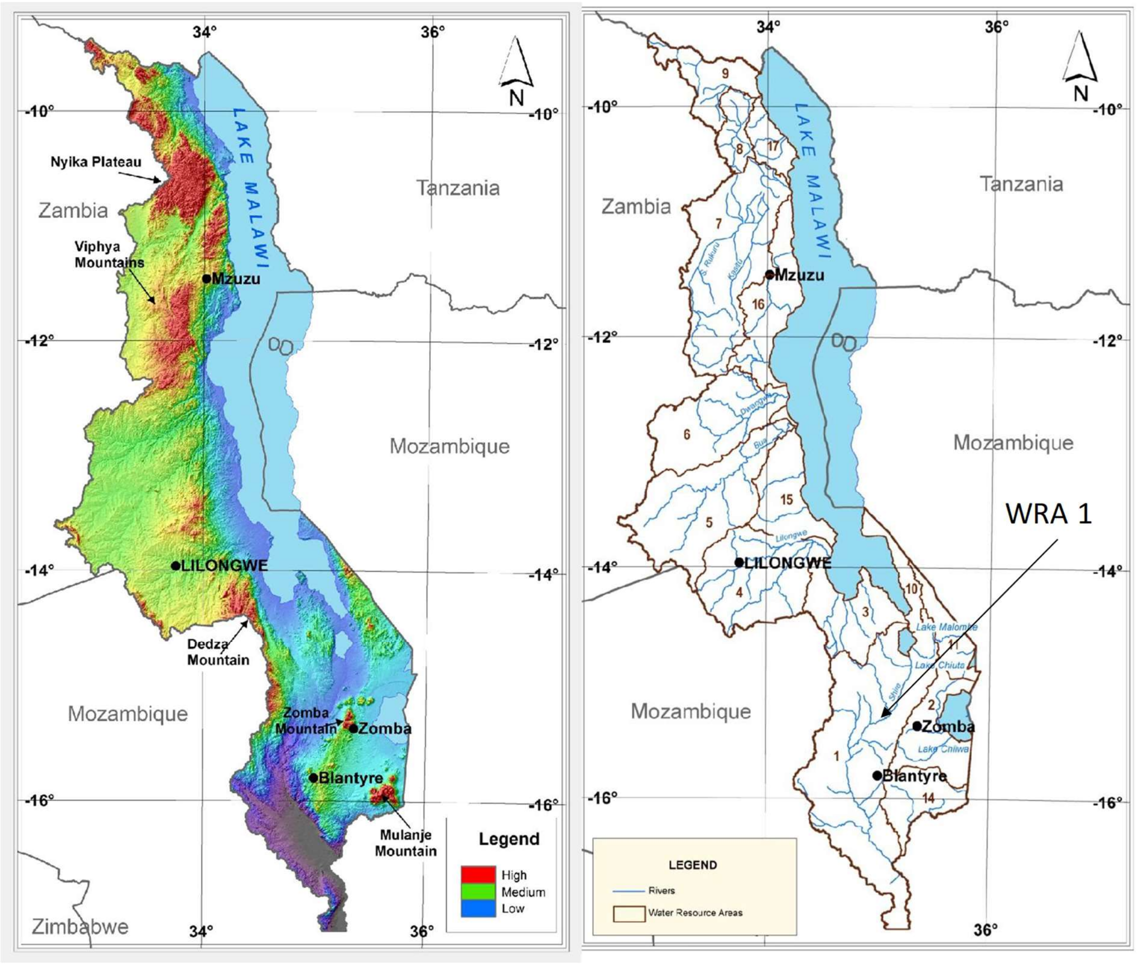

Figure 2a. Location of WRA 1with major rivers and topography shown.

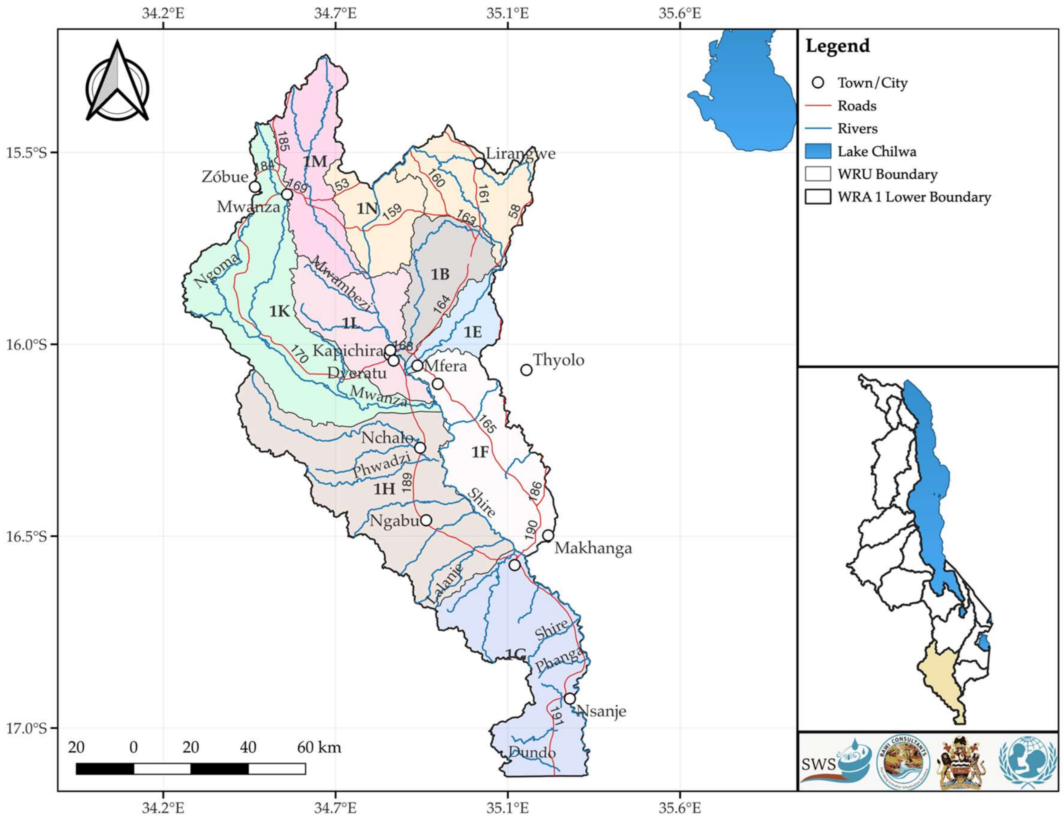

Figure 2b. Water Resource Area 1 Lower Shire with associated Water Resource Units

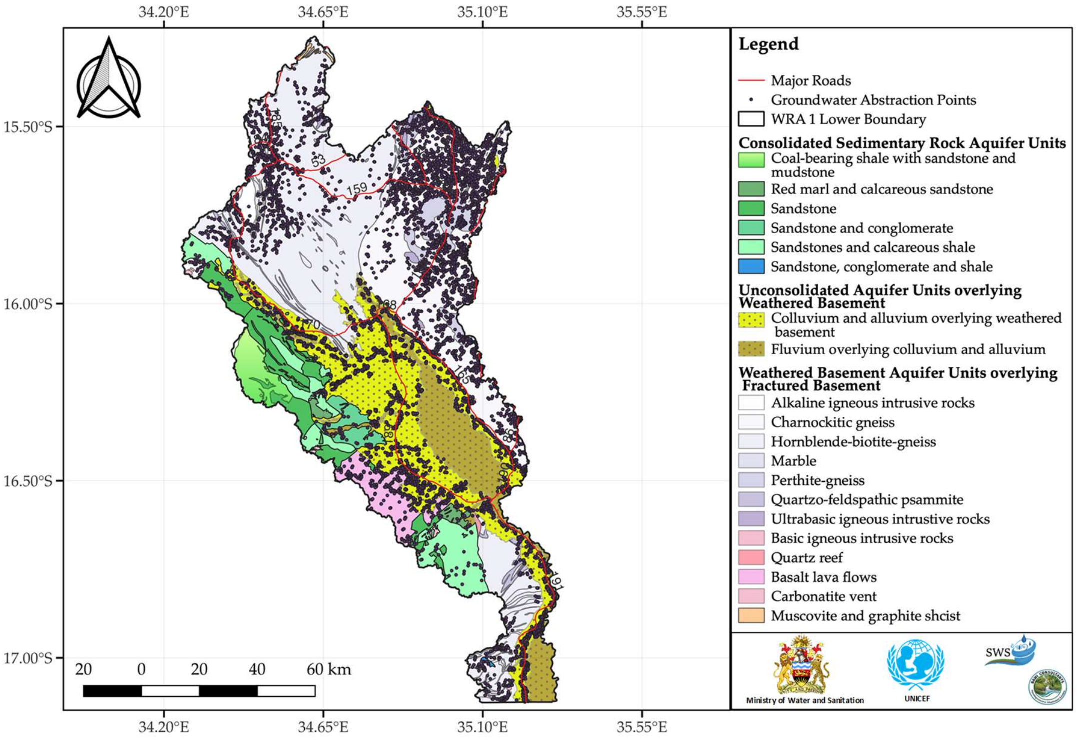

Figure 3. Distribution of groundwater abstraction points in the Lower Shire section of WRA 1.

Groundwater Abstraction in WRA 1 Lower Shire

Public abstraction points for groundwater are numerous in WRA 1 Lower Shire (**Figure 3, Table 2**) and it should be noted there are likely unaudited private groundwater abstraction points. Of the 11,139 known groundwater abstraction points in the Lower Shire, 85.9% are improved sources (with 605 being protected dug wells and 1,161 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 Lower Shire, only 56.7% are fully functional (defined as providing water at design specification).

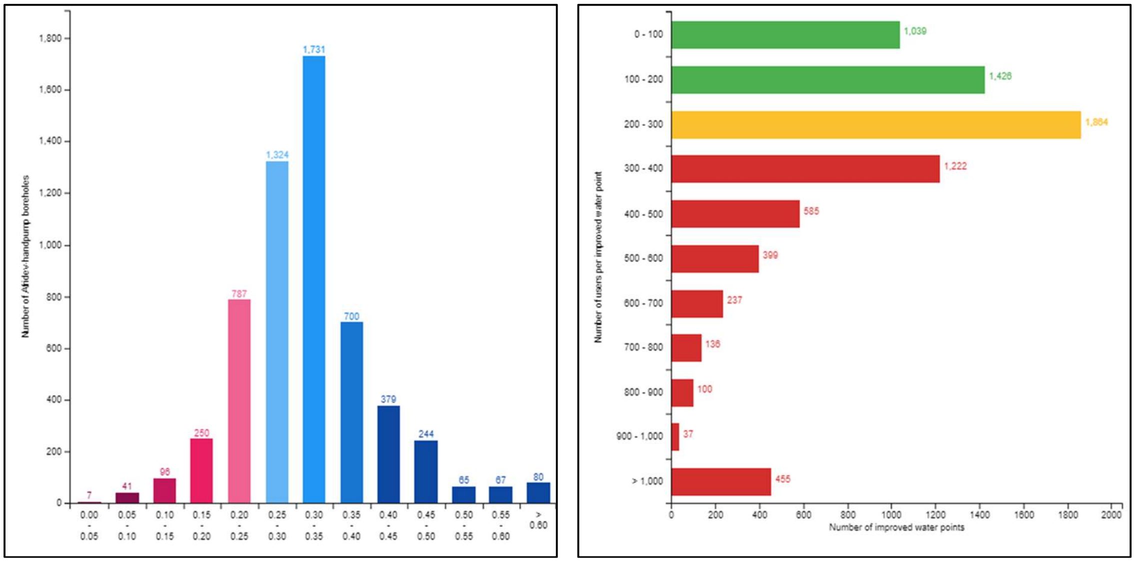

Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 1 Lower Shire (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction 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 1from 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, 9% of groundwater abstraction points do not provide sufficient water (September through November) most likely due to water table declines (**Figure 5a and 5b**). Shallow boreholes and dug wells (protected and unprotected) are the most heavily impacted, impacting the functionality of these water supplies. There is a strong correlation between the depth of the groundwater water supplies and the decline in seasonal water availability, and is assumed this is due to shallow dug well supplies or improperly installed boreholes that are more at risk to lowering water tables resulting in lower functionality during the dry season.

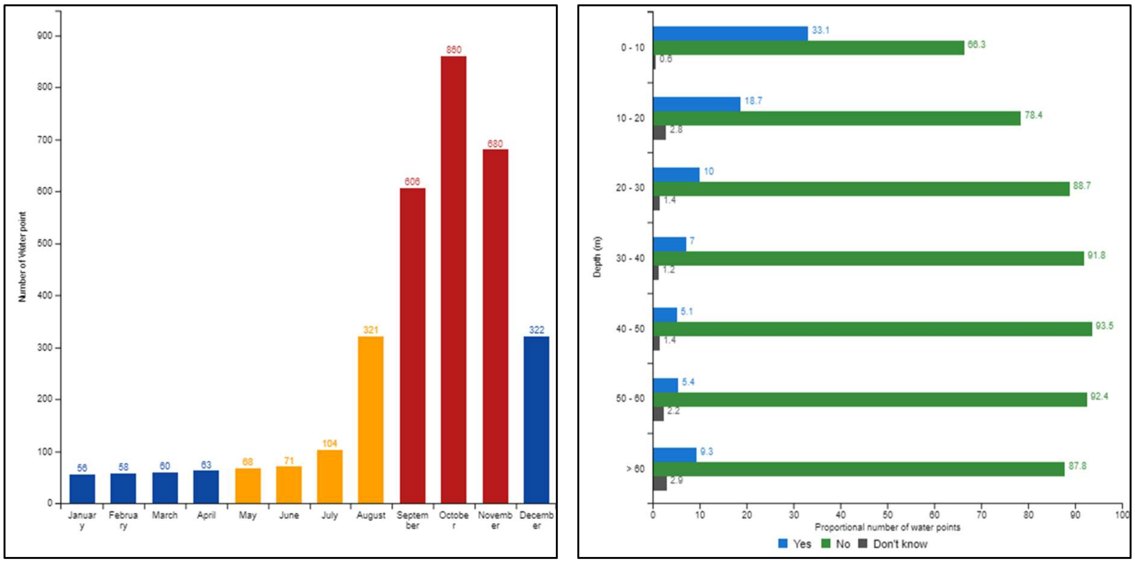

Figure 5a and 5b. Number of groundwater abstraction points in WRA 1 Lower Shire that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes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

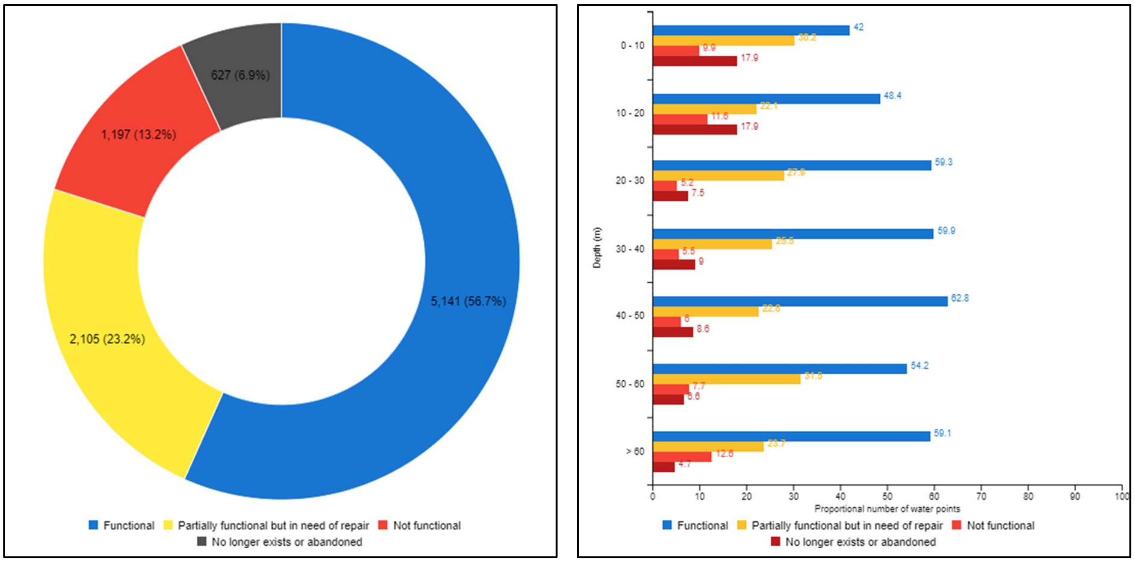

Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 1 Lower Shire [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020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

The operational status of groundwater abstraction points in WRA 1 Lower Shire is also linked to issues of infrastructure (e.g. pump / borehole) as well as aquifer stress. There are only 56.7% 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 Lower Shire WRA 1 Lower Shire [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	8,931
Protected dug well	605
Protected spring	34
Unprotected dug well	1,161
Unprotected spring	408

Description of Water Resources WRA 1 Lower 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 Km^2. 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 Rivi Rivers. WRA has been subdivided in the Hydrogeologic and Groundwater Quality Atlas into the Upper Shire and the Lower Shire. The Lower Shire Basin includes WRU 1C, 1D, 1E, 1F, 1G, 1H, 1K, 1L, 1M and 1N (**Figure 7a – 7j**) covering an area of 9,989 Km^2. 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 Lower 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.

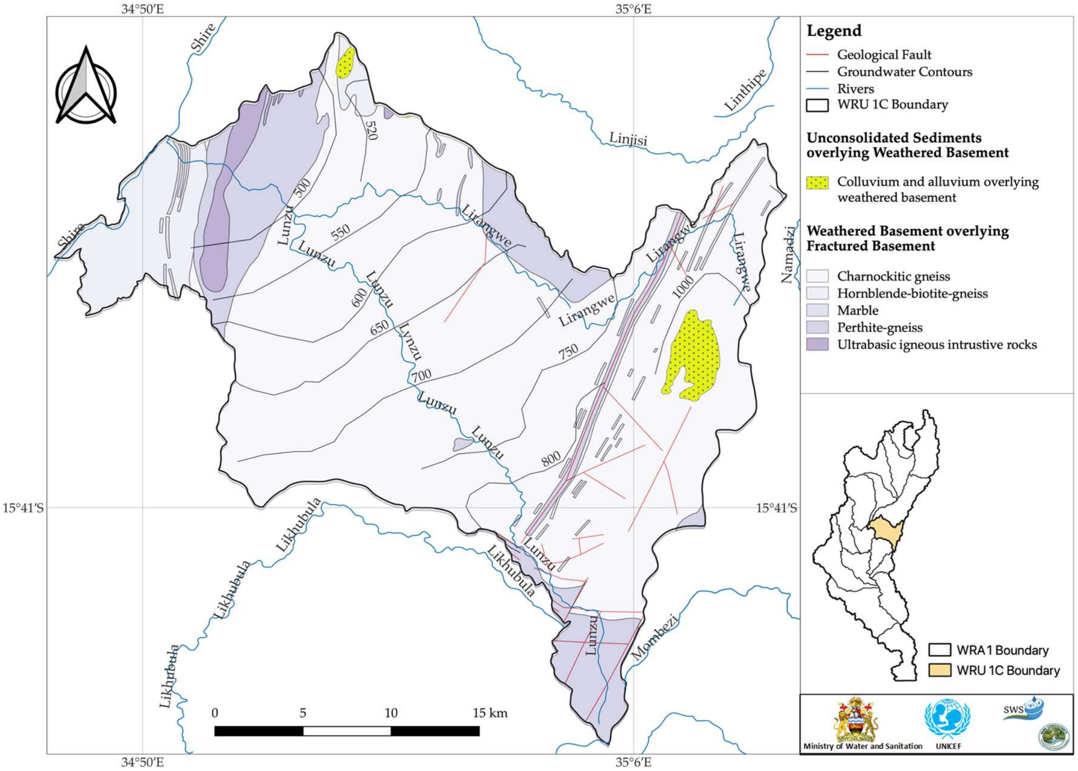

Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 1C wtihin Water Resource Area 1 (Lower Shire Catchment).

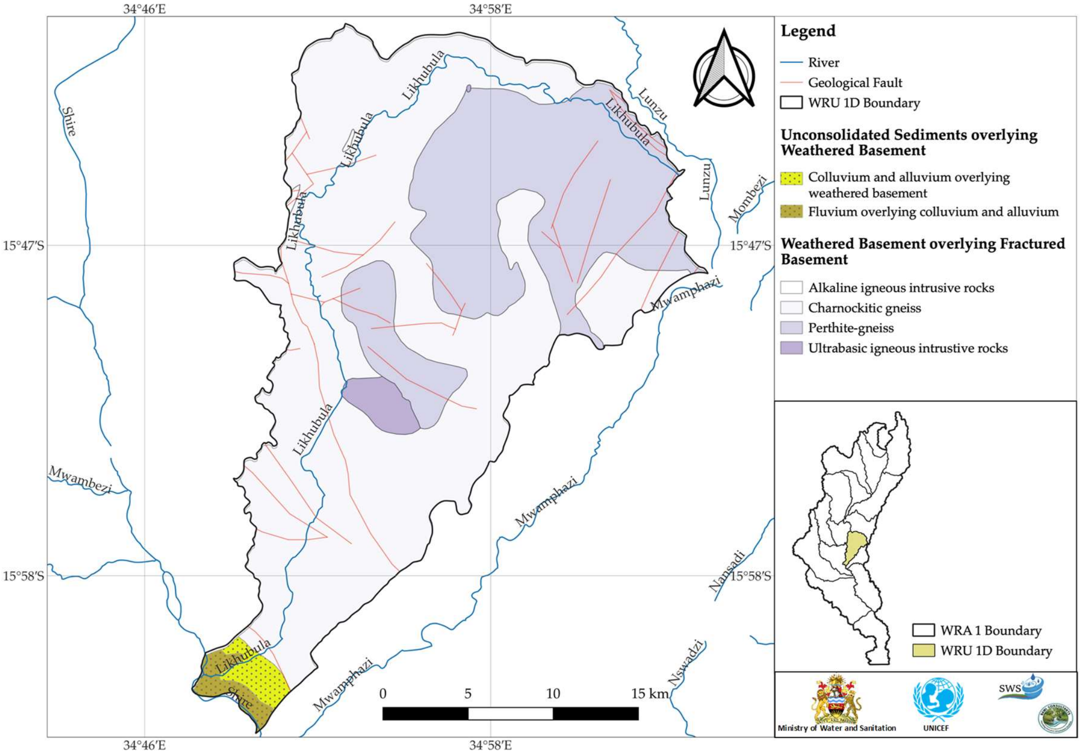

Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 1D wtihin Water Resource Area 1 (Lower Shire Catchment).

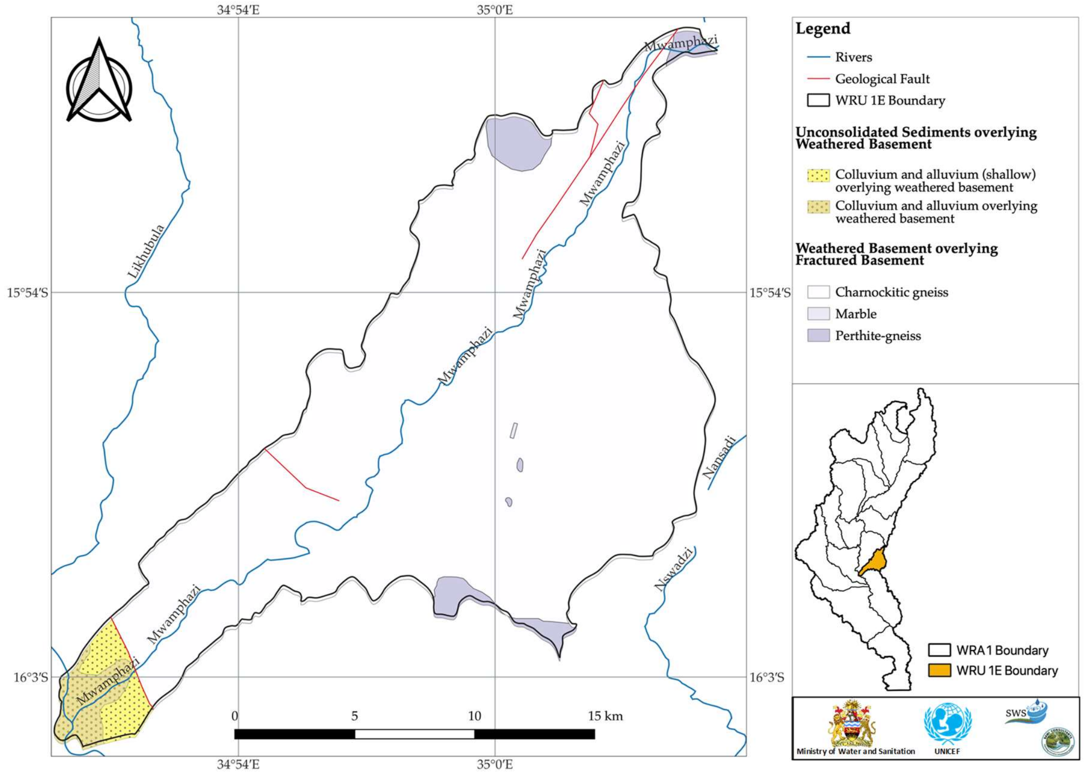

Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 1E wtihin Water Resource Area 1 (Lower Shire Catchment).

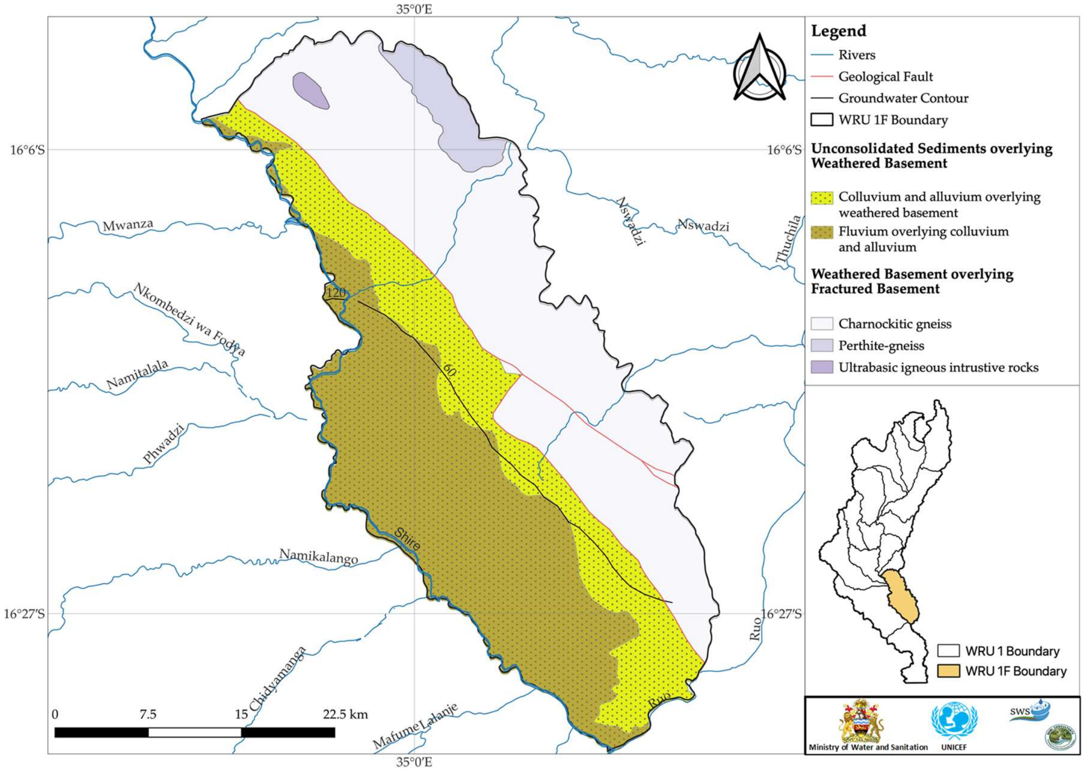

Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 1F wtihin Water Resource Area 1 (Lower Shire Catchment).

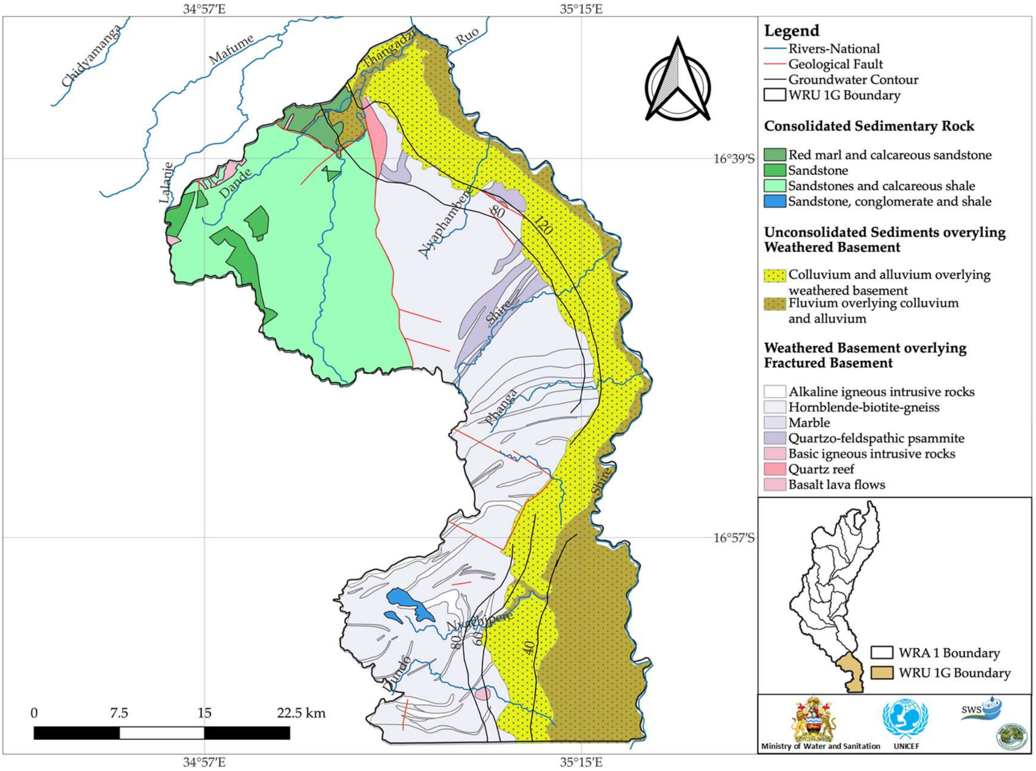

Figure 7e. Map showing the hydrogeologic units and water table for Water Resource Unit 1G wtihin Water Resource Area 1 (Lower Shire Catchment).

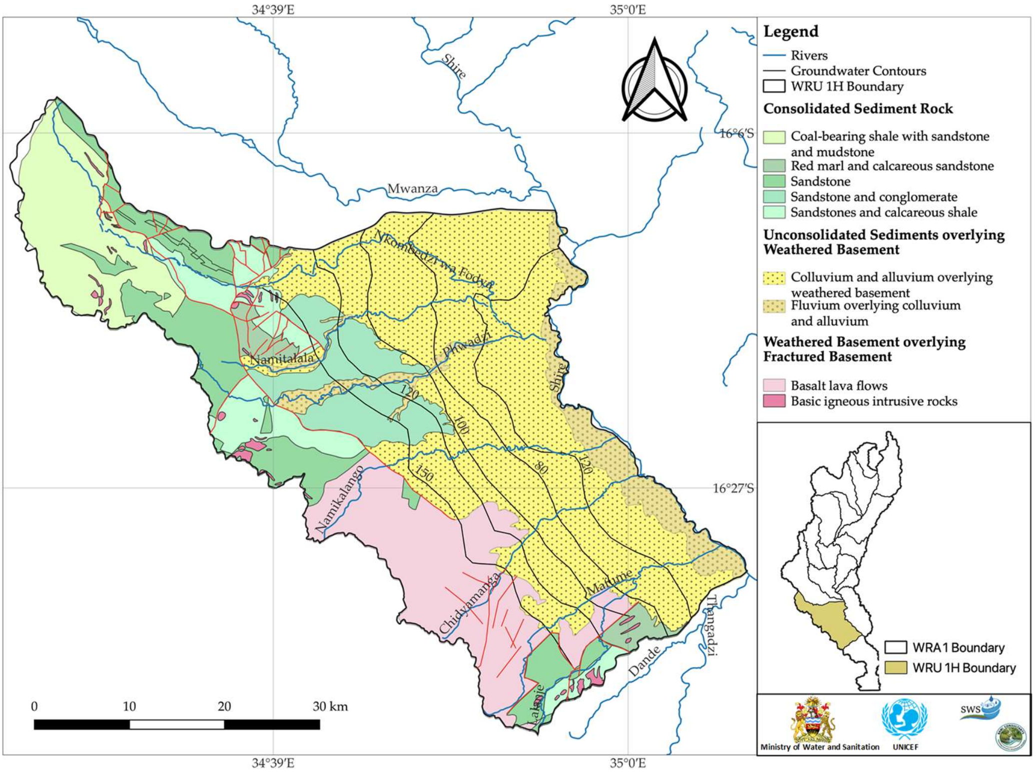

Figure 7f. Map showing the hydrogeologic units and water table for Water Resource Unit 1H wtihin Water Resource Area 1 (Lower Shire Catchment).

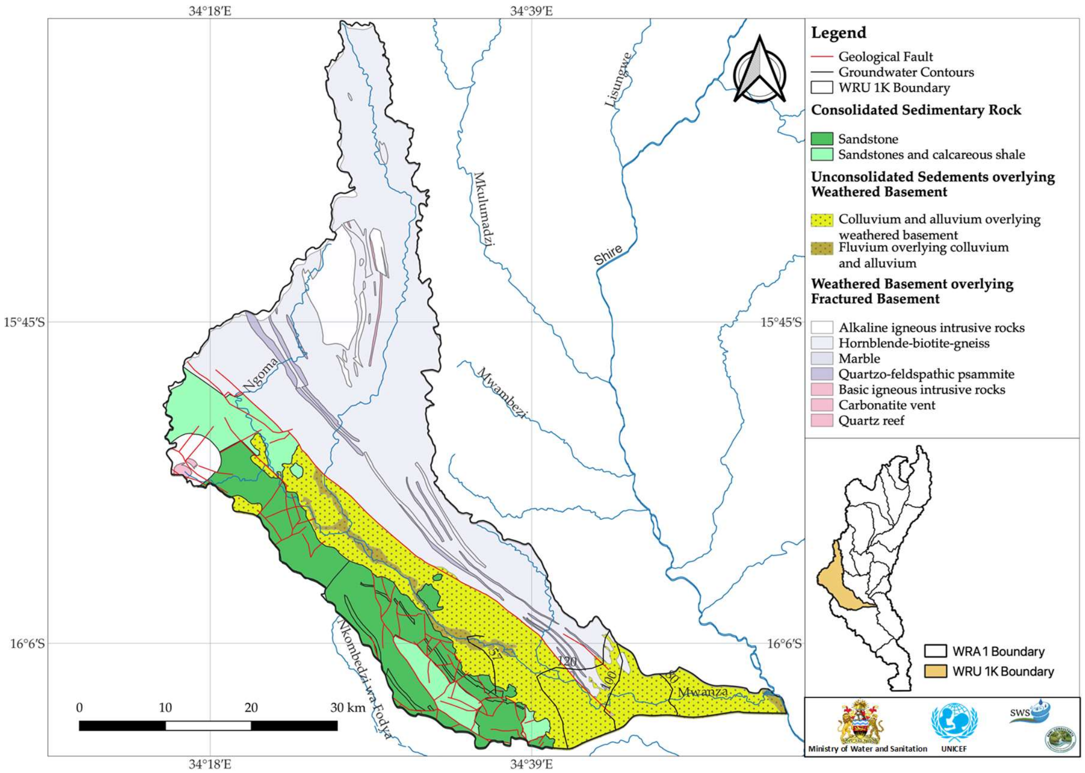

Figure 7g. Map showing the hydrogeologic units and water table for Water Resource Unit 1K wtihin Water Resource Area 1 (Lower Shire Catchment).

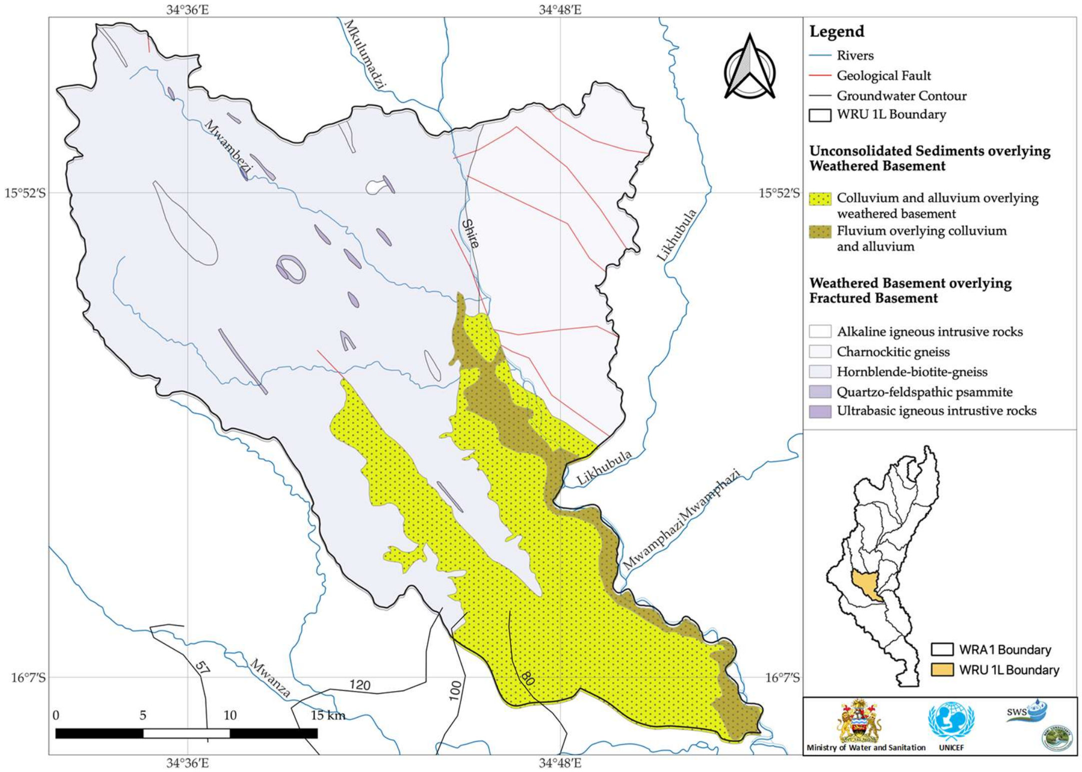

Figure 7h. Map showing the hydrogeologic units and water table for Water Resource Unit 1L wtihin Water Resource Area 1 (Lower Shire Catchment)

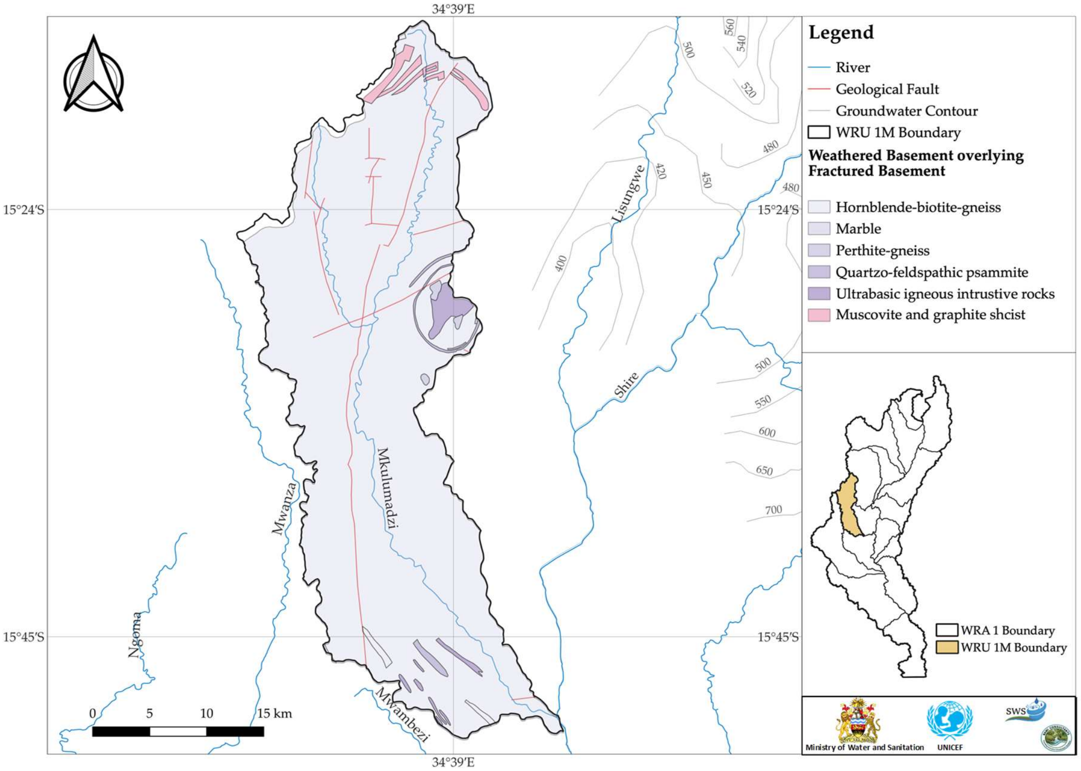

Figure 7i. Map showing the hydrogeologic units and water table for Water Resource Unit 1M wtihin Water Resource Area 1 (Lower Shire Catchment)

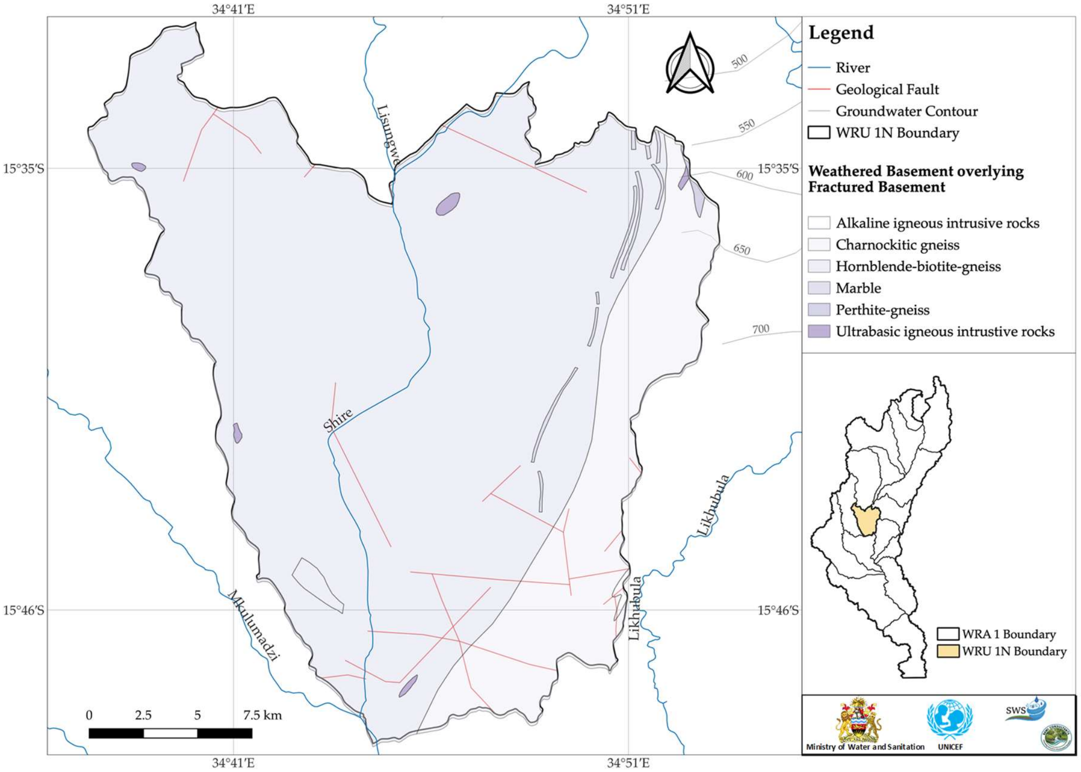

Figure 7j. Map showing the hydrogeologic units and water table for Water Resource Unit 1N wtihin Water Resource Area 1 (Lower Shire Catchment)

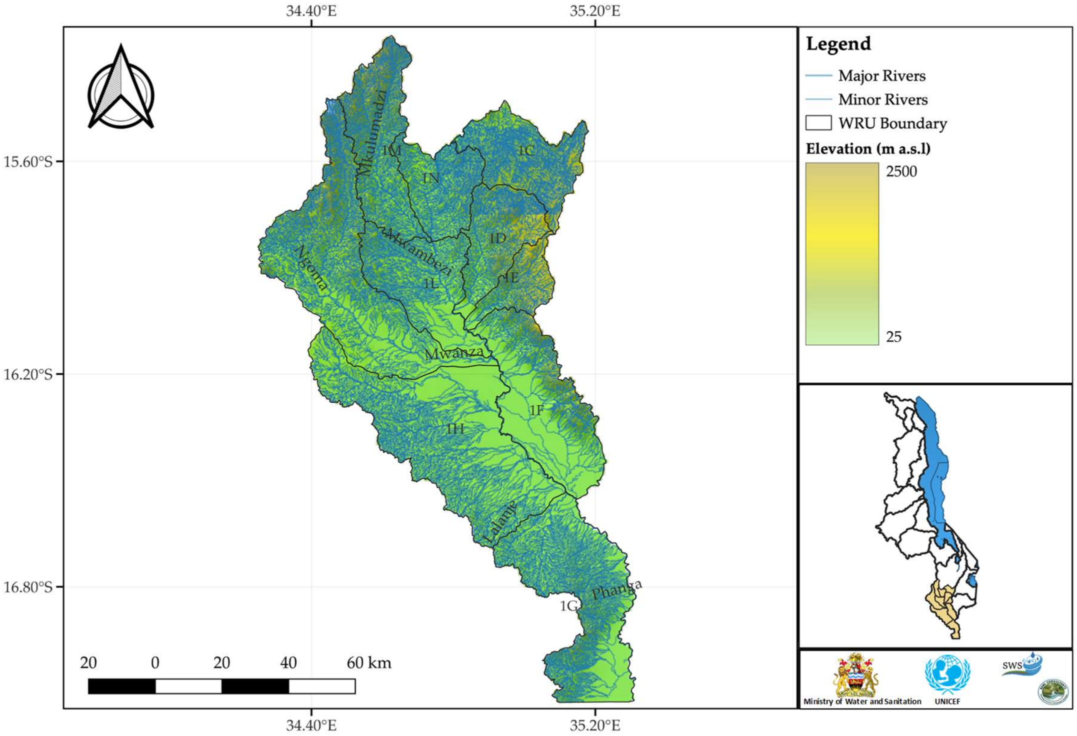

Figure 8. Drainage for the major rivers in the Lower Shire Water Resources Area 1.

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 Lower 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 Lower Shire WRA 1 are shown in **Figure 8**.

Geology – Solid

The lower section of WRA 1 is dominated by the Malawi Rift Valley. 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 NW - SE-trending Thyolo and Mwanza Fault Scarps; a series of basin margin normal faults to the northeast of the valley. Rift-parallel faulting is extensive in those rocks. Southwest of the fault scarp is the rift basin which hosts the Shire River as it begins to flow southeast toward Mozambique. Southwest of the rift basin lies the consolidated sedimentary rock of the Karoo supergroup which do not form a rift escarpment, instead rise from the rift valley at a gentler slope than the basement rock to the north. Lithologies here include Permian to Triassic sandstones, gravels, conglomerates, marls, siltstones, carbonaceous mudstones, shales, and some coal-bearing units. Lower Jurassic basalt lava flows occur extensively to the southeast, exposed as spheroidal weathered basalt.

Geology – Unconsolidated deposits

Quaternary – Tertiary colluvium, alluvium and lacustrine basins have led to wide rift valley plains in the Lower Shire Basin. Deposits arise from erosion and mass wasting of rift escarpment Basement rock. Thicknesses varies due to the tilted, block-faulted nature of underlying Basement sequences, but may be up to 150 m where sediments have accumulated against large normal faults on the rift valley's Eastern flank. As drilling for water-supply boreholes is frequently to around 50 m depth maximum the thickness of unconsolidated deposits is invariably not proven. Due to contrasting high and low energy depositional environments, deposits are heterogeneous, spatially and with depth. Coarse-grained, poorly sorted alluvial fans form basin flank, near-escarpment, permeable deposits. In contrast, lacustrine deposits with increased low fine-grained sands, silt and clay layers may be more common in the central basin areas. Unconsolidated (Superficial) deposits extensively fill the rift Basin from weathering of surrounding highland and underlying Basement rock. A complex mix of Quaternary fluvial, alluvial, and lacustrine deposits occur from extensional rifting of the Malawi Rift and lacustrine deposition along the Shire River floodplain and the Elephant Marshes. Fluvial deposits dominate the basin centre, deposited by the Shire River. Colluvium foothills border the north-Eastern rift escarpment along the Mwanza and Thyolo fault complex incised by small streams flowing perpendicular towards the basin centre. Isolated dambo wetlands are present in the low lying terrain.

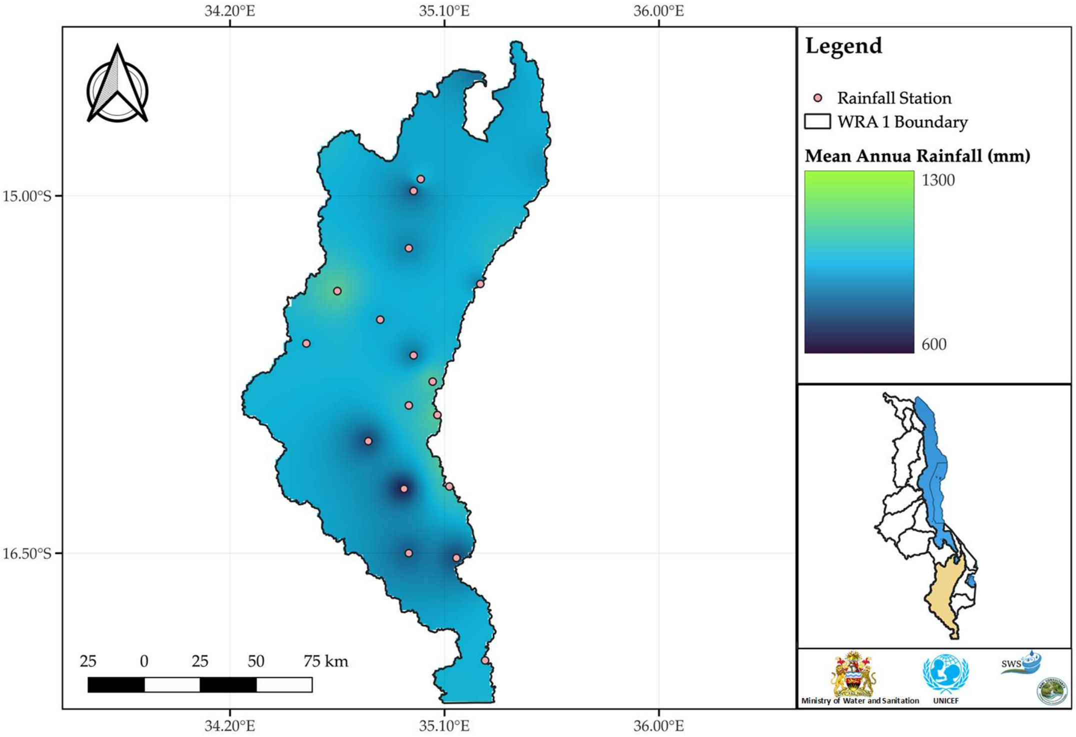

Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across both Upper Shire and Lower Shire of Water Resource Area 1 with the location of weather stations. Average rainfall measured is 924mm, average rainfall modelled is 950 +/- 59mm (range 671 to 1,139mm).

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.

Table 3. Calculated mean rainfall in each Water Resource Unit within the Lower 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	C	Chileka	842	965
	D	Chichiri/Mpemba	1,070	988
	E	Bvumbwe	1138	1,037
	F	Makhanga/Masambanjati	903	928
	G	Nsanje	981	947
	H	Nchalo/Ngabu	730	881
	K	Mwanza	979	956
	L	Chikwawa	751	907
	M	Neno	1,139	1,023
	N	- No Station -	-	1,026
	O	- No Station -	-	989
	P	Phalula/Walkers Ferry	914	920

Land use

Land use in the Lower Shire is largely dominated by rain fed cultivation and scrub 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. There is major initiative by Malawi Government of $500 million (USD) World Bank and African Development Bank Funded Shire Valley Transformation Project (SVTP) launched in the Lower SRB, which aims at diverting *c.* 5% (20–50 m3/s) of the Shire River flow into 130 km of feeder canals and drain network to provide gravity-fed irrigation of 45,000 hectares. There is a wealth of hydrologic information available through the Shire Valley Transformation Project that is not summarised here, but which should be reviewed by the reader.

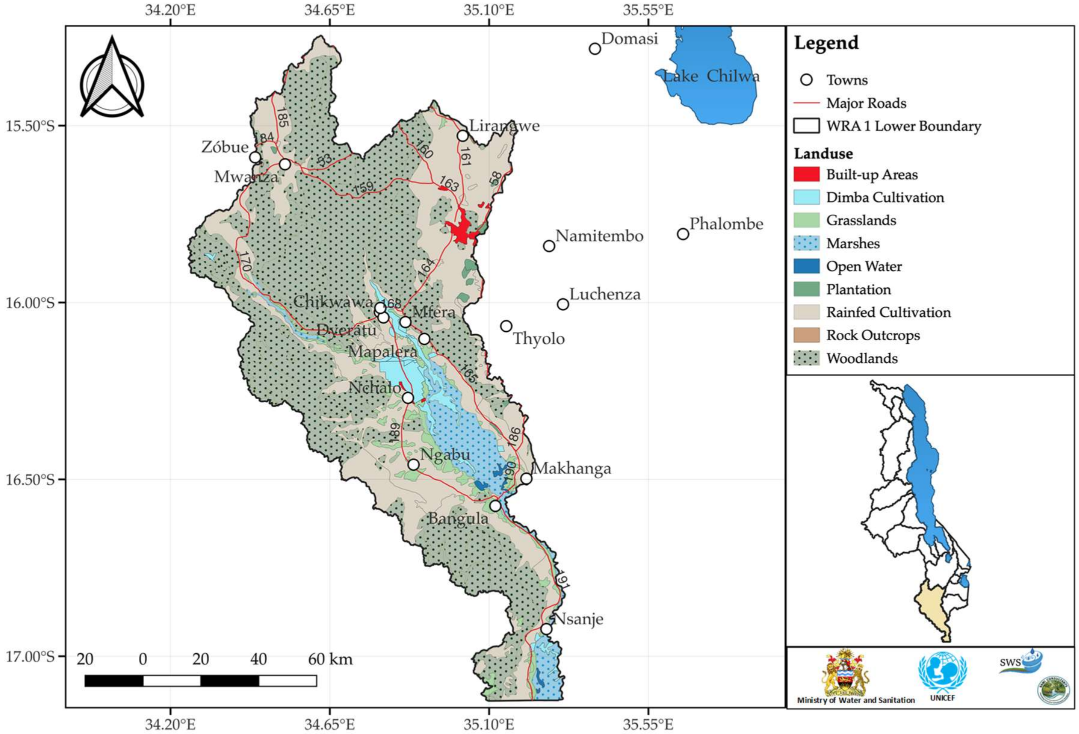

Figure 10. Land use in the Lower Shire WRA 1 is dominated by scrub woodlands, grasslands, marsh / wetlands, and rain fed / irrigated agriculture.

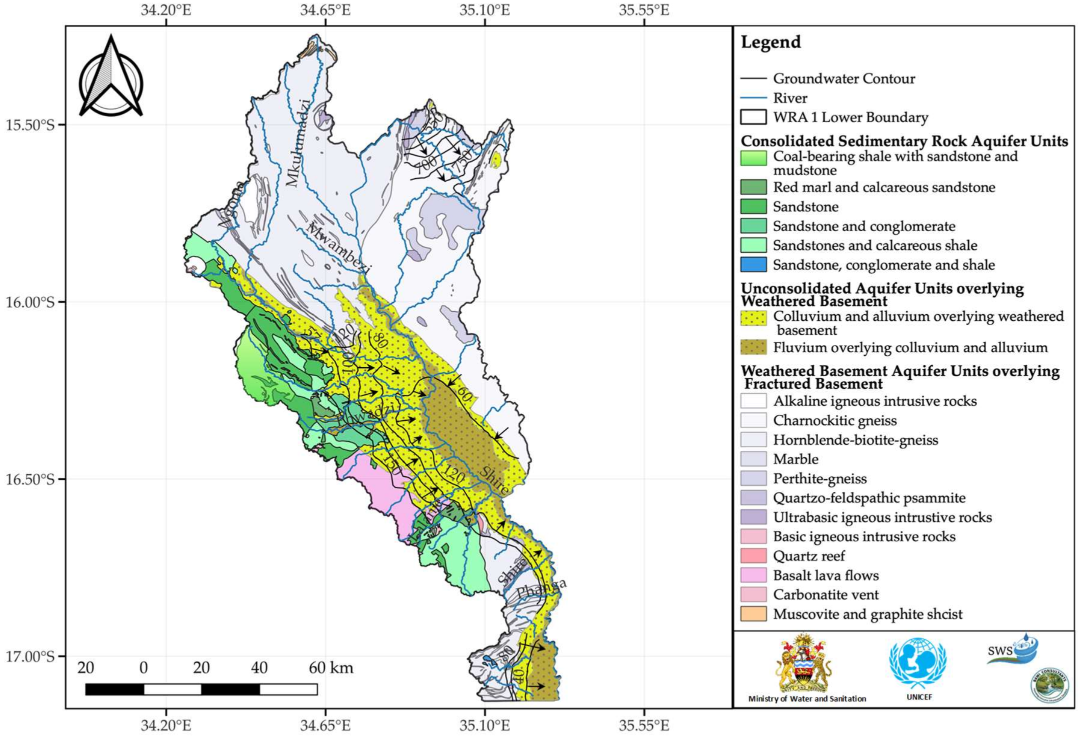

Figure 11. Groundwater level contours and flow direction in the Lower Shire of WRA 1 [1987 Hydrogeological Reconnaissance data] [water level contour interval 20m]

Hydrogeology of WRA 1 Lower Shire

Aquifer Properties

The dominant aquifer type in the Lower 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 the Lower Shire WRA 1 is based on prior hydrogeological reconnaissance.

A very reasonable first presumption though is that the WRA 1 modern-day groundwater flow regime (especially regional directions of flow as opposed to absolute water levels) may be expected to be similar to the circa 1987 benchmark water table presented. The natural groundwater flow regime in the WRA follows regional and broadly local topography and regional basin and sub-basin, catchment drainage. Groundwater and surface-water flow divides appear concurrent with groundwater drainage toward and base flow discharge to surface-waters, including (main) rivers, lakes and wetland areas. These characteristics may still largely be expected to apply.

Exception to the above benchmark modern validity may possibly be where (i) sizeable groundwater abstraction has induced regional flow regime changes with semi-local to regional cones of depression (lowered water tables) induced. Exception may also be where (ii) significant changes in recharge have occurred over extensive areas from land use changes such as deforestation increasing runoff and reducing recharge, climate change affecting recharge, and also direct abstraction of surface waters (for supplies irrigation) upstream or from river reaches formally leaking to and recharging local groundwater.

Groundwater heads in the Lower Shire near Chikwawa just downstream of the Rift escarpment are around 80 m msl, substantially below groundwater heads near to the Upper Shire upstream of the escarpment at 450 m msl. Whilst a distinct groundwater flow system, groundwater flows in the Lower Shire WRU catchments remain dominated by a flow field convergent on the Shire River and adjoining, extensive Elephant Marsh wetlands. Higher groundwater heads are found in the west of the Lower Shire Basin where higher elevations weathered or fractured Basement runoff – groundwater flows drain into the extensive lowland unconsolidated aquifer plain. High heads reaching 220 m asl in the narrow upper Mwanza Valley in the northwest WRU 1K drive flows south-westwards that are strongly convergent of the Mwanza River providing base flow support with moderately steep hydraulic gradients in the valley flanks towards the river of around 0.008 (0.8 %). Further south, the lowland plain is bounded by western heads in the unconsolidated aquifer of around 150 m asl upwards that drive flow quasi-Eastwards towards the Elephant Marsh – Shire River area.

Hydraulic gradients in the wider lowland plain declining Eastwards towards below 60 m asl at the Elephant Marsh are low, but spatially variable. Hydraulic gradients range from around 0.003 to 0.005 (0.3 to 0.5 %) and even lower to the northwest of the Elephant Marsh – Nchalo area at just 0.0015 (0.15 %). Where the lowland plain west of the Shire narrows south of Ngabu hydraulic gradients steepen somewhat becoming more uniform with values around 0.007 (0.7 %). Further south, downstream of the Thangadzi River confluence with the Shire, hydraulic gradients in the ever-narrowing unconsolidated aquifer obtained from the 80 to 60 m head contour decline further increase to around 0.012 (1.2 %) with flows draining to the Ndinde Marsh – Shire River at the southern tip of Malawi.

The 1F catchment East of the Shire – Elephant Marsh area to which it drains westwards contains a relatively thin strip of unconsolidated deposits bounded by steeply inclined weathered Basement. Hydraulic gradients calculated from the 80 to 60 m head declines are around 0.004 to 0.007 (0.4 to 0.7 %). Further south of the Elephant Marsh, the Shire River forms the national border with Mozambique; groundwater flows in Mozambique if following topography would be expected to be generally westwards towards the Shire River to which base flow discharge may be anticipated or the Ndinde Marsh wetland adjoining.

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 Lower 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 Lower 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 Lower Shire of WRA 1 there appears to borehole yields related to weathered basement overlying fractured basement aquifer units (some semi- to confined), with a number of production boreholes reporting yields in excess of 2l/s. In the Lower Shire of WRA 1 (**Figures 13a to 13j**) the sediments near the Shire River (colluvium, alluvial and fluvial unit) show lower yielding boreholes, in particular where there are reported yields <0.25l/s, with the exception of the Eastern 'shore' of the Shire River to the Mozambique border where there is higher yields to 2l/s with 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.


