Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 4

The Linthipe River Catchment

Ministry of Water and Sanitation

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It is recommended that citation for this work is made as follows:

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, Linthipe River Catchment, Water Resource Area 4, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-05-5 110pp*

ISBN 978-1-915509-05-5

Developed with the support of UNICEF (Malawi), BAWI (Malawi), SWS (Scotland) and The University of Strathclyde (Scotland)

1st Digital Edition (22nd March 2022)

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Acronyms and Abbreviations

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

Review of Malawi Hydrogeology

Groundwater in Water Resource Area 4 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.

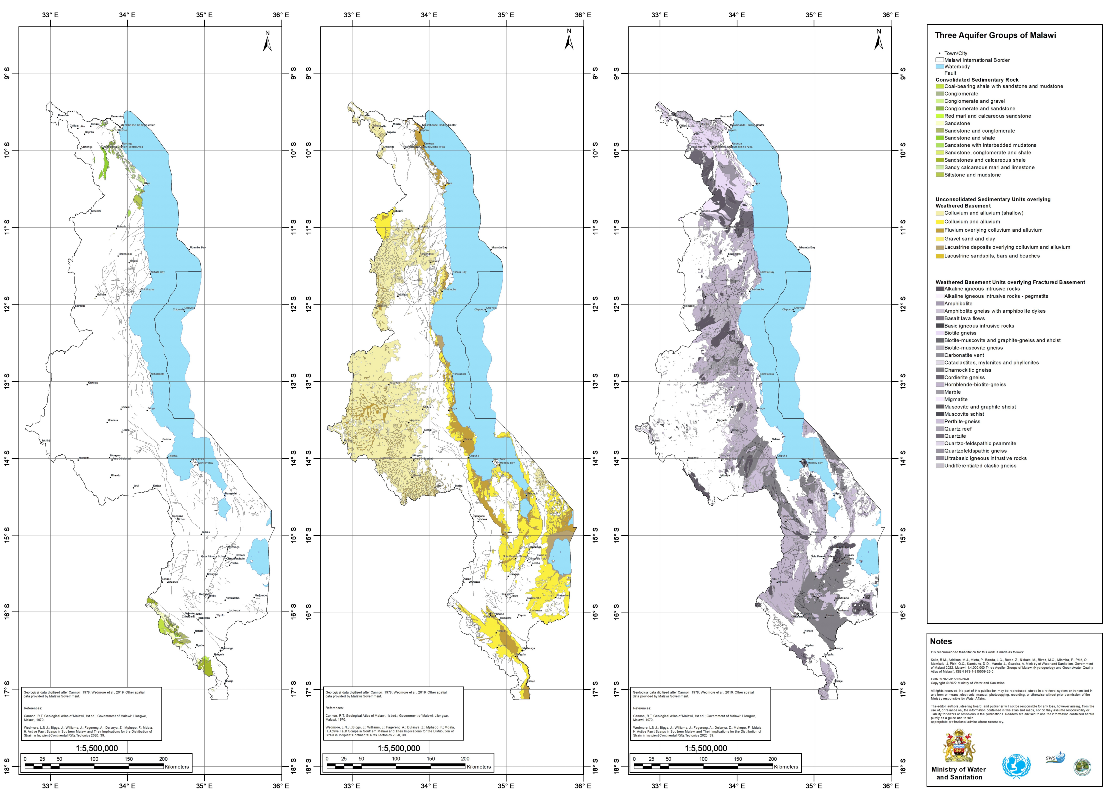

Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the center figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure shows weathered basement (including saprolitic) 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 saprolitic / saprock) zone, and also transmitted via fractures, fissures and joints in the fractured zone (most probable areas of highest hydraulic conductivity, K). The units may have limited storage, and the volume of groundwater available will be strongly dependant on the recharge catchment and interactions with surface water and rainfall-runoff at higher elevations. Therefore, detailed pump test analysis (sustainable yield determination) must be carried out for any large-scale abstractions combined with continuous monitoring of water levels and water quality (given possible geogenic sources and fast transport of groundwater contaminates e.g. e-coli from pit latrines).

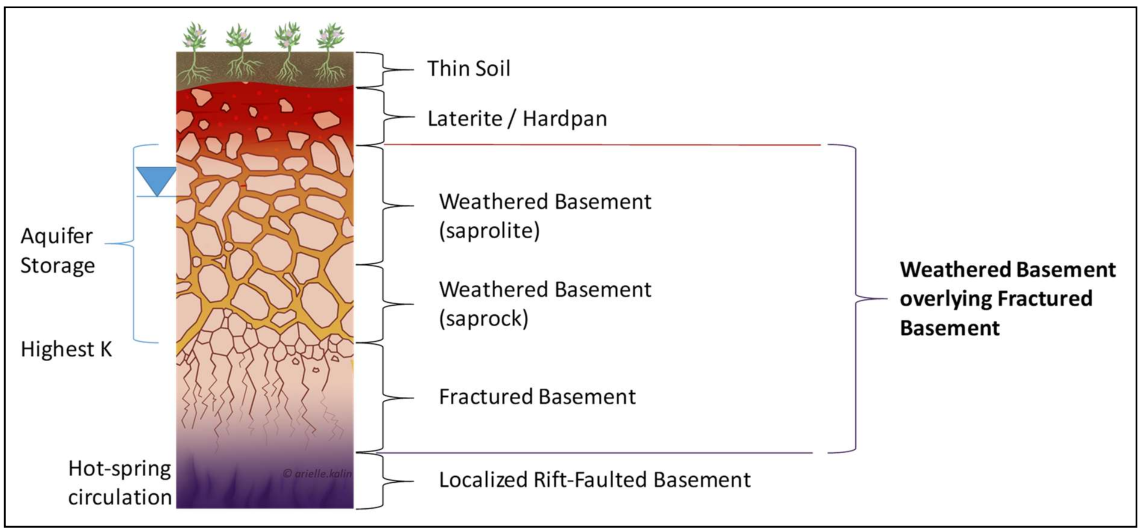

Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

Unconsolidated Colluvial and Alluvial Sedimentary Units overlying Weathered Basement

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

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

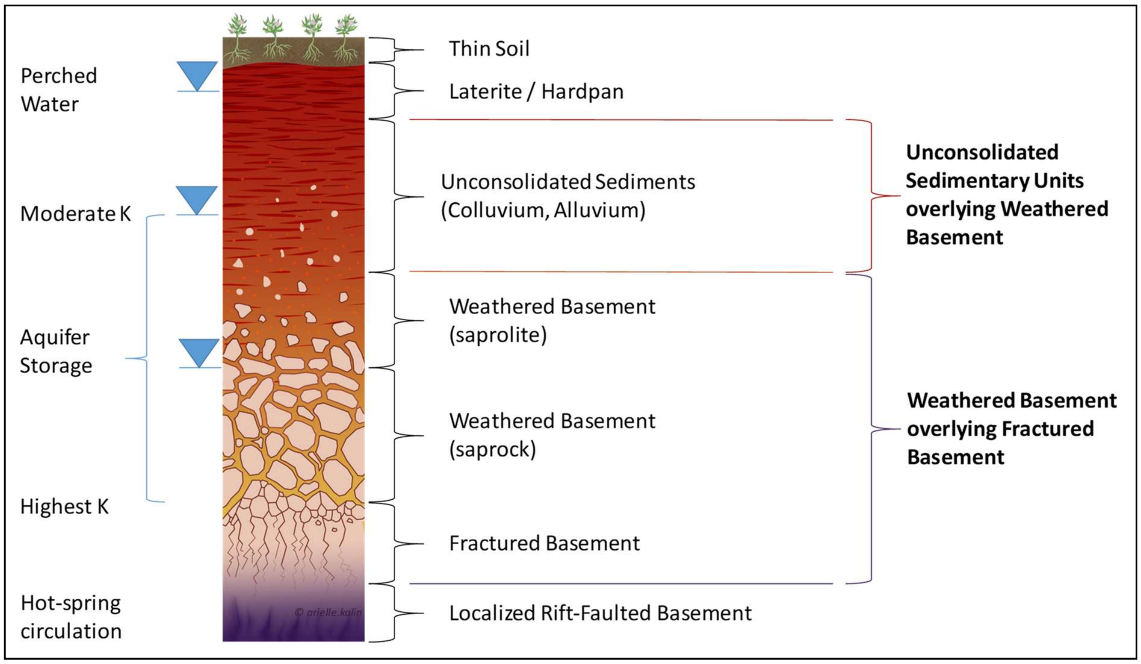

Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Unconsolidated Fluvial Sedimentary Units overlying Weathered Basement

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

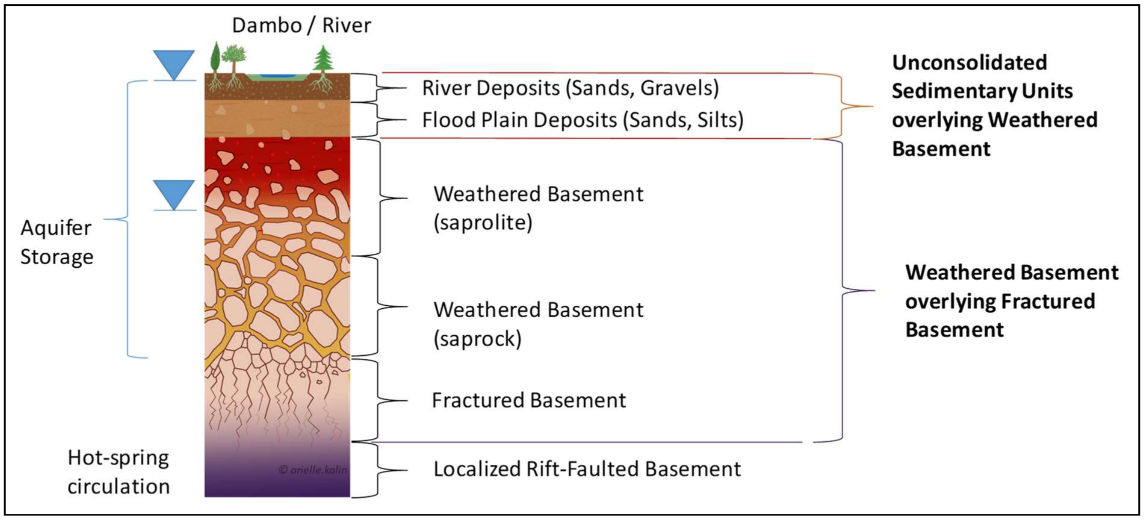

Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Idealised Cross Sectional Representation of Hydrostratigraphic Units (Aquifers)

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

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

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

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

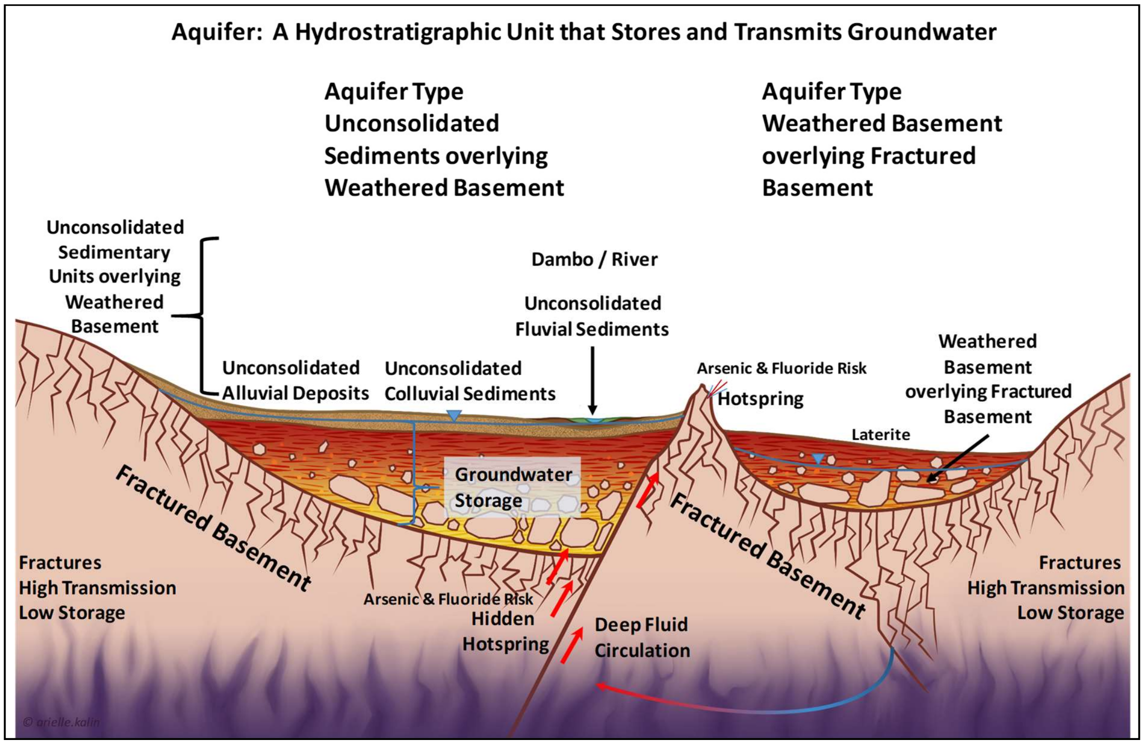

Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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

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

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

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

Water Resource Area 4 (WRA 4): The Linthipe River Catchment

Water Resource Area (WRA) 4 is mainly drained by Linthipe River, hence called the Linthipe River Catchment (**Figure 2a**), with an area coverage of 8,957 Km^2. The Linthipe River dominates the major riverine inflows from the area into Lake Malawi (consisting of Linthipe, Lilongwe, Diamphwe, Lifidzi, Lingadzi, Likuni, Katete, Lumbadzi, Lifisi rivers) (**Figure 2b**). It has notable water storage reservoirs that include the Kamuzu Dam I (of storage capacity 4.5 million m3) and adjacent Kamuzu Dam II (18.5 million m^3) on the Lilongwe River and primarily supply the capital Lilongwe City. The WRA 4 comprises four contrasting physiographic zones: the highlands; the plateau areas; the Rift Valley escarpment; and the Rift Valley lakeshore plains. These distinct geographic features coupled with the remote upland plateau occurrence of extensive 'dambo' grass-covered swampy valley(s) influences flow direction towards Lake Malawi. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of seasonal tropical convergence zone precipitation and adjective storms from moisture carried from the Mozambique channel. Water Resources Area 4 is trans-boundary for both surface and groundwater and it borders on Lake Malawi which is governed by Trans-boundary water sharing agreements. Therefore, Integrated Water Resources Management (IWRM) must be implemented within international water resources agreements.

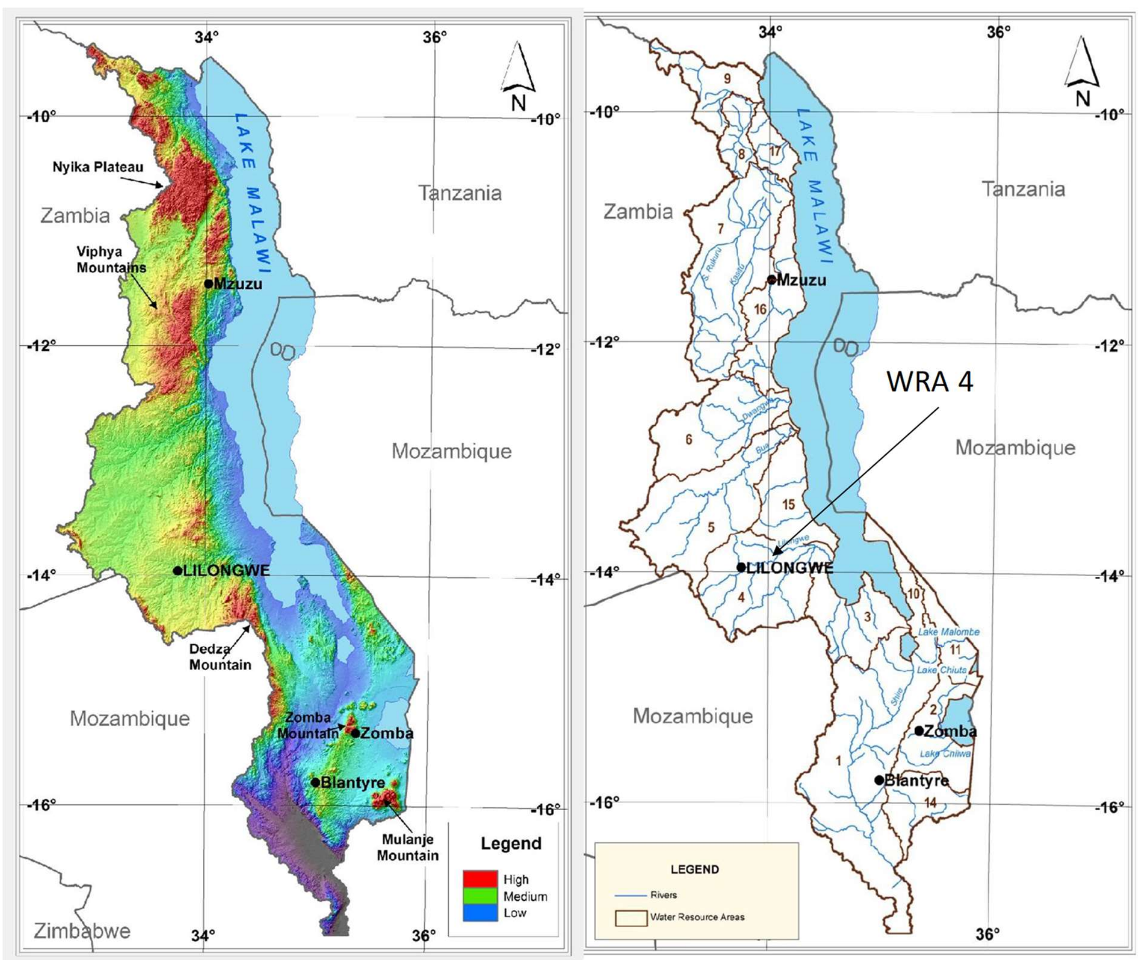

Figure 2a. Location of WRA 4 with major rivers and topography shown**.**

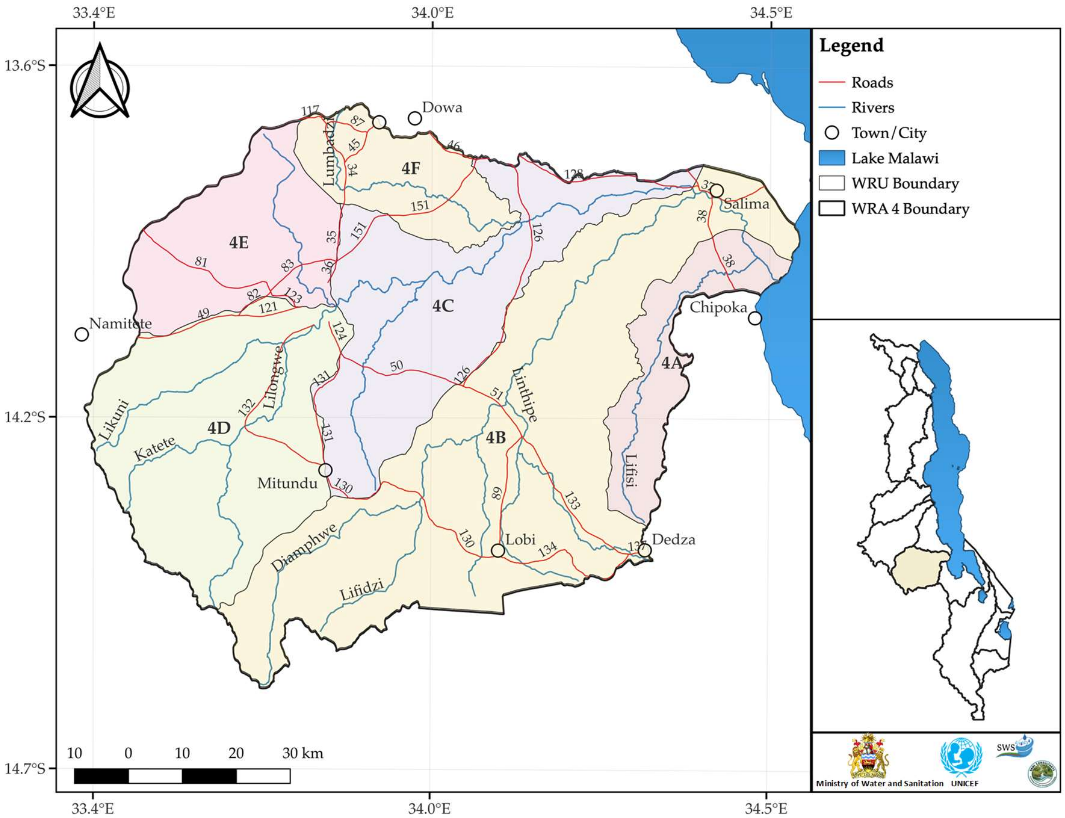

Figure 2b. Location of WRA 4 with Water Resource Units.

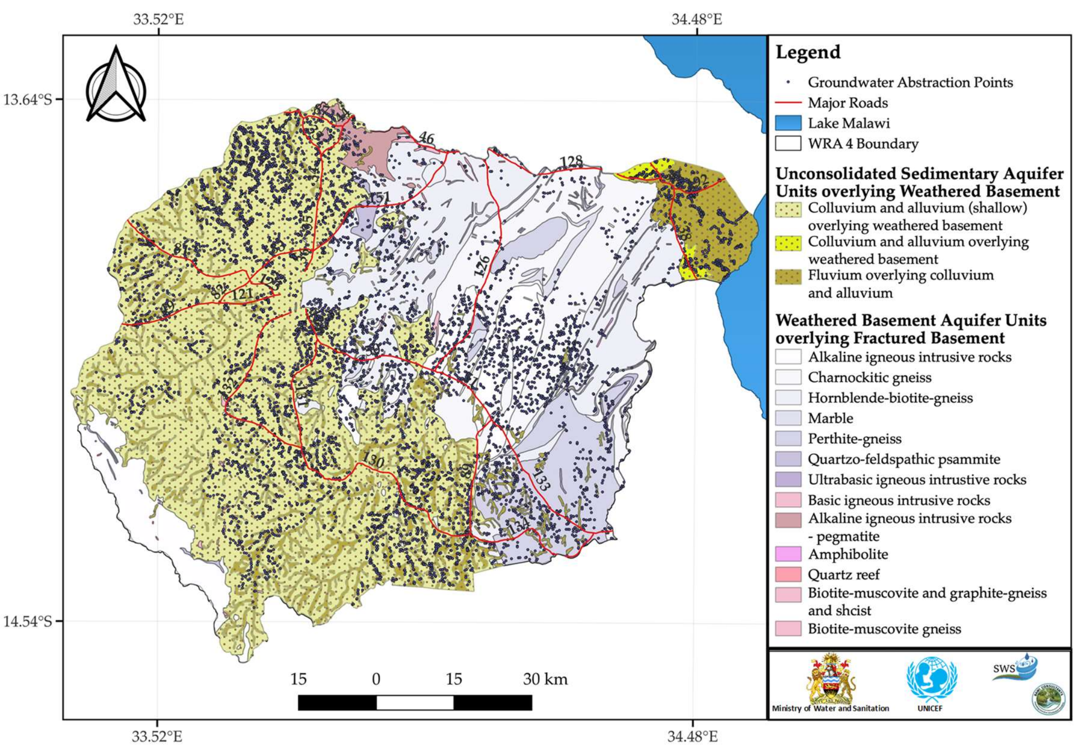

Figure 3. Distribution of groundwater abstraction points in WRA 4.

Groundwater Abstraction in WRA 4

Public abstraction points for groundwater are numerous in WRA 4 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 11,338 known groundwater abstraction points, only 79.3% are improved sources (with 1,299 being protected dug wells and 2,325 unprotected dug wells). The mid-point distribution of water point yield (at hand pump) is between 0.25 and 0.30 l/s (**Figure 4a**), however it should be noted that this is an expected range of the Afridev, Maldev, Elephant and India 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 4, only 68.1% are fully functional (defined as providing water at design specification).

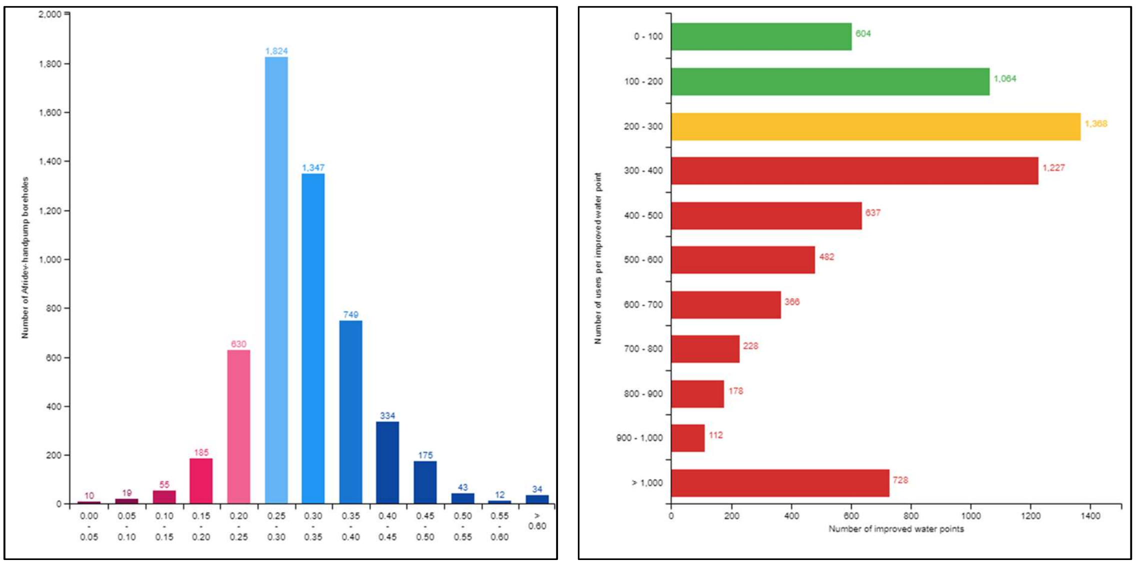

Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 4 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point.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

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

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 15.6% 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.

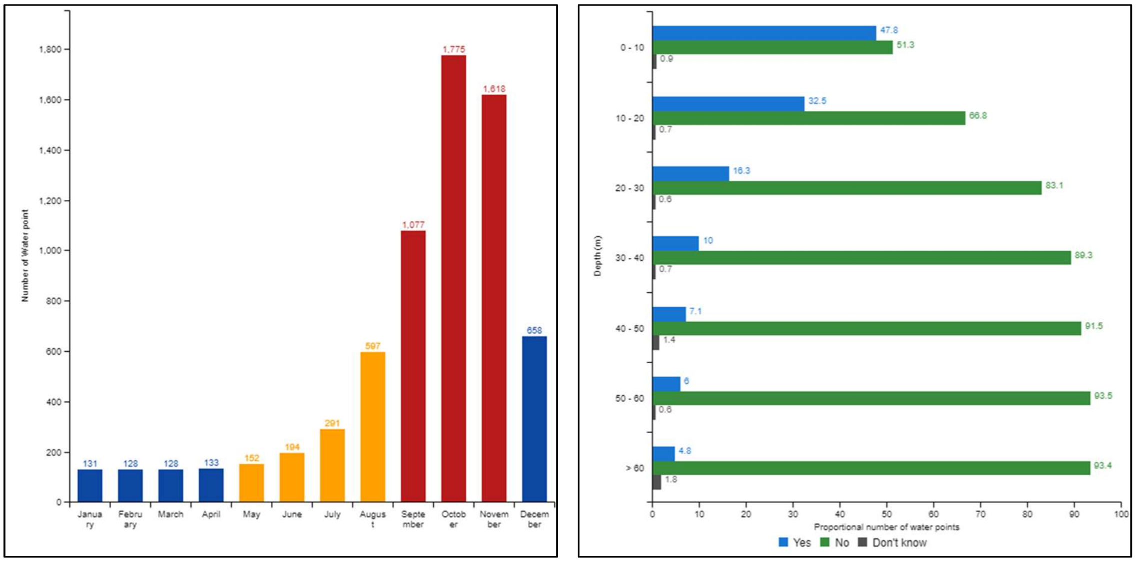

Figure 5a and 5b. Number of groundwater abstraction points in WRA 4 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

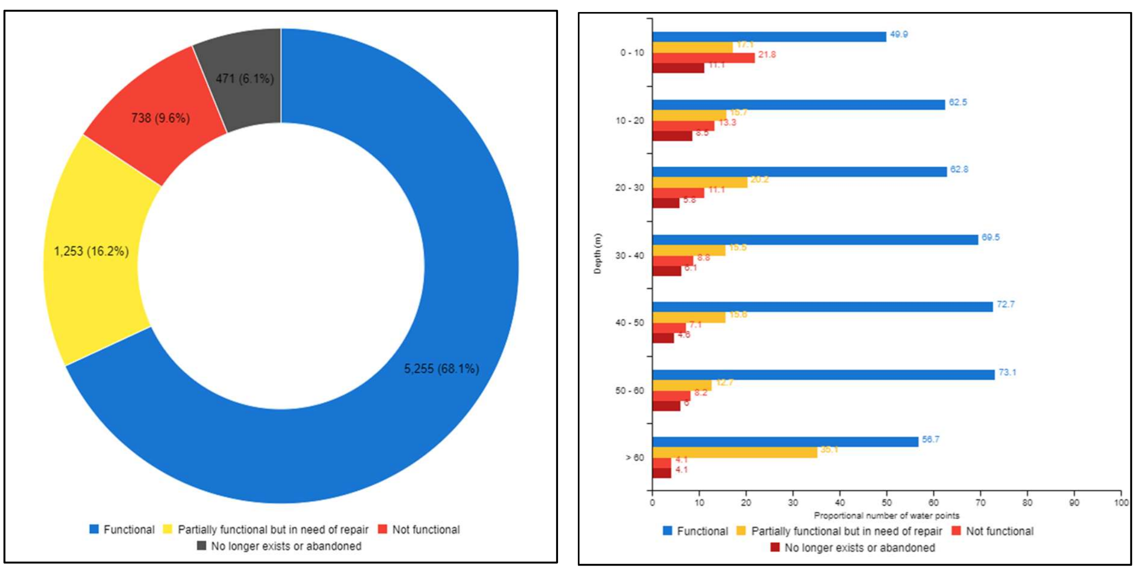

Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 4 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water Point Survey]

The operational status of groundwater abstraction points is also linked to issues of infrastructure (e.g. pump / borehole) as well as aquifer stress. There are only 68.1% of groundwater abstraction supplies which are operation at design parameters, and the distribution of functional, partly functional, non-functional and abandoned groundwater abstraction points is relatively constant with depth of abstraction point (**Figure 6a and 6b**). This indicates groundwater supply is impacted by both infrastructure quality and aquifer stress, and there is a need to undertake evaluation of stranded groundwater assets in WRA 4 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 4 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	7,675
Protected dug well	1,299
Protected spring	13
Unprotected dug well	2,325
Unprotected spring	26

Description of Water Resources WRA 4

Water resources management according to the Water Resource Act (2013) Malawi is devolved to sub-basin Water Resource Units (WRUs), and Integrated Water Resources Management (IWRM) should be managed at this sub-basin scale Water Resources Area (WRA) 7 is in northern part of Malawi and consists of six (6) Water Resource Units (WRUs): WRU 4A, WRU 4B, WRU 4C, WRU 4E, WRU 4D, WRU 4E, and WRU 4F (**Figure 7a – 7f**). It covers a vast area of about 12,720 Km^2, which is largely drained by the Linthipe thus called the Linthipe River Catchment. Groundwater is Trans Boundary between Zambia and Malawi, and the catchment drains to Lake Malawi which is also Transboundary. Therefore, IWRM must be managed within the framework of international arrangements.

Development pressures ranging from population boom (estimated at 3% annually) and rapid urbanisation remain key water resources management bottlenecks requiring unwavering resolve. The area's diverse social dimensions see most rural communities engaging in rigorous small holder farming; but increasing demand in use of charcoal as a source of energy continues to pose a daunting environmental threat. Thus, the area faces accelerating rate of deforestation resulting in increased runoff, abridged groundwater recharge, and fast-tracked erosion, which causes sedimentation of surface water bodies and a decline in water-supply reservoir capacities. This is evinced in shrinking of the Kamuzu Dams I and II and challenges for groundwater recharge and groundwater supplies. A recent report (on the groundwater resources of the Lilongwe area covering much of WRA 4) by Lilongwe Water Board with GMS and HydroConsult is a starting point for detailed local scale hydrogeologic assessment, but it is highly overly simplistic, with mapping that assumes contiguous groundwater aquifer resources, and results that over estimates recharge significantly.

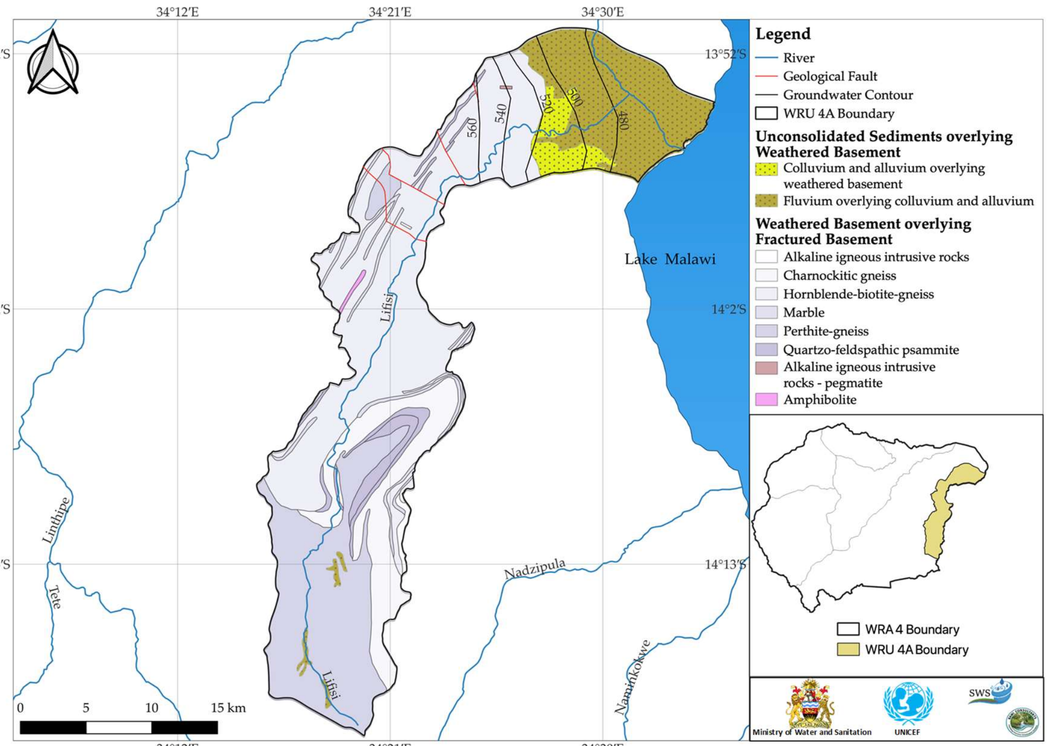

Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 4A wtihin Water Resource Area 4 (Linthipe River Catchment).

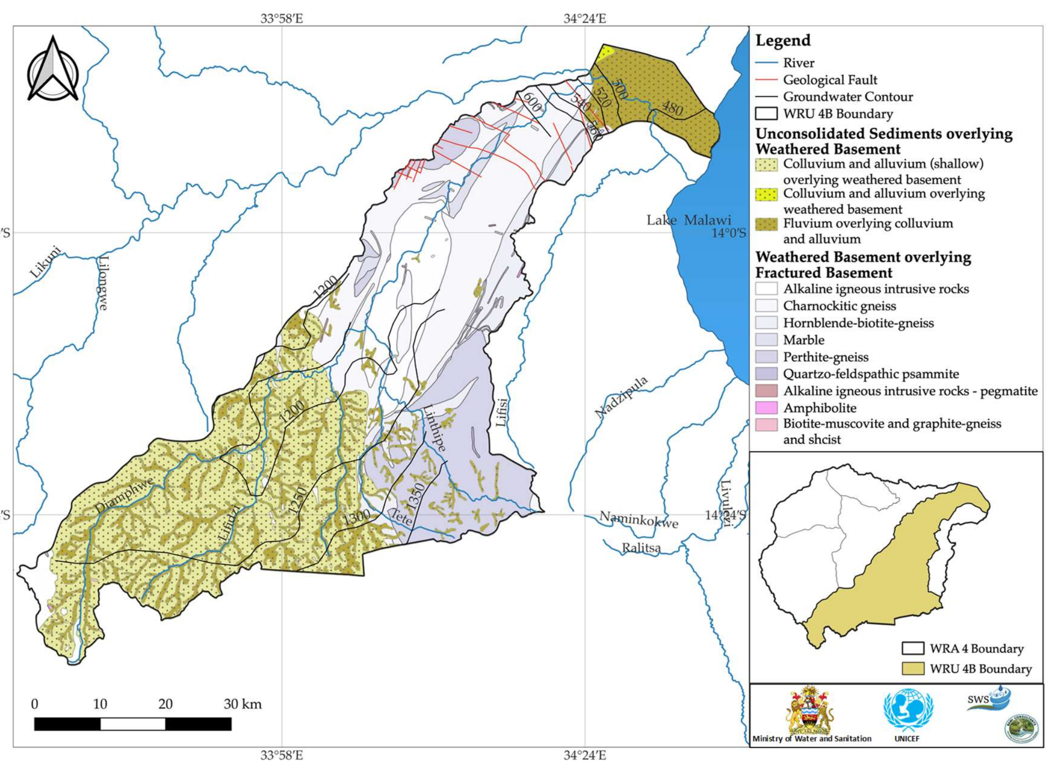

Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 4B wtihin Water Resource Area 4 (Linthipe River Catchment).

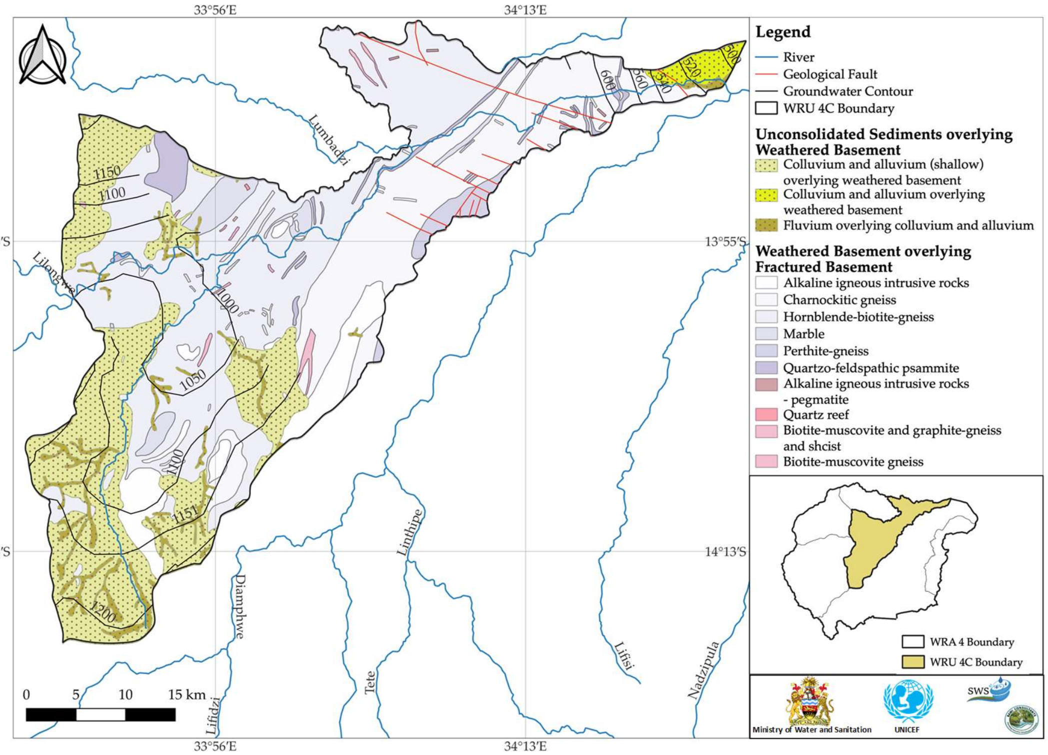

Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 4C wtihin Water Resource Area 4 (Linthipe River Catchment).

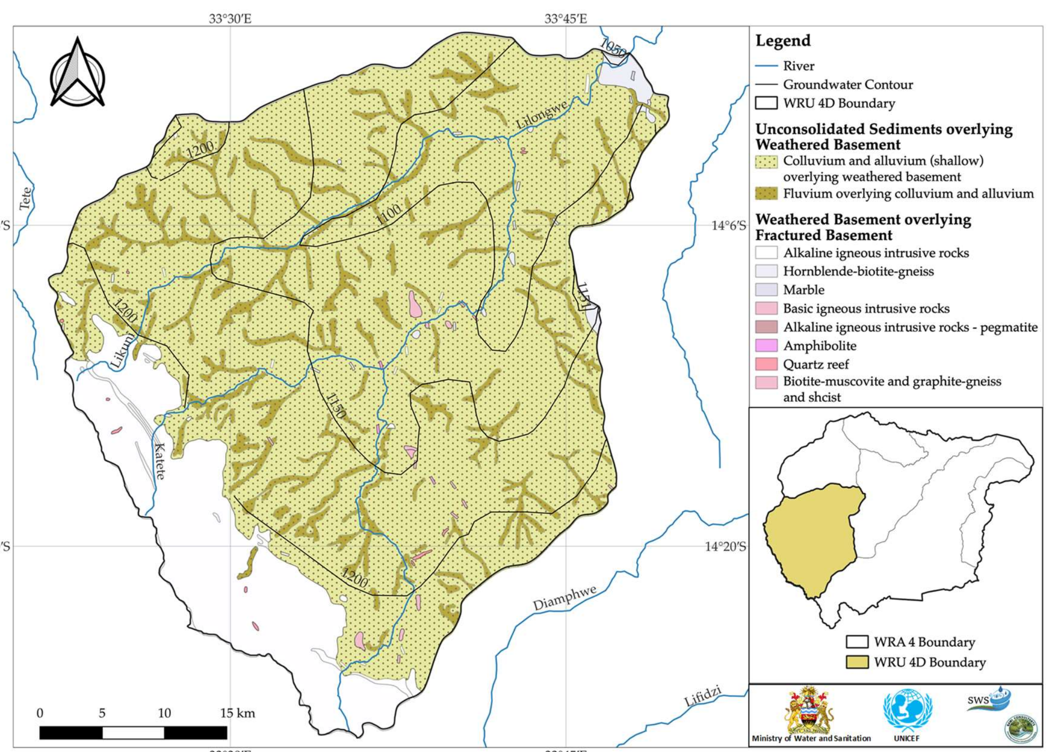

Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 4D wtihin Water Resource Area 4 (Linthipe River Catchment).

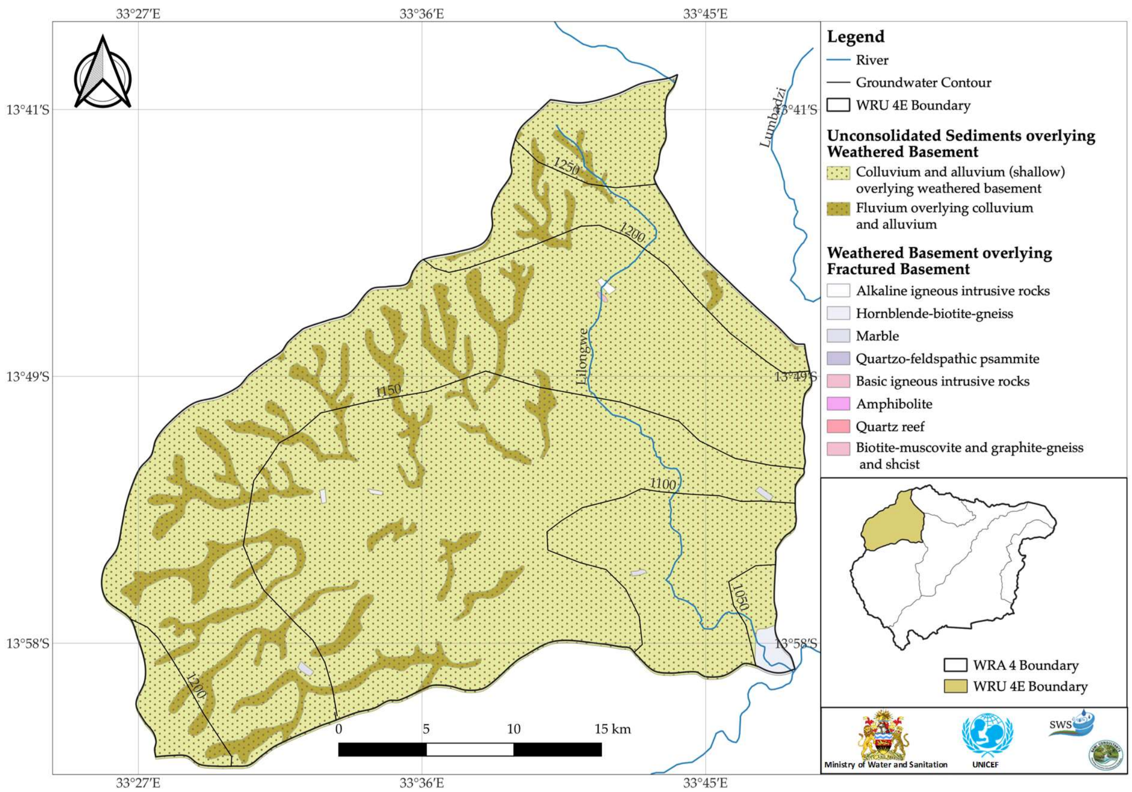

Figure 7e. Map showing the hydrogeologic units and water table for Water Resource Unit 4E wtihin Water Resource Area 4 (Linthipe River Catchment).

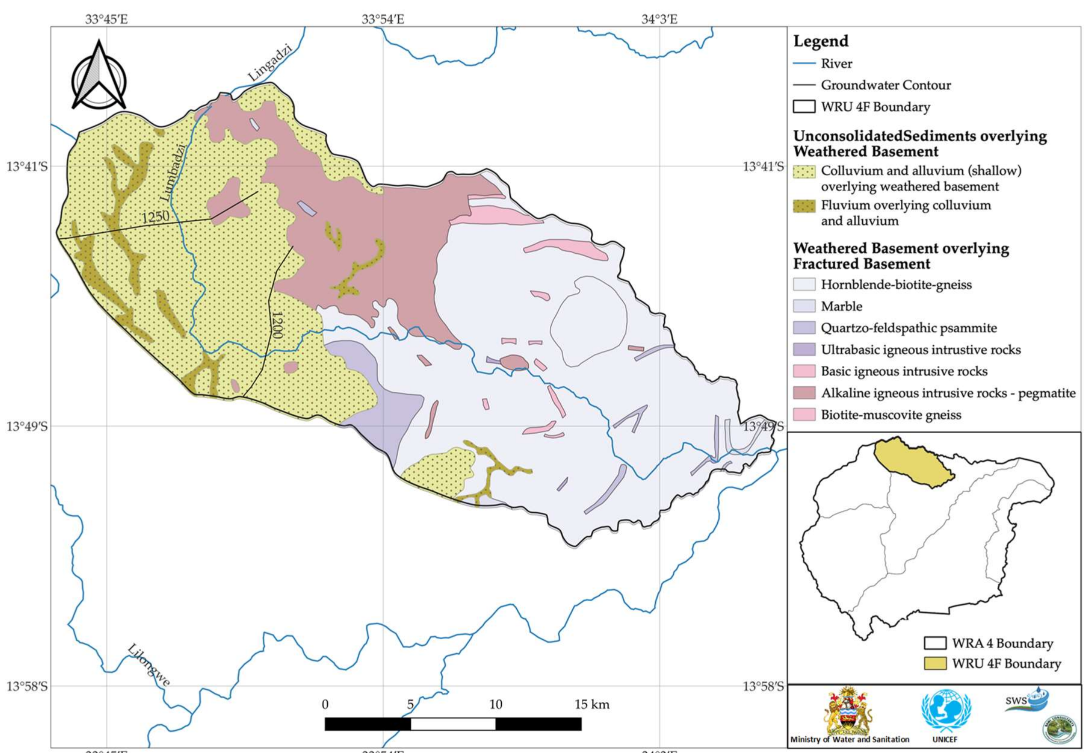

Figure 7f. Map showing the hydrogeologic units and water table for Water Resource Unit 4F wtihin Water Resource Area 4 (Linthipe River Catchment).

Topography and Drainage

WRA 4 comprises four contrasting physiographic zones: the highlands; the plateau areas; the Rift Valley escarpment; and the Rift Valley lakeshore plains. These distinct geographic features coupled with the remote upland plateau occurrence of extensive 'dambo' grass-covered swampy valley(s) influences flow direction towards Lake Malawi. (**Figure 8**).

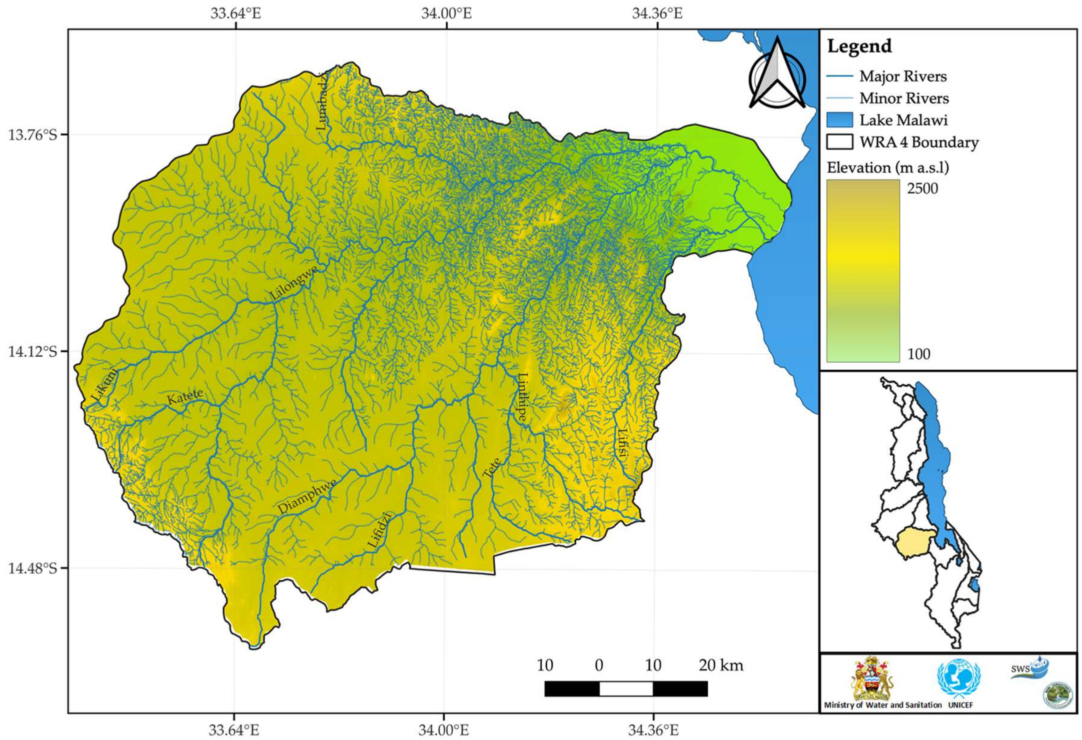

Figure 8. Drainage for the major rivers in Water Resources Area 4.

Geology – Solid

The eastern section of WRA 4 is dominated by Precambrian - Lower Palaeozoic Malawi Basement Complex of metamorphic and igneous rocks. Geological structure is controlled by the Malawi Rift Valley; WRA 4's eastern section comprises the western rift escarpment of the Malawi Rift. Rift margin normal faults are abundant in this region and dissect basement rocks along the strike of the rift valley (**Figure 7a – 7f**). Predominant lithology is Precambrian - Lower Palaeozoic perthite-gneiss which dominates northwest of Dedza, charnockitic gneiss and granulite, and hornblende-gneisses. Regional-scale anorthosite and anorthositic gneiss occur in the centre. West of the fault scarp is the Kasungu-Lilongwe Plain which hosts the Lilongwe and Linthipe river basins. Beneath sedimentary cover, weathered basement sequences of unknown lithology persist across the region. The far western section at the border with Mozambique hosts the Dzalanyama Range; an isolated mountain range composed of granite.

Geology – Unconsolidated deposits

WRA 4's east is dominated by Tertiary - Recent unconsolidated sediments which overlie weathered basement rock. The area is a regional sedimentary basin bounded by the Malawi Rift escarpment to the east, and the Dzalanyama Range to the west, predominantly composed of colluvium and alluvium from surrounding highlands. The basin hosts the Lilongwe and Linthipe rivers which drain the area east, crossing the rift escarpment and into the rift valley at Lake Malawi. Fluvial sediments and river dambos are abundant where rivers and ephemeral streams occur within the basin.

Climate

As part of the Lake Malawi Basin, the WRA 4 experiences a tropical–continental climate with two distinct seasons: a wet season from November to April, and a dry season from May to October. The dry season is characterized by south-easterly trade winds (the Mwera) and the wet season by weaker north-easterly winds (the Mpoto). The Inter Tropical Convergence Zone (ITCZ), the Zaire Air Boundary (ZAB), and tropical cyclones are the three large-scale (synoptic) systems that bring rainfall to the basin. Based on 2000–2018 precipitation data gathered from Malawi's Department of Climate Change and Meteorological Services (DCCMS). Annual rainfall in the catchment area exhibits a mean of 879 mm and a GIS modelled average of 912mm+/-49mm and a modelled range of 819 mm – 1,137mm (**Figure 9**). Temperatures are also influenced by the diverse topography, typically decreasing with increasing altitude. Maxima occur in October/November and minima in June/July. Malawi is vulnerable to climate change influence, arguably already occurring based on increased drought and flood event frequencies.

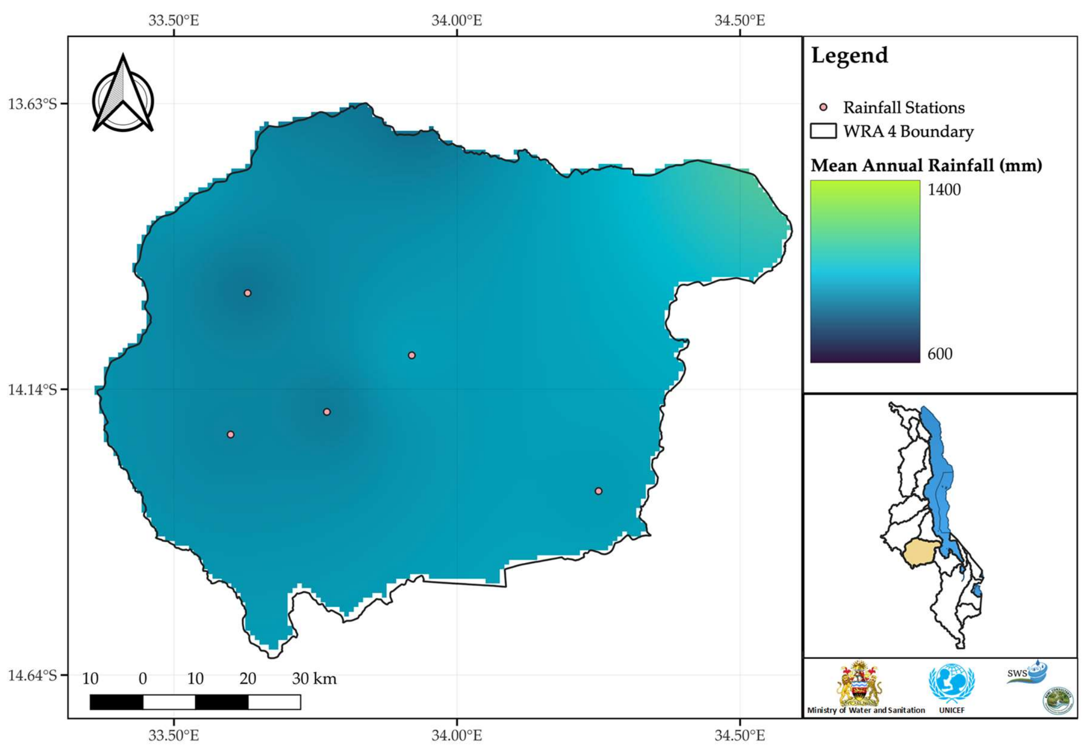

Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 4 with the location of weather stations. Average rainfall measured is 822mm, average rainfall modelled is 912 +/- 49mm (range 819 to 1,137mm).

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 4. 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)
4	A	- No Station -	-	922
	B	Dedza	922	940
	C	Nathenje	930	832
	D	Dzalanyama/Bunda	855	876
	E	Chitedze	865	874
	F	- No Station -	-	865

Land use

The WRA 4 Land use is mainly by rain fed cultivation, grasslands, and woodlands, with some marshes. Extractive water use is mostly irrigation and domestic water supply to Mzuzu, Mzimba, Rumphi townships. WRA 4 includes the Lilongwe Conurbation with a significant population growth and various townships and built up areas. This rapid and extensive urbanisation likely impacts the quality and quantity of groundwater in these areas resulting from indiscriminate groundwater abstraction and the effects of industrial and domestic wastes.

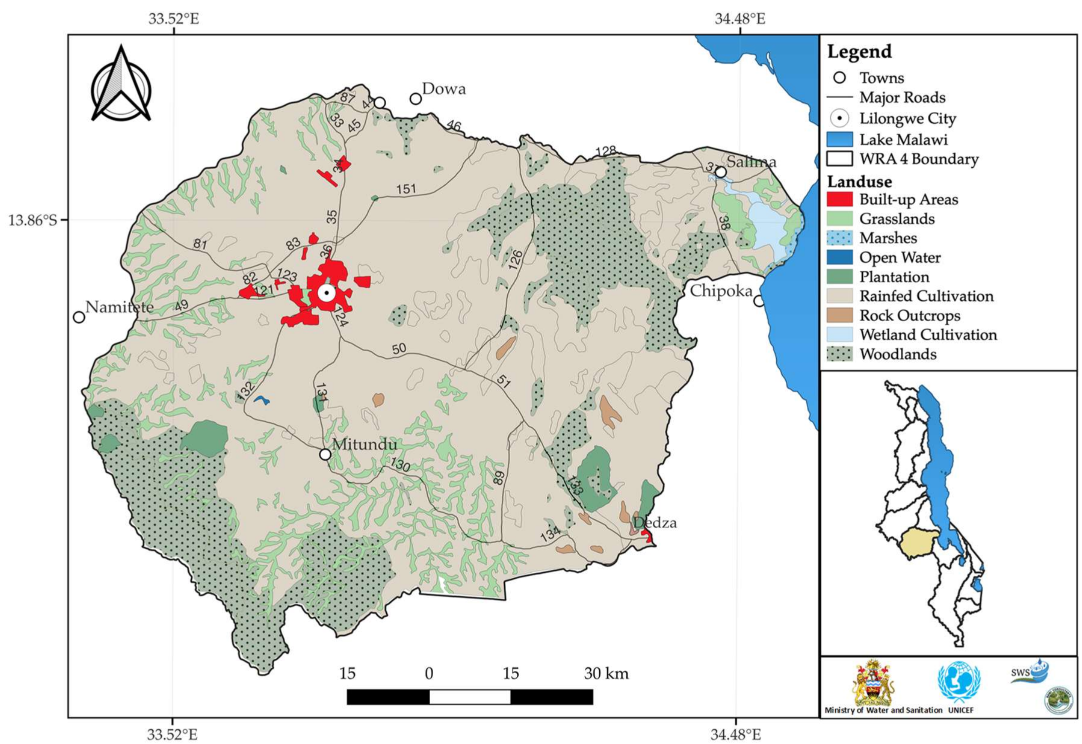

Figure 10. Land use in WRA 4 is dominated by woodlands, grasslands, rain fed agriculture and urbanisation.

Hydrogeology of WRA 4

Aquifer Properties

The dominant aquifer type in WRA 4 is colluvium overlying weathered and fractured basement overlain by fluvial sediments in river channels. Groundwater-surface water dominates the groundwater flow directions in the west-central region of WRA 4. Near dambos finer flood deposits interbed 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. Caution is urged not to extrapolate limited data over a wider region in WRA 4 given the localised groundwater – surface water connections.

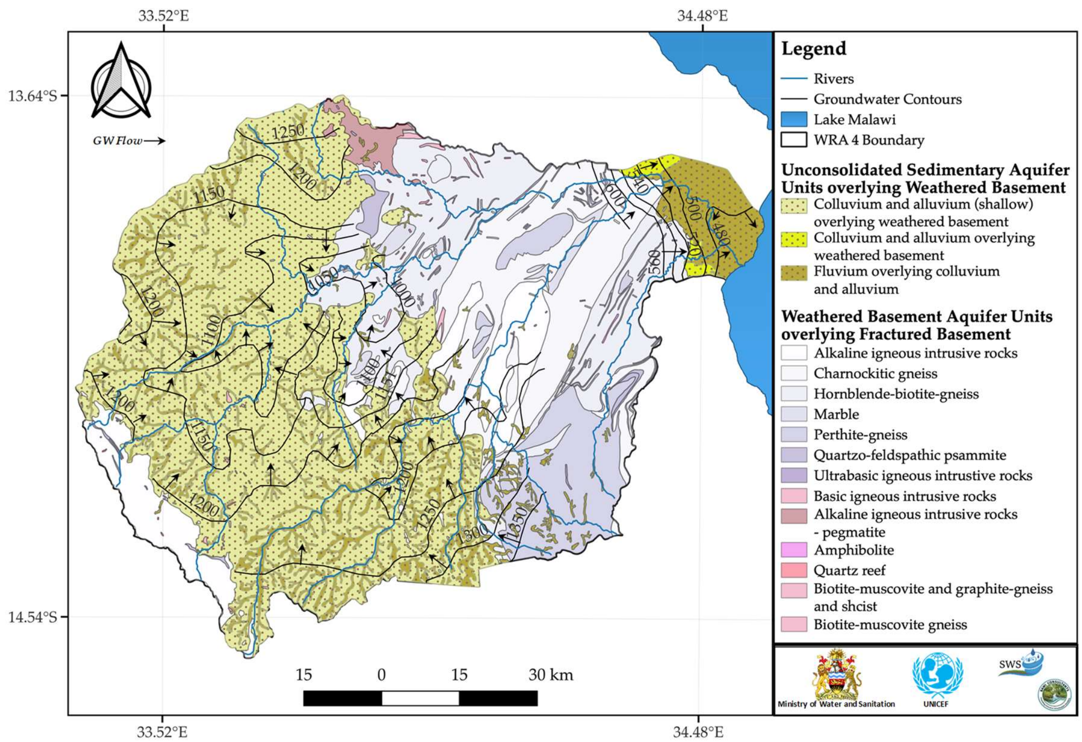

Figure 11. Groundwater level contours and flow direction in WRA 4 [1987 Hydrogeological Reconnaissance data] [water level contour interval 50m upland and 20m near Lake Malawi]

Groundwater levels and flow regime

The Ministry of Water and Sanitation database has measurements of resting water levels in many boreholes, however there is no high resolution elevation data that corresponds with this data, therefore groundwater level data for WRA 4 is based on prior hydrogeological reconnaissance.

Groundwater level data for WRA 4 based on prior hydrogeological reconnaissance confirm a system flow regime following topographic drainage (**Figure 11**). Although groundwater head contours appear somewhat complex within the Lilongwe Plain plateau area in the central west of WRA 4 sits, detailed inspection confirms flows follow local and regional surface topography. Groundwater flows in the weathered Basement (and overlying unconsolidated deposits) converge on the various river systems with groundwater flow divides aligning with the internal surface-water divide - WRU boundaries. For instance, WRU 4B contouring shows high heads at 1350 m asl close to the Dedza Mountain area Linthipe source with flows convergent on the elongated 1200 m asl head contour surrounding the Linthipe and Diamphwe rivers. Just further north, a groundwater divide occurs at the WRU boundary and an adjacent 1200 m msl contour in WRU 4D is seen to encircle the Lilongwe headwaters with groundwater flows convergent on the Lilongwe and Likuni river confluence on the outskirts of Lilongwe City. High base flows are evident from marked inflection of head contours extending upstream around rivers. Hydraulic gradients in the basin south west are quite variable, but moderate to low ranging from around 0.007 to 0.003 reflecting the shallow gradient topography and the widespread occurrence of dambo wetlands controlling local head distributions. For a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2, groundwater velocities would range from 5.5 to 13 m/yr for these gradients.

The Rift Valley lakeshore plains are relatively wide, extending from about 15 to 30 km inland from the Lake Malawi shoreline with hydraulic head contours approximately parallel to the shoreline confirming groundwater flow towards and discharge to Lake Malawi. Or alternatively, discharge as base flow to the Lilongwe, Linthipe and smaller Lifisi rivers or the near coast wetland area on the extensive Linthipe estuary promontory near Maganga. Hydraulic gradients over a head drop of 560 m to 500 m asl vary between 0.006 to 0.011 becoming shallower on the flat promontory closer to the shoreline. Head contours close to the river systems suggest variable surface-water – groundwater flow relationships occur across the lakeshore plain. The Linthipe River area data reveal: (i) higher head contours 560 to 600 m are seen to weakly converge on the rivers indicative of base flows to the rivers driven by drainage into the unconsolidated deposits from the adjoining fractured Basement; (ii) contours 520 to 540 m convexly 'bowing' out towards the shoreline signifying river influent flow leakage to groundwater over that intermediate reach; and, (iii) closer to the shoreline, a 480 m contour that is strongly convergent on the river signifying a return to groundwater base flow into the river near its lake estuary.

Aquifer / Borehole Yield

In most WRA's in Malawi, the borehole yield data held by the Ministry does not appear to follow the anticipated distribution based on aquifer lithology. **Figure 12** provides the distribution of the data held by the Ministry of Water and Sanitation for each WRU, and it is clear the distribution is skewed toward values of < 0.25l/s. This is suspect and likely represents substandard well construction for boreholes to meet a minimum borehole yield for the Afridev pump rather than to drill and test each groundwater well to determine the exact aquifer properties at each location. However, in WRA 4 there appears to be a trend to higher borehole yields related to alluvium aquifer units, with a number of production boreholes reporting yields in excess of 2l/s. In WRA 4 (**Figures 13a to 13f**) there is some potential in the colluvium, alluvial and fluvial units for higher yielding boreholes, in particular in WRU 4C where there are reported yields over 2l/s, and there is potential for artesian confined systems along the escarpment but detailed hydrogeological on-site mapping should be undertaken to confirm, and site specific hydrogeological investigation is strongly recommended for implementation of 'solar pumped' water supplies before full implementation.

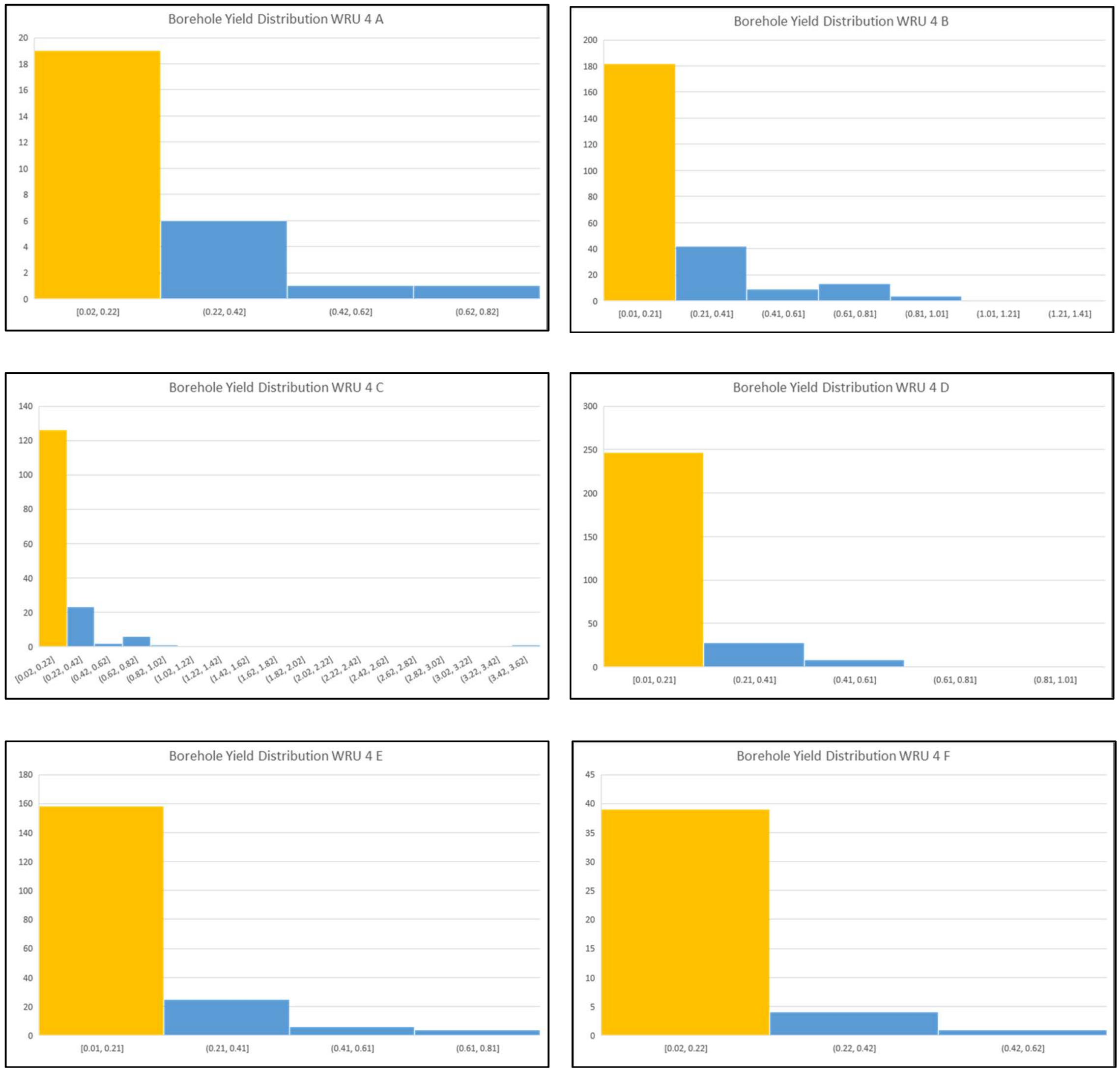

Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 4 (WRU 4A, 4B, 4C, 4D, 4E, 4F) (y axis = *n* observations)

There are general trends which suggest the highest borehole yields are found in alluvial aquifers in the order of 2 l/s but it is recommended that data on sediment distributions from drilling records are geospatially located from Ministry records to develop hydrogeological cross sections for interpretation. The highest yielding boreholes in basement aquifers will likely be located mainly along linear structures and main streams and near contacts between different aquifers.