Borehole Yield Distribution WRU 1 C

Borehole Yield Distribution WRU 1 D

Borehole Yield Distribution WRU 1 E

Borehole Yield Distribution WRU 1 F

Borehole Yield Distribution WRU 1 G

Borehole Yield Distribution WRU 1 H

Borehole Yield Distribution WRU 1 K

Borehole Yield Distribution WRU 1 L

Borehole Yield Distribution WRU 1 M

Borehole Yield Distribution WRU 1 N

Figure 12. Distribution of Borehole Yield Data in WRUs held by the MoWS (y axis = *n* observations)

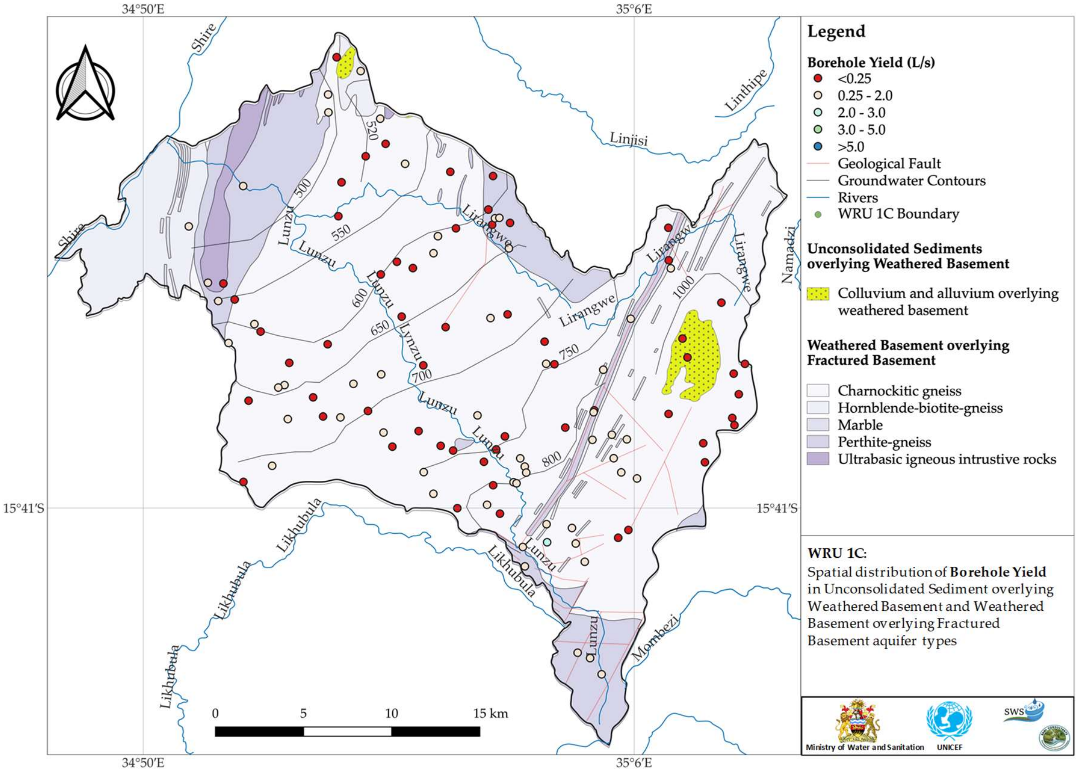

Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1C.

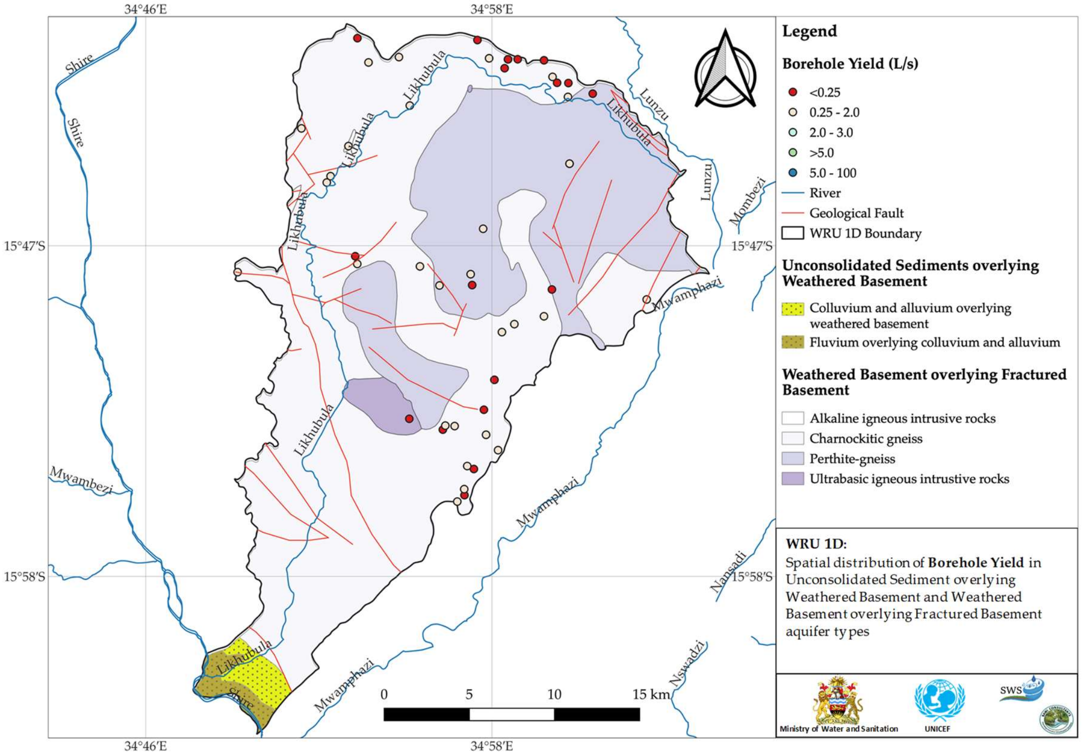

Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1D.

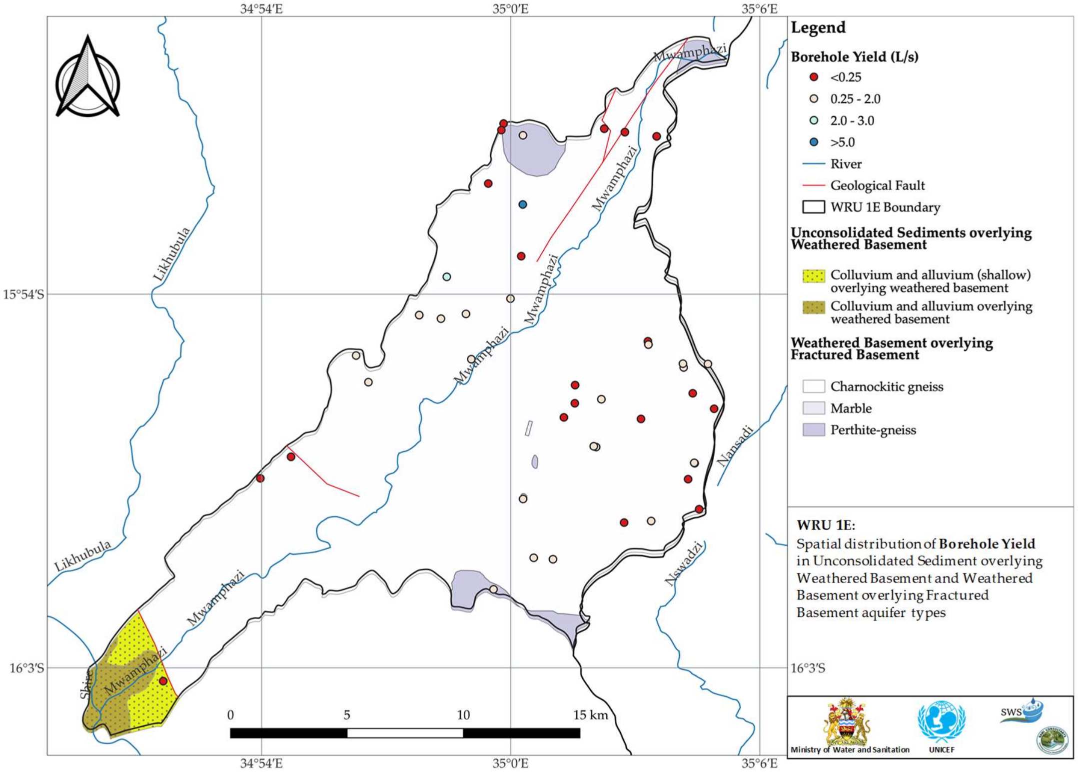

Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1E.

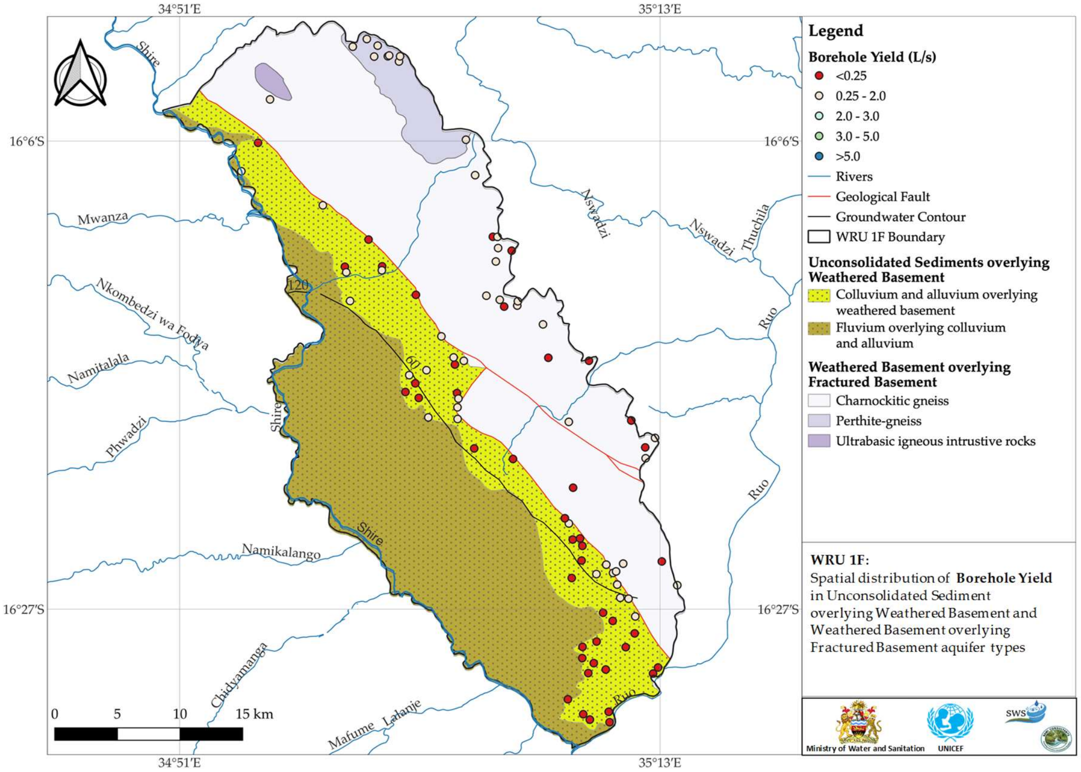

Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1F.

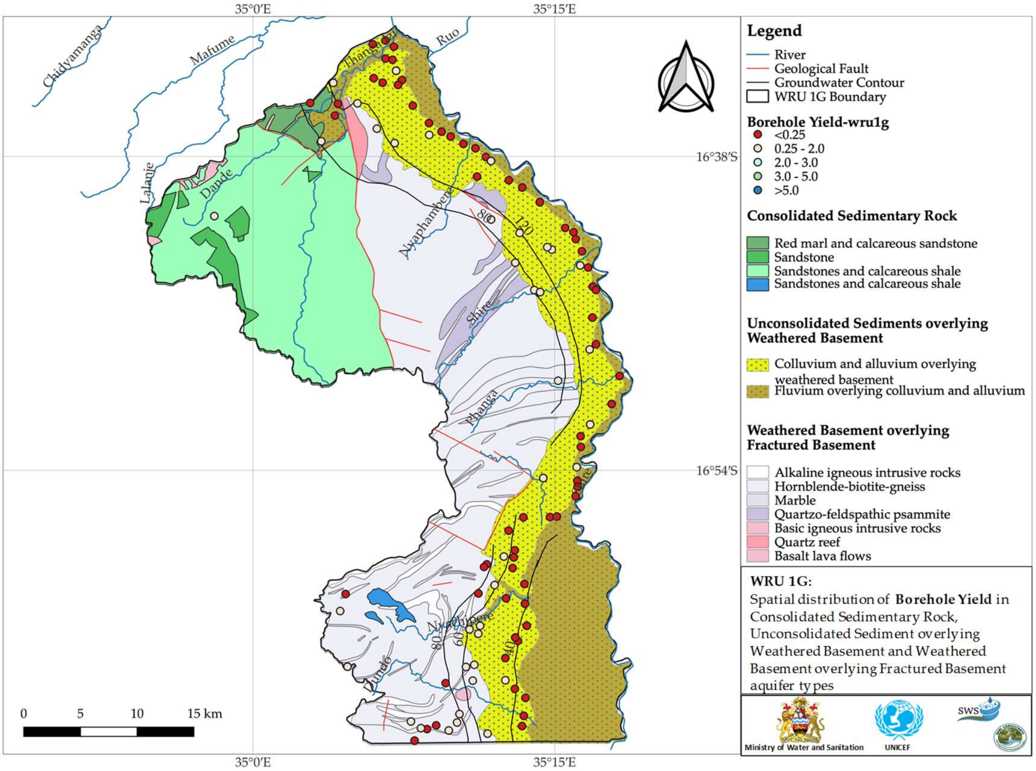

Figure 13e. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1G.

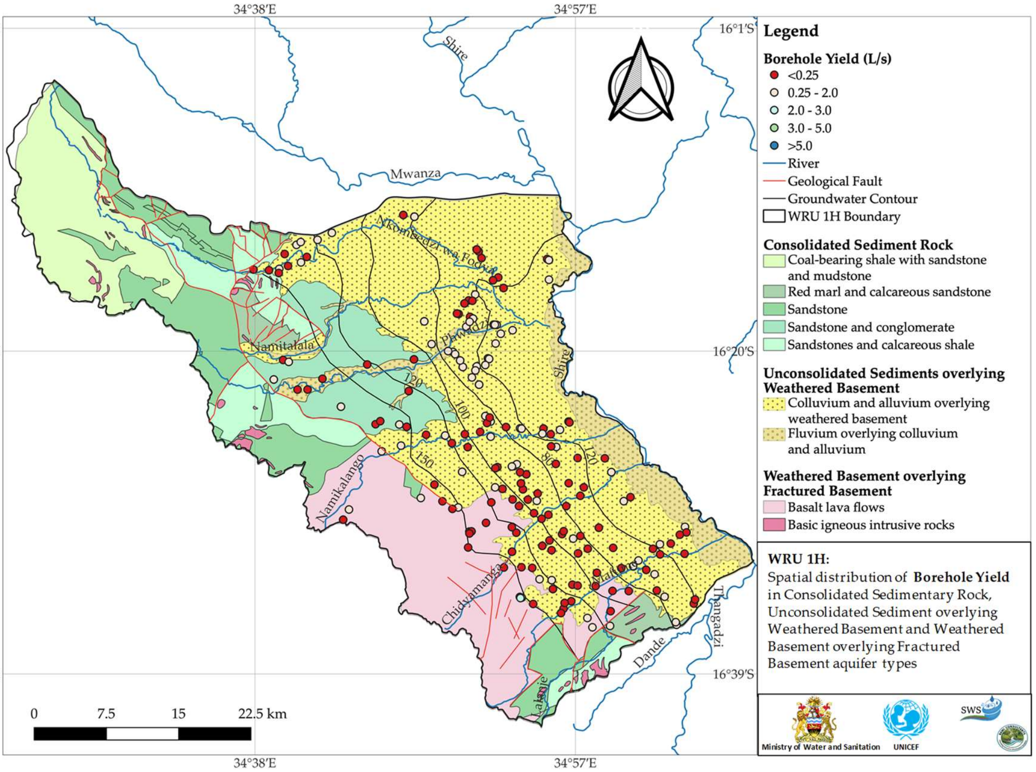

Figure 13f. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1H.

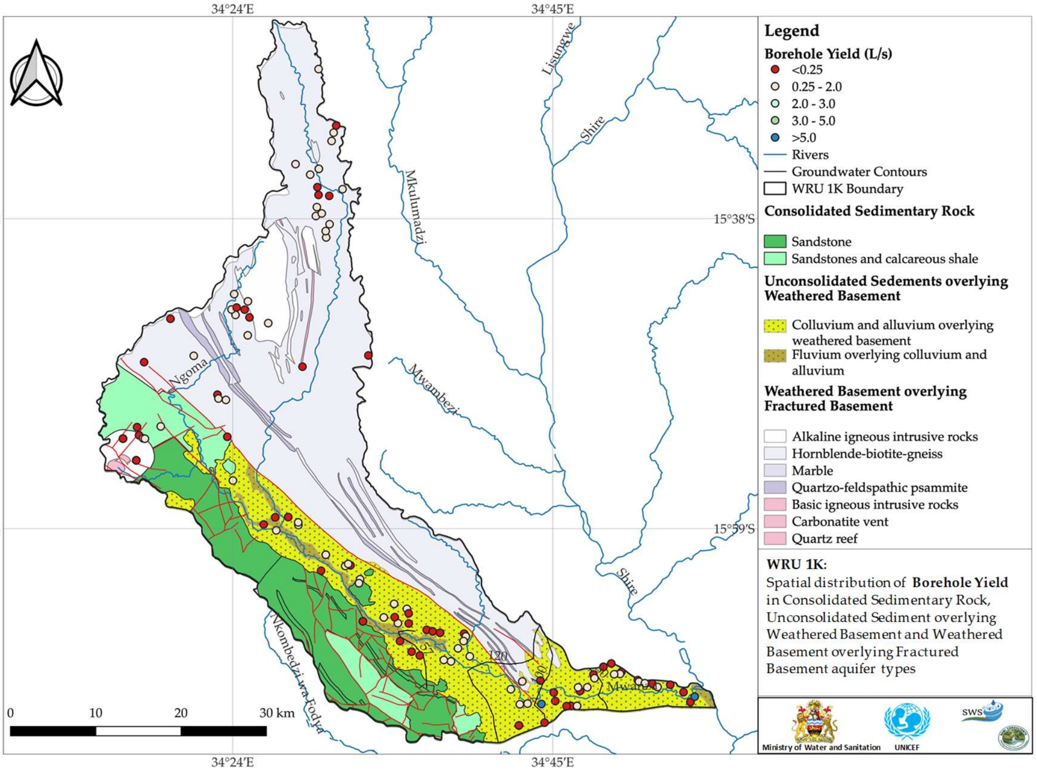

Figure 13g. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1K.

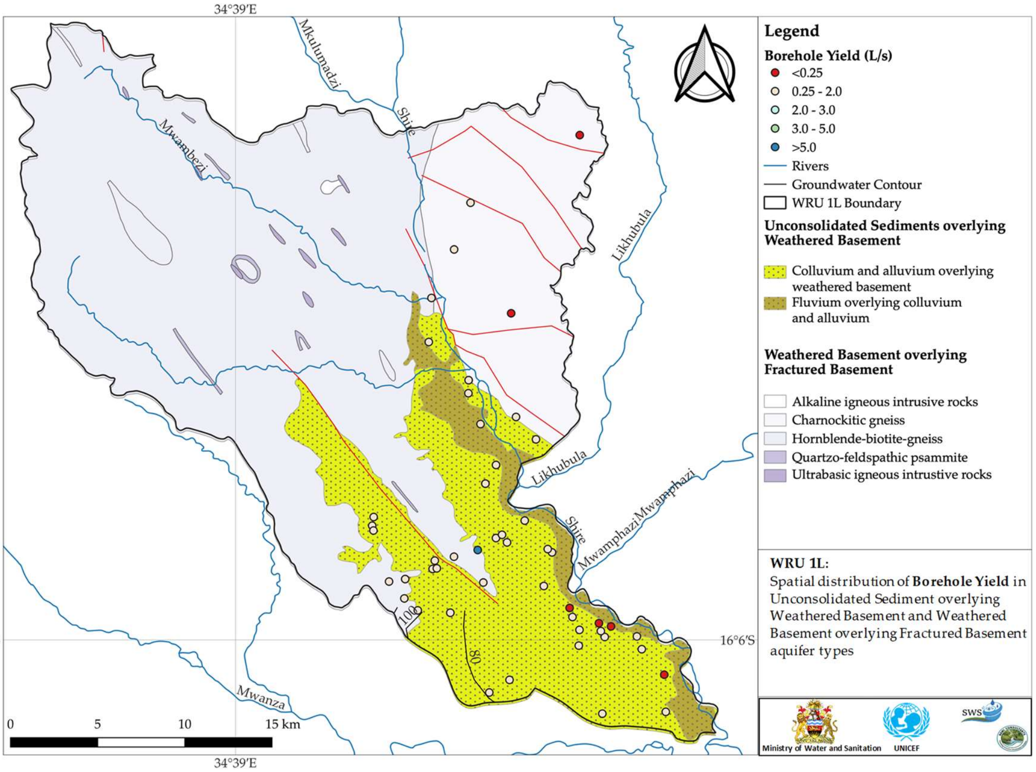

Figure 13h. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1L.

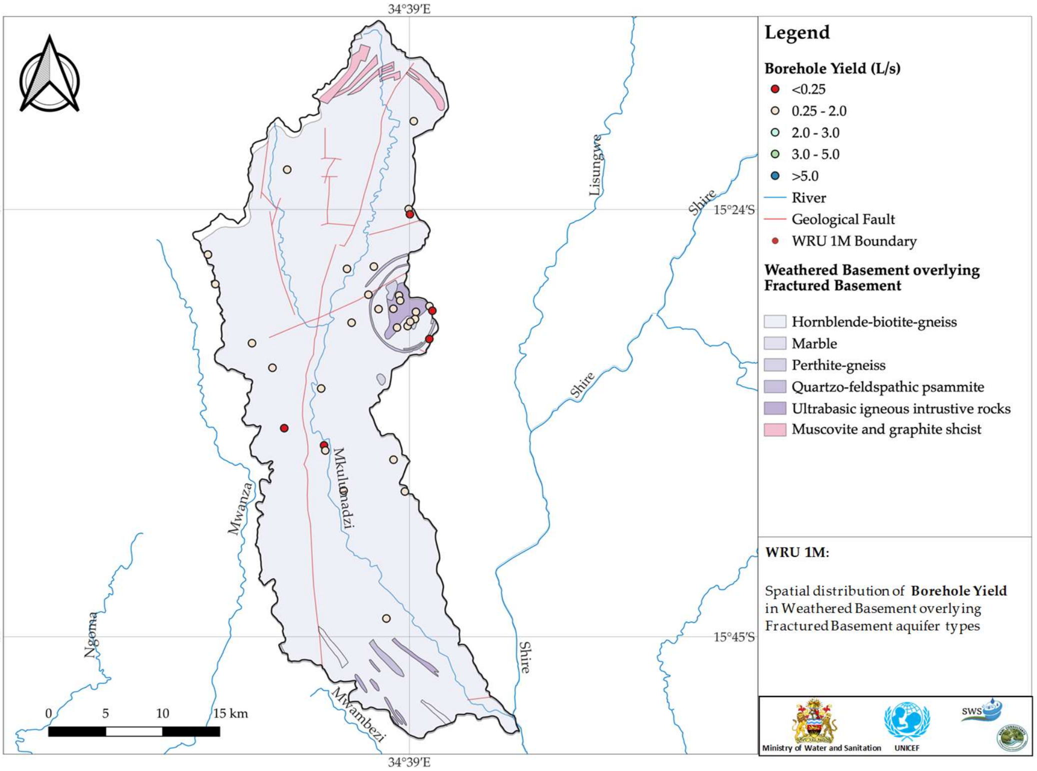

Figure 13i. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1M.

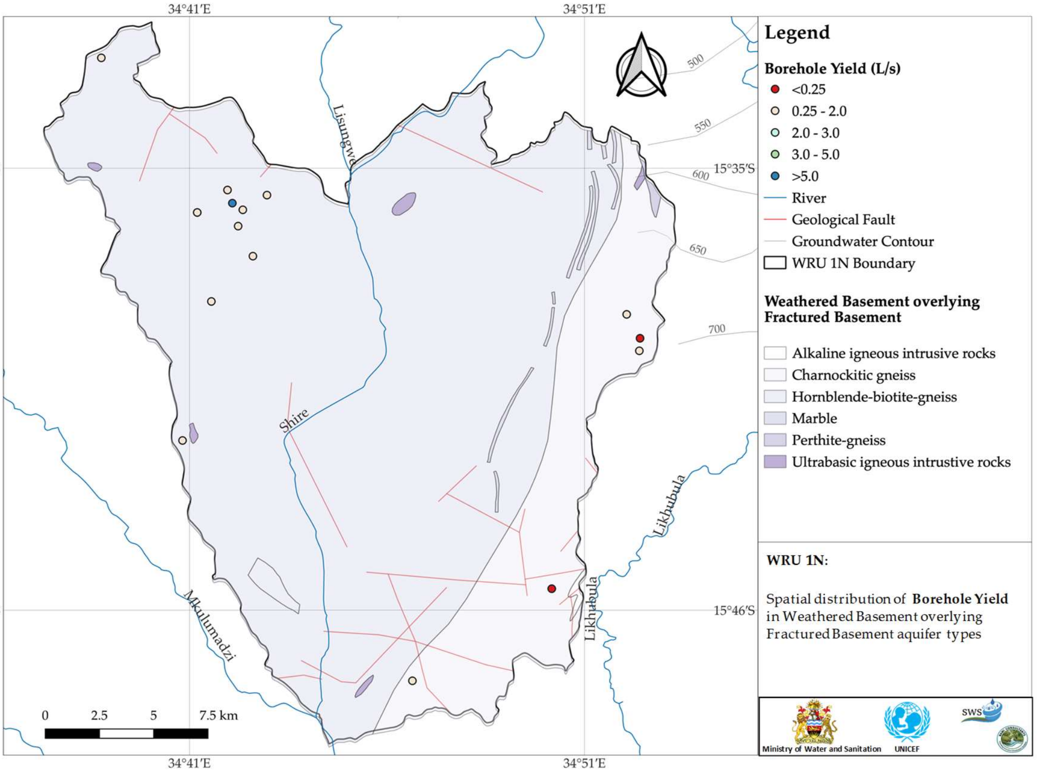

Figure 13j. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 1N.

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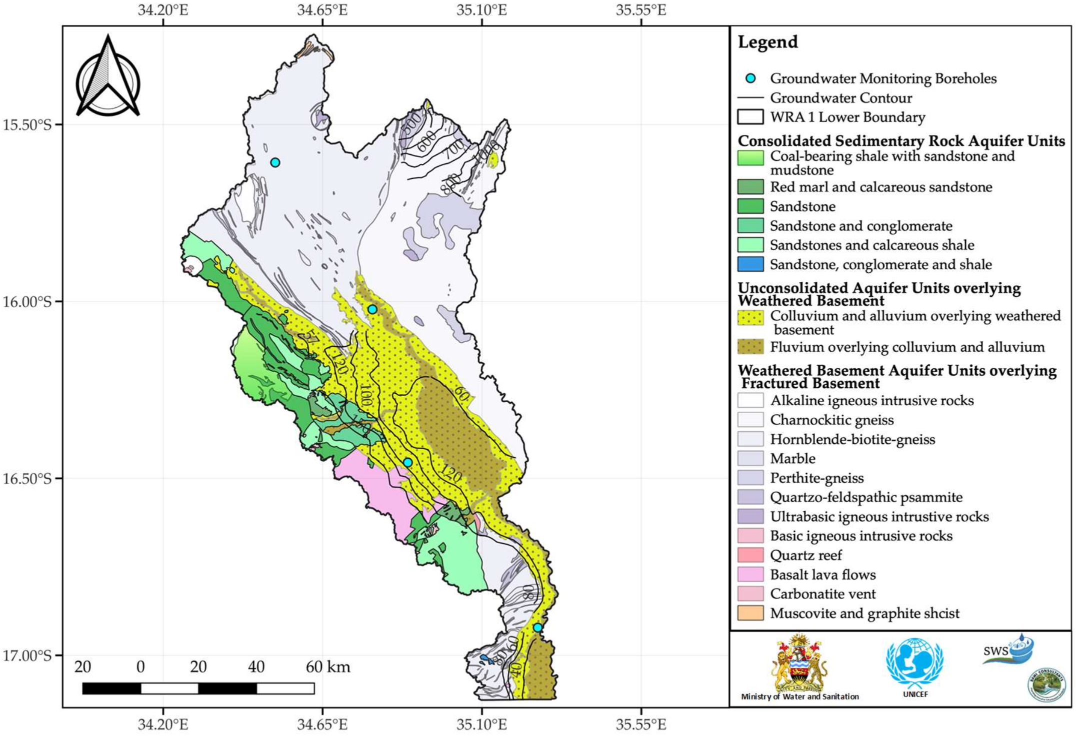


Figure 14a. Location of Groundwater Monitoring Points in the Lower Shire Water Resources Area 1.

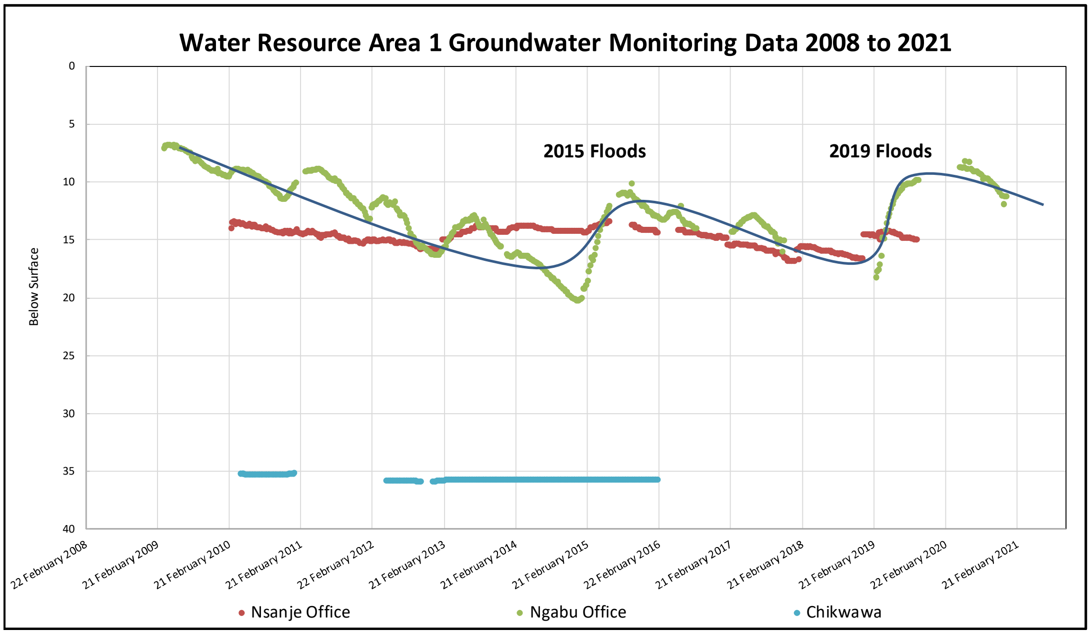


Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in the Lower Shire Water Resources Area 1 (units assumed to be meters below ground level).

Groundwater Table Variations

There are a number of operational groundwater monitoring stations within the Lower 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 Ngabu and Nsanje 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 1- and 5-meter annual change in groundwater table, with long-term trends of over 10 meters that clearly relate to climate variability (floods that provide substantial recharge events with interspersed water table decline) 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 1C, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	0.0	10%	35%	0.02	0.10	0.0	0.0	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	11.9	10%	30%	0.02	0.06	23.8	214.1	
W & F Basement	723.3	1%	10%	0.02	0.03	144.7	2,169.9	
	Area of WRU (km^2)	1C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*168.5*	*2,384.1*	*Total Volume Groundwater*
	735.2	965	Average Rainfall in WRU	9.65	72.375	7.1	53.2	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]						24	45	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 1D, 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	7.9	10%	35%	0.02	0.10	15.8	276.4	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	8.5	10%	30%	0.02	0.06	17.0	153.2	
W & F Basement	600.2	1%	10%	0.02	0.03	120.0	1,800.6	
	Area of WRU (km^2)	1D	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*152.9*	*2,230.2*	*Total Volume Groundwater*
	616.6	988	Average Rainfall in WRU	9.88	74.1	6.1	45.7	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]						25	49	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 1E, 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	7.5	10%	35%	0.02	0.10	14.9	261.0	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	6.5	10%	30%	0.02	0.06	13.1	117.9	
W & F Basement	320.8	1%	10%	0.02	0.03	64.2	962.4	
	Area of WRU (km^2)	1E	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*92.2*	*1,341.3*	*Total Volume Groundwater*
	334.8	1037	Average Rainfall in WRU	10.37	77.775	3.5	26.0	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]						27	52	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 1F, 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	415.4	10%	35%	0.02	0.10	830.8	14,539.3	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	233.4	10%	30%	0.02	0.06	466.7	4,200.4	
W & F Basement	536.4	1%	10%	0.02	0.03	107.3	1,609.3	
	Area of WRU (km^2)	1F	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,404.8*	*20,349.0*	*Total Volume Groundwater*
	1,185.2	928	Average Rainfall in WRU	9.28	69.6	11.0	82.5	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]						128	247	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 1G, 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	334.0	3%	15%	0.02	0.10	200.4	5,010.2	
Fluvial Units	215.4	10%	35%	0.02	0.10	430.9	7,540.5	
Lacustrine units	0.8	10%	35%	0.02	0.03	1.5	8.0	
Colluvial etc.	297.4	10%	30%	0.02	0.06	594.9	5,353.8	
W & F Basement	608.5	1%	10%	0.02	0.03	121.7	1,825.4	
	Area of WRU (km^2)	1G	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,349.4*	*19,737.8*	*Total Volume Groundwater*
	1,456.1	947	Average Rainfall in WRU	9.47	71.025	13.8	103.4	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]						98	191	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 1H, 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	758.3	3%	15%	0.02	0.10	455.0	11,373.8	
Fluvial Units	135.2	10%	35%	0.02	0.10	270.3	4,731.0	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	867.6	10%	30%	0.02	0.06	1,735.2	15,616.6	
W & F Basement	348.4	1%	10%	0.02	0.03	69.7	1,045.1	
	Area of WRU (km^2)	1H	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,530.1*	*32,766.5*	*Total Volume Groundwater*
	2,109.4	881	Average Rainfall in WRU	8.81	66.075	18.6	139.4	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]						136	235	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 1K, 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	1.7	10%	35%	0.02	0.10	3.4	60.3	
Lacustrine units	2.5	10%	35%	0.02	0.03	5.0	26.5	
Colluvial etc.	7.6	10%	30%	0.02	0.06	15.2	136.9	
W & F Basement	1,818.3	1%	10%	0.02	0.03	363.7	5,455.0	
	Area of WRU (km^2)	1K	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*387.4*	*5,678.7*	*Total Volume Groundwater*
	1,830.2	956	Average Rainfall in WRU	9.56	71.7	17.5	131.2	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]						22	43	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 4h. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 1L, 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	35.3	10%	35%	0.02	0.10	70.7	1,236.7	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	180.7	10%	30%	0.02	0.06	361.3	3,252.1	
W & F Basement	635.5	1%	10%	0.02	0.03	127.1	1,906.4	
	Area of WRU (km^2)	1L	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*559.1*	*6,395.3*	*Total Volume Groundwater*
	851.5	907	Average Rainfall in WRU	9.07	68.025	7.7	57.9	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]						72	110	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

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

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	0.0	10%	35%	0.02	0.10	0.0	0.0	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	0.0	10%	30%	0.02	0.06	0.0	0.0	
W & F Basement	870.8	1%	10%	0.02	0.03	174.2	2,612.4	
	Area of WRU (km^2)	1M	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*174.2*	*2,612.4*	*Total Volume Groundwater*
	870.8	1023	Average Rainfall in WRU	10.23	76.725	8.9	66.8	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						20	39	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

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

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	0.0	10%	35%	0.02	0.10	0.0	0.0	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	0.0	10%	30%	0.02	0.06	0.0	0.0	
W & F Basement	573.5	1%	10%	0.02	0.03	114.7	1,720.4	
	Area of WRU (km^2)	1N	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*114.7*	*1,720.4*	*Total Volume Groundwater*
	573.5	1026	Average Rainfall in WRU	10.26	76.95	5.9	44.1	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						19	39	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 1ranges between 100.1 Million Cubic Meters (MCM) and 750.2 MCM per year, with a mean age of groundwater of 82 years across the Water Resource Area **(Tables 4a to 4j)**. 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 Lower Shire

Groundwater major-ion water quality in WRA 1for data available within the Ministry of Water and Sanitation is available and is limited here 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 1water quality data suggest most water has expected geochemical changes from water-rock interactions dominated by Ca-Mg-HCO_3 type waters with a trend for increasing Na-Cl-SO_4 likely due to fault zone fluids or evaporative enrichment, but given the increases in sulphate and high fluoride measurements, geologic sources are more likely for the extreme concentrated waters (**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. The majority of more saline water points occur within the central basin alluvial deposits. Elevated concentrations also occur in the northwest areas underlain by the Cretaceous Lupata sandstone. The most consistent low-salinity area occurred in the western basin areas where groundwater was drawn from the Karoo basalt basement rock. The Karoo basalt water points were significantly less saline than the alluvial aquifer and Lupata sandstone points.

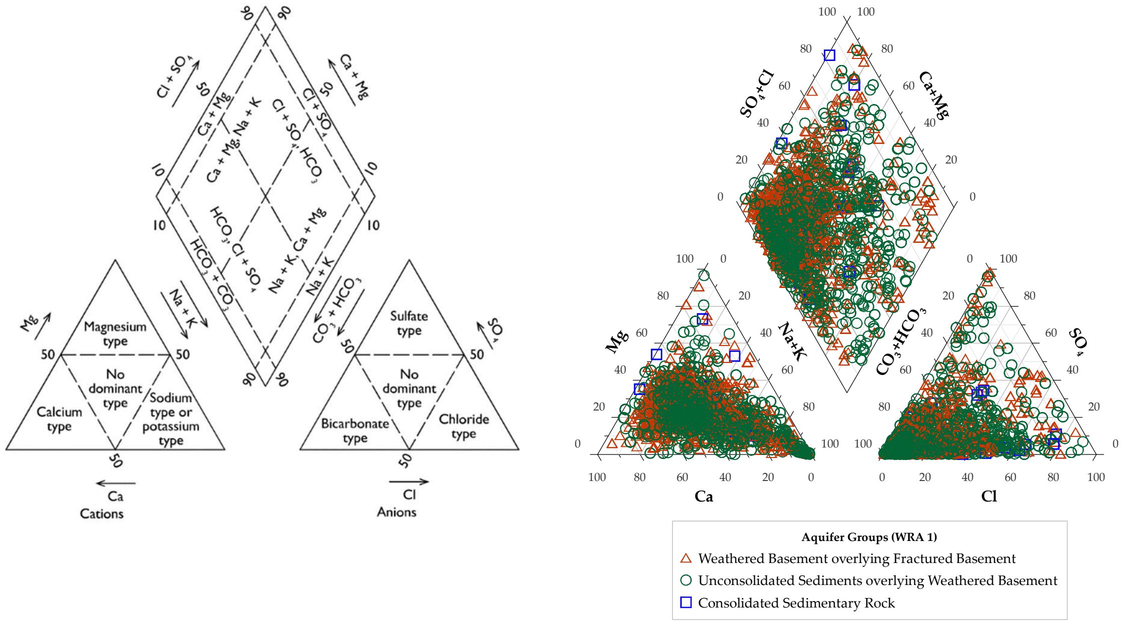


Figure 14a, 14b. Piper Diagrammes of Groundwater Samples in WRA 1and for each Aquifer Type in WRA 1.

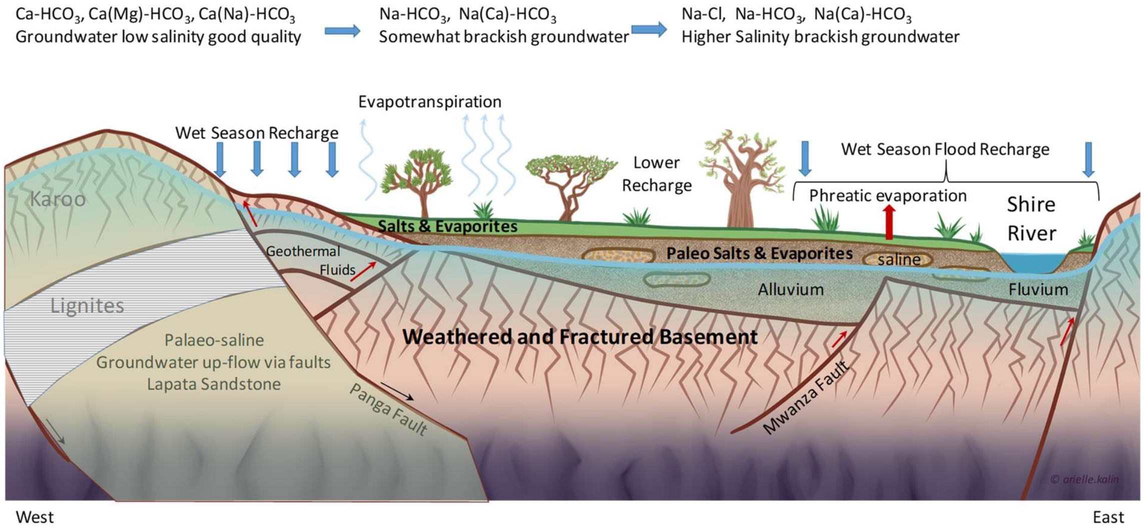


Figure 14c. Idealised cross section of WRA 1 showing the likely influences of evaporative enrichment of groundwater salinity coupled with fluid flow along rift faults.

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.

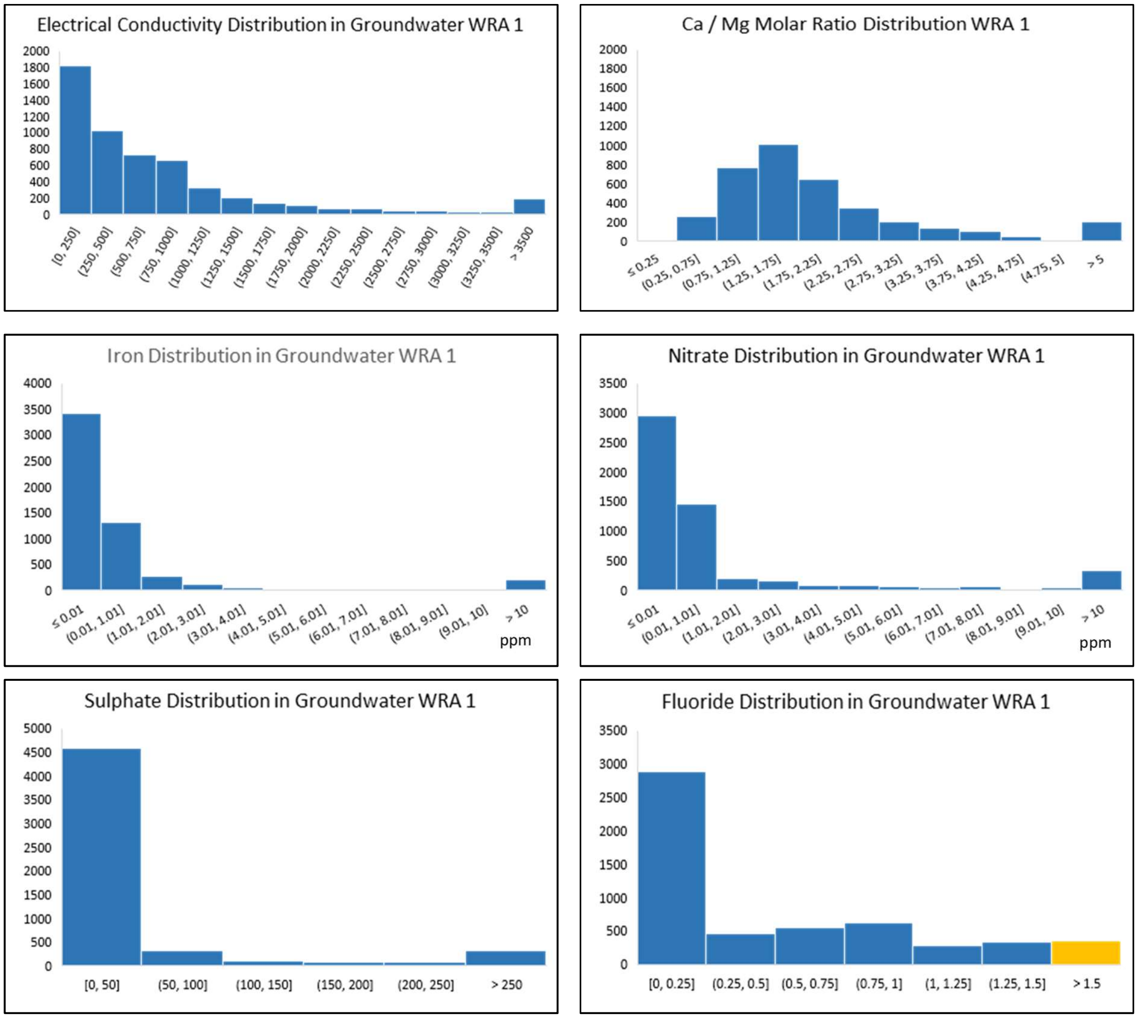


Figure 15 Distribution of chemical species in groundwater within WRA 1 (y axis = *n* observations)

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.

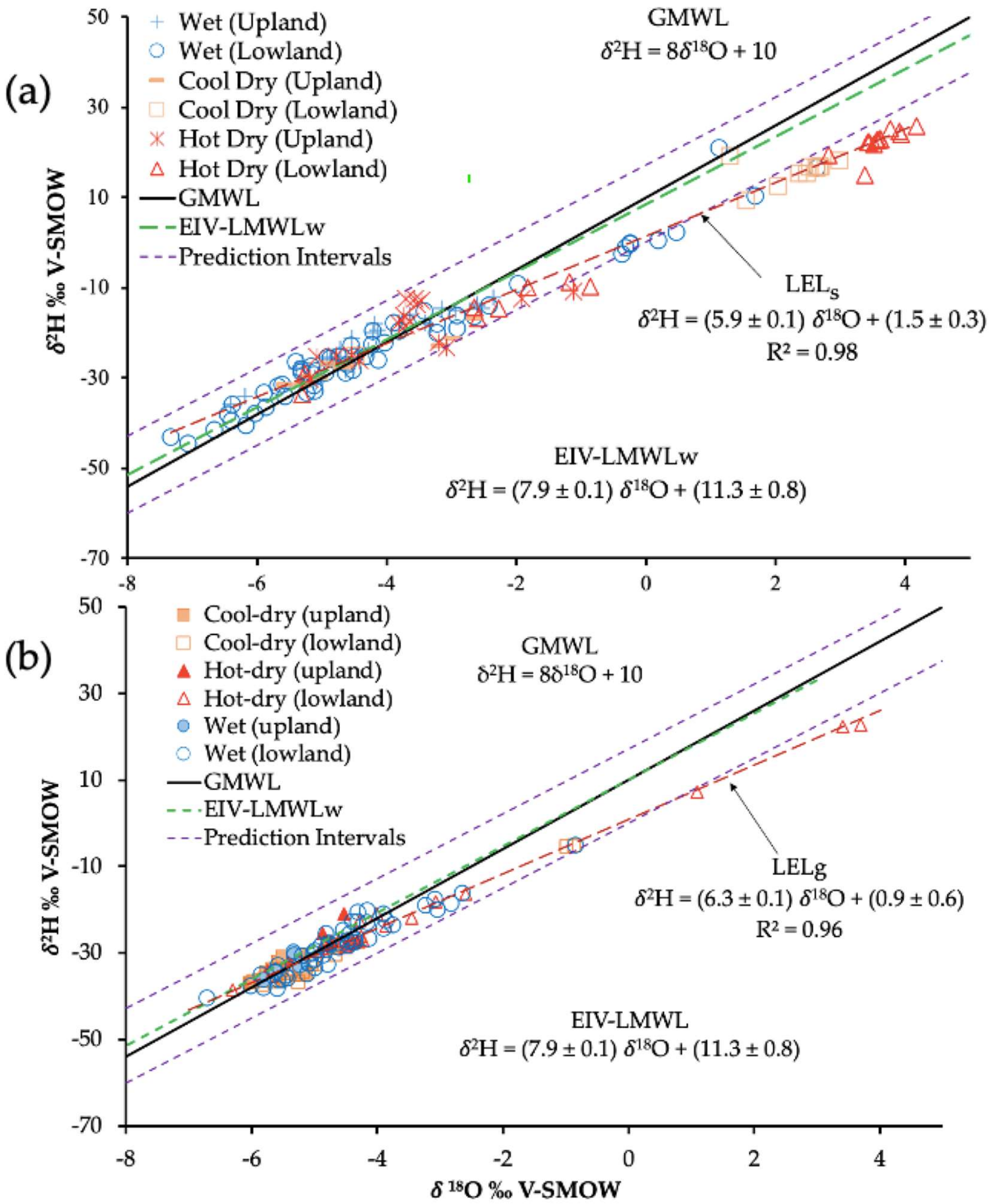


Figure 16a and 16b. Stable isotope measurements of groundwater in WRA showing the effects of evaporation on (a) surface water and (b) groundwater samples for the 3 seasons Cool-Dry, Hot-Dry and Wed (after Banda et al 2019).

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 Lower 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.

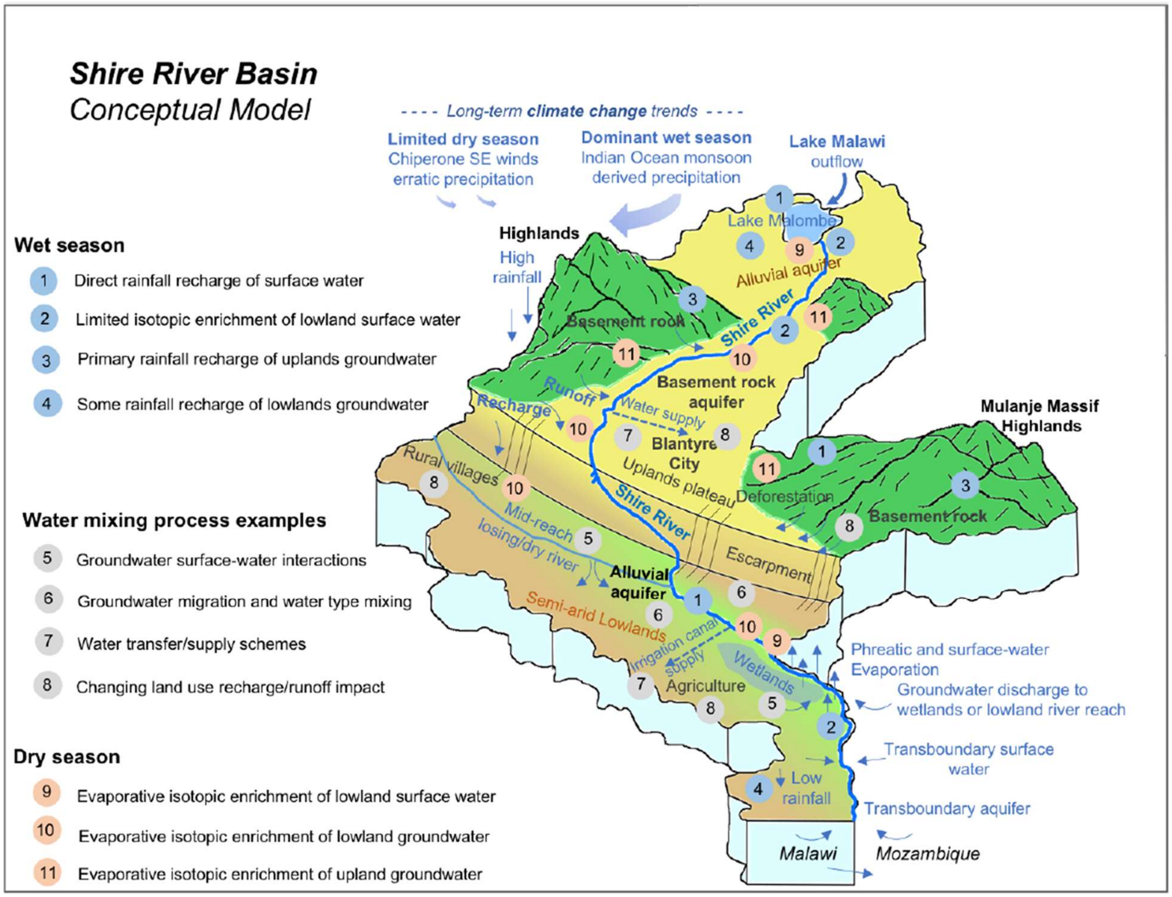
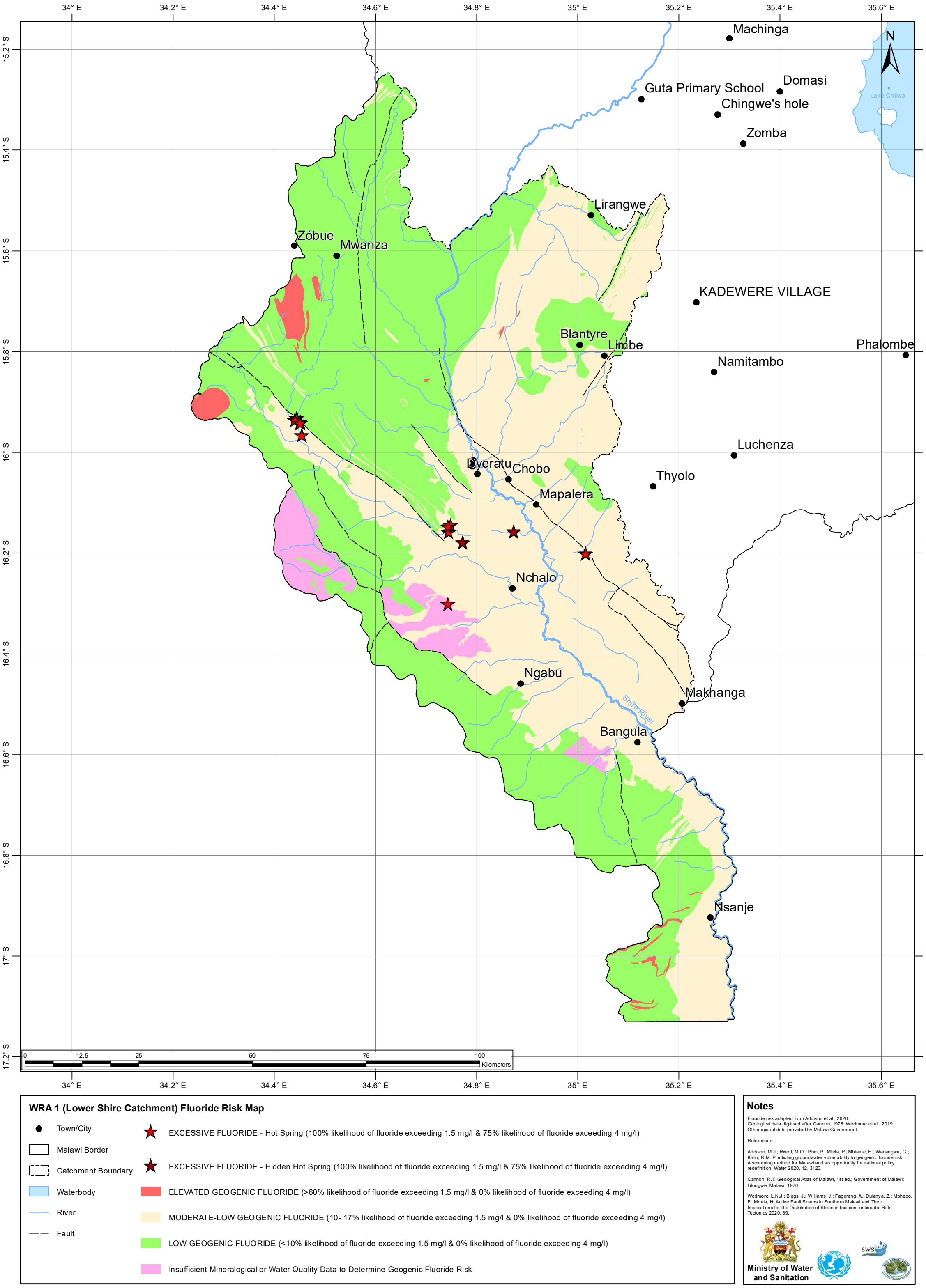


Figure 16c. Conceptual model of isotope hydrology for the Shire Basin WRA 1 (after Banda et al 2019).

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 significantly above both WHO and Malawi standards, exceeding 3,500mg/l (max 17,000 mg/l). The lack of routine and wide-spread water quality analyses targeted to hydrostratigraphic units 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.



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

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

The majority of more saline groundwater occurs within areas overlain by soils of high expansive clay content prone to dry-season fracturing. Salinity is significantly higher in areas characterised by lithomorphic vertisols, topovertisols and shallow grey-brown earths in comparison to groundwaters sampled from areas characterised by lithosols. A significant inverse relationship exists between salinity and the distance to the nearest river (Rivett et al 2019) as expected from periodic flooding (as evident in water table fluctuation data) and evaporation cycles of the hot-dry climate of the Lower Shire causing ion enrichment. This suggests a need for increased sample-point density (vertically) and consideration of water-abstraction depths to resolve controls upon salinity occurrence in often transient near-river environments.

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 (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 1.