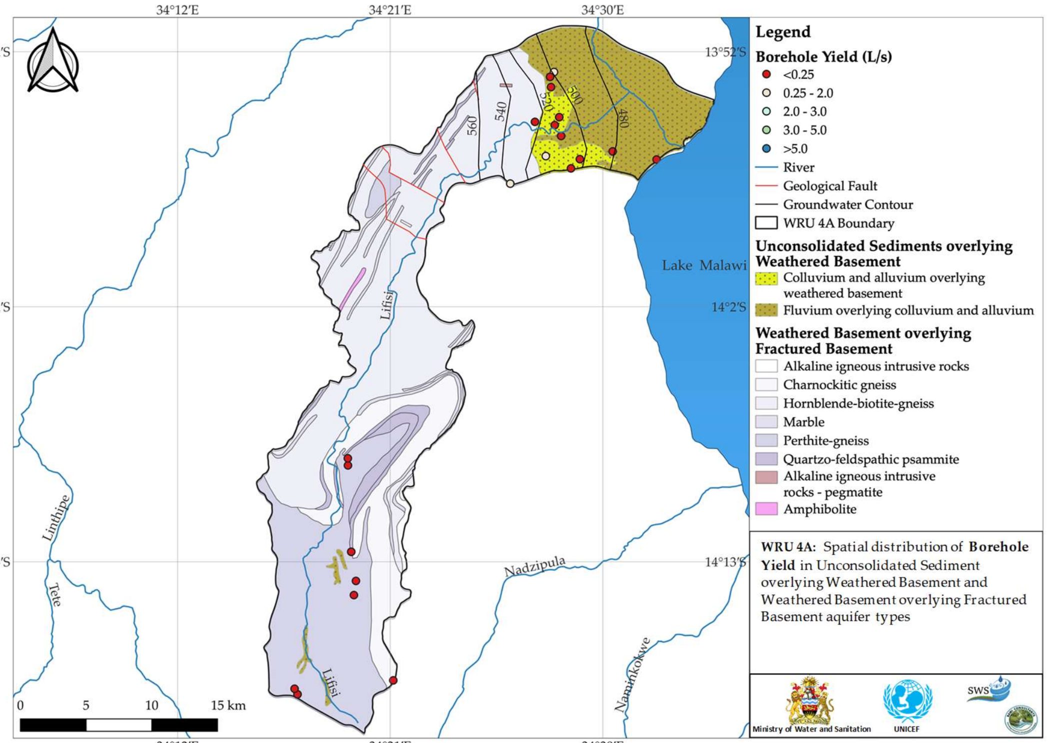

Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 4A.

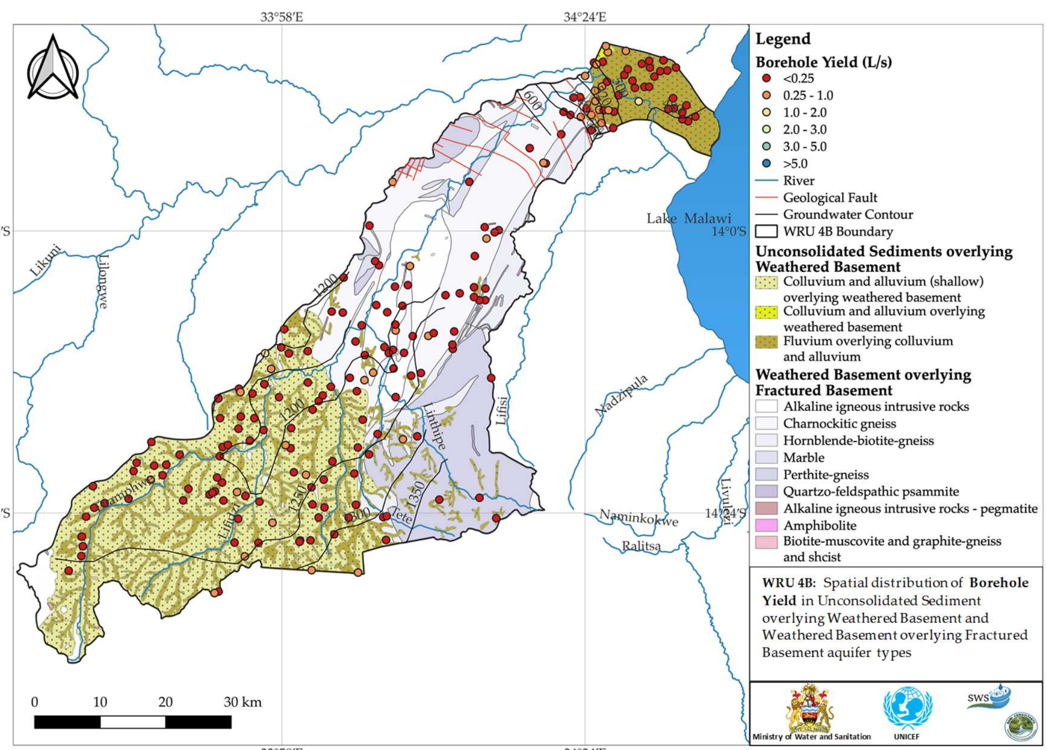

Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 4B.

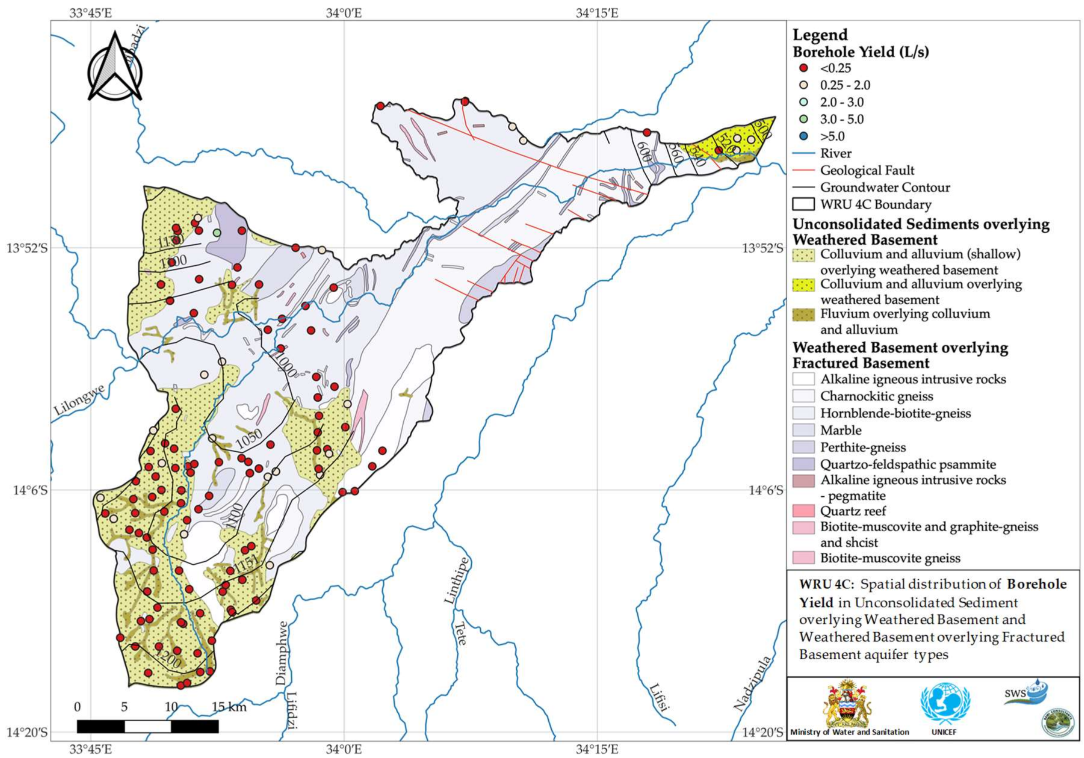

Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 4C.

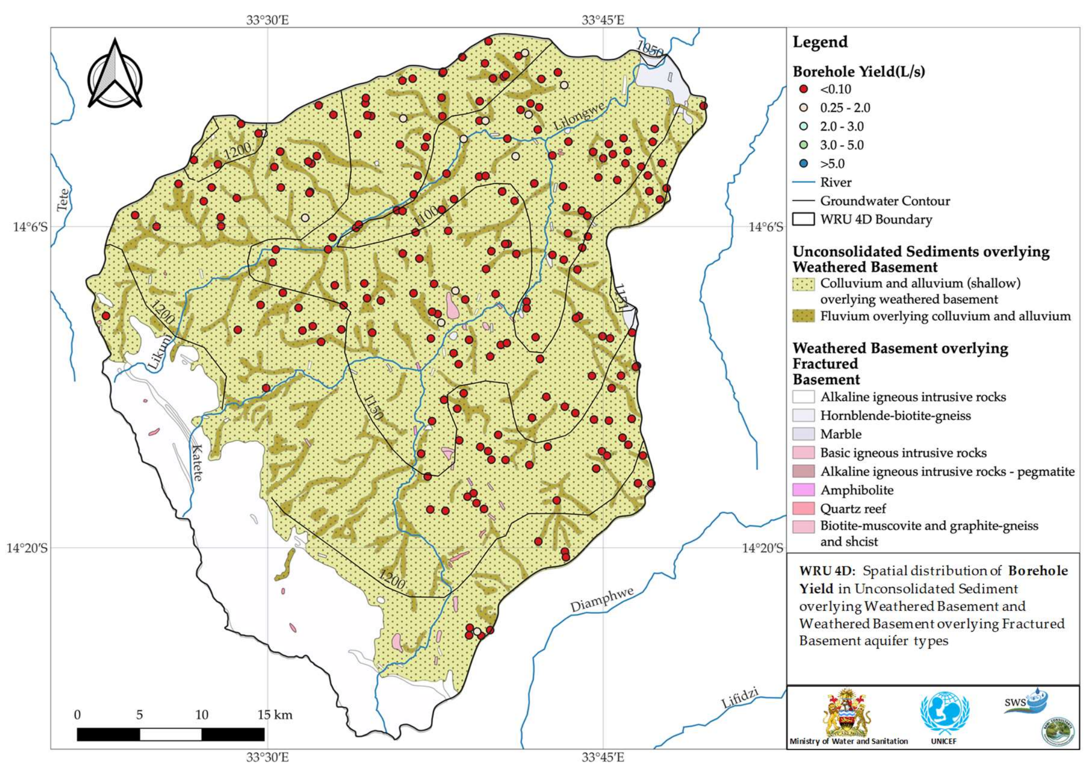

Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 4D.

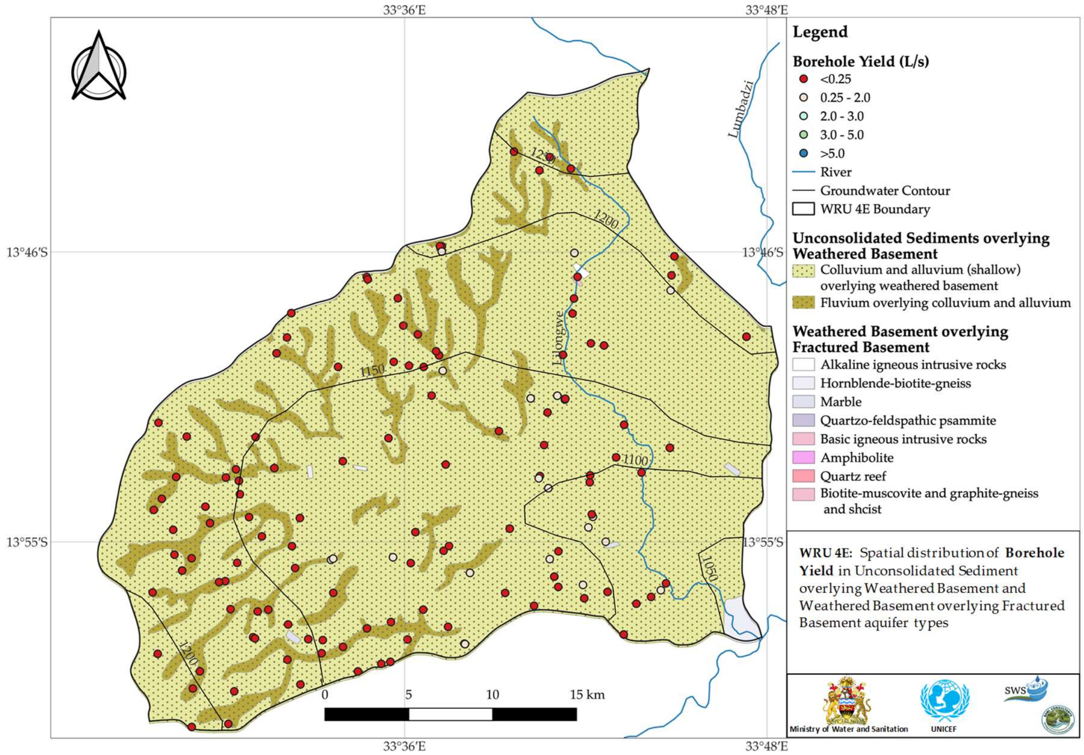

Figure 13e. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 4E.

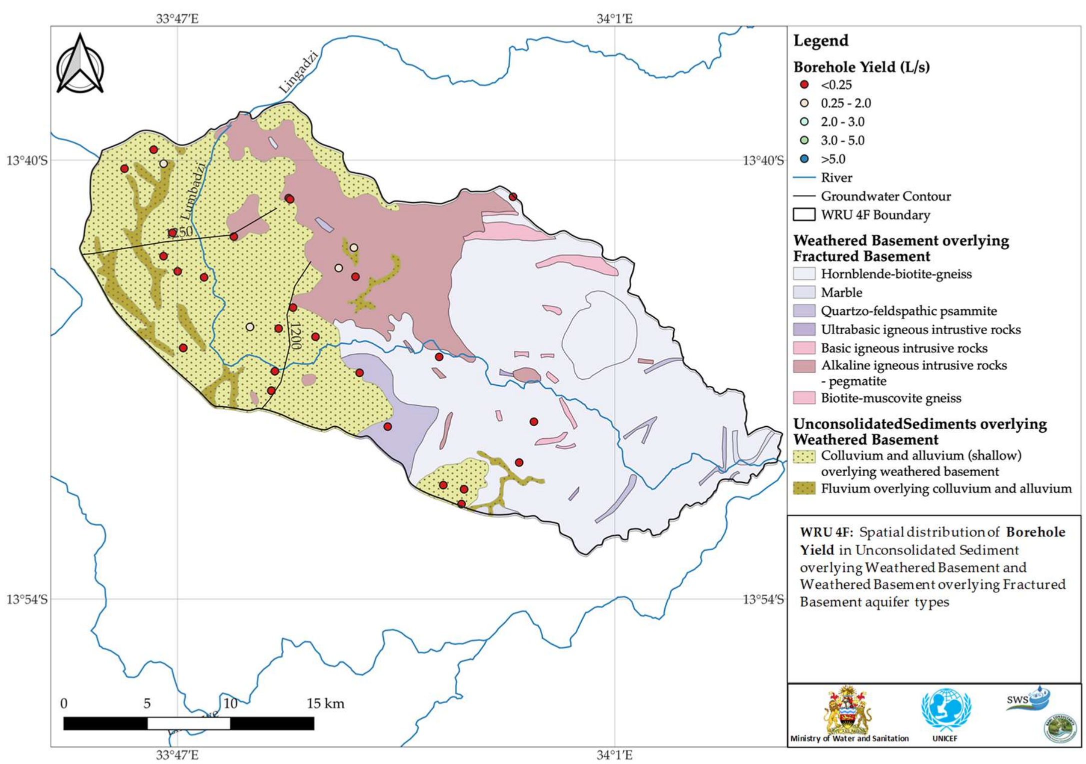

Figure 13f. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 4F.

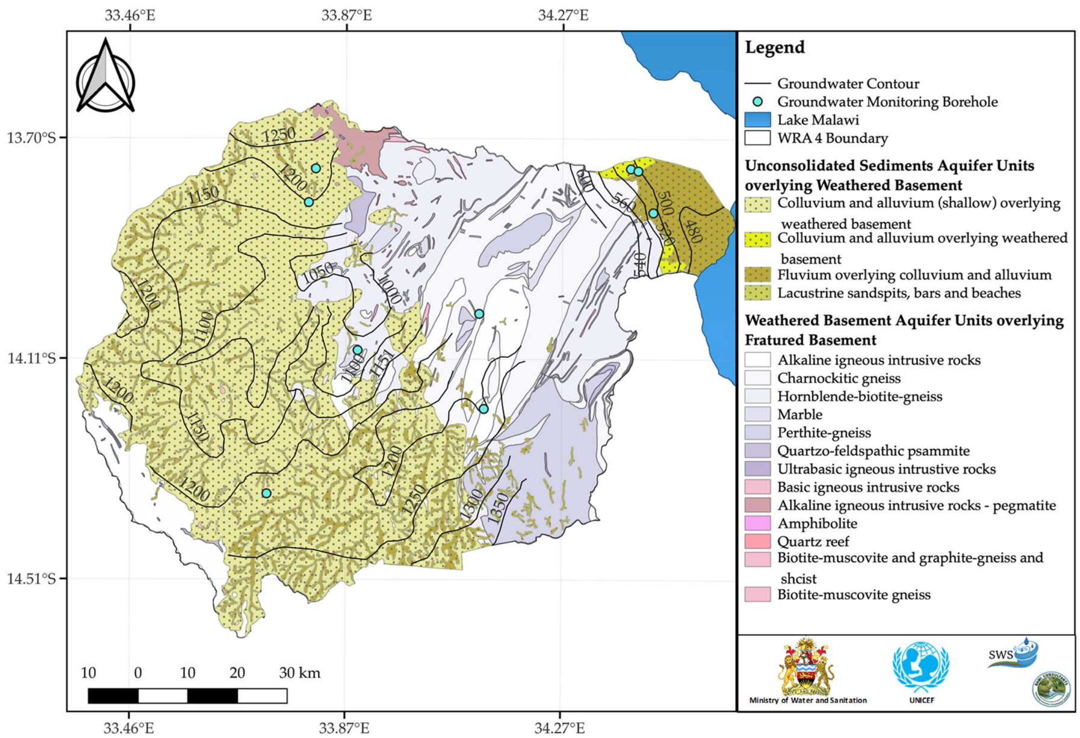

Figure 14a. Location of groundwater monitoring points in WRA 4.

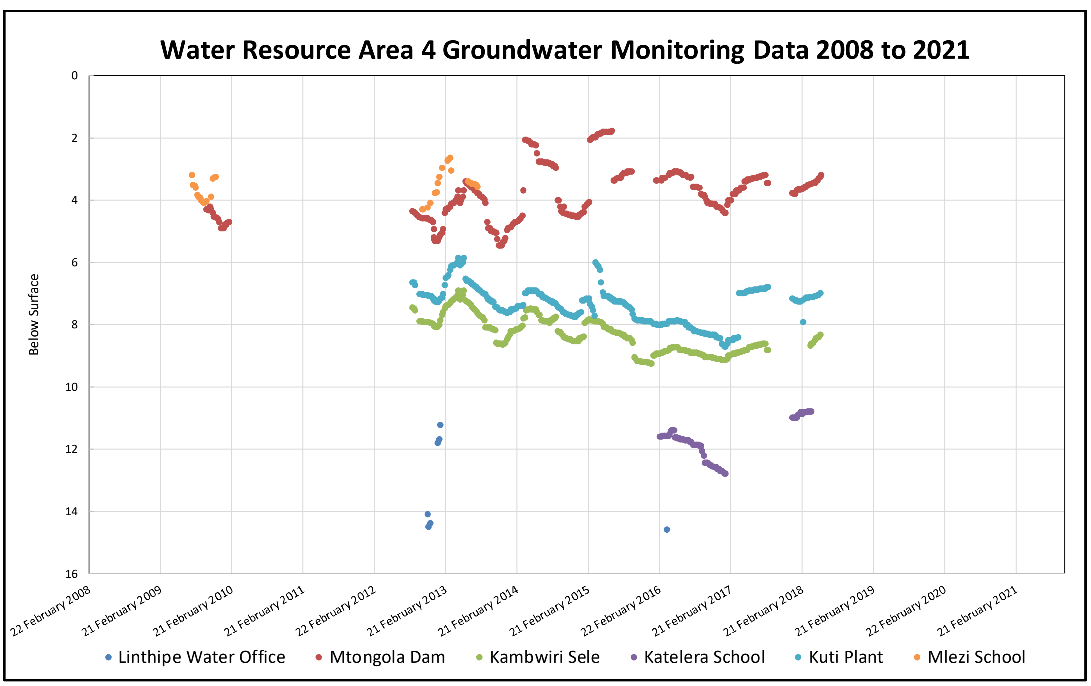

Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 6. (units assumed to be meters below ground level).

Groundwater Table Variations

There is a number of semi-operational groundwater monitoring station within WRA 4 that have data (**Figure 14a** and **Figure 14b**). Unfortunately, the data is not complete for most sites and does not cover enough time to follow climate changes, but there is a possible low amplitude (ca 1m per annum) variation in the water table at Mtongola Dam, but there is also a short amplitude change of up to 3 meters at each site and a general decline for the Linthipe Water Office and Kuti Plant sites. Data from the 2020 National Survey suggested seasonal water table declines in shallow groundwater supplies and this is supported by the data in **Figure 14b**. It is possible that long-term trends may relate to climate variability (rainfall, recharge and surface-water groundwater relationships). Given there are no borehole logs and multi-level installations that separate different hydro-stratigraphic units, the true nature of surface water / groundwater interaction and recharge effects cannot be determined from the data or the current monitoring network. It is recommended that multi-level installations are placed into each hydrostratigraphic unit is an area for future investment. Given the relationship of the water table and the rivers, monitoring of the surface water and groundwater tables is strongly advised where interaction likely occurs, especially if solar boreholes are used.

Groundwater recharge

The groundwater volume in each WRU was calculated using the estimated range of porosities published by McDonald et al. (2021) and the range of saturated thickness for each aquifer type (based on the depth of boreholes and water strikes per agreement with the Ministry of Water and Sanitation). These are considered to be more accurate than estimates from other studies which suggested up to 120mm of recharge (13% of rainfall), these published estimates are unrealistically high and estimates of between 1 and 7.5% of rainfall are used in here.

Table 4a. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 4A, 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	97.2	10%	35%	0.02	0.10	194.4	3,401.1	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	19.9	10%	30%	0.02	0.06	39.8	358.4	
W & F Basement	459.7	1%	10%	0.02	0.03	91.9	1,379.0	
	Area of WRU (km^2)	4A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*326.1*	*5,138.5*	*Total Volume Groundwater*
	576.8	922	Average Rainfall in WRU	9.22	69.15	5.3	39.9	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]						61	129	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 4B, 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 High Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	632.3	10%	35%	0.02	0.10	1,264.6	22,130.8	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	964.3	10%	30%	0.02	0.06	1,928.6	17,357.7	
W & F Basement	1,675.7	1%	10%	0.02	0.03	335.1	5,027.2	
	Area of WRU (km^2)	4B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*3,528.4*	*44,515.7*	*Total Volume Groundwater*
	3,272.4	940	Average Rainfall in WRU	9.4	70.5	30.8	230.7	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]						115	193	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 4C, 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	57.6	10%	35%	0.02	0.10	115.2	2,015.6	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	421.3	10%	30%	0.02	0.06	842.6	7,583.2	
W & F Basement	1,136.0	1%	10%	0.02	0.03	227.2	3,407.9	
	Area of WRU (km^2)	4C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,184.9*	*13,006.7*	*Total Volume Groundwater*
	1,614.8	832	Average Rainfall in WRU	8.32	62.4	13.4	100.8	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]						88	129	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 4D, 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	202.4	10%	35%	0.02	0.10	404.8	7,083.3	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	1,348.6	10%	30%	0.02	0.06	2,697.3	24,275.3	
W & F Basement	296.1	1%	10%	0.02	0.03	59.2	888.2	
	Area of WRU (km^2)	4D	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*3,161.2*	*32,246.7*	*Total Volume Groundwater*
	1,847.1	876	Average Rainfall in WRU	8.76	65.7	16.2	121.4	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]						195	266	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 4E, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	113.6	10%	35%	0.02	0.10	227.3	3,977.7	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	833.3	10%	30%	0.02	0.06	1,666.5	14,998.6	
W & F Basement	6.3	1%	10%	0.02	0.03	1.3	19.0	
	Area of WRU (km^2)	4E	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,895.1*	*18,995.3*	*Total Volume Groundwater*
	953.2	874	Average Rainfall in WRU	8.74	65.55	8.3	62.5	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]						227	304	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 4F, 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	22.8	10%	35%	0.02	0.10	45.7	799.4	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	199.2	10%	30%	0.02	0.06	398.4	3,585.6	
W & F Basement	394.5	1%	10%	0.02	0.03	78.9	1,183.4	
	Area of WRU (km^2)	4F	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*523.0*	*5,568.4*	*Total Volume Groundwater*
	616.5	865	Average Rainfall in WRU	8.65	64.875	5.3	40.0	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]						98	139	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 4 ranges between 79.3 Million Cubic Meters (MCM) and 598 MCM per year, with a mean age of groundwater of 162 years across the Water Resource Area **(Tables 4a to 4f**). This is substantially **lower than the estimates by the Lilongwe Water Board / GMS / Hydroconsult study** which suggested 1,818 Million Cubic Meters per year and the calculation made in the idealistic Lilongwe Board study is suspect. 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 4

Groundwater major-ion water quality in WRA 4 for data available within the Ministry of Water and Sanitation is available but is limited to those analyses which have geospatial information and data which was reported as 'zero' or below reported minimum detection limits were ignored (**Table 5**).

Table 5. Distribution of dissolved species in groundwater WRA 4. 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 4	pH	EC (as TDS mg/l)	Cl (mg/l)	SO_4 (mg/l)	NO_3 (mg/l)	F (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Fe (mg/l)
Mean	7.4	413	14.3	35.9	0.4	0.7	22.1	2.9	37.5	15.7	0.5
Std Dev	0.7	338	12	71	0.5	0.6	22	2.0	31.6	12.6	1.0
Median	7.3	308	12.4	13.0	0.3	0.6	15.0	2.4	27.0	11.7	0.1
Max	8.9	3,290	128	883	5	3.8	200	17	293	116	5.6
Min	5.3	6.3	0.2	0.1	0.0	0.0	5.0	0.1	6.3	1.5	0.0
n	425	424	422	419	283	267	379	379	379	379	62

Piper plots of the WRA 4 water quality data suggest most water has expected geochemical changes from water-rock interactions dominated by Ca-Mg-HCO_3 type waters with a clear trend within the weathered basement overlying fractured basement for increasing Na-Cl-SO_4 likely due to fault zone fluids given the increases in sulphate and high fluoride measurements, geologic sources are more likely (**Figure 14a and 14b**). 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 near Lake Malawi there are zones of high EC groundwater most likely related to evaporative enrichment.

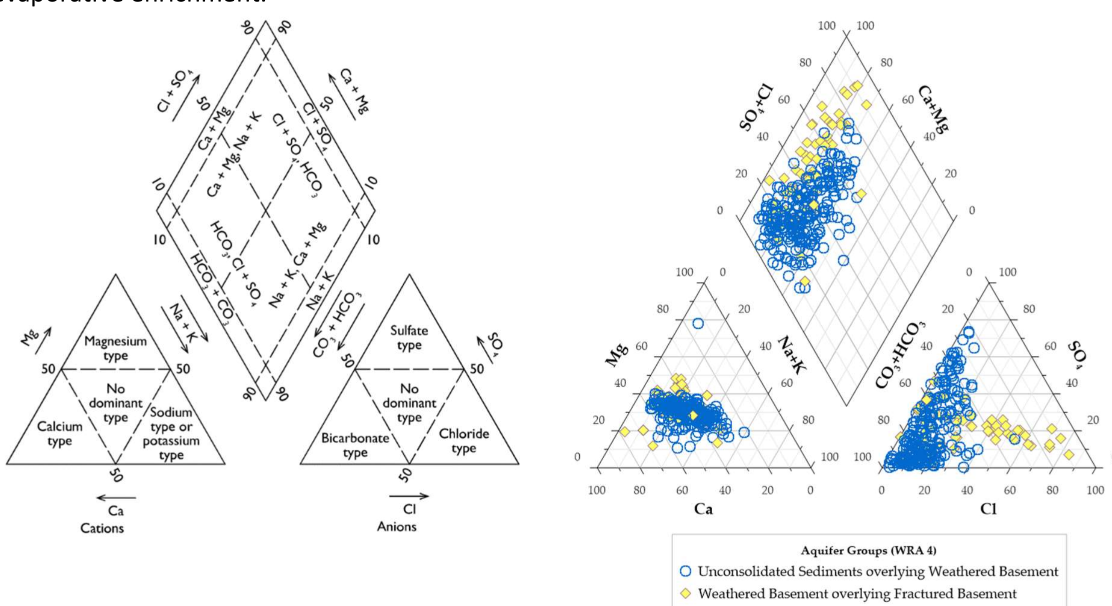

Figure 14a, 14b. Piper Diagrammes of Groundwater Samples in WRA 4 and for each Aquifer Type in WRA 4.

The distribution of key dissolved water quality species in groundwater of WRA 4 is provided however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine in WRA 4, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

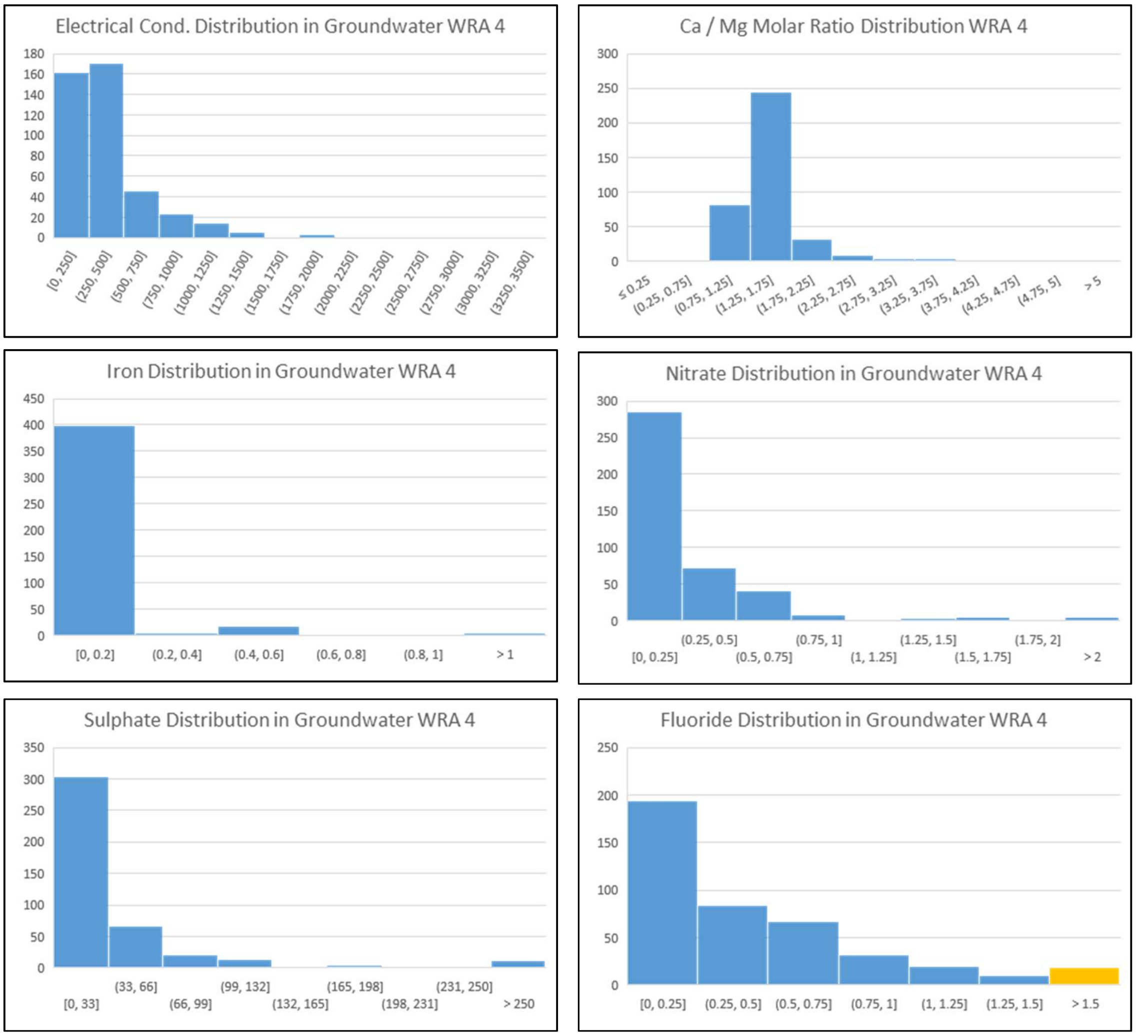

Figure 15 Distribution of chemical species in groundwater within WRA 4 (y axis = *n* observations).

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 4 (**Table 4** and **Figure 15**) is low however the lack of routine and wide-spread water quality analyses held by the Ministry of Water and Sanitation does not allow for interpretation with respect to hydrogeologic units. There are a number of published works that provide interpretation of water quality at local scale in WRA 4 (Wanda 2016, Wanda et al 2014, Wanda et al 2013, Rieger et al 2016, Msilimba and Wanda 2013, Dzimbiri et al 2021, Wanda et al 2011). It is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation.

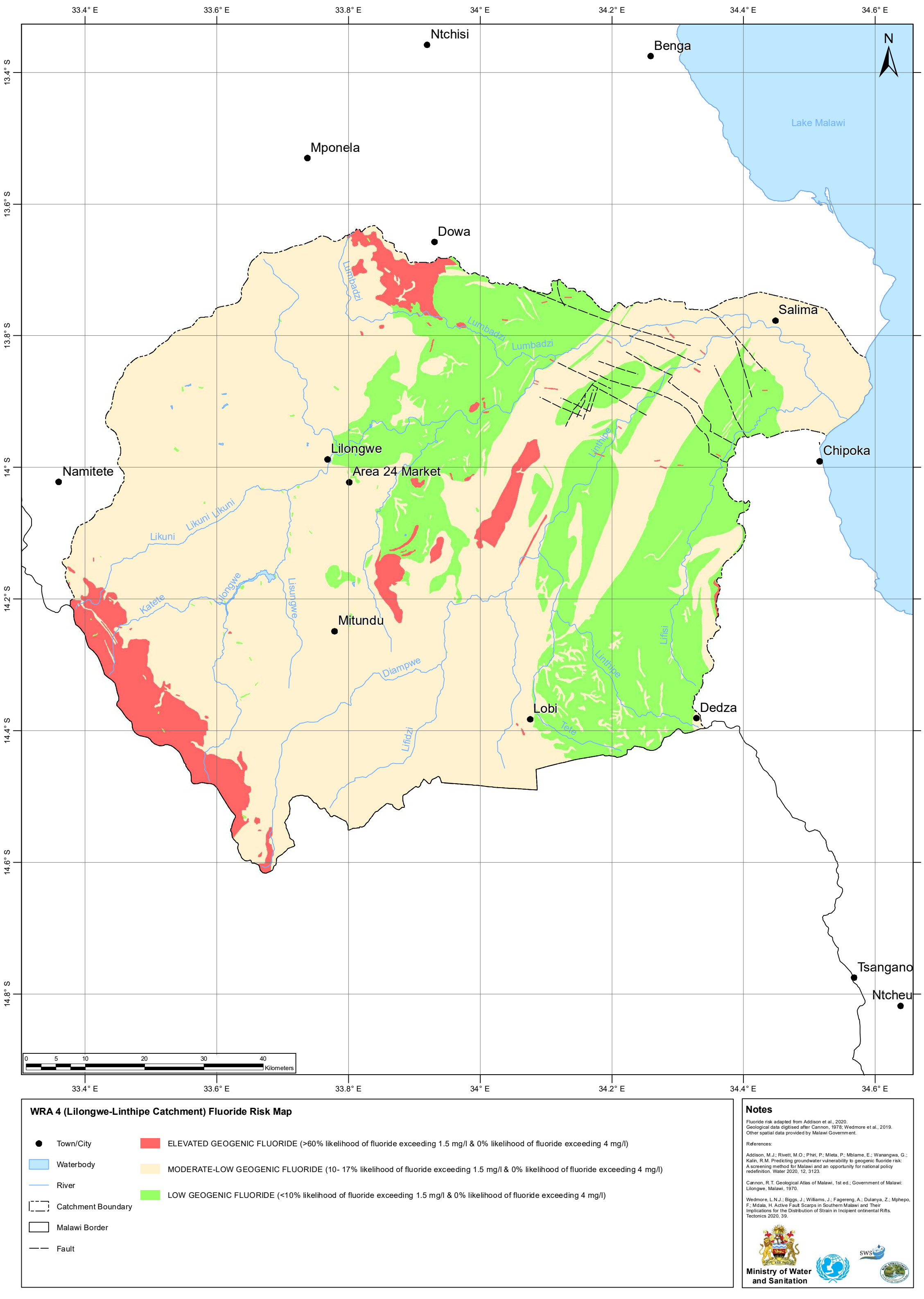

Figure 16. Groundwater Fluoride Risk Map WRA 4 (after Addison et. al. 2021).

Fluoride

Even though there is little prevalence of hot springs in WRA 4, the wide range of fluoride-bearing minerals places WRA 4 in a **Higher Risk** category for fluoride in groundwater. There are known areas of fluorosis (Addison et al 2021). Groundwater data drawn from the recent national-scale assessments (**Figure 16**) reveals a significant number of analyses are above 1.5mg/l, known areas where fault zones underlie aquifers (**Figure 16**) should be targeted for re-analysis as given the co-location with major faults, those water points in proximity to the faults have an increased risk of F > 1.5 mg/l. Additionally, surface water supplies from the areas where basement geology contains fluoride bearing minerals should be monitored for groundwater and any spring runoff that may contain fluoride. The current water quality monitoring data held by the Ministry of Water and Sanitation is insufficient to manage this risk and it is recommended that a detailed and systematic survey of groundwater quality in WRA 4 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 4 with no elevated levels round, however arsenic risks may exist due to the presence of hot springs on the western rift zone, this remain unproven due to a lack of routine, geospatially managed WQ analyses. It is recommended that a detailed and systematic survey of groundwater quality in WRA 4 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 4.

	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**
4A	84,724	90,526	96,501	102,275	108,154	103,559	316,298,981	379,559
4B	630,129	672,440	714,285	756,231	798,888	809,824	2,366,170,419	2,839,405
4C	461,244	491,692	524,865	576,798	604,374	590,868	1,754,913,507	2,105,896
4D	636,640	671,471	703,608	789,936	767,769	861,943	2,392,938,121	2,871,526
4E	399,101	420,471	442,133	506,487	484,147	492,113	1,482,004,003	1,778,405
4F	131,076	141,092	150,603	163,269	170,533	165,996	498,188,135	597,826
WRA 4	**2,342,913**	**2,487,691**	**2,631,996**	**2,894,998**	**2,933,866**	**3,024,302**	**8,810,513,166**	**10,572,616**

A recent publication by Rivett et al (2022) provided strong evidence of pit-latrine induced e-coli contamination of groundwater supplies regardless of season (wet / dry). Water resource unit 7 has a modelled calculated total of 10,572,616 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 681,389. WRA 4 covers roughly 7.7% 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, 14,558 metric tonnes of fertiliser would be used in WRA 4 per year which is 84 times less than faecal matter was added to this WRA this 10-year period.

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Water Resource Unit (WRA) 4 Figures

Figure WRA 4.0: Aquifer Units and Groundwater Level Contours Water Resources Area 4

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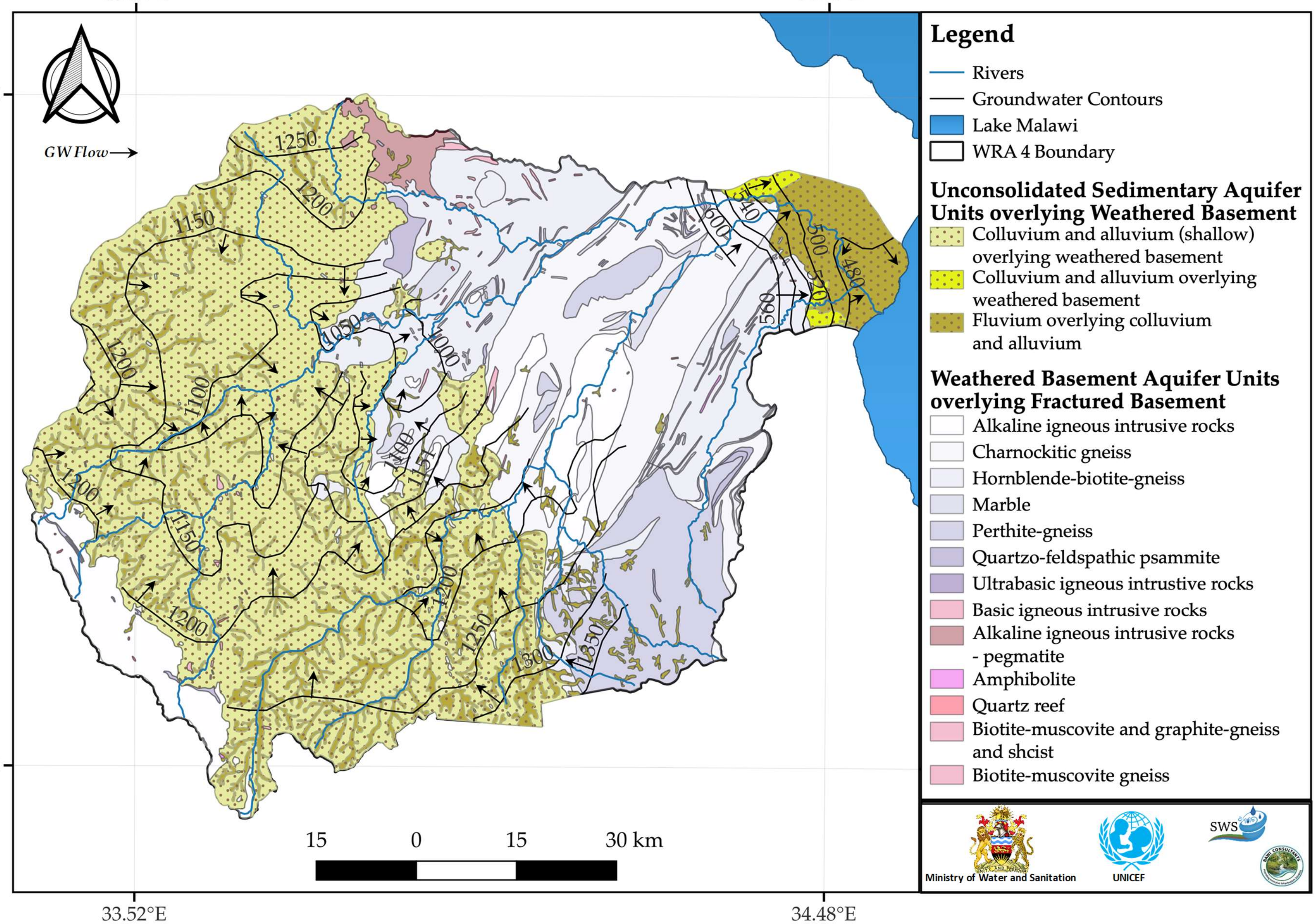


WRU 4A Figures

Figure WRU 4A.1 Land Use and Major Roads

Figure WRU 4A.2 Rivers and Wetlands

Figure WRU 4A.3 Hydrogeology Units and Water Table

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

Figure WRU 4A.5 Groundwater Chemistry Distribution of Sulphate [ppm]

Figure WRU 4A.6 Groundwater Chemistry Distribution Chloride [ppm]

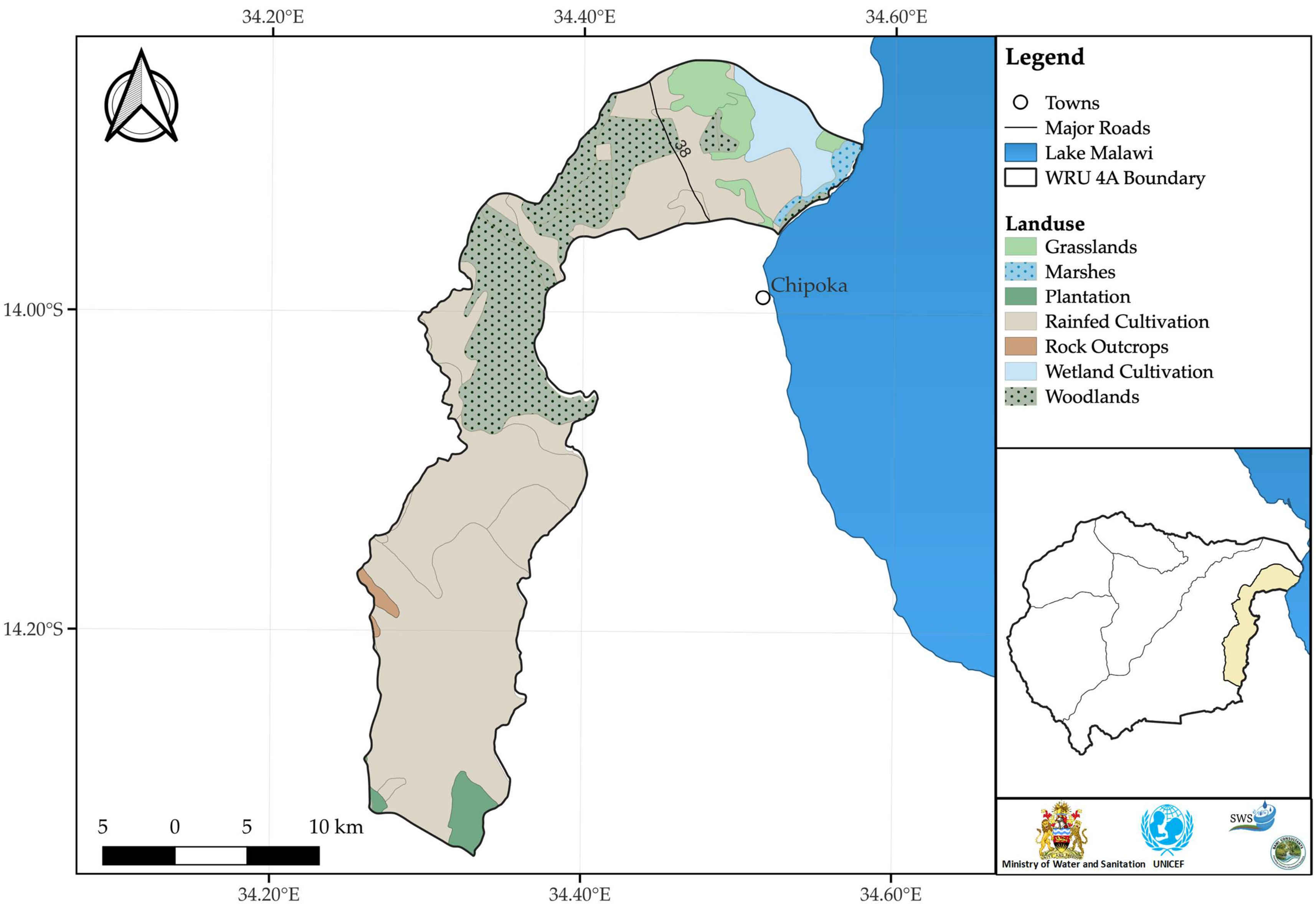
Figure WRU 4A.7 Groundwater Chemistry Distribution Sodium [ppm]

Figure WRU 4A.8 Groundwater Chemistry Distribution Calcium [pm]

Figure WRU 4A.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 4A.10 Borehole Yield Map for data held by the Ministry

Figure WRU 4A.1 Land Use and Major Roads



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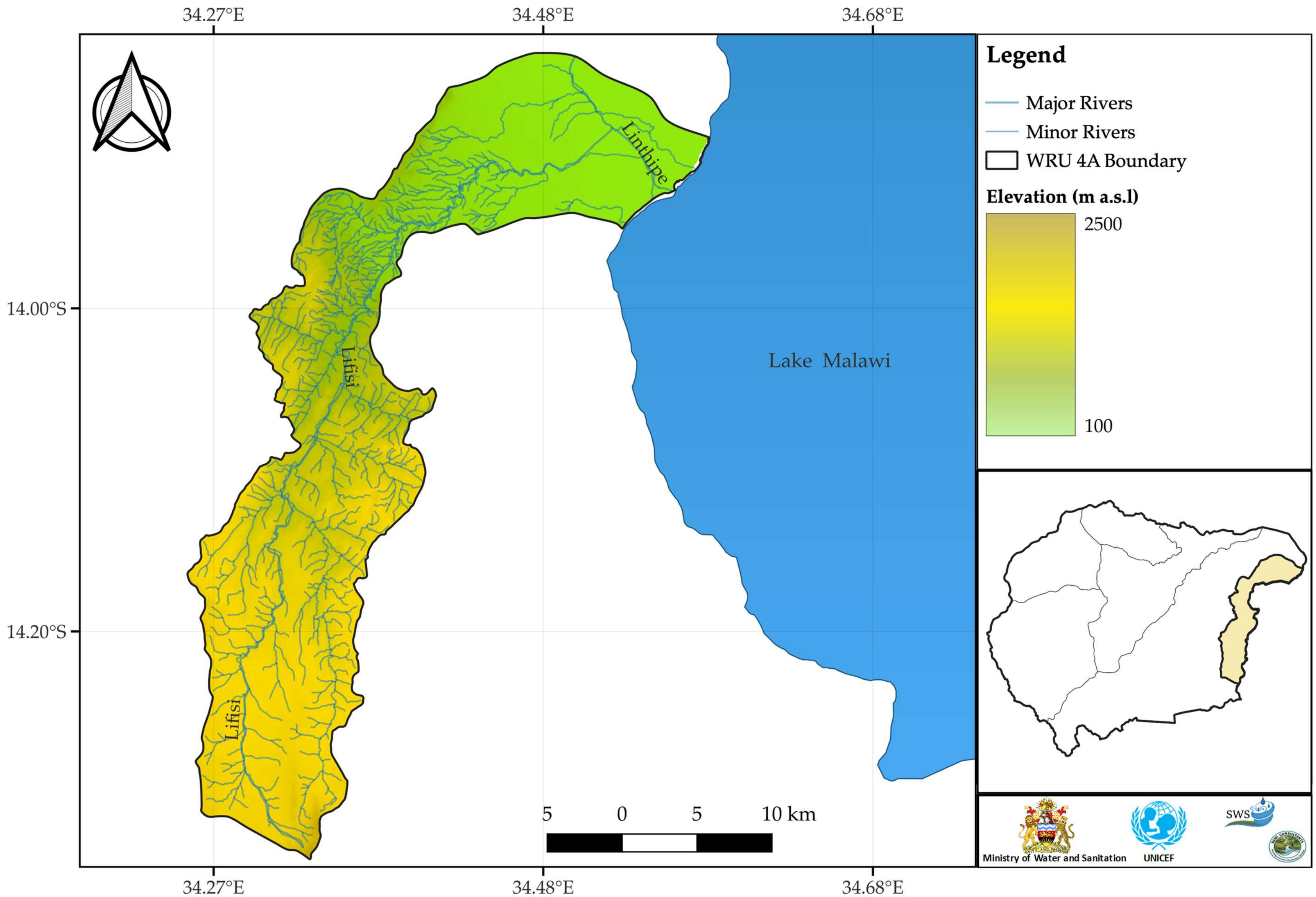

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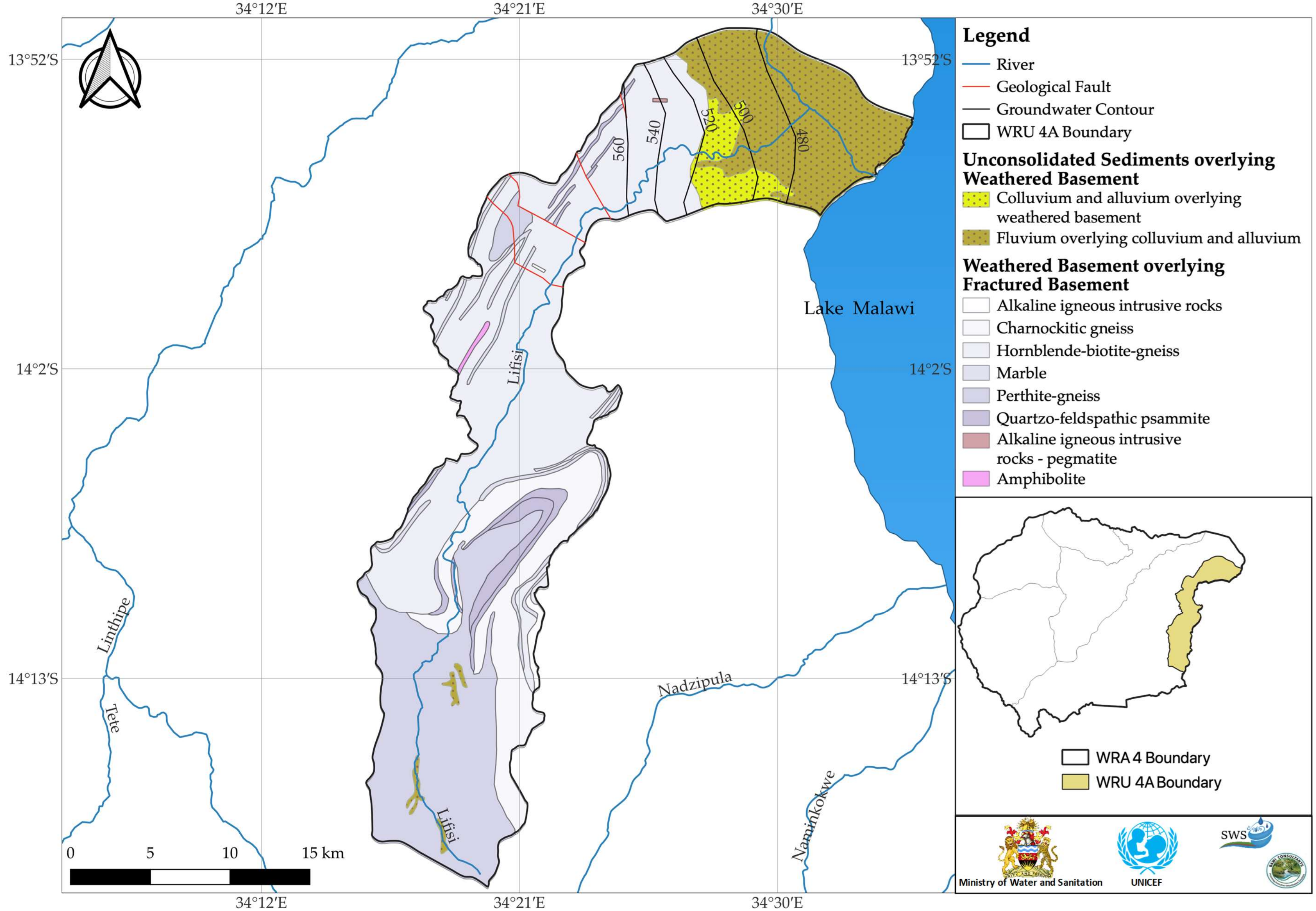

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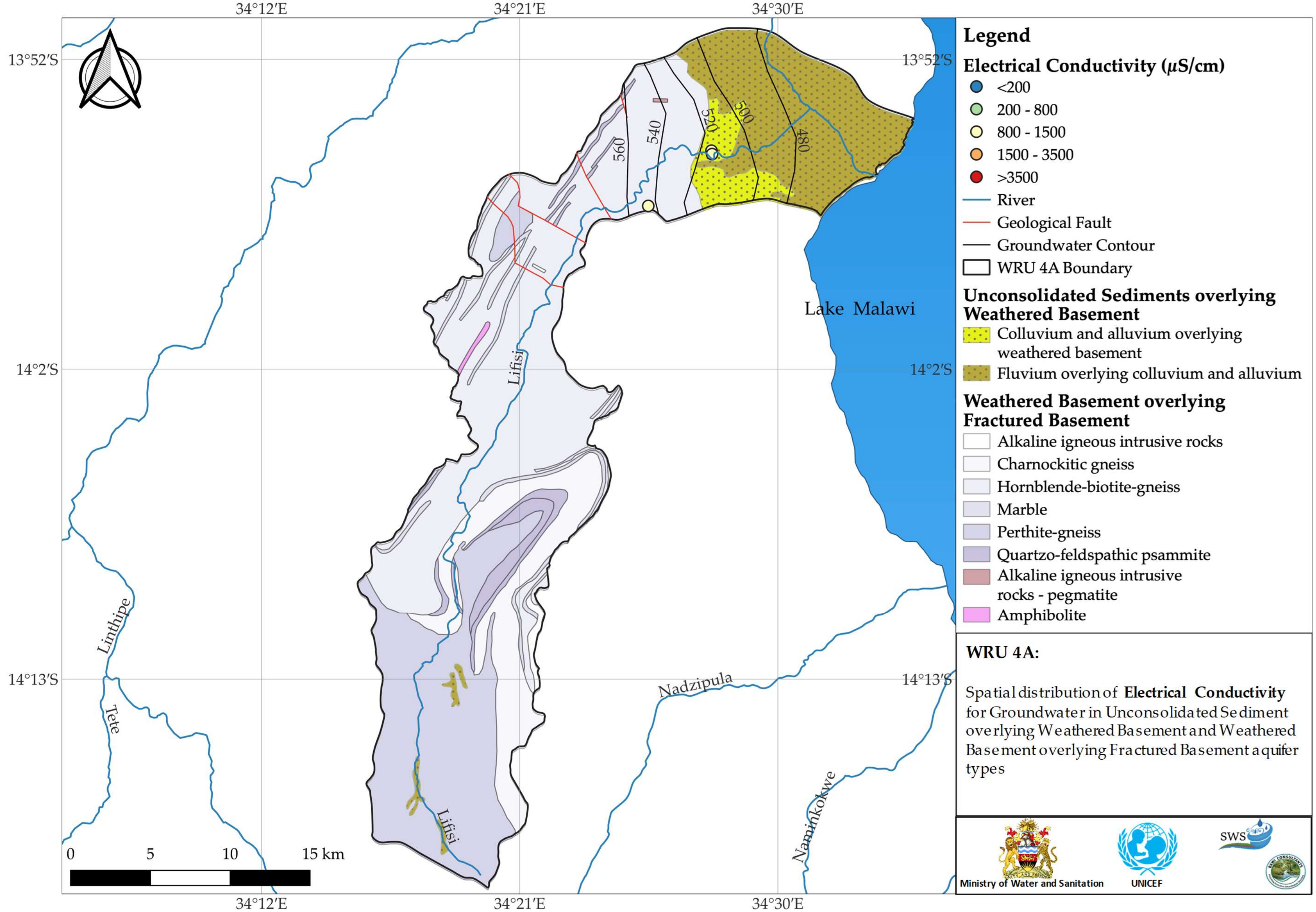
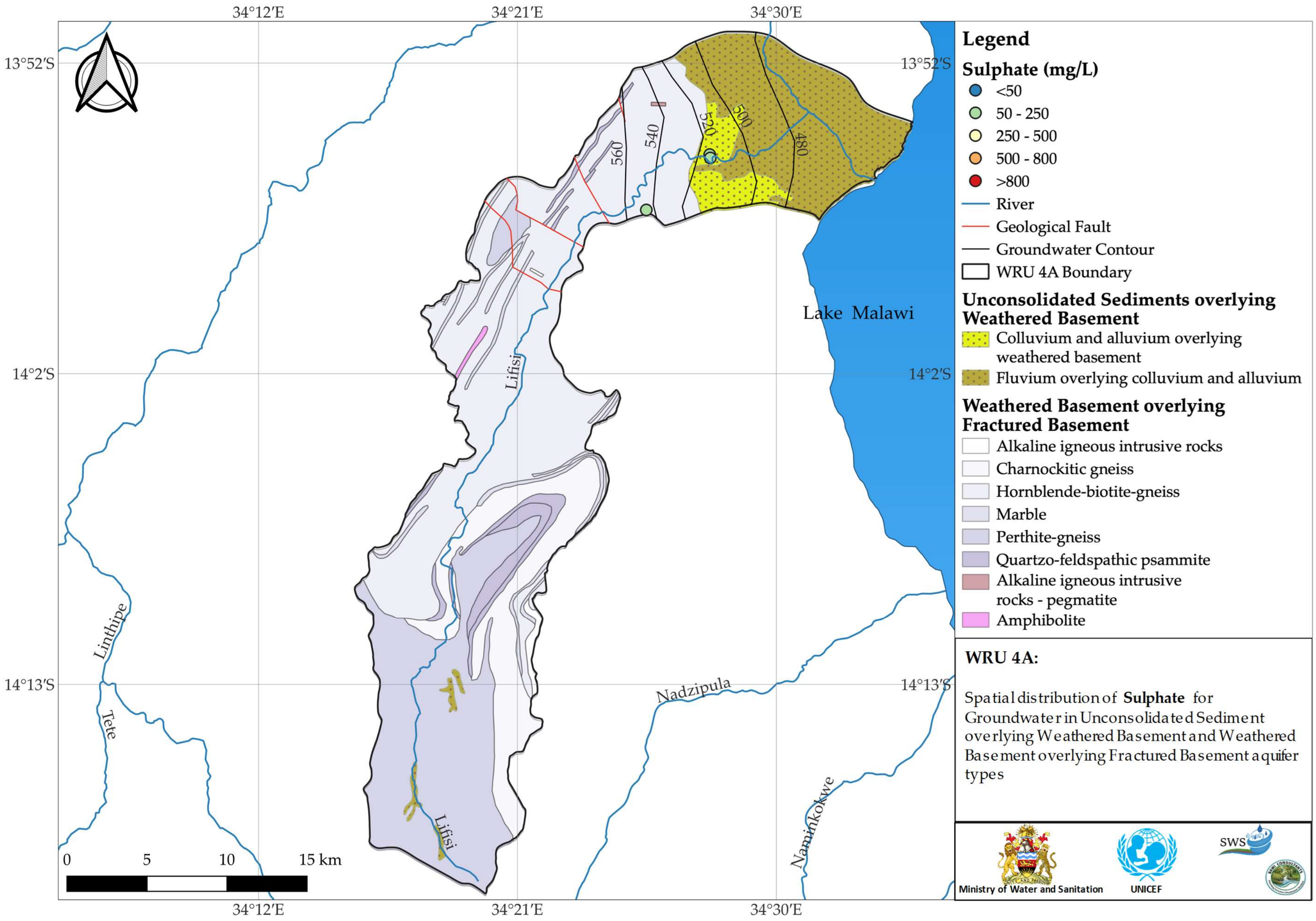


Figure WRU 4A.5 Groundwater Chemistry Distribution Sulphate



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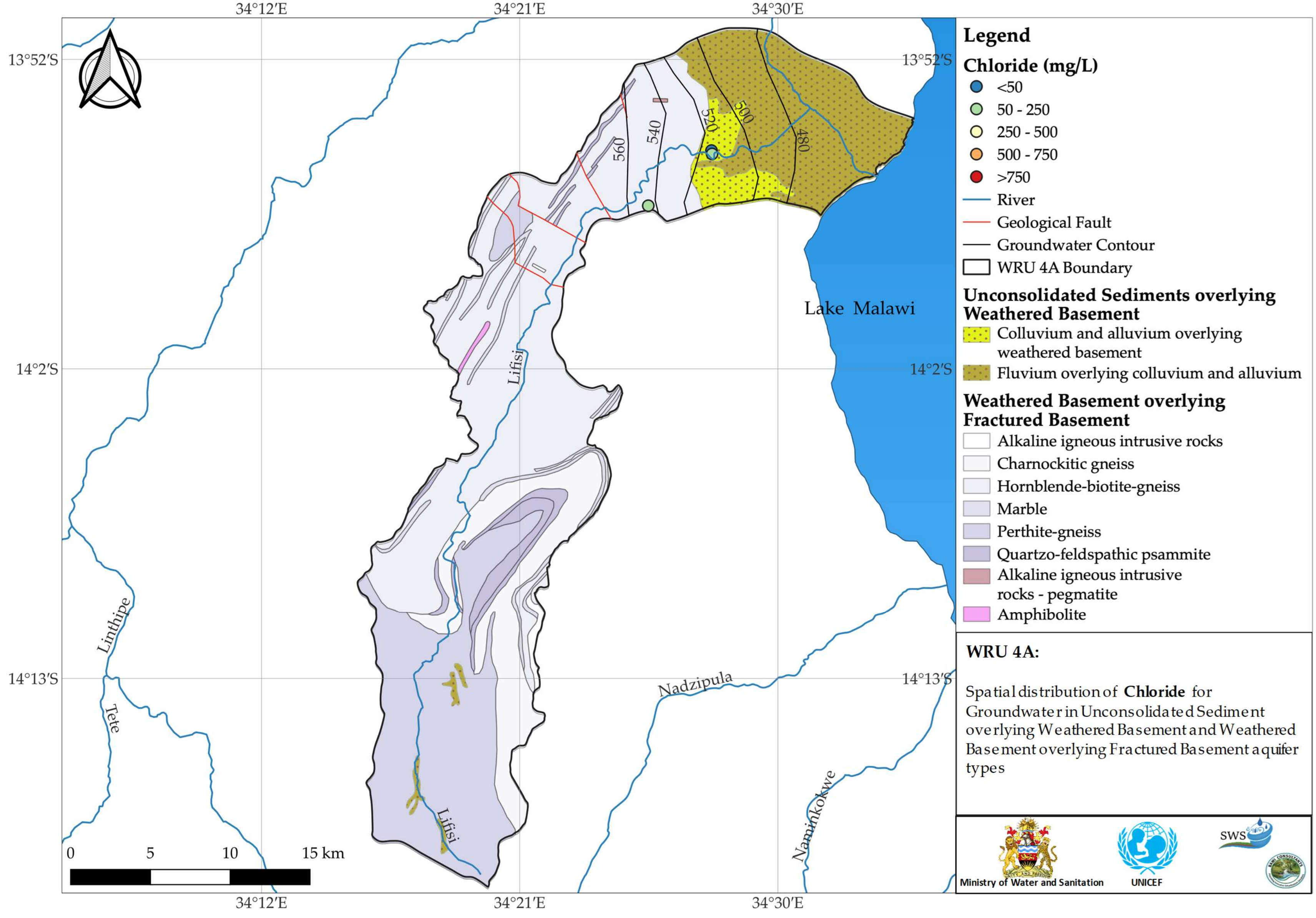

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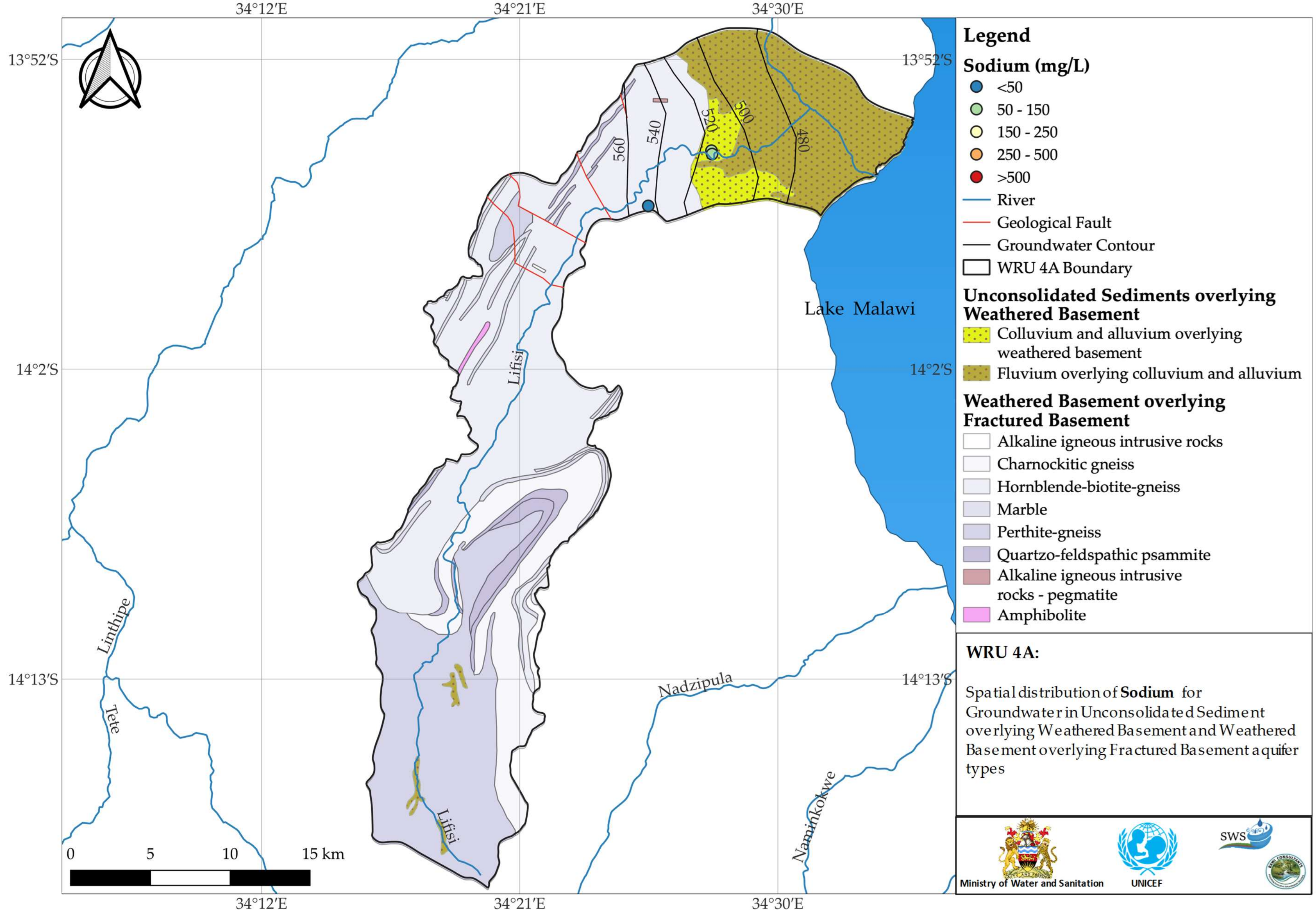