	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**
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-latrine 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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Maps and Figures

Water Resource Unit (WRA) 1 Figures

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

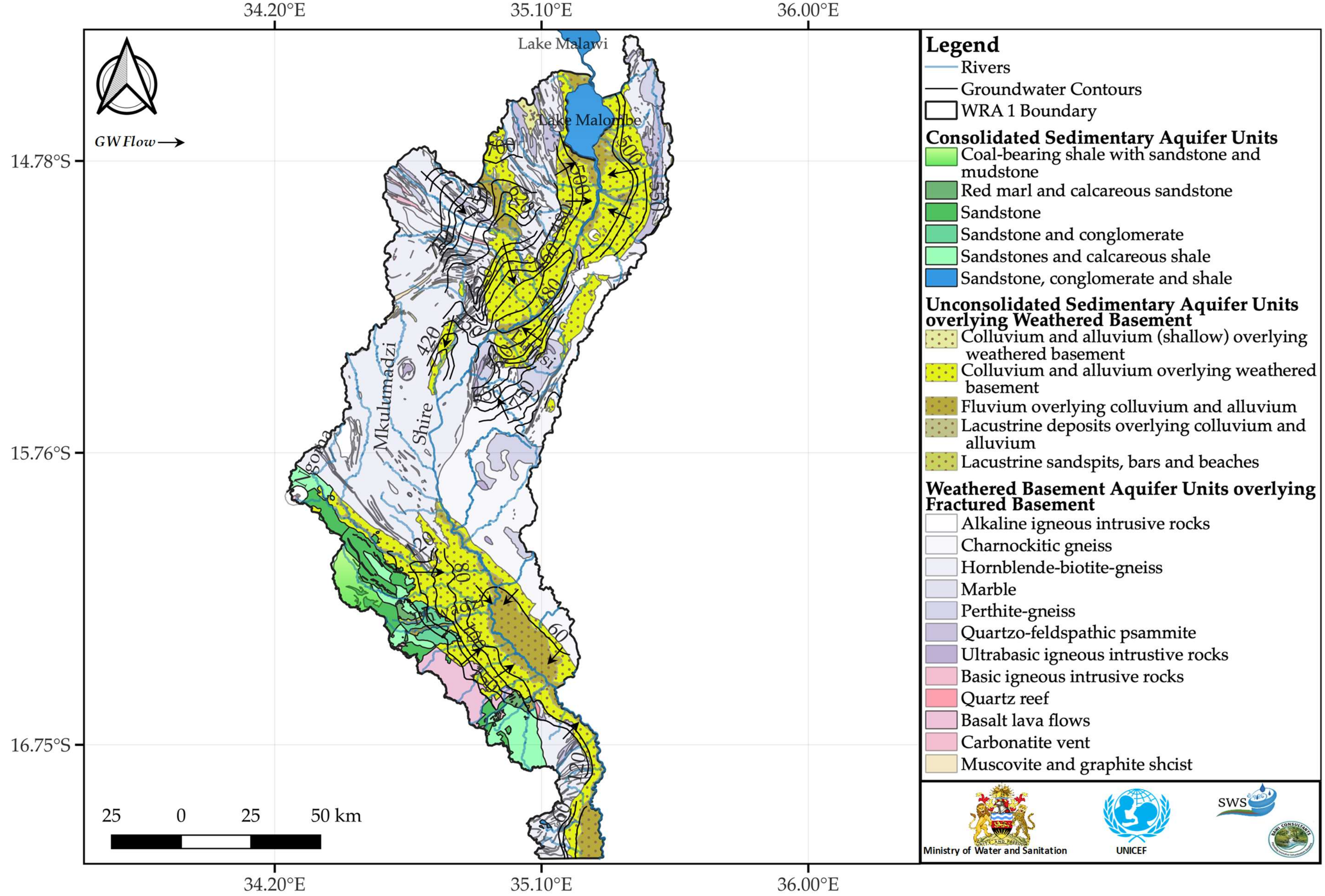
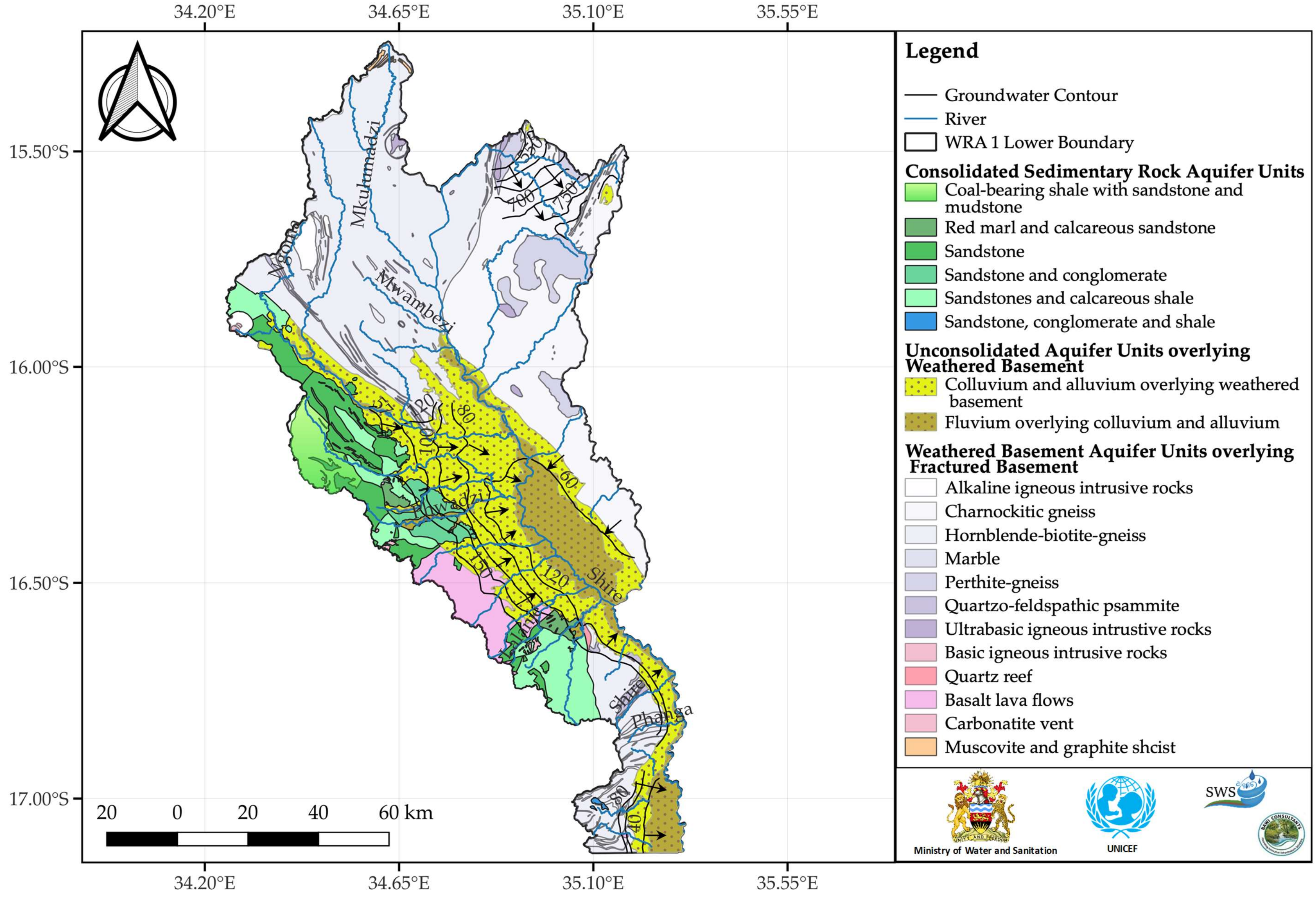


Figure WRA 1.1: Aquifer Units and Groundwater Level Contours Lower Shire WRA 1



WRU 1A Figures

Figure WRU 1C.1 Land Use and Major Roads

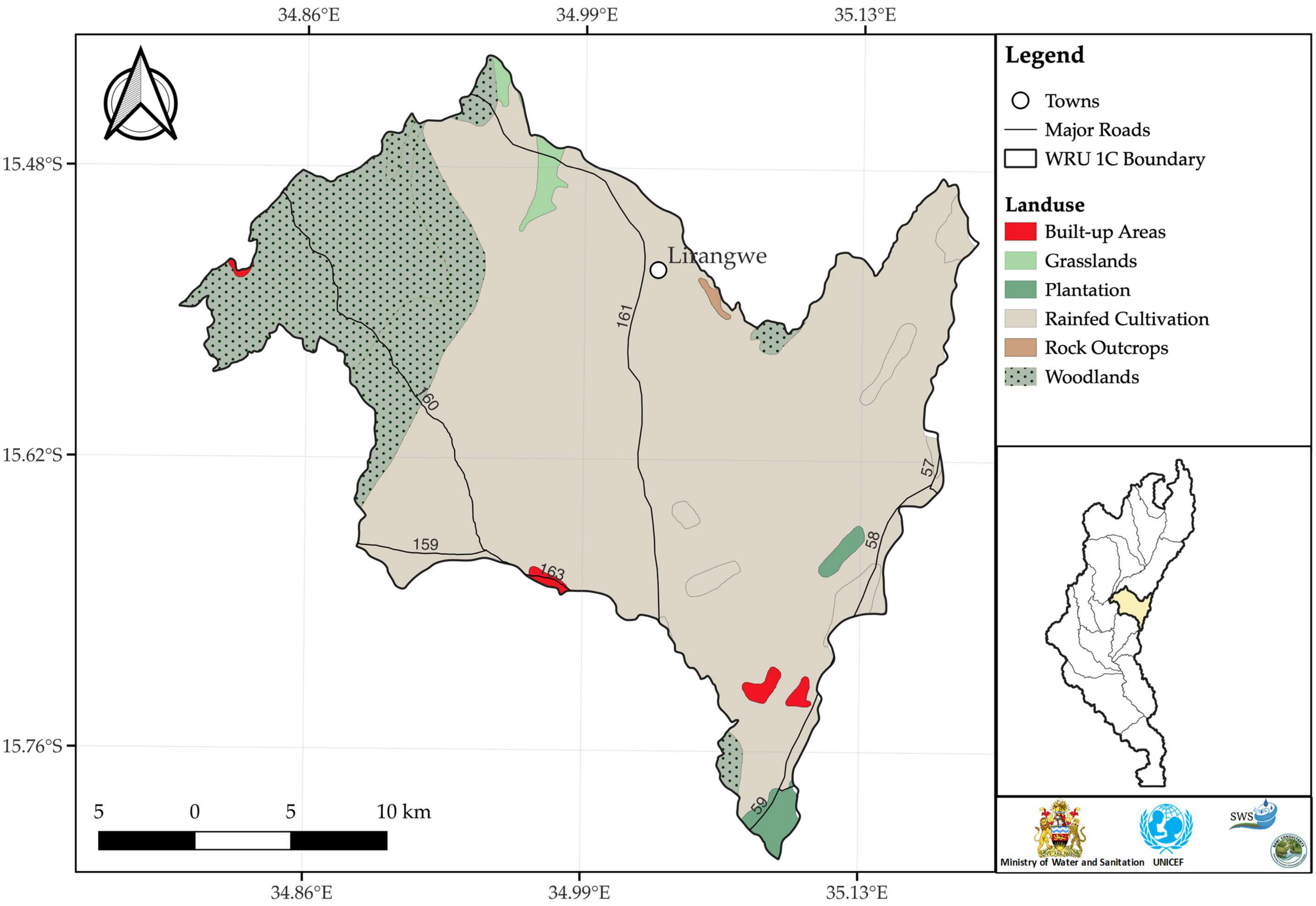


Figure WRU 1C.2 Rivers and Wetlands

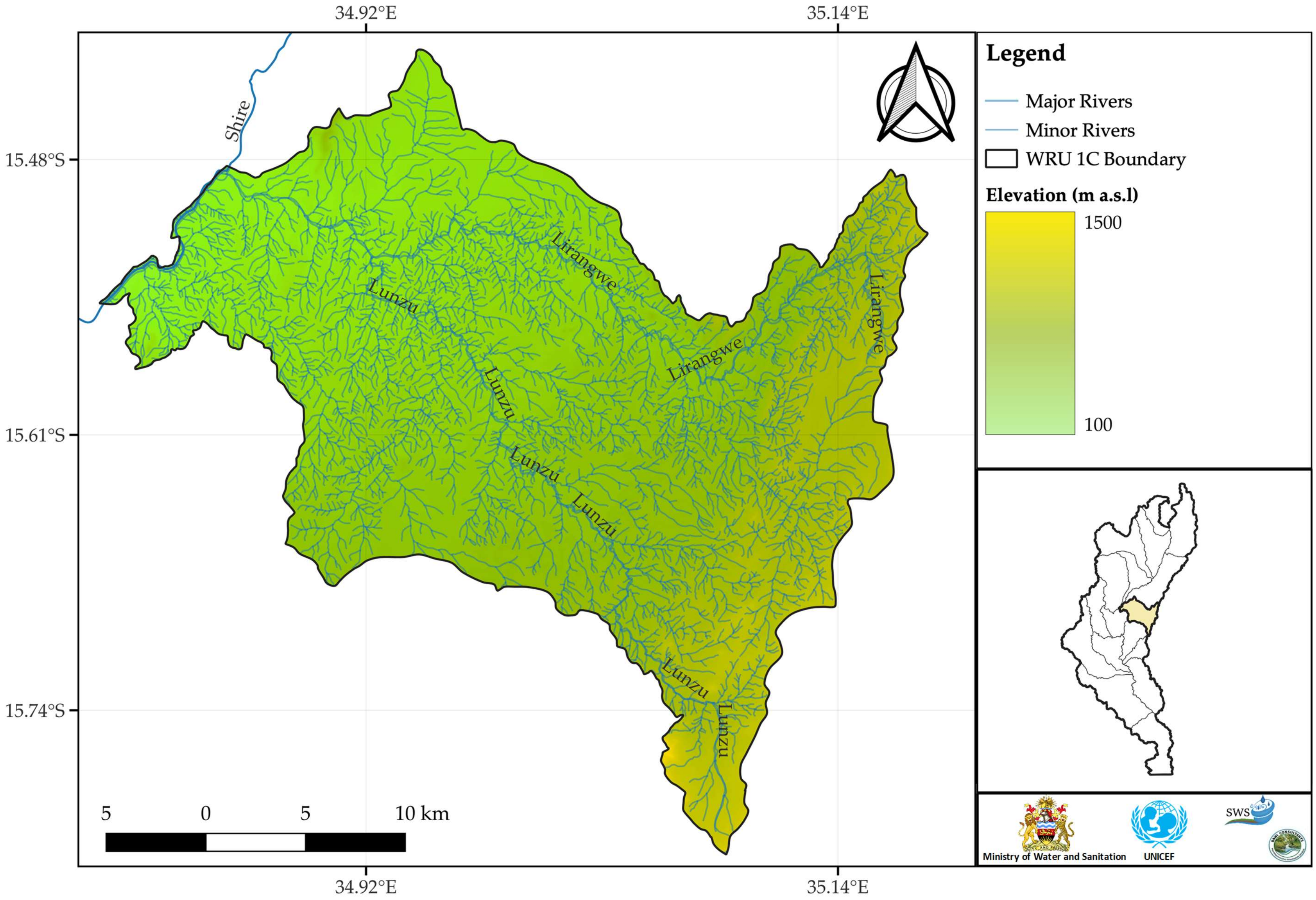


Figure WRU 1C.3 Hydrogeology Units and Water Table

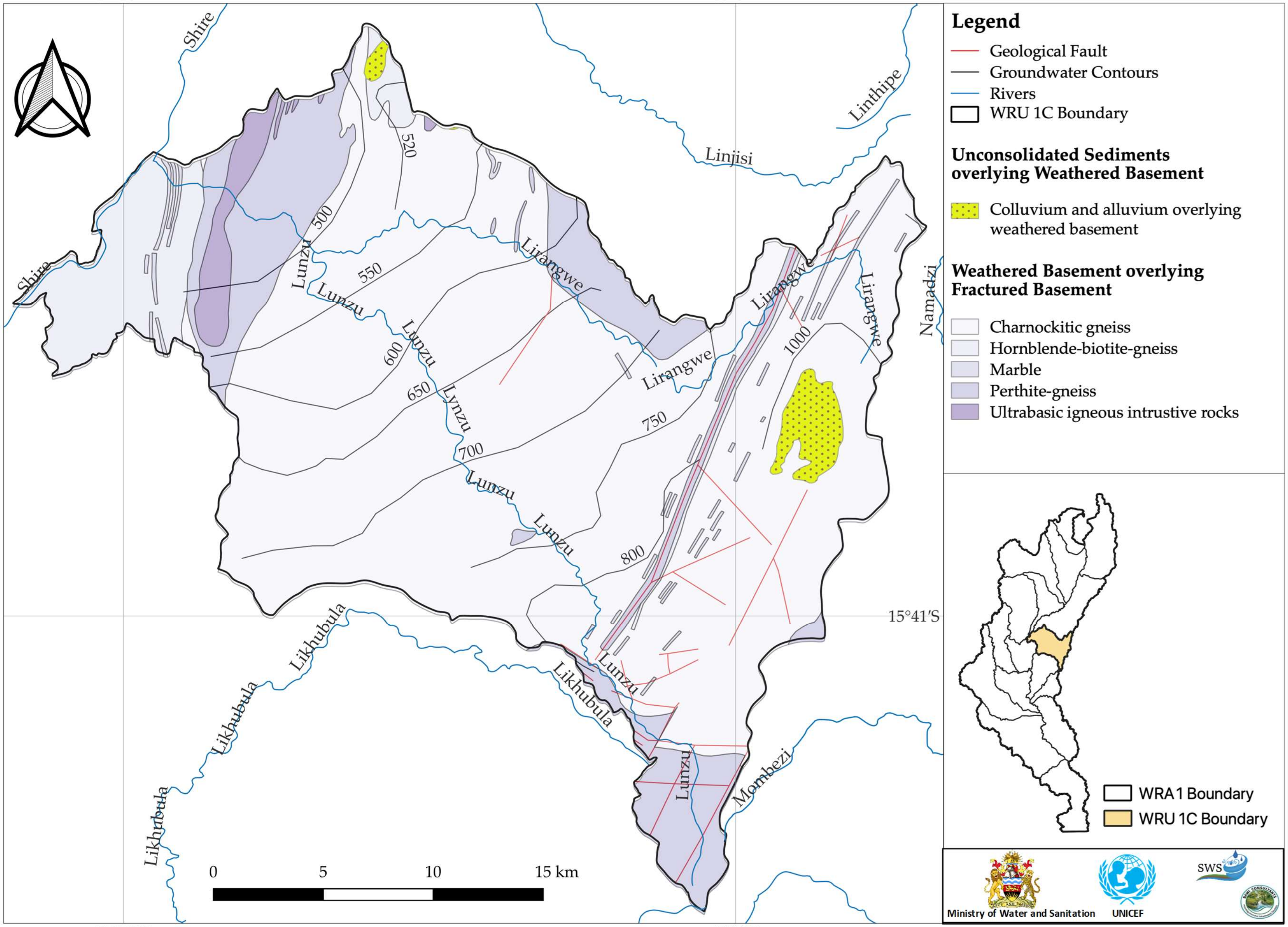


Figure WRU 1C.4 Groundwater Chemistry Distribution Electrical Conductivity

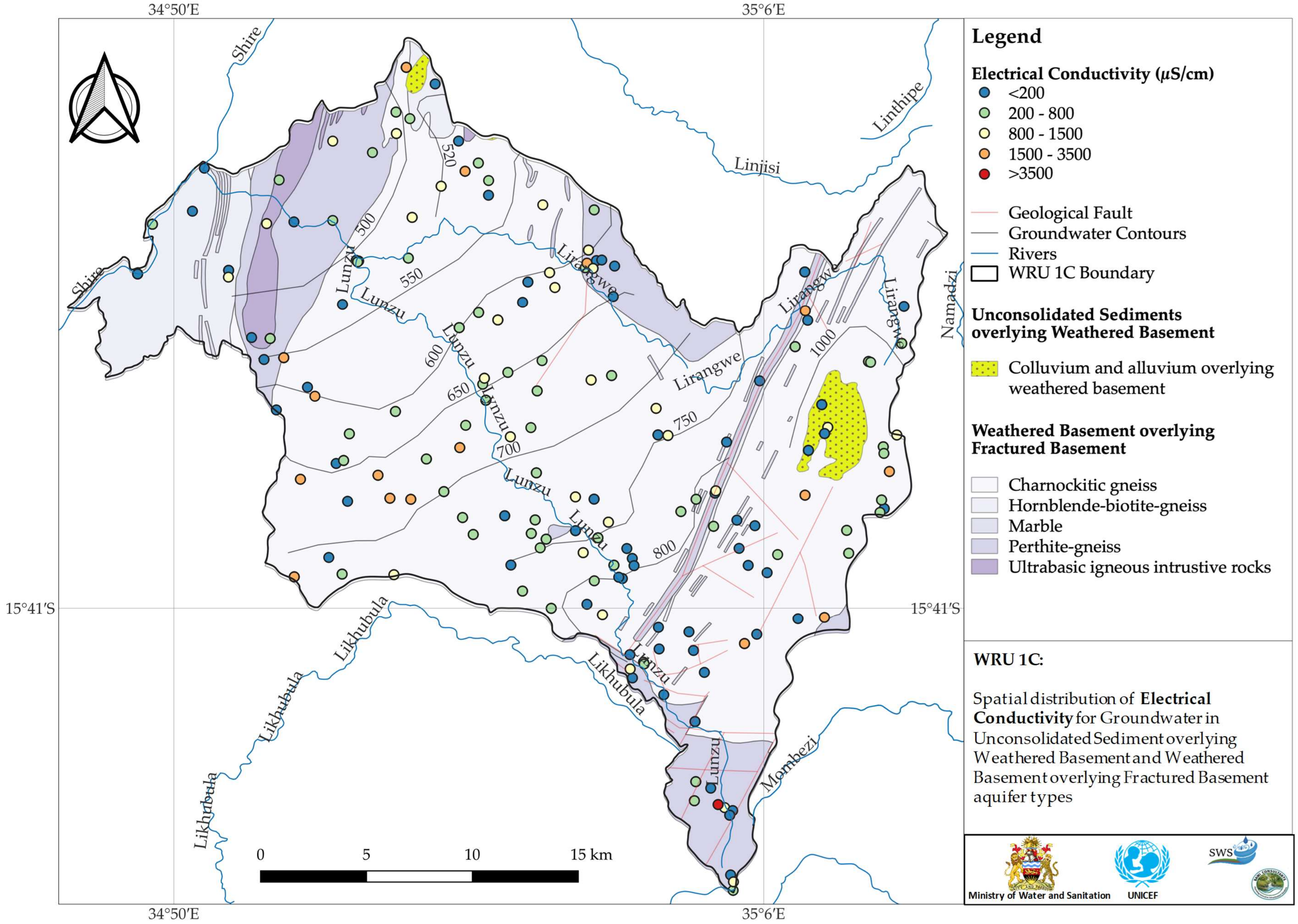


Figure WRU 1C.5 Groundwater Chemistry Distribution Sulphate

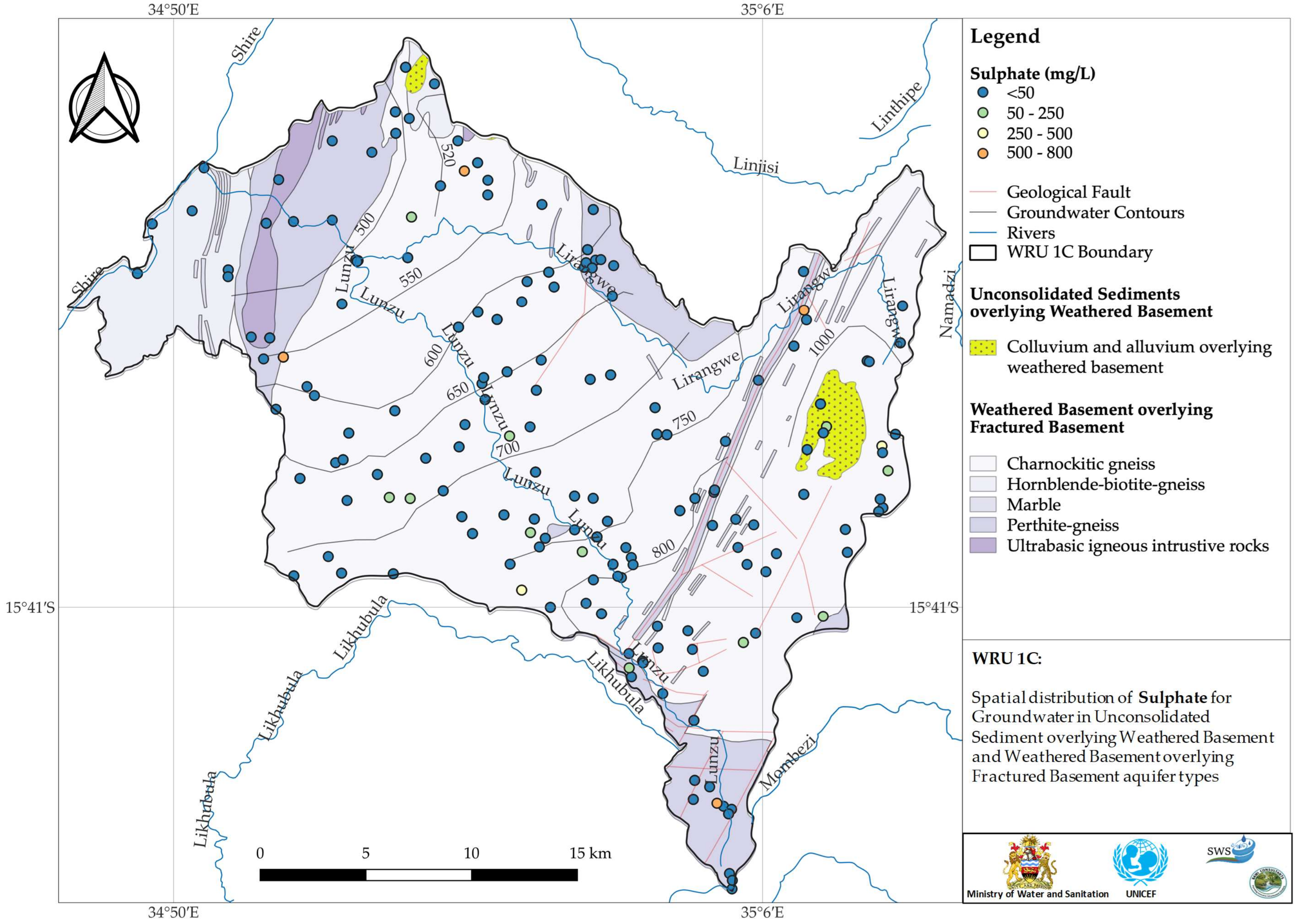


Figure WRU 1C.6 Groundwater Chemistry Distribution Chloride

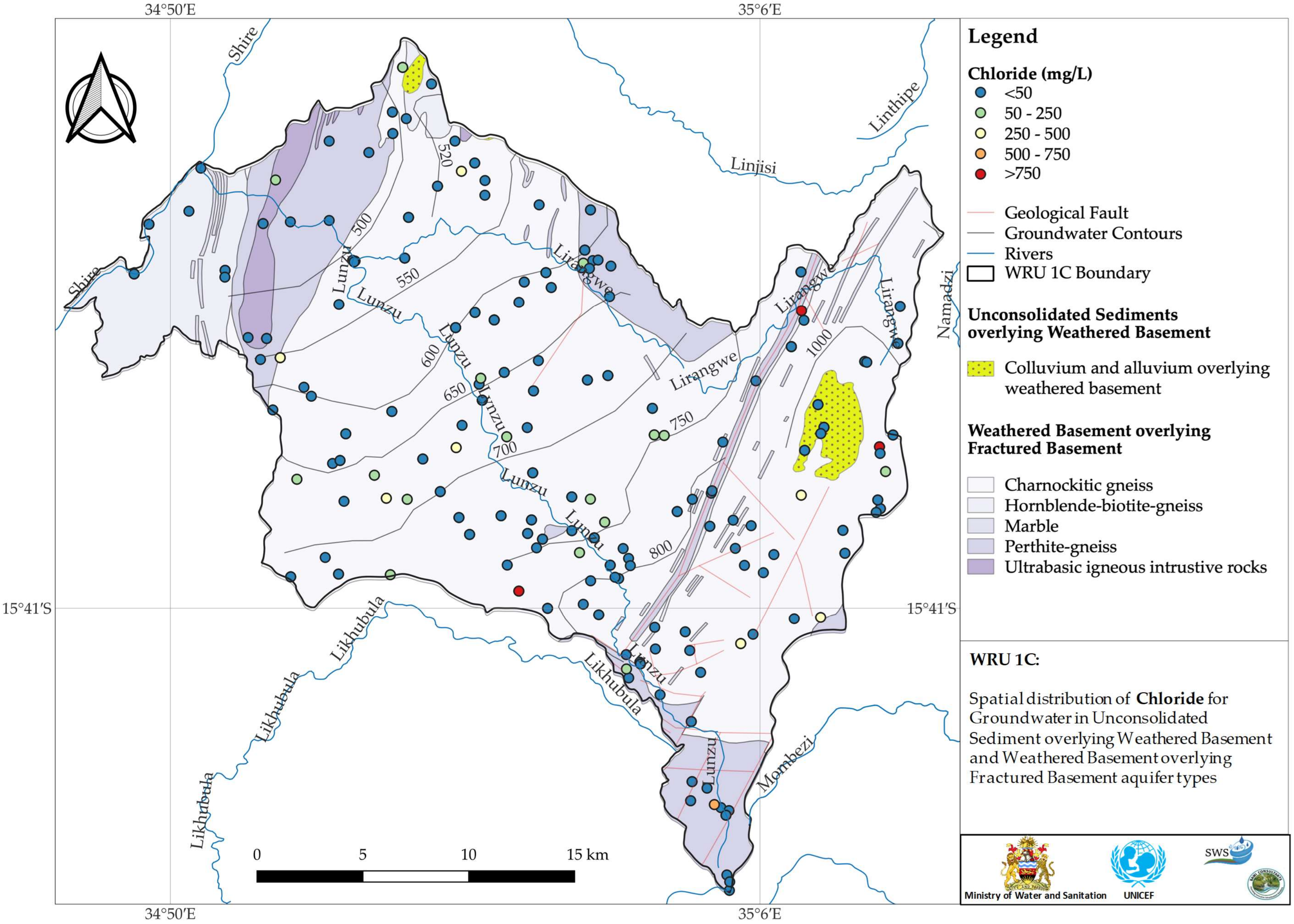


Figure WRU 1C.7 Groundwater Chemistry Distribution Sodium

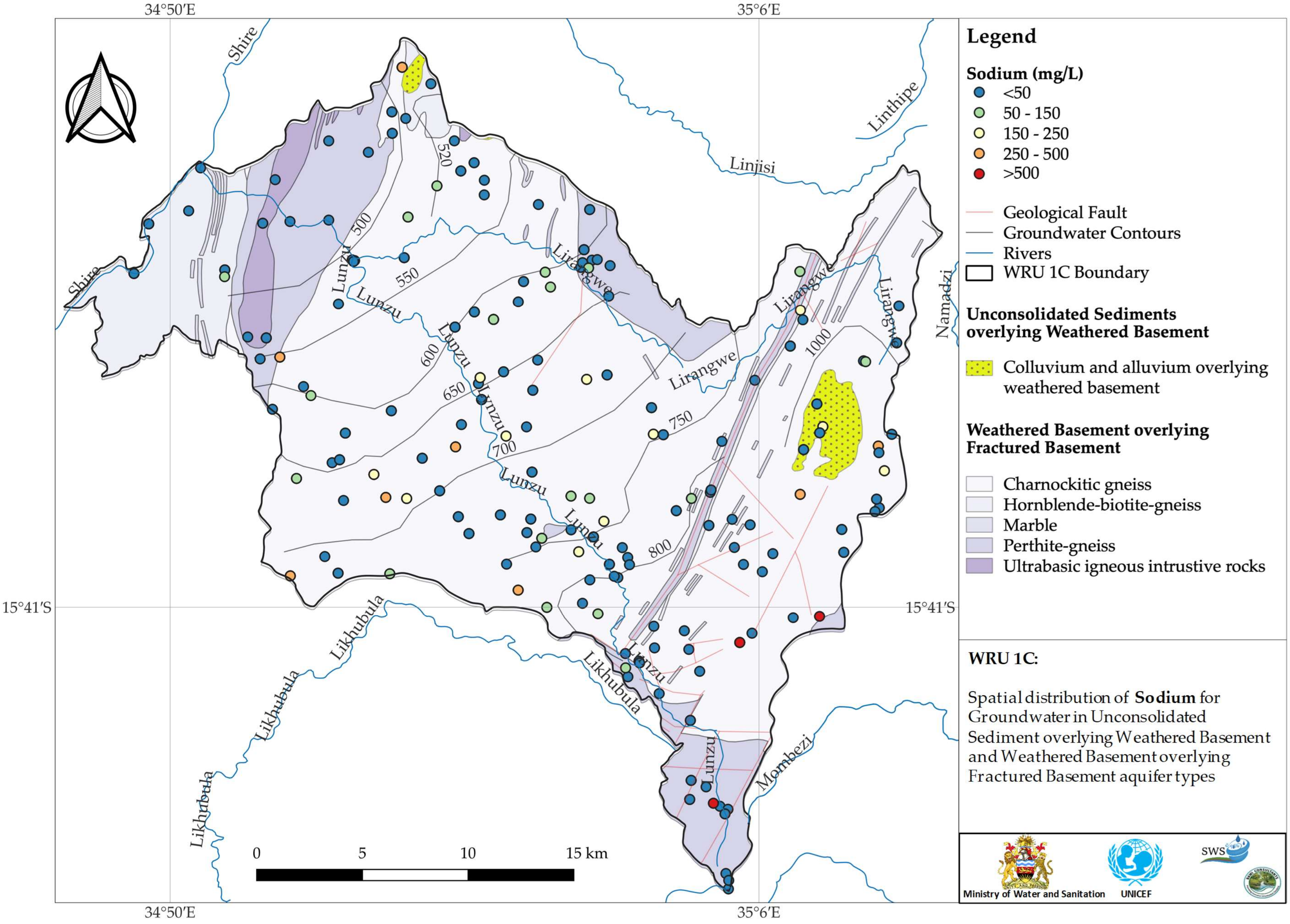


Figure WRU 1C.8 Groundwater Chemistry Distribution Calcium

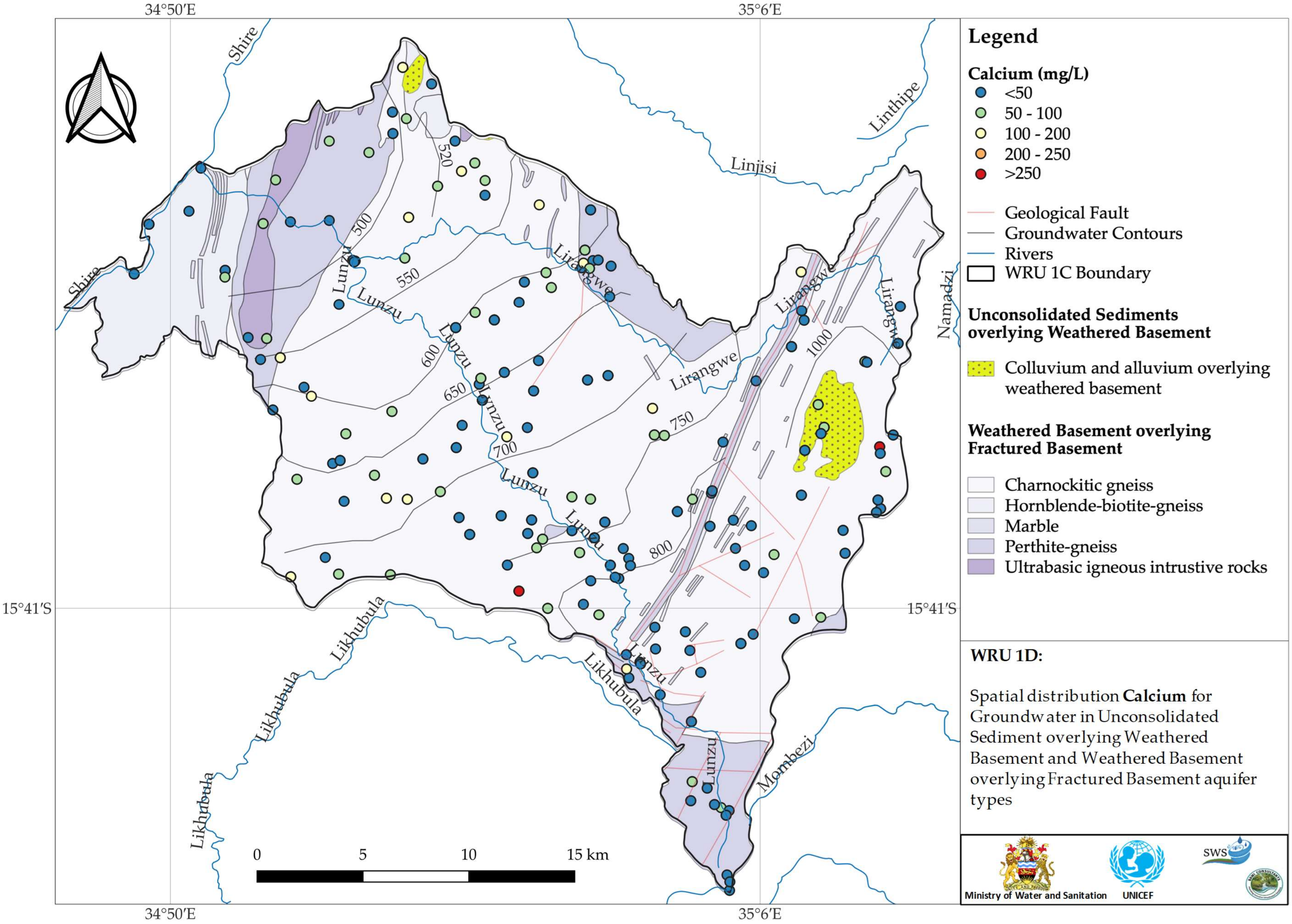


Figure WRU 1C.9 Piper Diagram of water quality results with respect to the major aquifer type

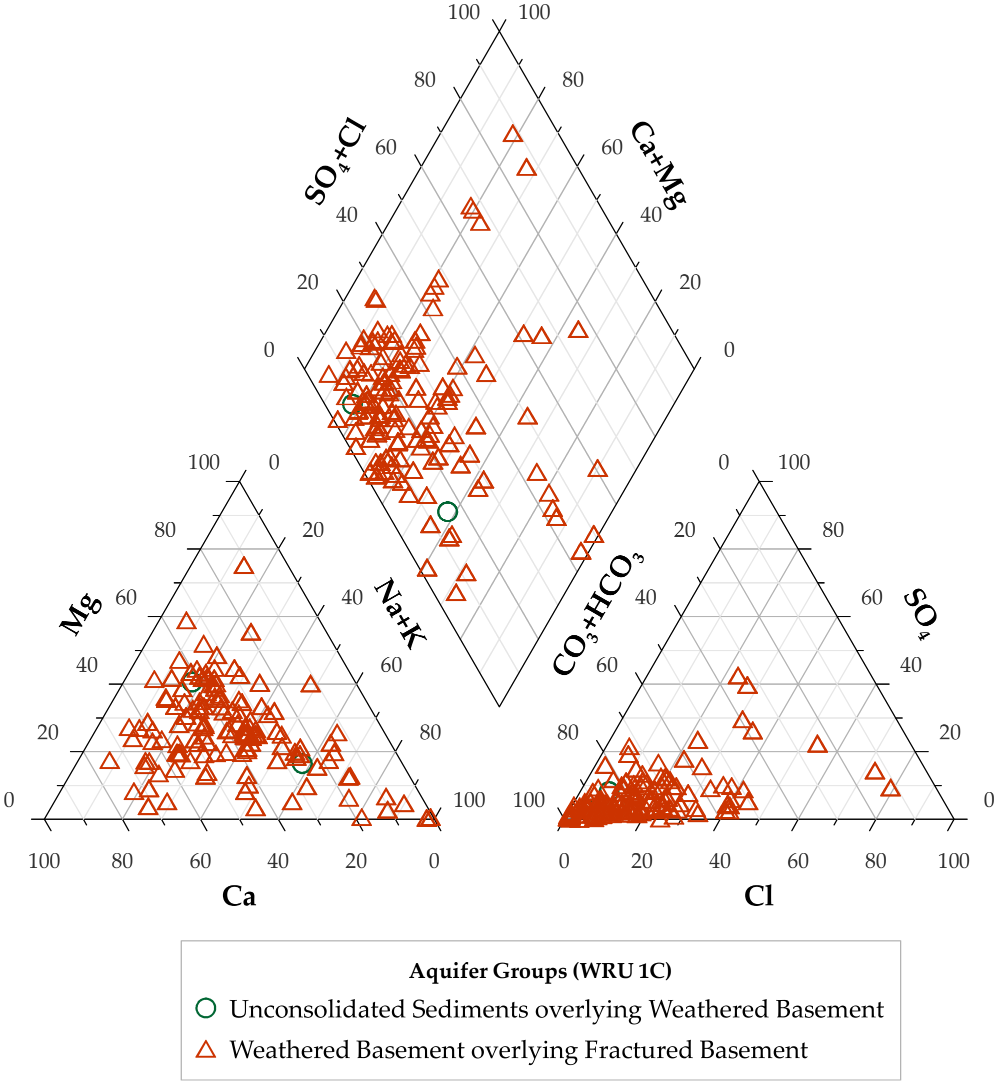
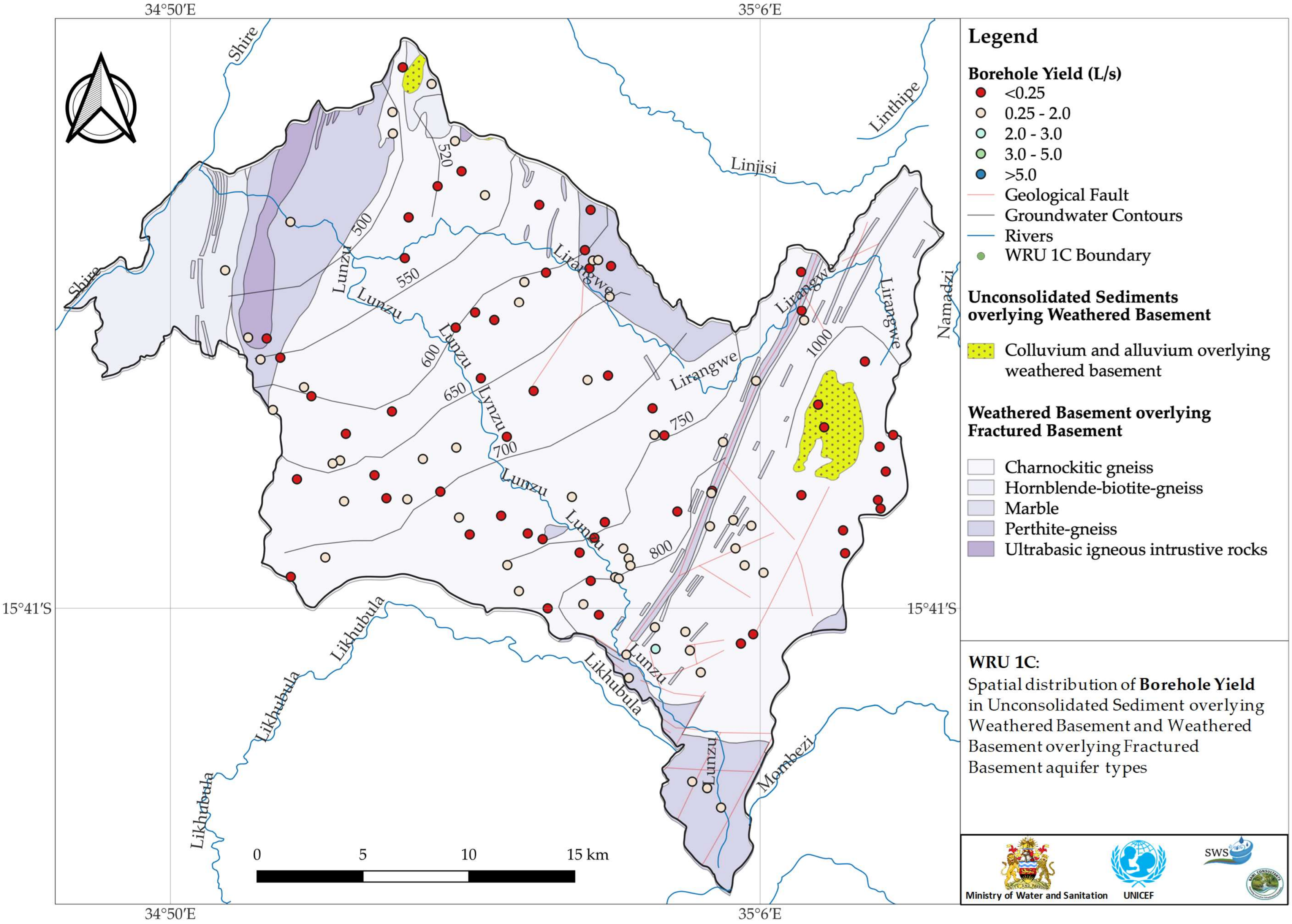


Figure WRU 1C.10 Borehole Yield Map for data held by the Ministry



WRU 1D Figures

Figure WRU 1D.1 Land Use and Major Roads

Figure WRU 1D.2 Rivers and Wetlands

Figure WRU 1D.3 Hydrogeology Units and Water Table

Figure WRU 1D.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 1D.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 1D.6 Groundwater Chemistry Distribution Chloride

Figure WRU 1D.7 Groundwater Chemistry Distribution Sodium

Figure WRU 1D.8 Groundwater Chemistry Distribution Calcium

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

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

Figure WRU 1D.1 Land Use and Major Roads

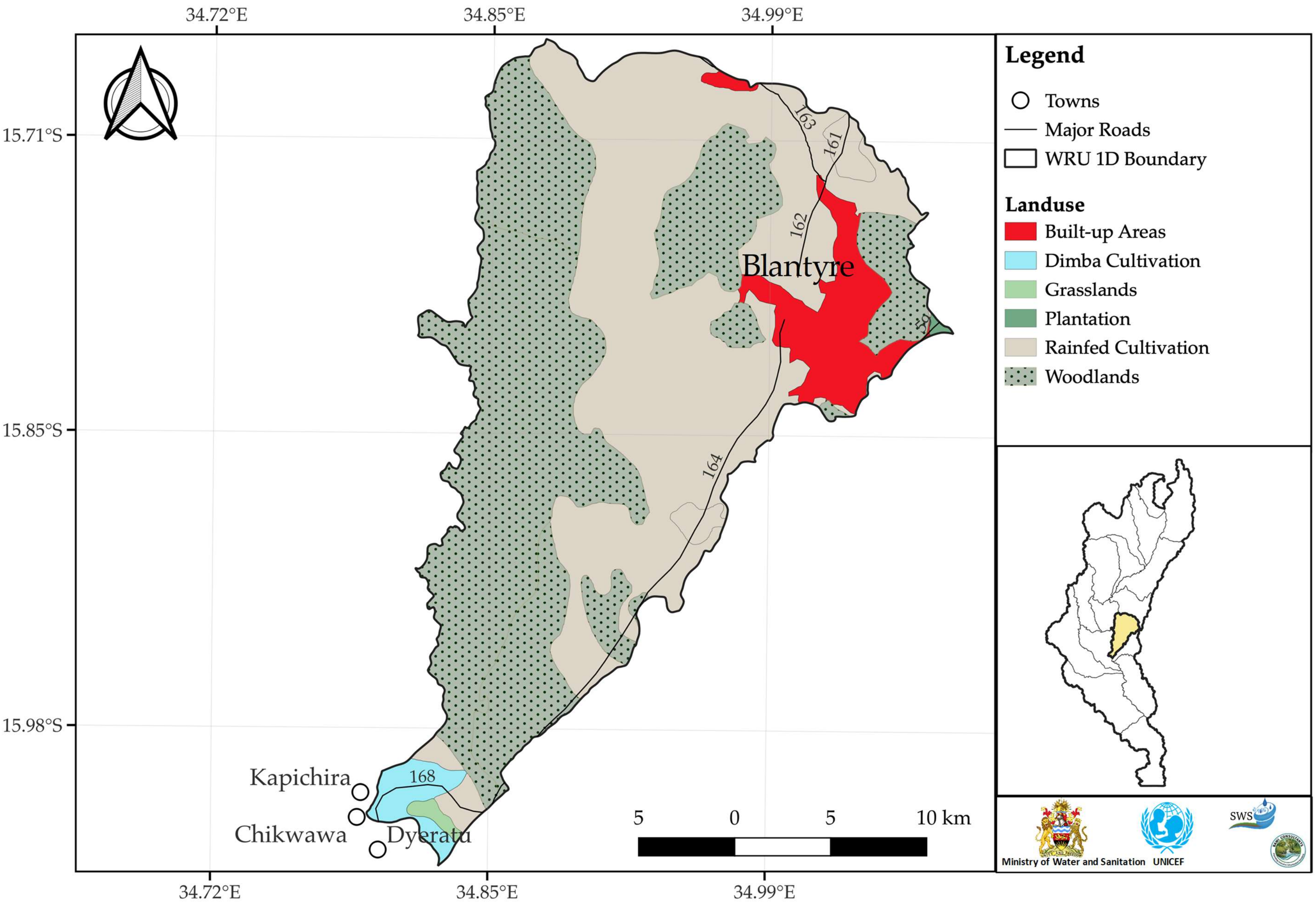


Figure WRU 1D.2 Rivers and Wetlands

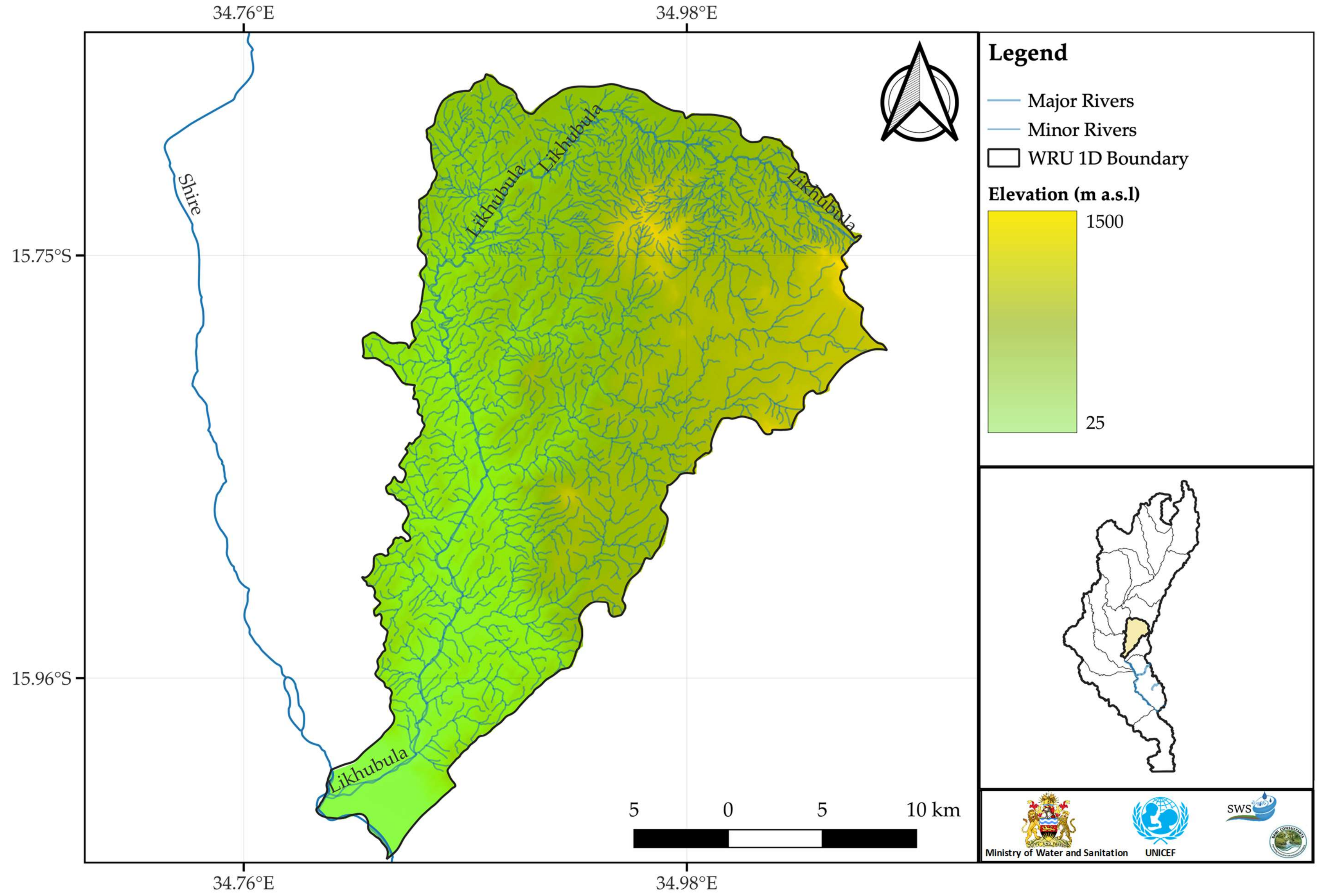


Figure WRU 1D.3 Hydrogeology Units and Water Table

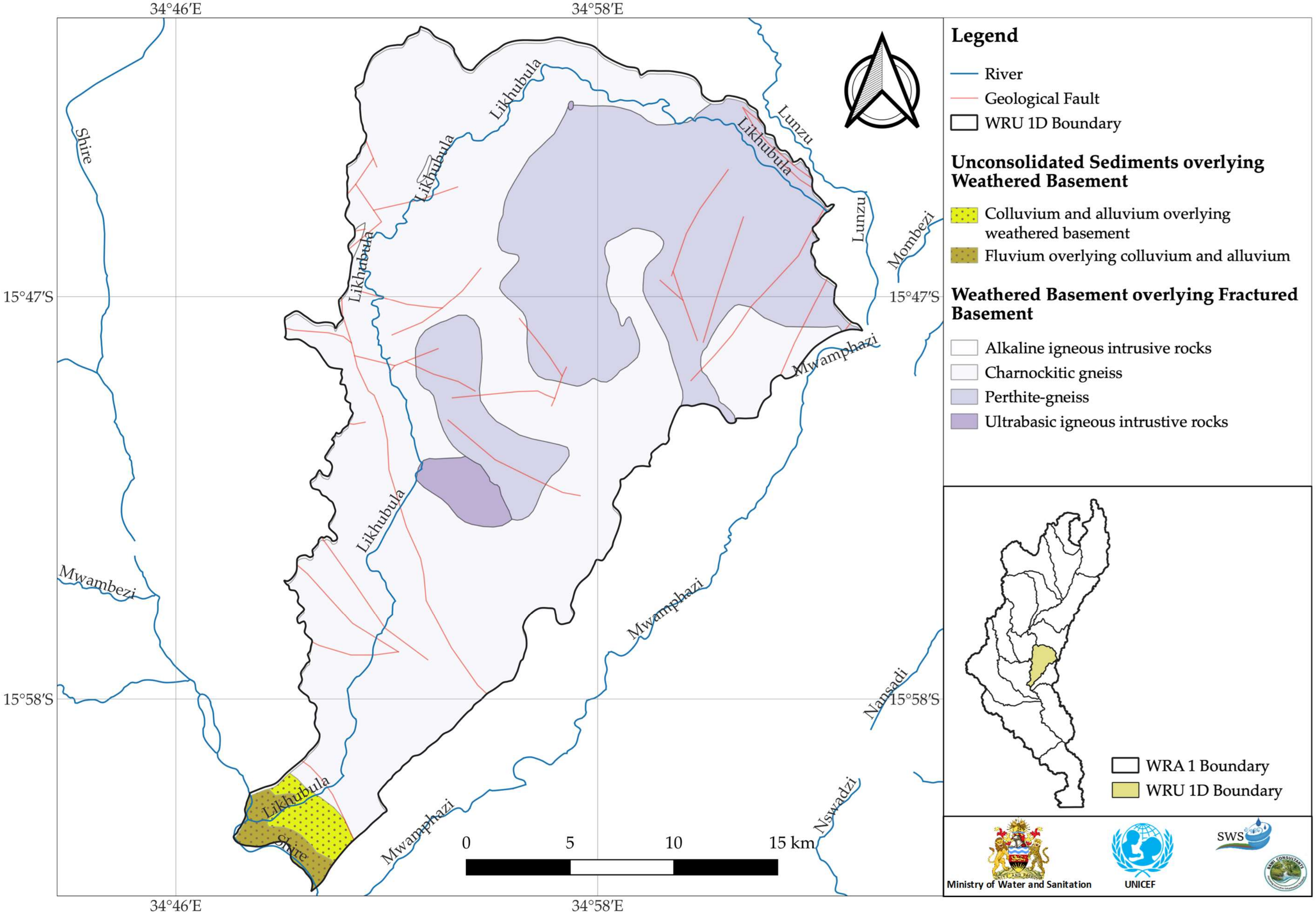
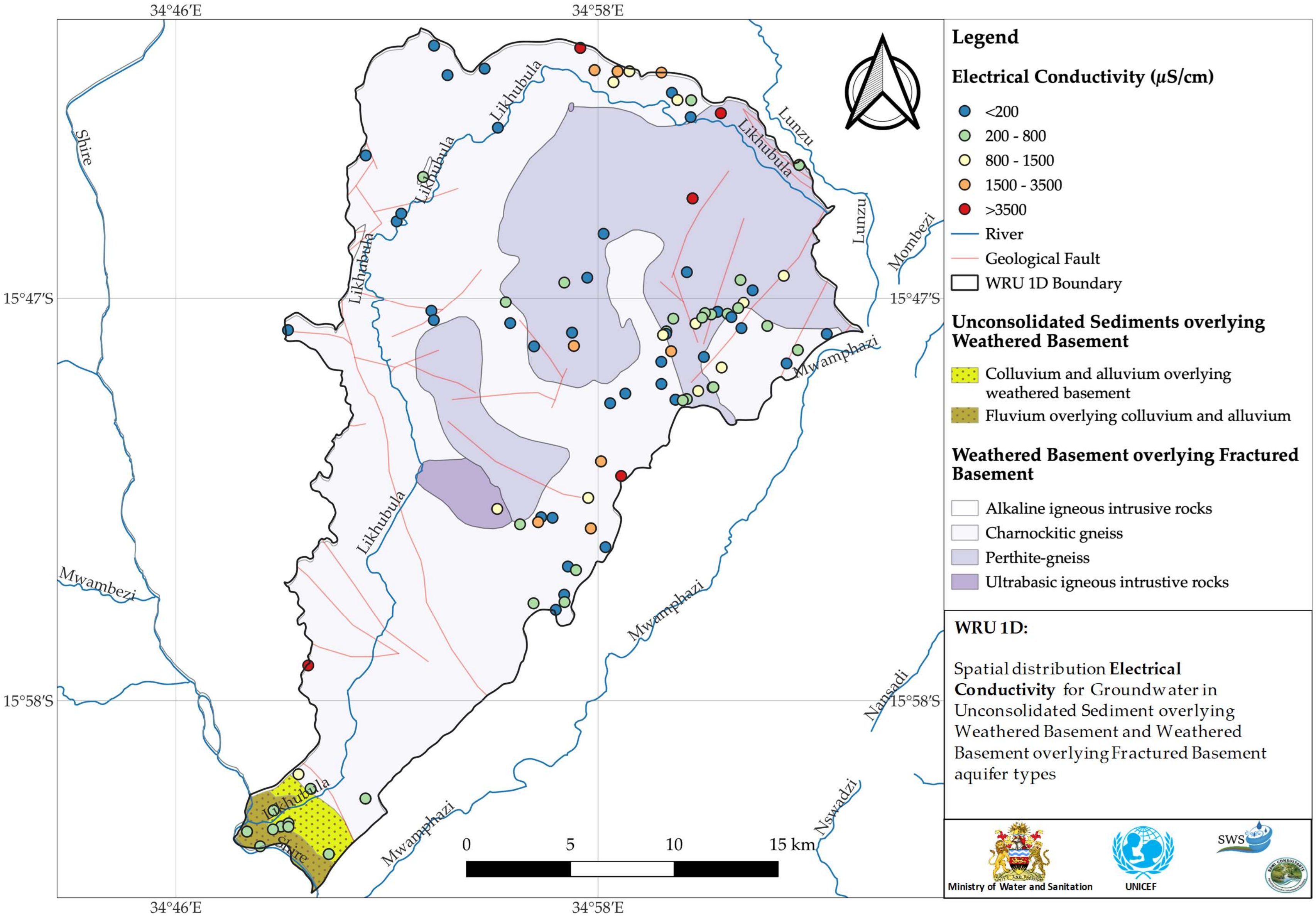


Figure WRU 1D.4 Groundwater Chemistry Distribution Electrical Conductivity



WRU 1D:

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

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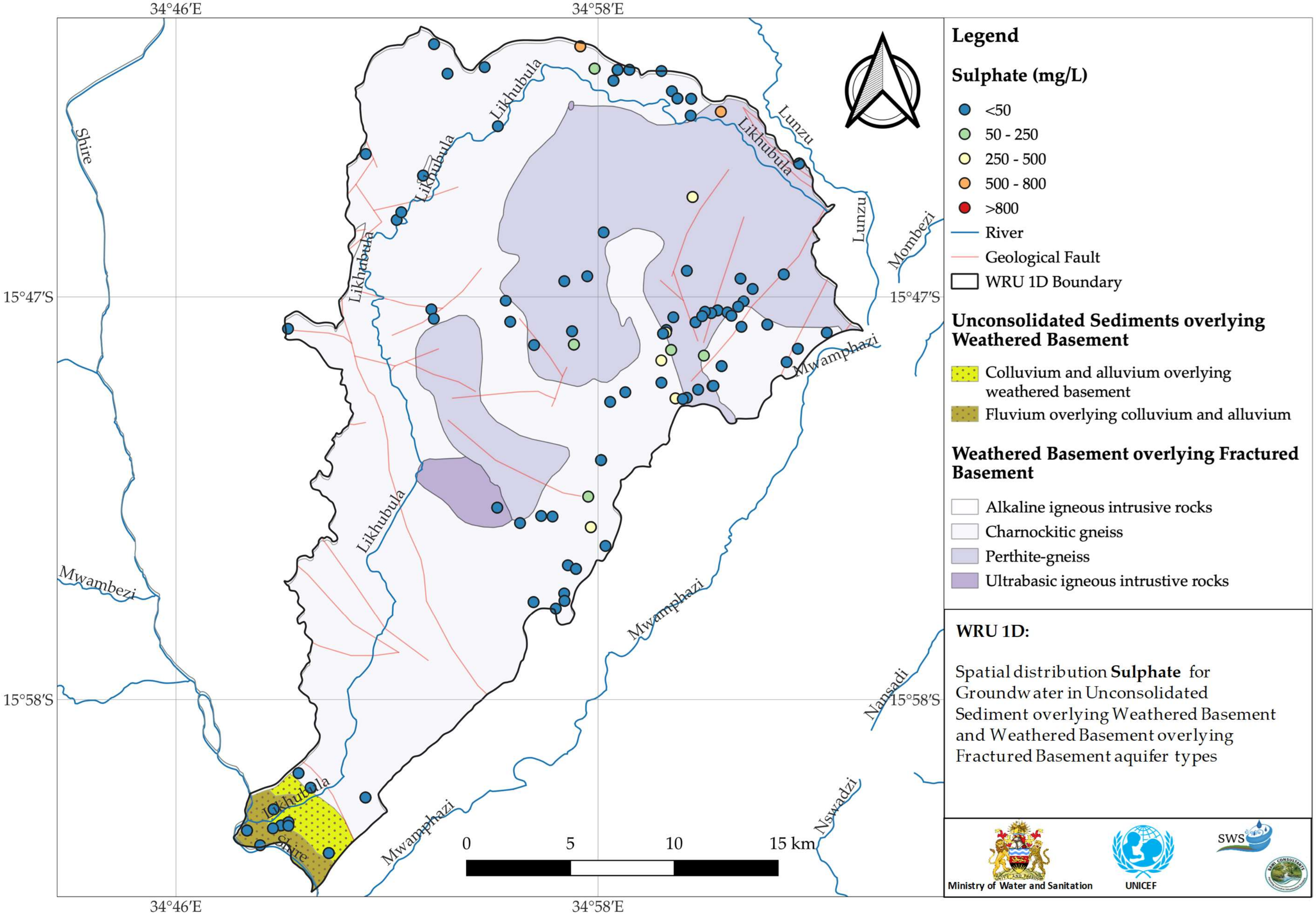
Figure WRU 1D.5 Groundwater Chemistry Distribution of Sulphate



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

Figure WRU 1D.6 Groundwater Chemistry Distribution Chloride

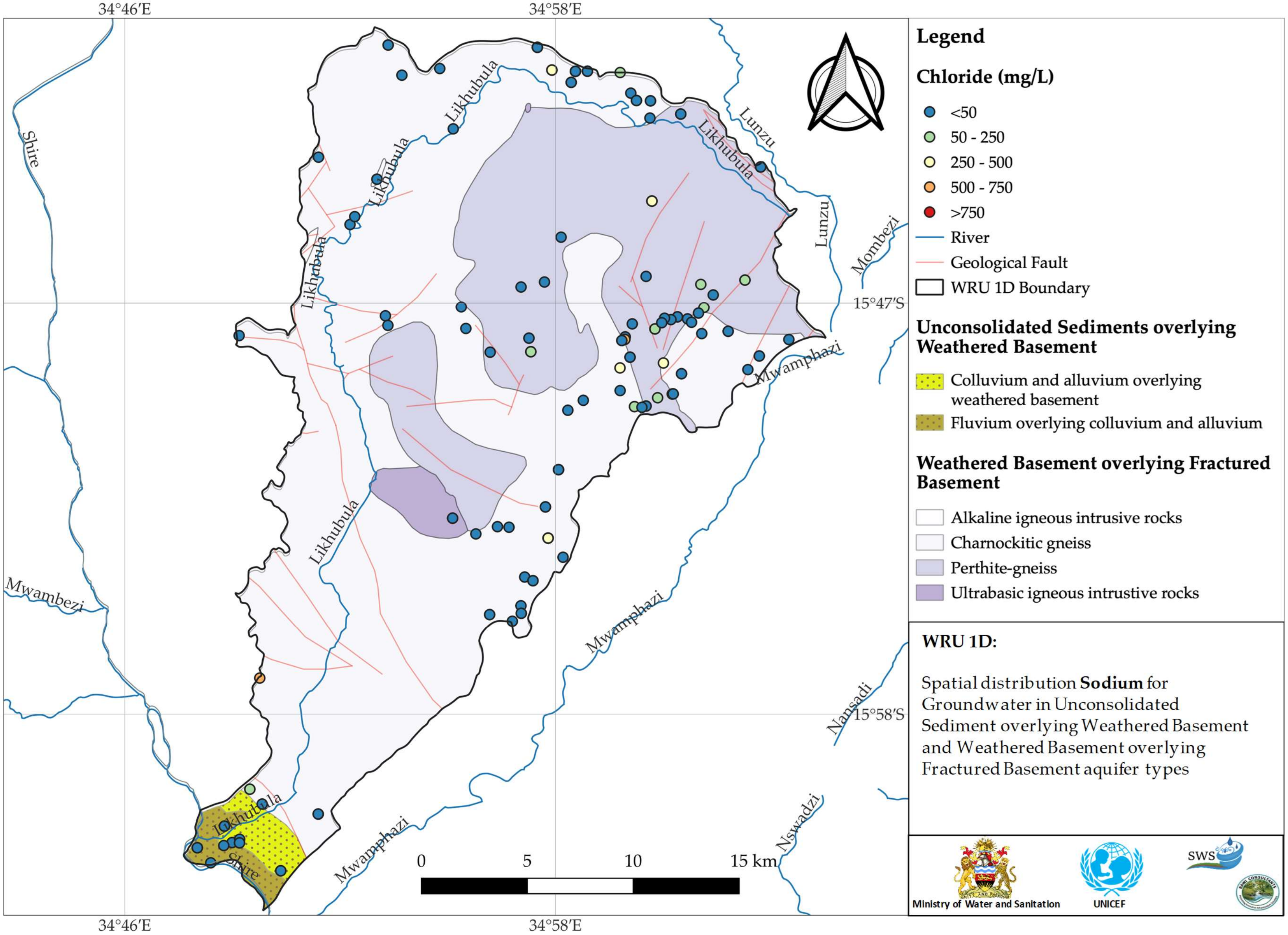
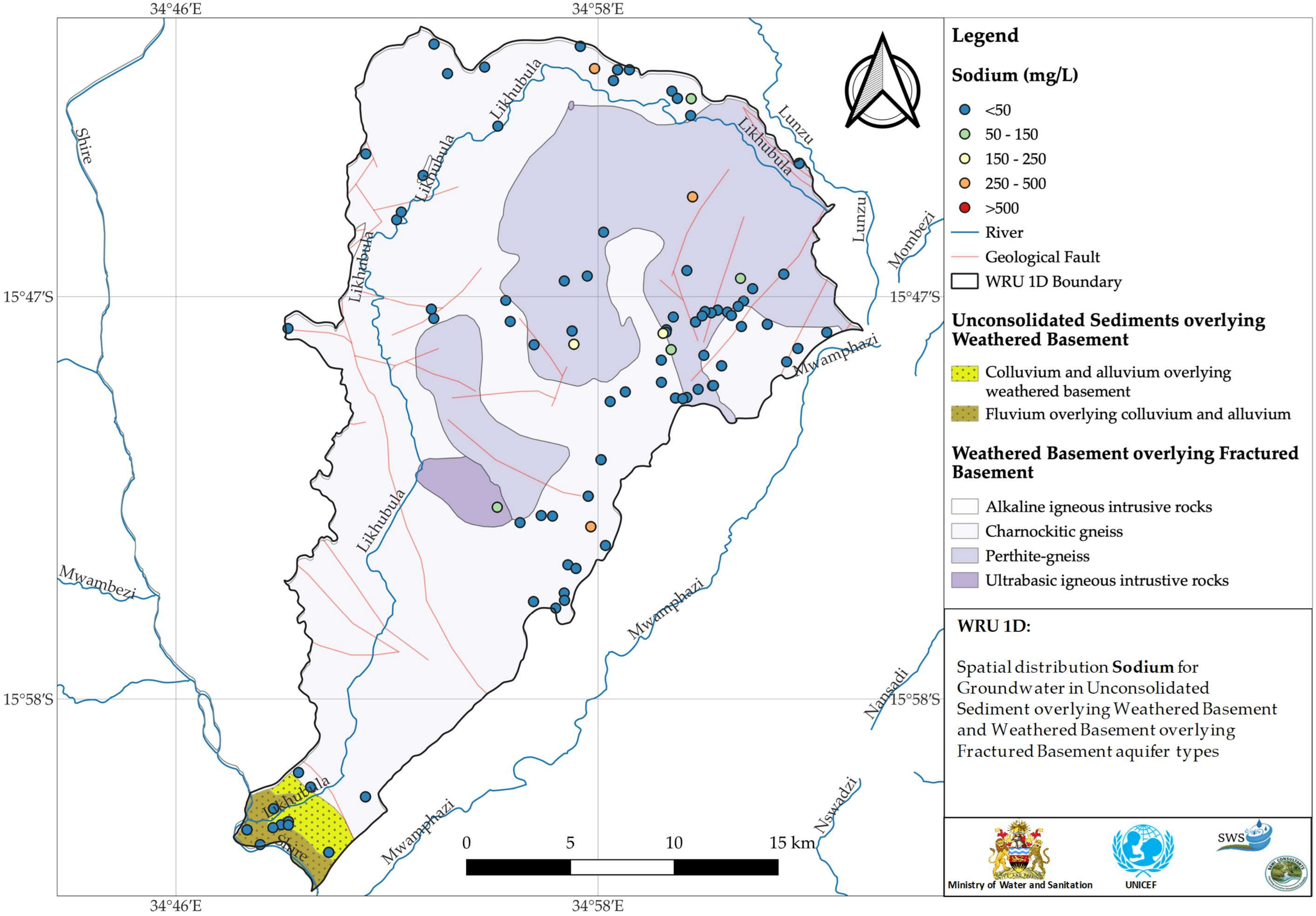