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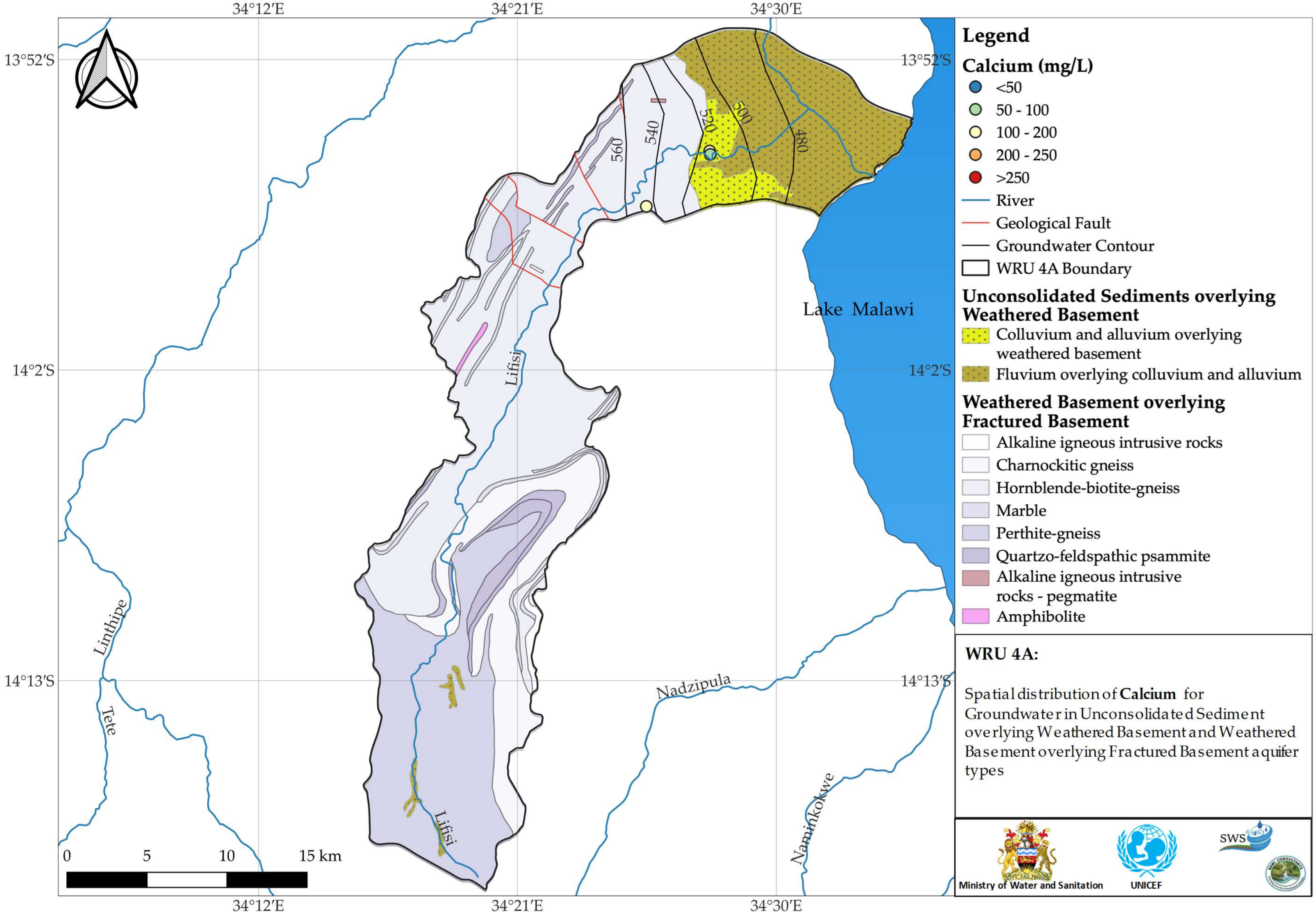


Figure WRU 4A.9 Piper Diagram of water quality results with respect to the major aquifer type

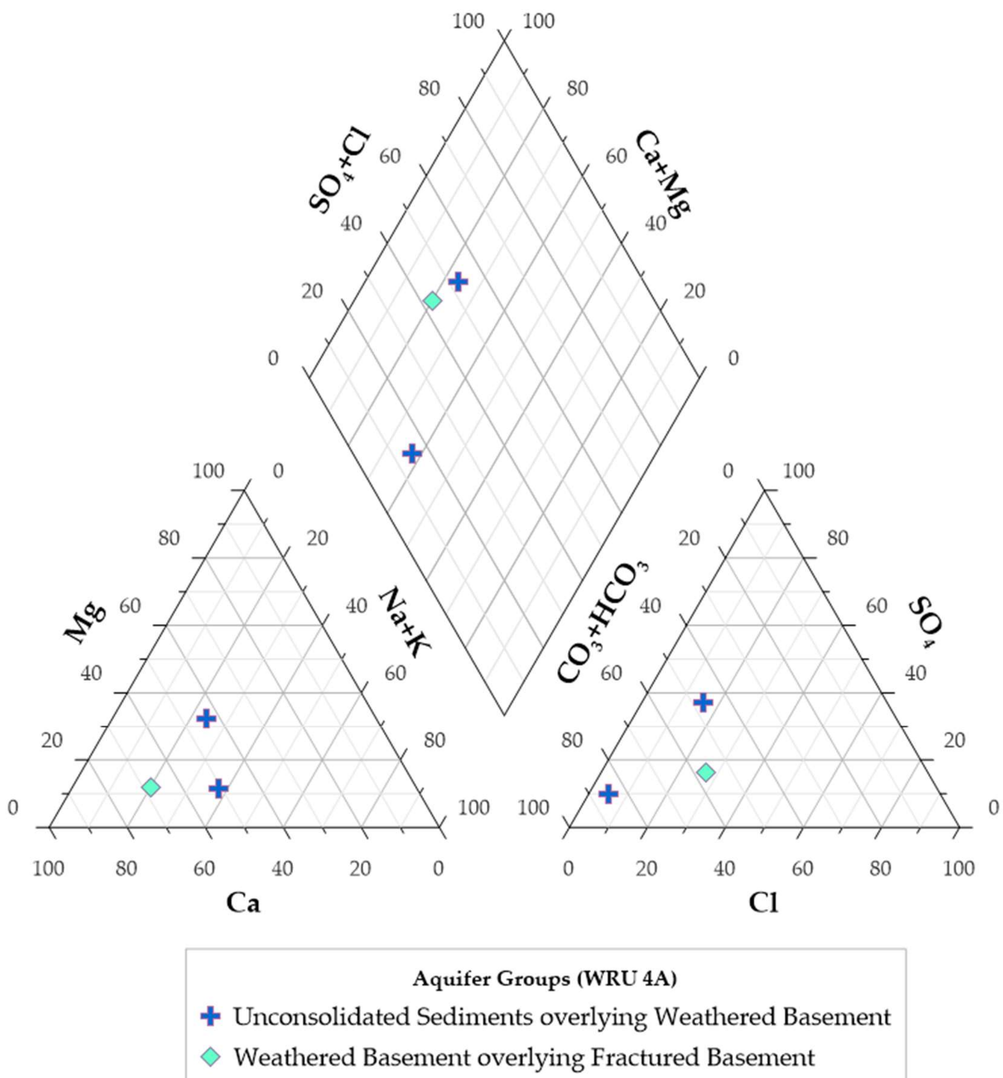
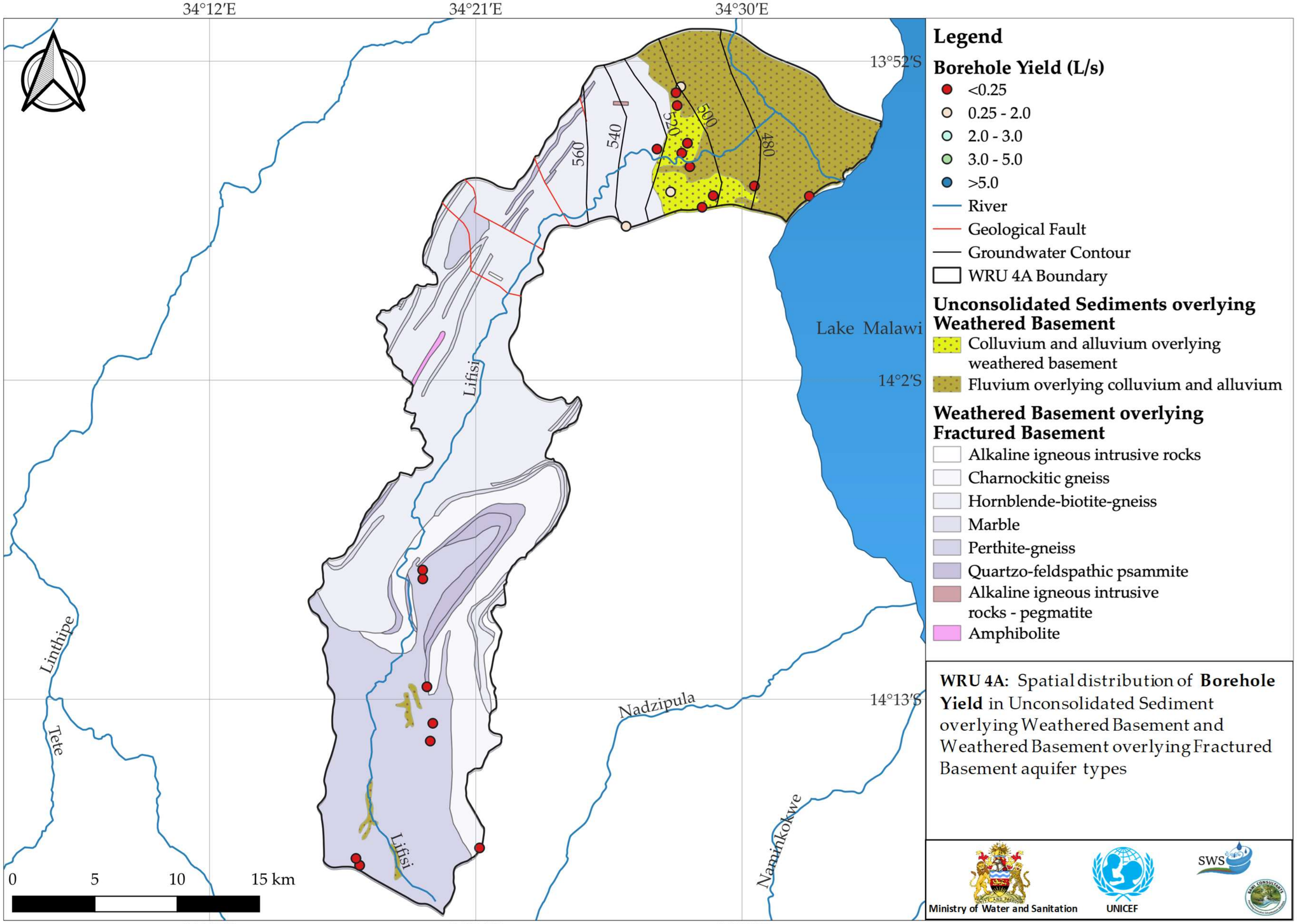


Figure WRU 4A.10 Borehole Yield Map for data held by the Ministry



WRU 4B Figures

Figure WRU 4B.1 Land Use and Major Roads

Figure WRU 4B.2 Rivers and Wetlands

Figure WRU 4B.3 Hydrogeology Units and Water Table

Figure WRU 4B.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 4B.5 Groundwater Chemistry Distribution of Sulphate

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Figure WRU 4B.8 Groundwater Chemistry Distribution Calcium

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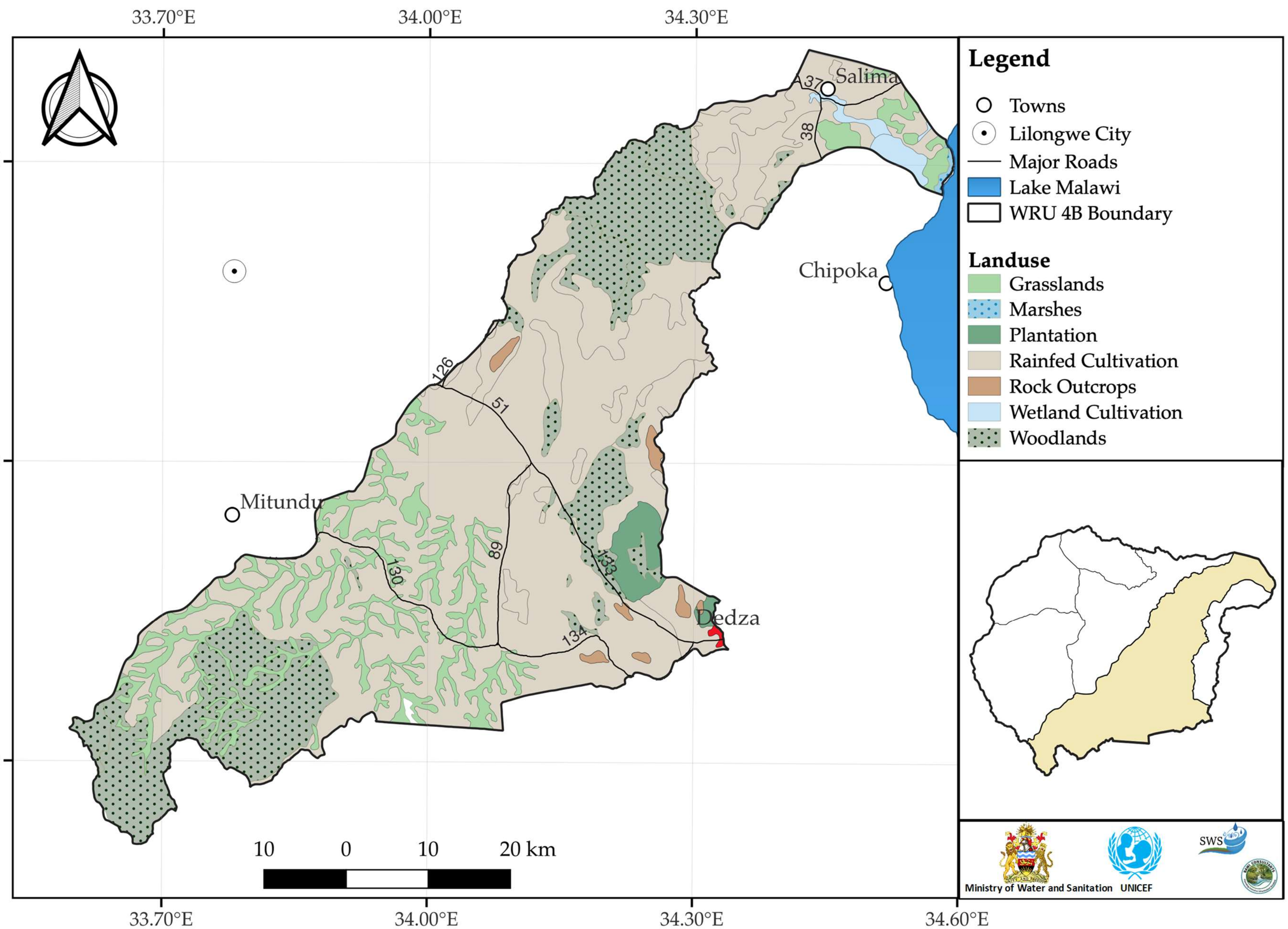


Figure WRU 4B.2 Rivers and Wetlands

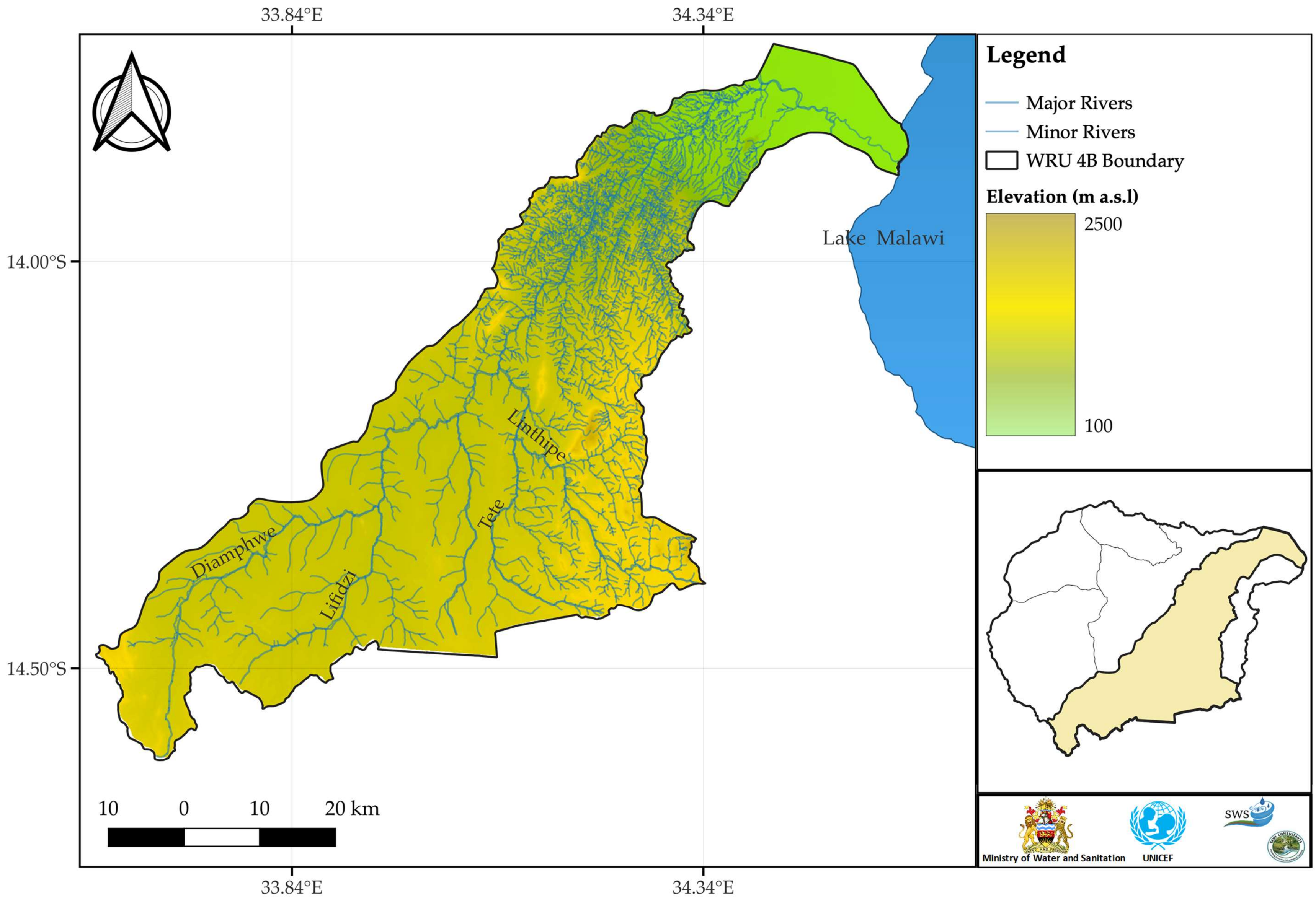


Figure WRU 4B.3 Hydrogeology Units and Water Table

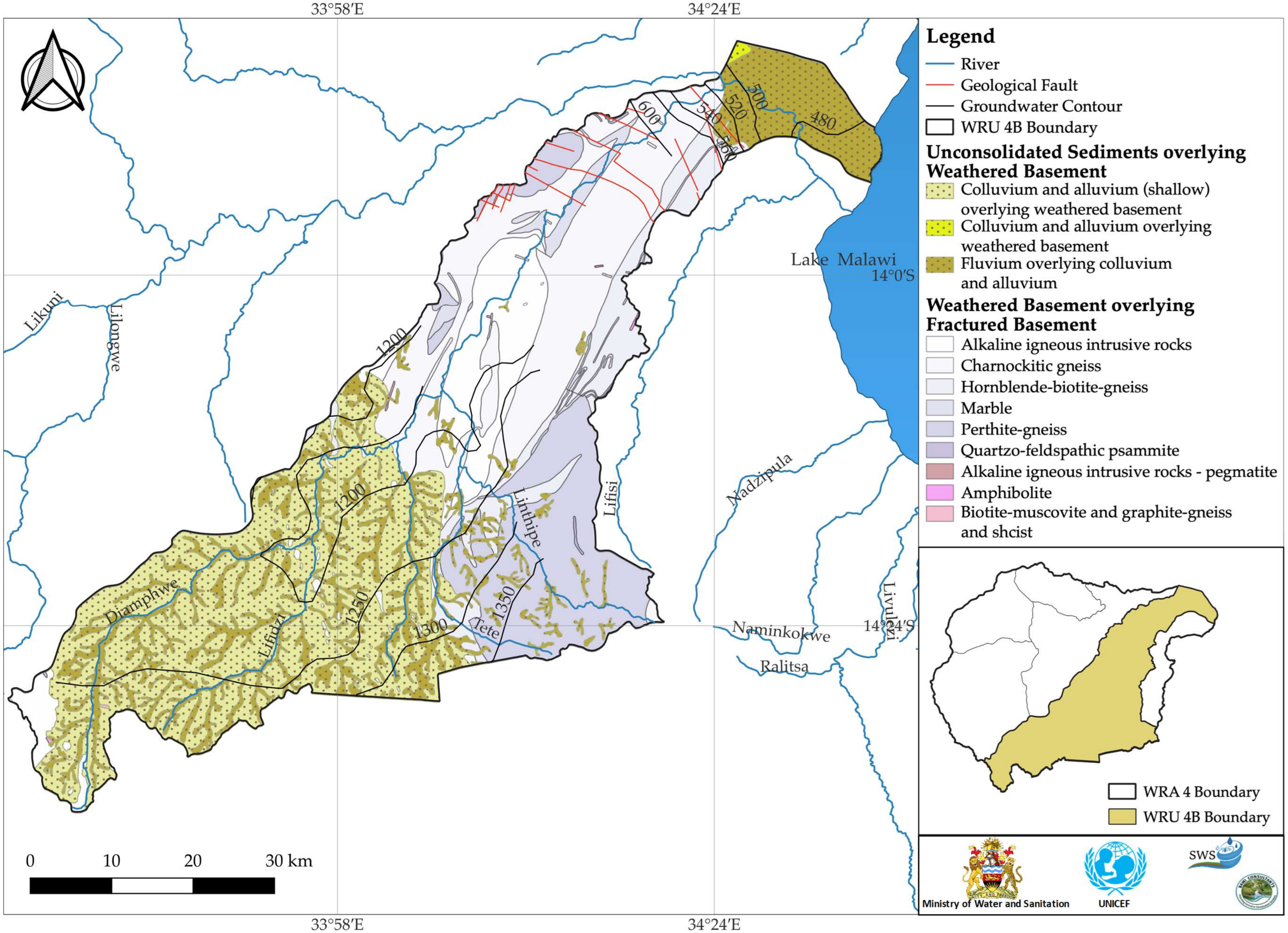


Figure WRU 4B.4 Groundwater Chemistry Distribution Electrical Conductivity

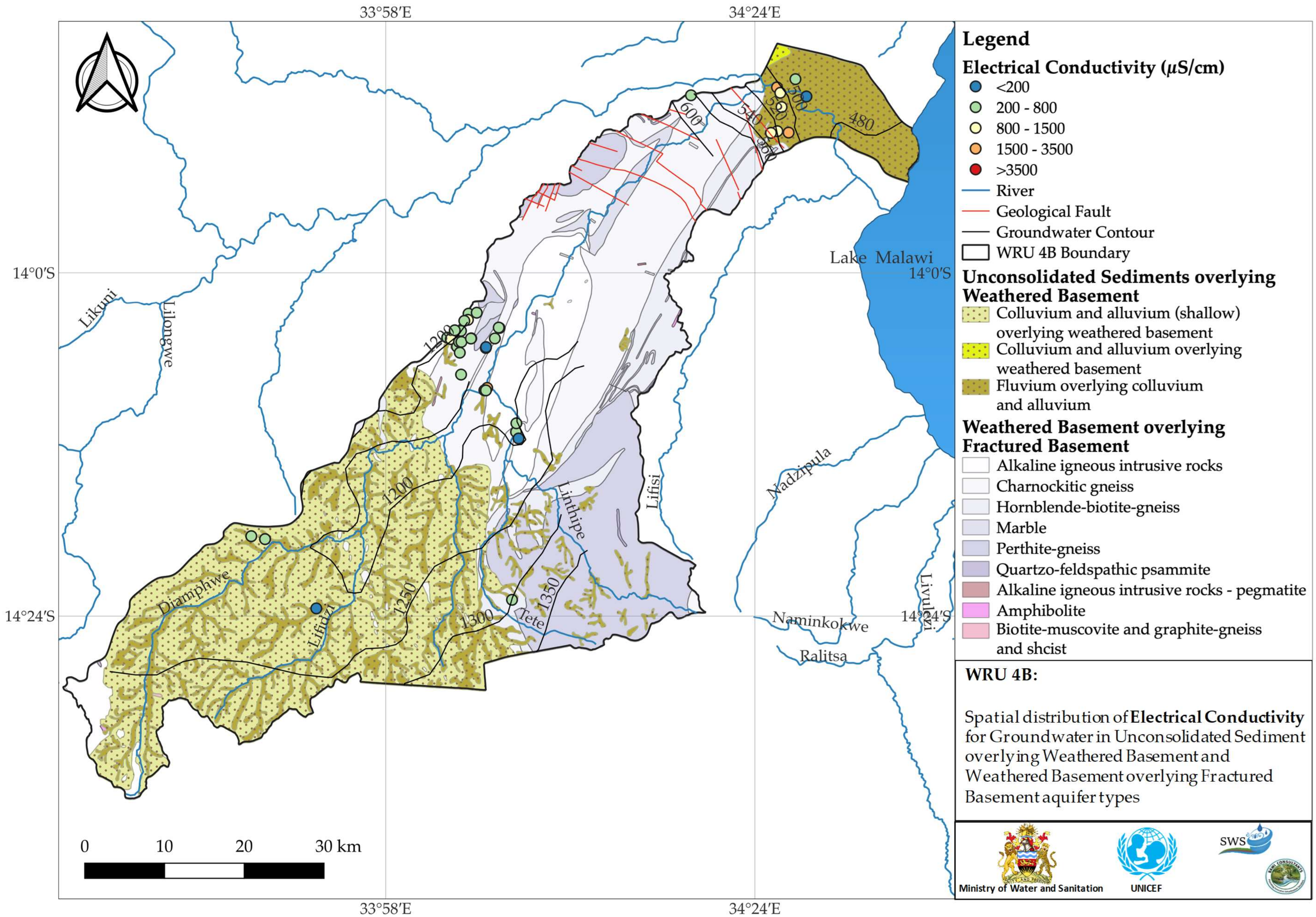


Figure WRU 4B.5 Groundwater Chemistry Distribution of Sulphate

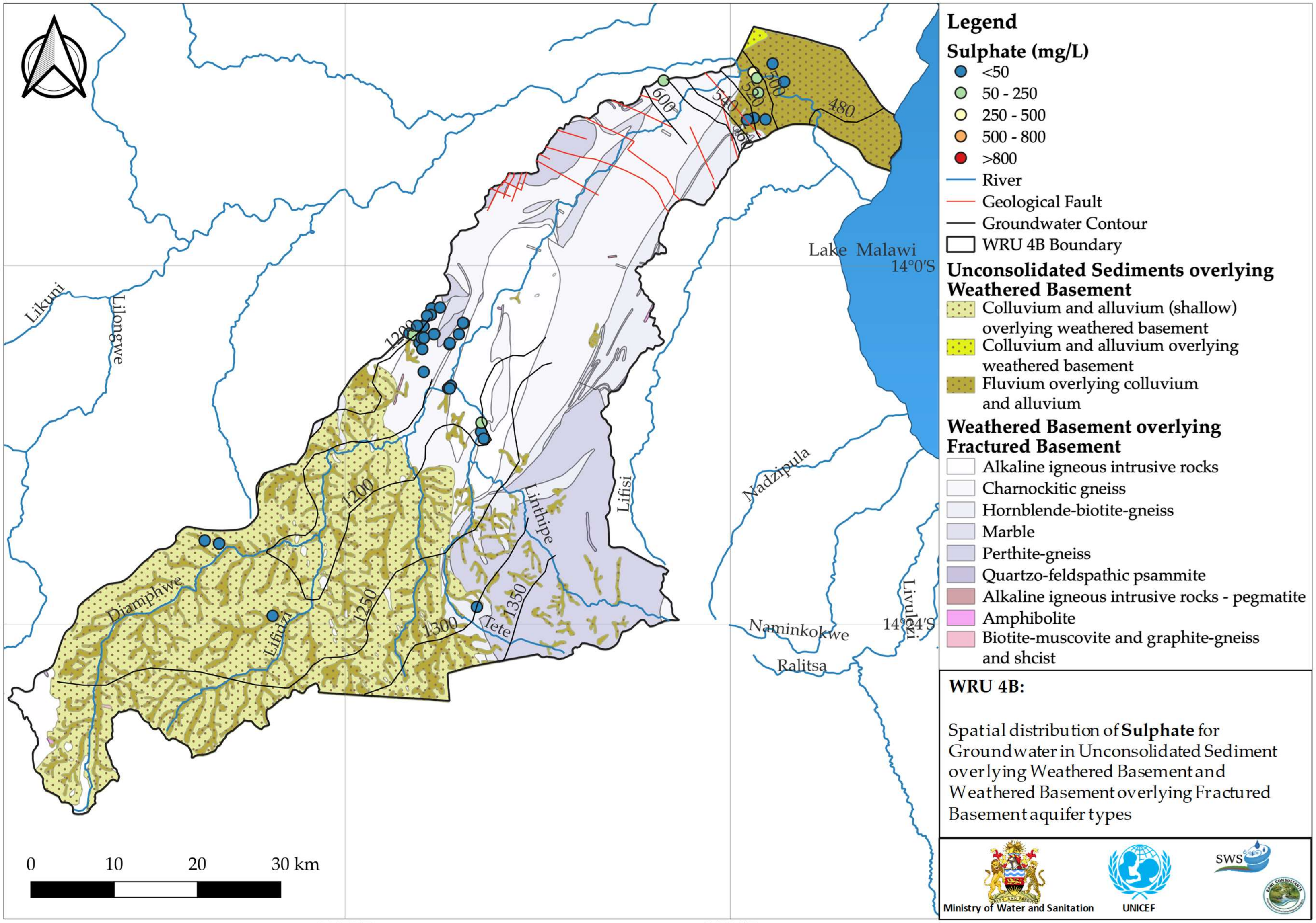
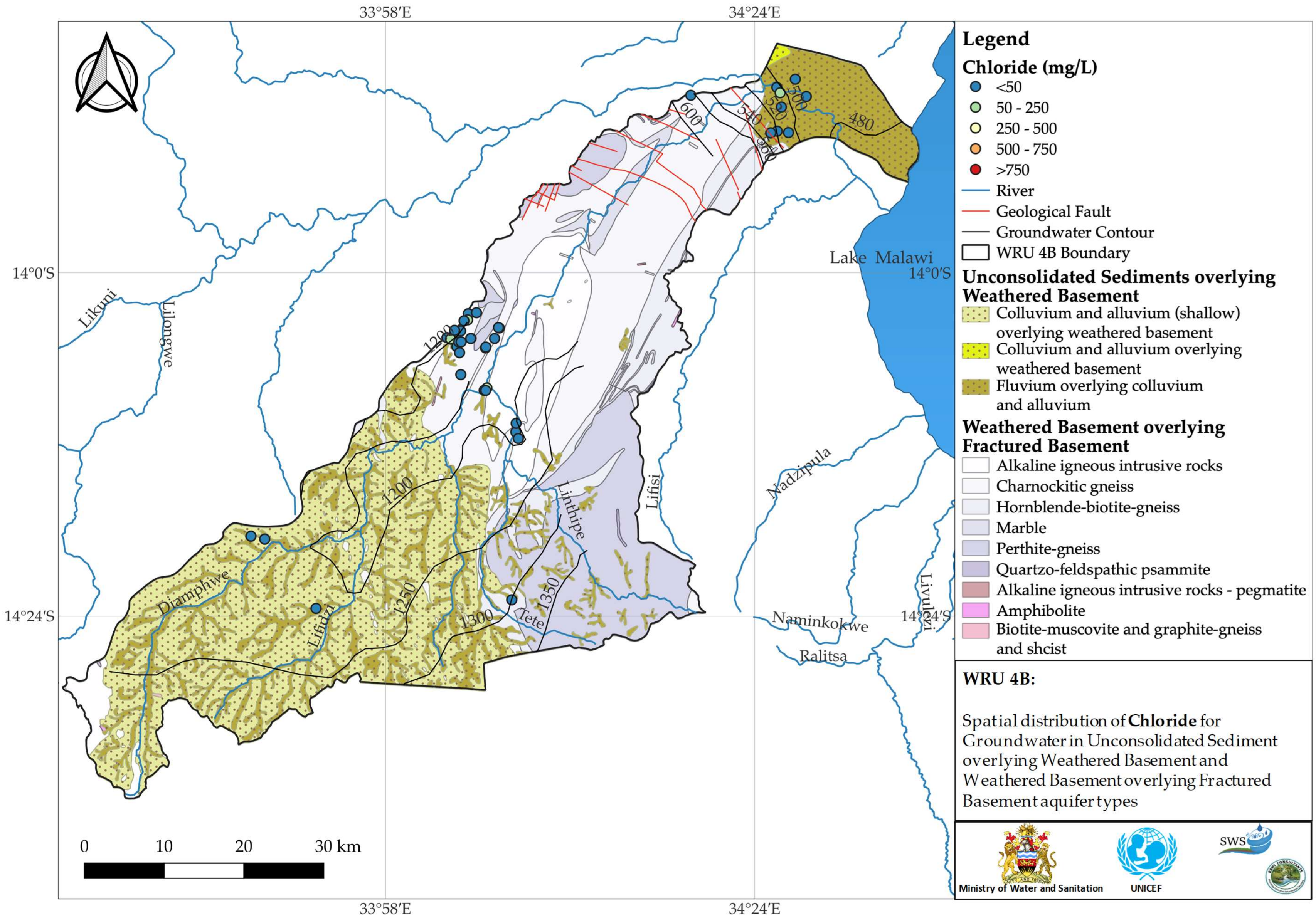


Figure WRU 4B.6 Groundwater Chemistry Distribution Chloride



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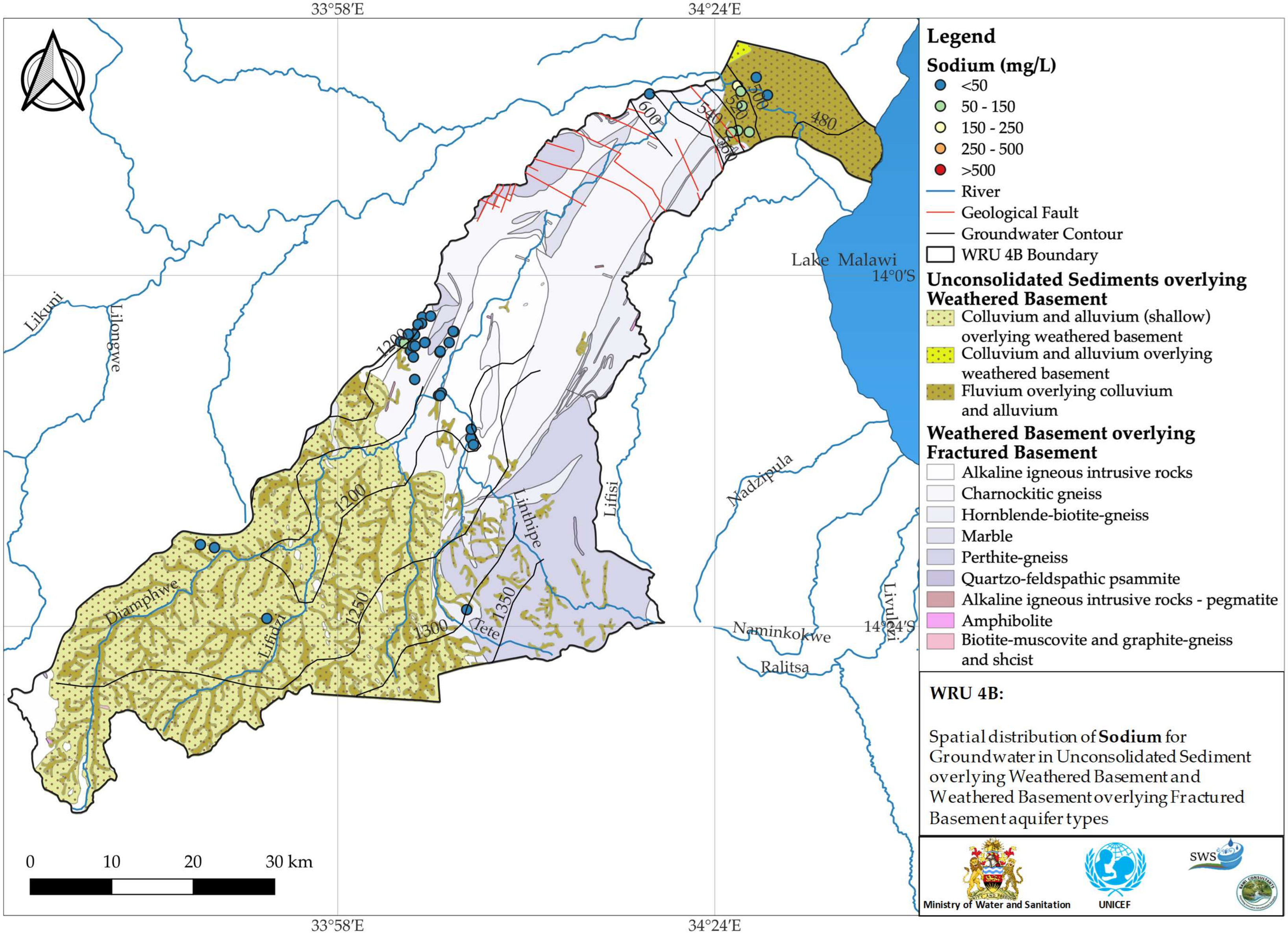


Figure WRU 4B.8 Groundwater Chemistry Distribution Calcium

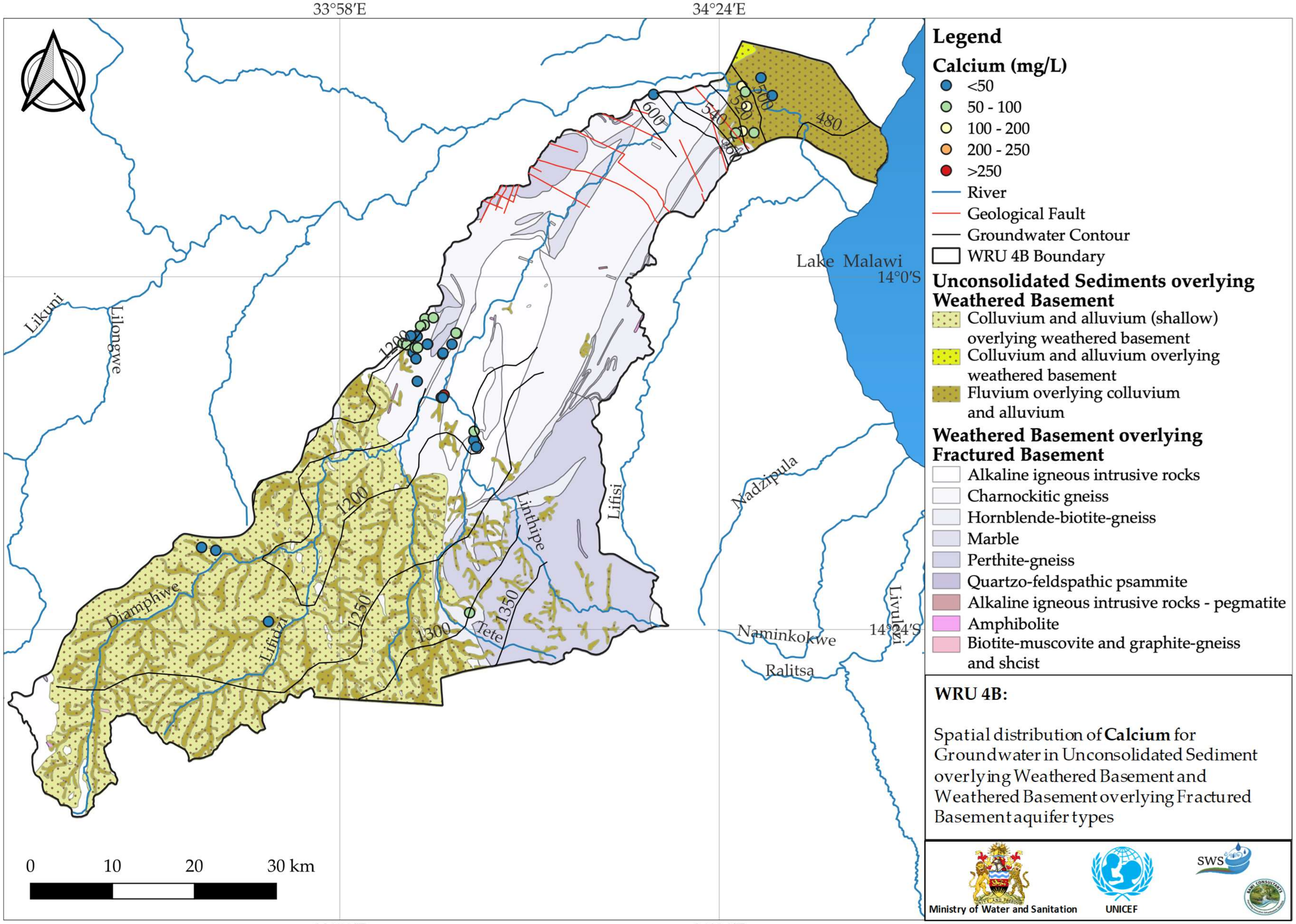


Figure WRU 4B.9 Piper Diagram of water quality results with respect to the major aquifer type

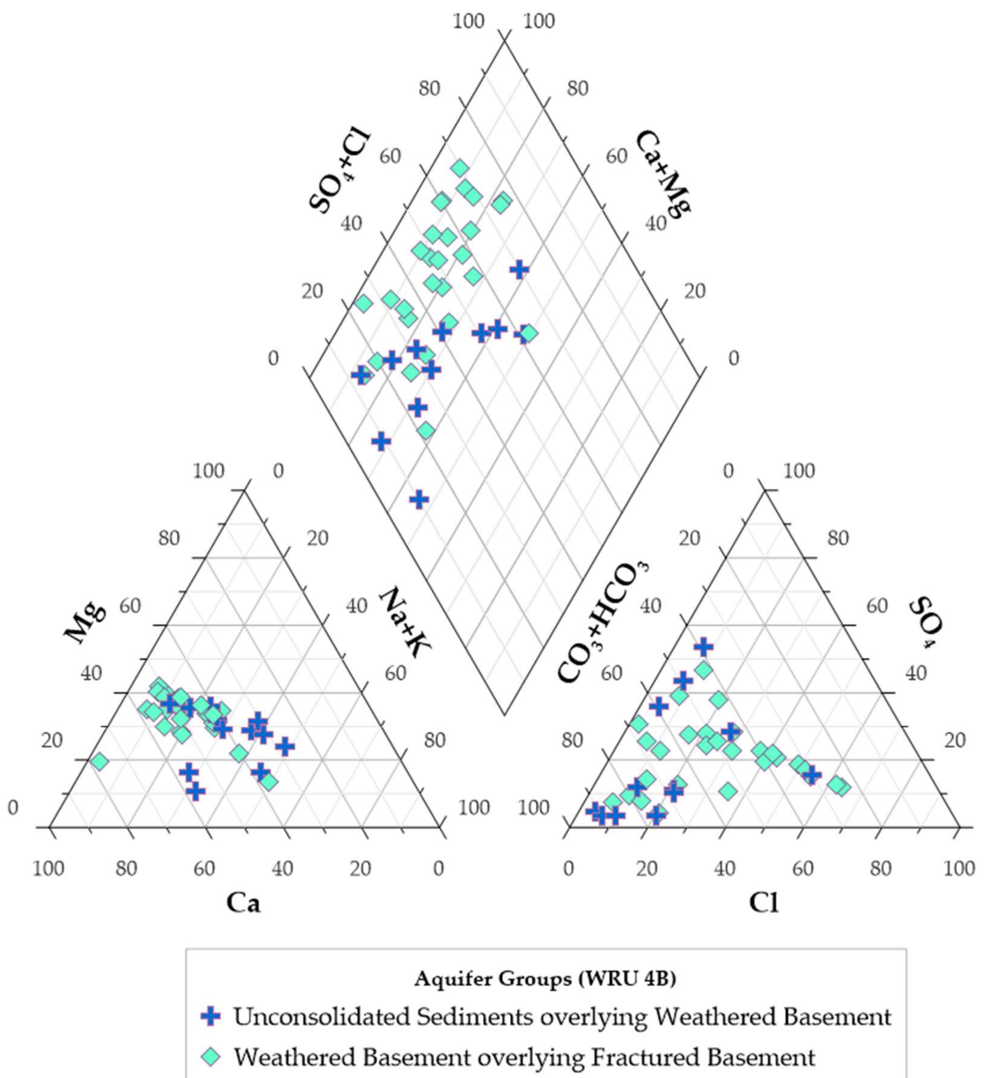
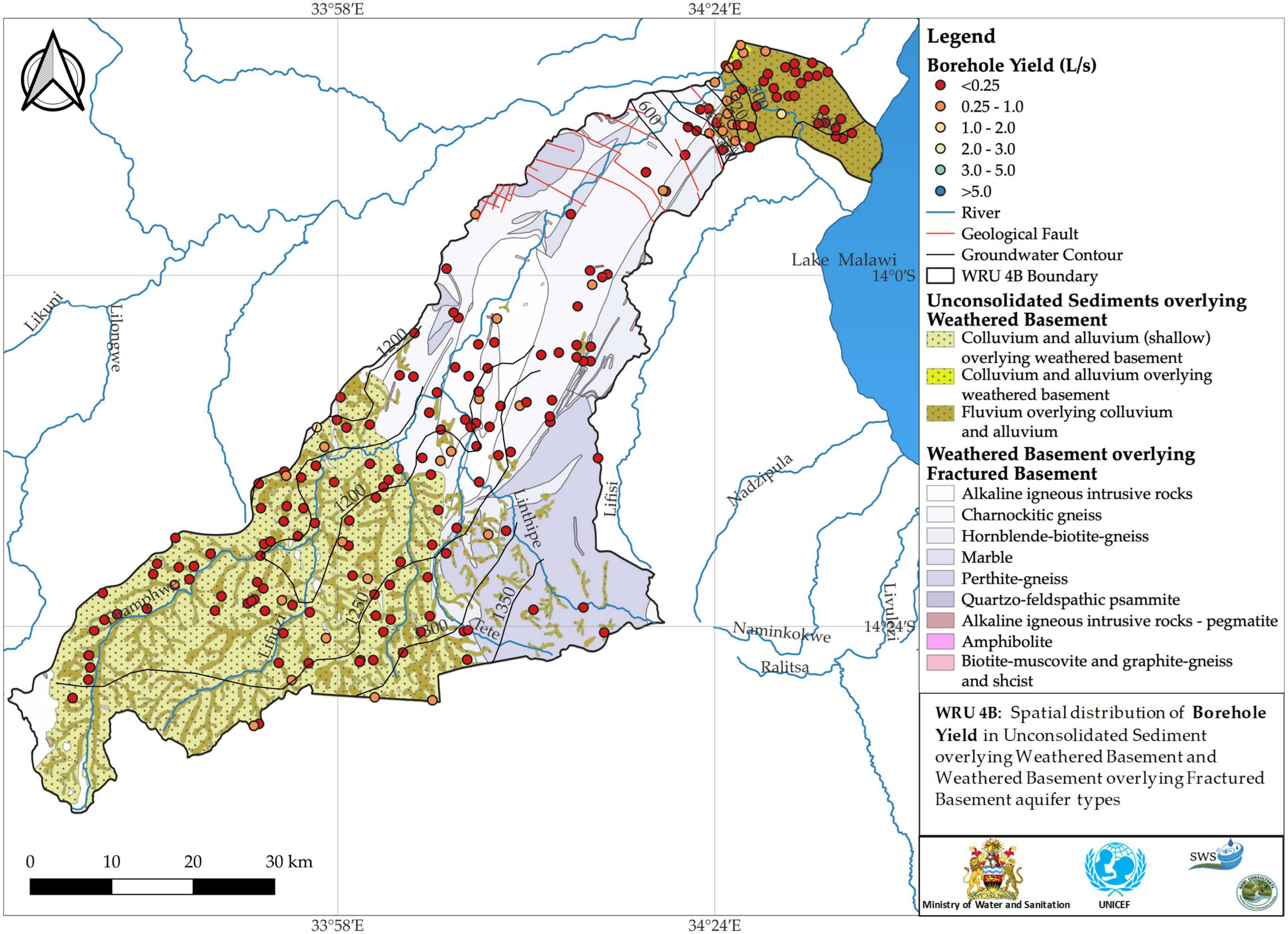


Figure WRU 4B.10 Borehole Yield Map for data held by the Ministry



WRU 4C Figures

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Figure WRU 4C.2 Rivers and Wetlands

Figure WRU 4C.3 Hydrogeology Units and Water Table

Figure WRU 4C.4 Groundwater Chemistry Distribution Electrical Conductivity

Figure WRU 4C.5 Groundwater Chemistry Distribution of Sulphate

Figure WRU 4C.6 Groundwater Chemistry Distribution Chloride

Figure WRU 4C.7 Groundwater Chemistry Distribution Sodium

Figure WRU 4C.8 Groundwater Chemistry Distribution Calcium

Figure WRU 4C.9 Piper Diagram of water quality results with respect to the major aquifer type