Figure WRU 1D.7 Groundwater Chemistry Distribution Sodium



WRU 1D:

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

Figure WRU 1D.8 Groundwater Chemistry Distribution Calcium

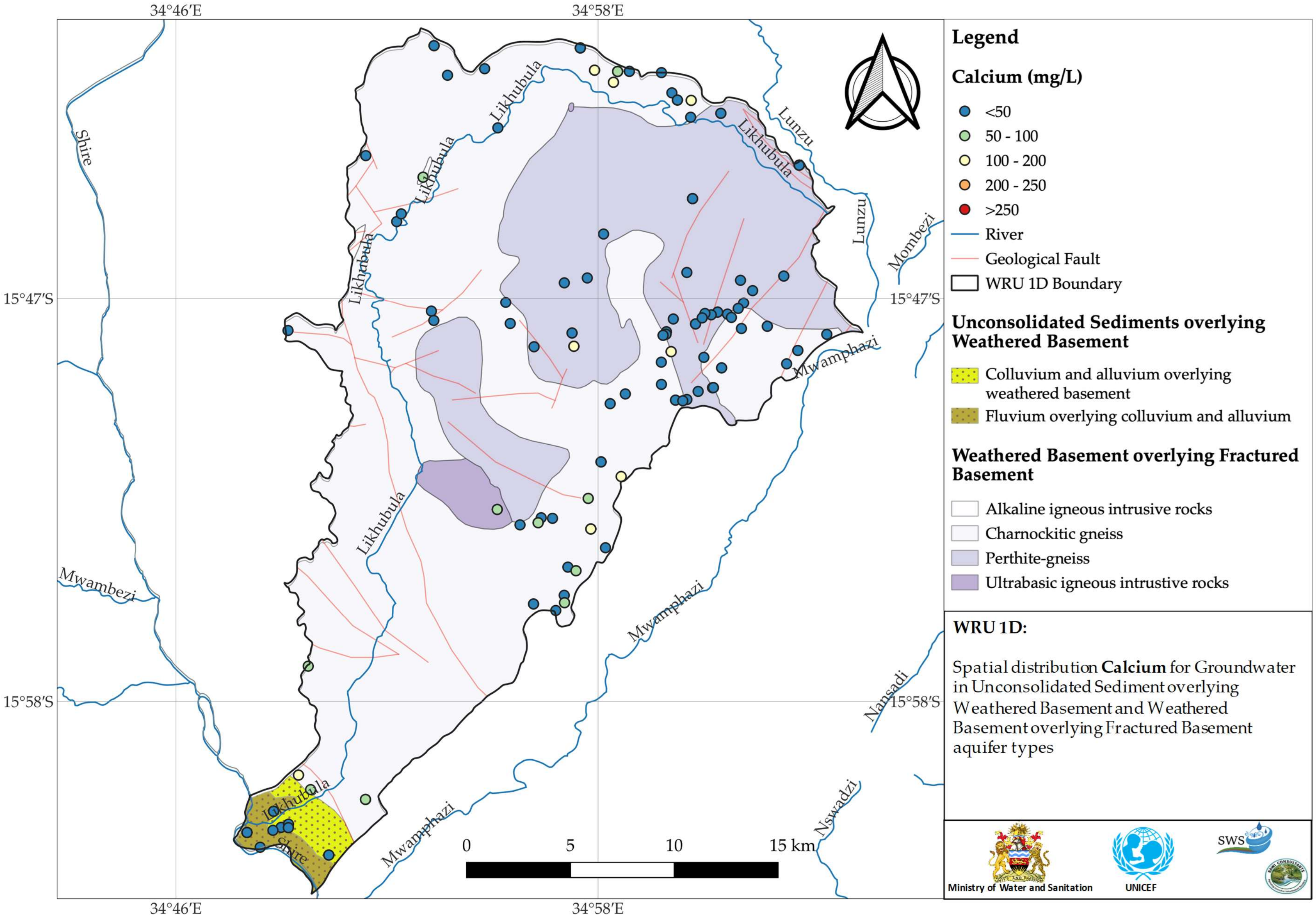


Figure WRU 1D.9 Piper Diagram of water quality results with respect to the major aquifer type

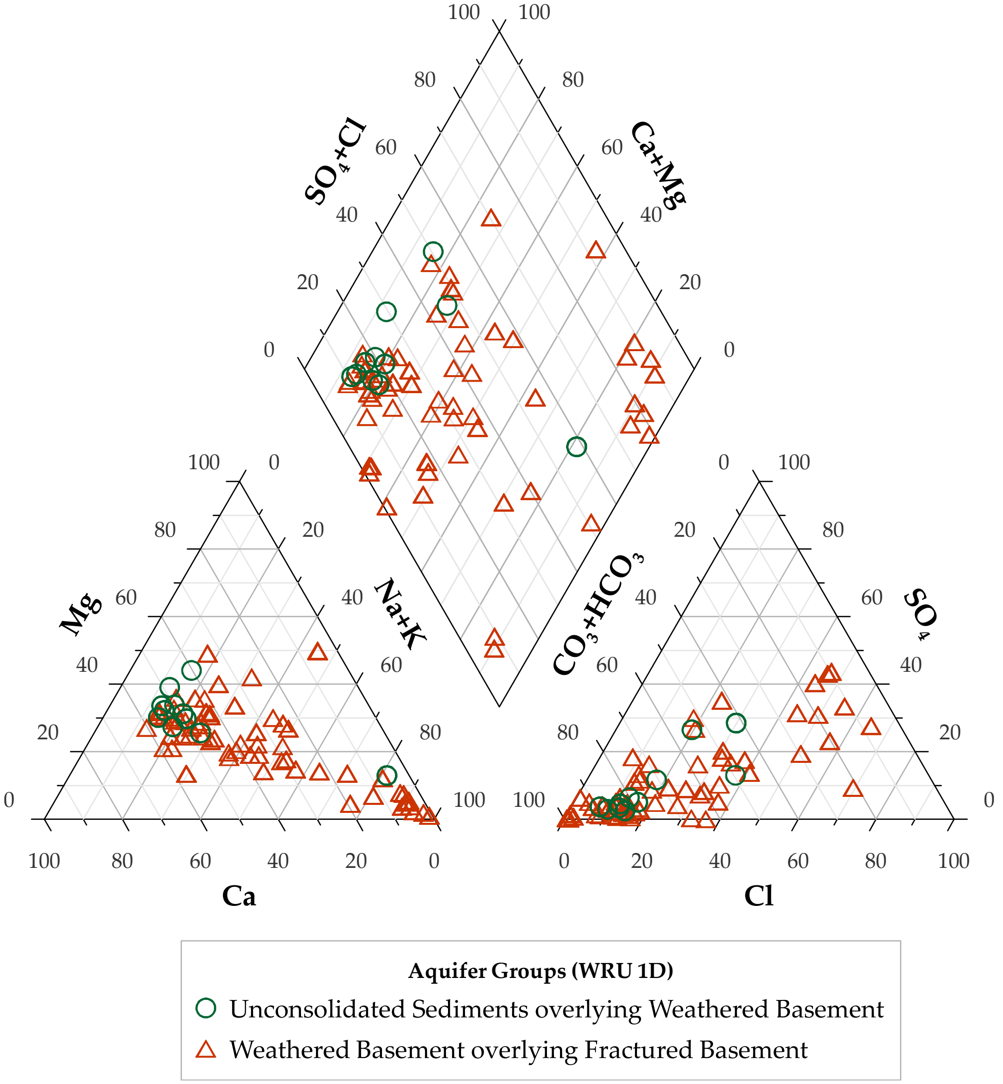
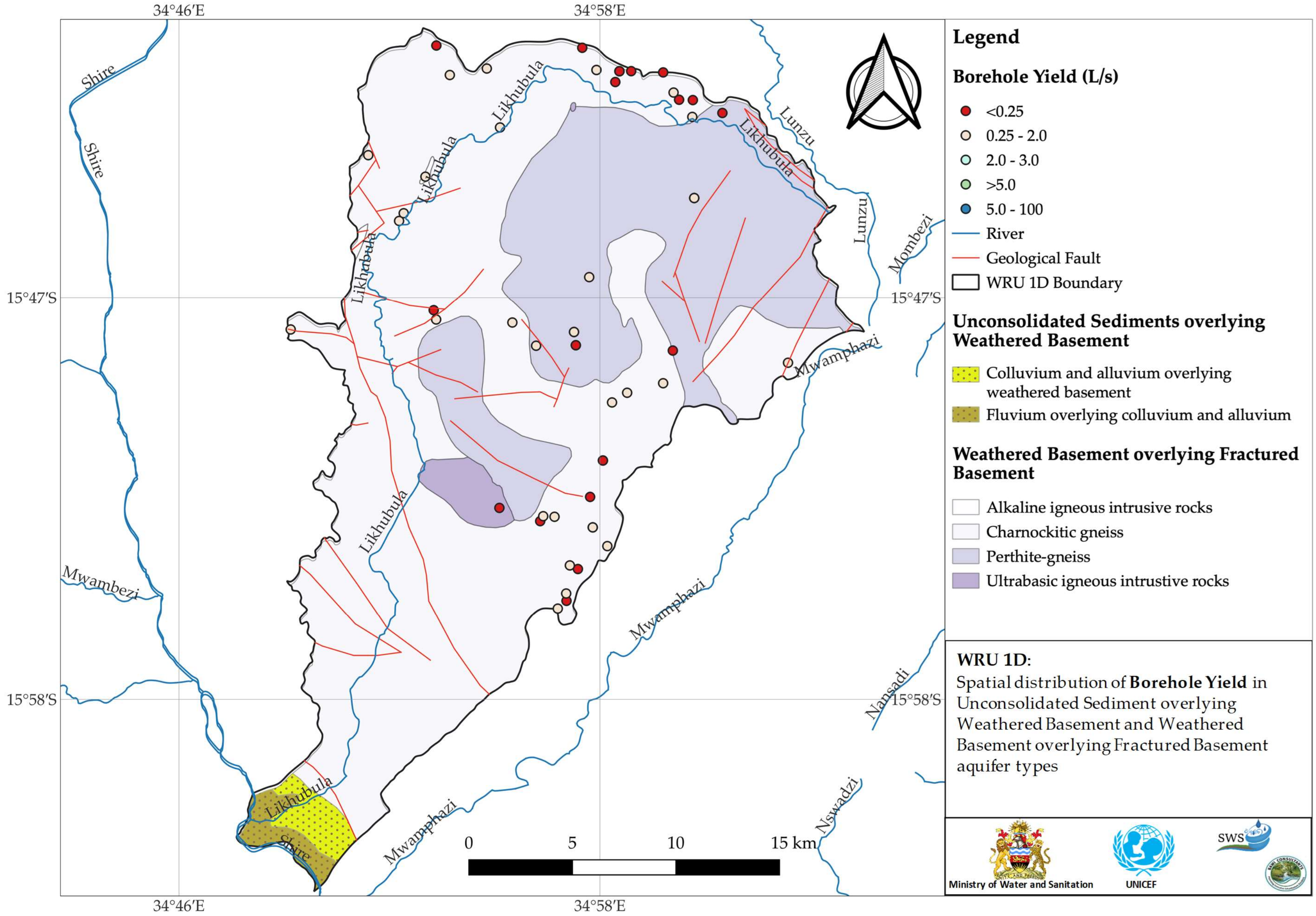


Figure WRU 1D.10 Borehole Yield Map for data held by the Ministry



WRU 1E Figures

Figure WRU 1E.1 Land Use and Major Roads

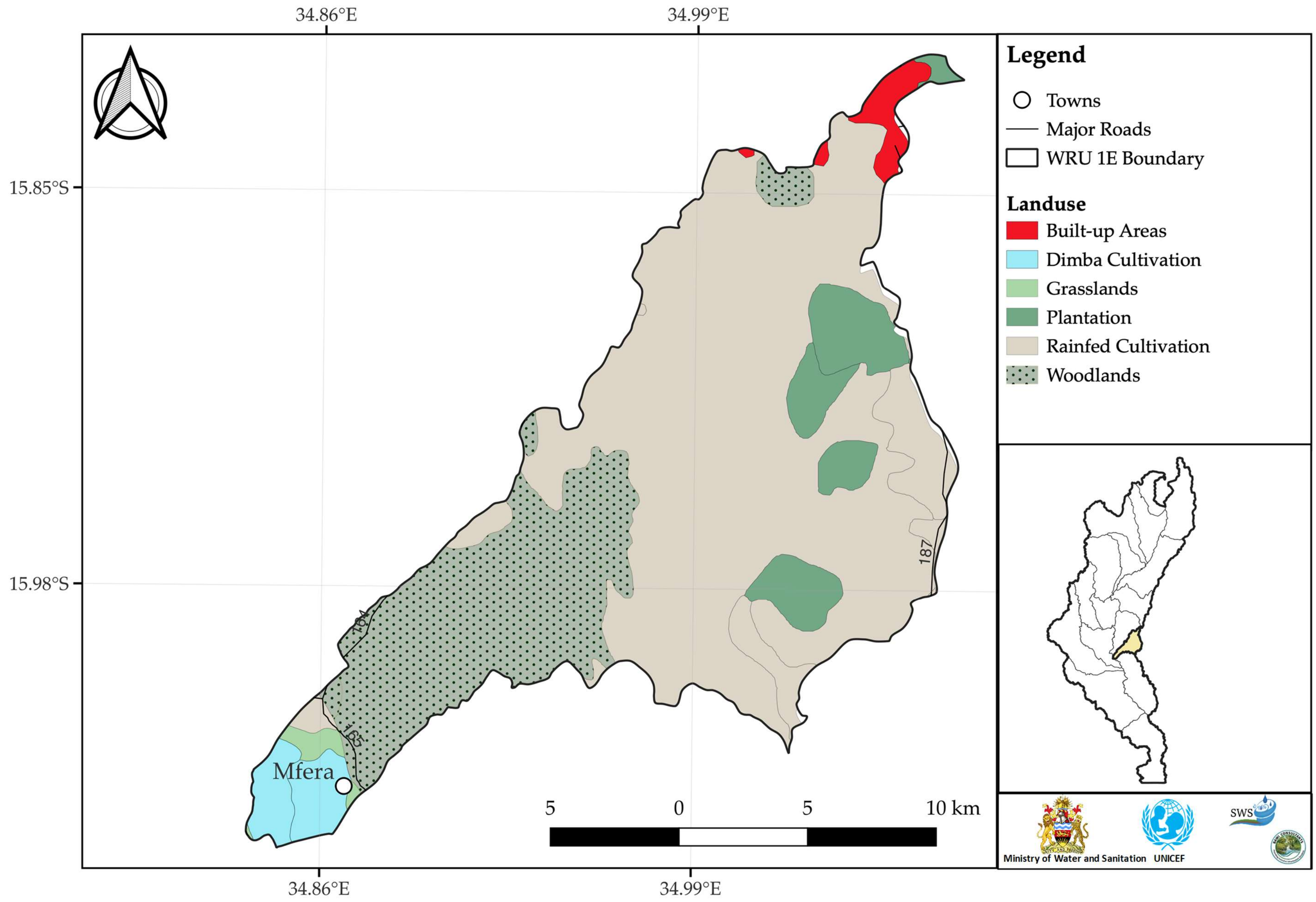


Figure WRU 1E.2 Rivers and Wetlands

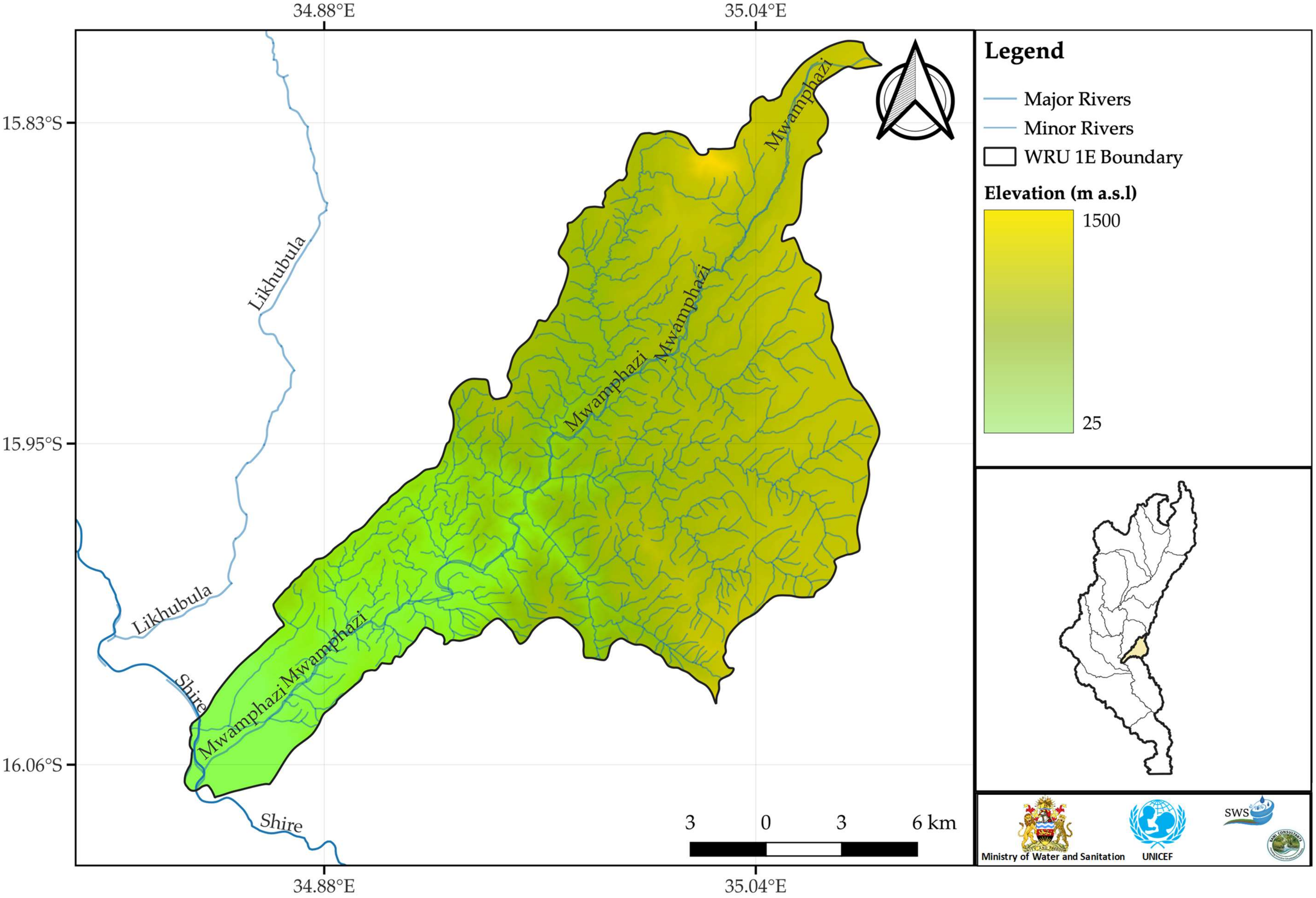


Figure WRU 1E.3 Hydrogeology Units and Water Table

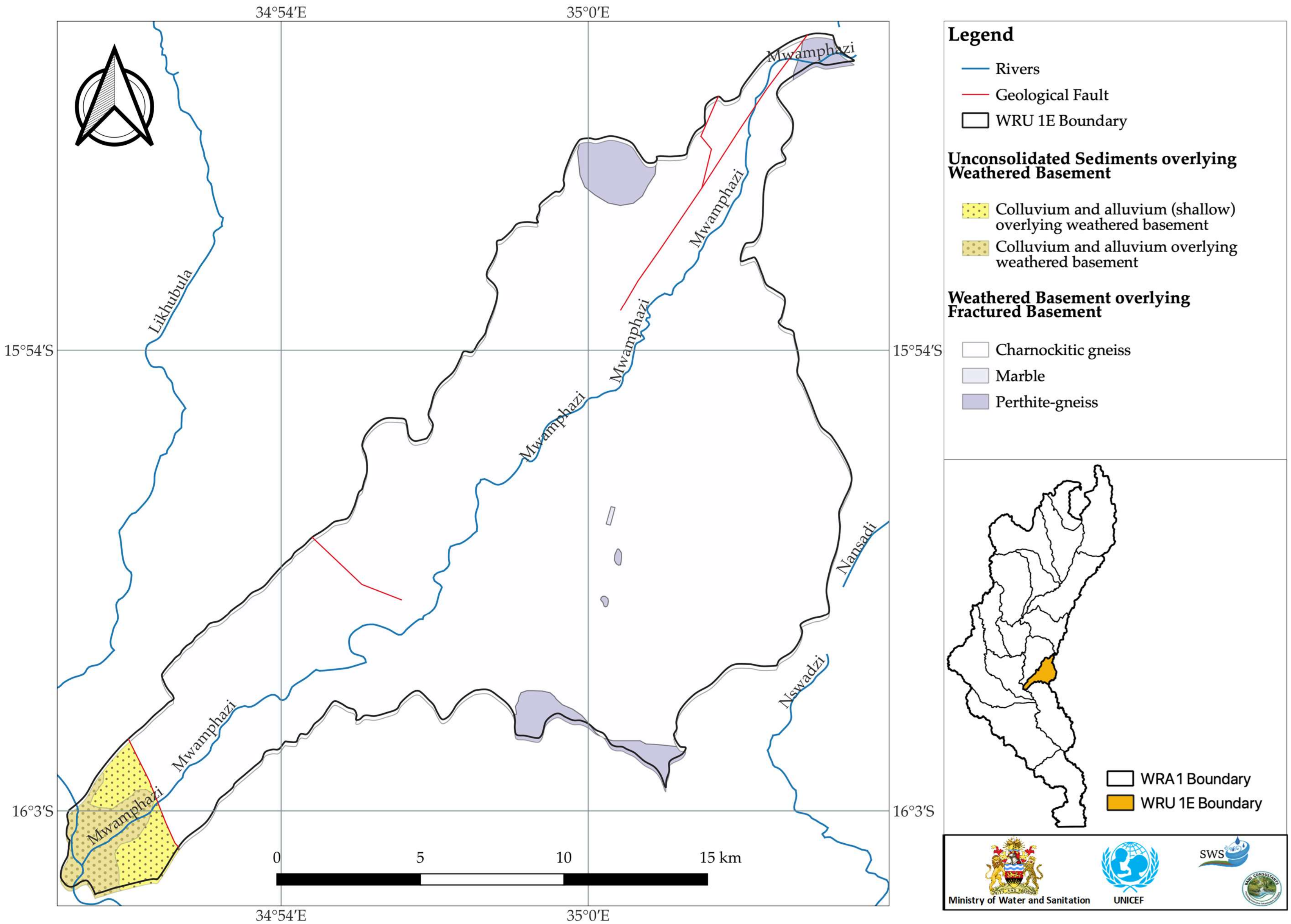


Figure WRU 1E.4 Groundwater Chemistry Distribution Electrical Conductivity

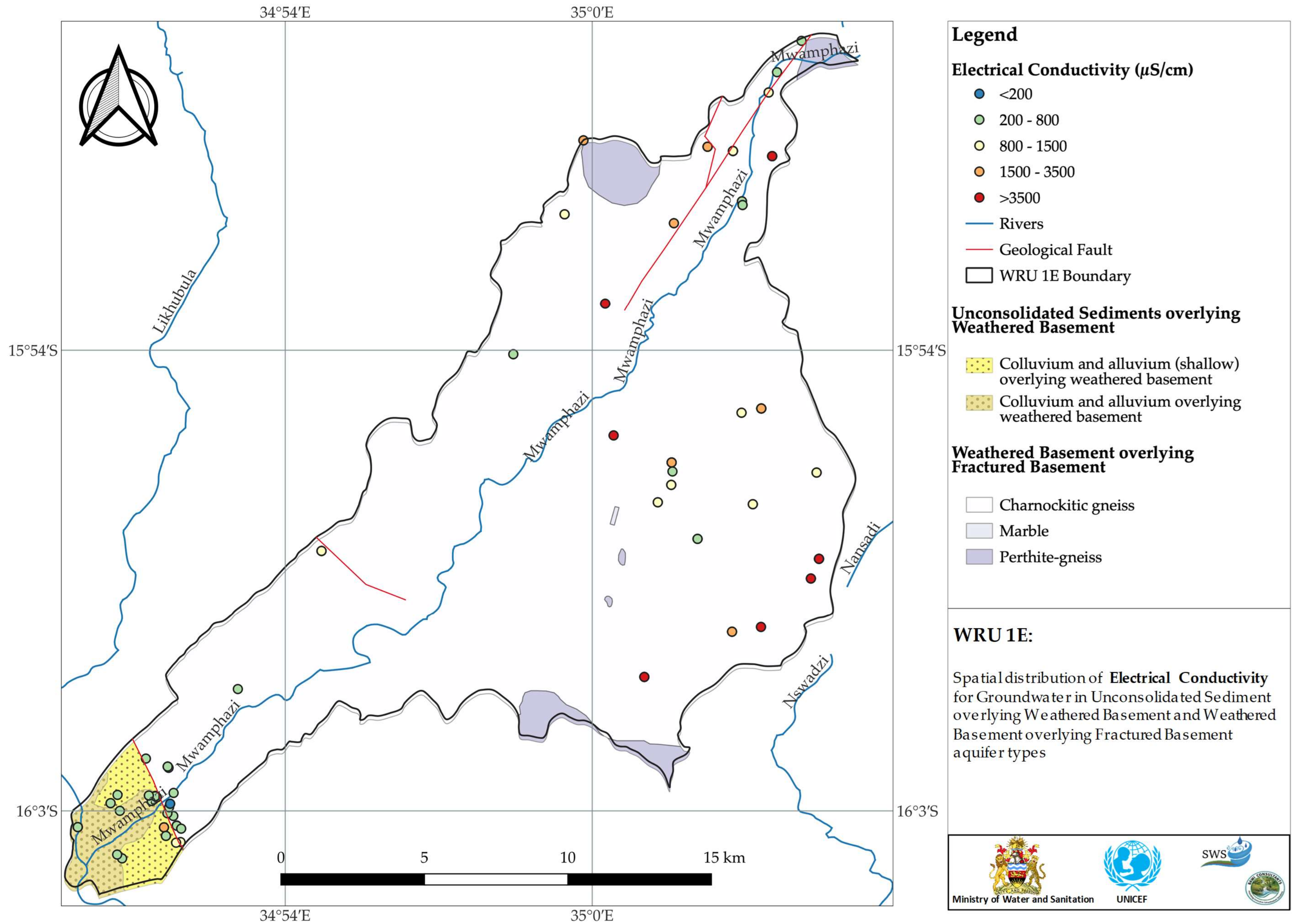
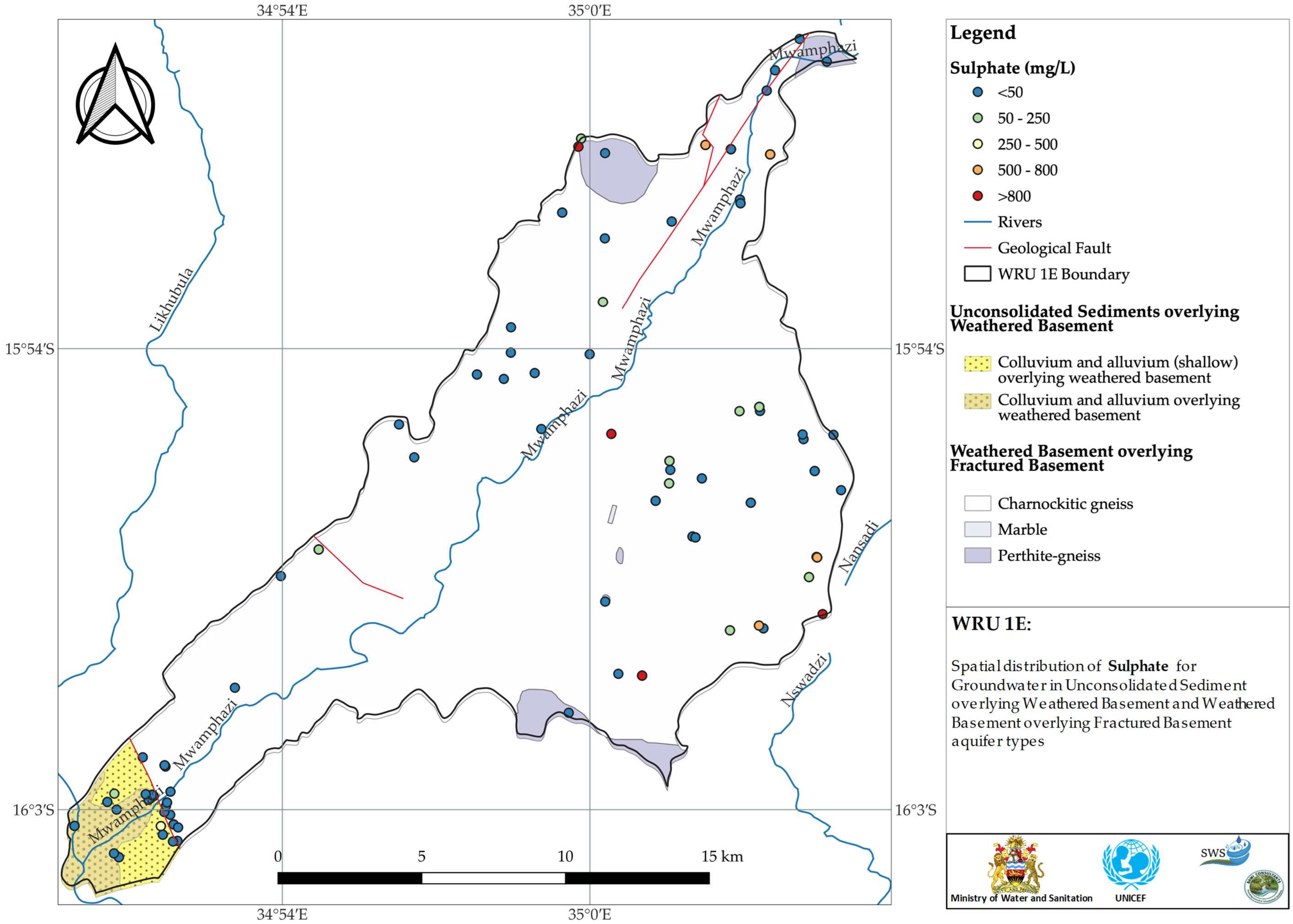


Figure WRU 1E.5 Groundwater Chemistry Distribution of Sulphate



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

Figure WRU 1E.6 Groundwater Chemistry Distribution Chloride

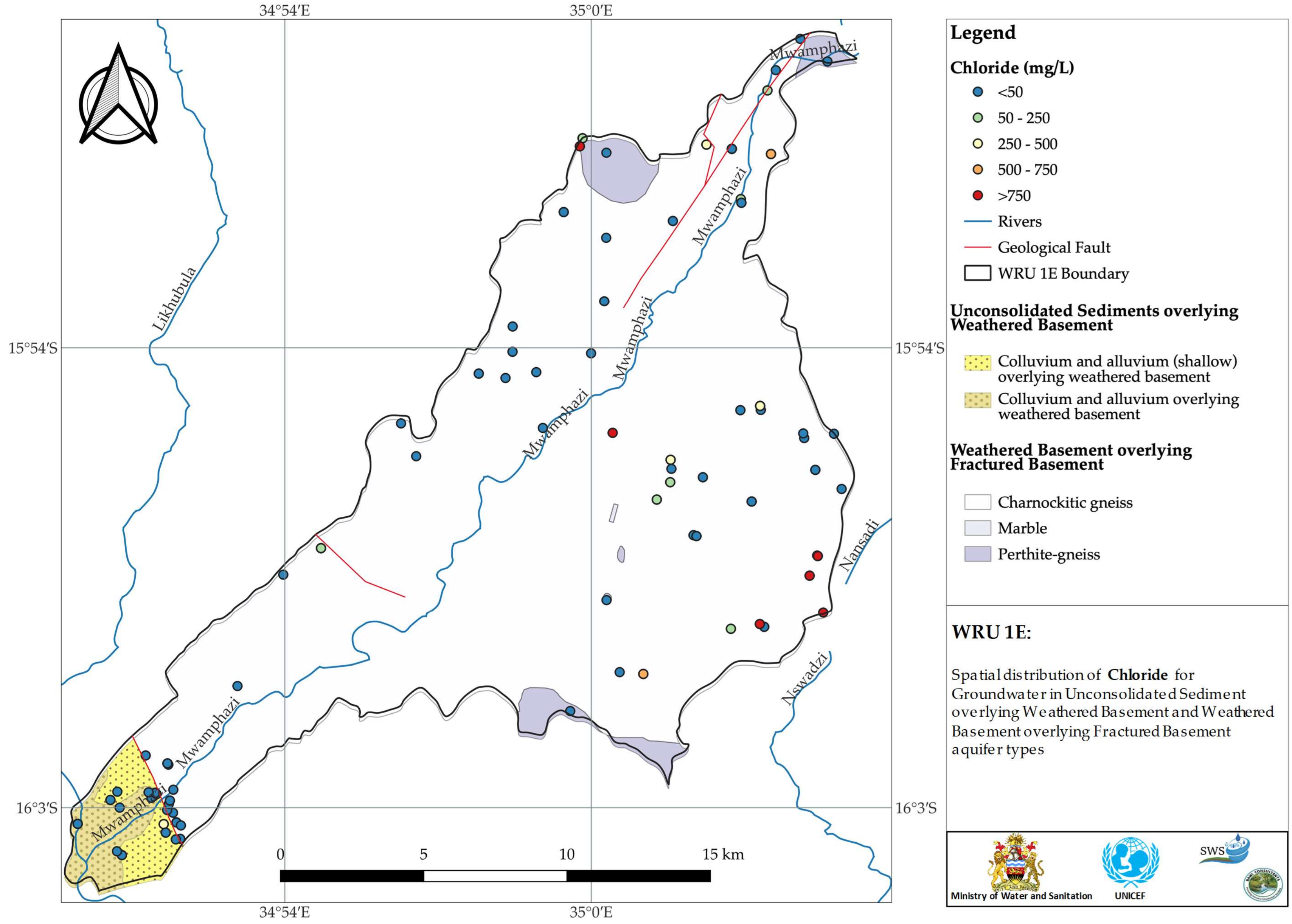


Figure WRU 1E.7 Groundwater Chemistry Distribution Sodium

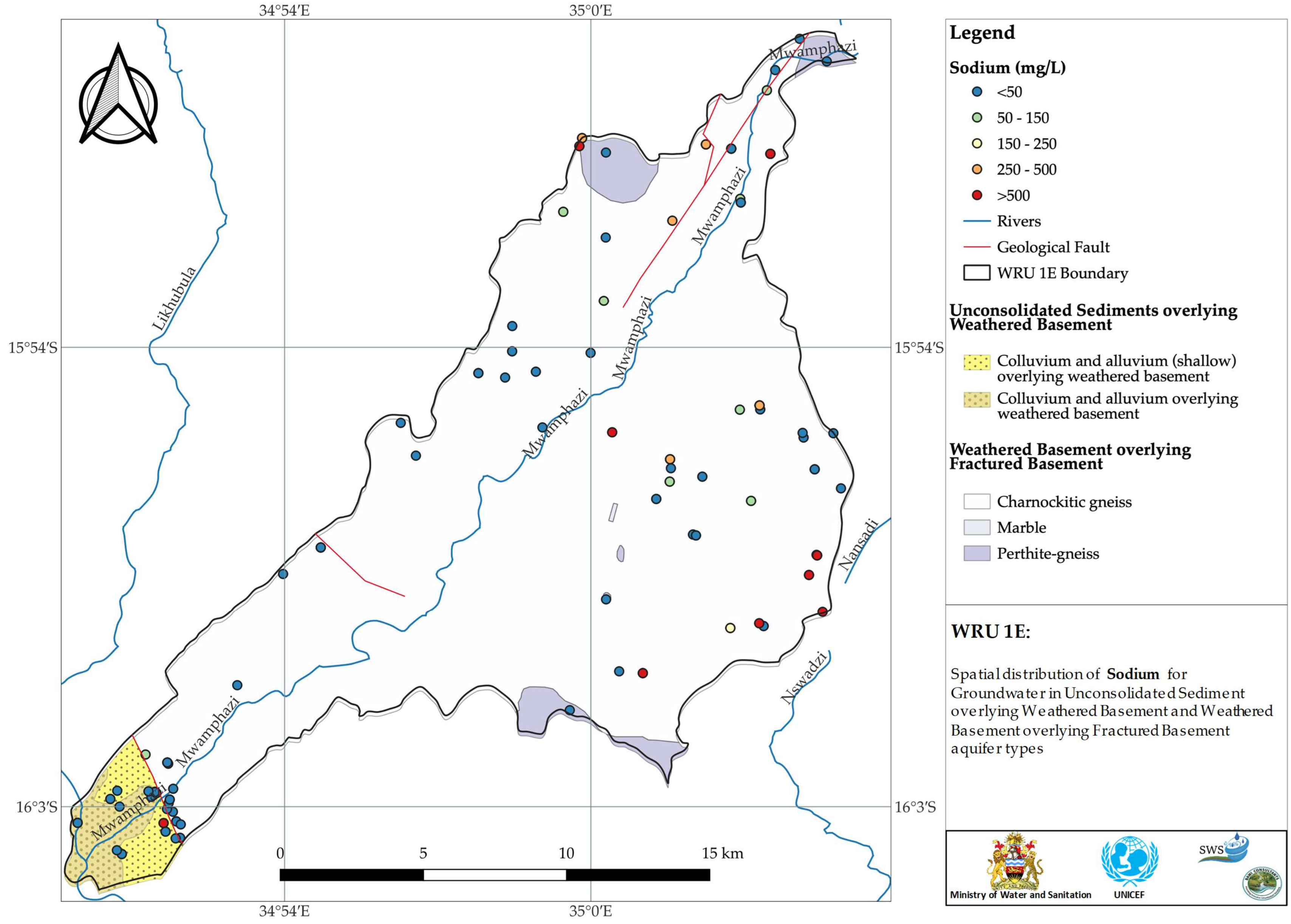
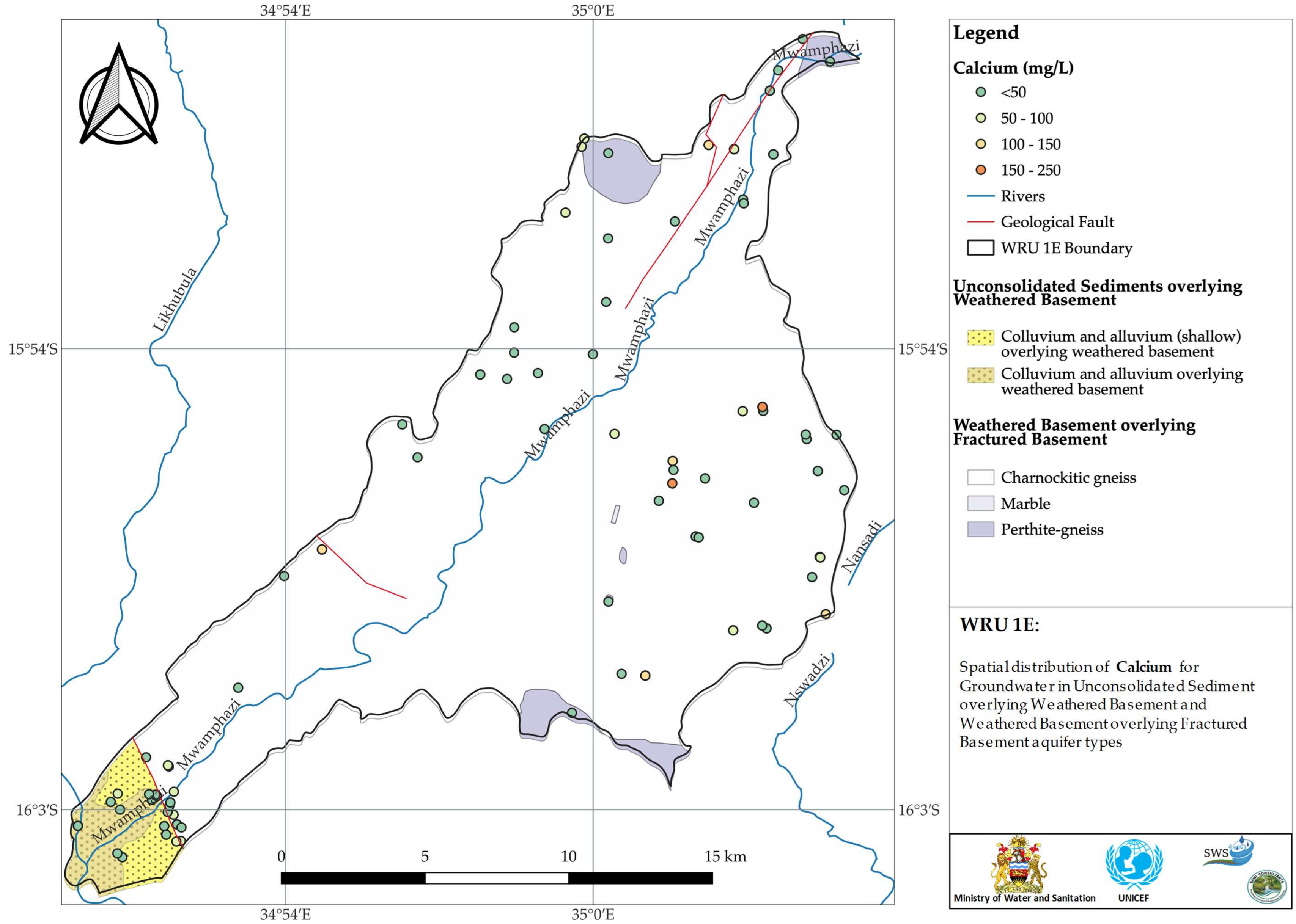


Figure WRU 1E.8 Groundwater Chemistry Distribution Calcium



WRU 1E:

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

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

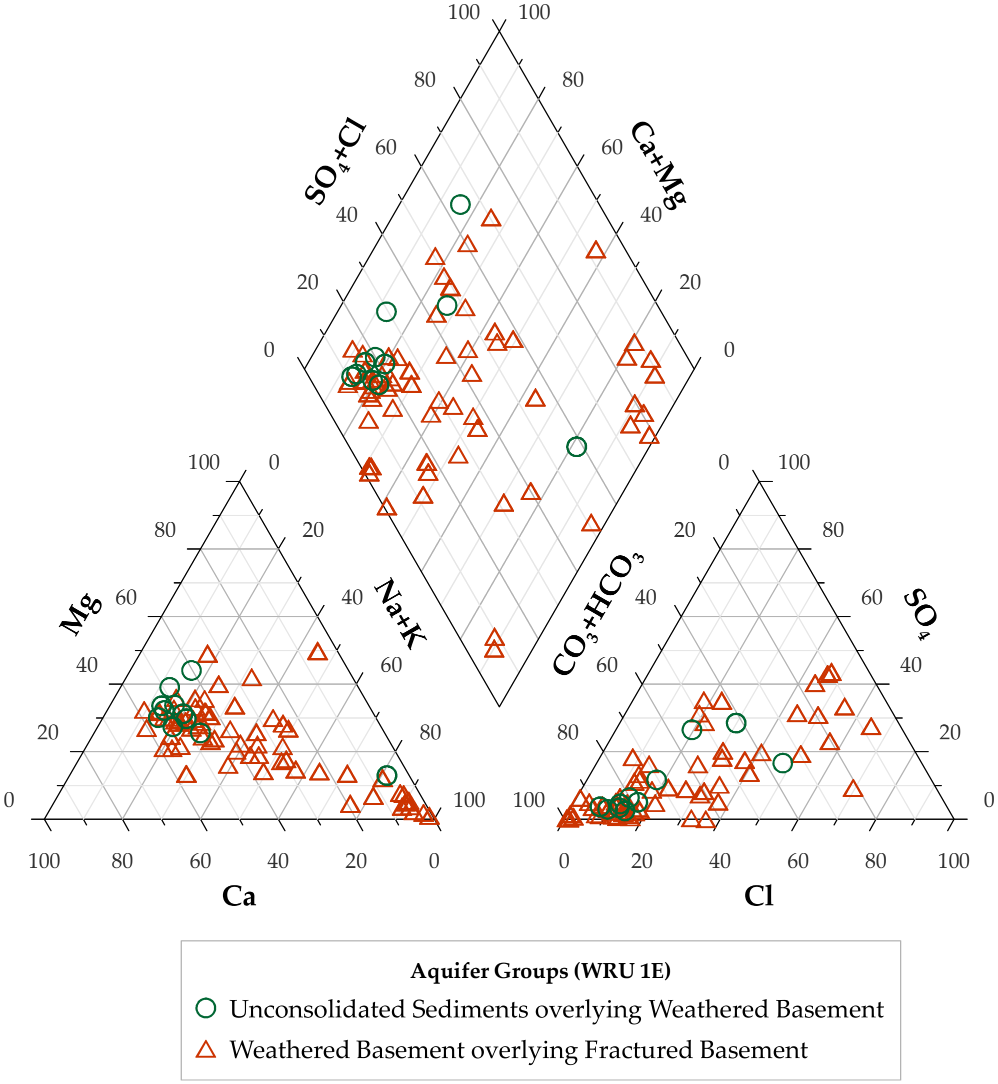
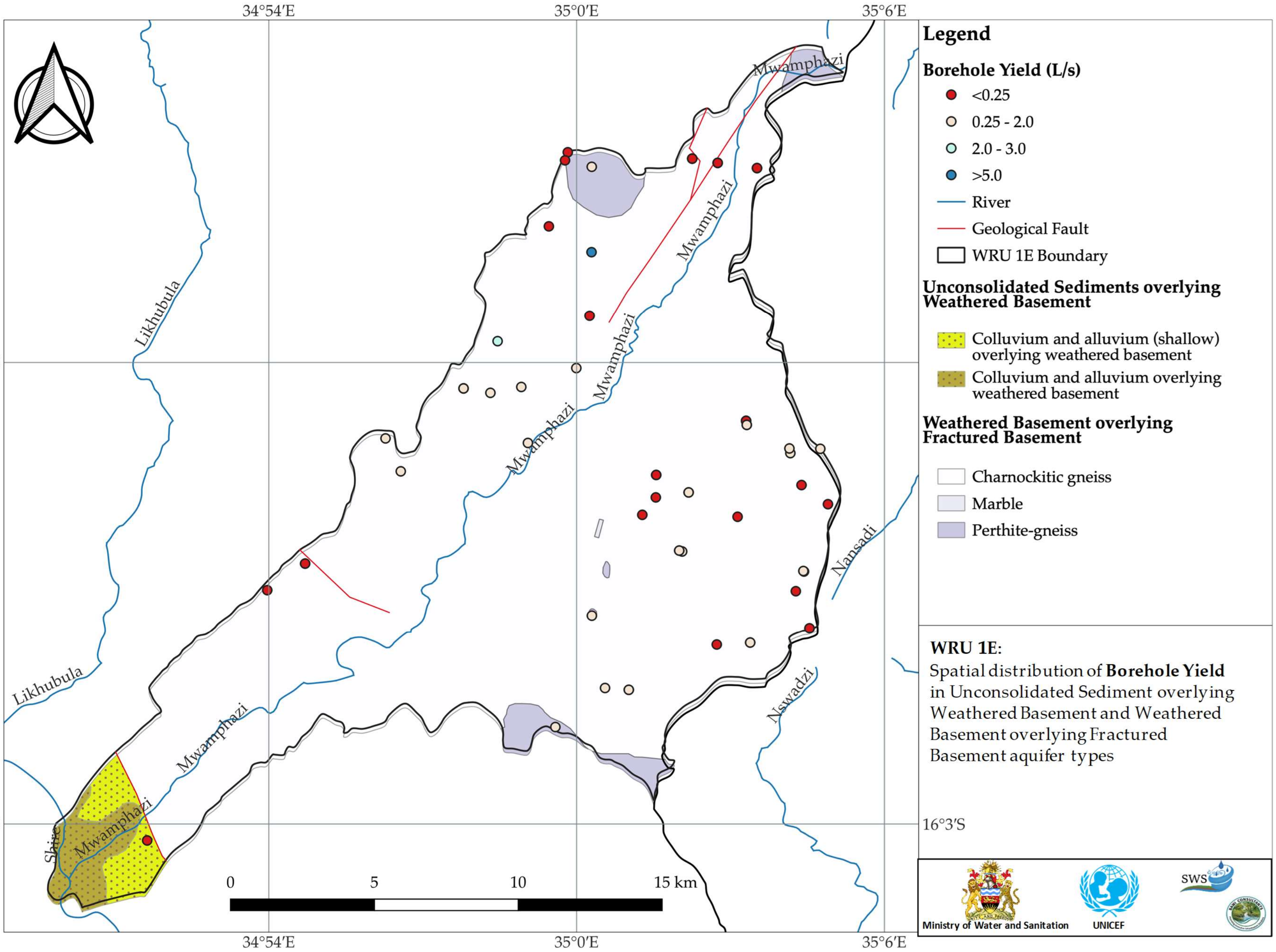


Figure WRU 1E.10 Borehole Yield Map for data held by the Ministry



WRU 1F Figures

Figure WRU 1F.1 Land Use and Major Roads

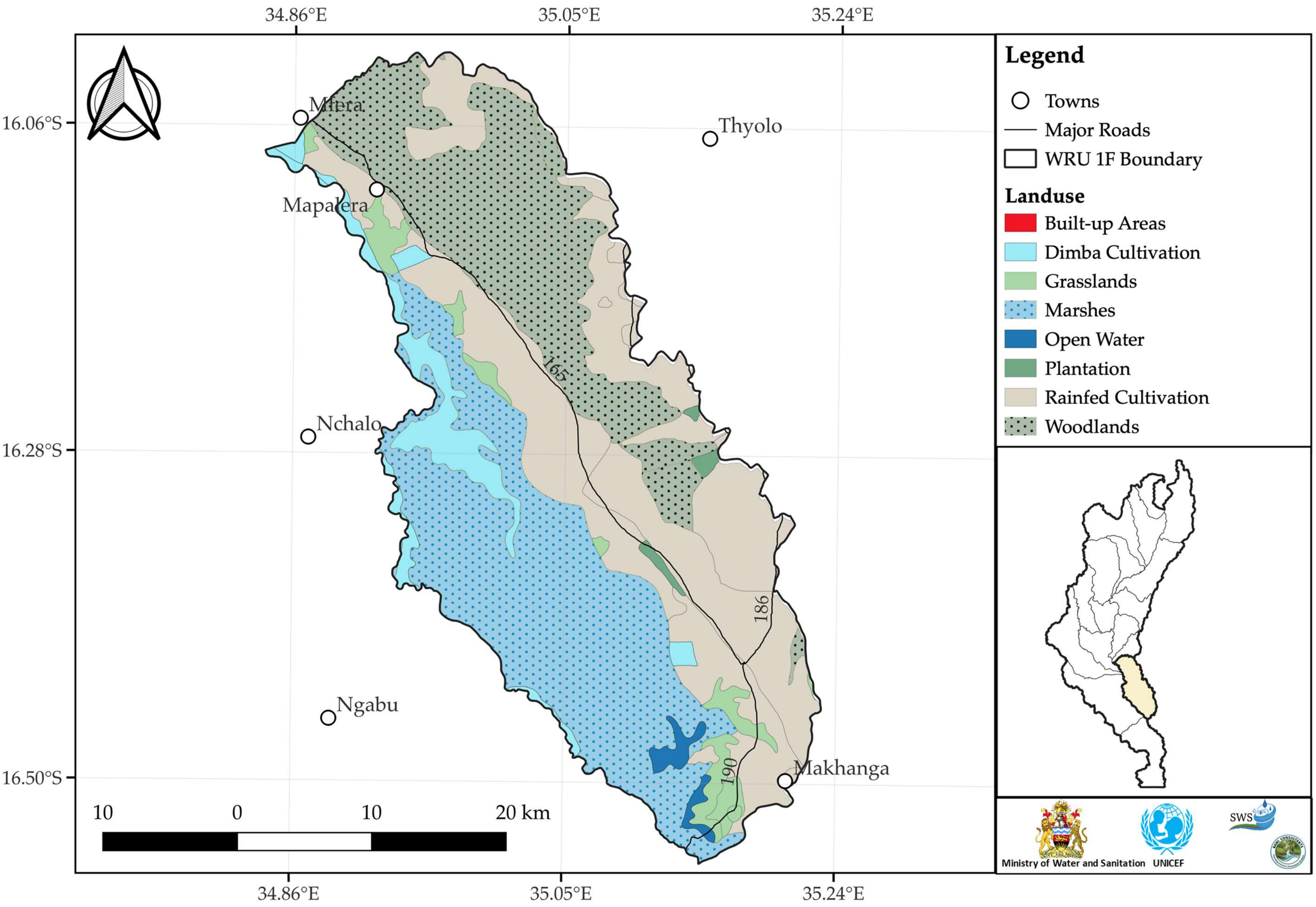


Figure WRU 1F.2 Rivers and Wetlands

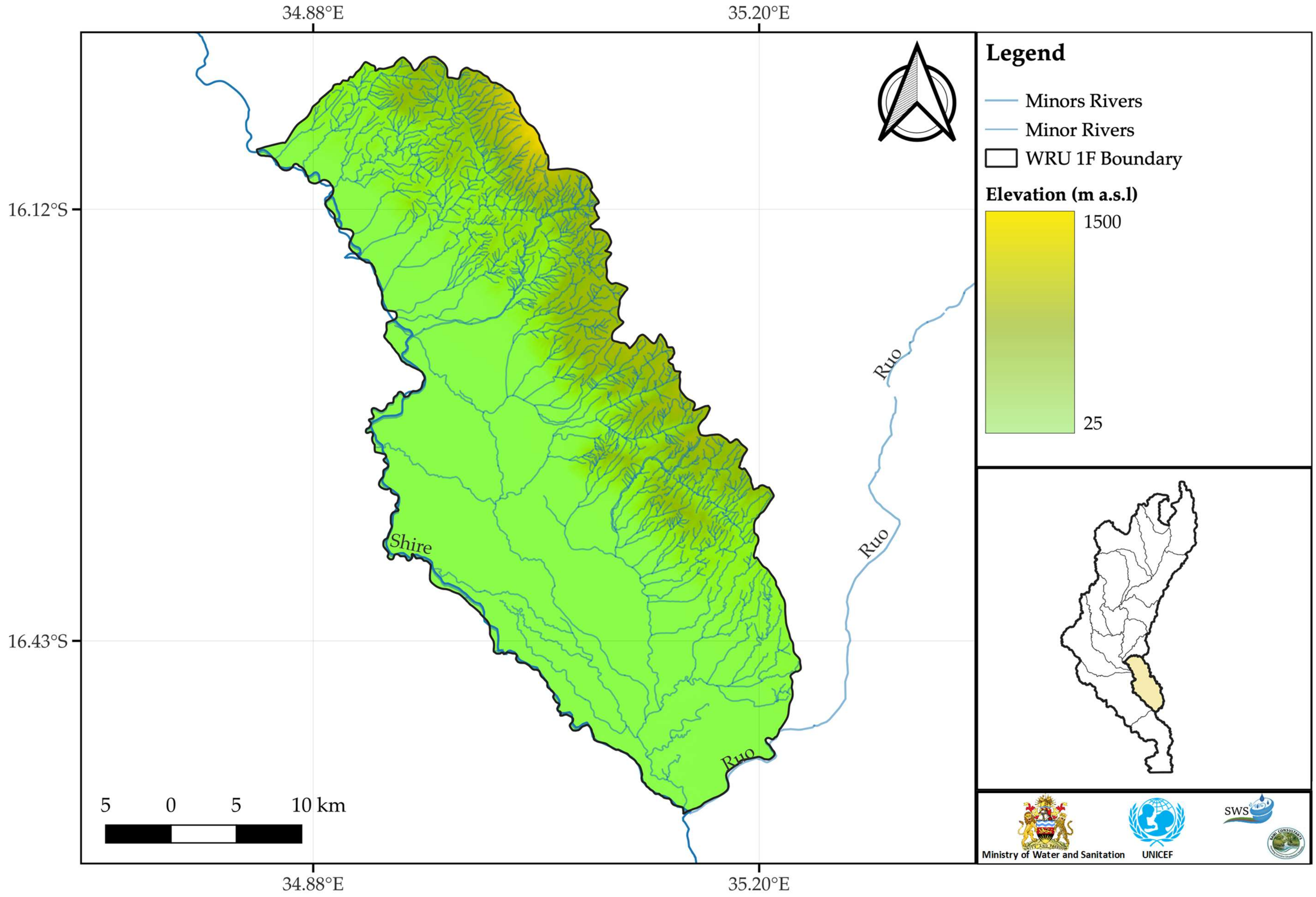


Figure WRU 1F.3 Hydrogeology Units and Water Table

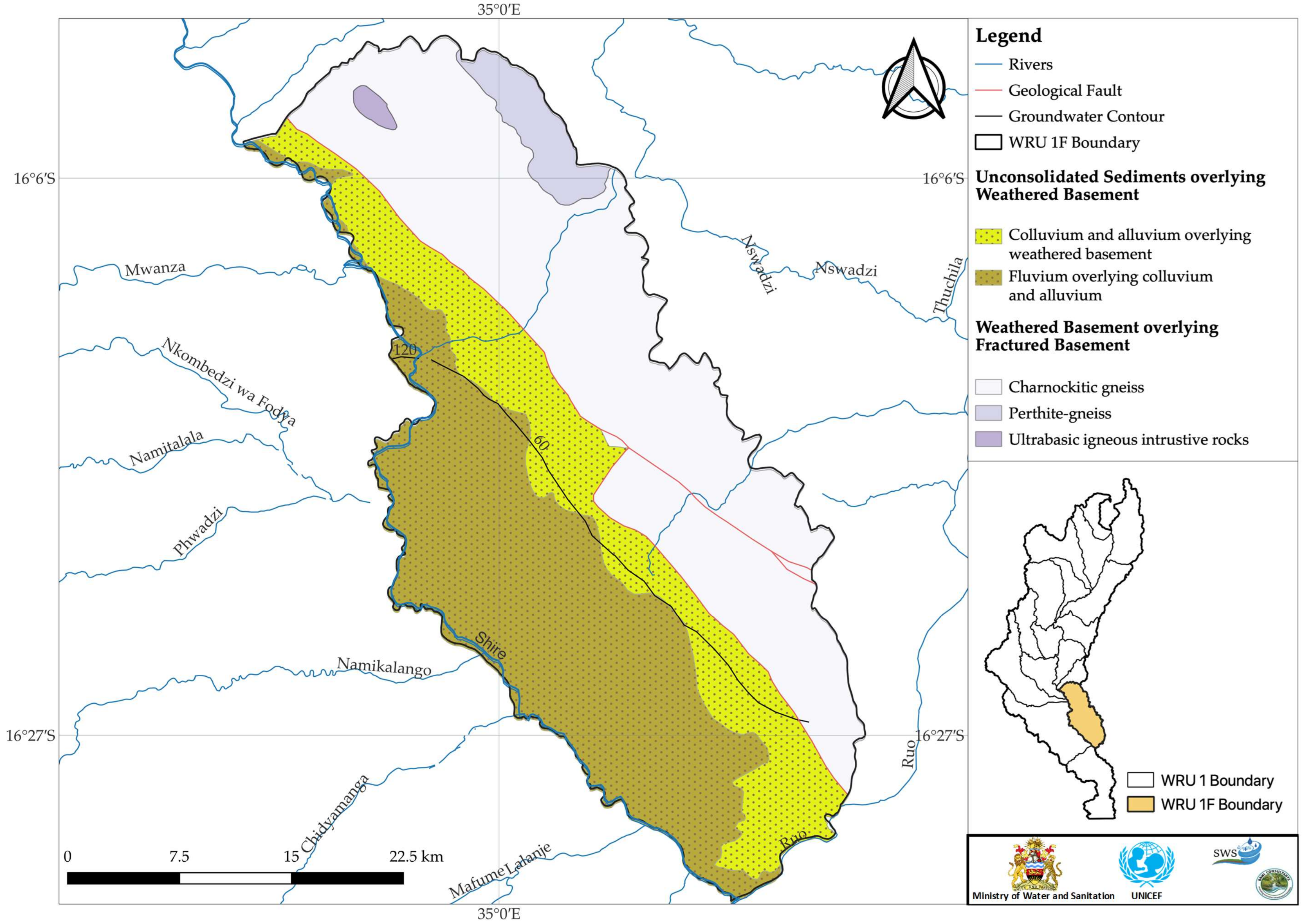
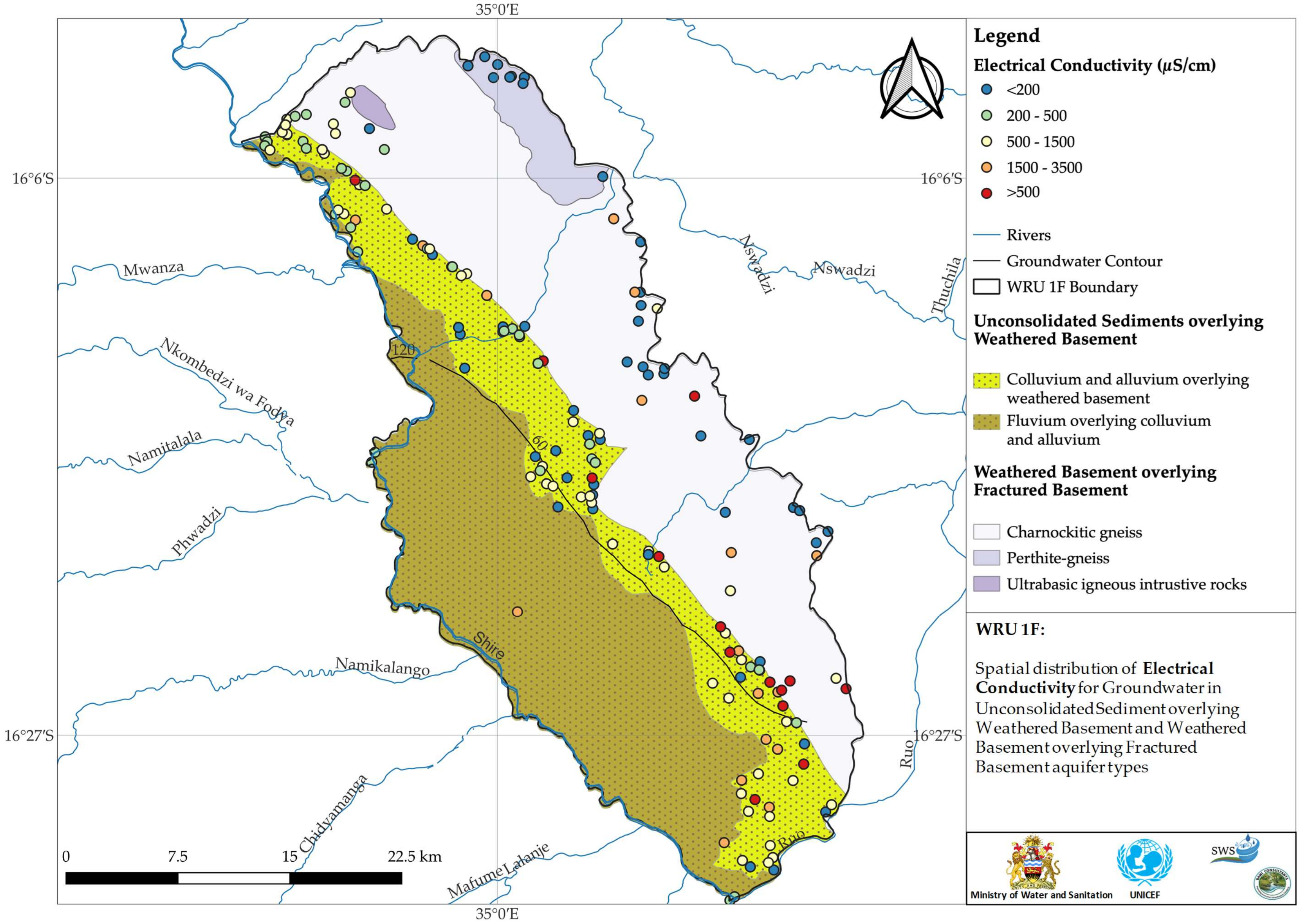


Figure WRU 1F.4 Groundwater Chemistry Distribution Electrical Conductivity



WRU 1F:

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

Figure WRU 1F.5 Groundwater Chemistry Distribution of Sulphate

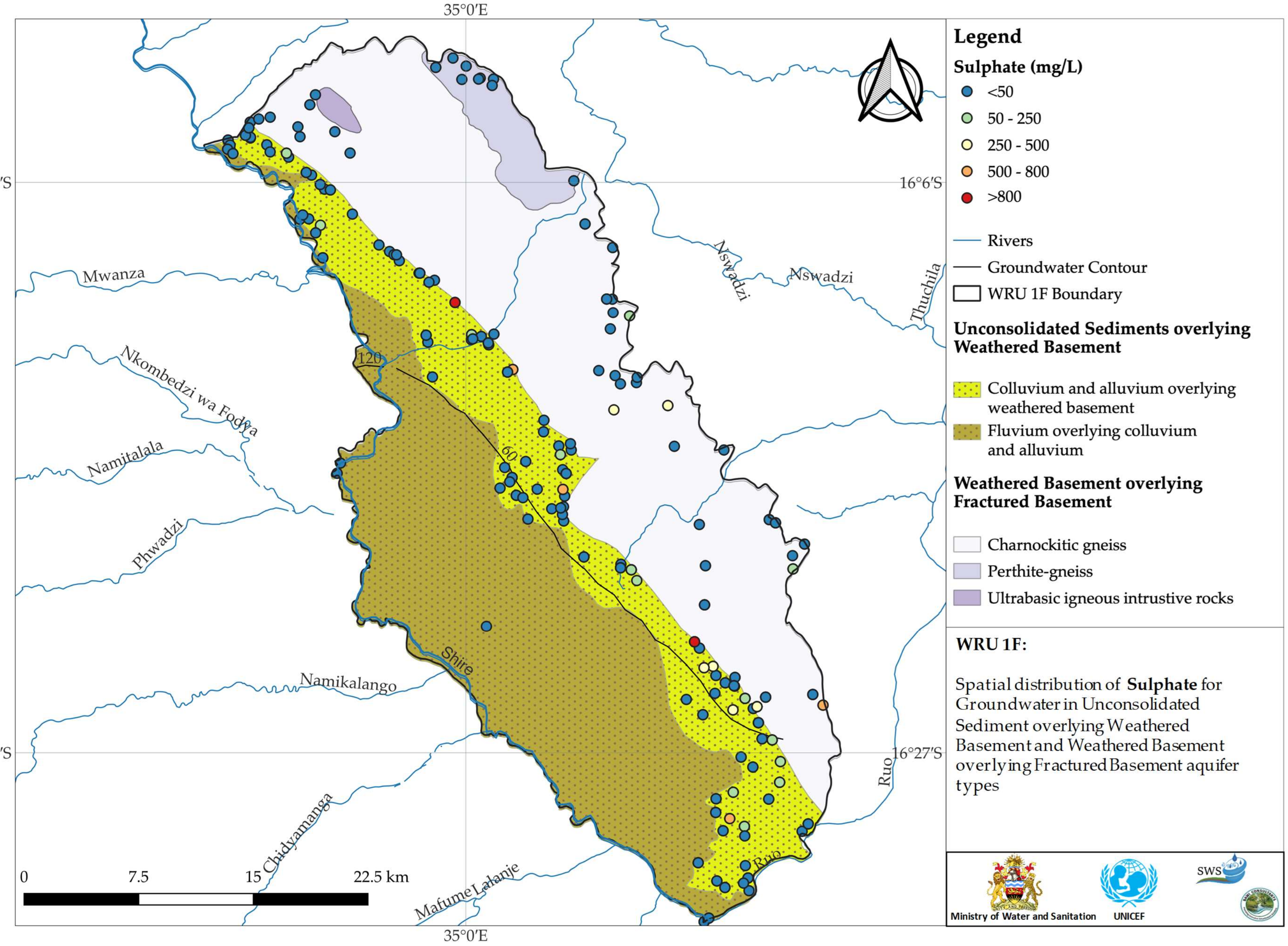


Figure WRU 1F.6 Groundwater Chemistry Distribution Chloride

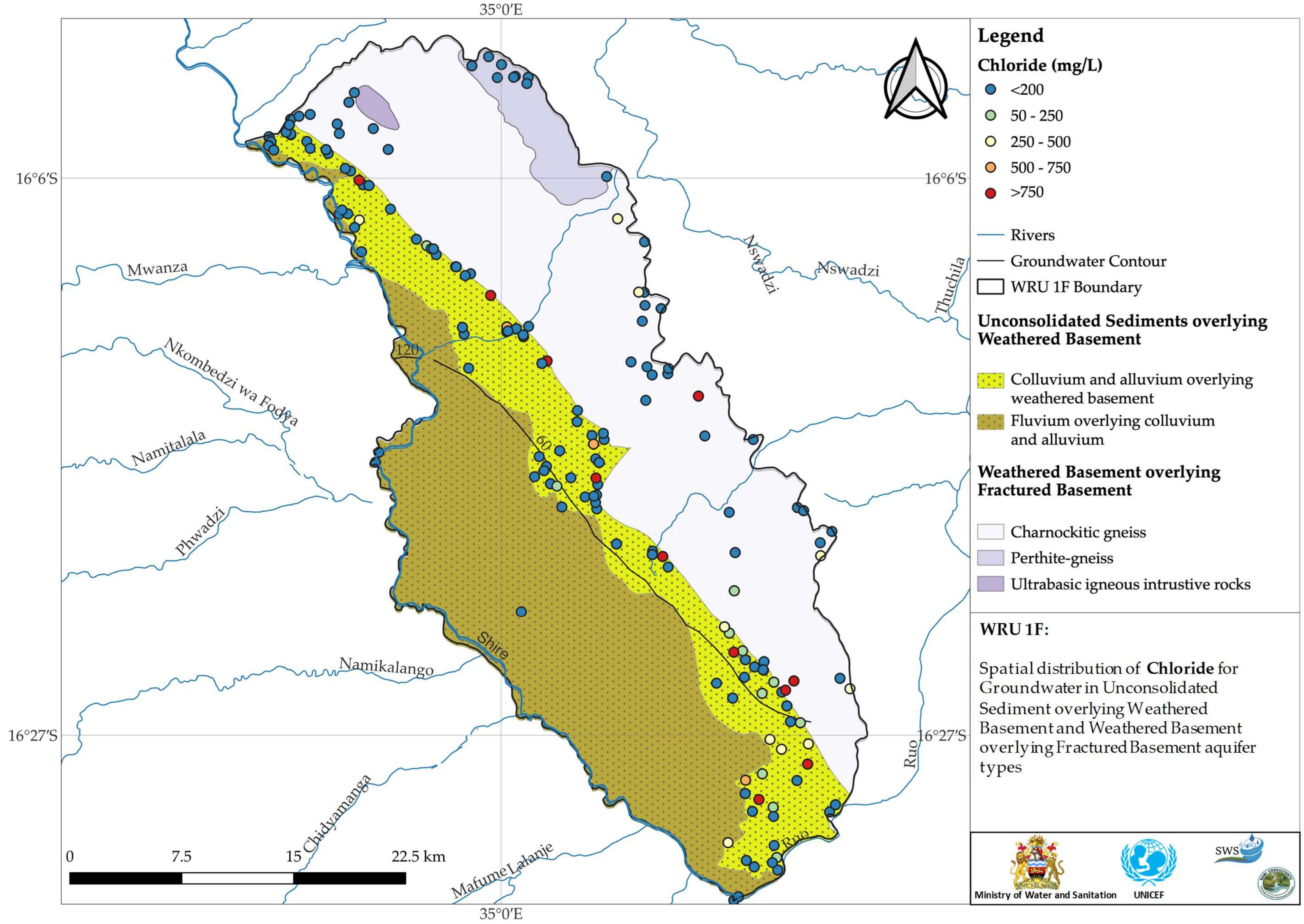


Figure WRU 1F.7 Groundwater Chemistry Distribution Sodium

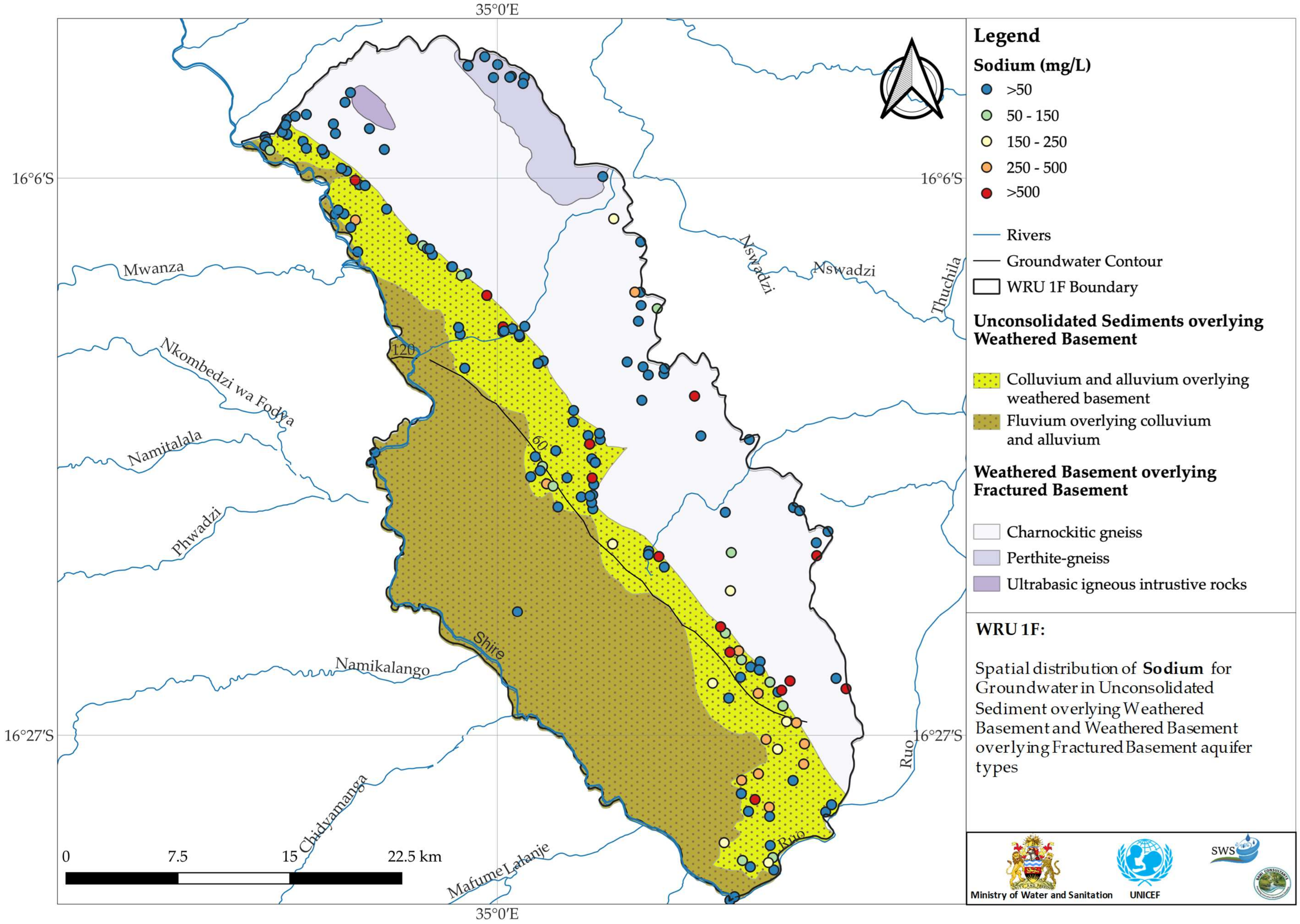


Figure WRU 1F.8 Groundwater Chemistry Distribution Calcium

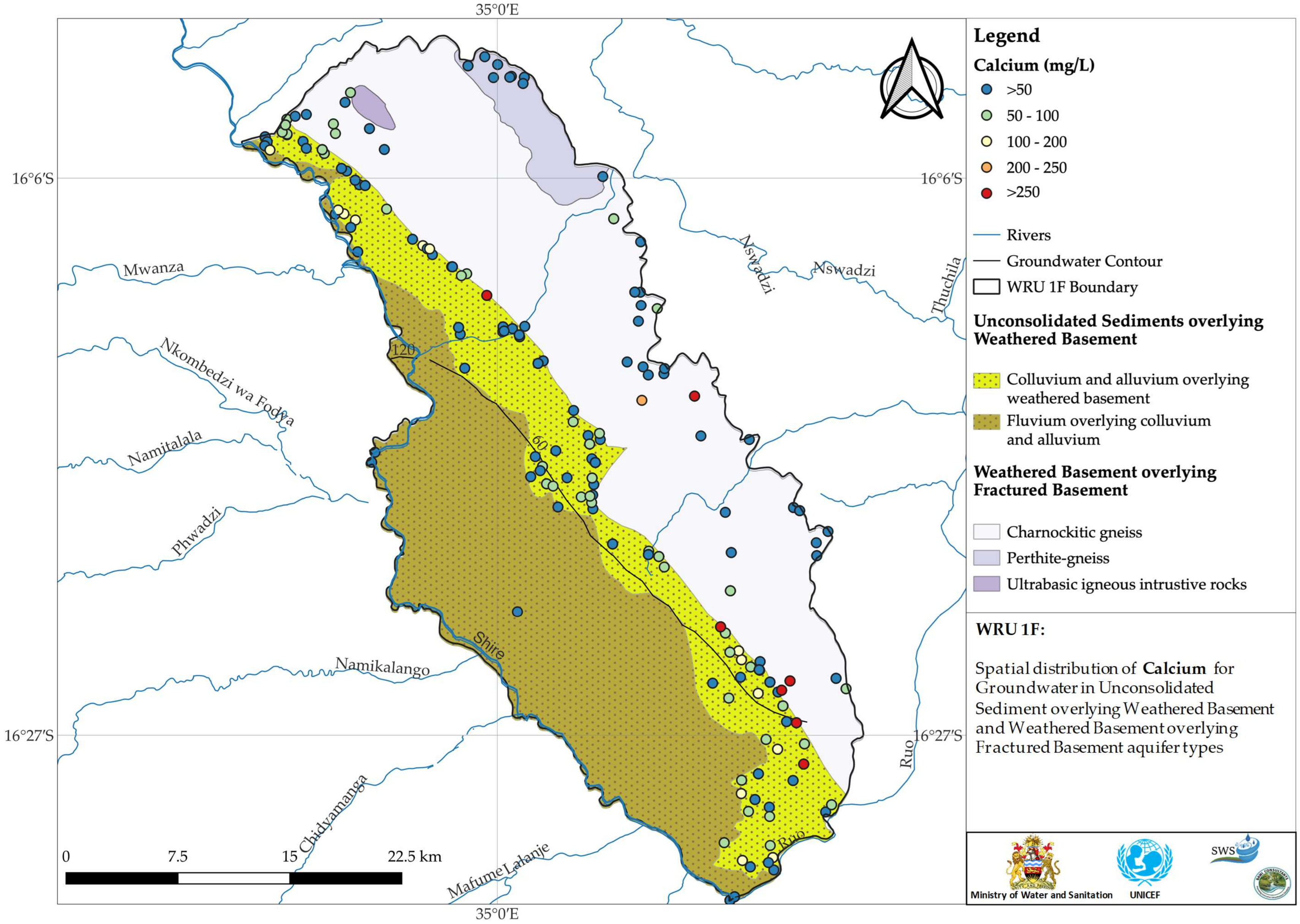


Figure WRU 1F.9 Piper Diagram of water quality results with respect to the major aquifer type

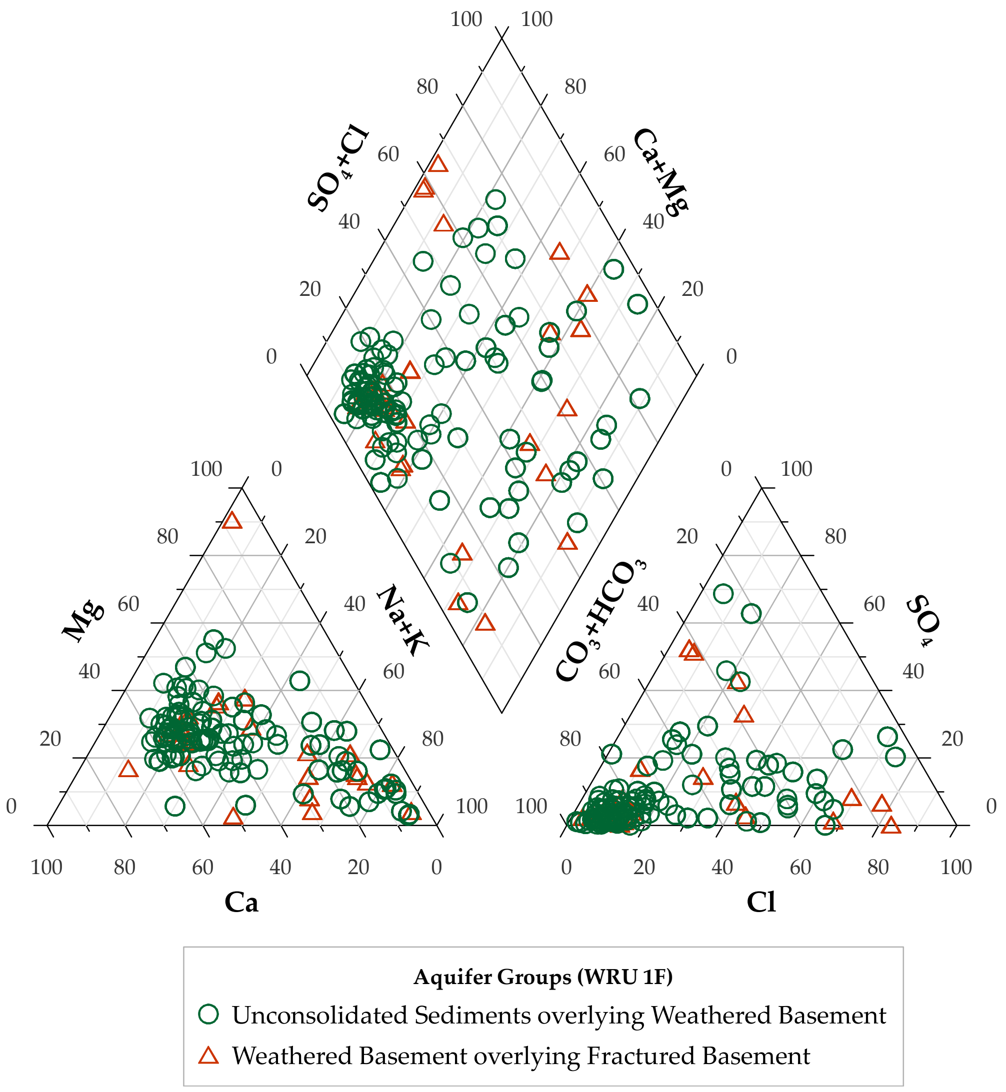
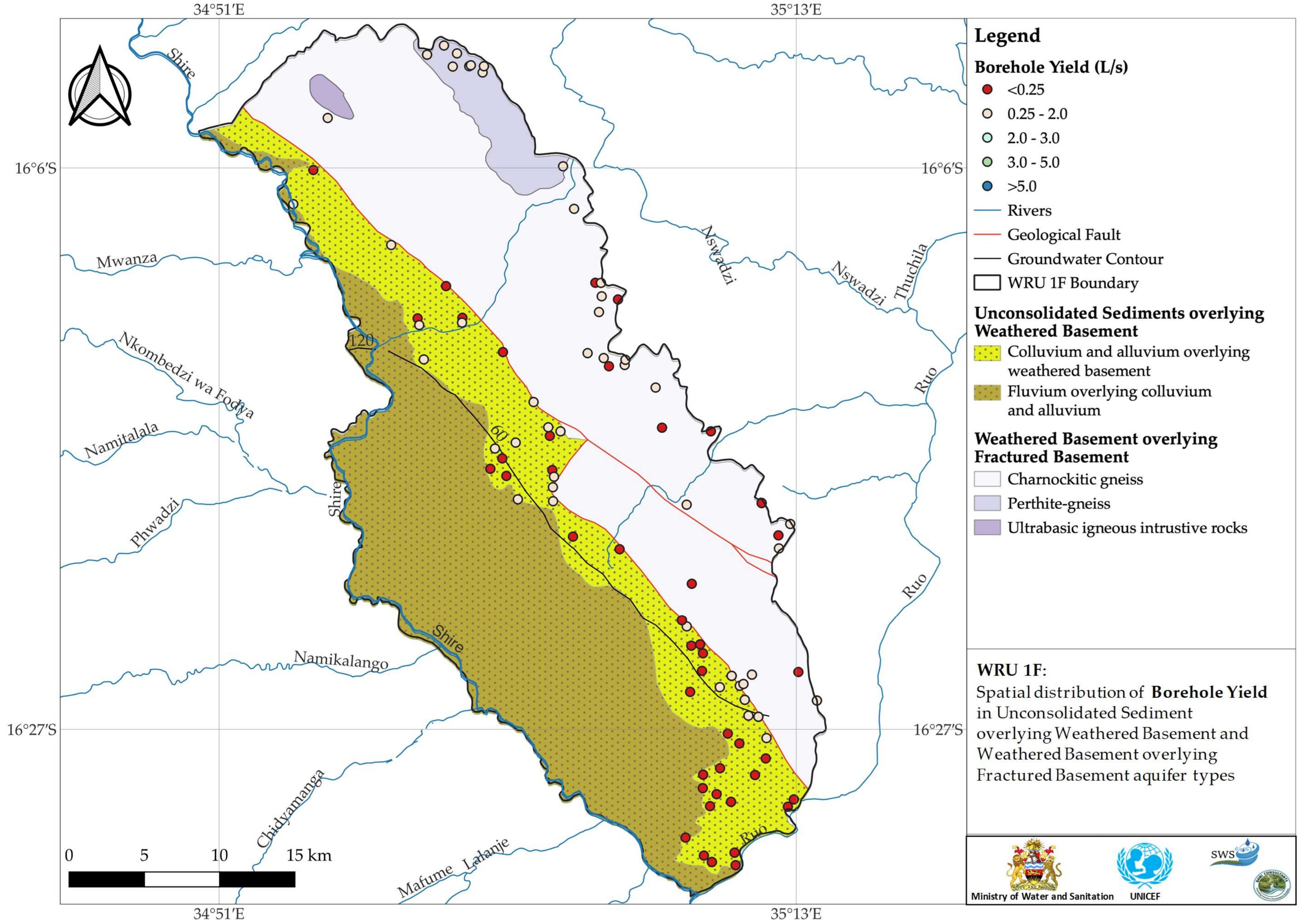


Figure WRU 1F.10 Borehole Yield Map for data held by the Ministry



WRU 1G Figures

Figure WRU 1G.1 Land Use and Major Roads

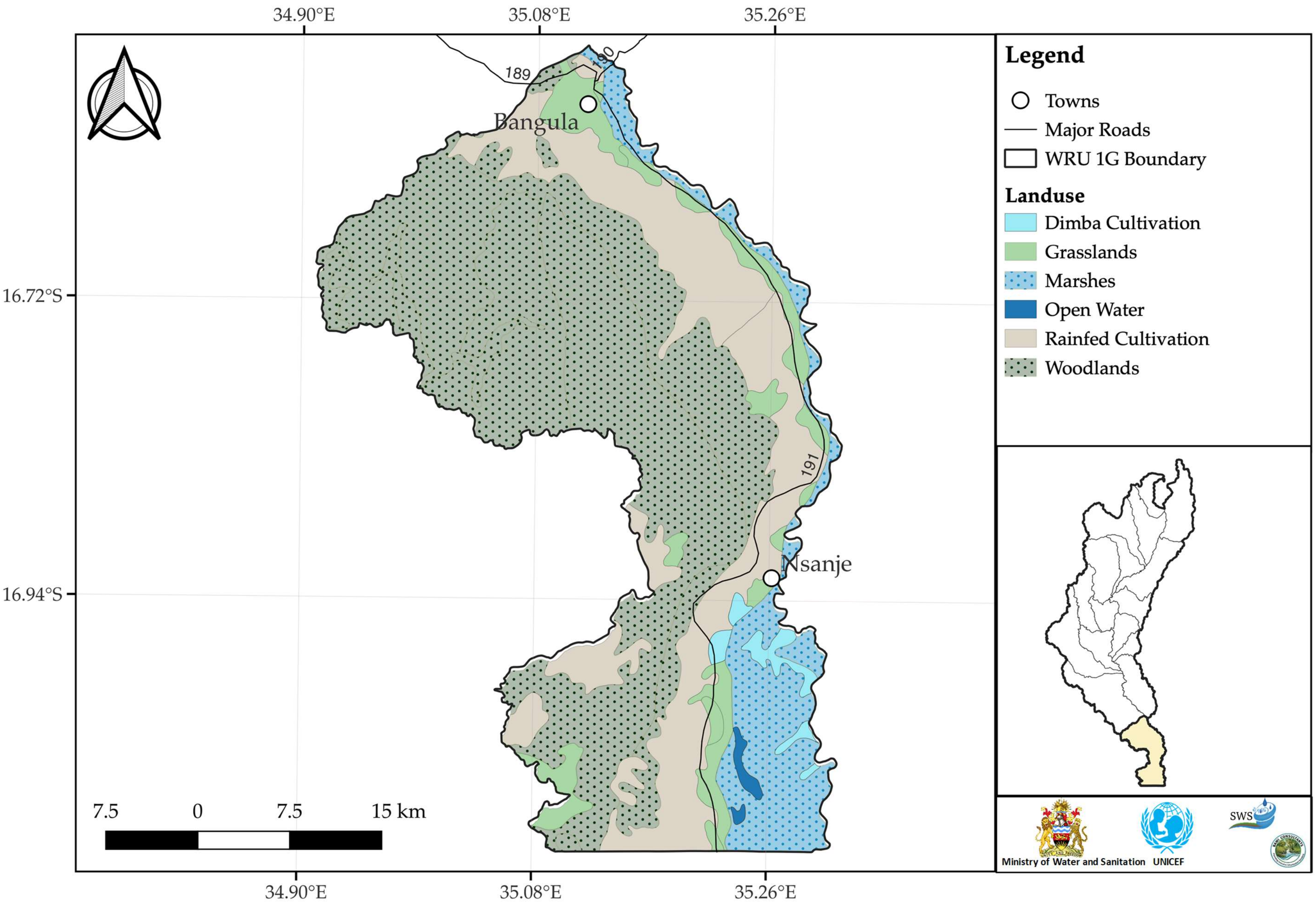


Figure WRU 1G.2 Rivers and Wetlands

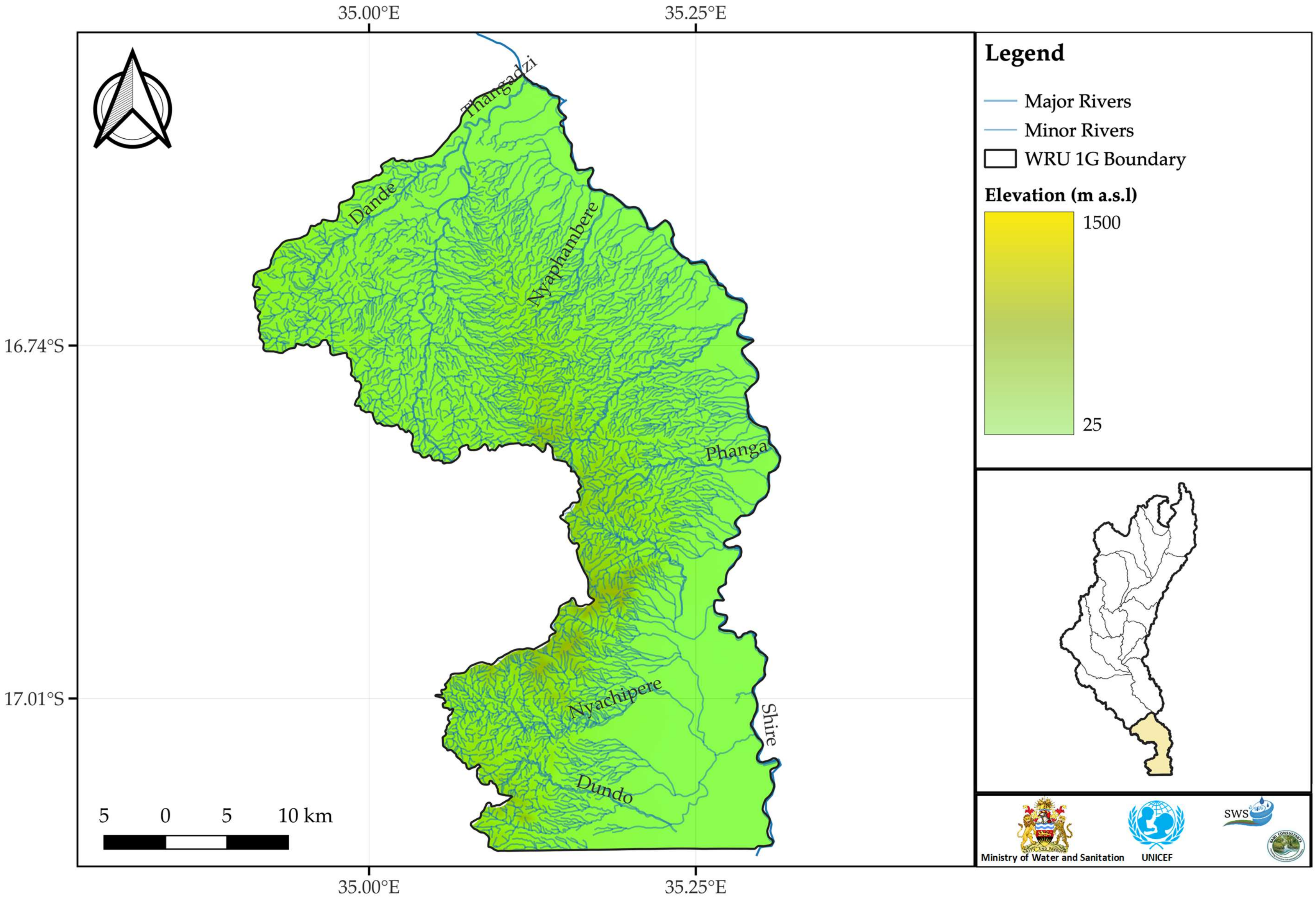


Figure WRU 1G.3 Hydrogeology Units and Water Table

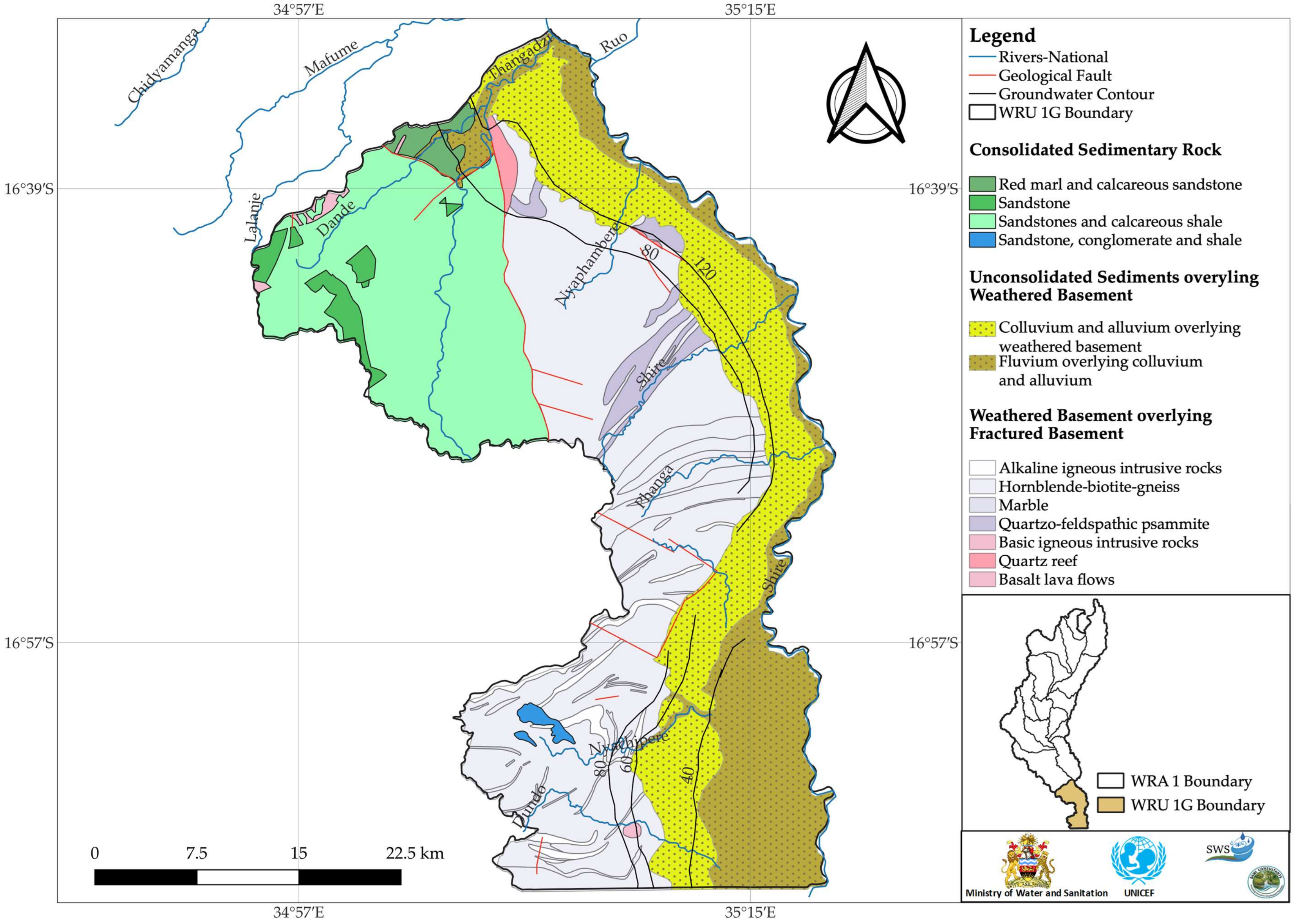


Figure WRU 1G.4 Groundwater Chemistry Distribution Electrical Conductivity

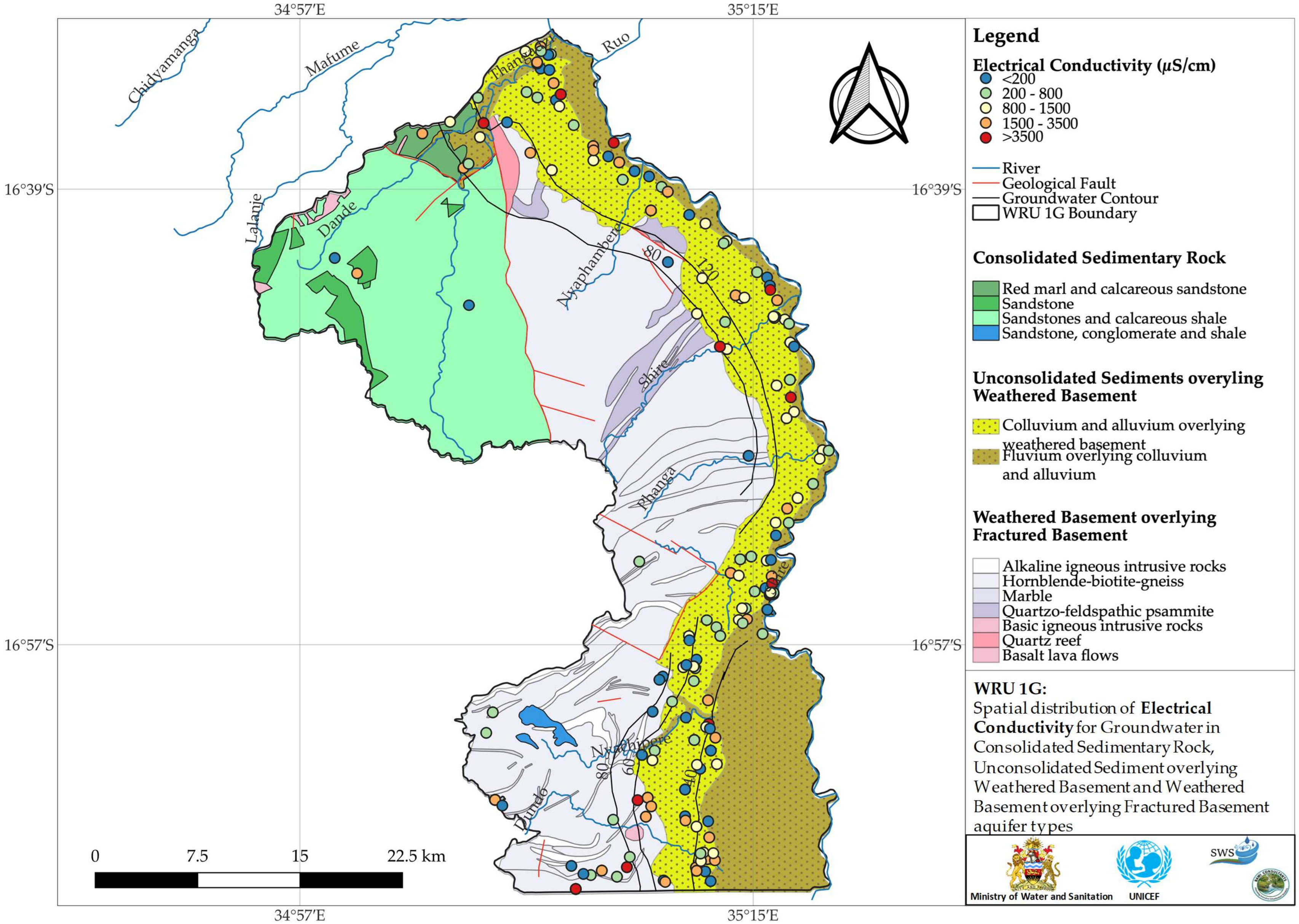


Figure WRU 1G.5 Groundwater Chemistry Distribution of Sulphate

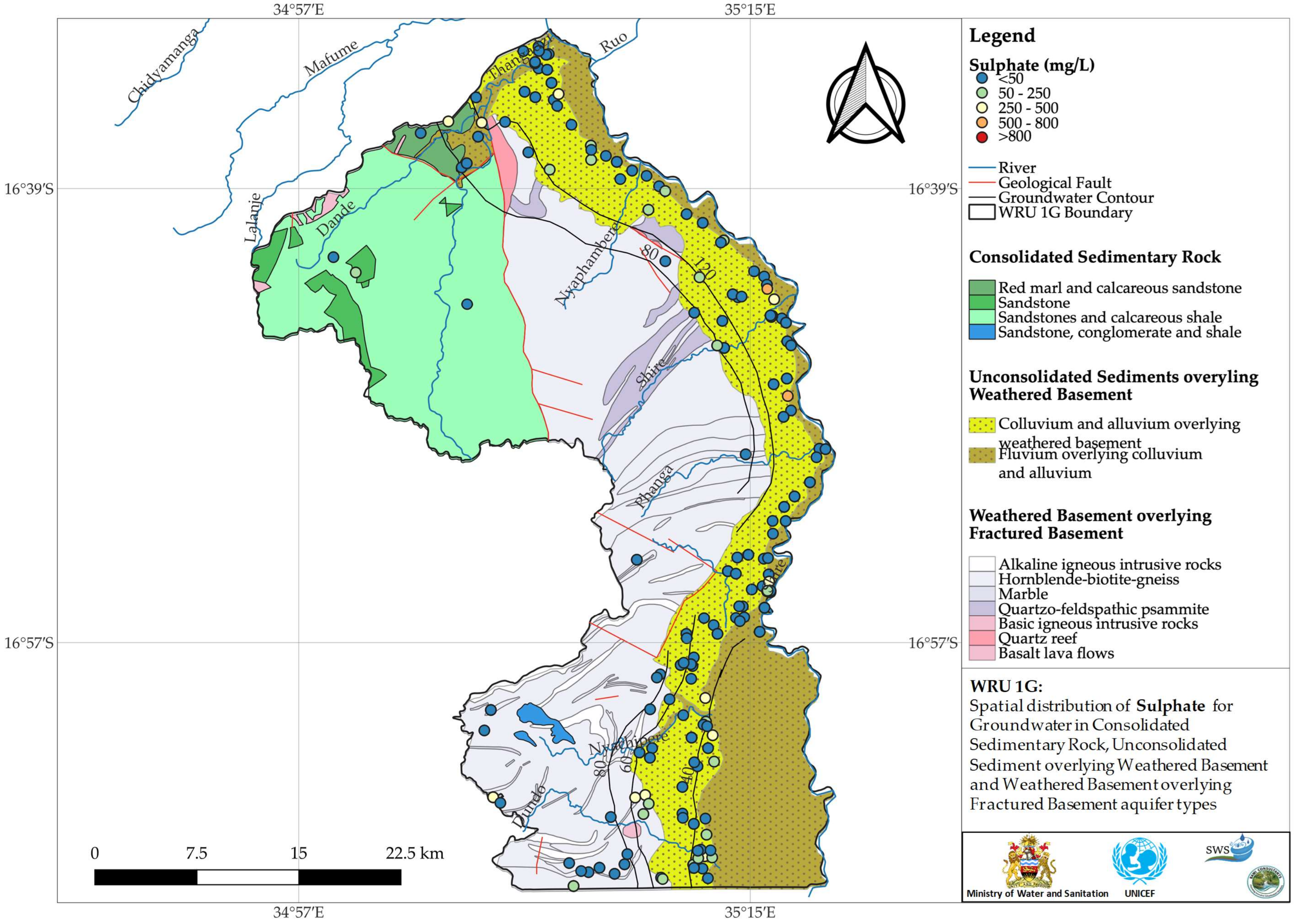


Figure WRU 1G.6 Groundwater Chemistry Distribution Chloride

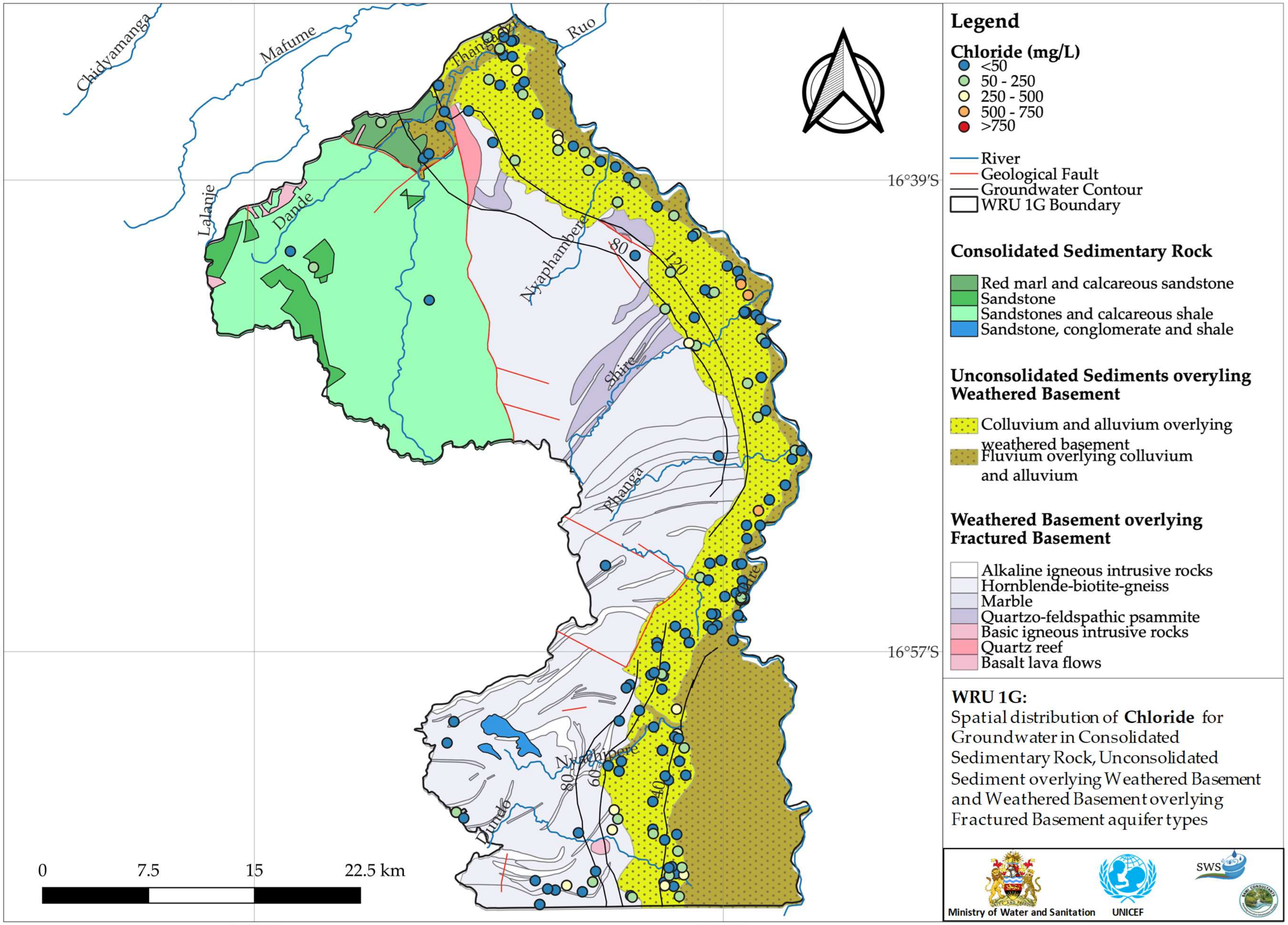


Figure WRU 1G.7 Groundwater Chemistry Distribution Sodium

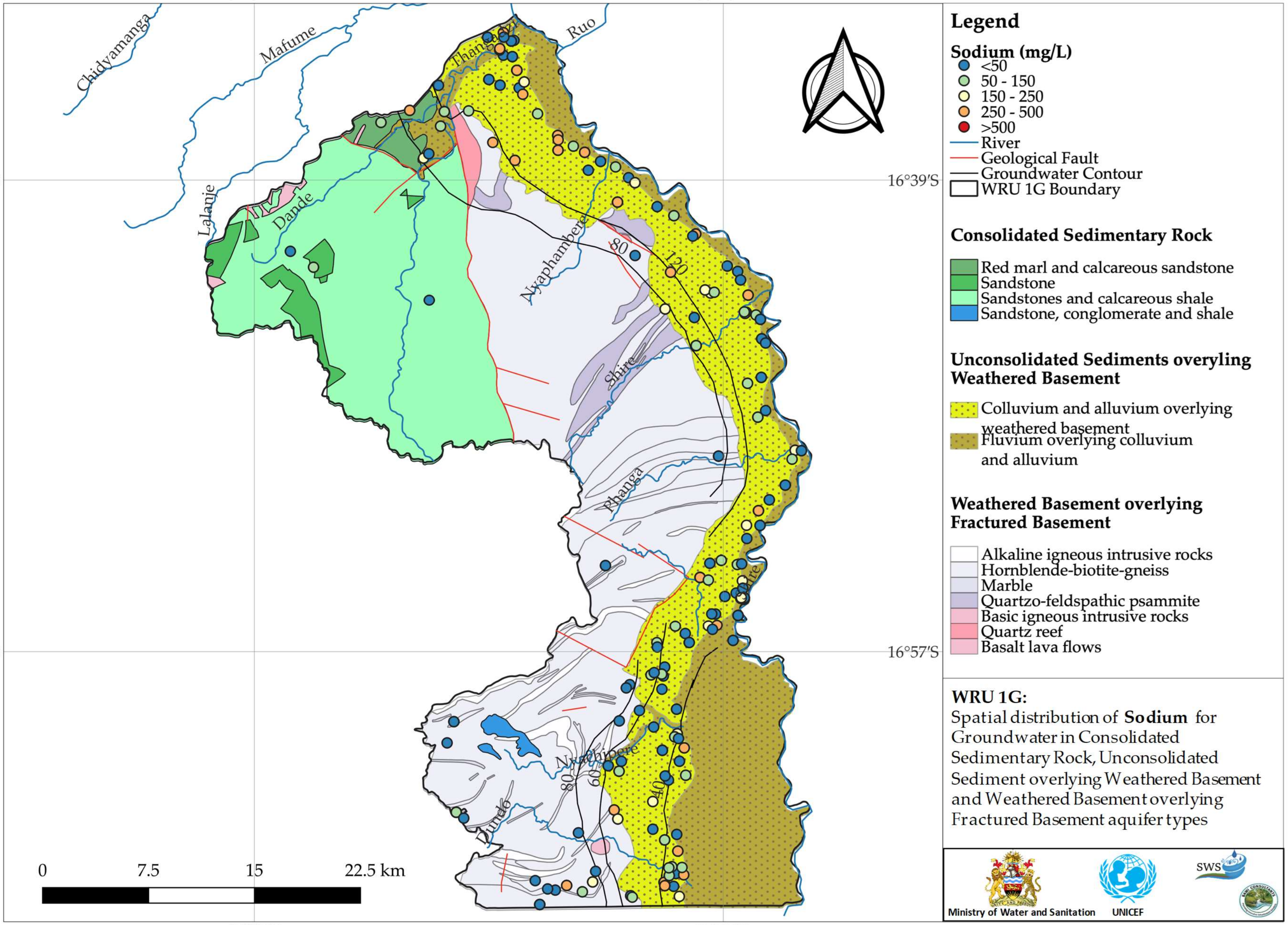


Figure WRU 1G.8 Groundwater Chemistry Distribution Calcium

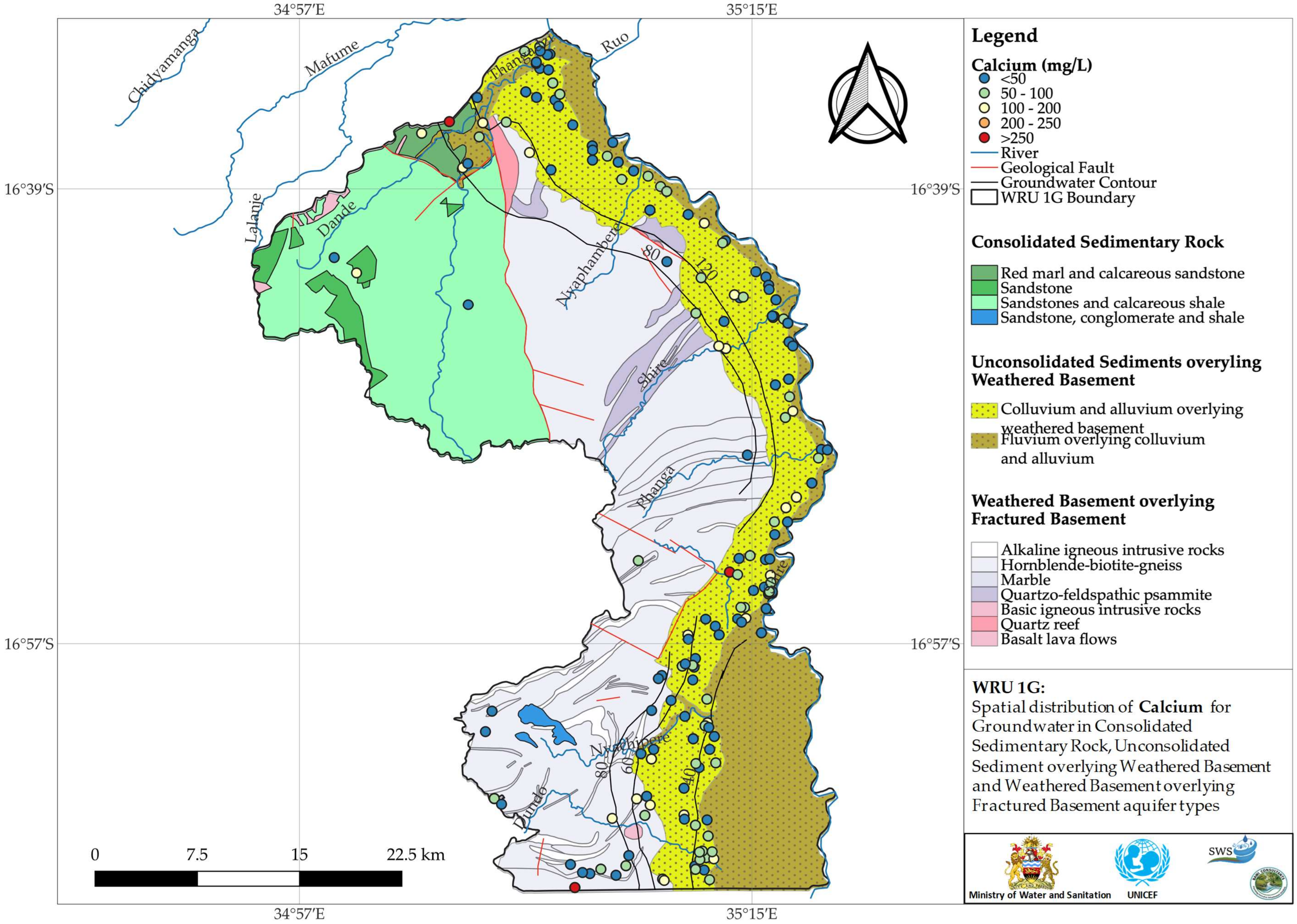


Figure WRU 1G.9 Piper Diagram of water quality results with respect to the major aquifer type

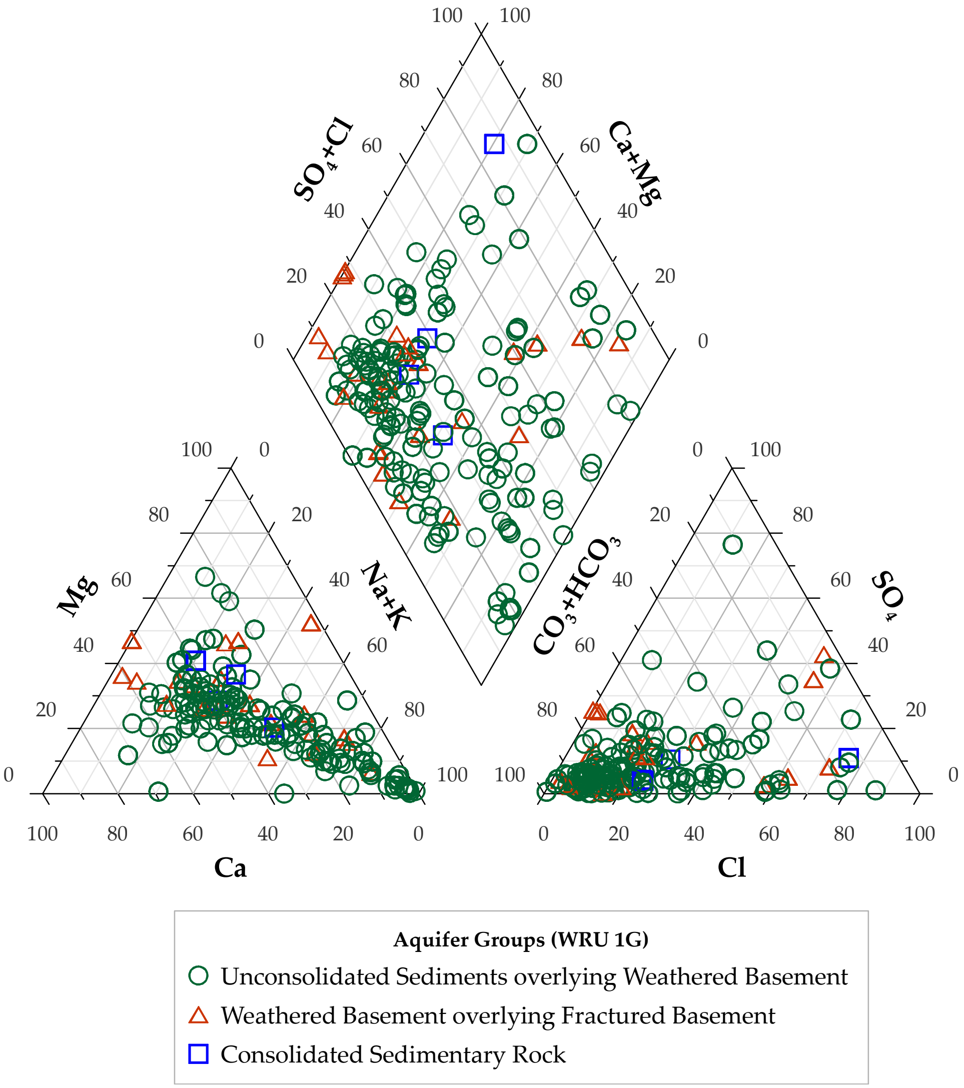
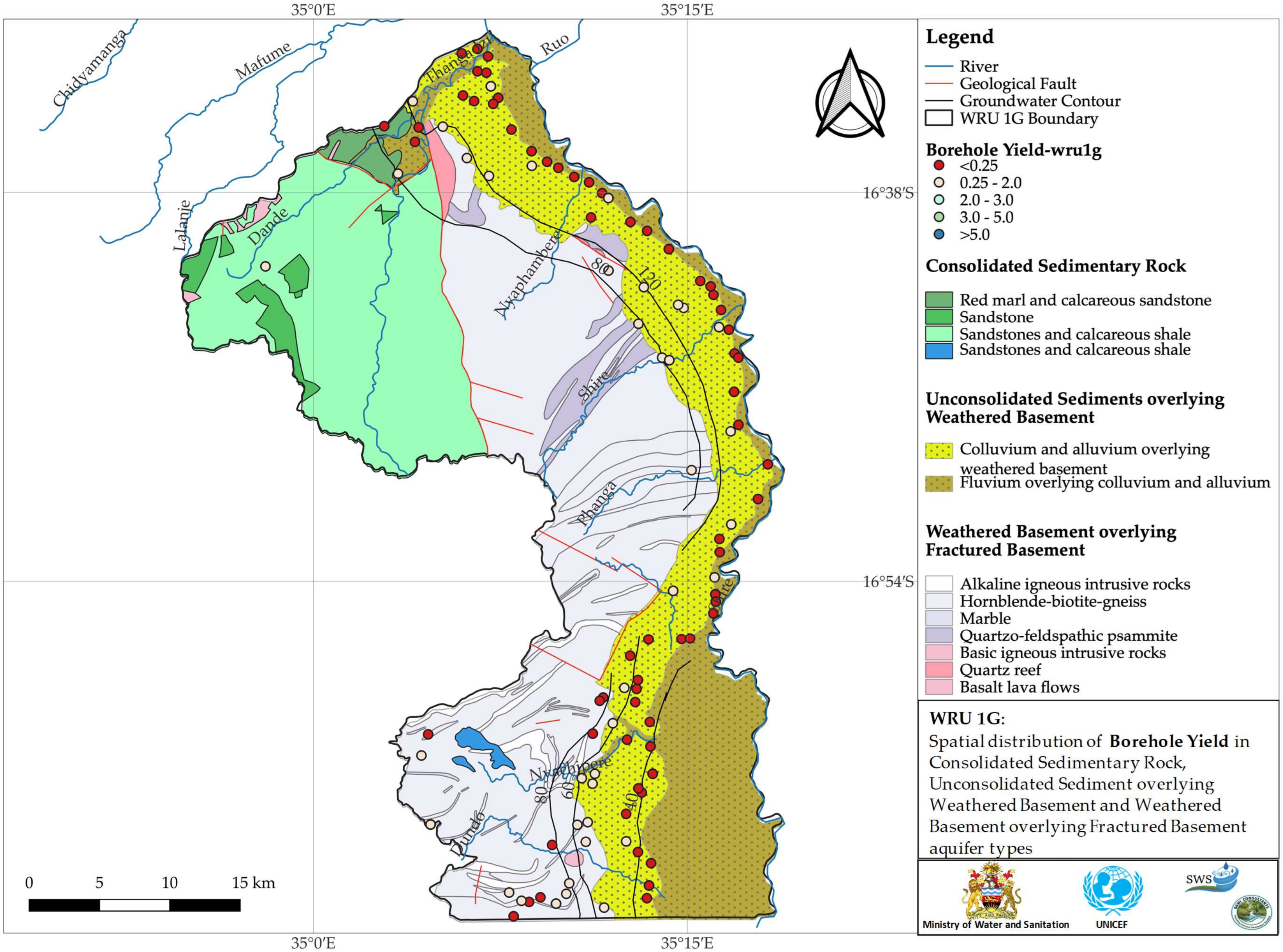