Figure WRU 4C.10 Borehole Yield Map for data held by the Ministry

Figure WRU 4C.1 Land Use and Major Roads

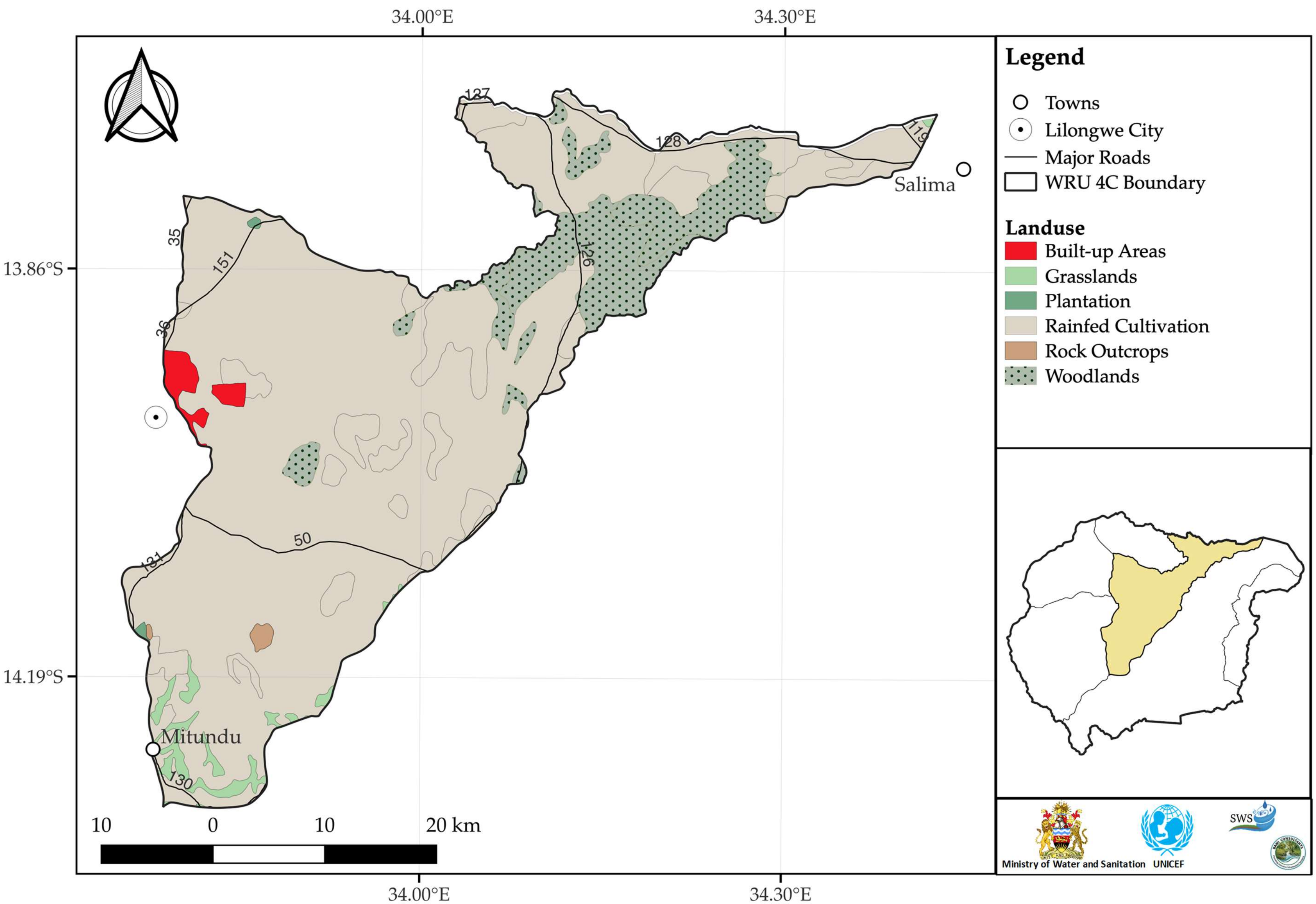


Figure WRU 4C.2 Rivers and Wetlands

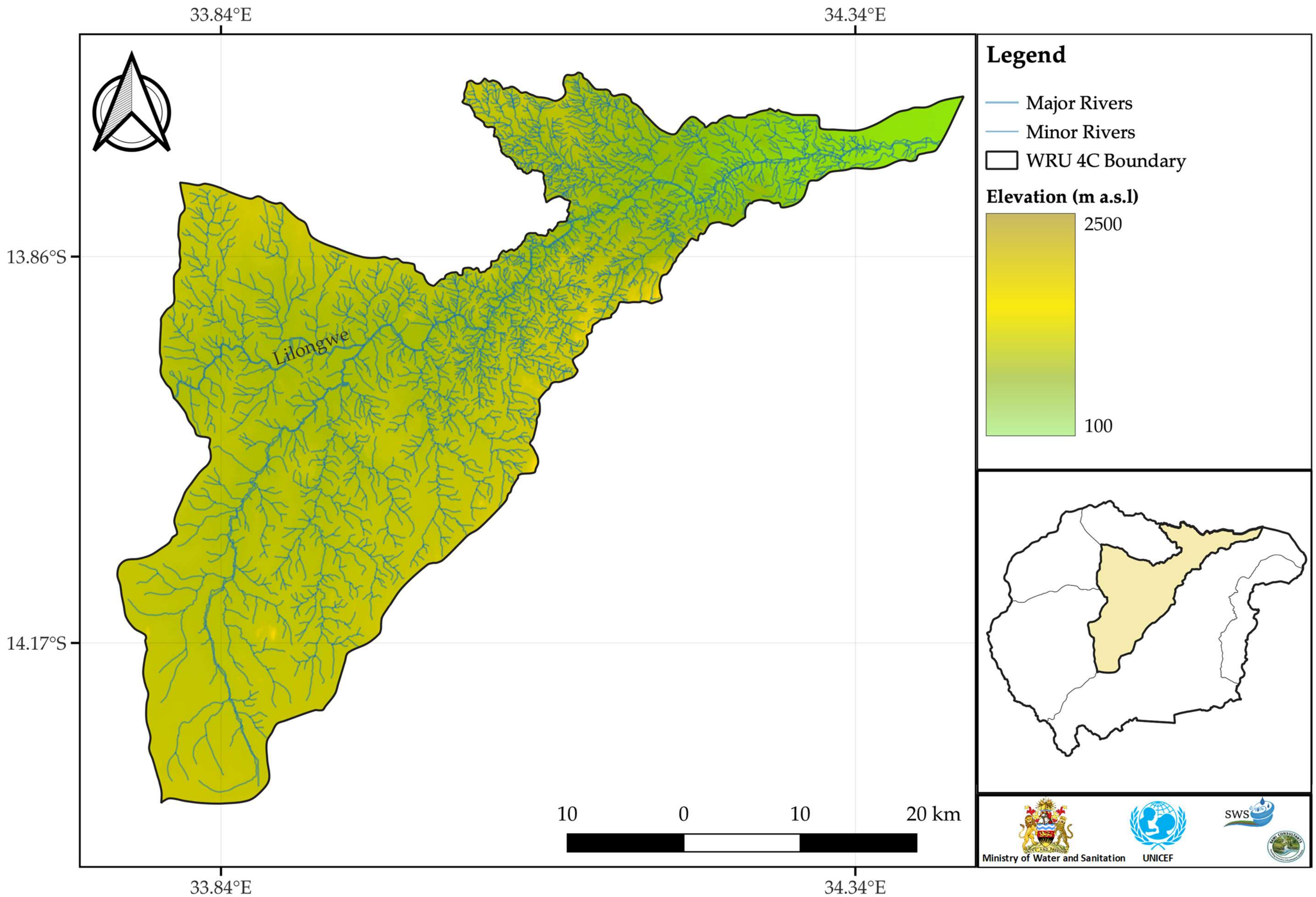


Figure WRU 4C.3 Hydrogeology Units and Water Table

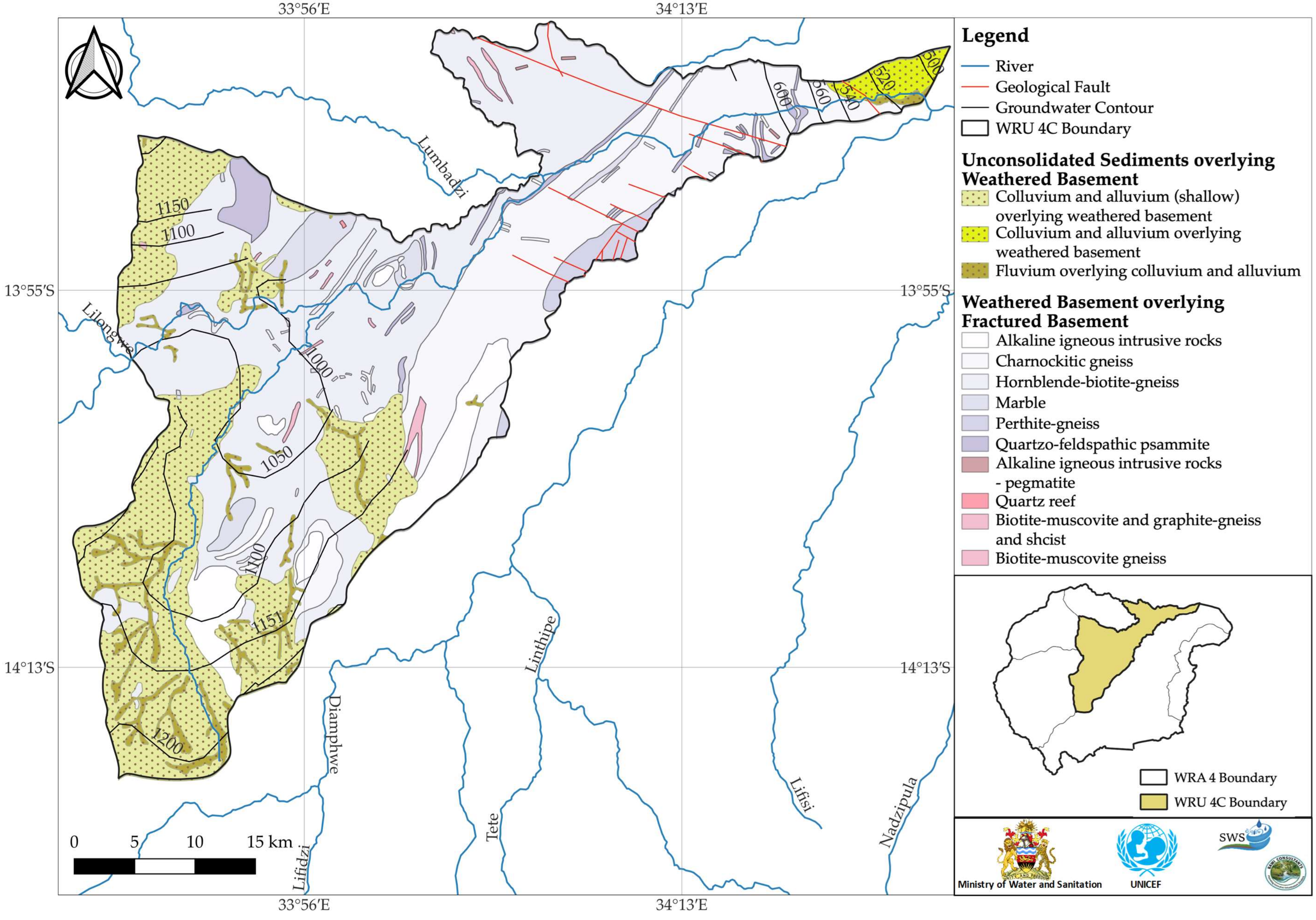


Figure WRU 4C.4 Groundwater Chemistry Distribution Electrical Conductivity

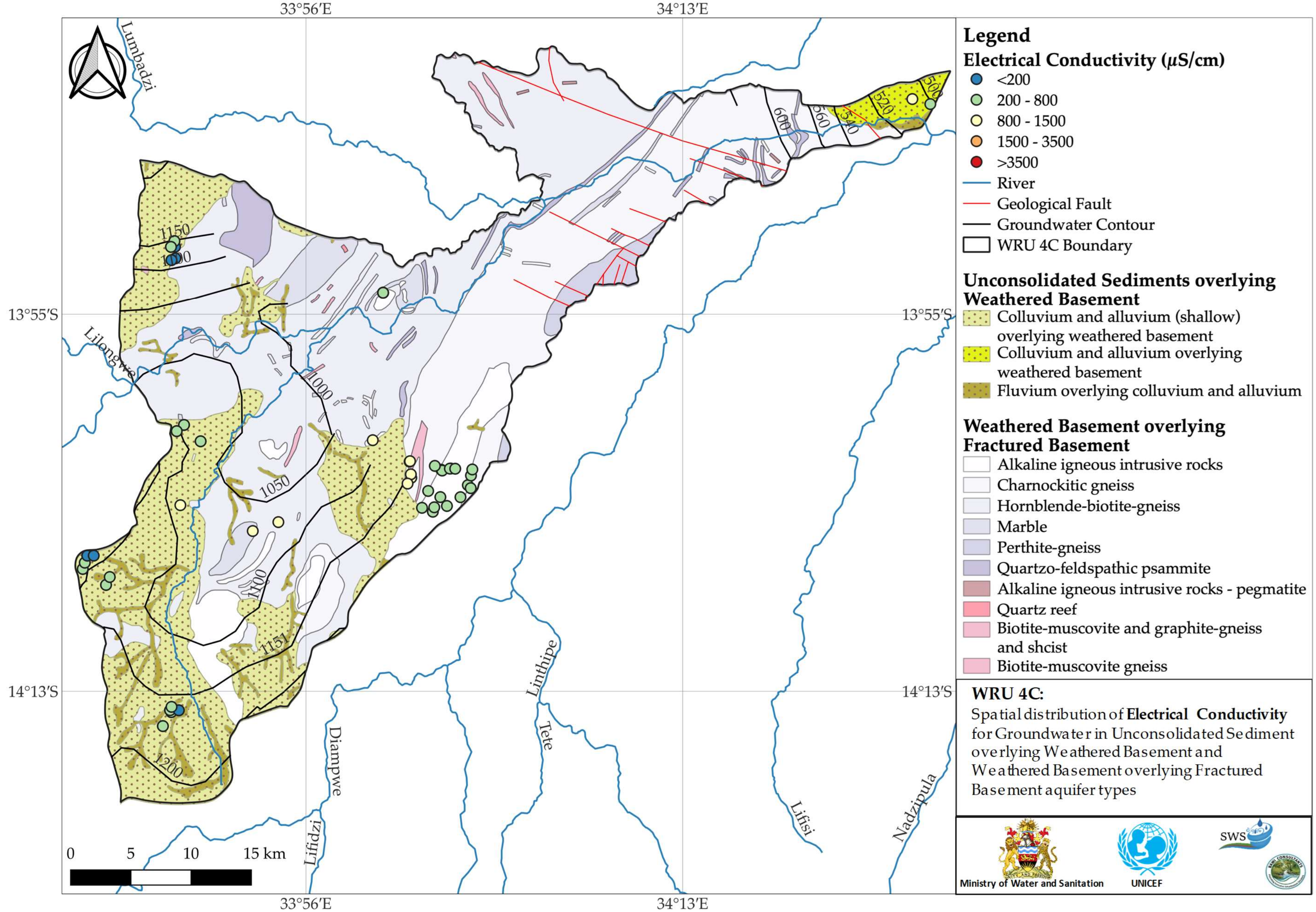


Figure WRU 4C.5 Groundwater Chemistry Distribution of Sulphate

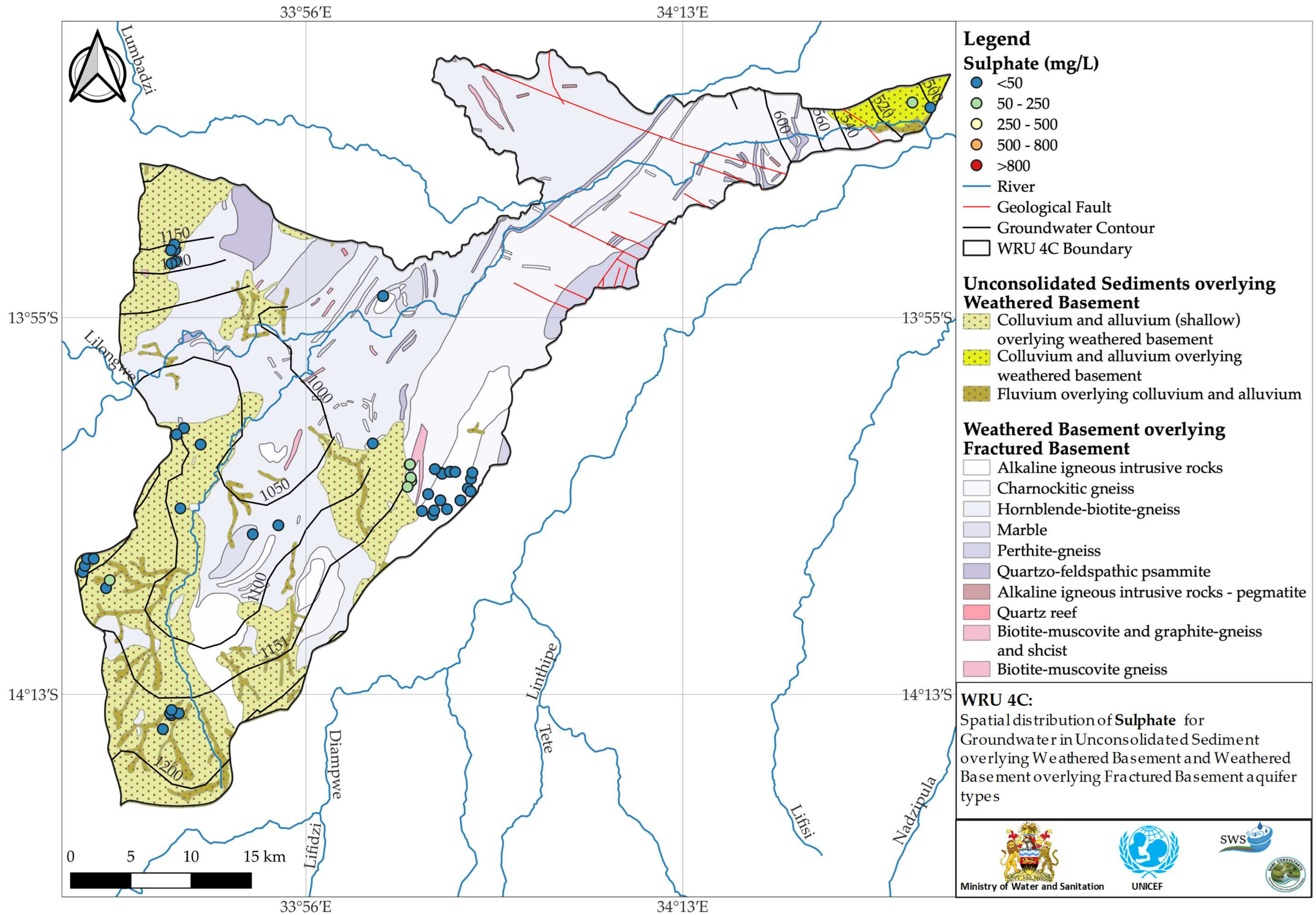


Figure WRU 4C.6 Groundwater Chemistry Distribution Chloride

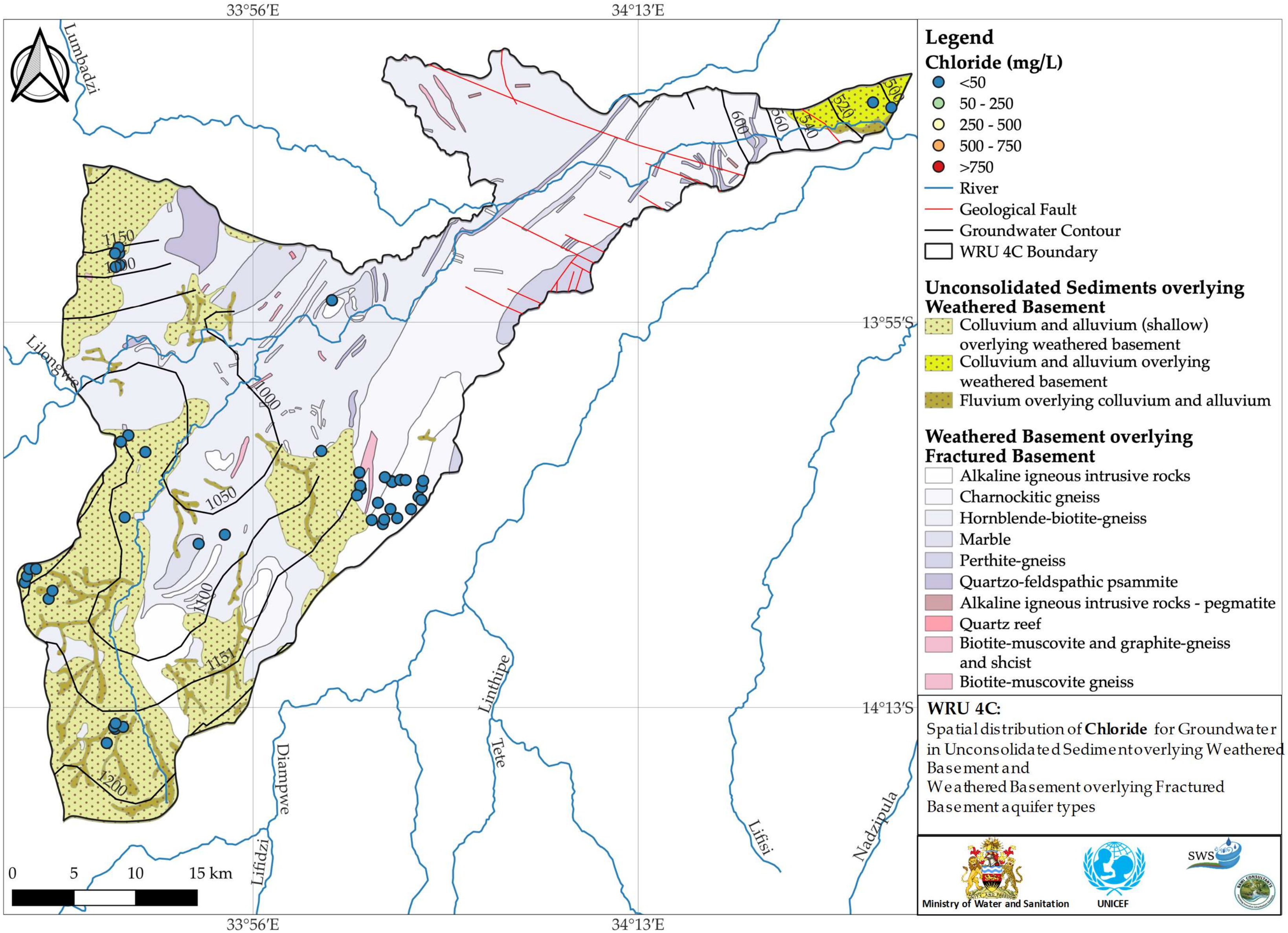


Figure WRU 4C.7 Groundwater Chemistry Distribution Sodium

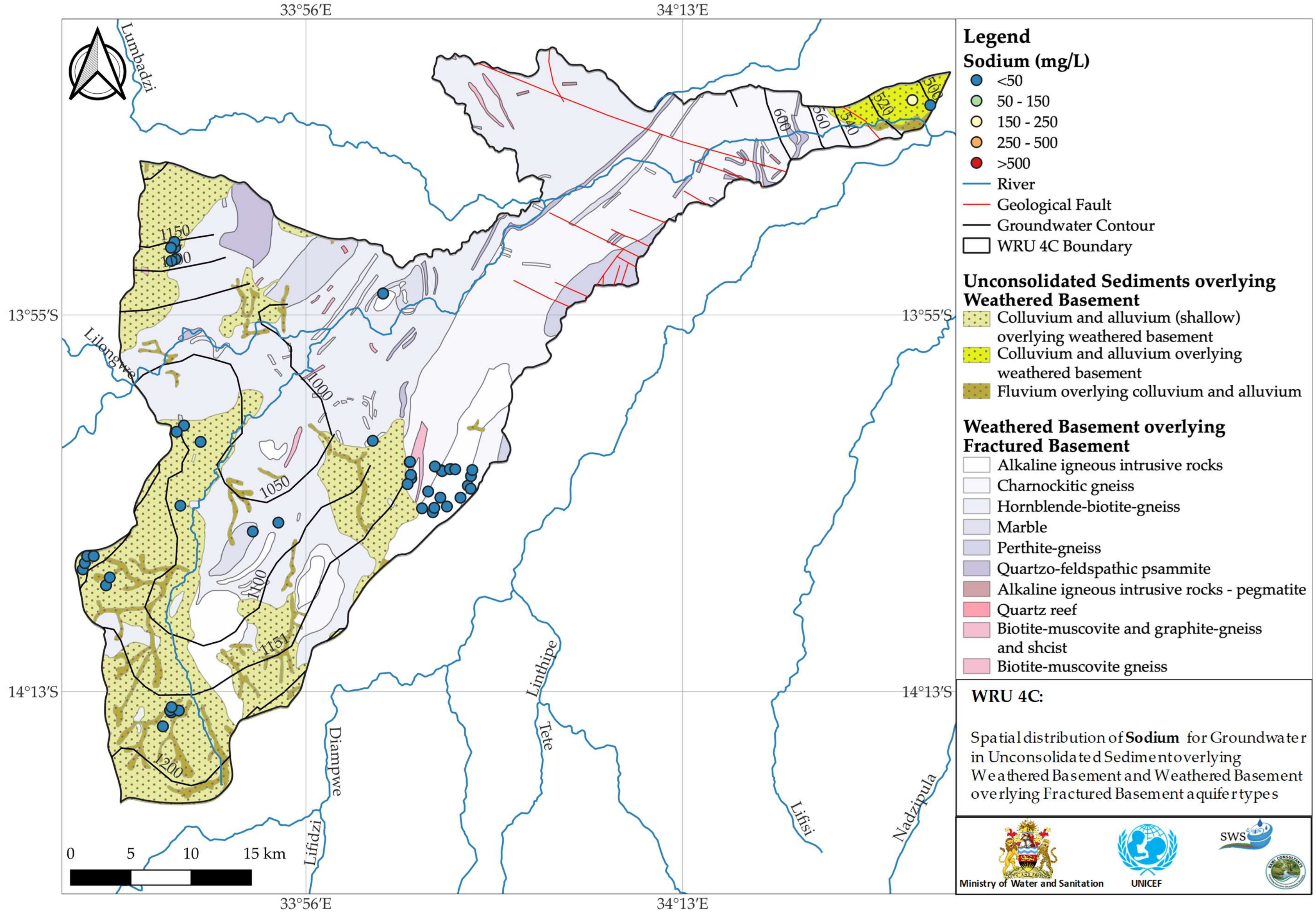


Figure WRU 4C.8 Groundwater Chemistry Distribution Calcium

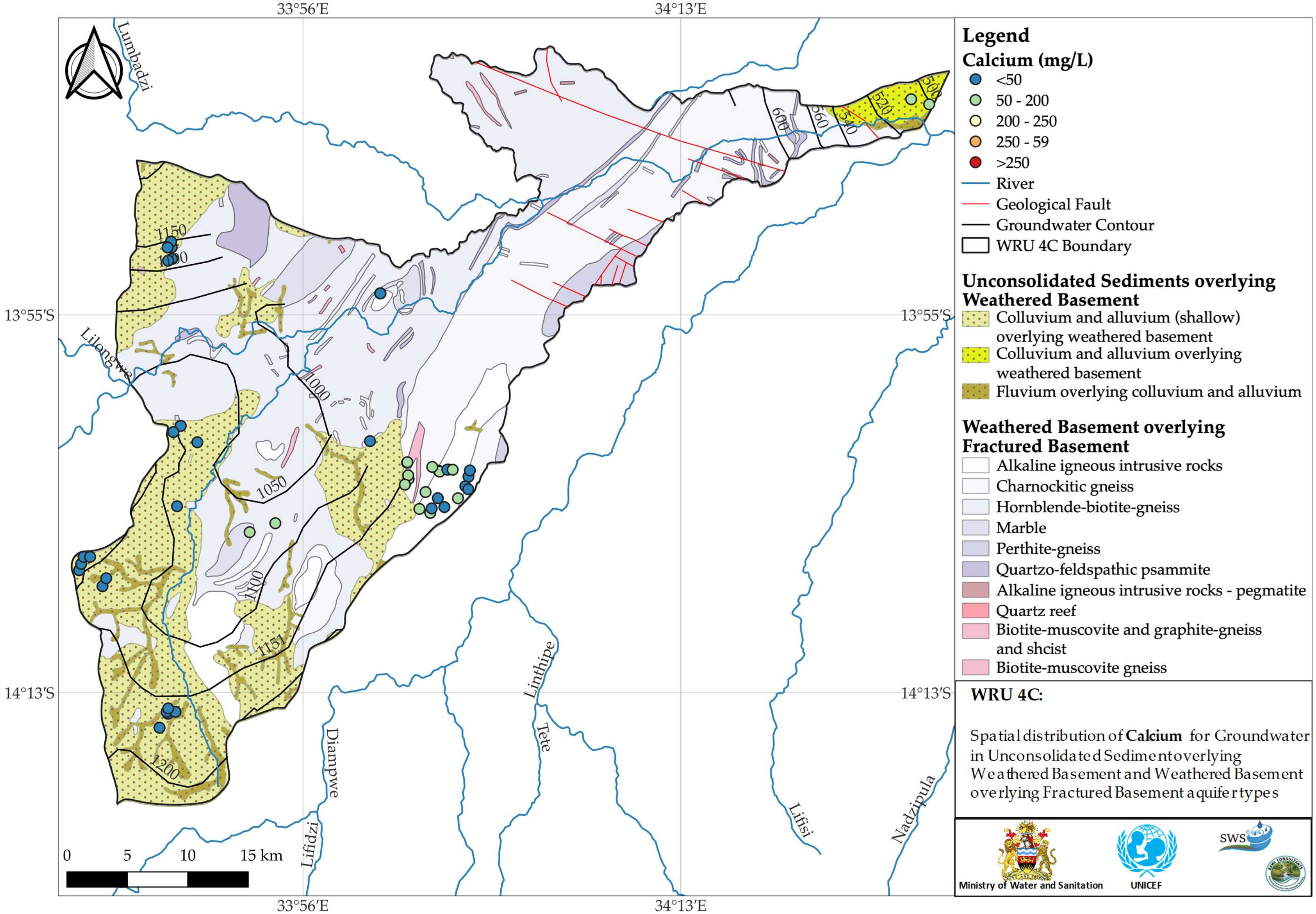


Figure WRU 4C.9 Piper Diagram of water quality results with respect to the major aquifer type

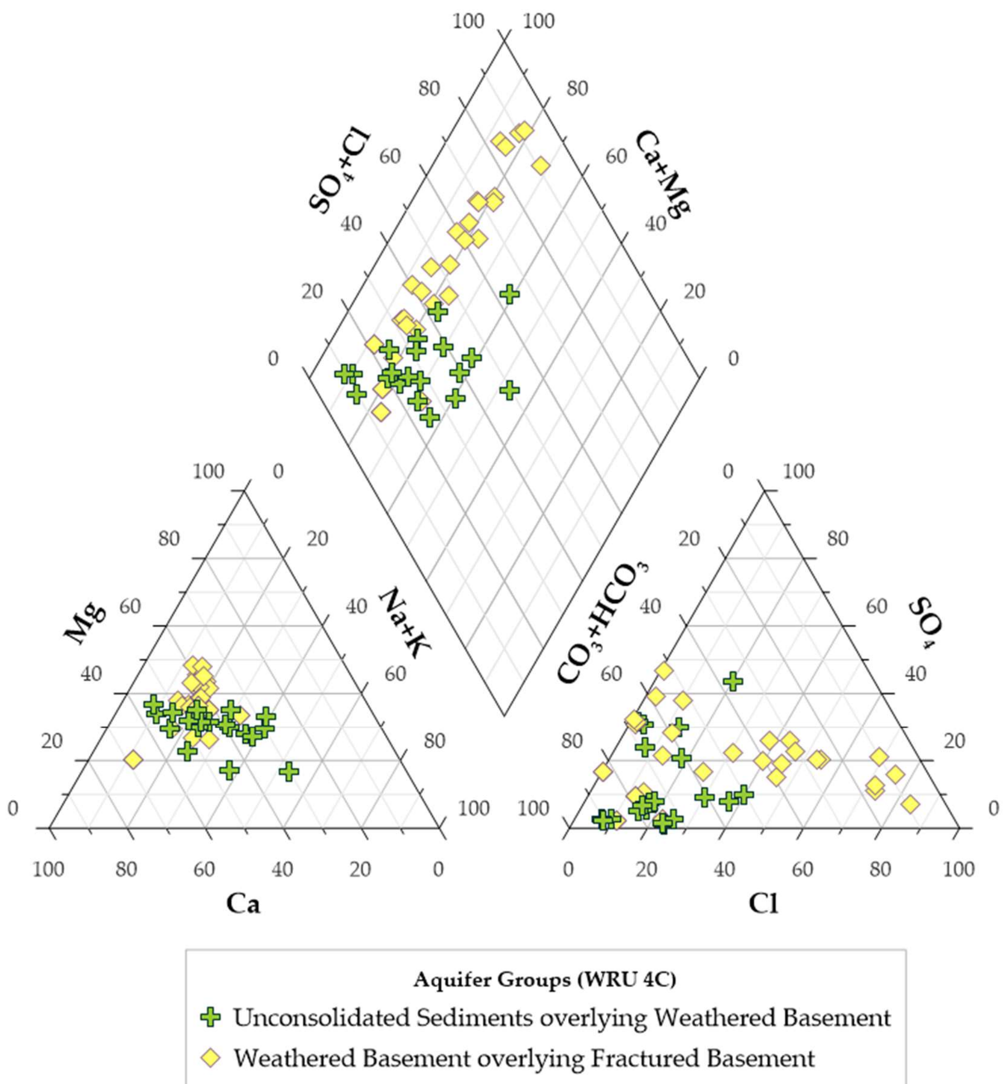
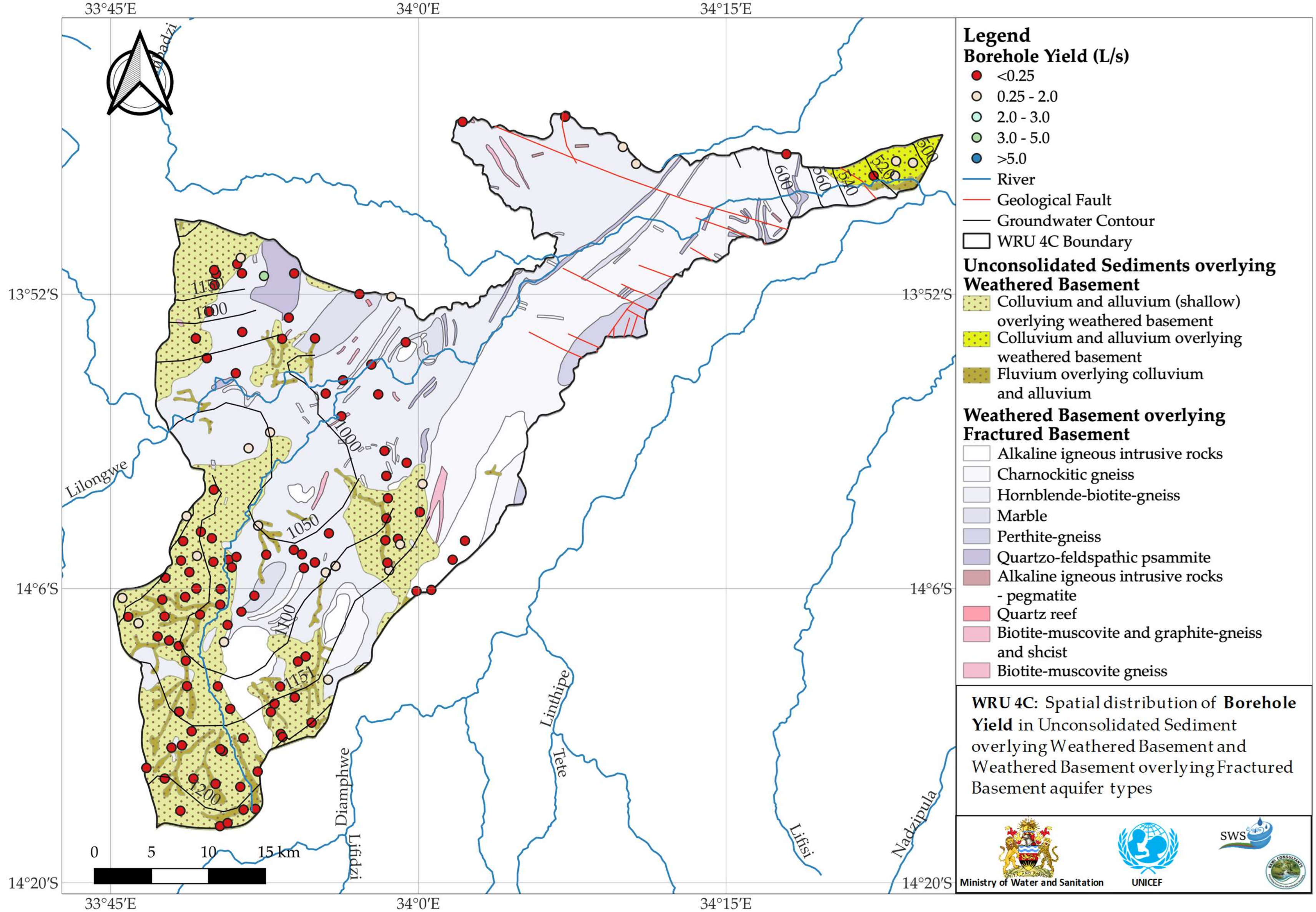


Figure WRU 4C.10 Borehole Yield Map for data held by the Ministry



WRU 4D Figures

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Figure WRU 4D.10 Borehole Yield Map for data held by the Ministry