Figure WRU 1G.10 Borehole Yield Map for data held by the Ministry



WRU 1H Figures

Figure WRU 1H.1 Land Use and Major Roads

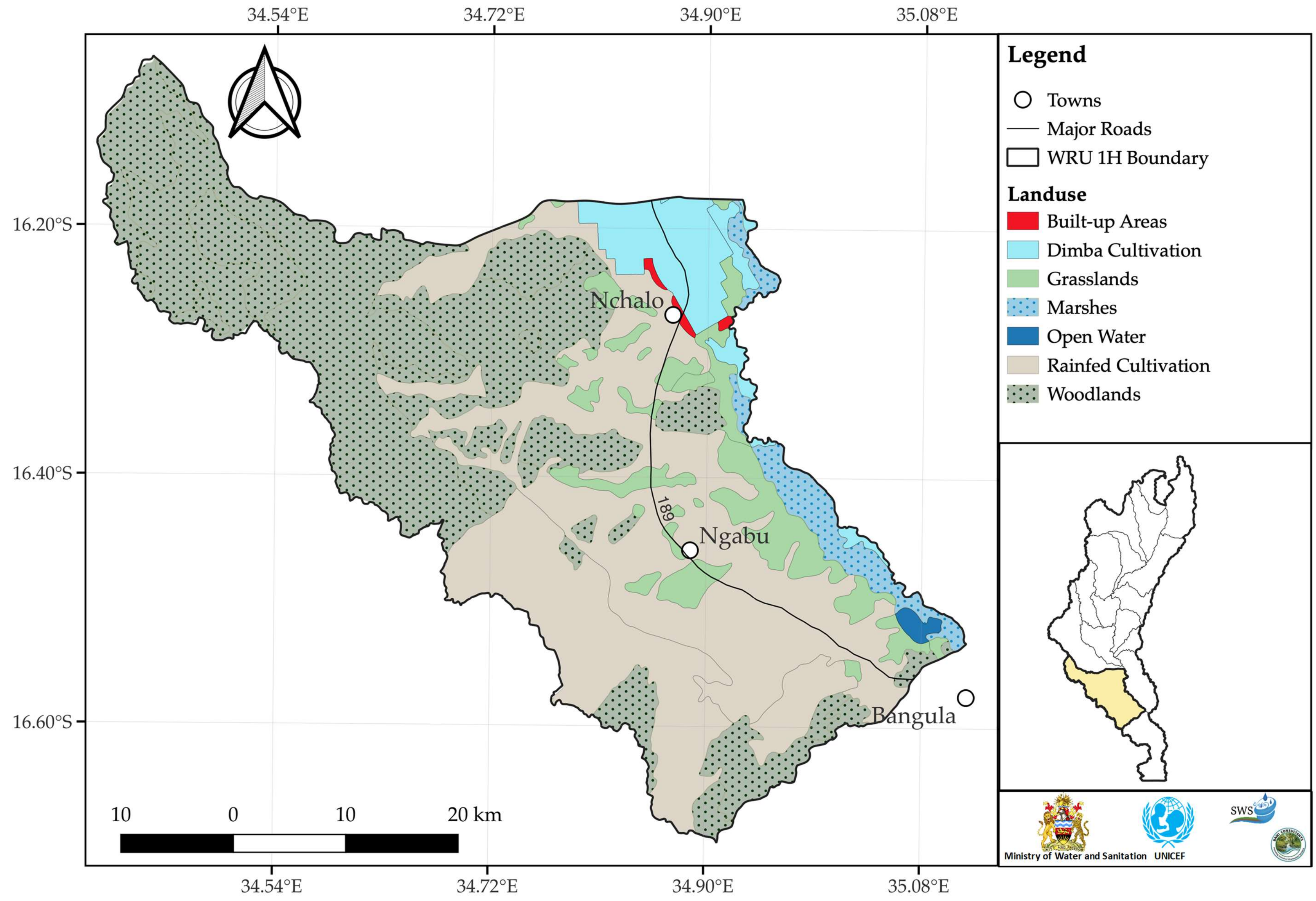


Figure WRU 1H.2 Rivers and Wetlands

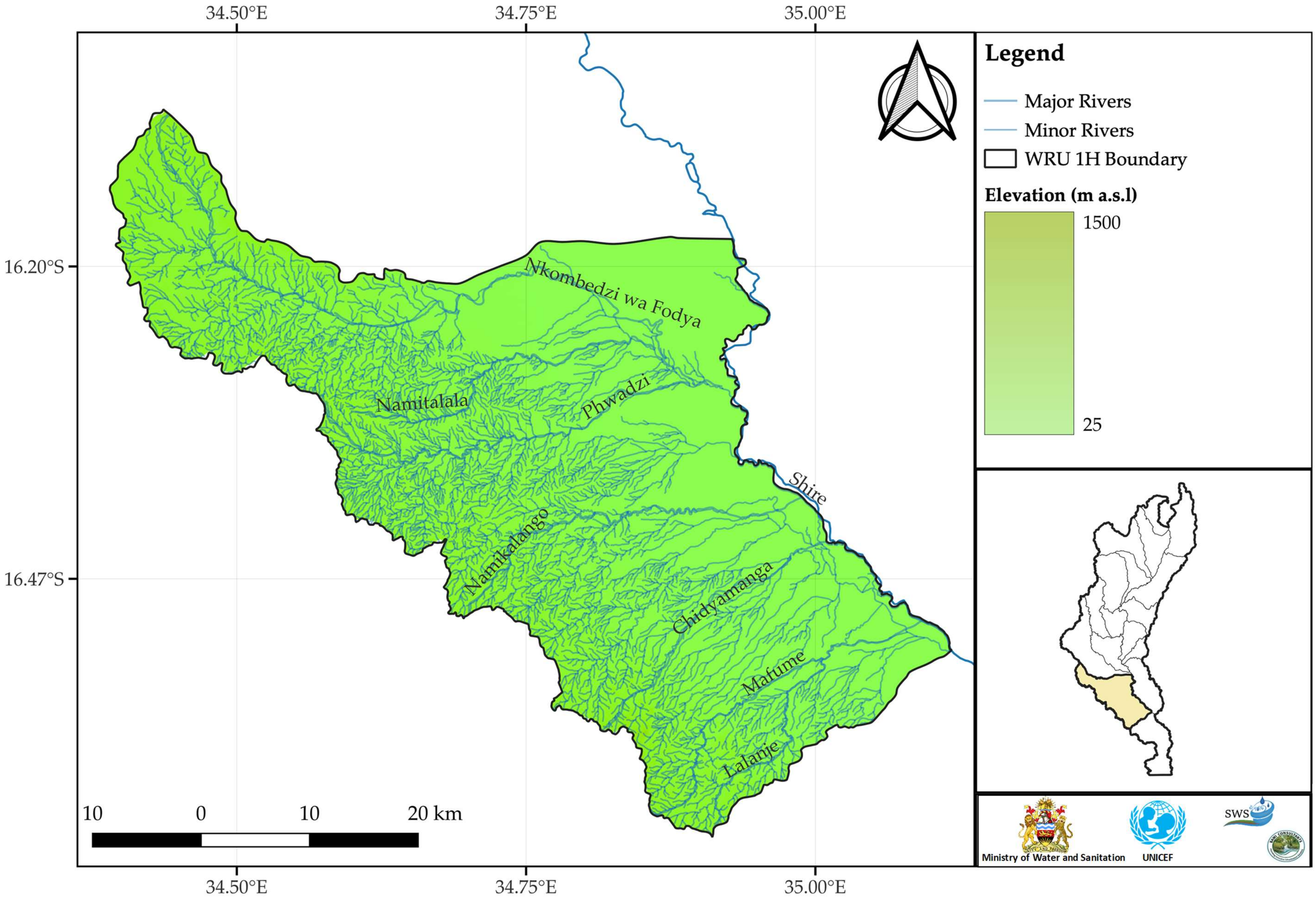


Figure WRU 1H.3 Hydrogeology Units and Water Table

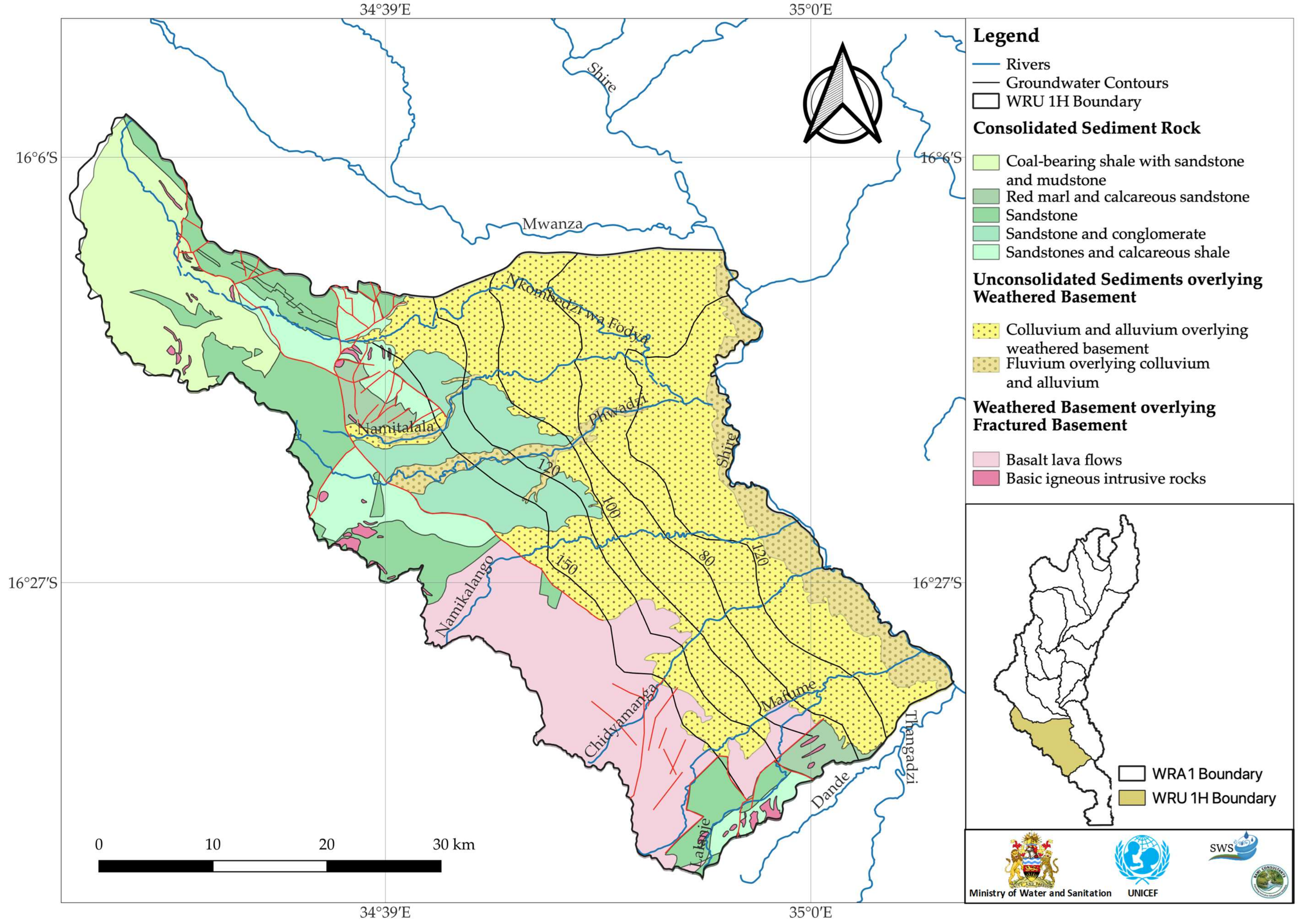


Figure WRU 1H.4 Groundwater Chemistry Distribution Electrical Conductivity

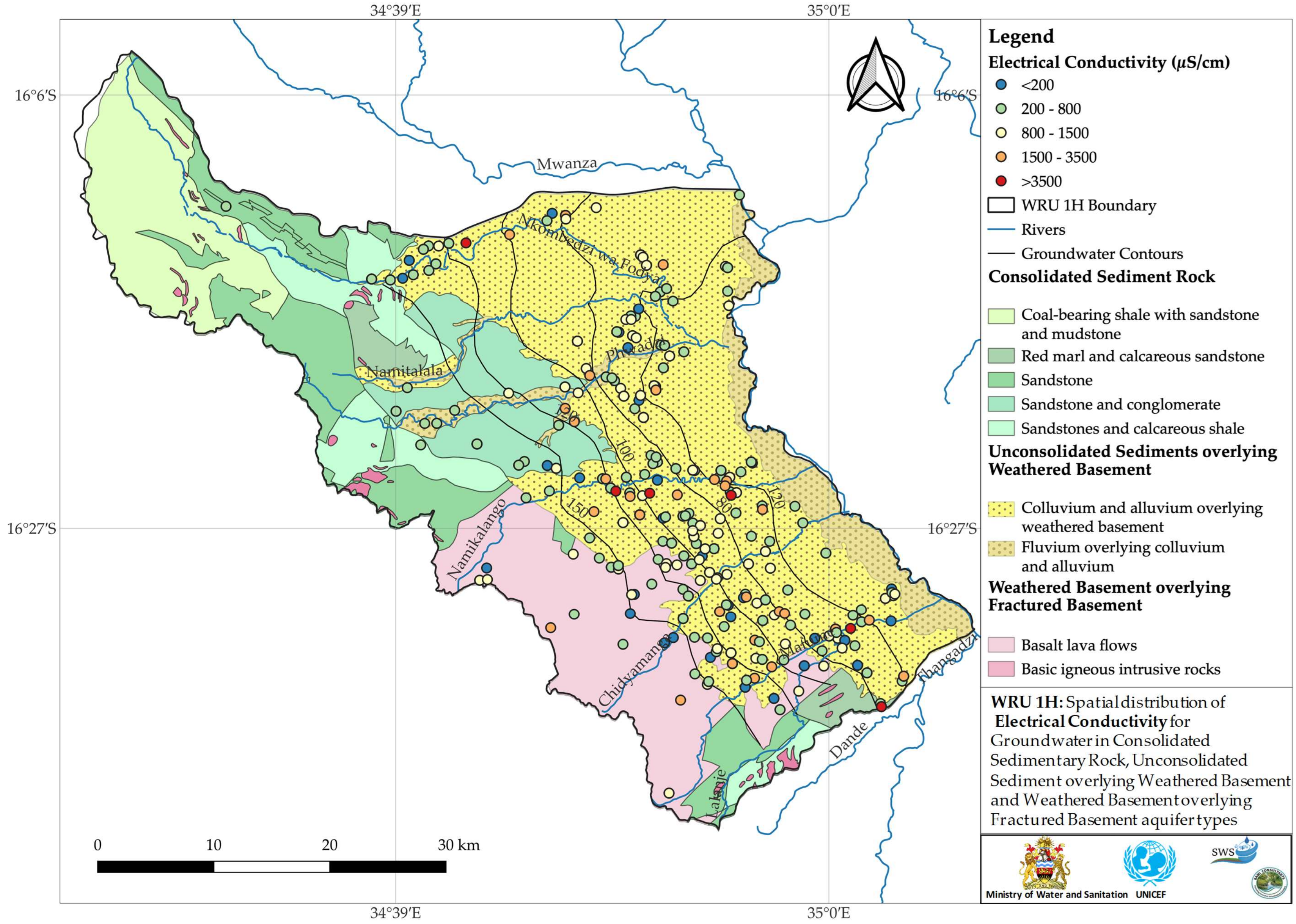
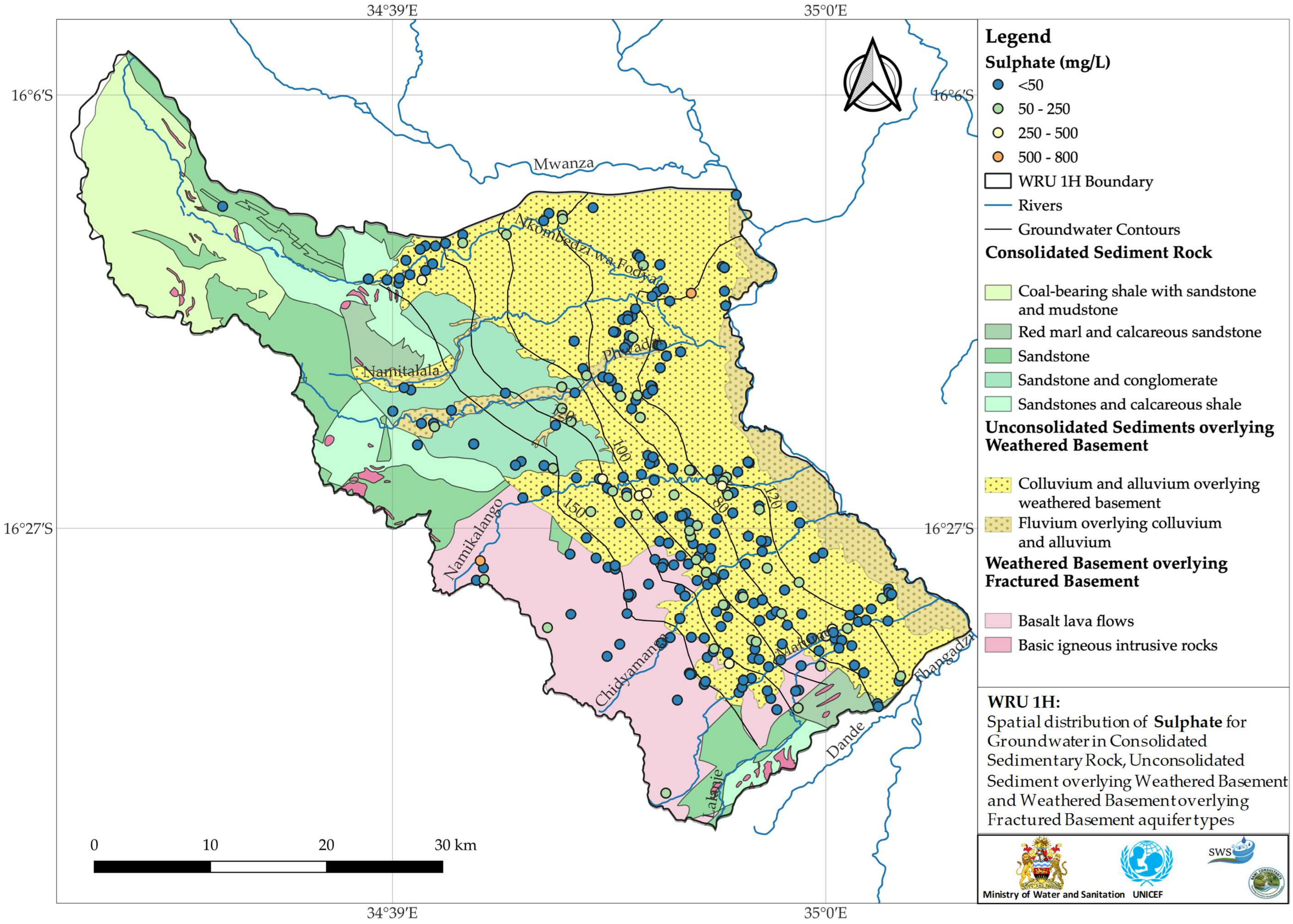


Figure WRU 1H.5 Groundwater Chemistry Distribution of Sulphate



WRU 1H:
Spatial distribution of **Sulphate** for Groundwater in Consolidated Sedimentary Rock, Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 1H.6 Groundwater Chemistry Distribution Chloride

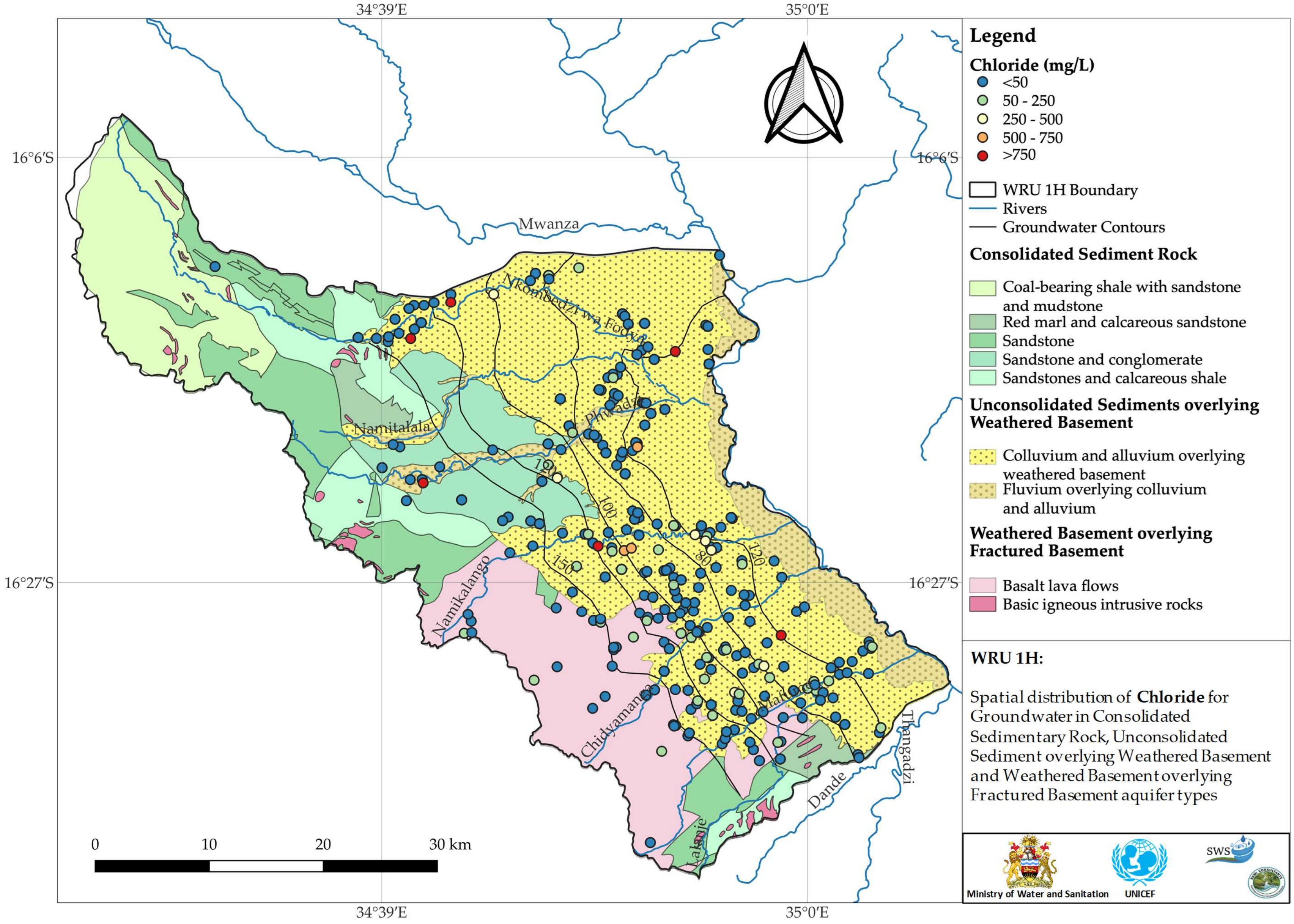
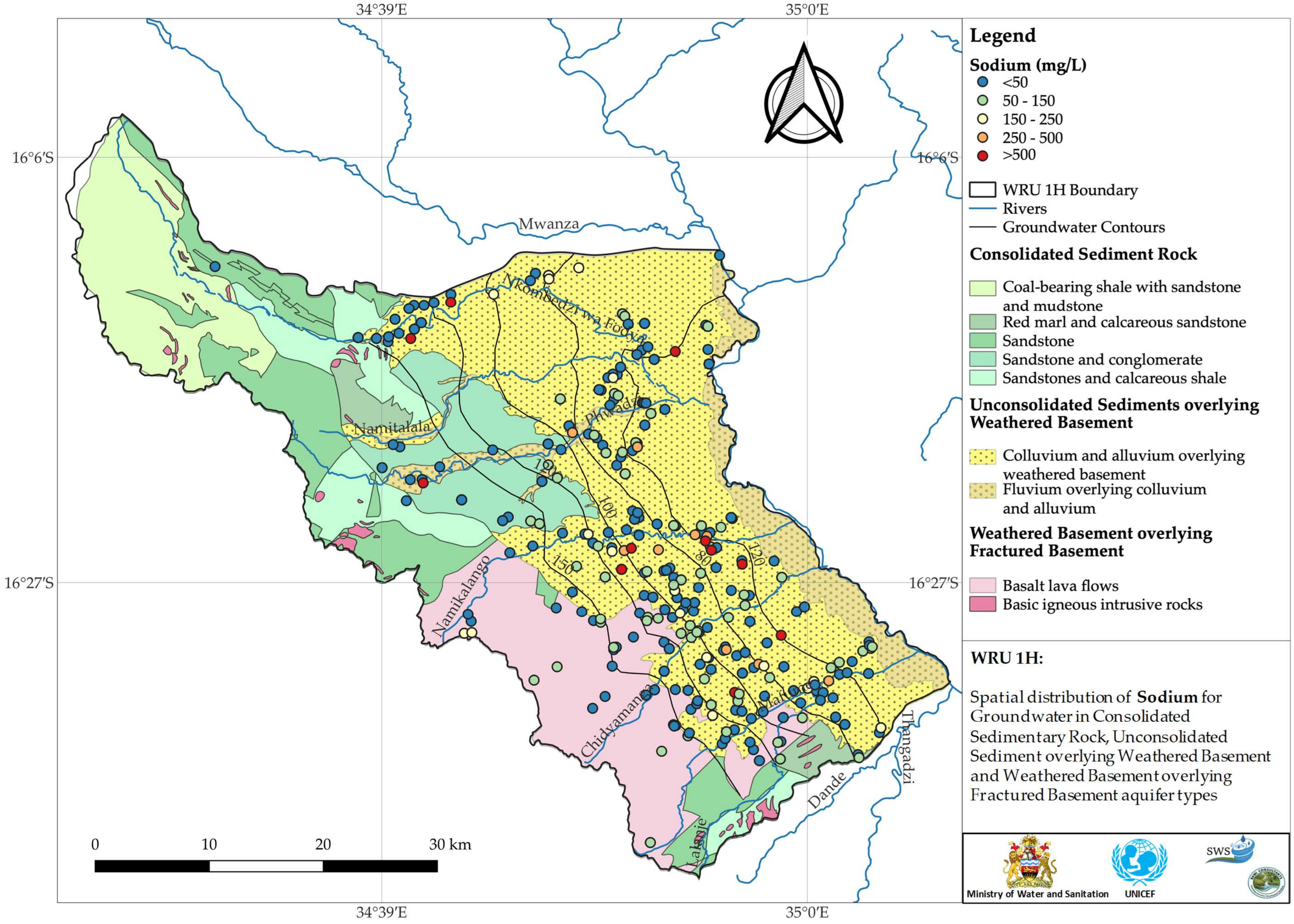


Figure WRU 1H.7 Groundwater Chemistry Distribution Sodium



WRU 1H:

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

Figure WRU 1H.8 Groundwater Chemistry Distribution Calcium

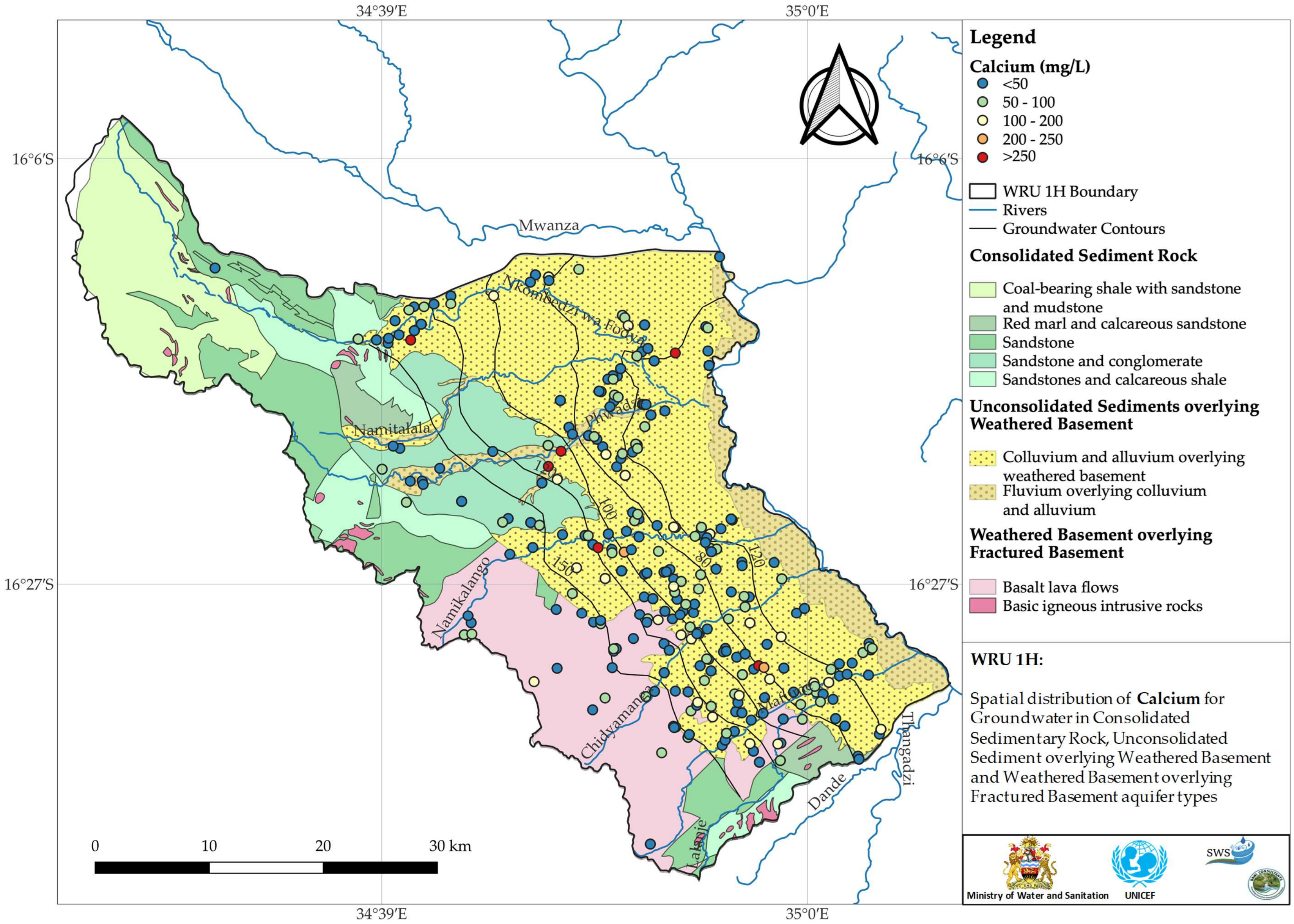


Figure WRU 1H.9 Piper Diagram of water quality results with respect to the major aquifer type

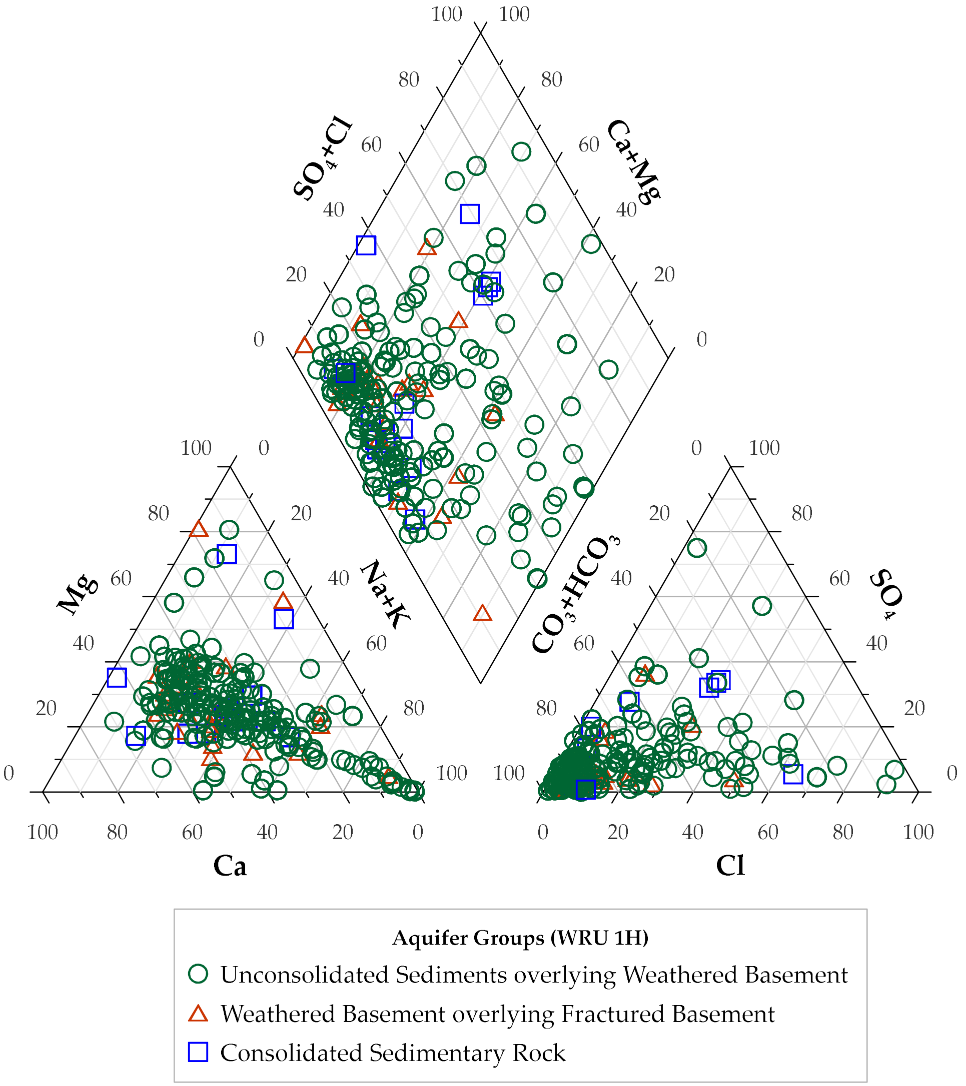
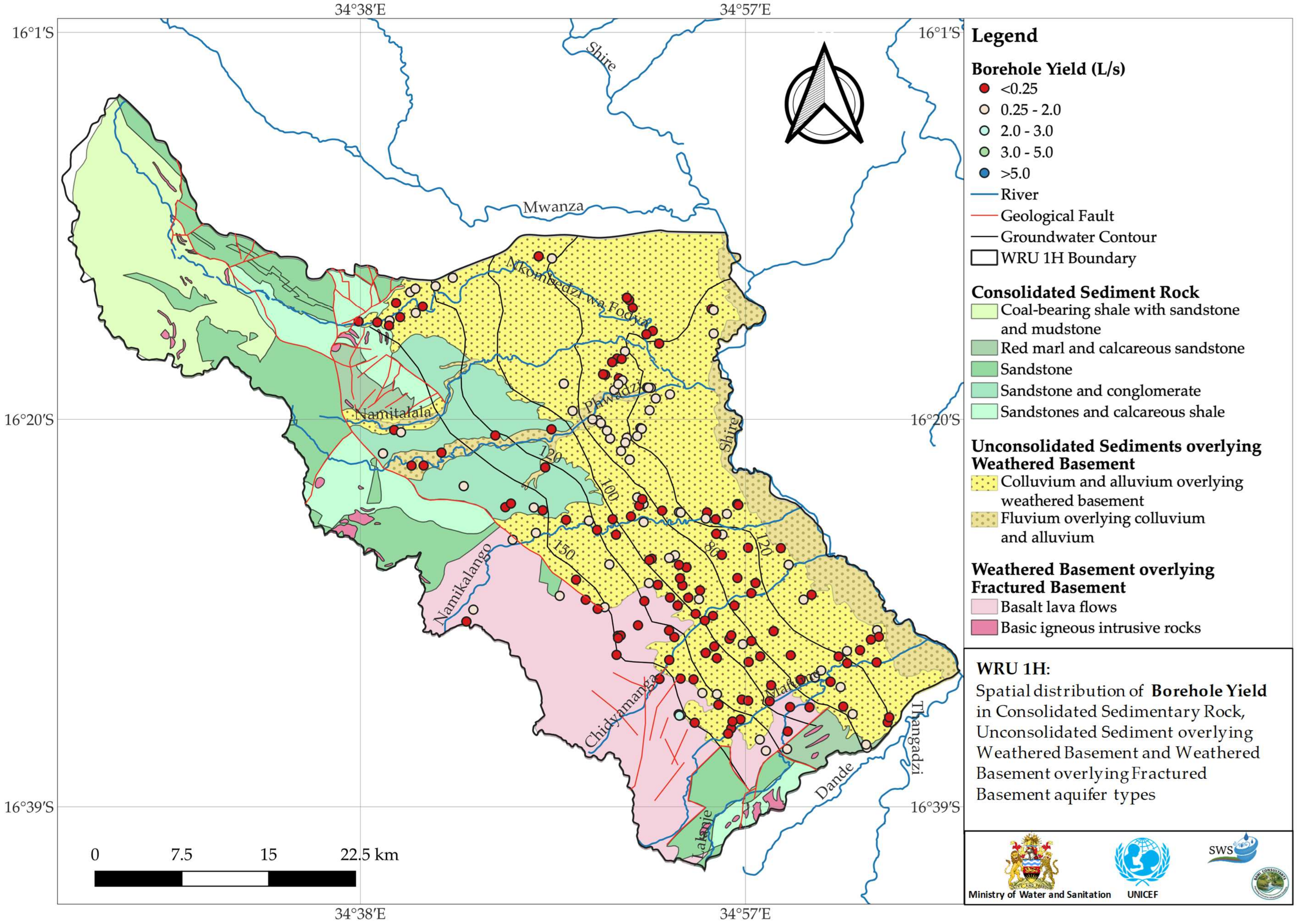


Figure WRU 1H.10 Borehole Yield Map for data held by the Ministry



WRU 1K Figures

Figure WRU 1K.1 Land Use and Major Roads

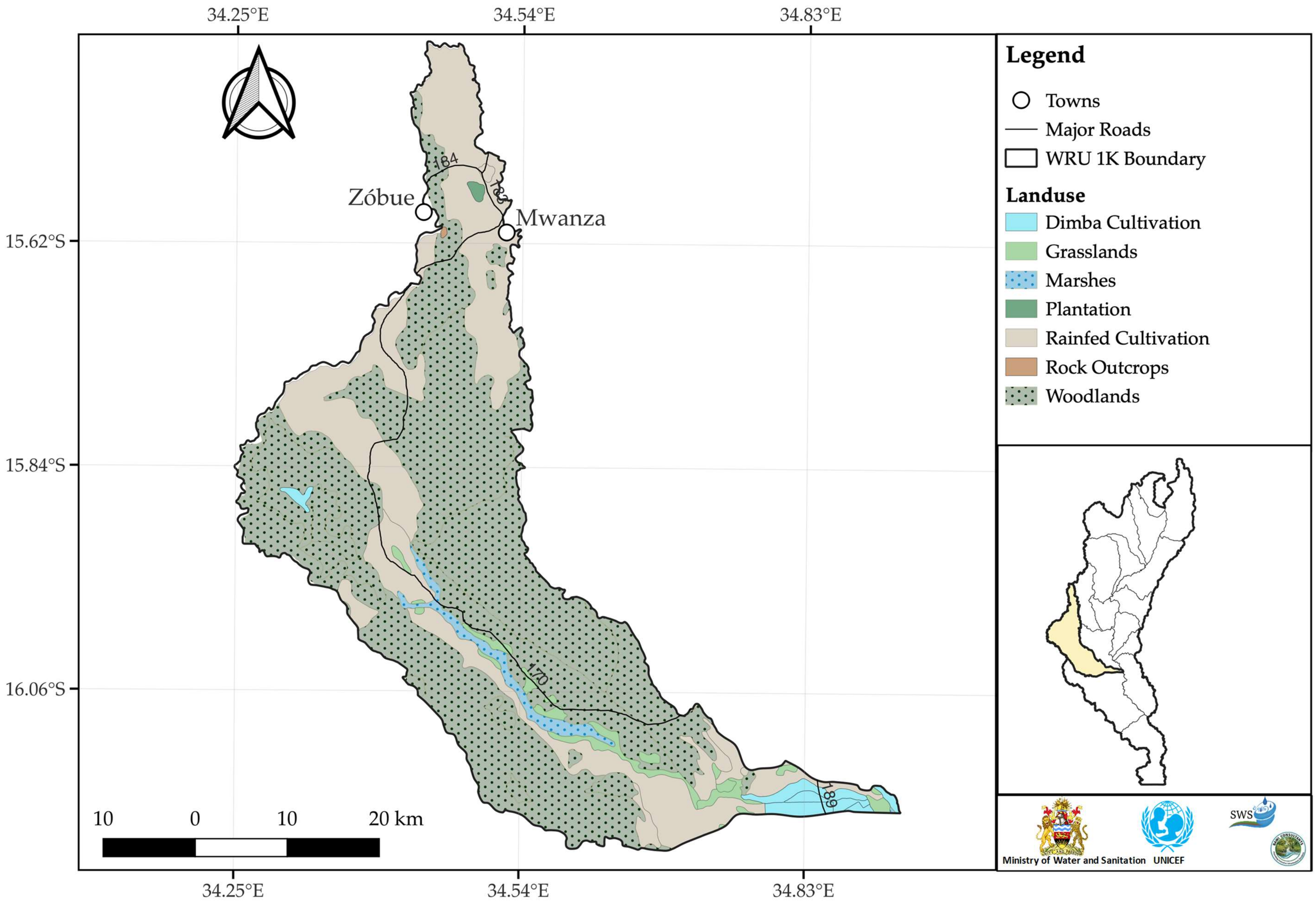


Figure WRU 1K.2 Rivers and Wetlands

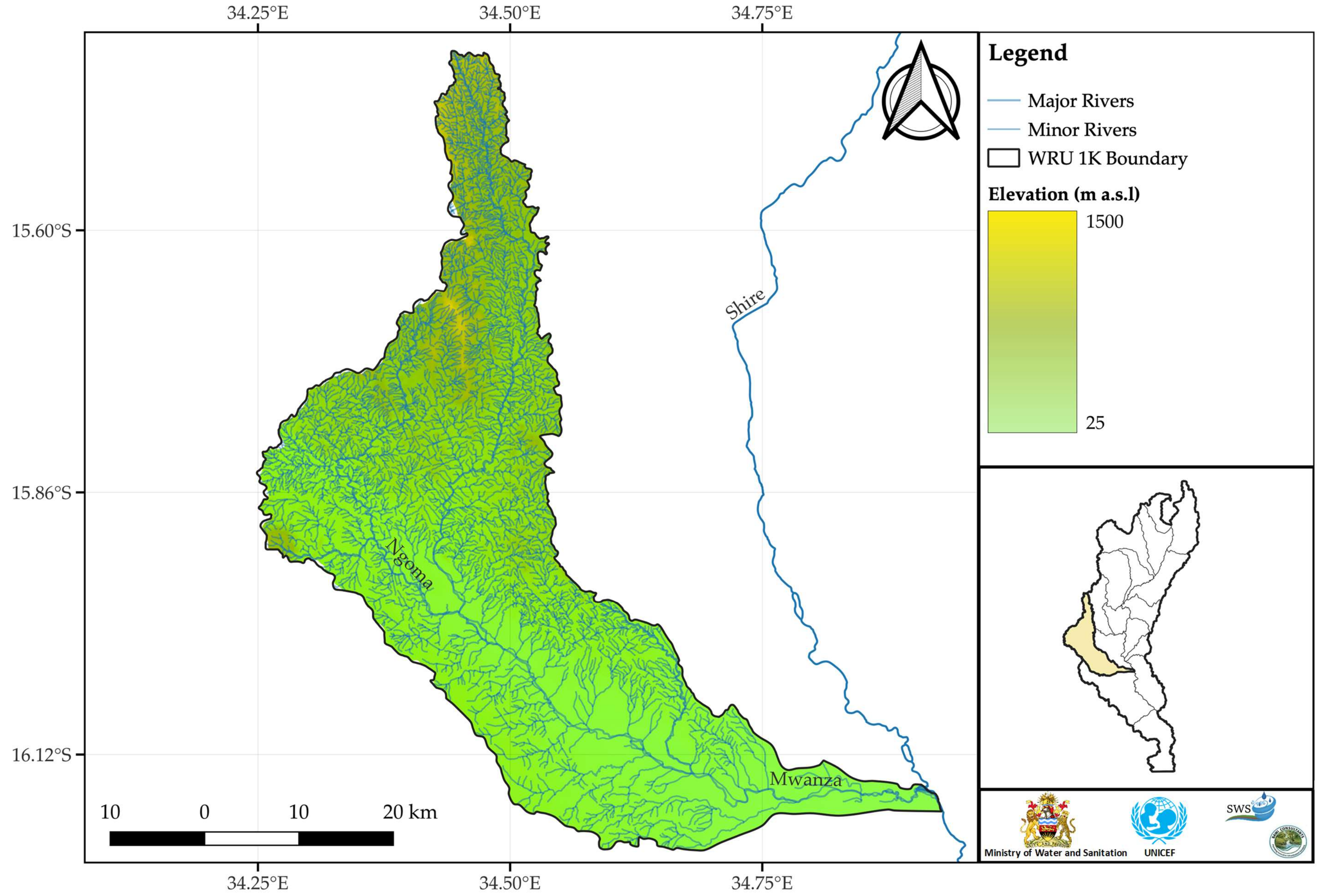


Figure WRU 1K.3 Hydrogeology Units and Water Table

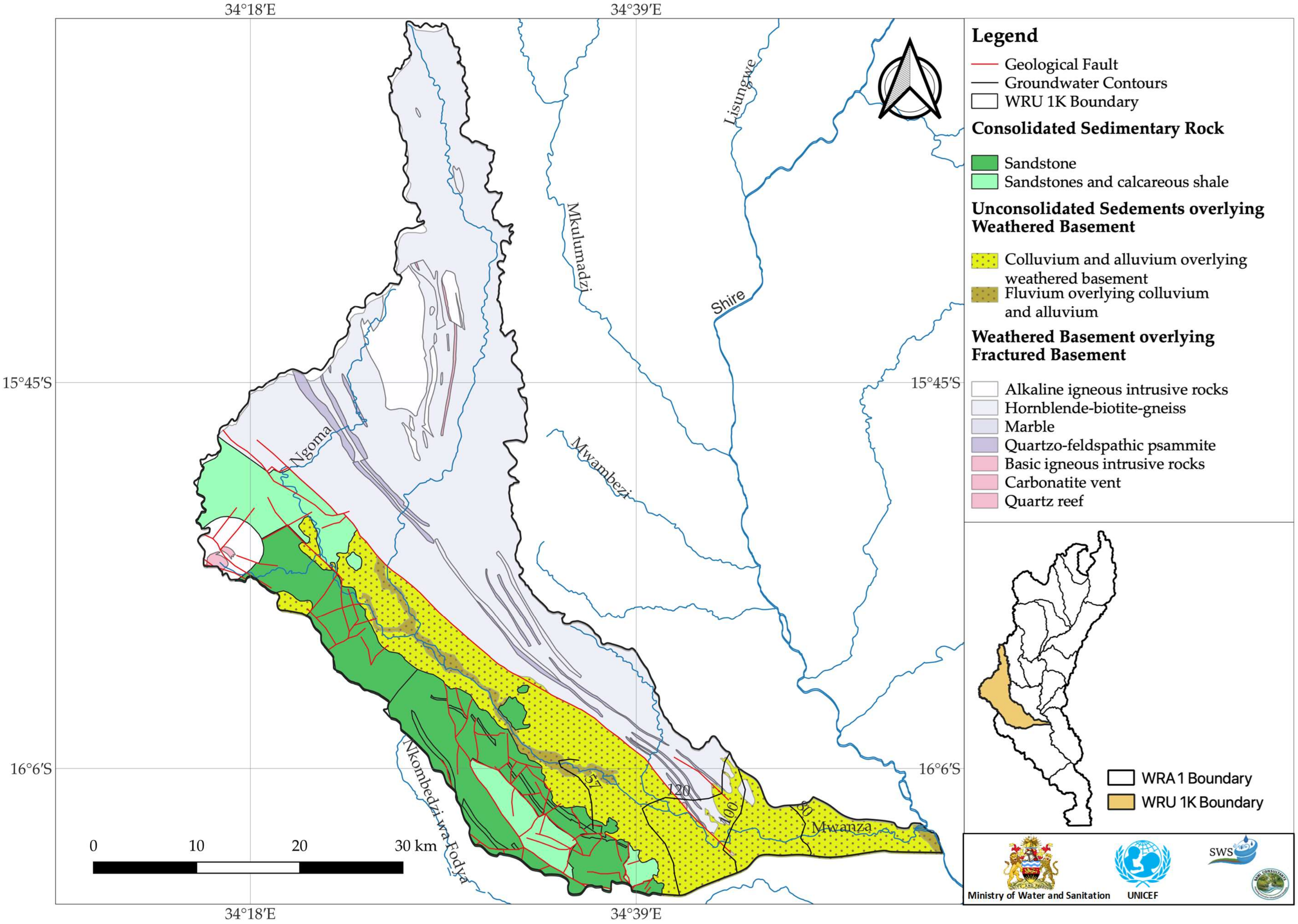


Figure WRU 1K.4 Groundwater Chemistry Distribution of Electrical Conductivity

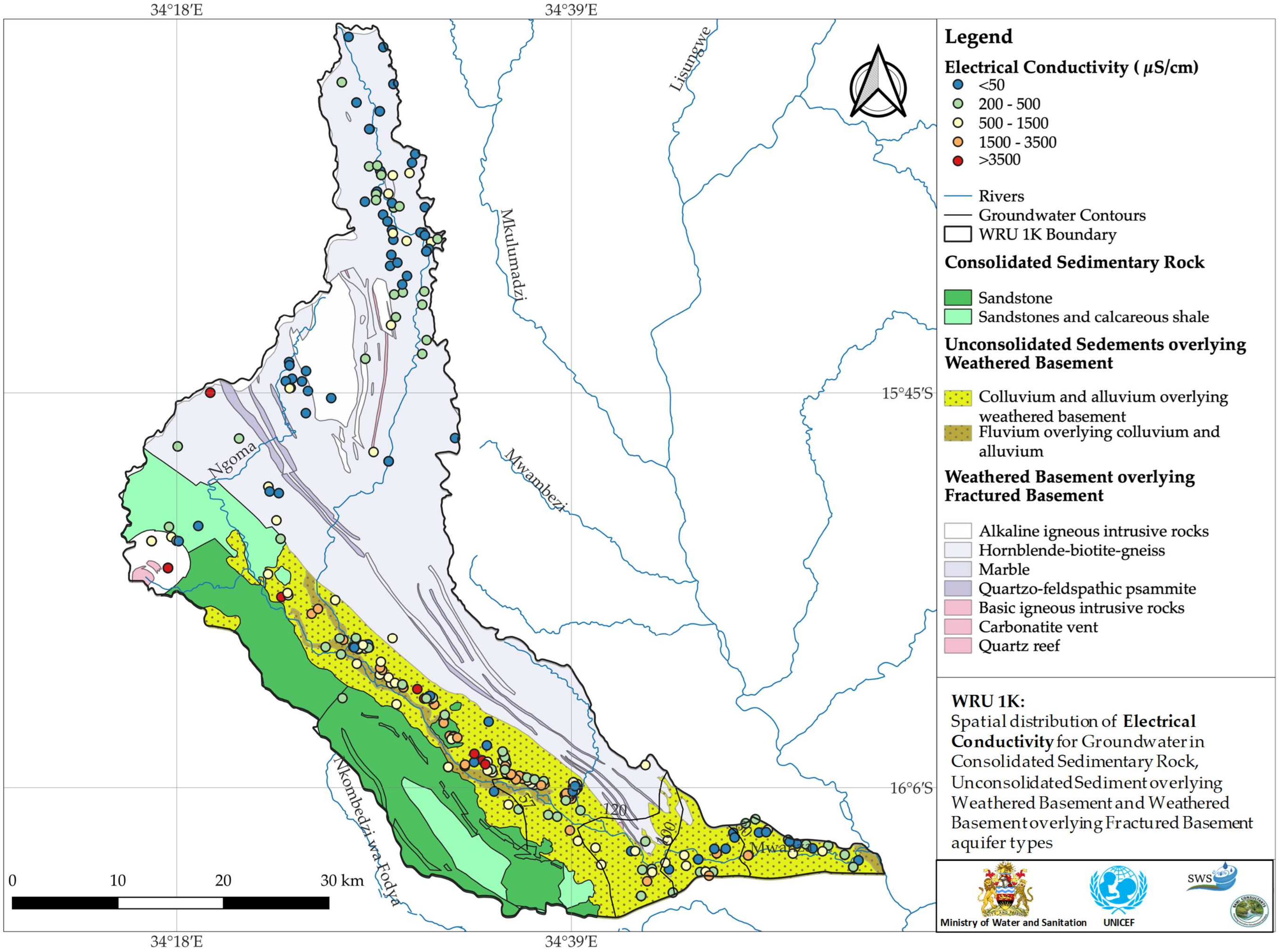


Figure WRU 1K.5 Groundwater Chemistry Distribution of Sulphate

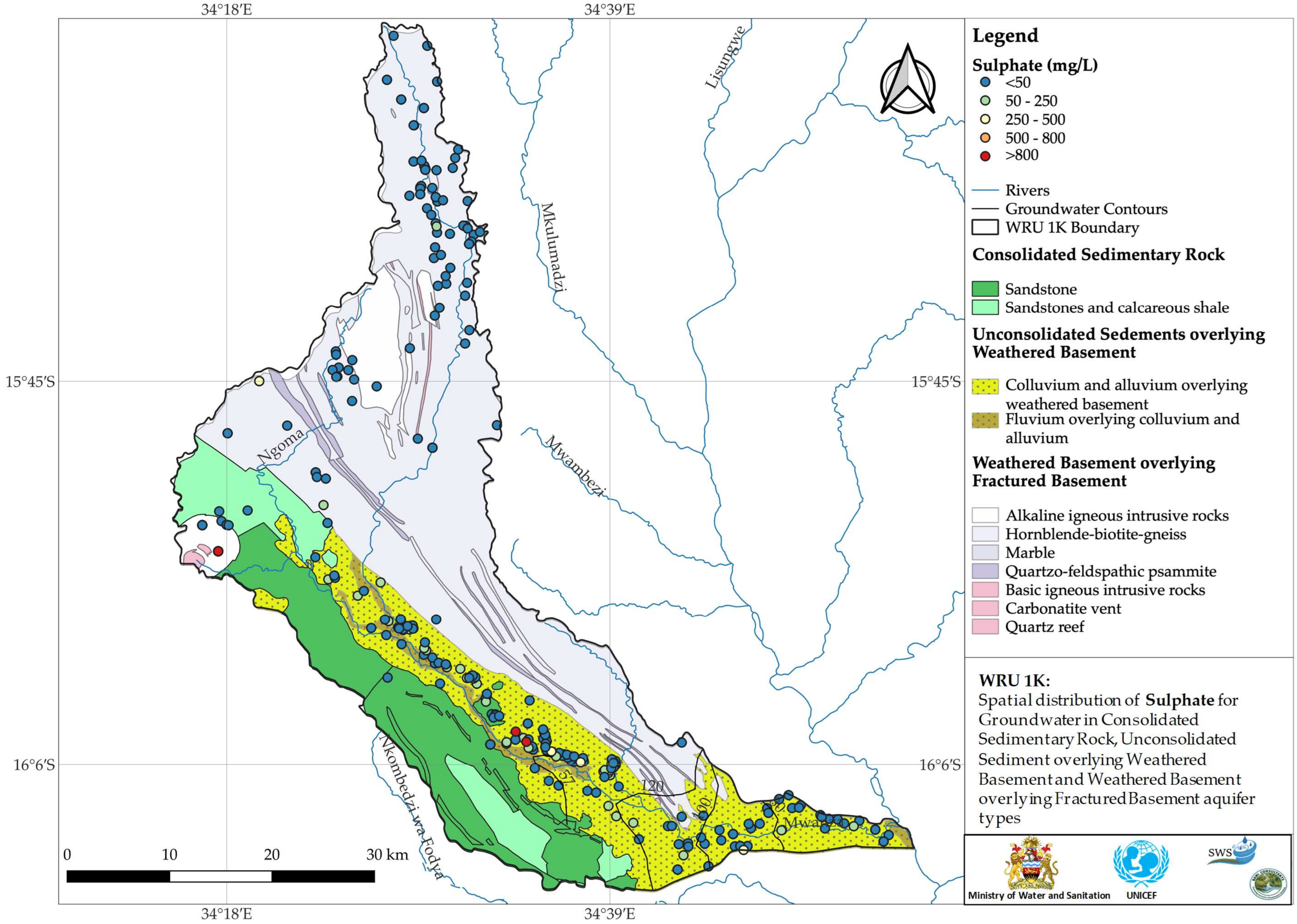


Figure WRU 1K.6 Groundwater Chemistry Distribution Chloride

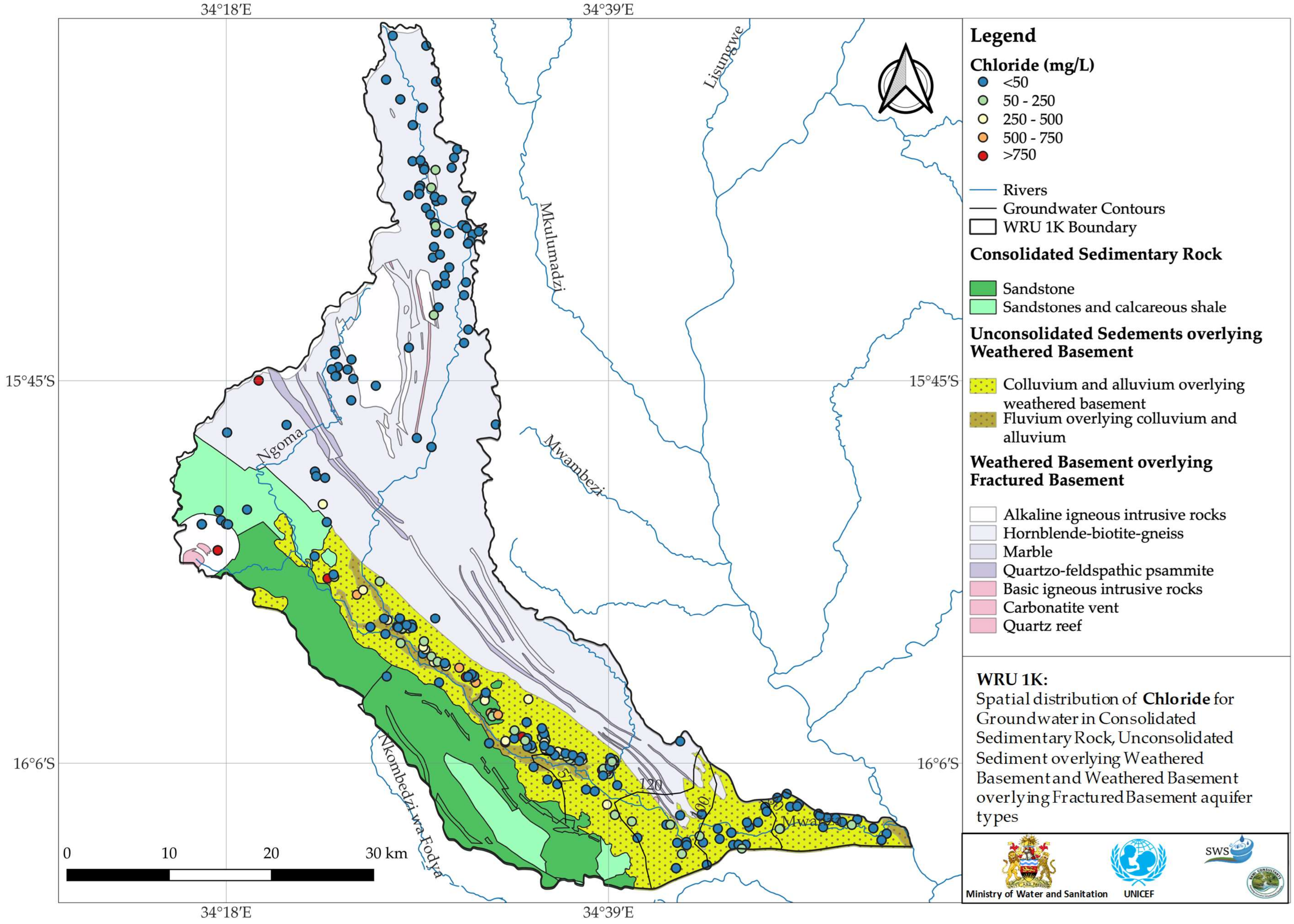


Figure WRU 1K.7 Groundwater Chemistry Distribution Sodium

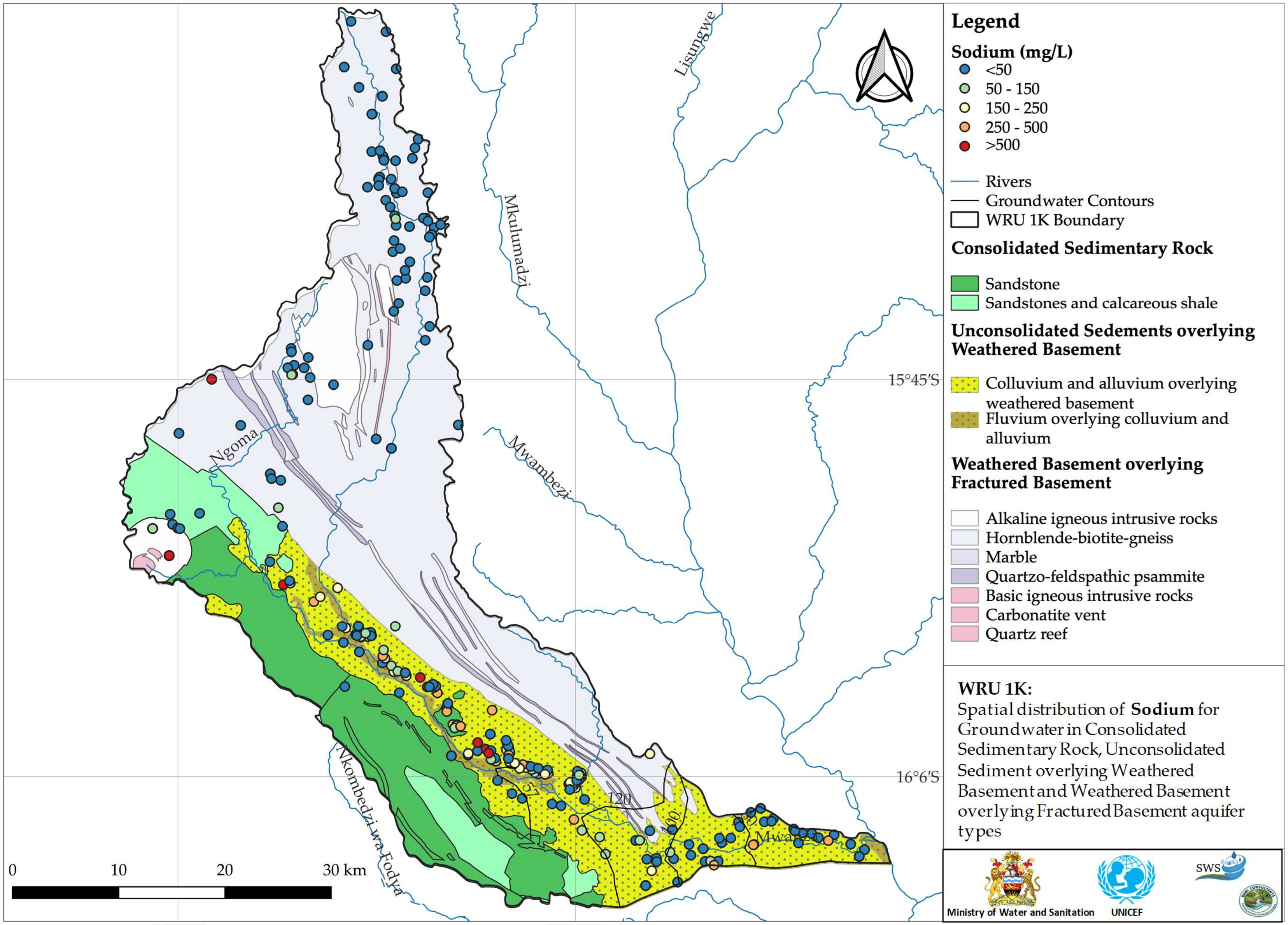
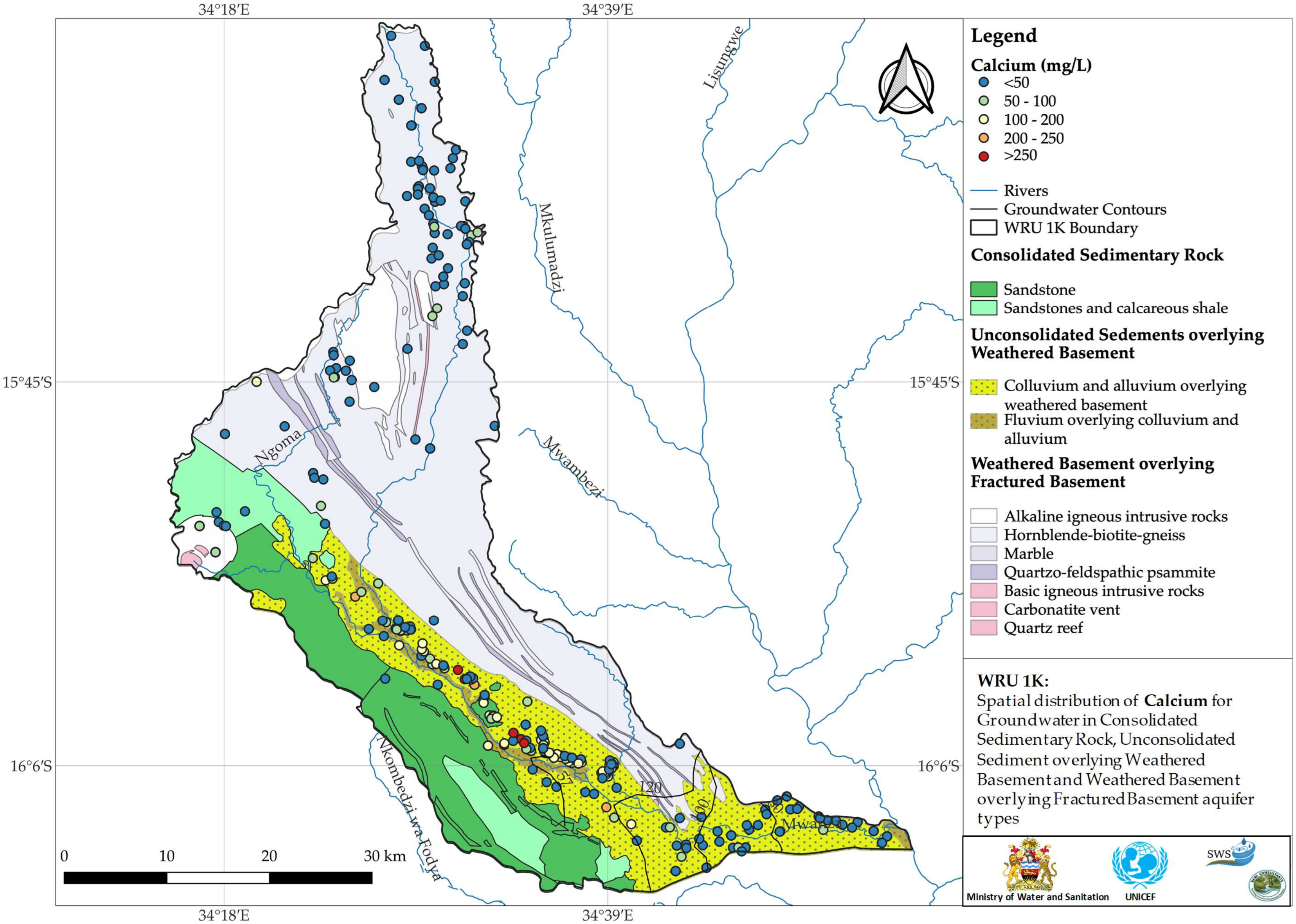


Figure WRU 1K.8 Groundwater Chemistry Distribution Calcium



WRU 1K:
Spatial distribution of **Calcium** for Groundwater in Consolidated Sedimentary Rock, Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

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

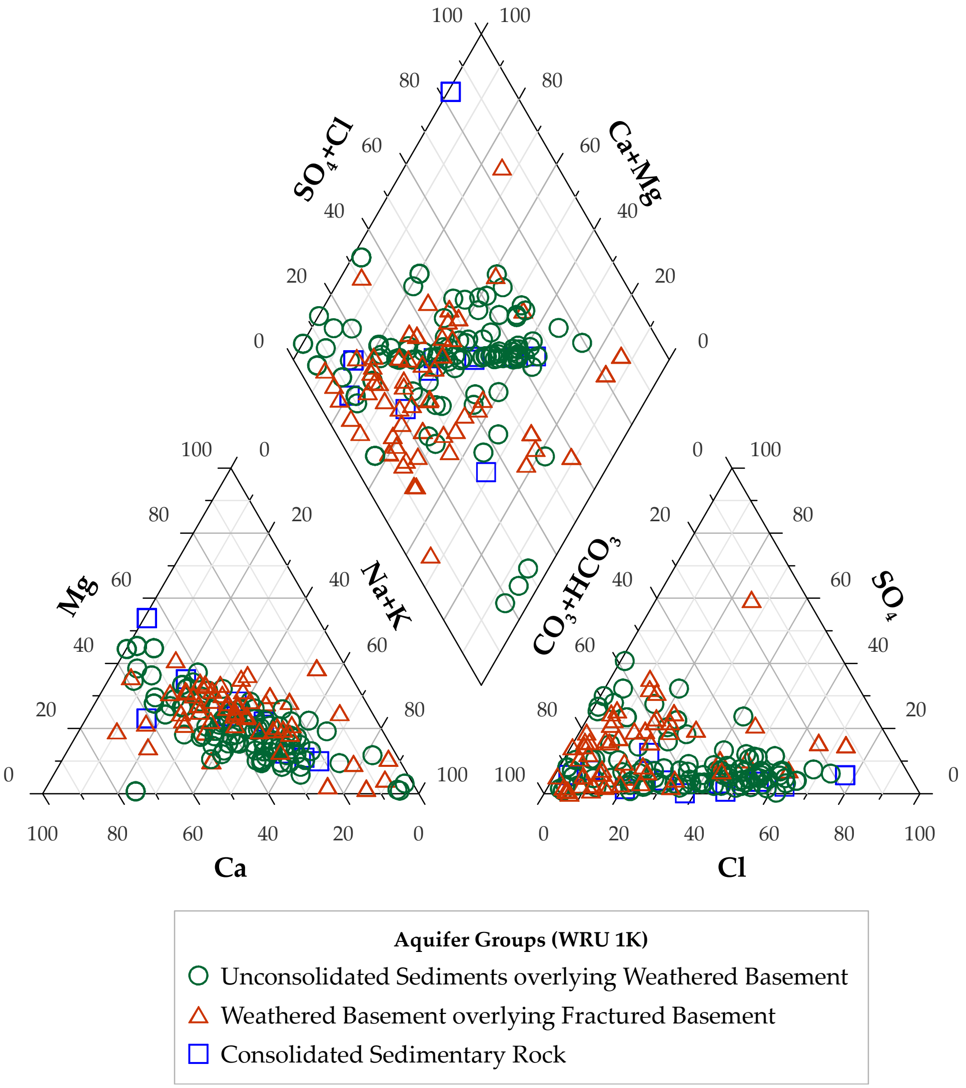
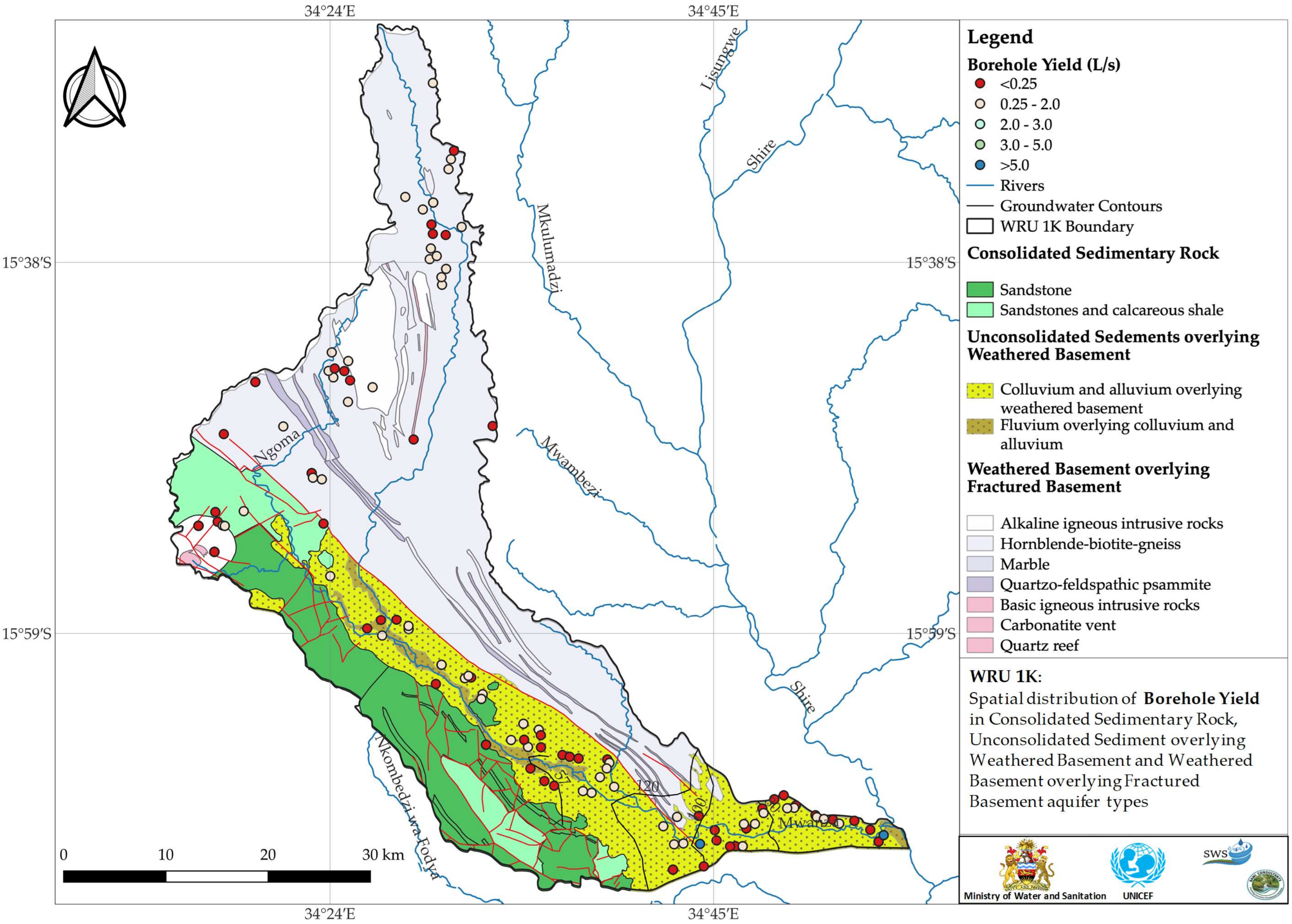


Figure WRU 1K.10 Borehole Yield Map for data held by the Ministry



WRU 1K:

Spatial distribution of **Borehole Yield** in Consolidated Sedimentary Rock, Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

WRU 1L Figures

Figure WRU 1L.1 Land Use and Major Roads

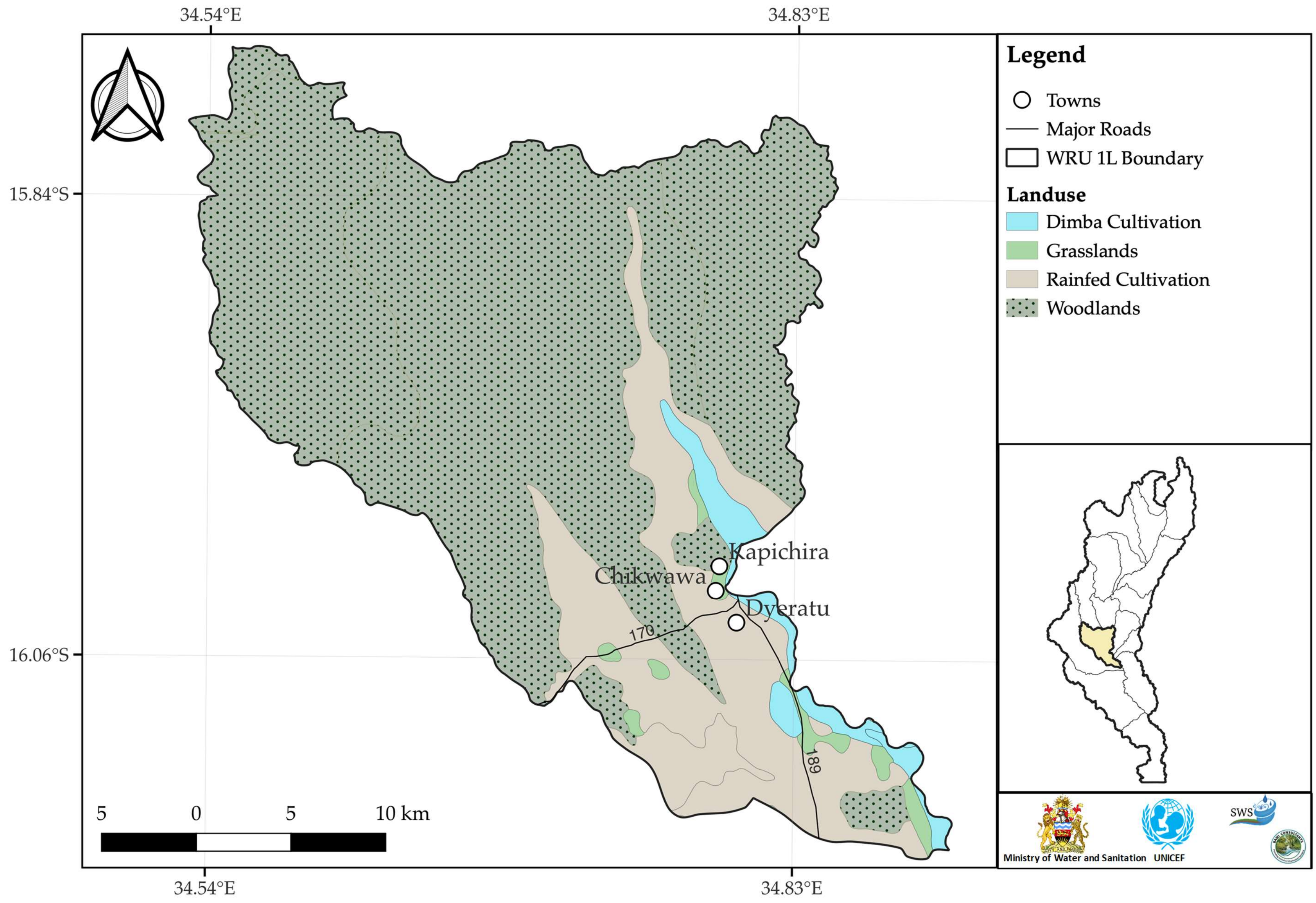


Figure WRU 1L.2 Rivers and Wetlands

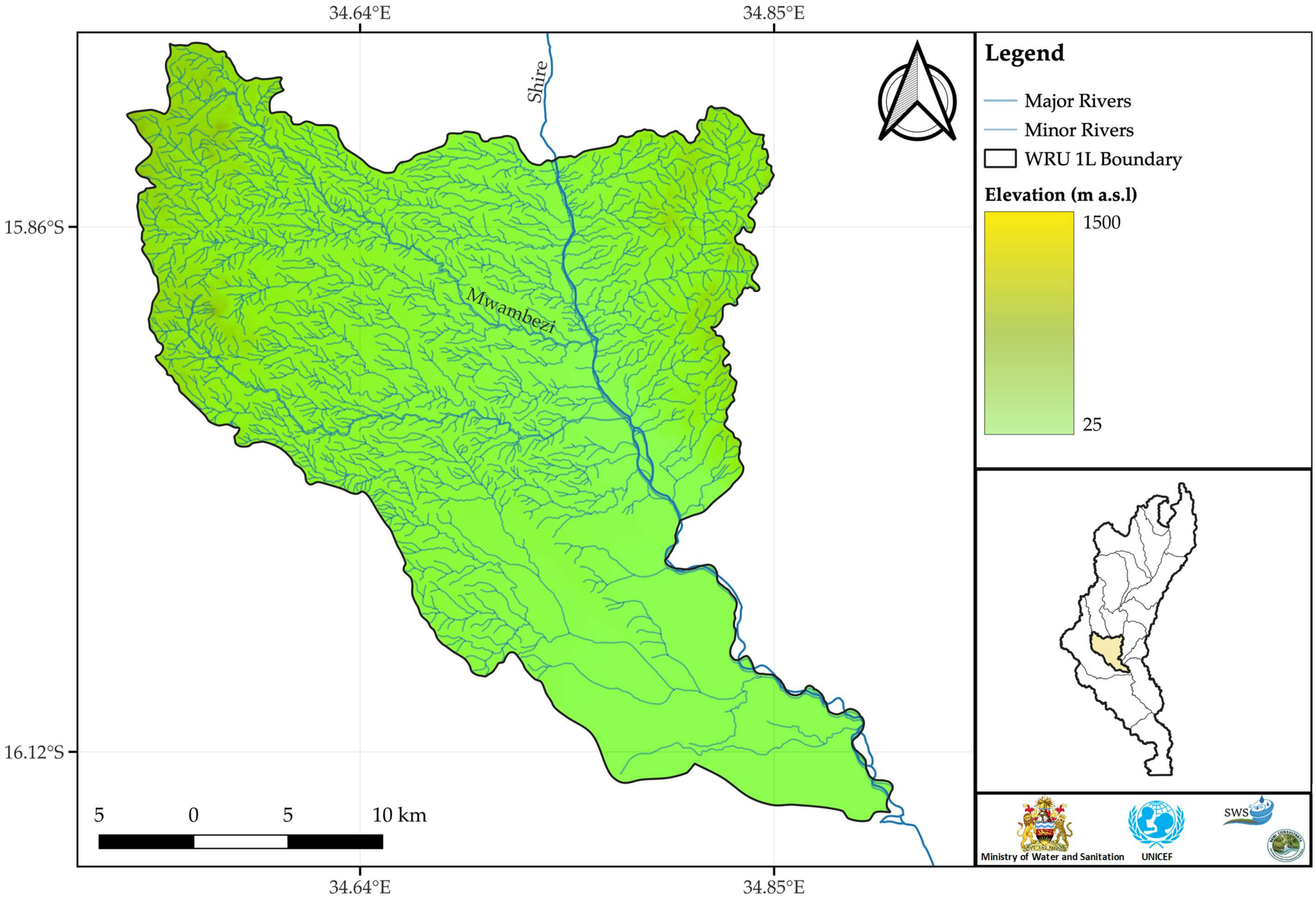


Figure WRU 1L.3 Hydrogeology Units and Water Table

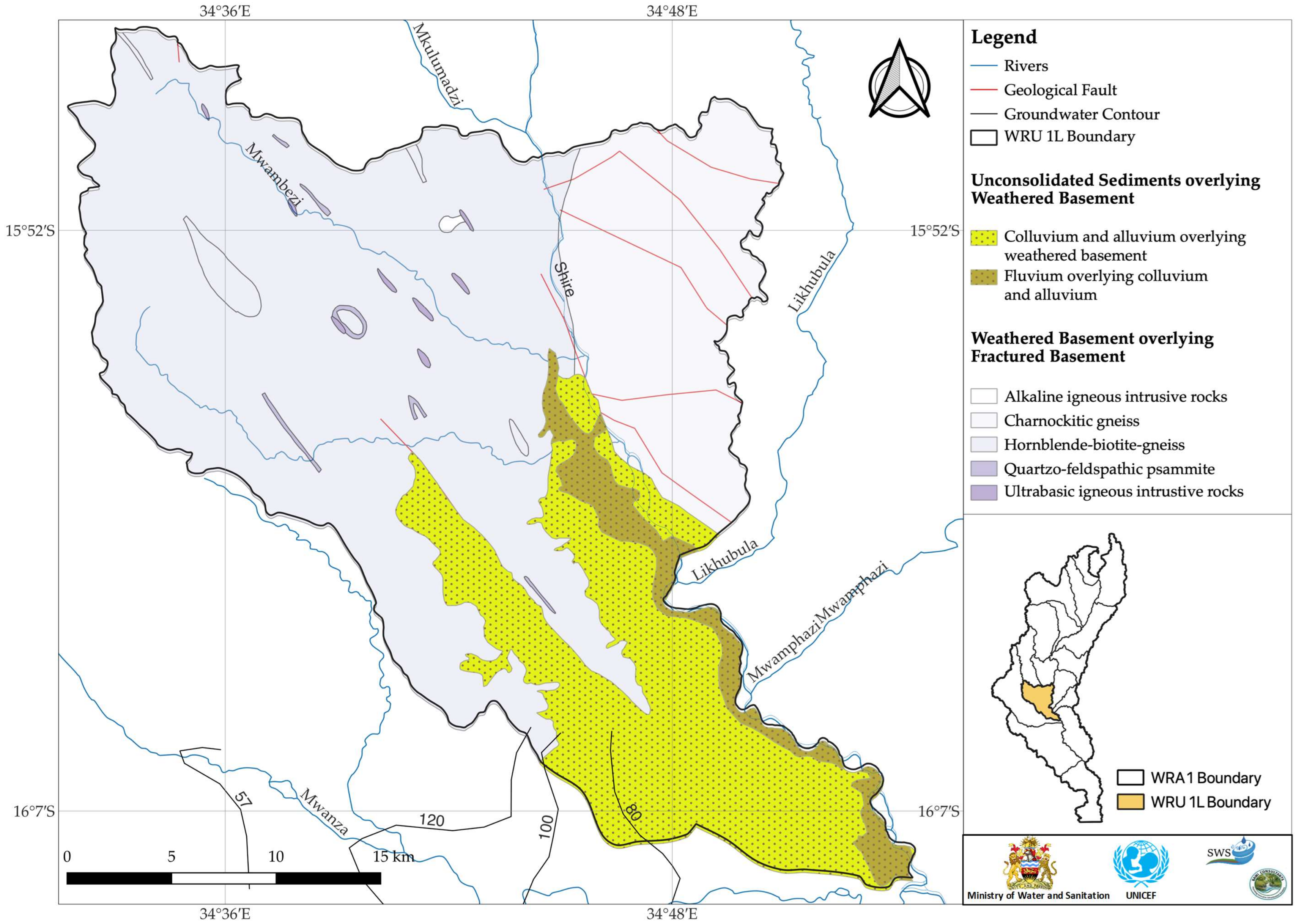


Figure WRU 1L.4 Groundwater Chemistry Distribution of Electrical Conductivity

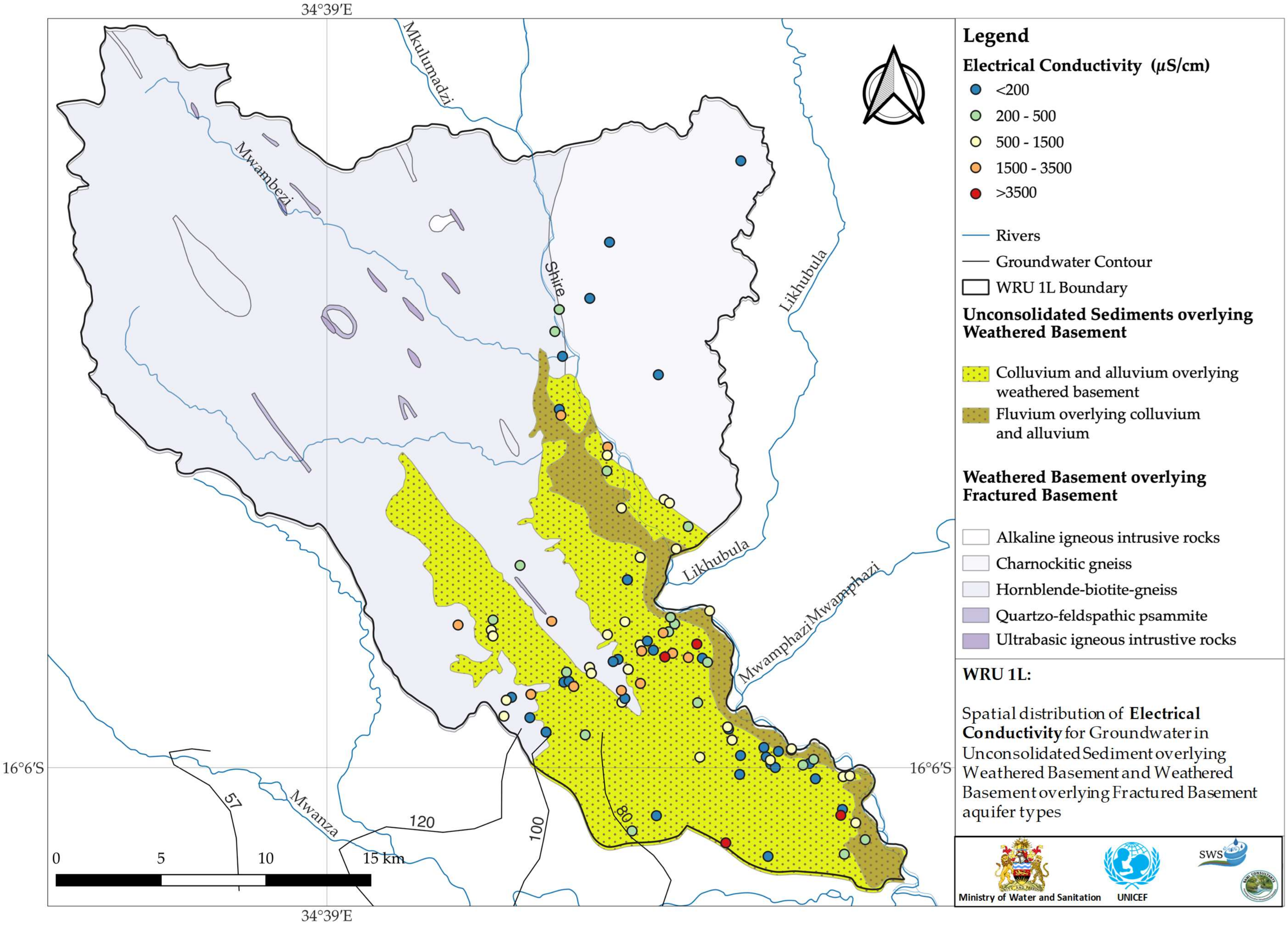


Figure WRU 1L.5 Groundwater Chemistry Distribution of Sulphate

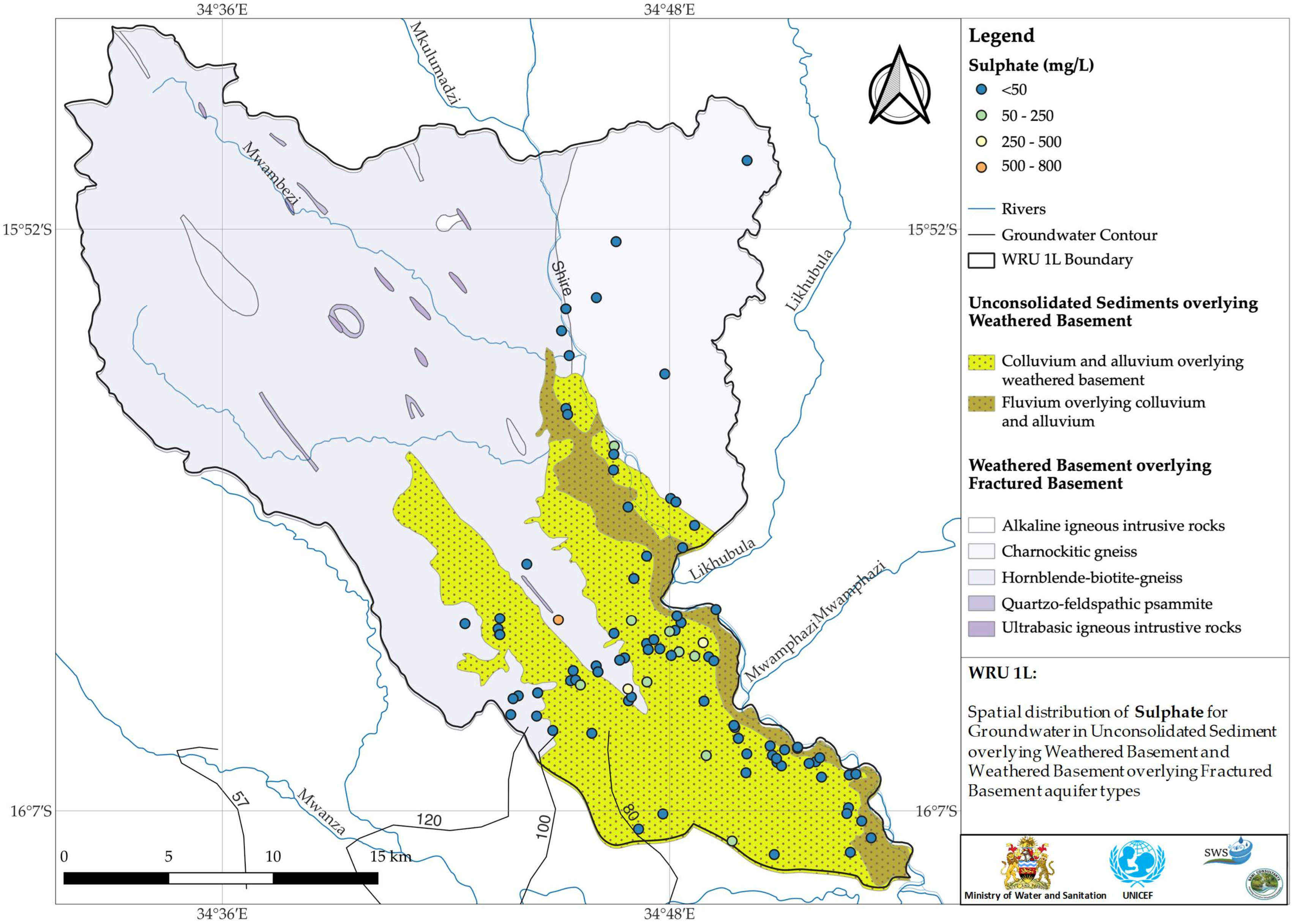
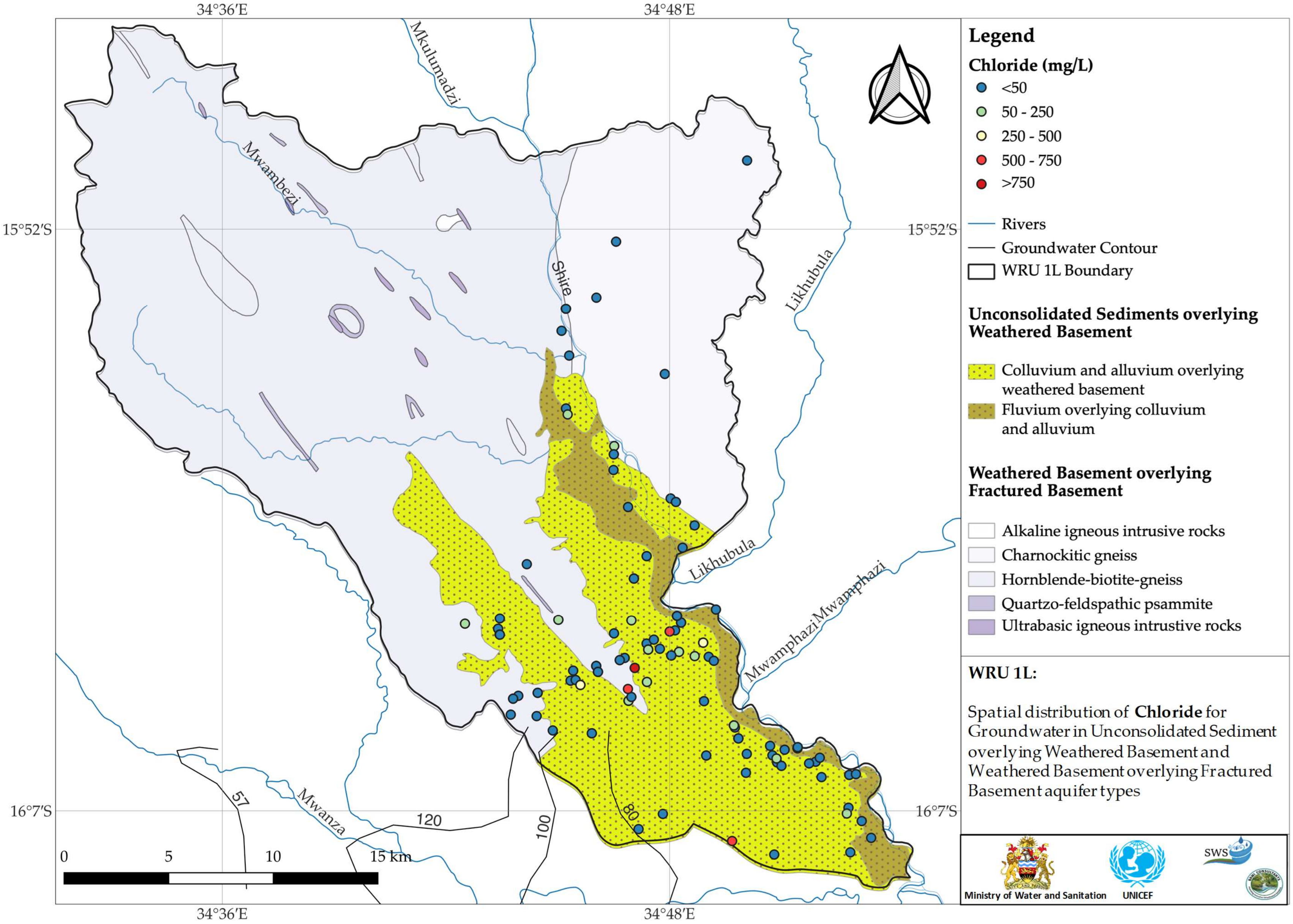


Figure WRU 1L.6 Groundwater Chemistry Distribution Chloride



WRU 1L:

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

Figure WRU 1L.7 Groundwater Chemistry Distribution Sodium

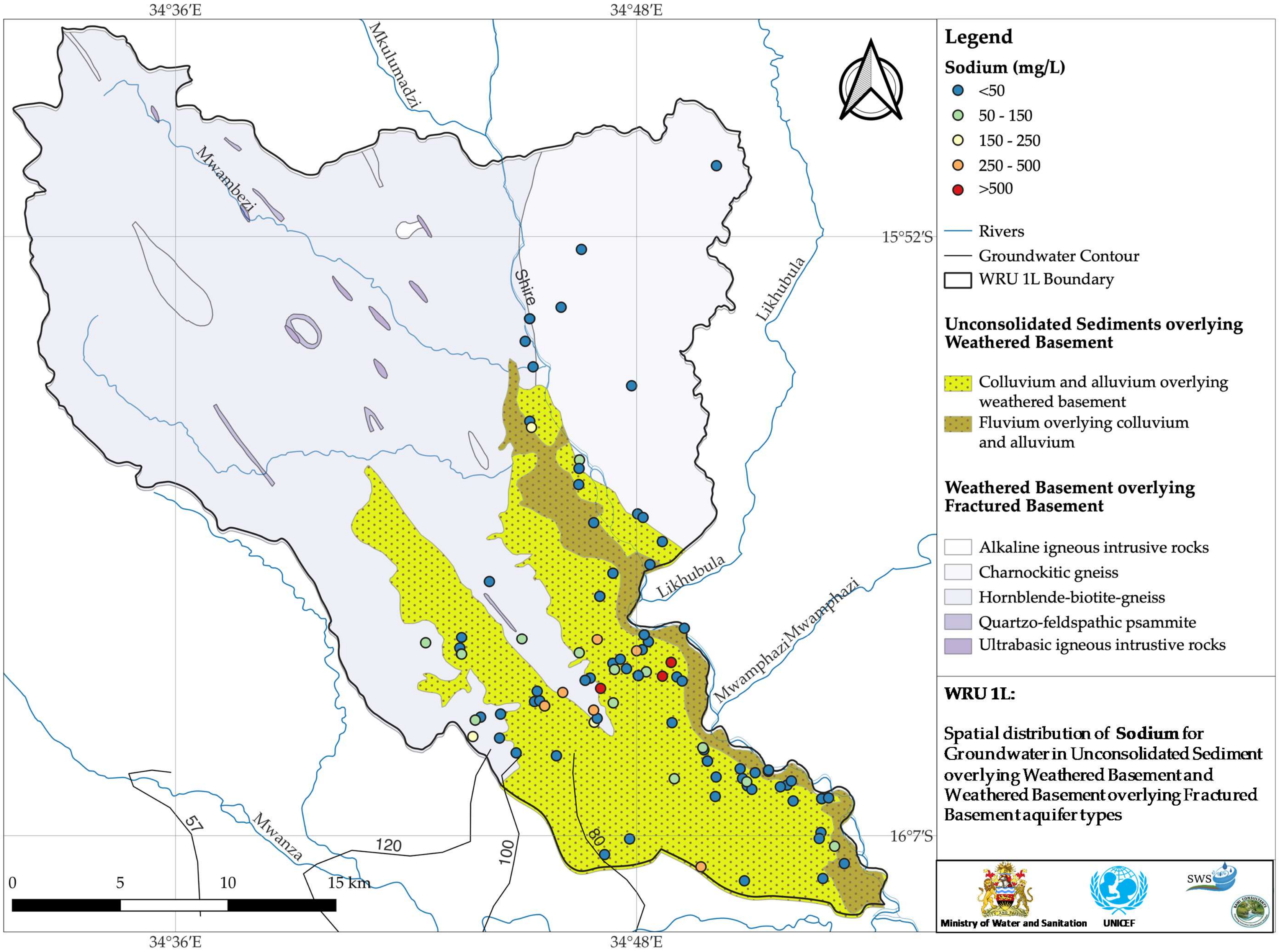
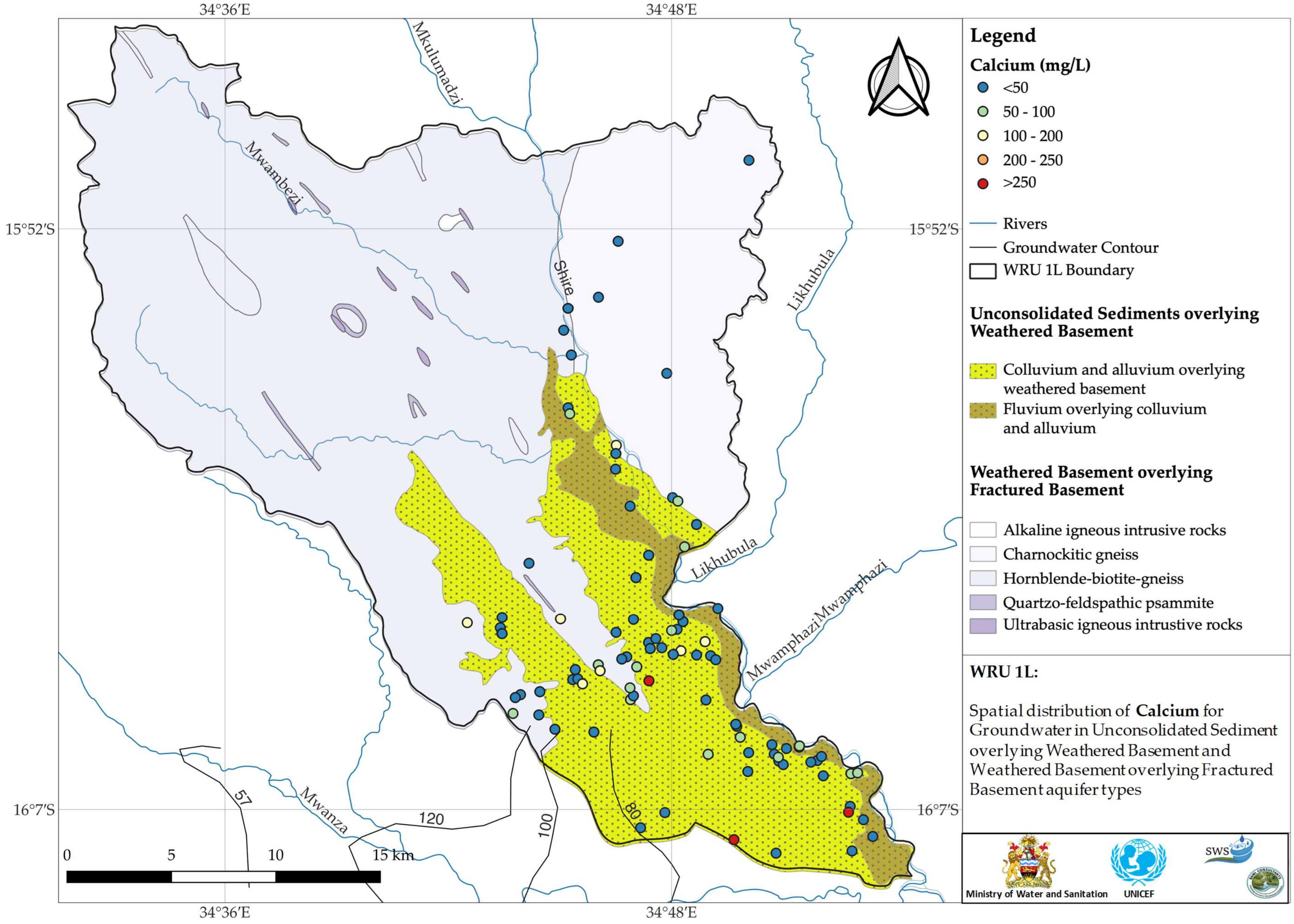


Figure WRU 1L.8 Groundwater Chemistry Distribution Calcium



WRU 1L:

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

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

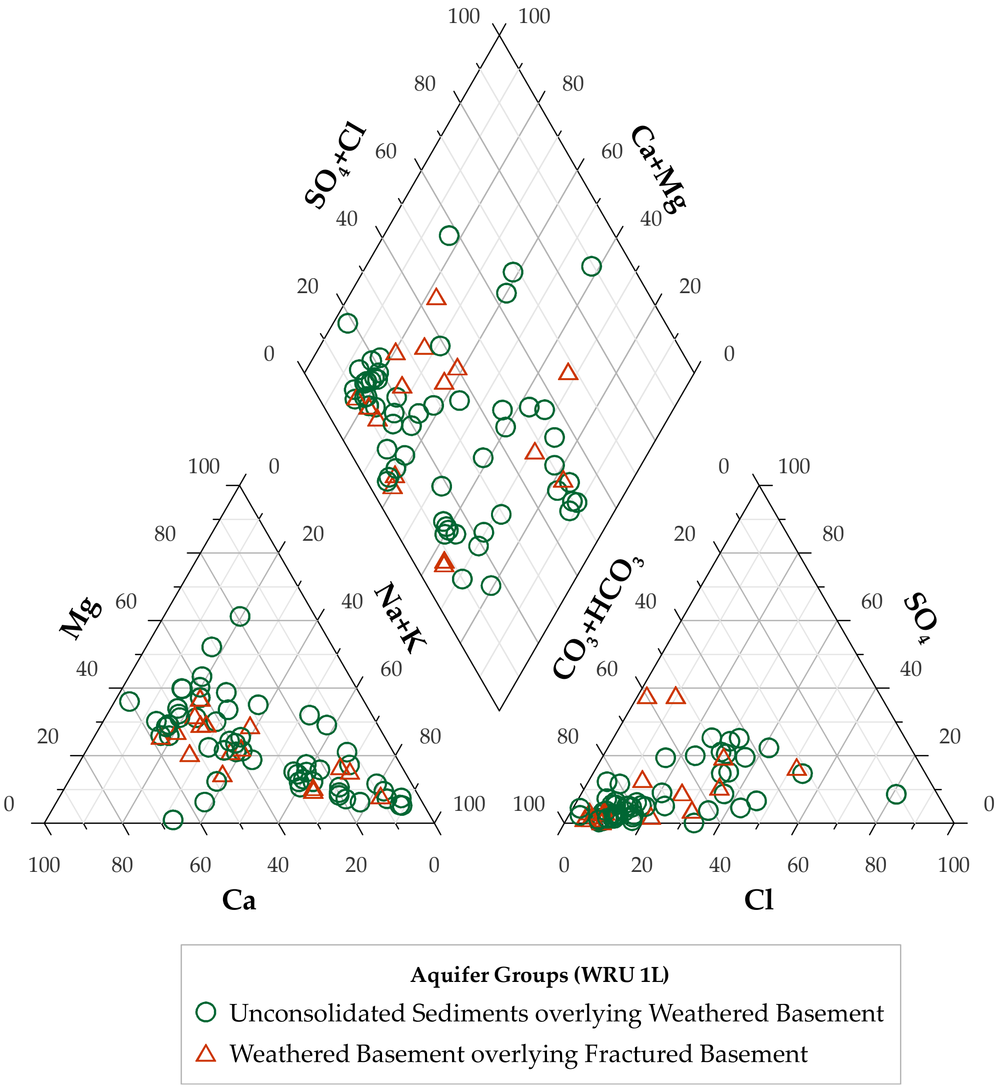
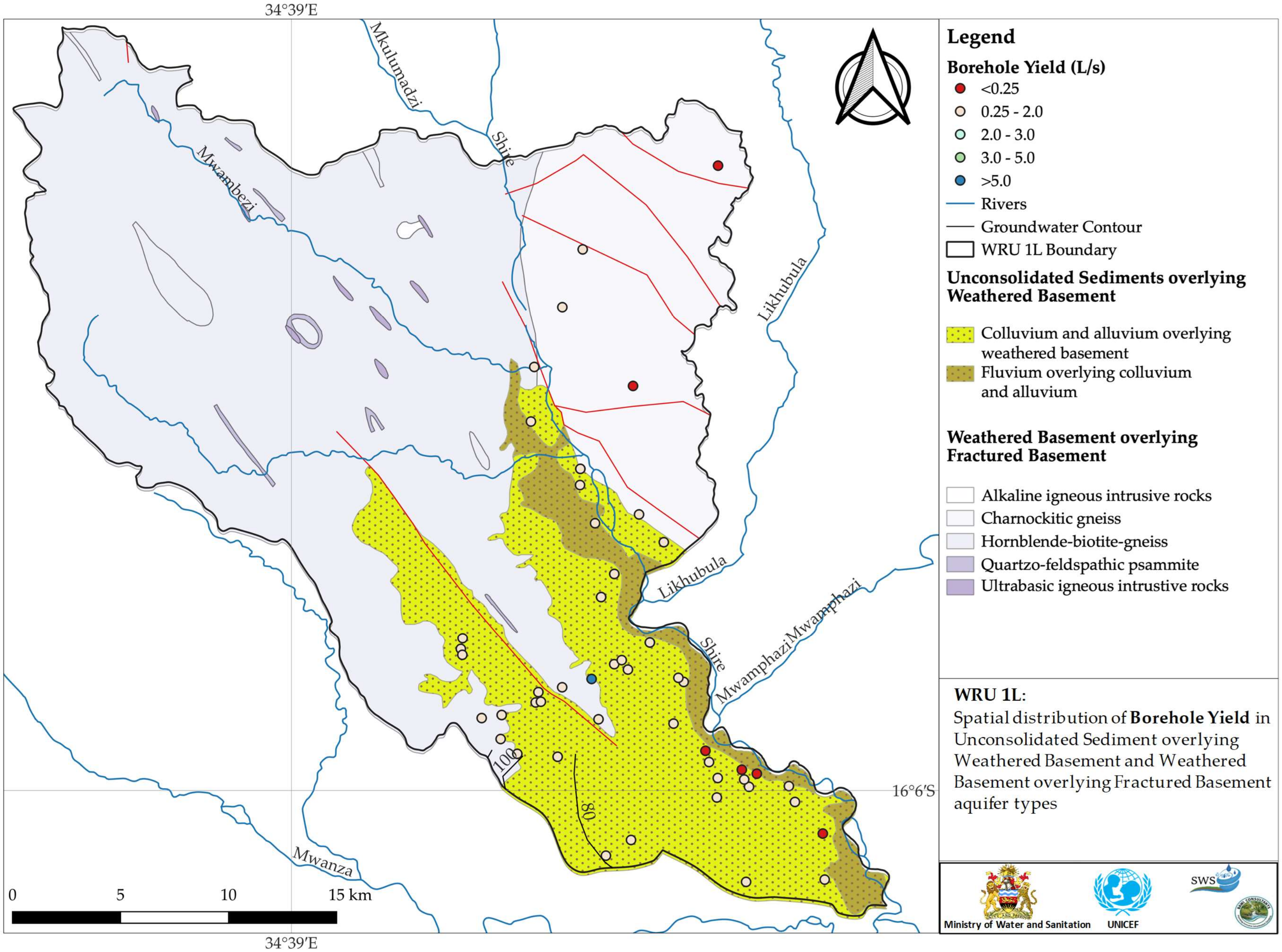


Figure WRU 1L.10 Borehole Yield Map for data held by the Ministry



WRU 1M Figures

Figure WRU 1M.1 Land Use and Major Roads

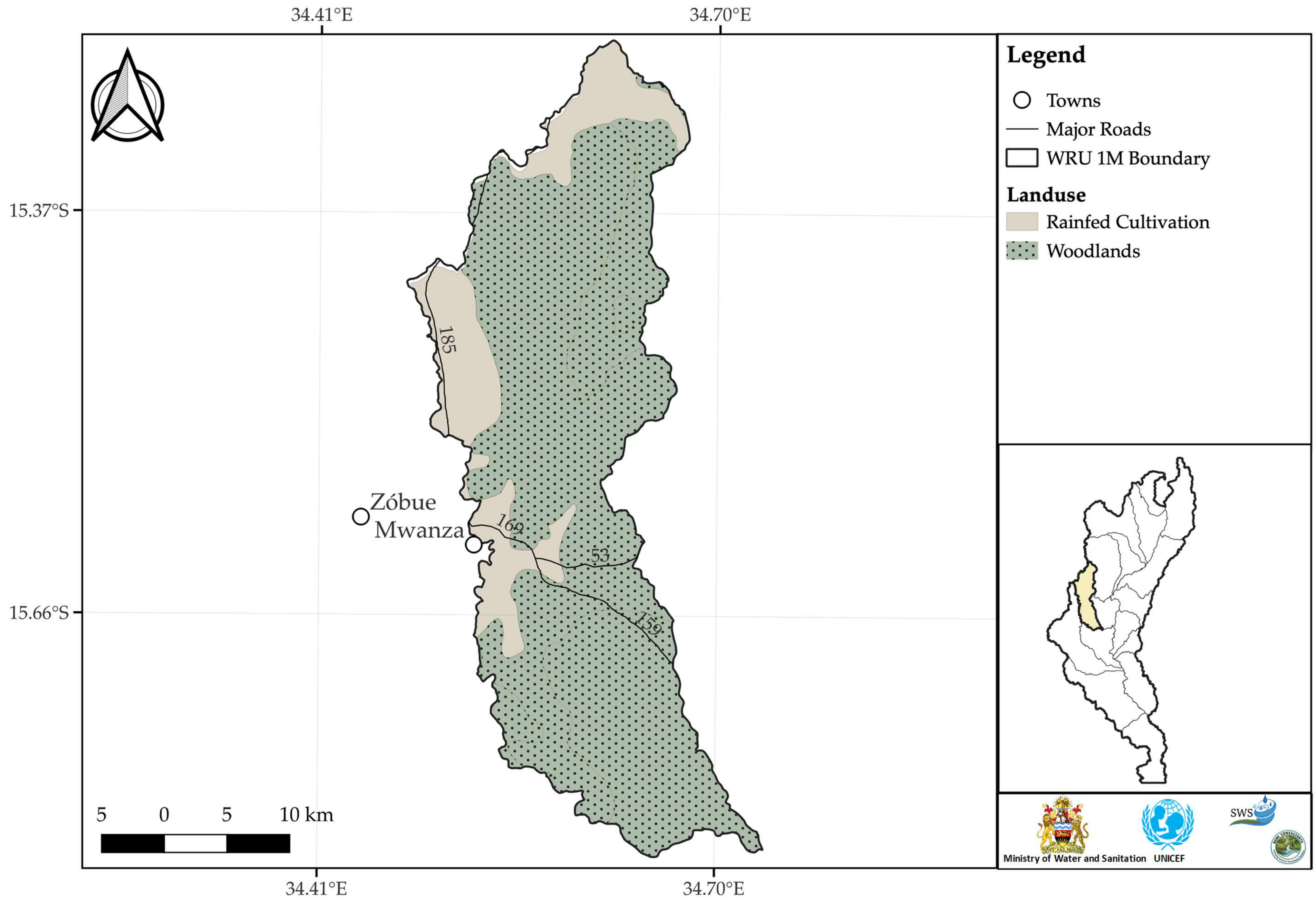


Figure WRU 1M.2 Rivers and Wetlands

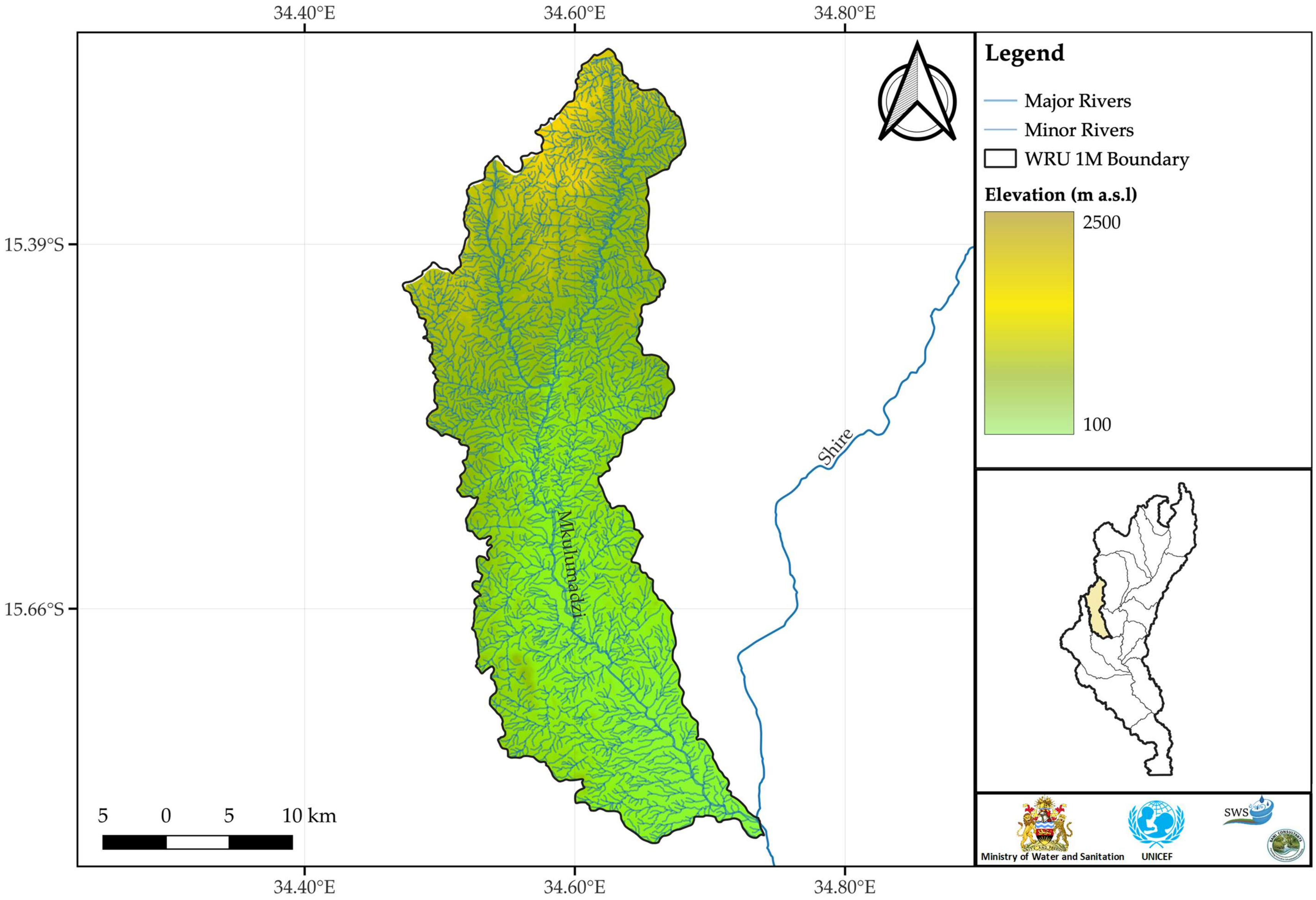


Figure WRU 1M.3 Hydrogeology Units and Water Table

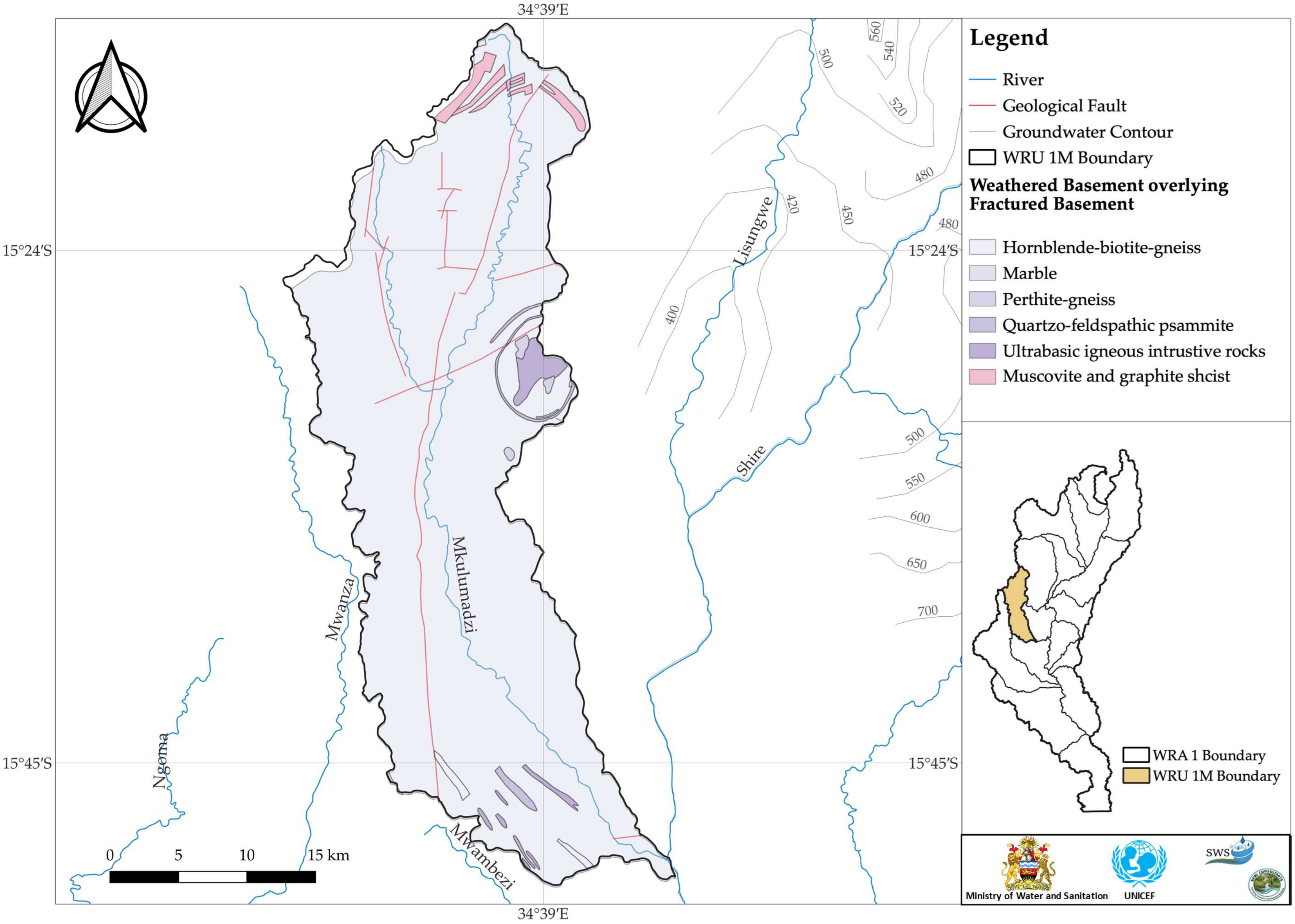


Figure WRU 1M.4 Groundwater Chemistry Distribution of Electrical Conductivity

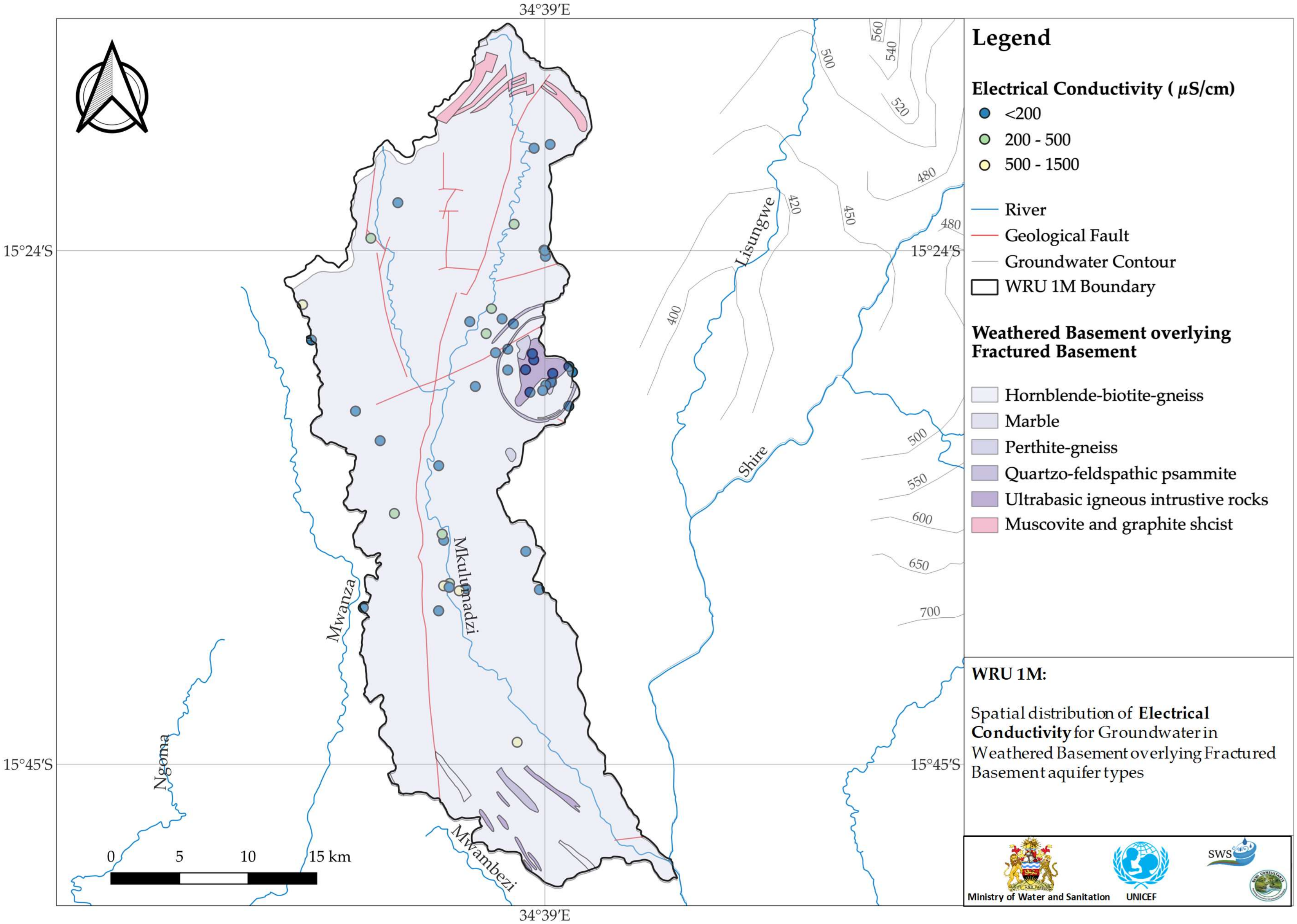


Figure WRU 1M.5 Groundwater Chemistry Distribution of Sulphate

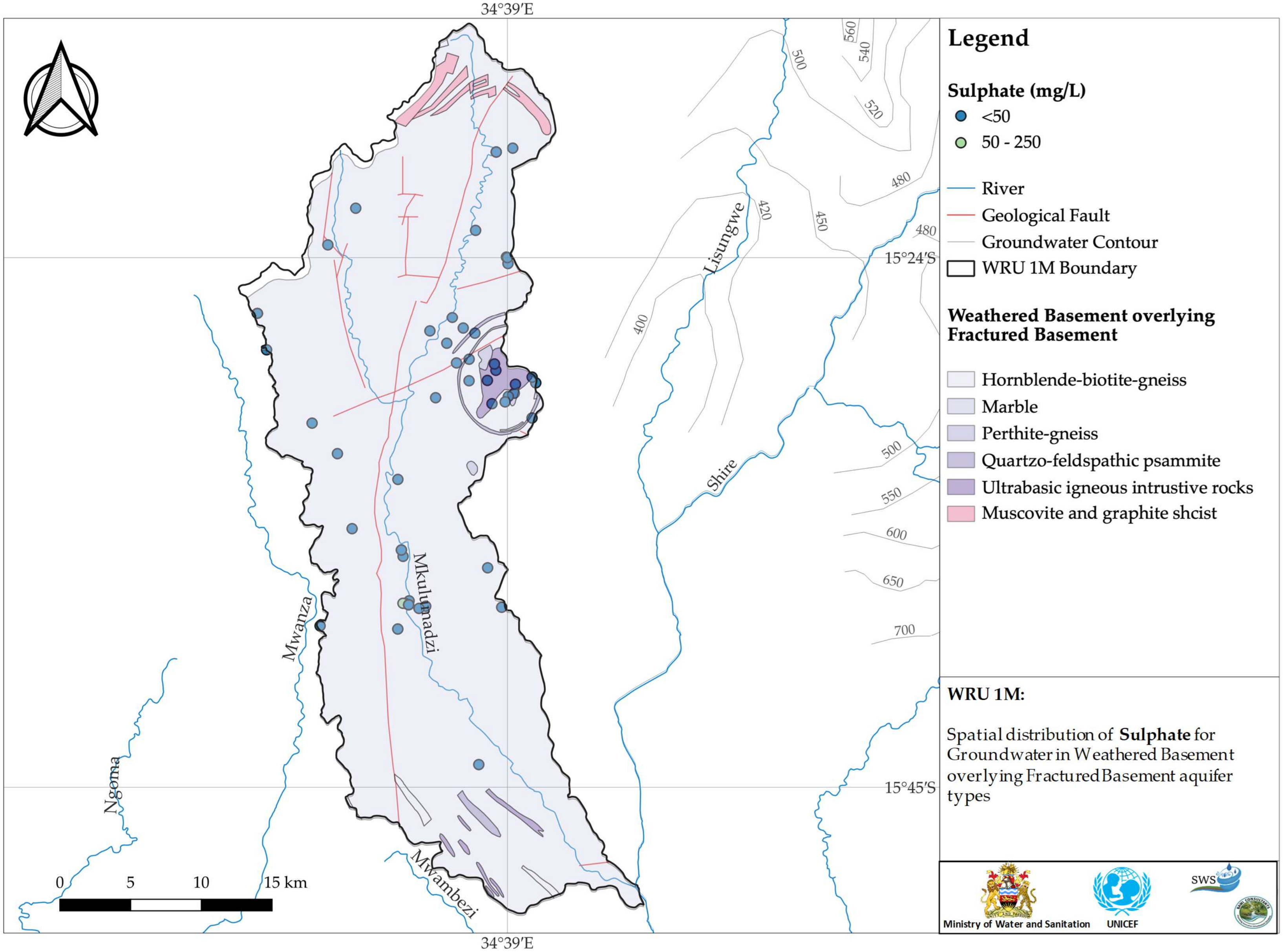


Figure WRU 1M.6 Groundwater Chemistry Distribution Chloride

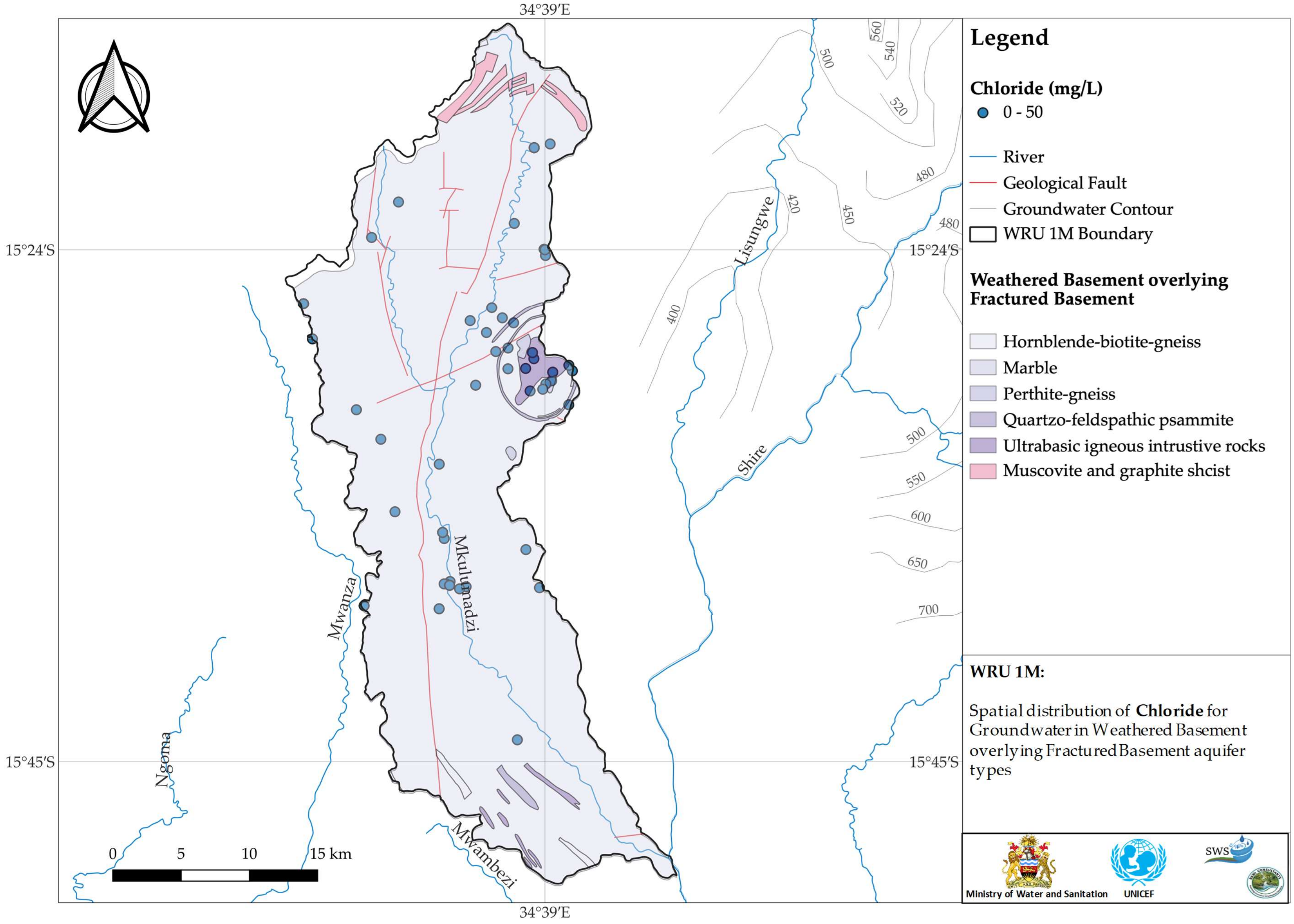


Figure WRU 1M.7 Groundwater Chemistry Distribution Sodium

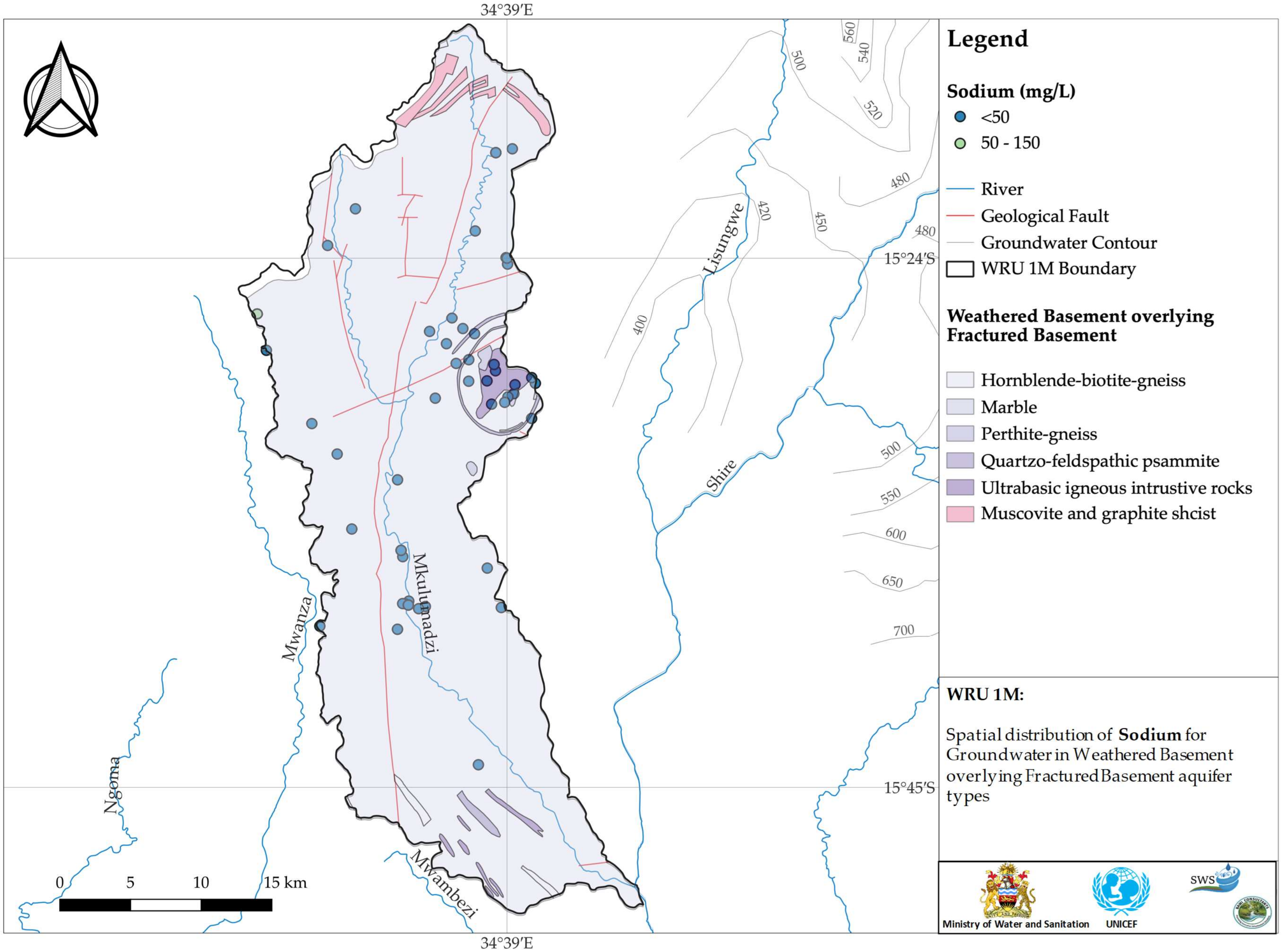


Figure WRU 1M.8 Groundwater Chemistry Distribution Calcium

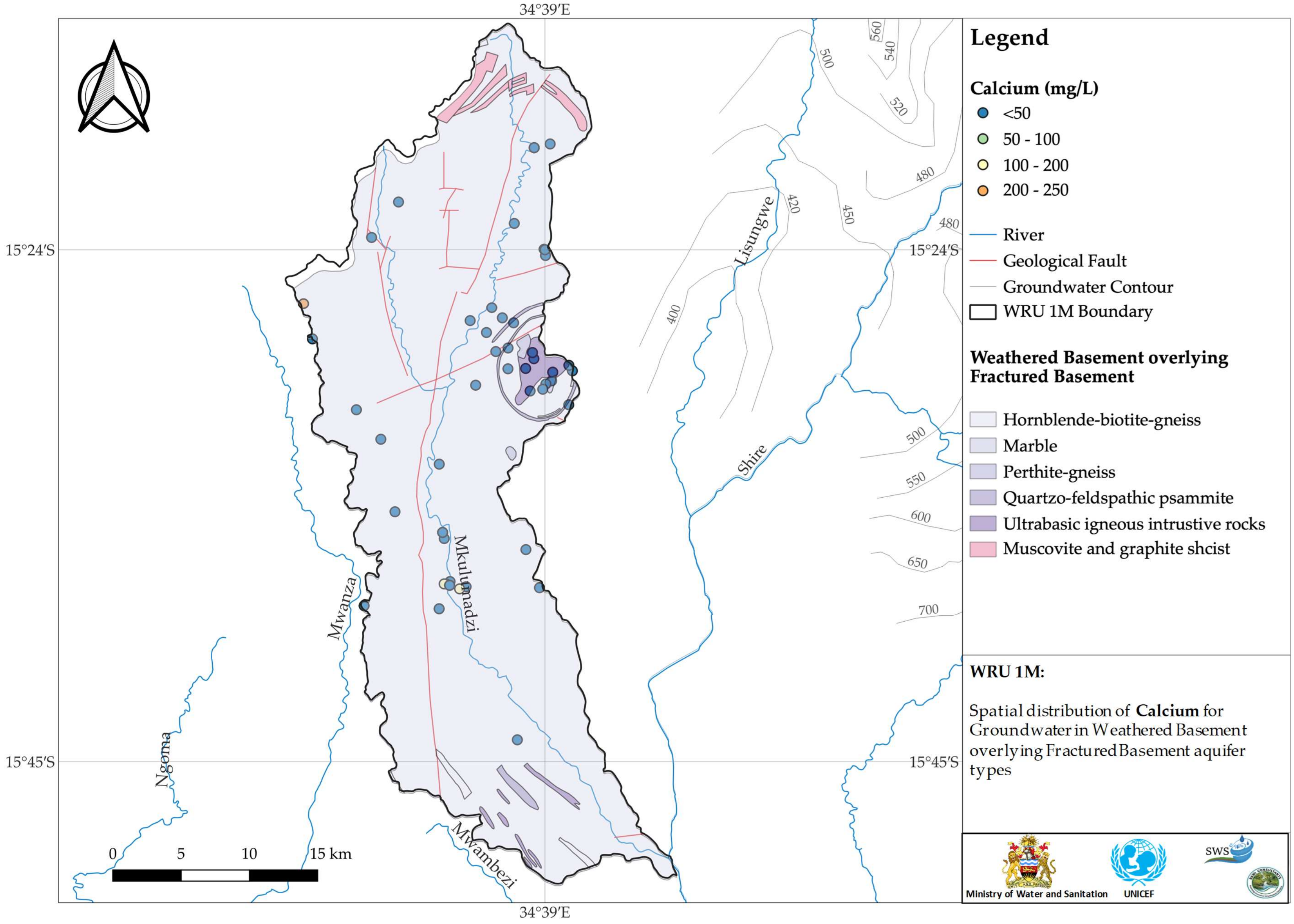


Figure WRU 1M.9 Piper Diagram of water quality results with respect to the major aquifer type

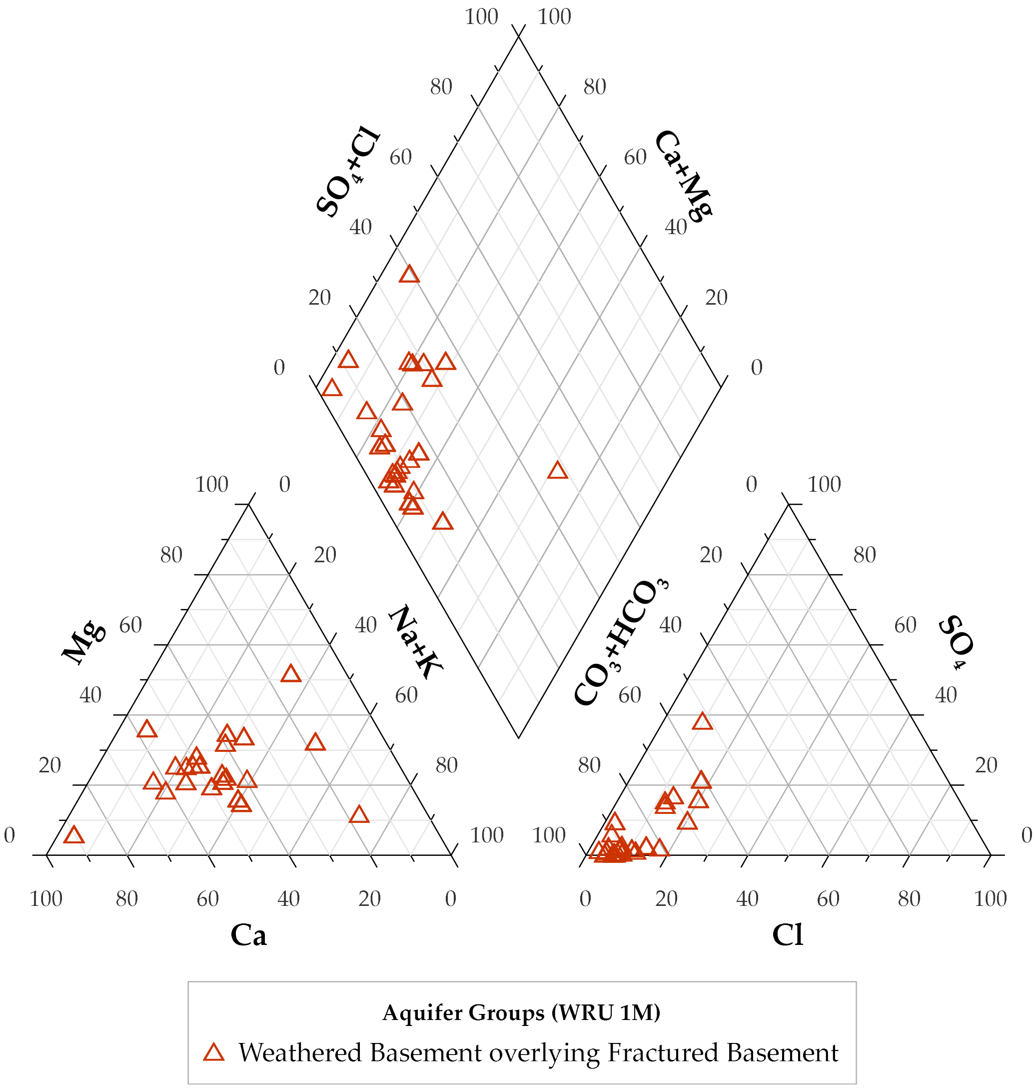
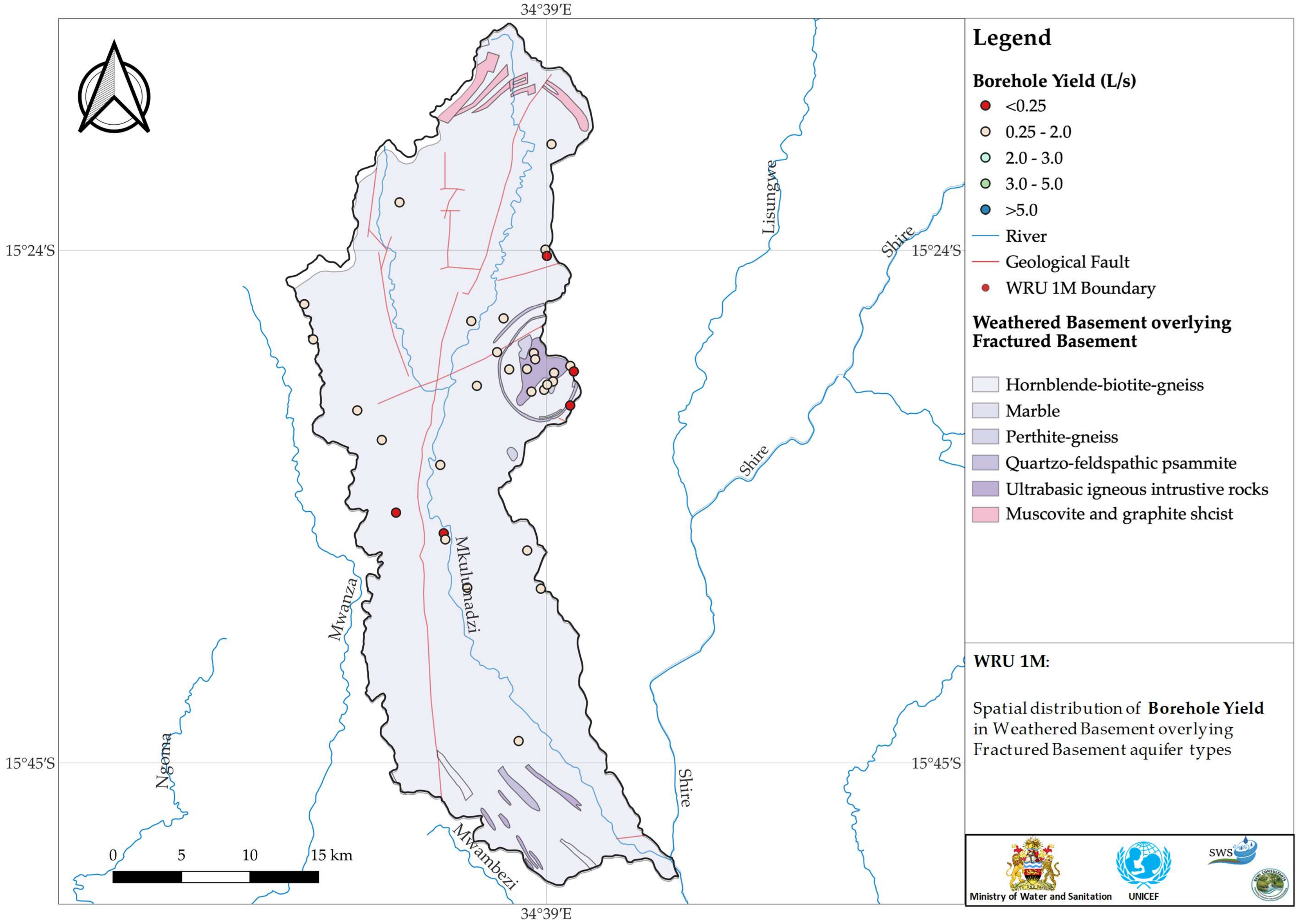


Figure WRU 1M.10 Borehole Yield Map for data held by the Ministry



WRU 1N Figures

Figure WRU 1N.1 Land Use and Major Roads

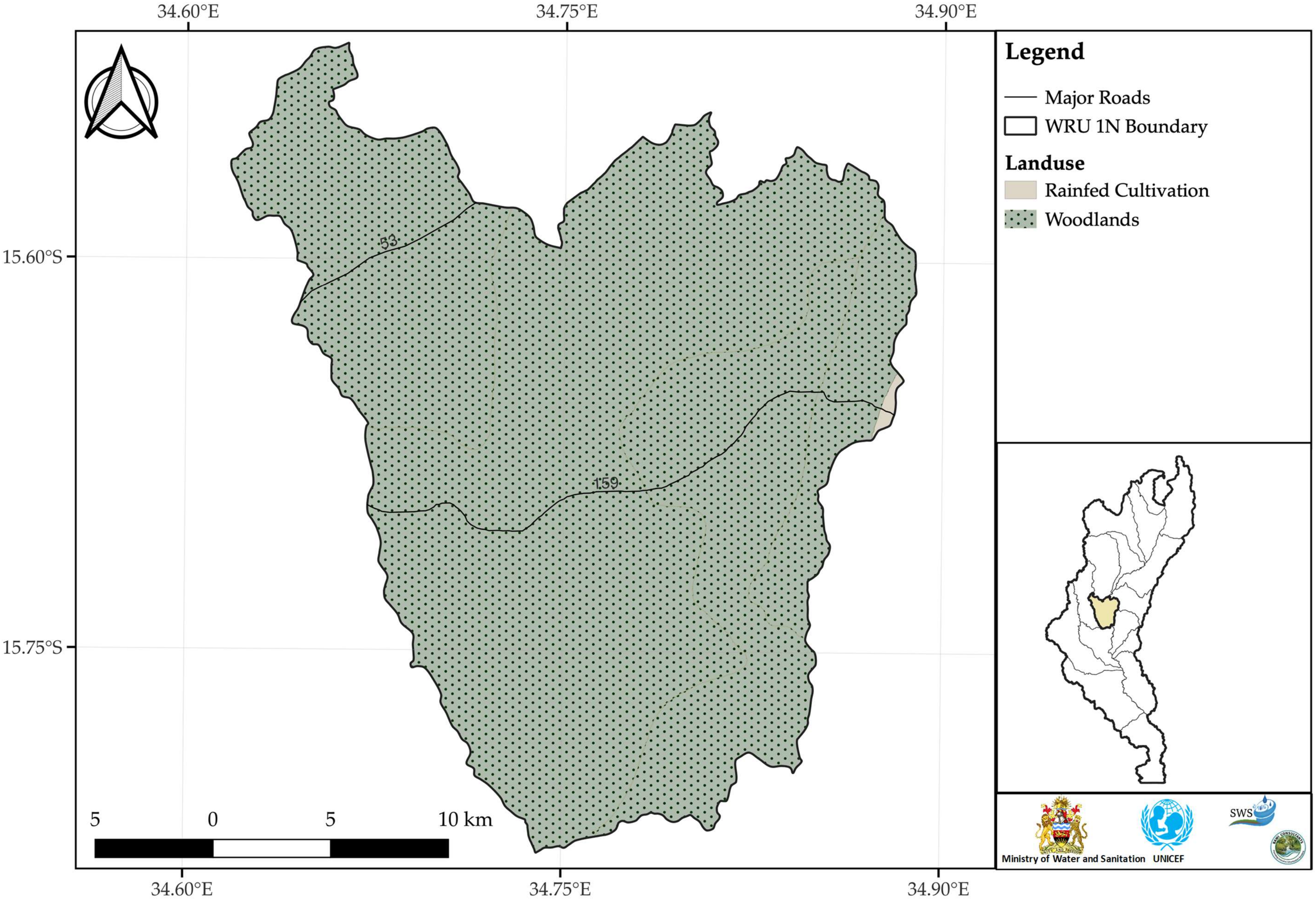


Figure WRU 1N.2 Rivers and Wetlands

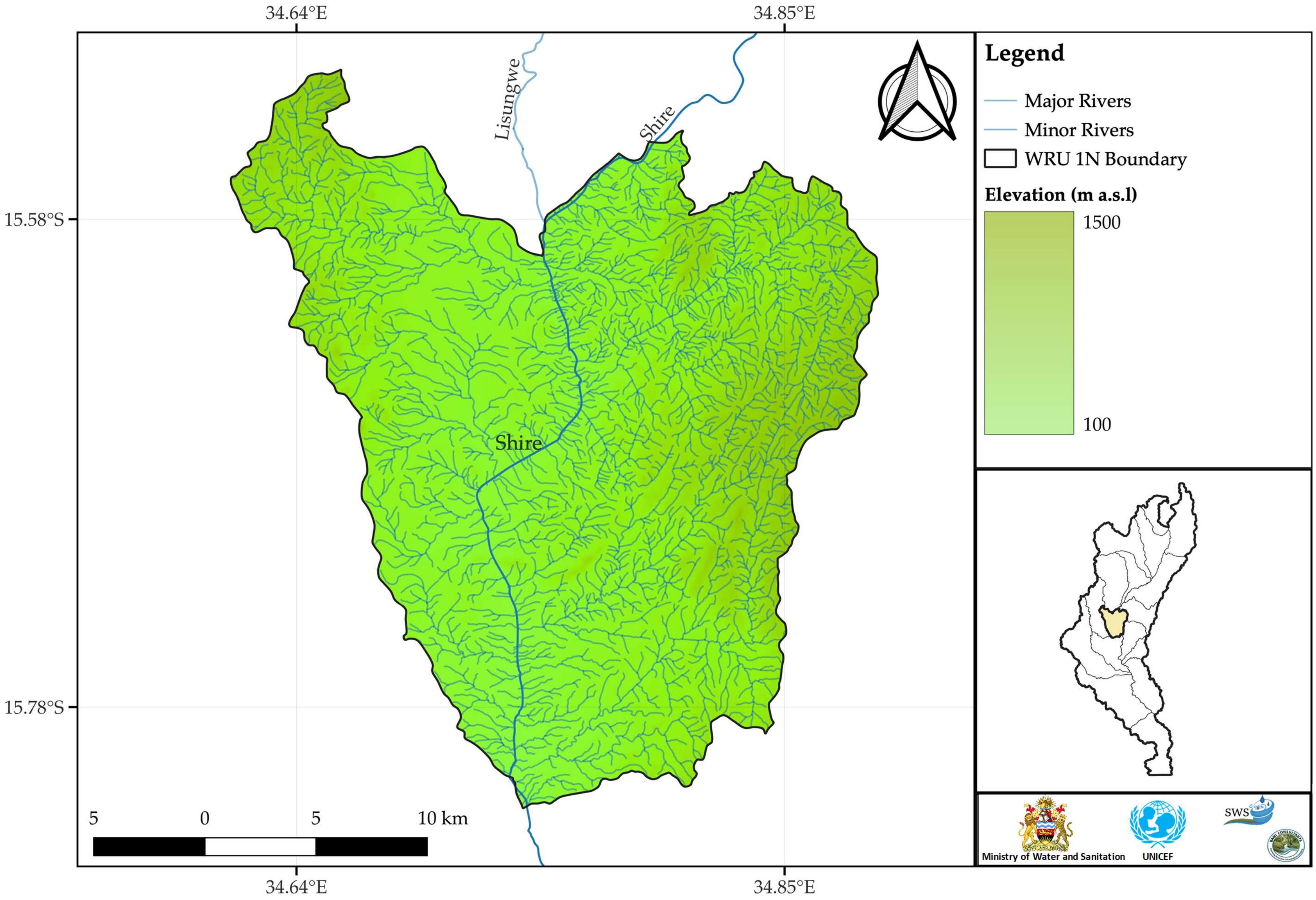


Figure WRU 1N.3 Hydrogeology Units and Water Table

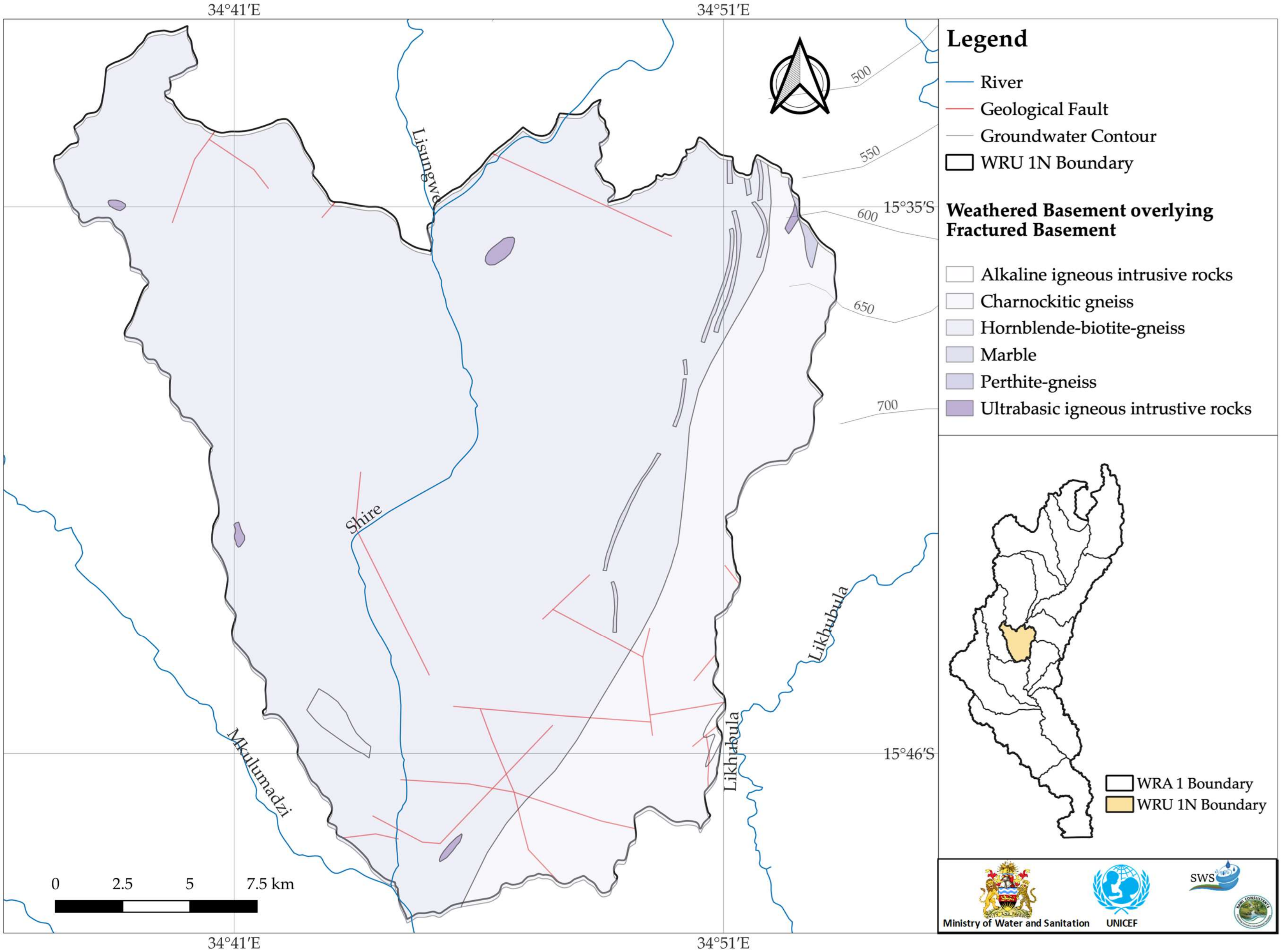


Figure WRU 1N.4 Groundwater Chemistry Distribution of Electrical Conductivity

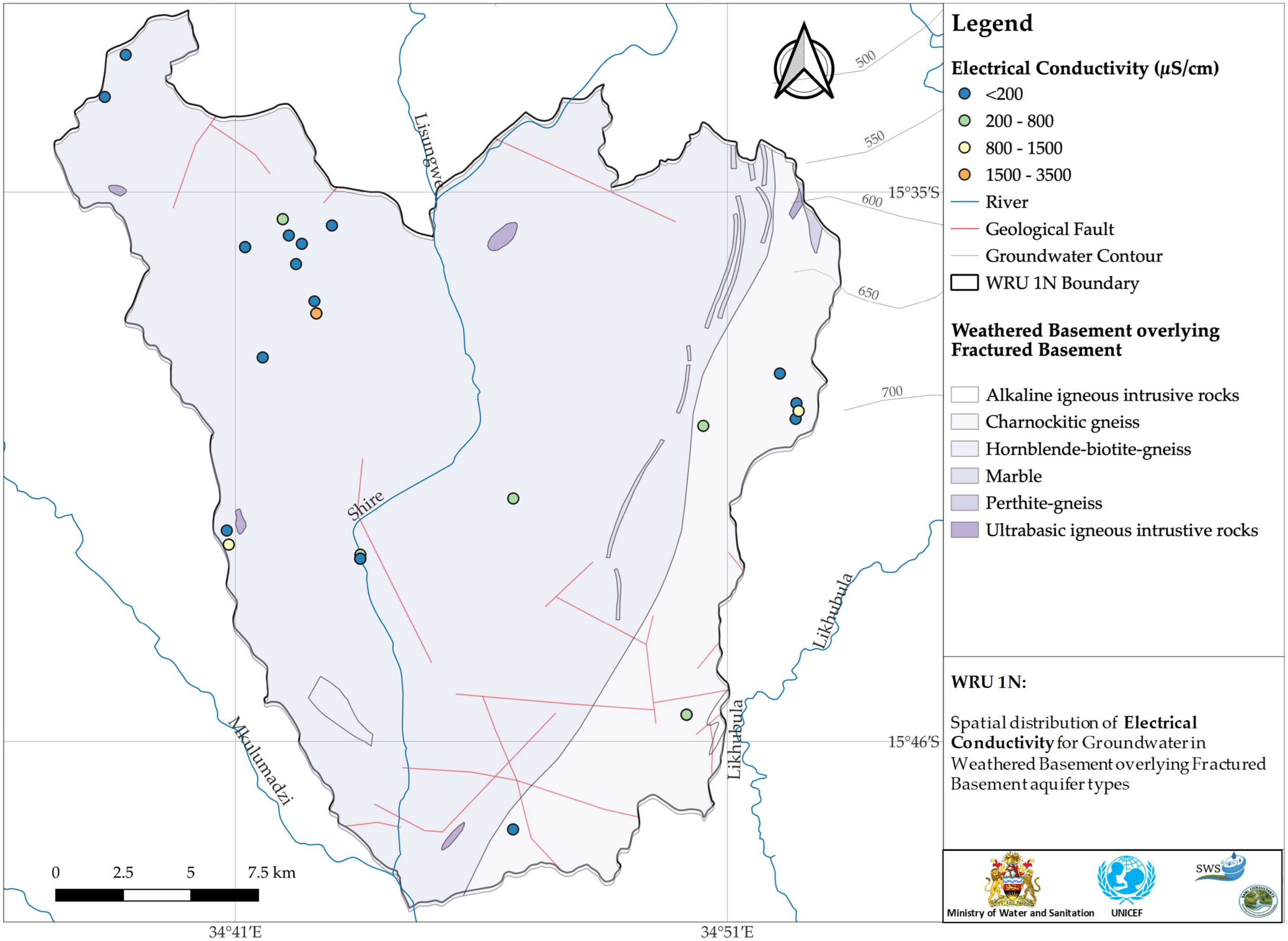


Figure WRU 1N.5 Groundwater Chemistry Distribution of Sulphate

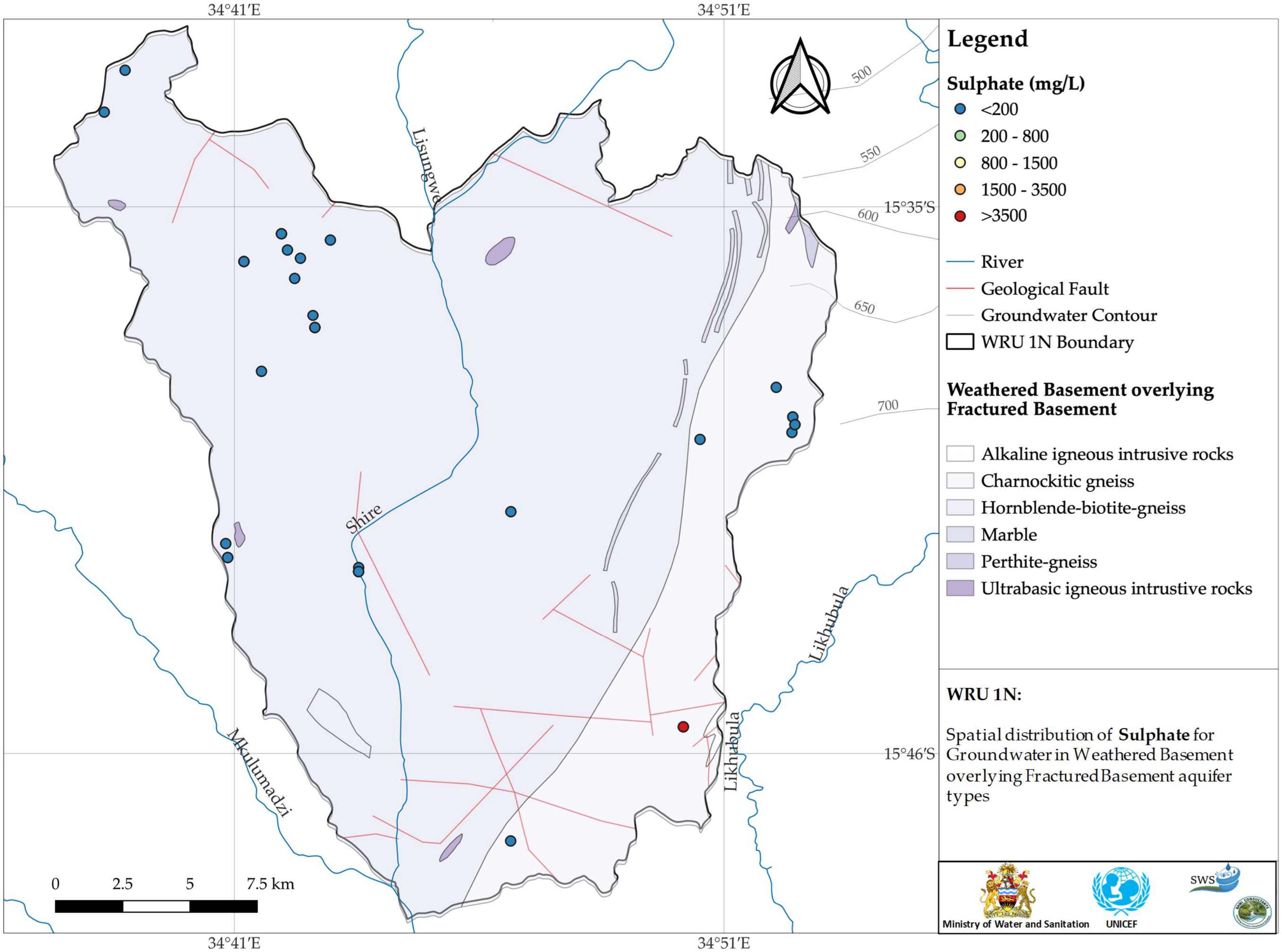


Figure WRU 1N.6 Groundwater Chemistry Distribution Chloride

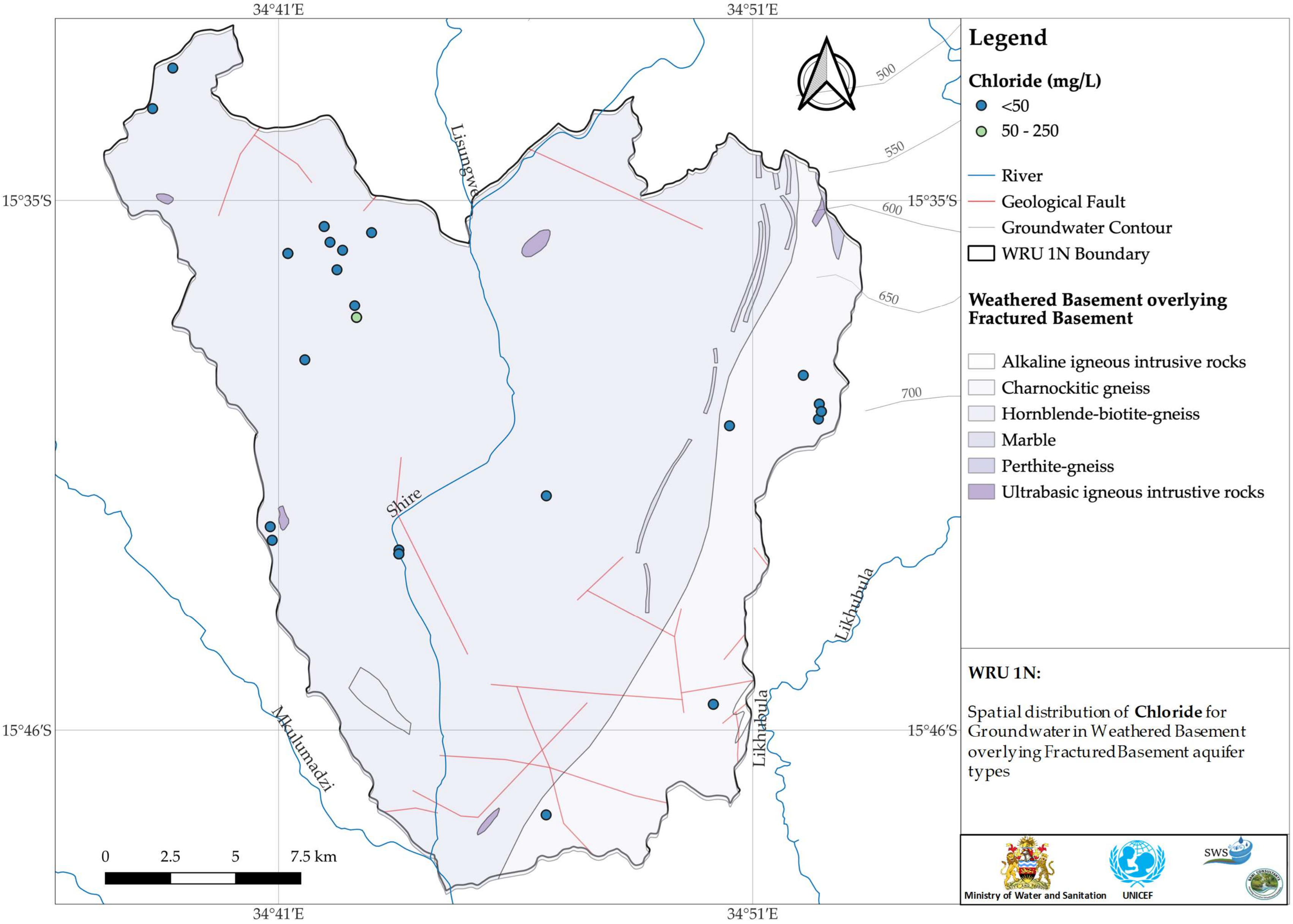


Figure WRU 1N.7 Groundwater Chemistry Distribution Sodium

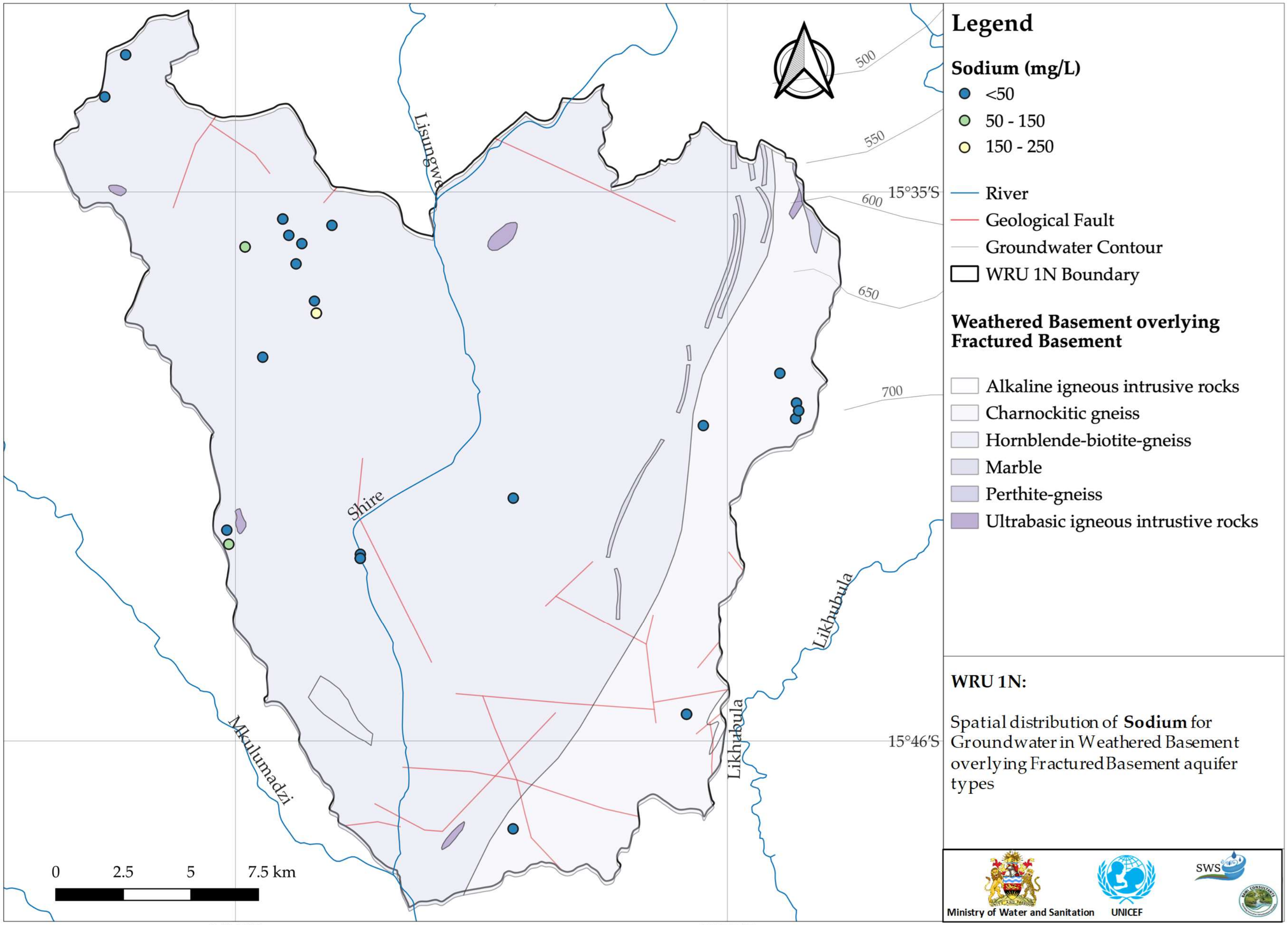
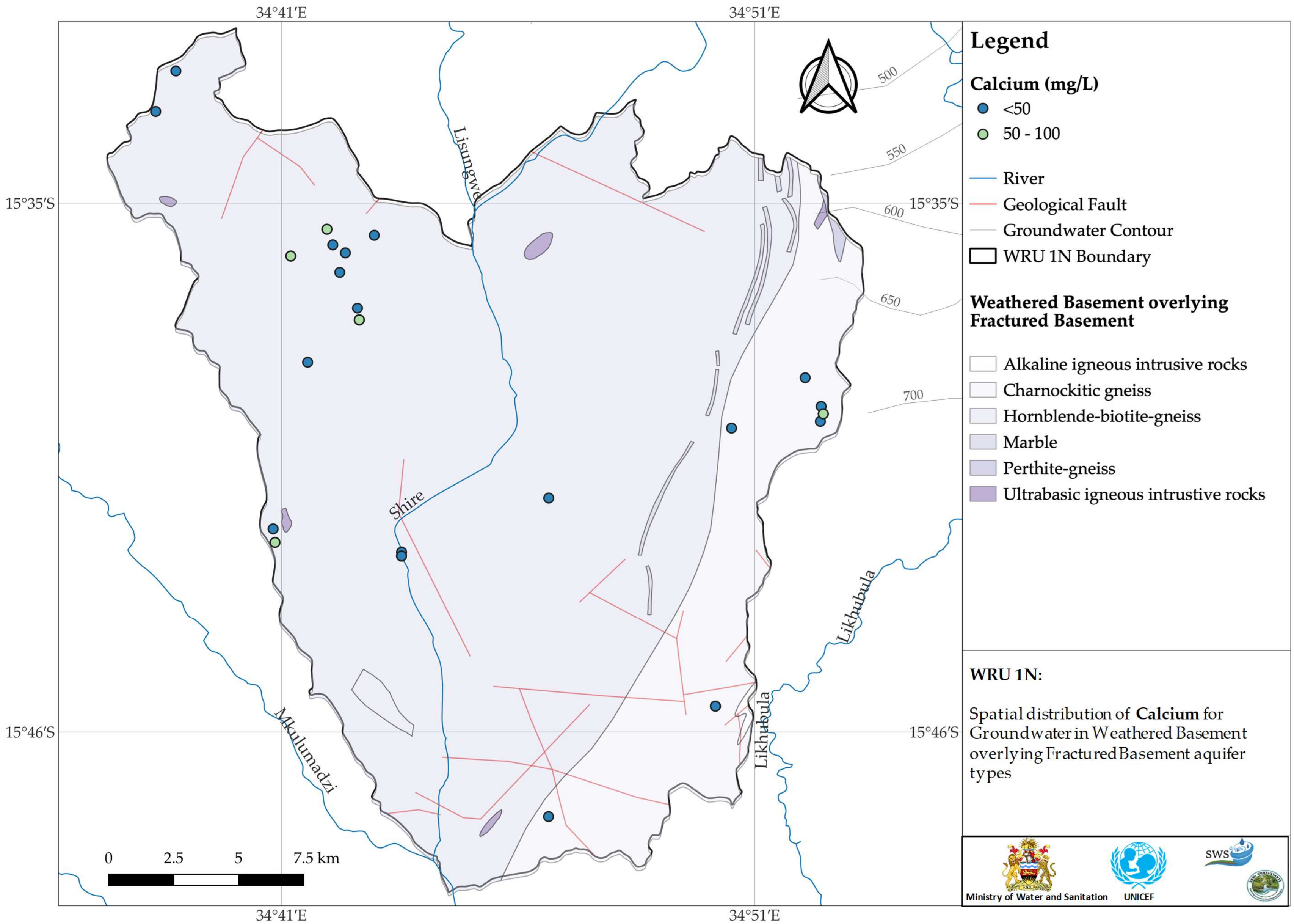


Figure WRU 1N.8 Groundwater Chemistry Distribution Calcium



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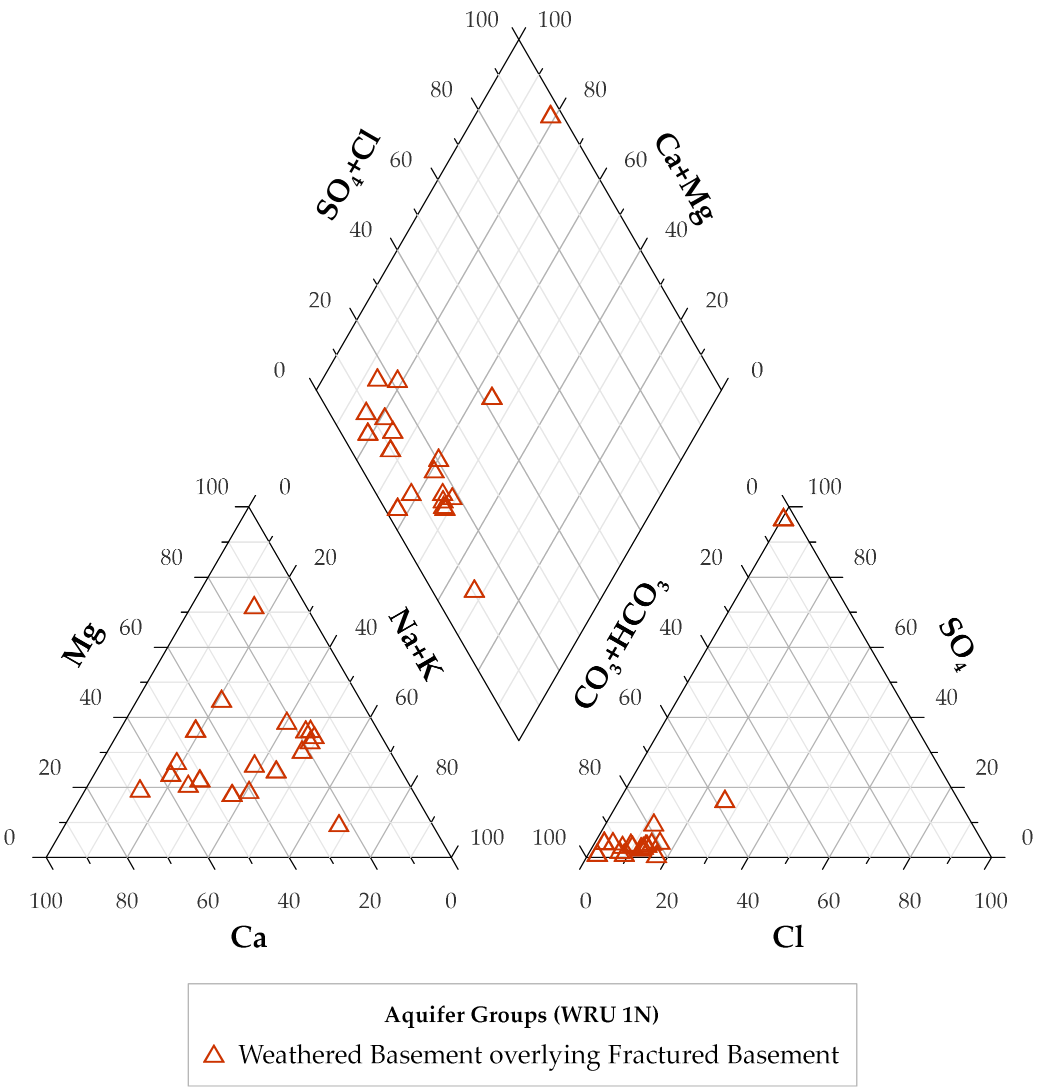
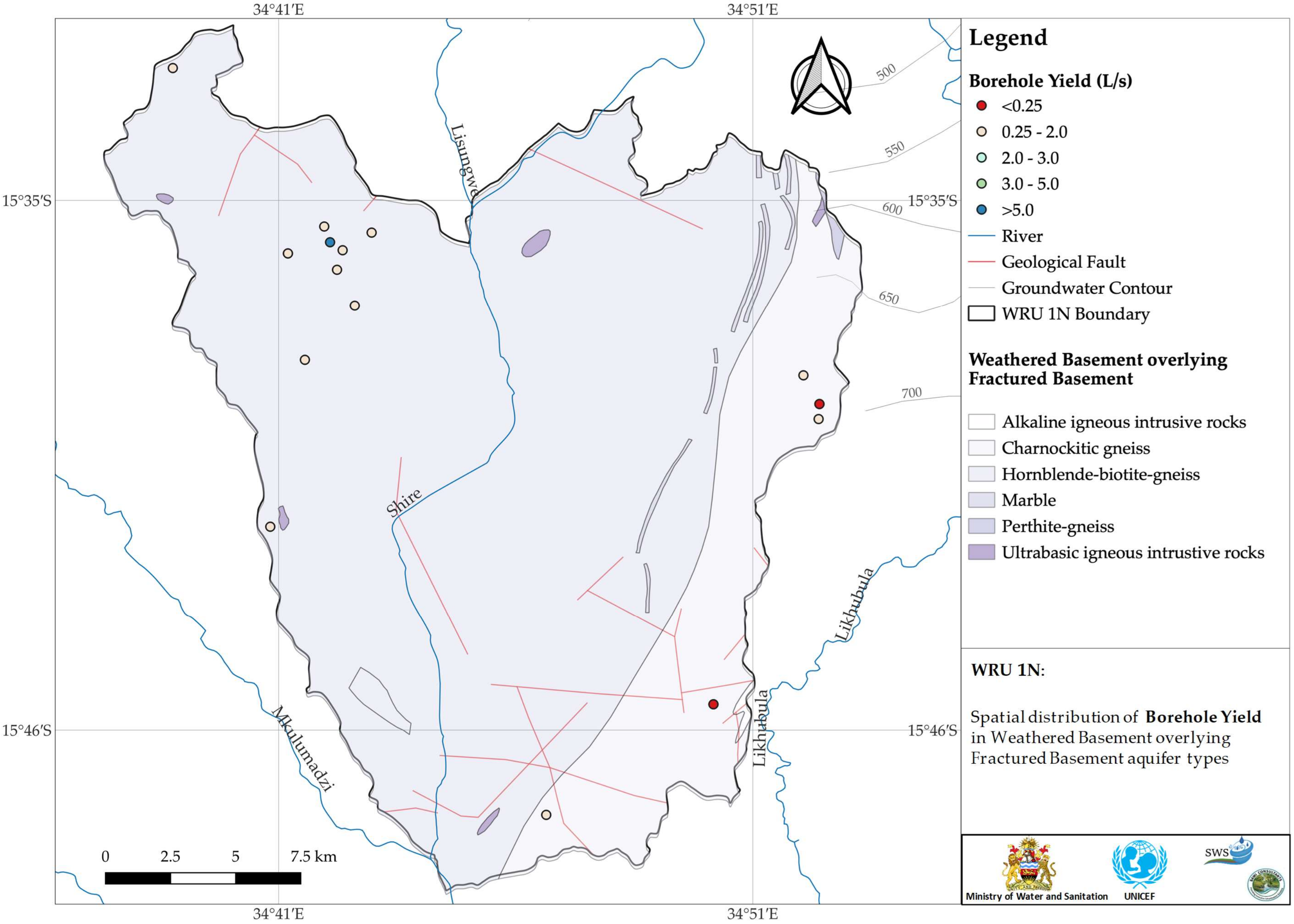


Figure WRU 1N.10 Borehole Yield Map for data held by the Ministry



Ministry of Water and Sanitation

Hydrogeology and Groundwater Quality Atlas of Malawi

Reference: Kalin, R.M., Mleta, P., Addison, M.J.; Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A., Hinton, R. (2022) *Hydrogeology and Groundwater Quality Atlas of Malawi Water Resource Area 1 Lower Shire, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-02-4 167pp*