Figure WRU 4D.1 Land Use and Major Roads

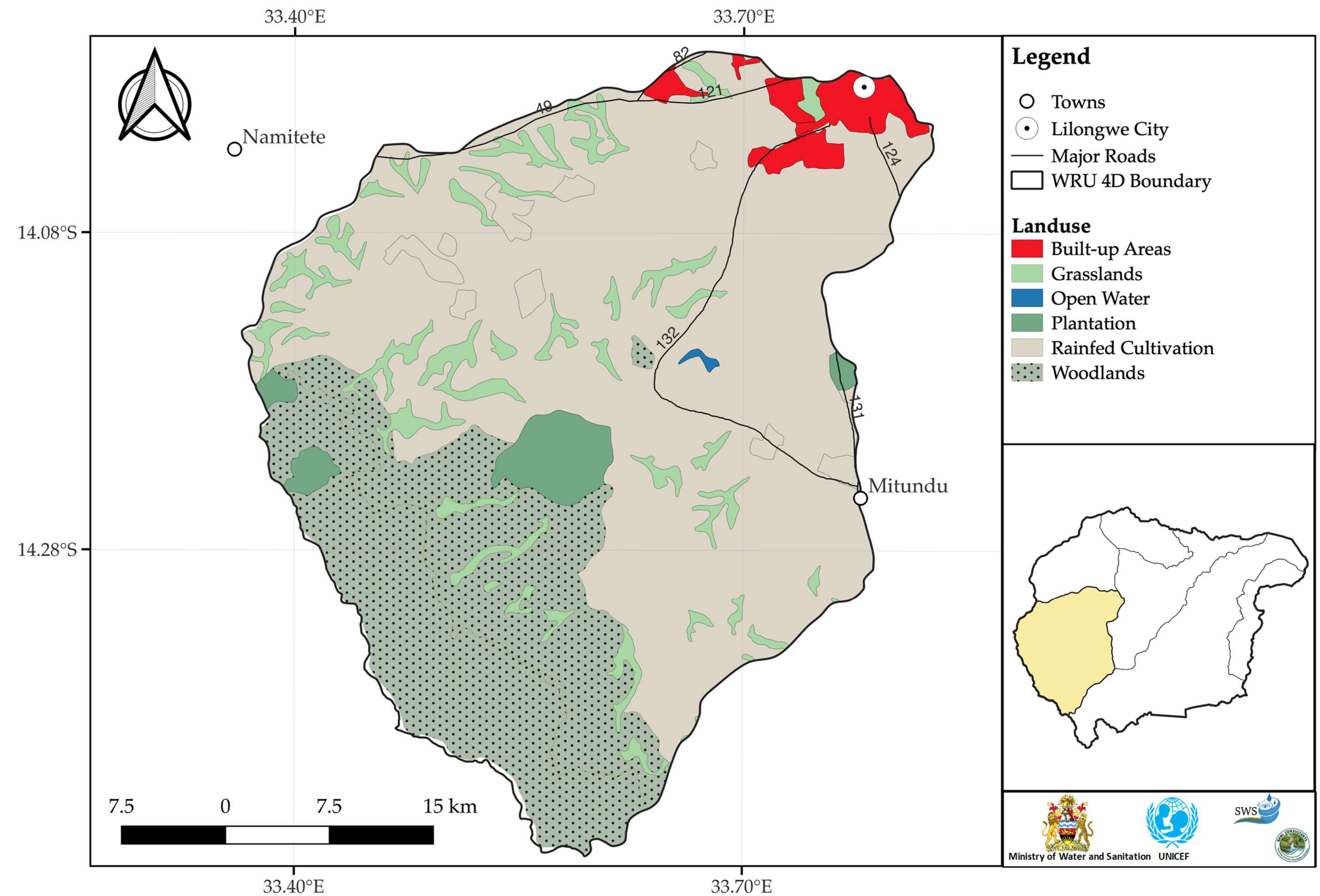


Figure WRU 4D.2 Rivers and Wetlands

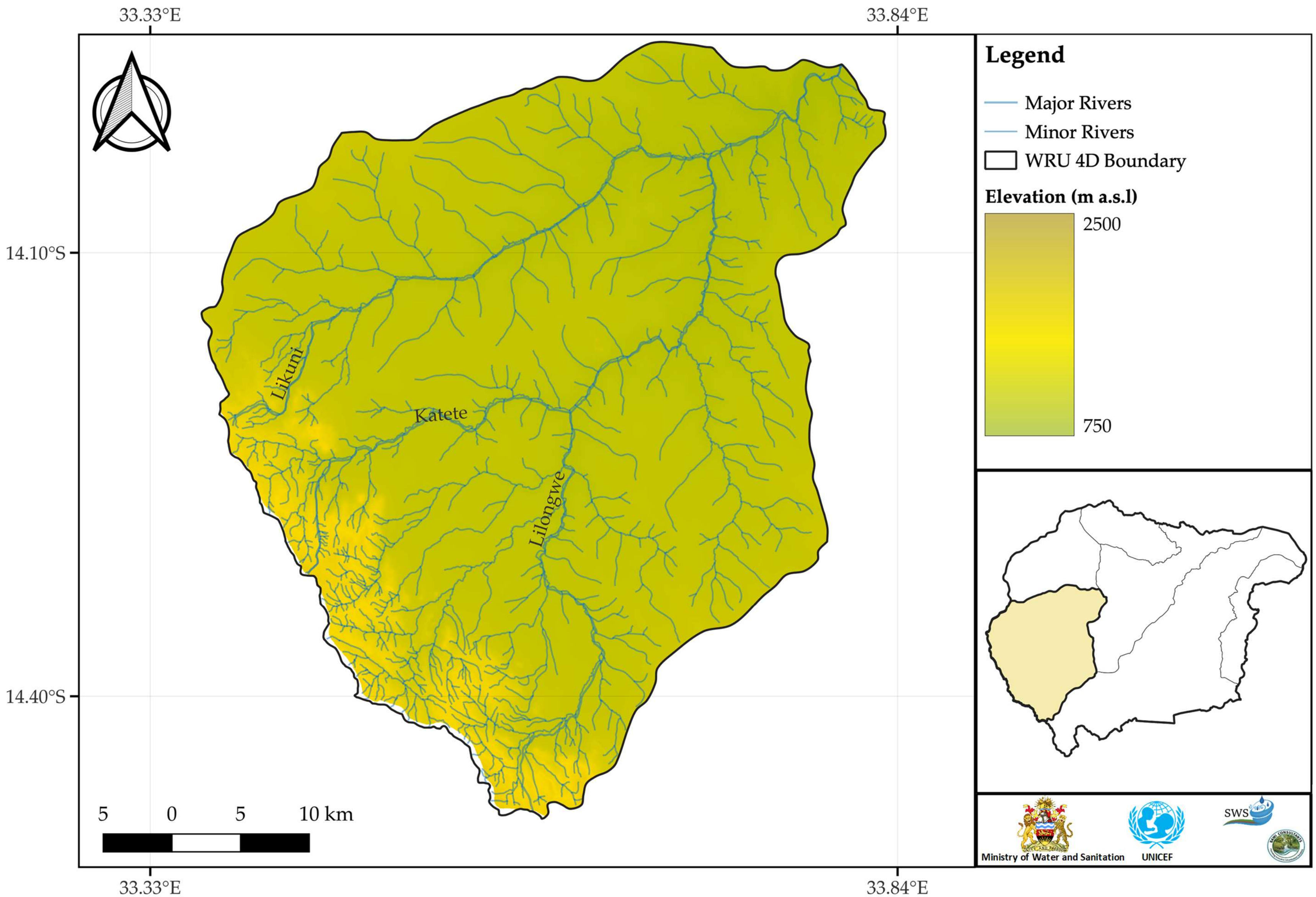


Figure WRU 4D.3 Hydrogeology Units and Water Table

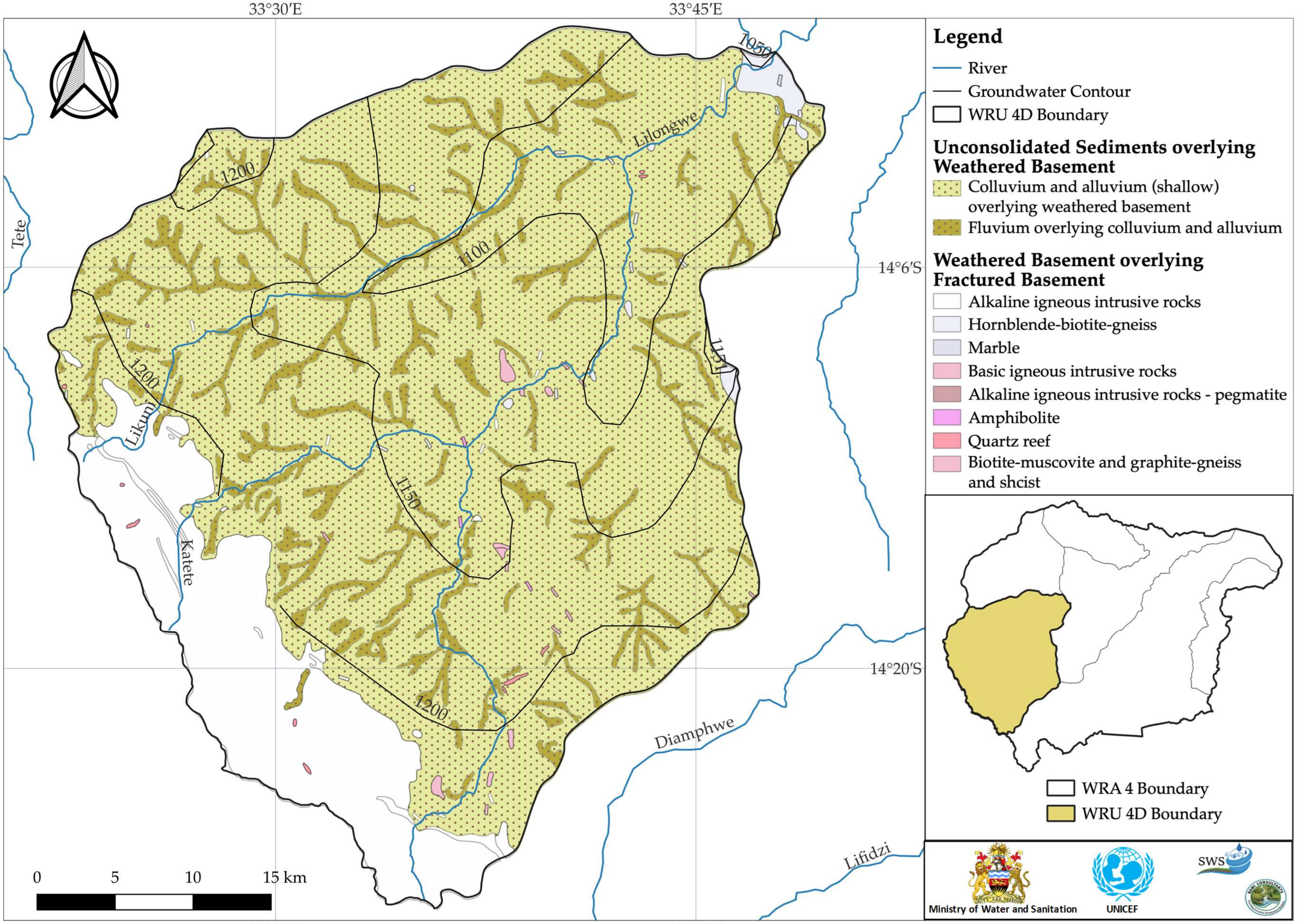


Figure WRU 4D.4 Groundwater Chemistry Distribution Electrical Conductivity

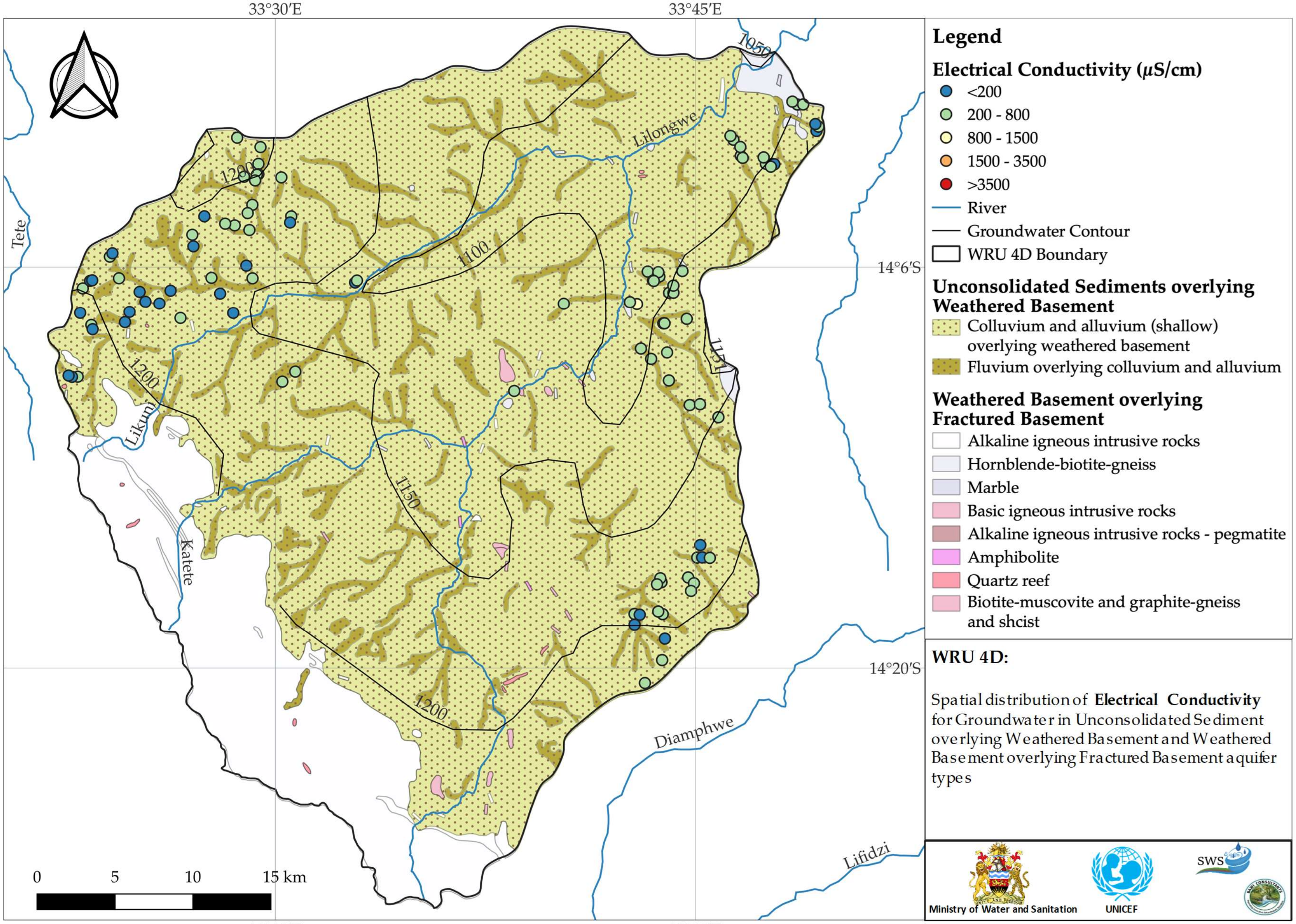


Figure WRU 4D.5 Groundwater Chemistry Distribution of Sulphate

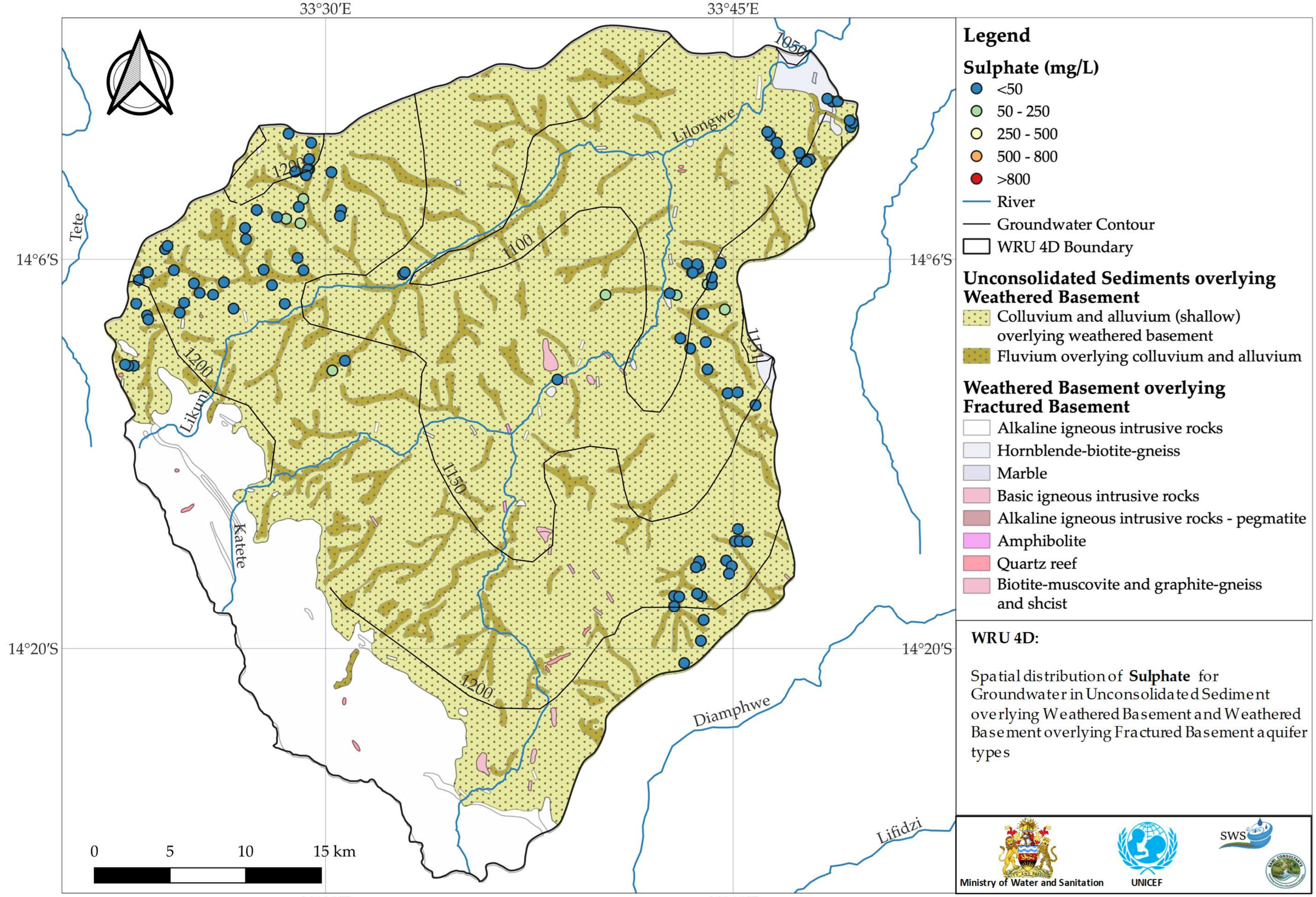


Figure WRU 4D.6 Groundwater Chemistry Distribution Chloride

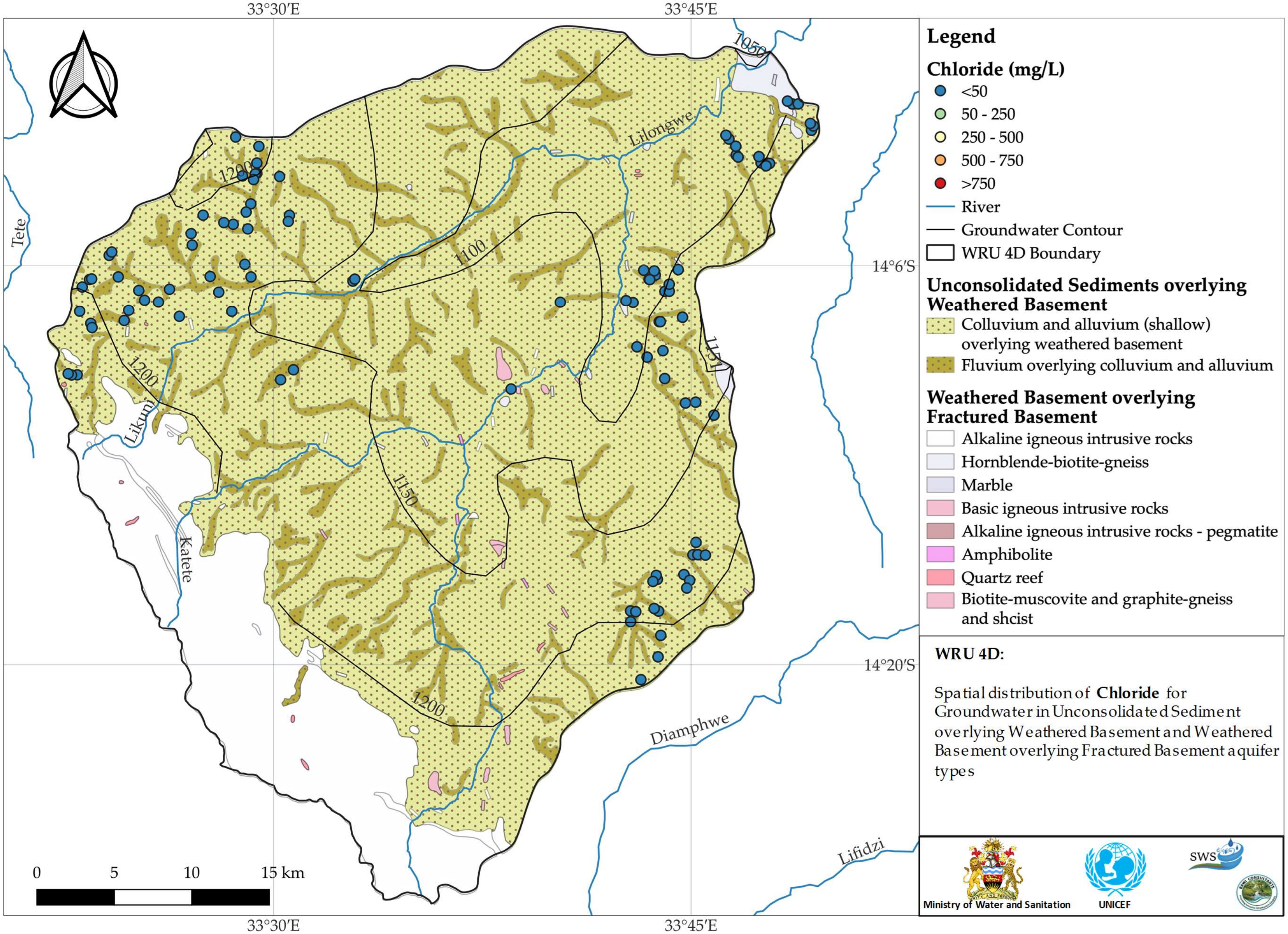


Figure WRU 4D.7 Groundwater Chemistry Distribution Sodium

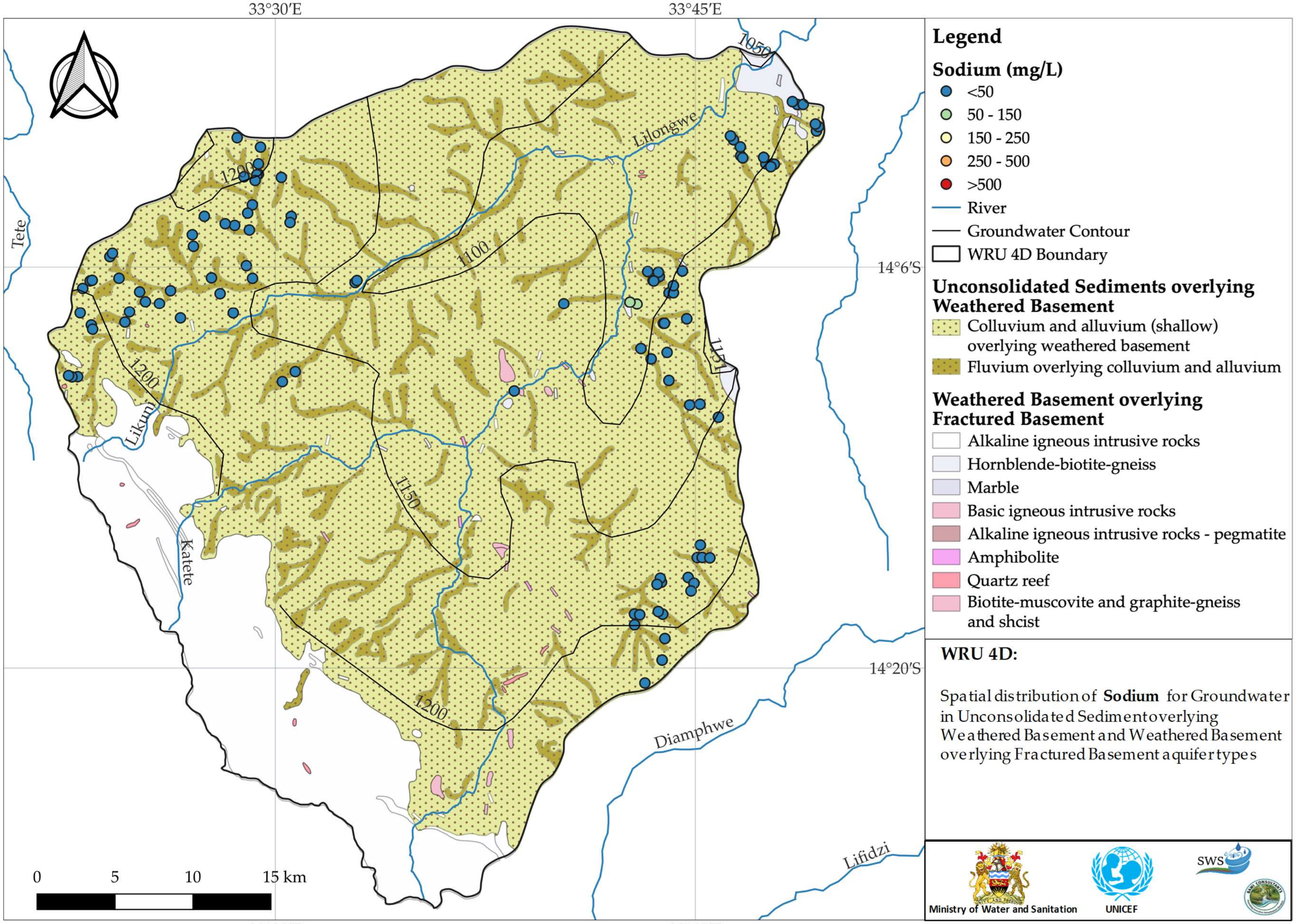


Figure WRU 4D.8 Groundwater Chemistry Distribution Calcium

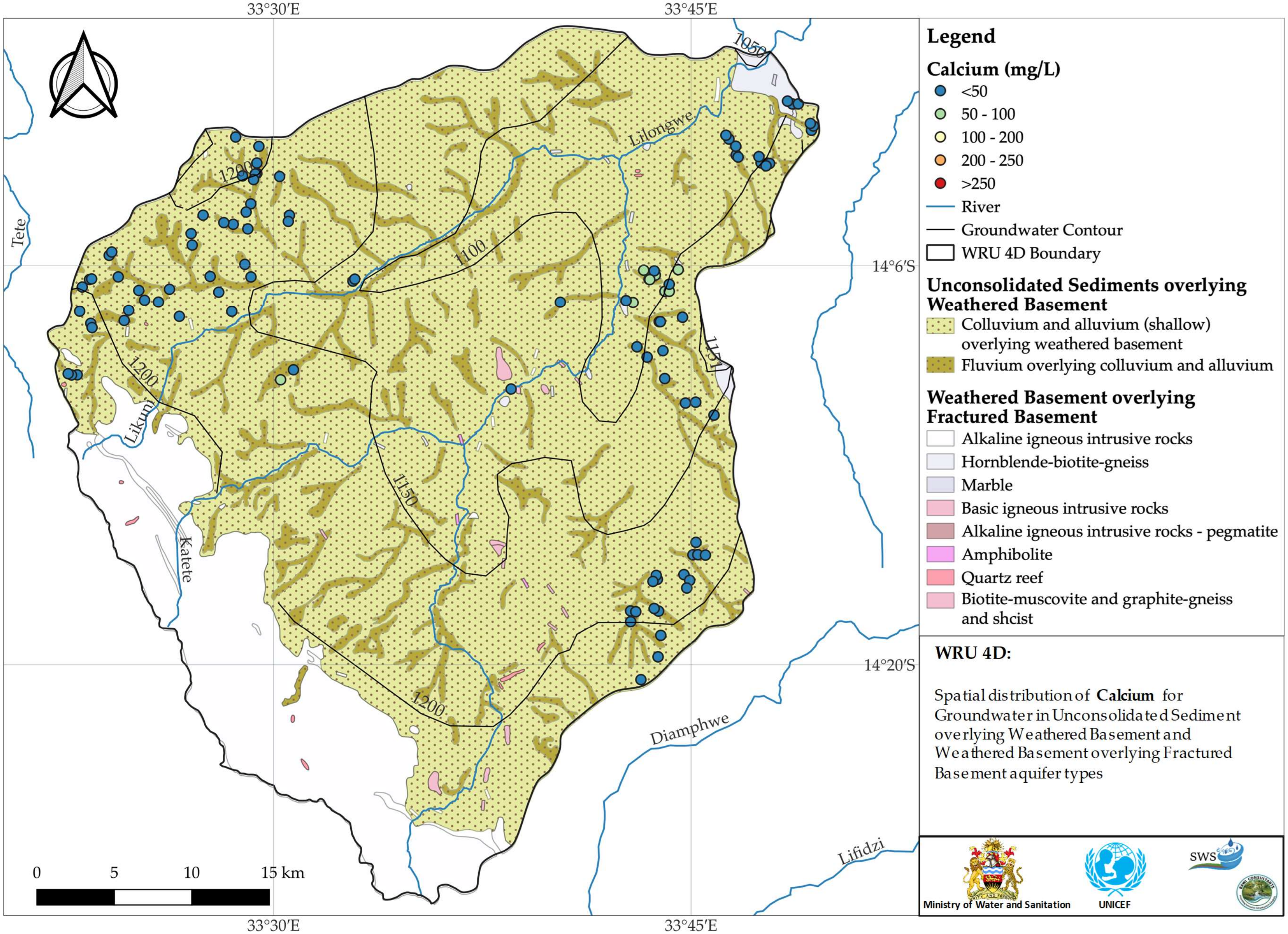


Figure WRU 4D.9 Piper Diagram of water quality results with respect to the major aquifer type

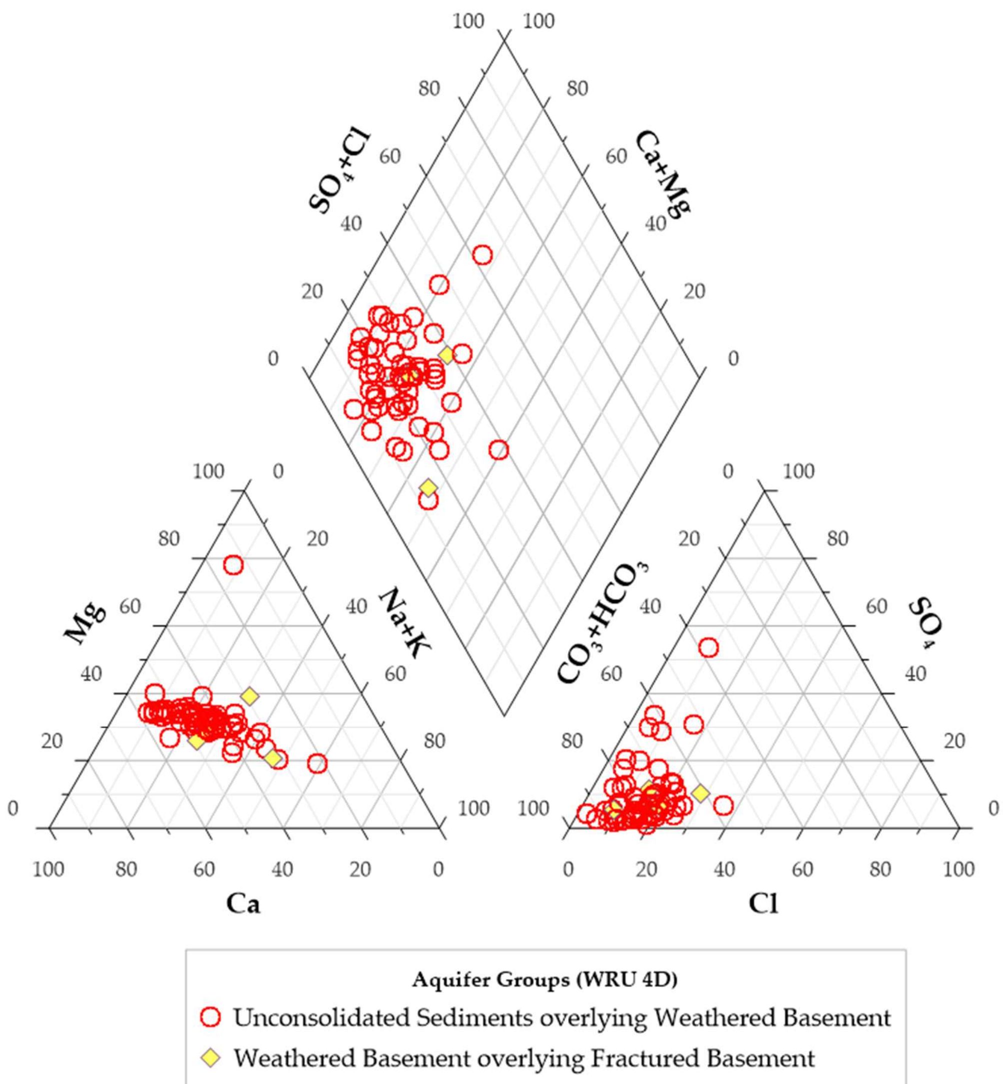
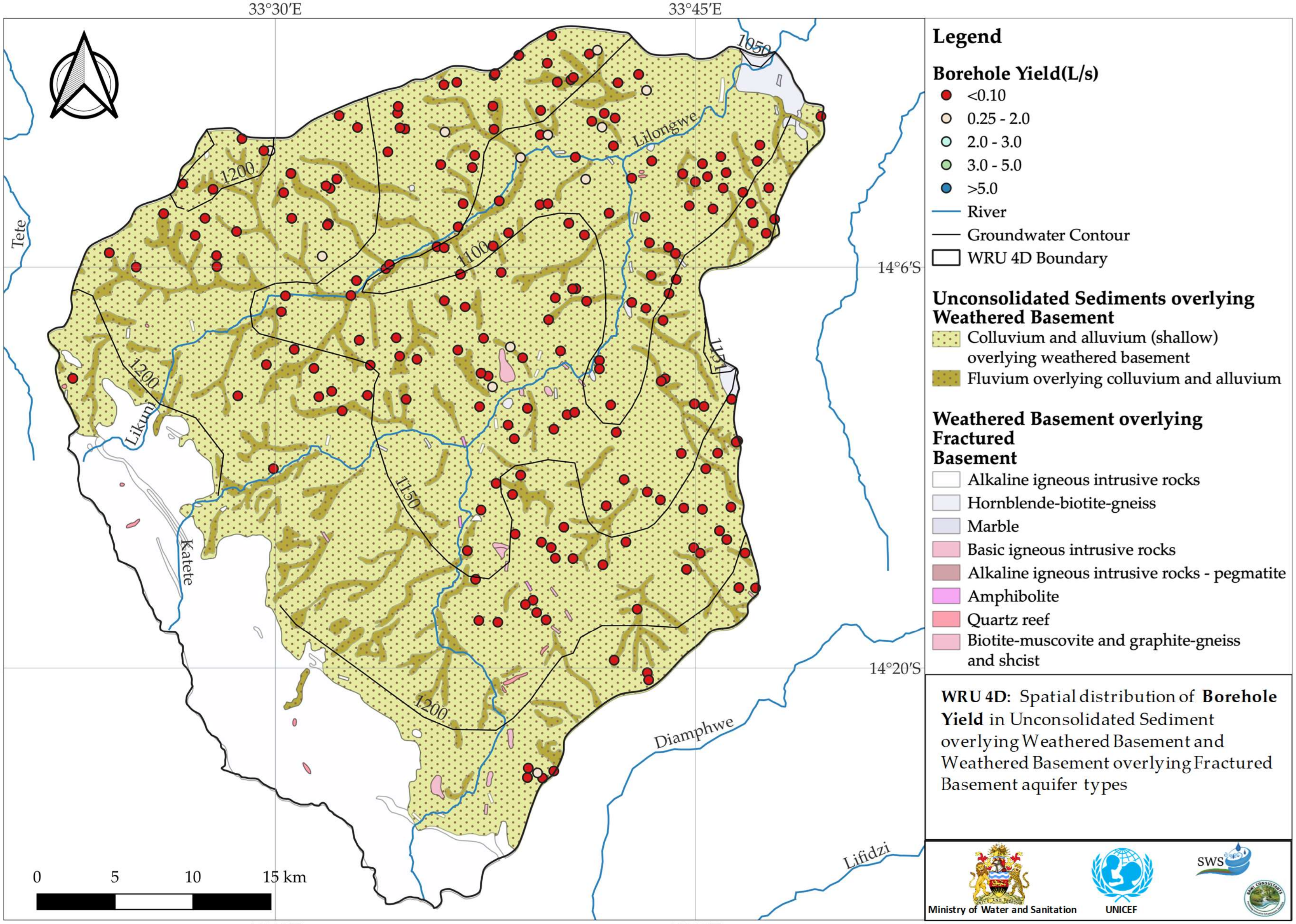


Figure WRU 4D.10 Borehole Yield Map for data held by the Ministry



WRU 4E Figures

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Figure WRU 4E.9 Piper Diagram of water quality results with respect to the major aquifer type

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Figure WRU 4E.1 Land Use and Major Roads

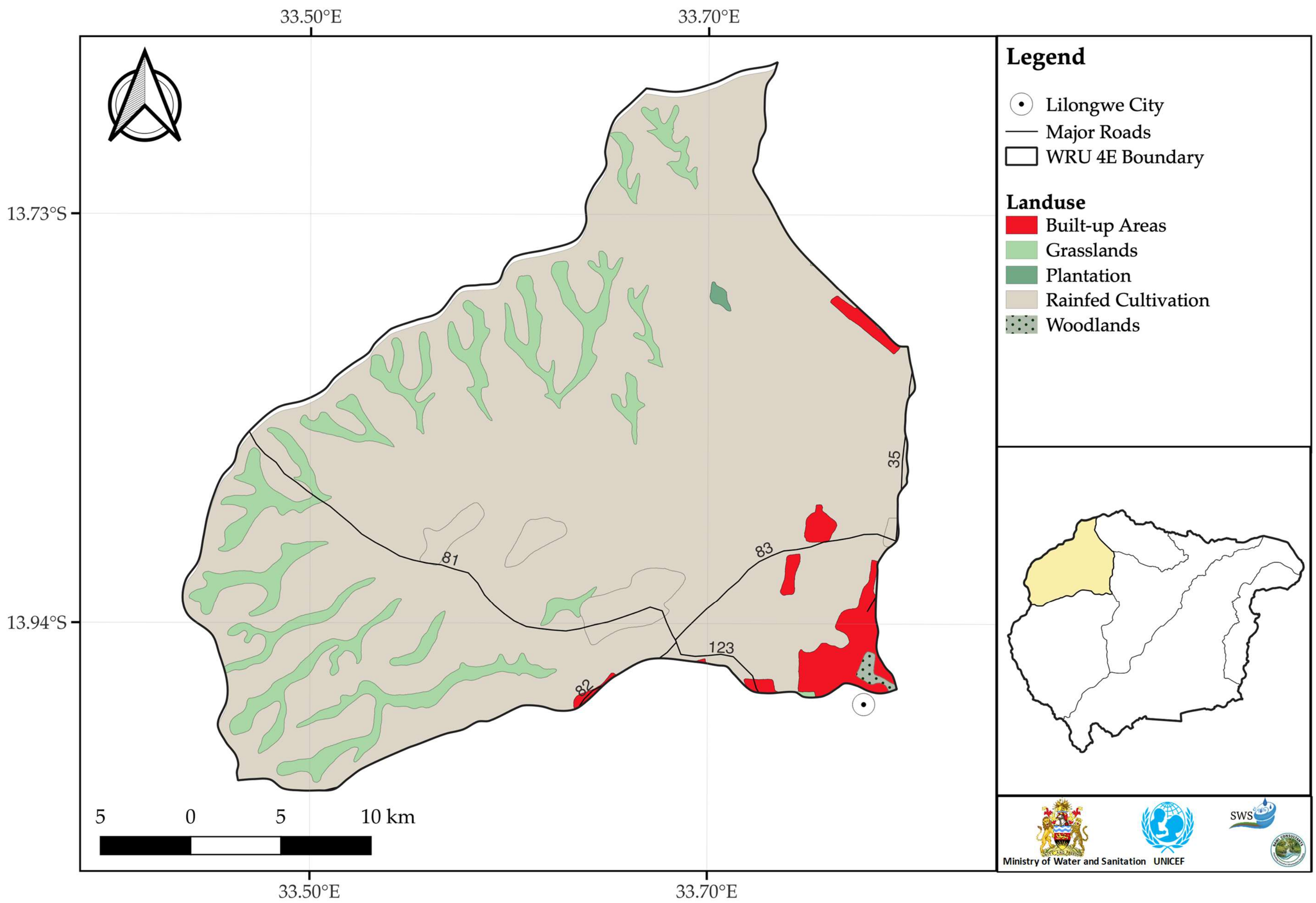


Figure WRU 4E.2 Rivers and Wetlands

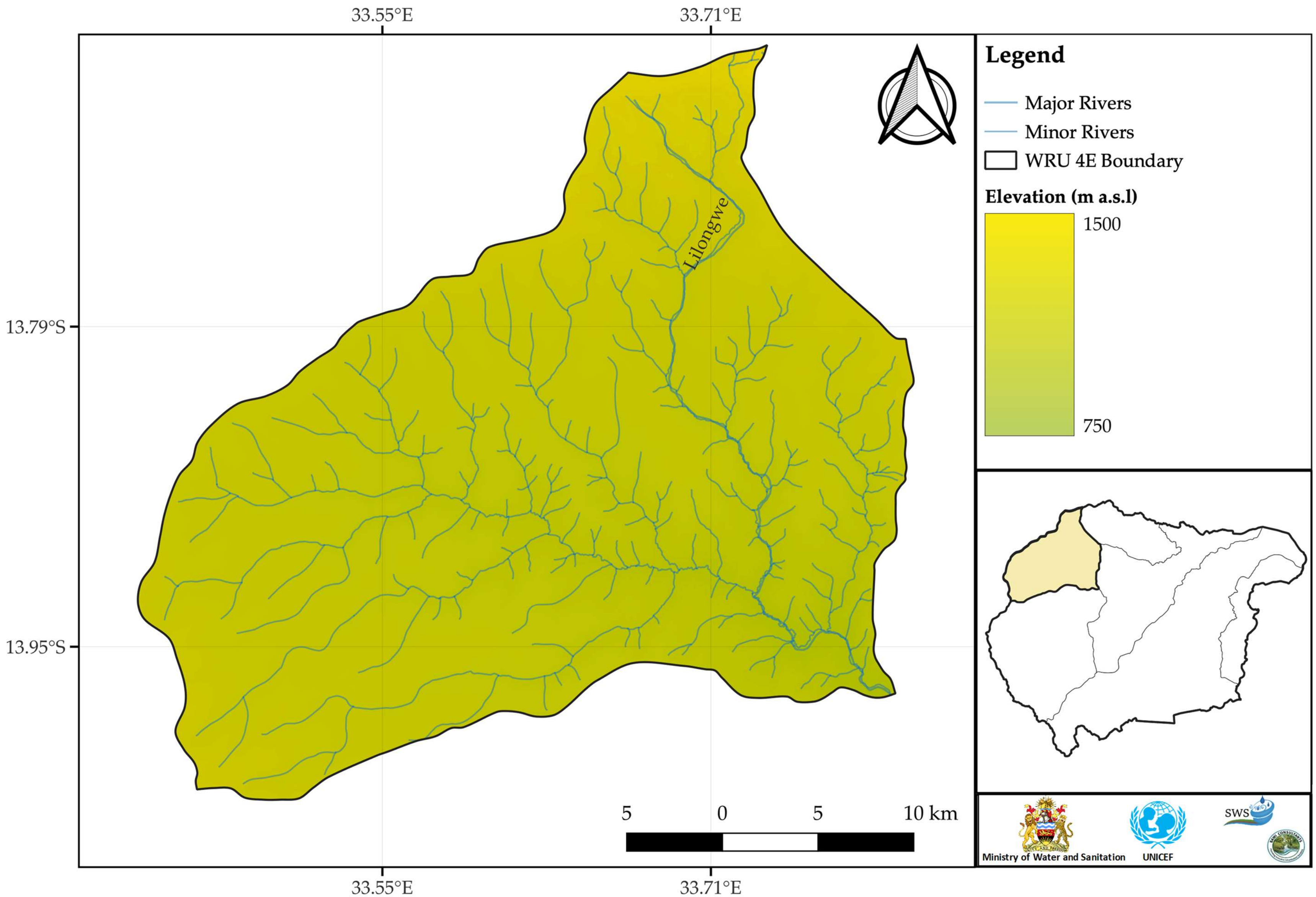


Figure WRU 4E.3 Hydrogeology Units and Water Table

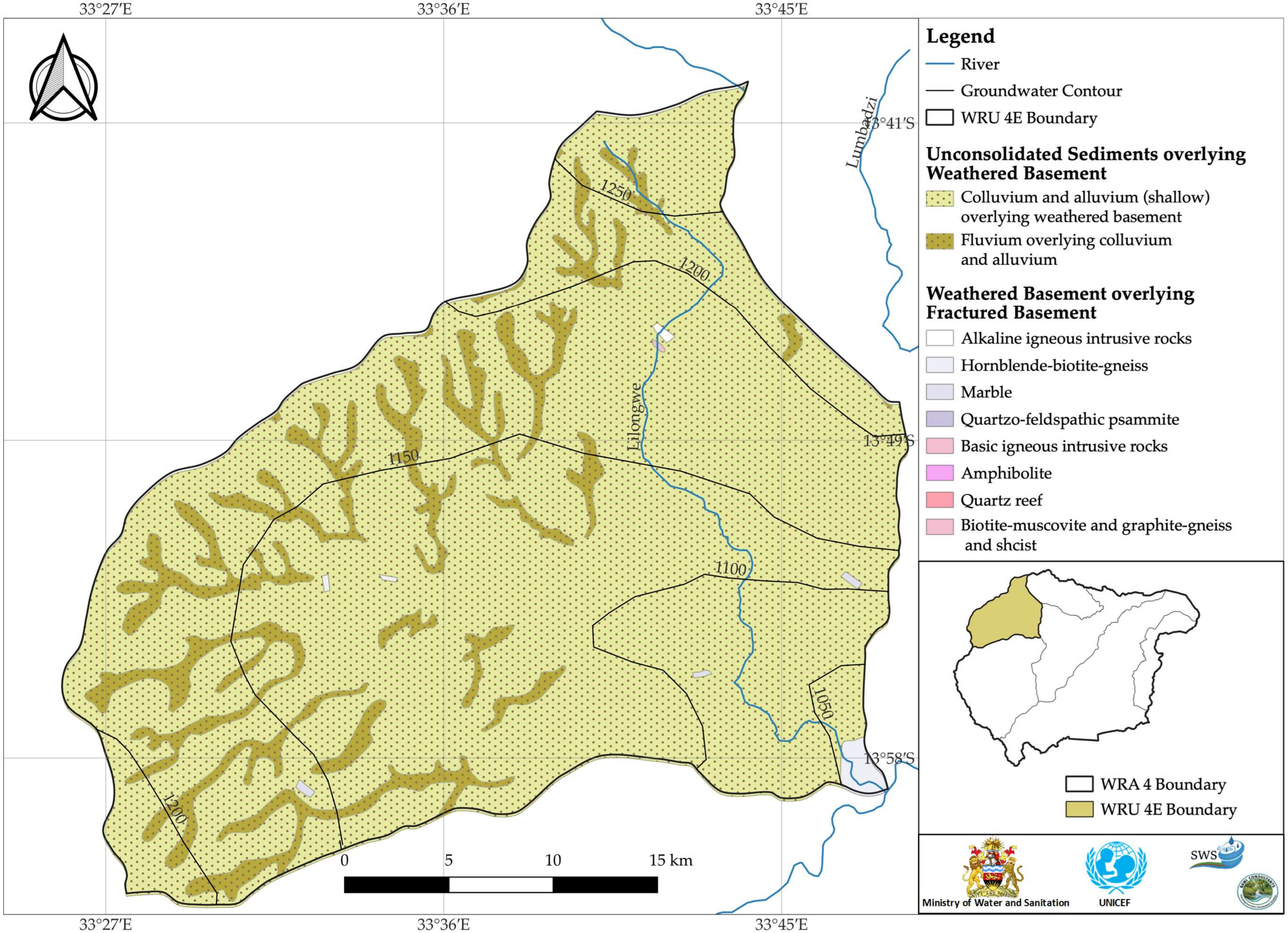


Figure WRU 4E.4 Groundwater Chemistry Distribution Electrical Conductivity

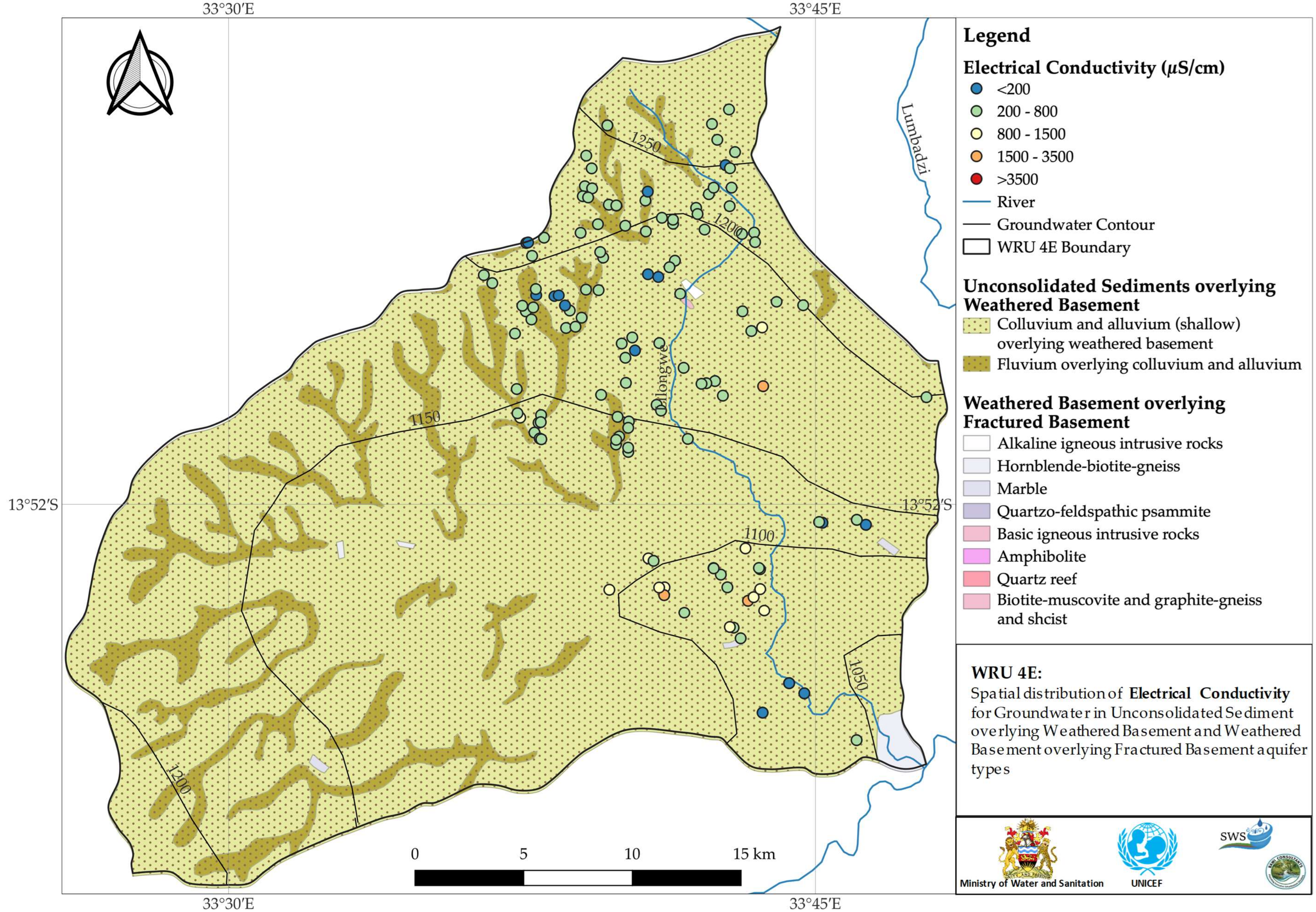


Figure WRU 4E.5 Groundwater Chemistry Distribution of Sulphate

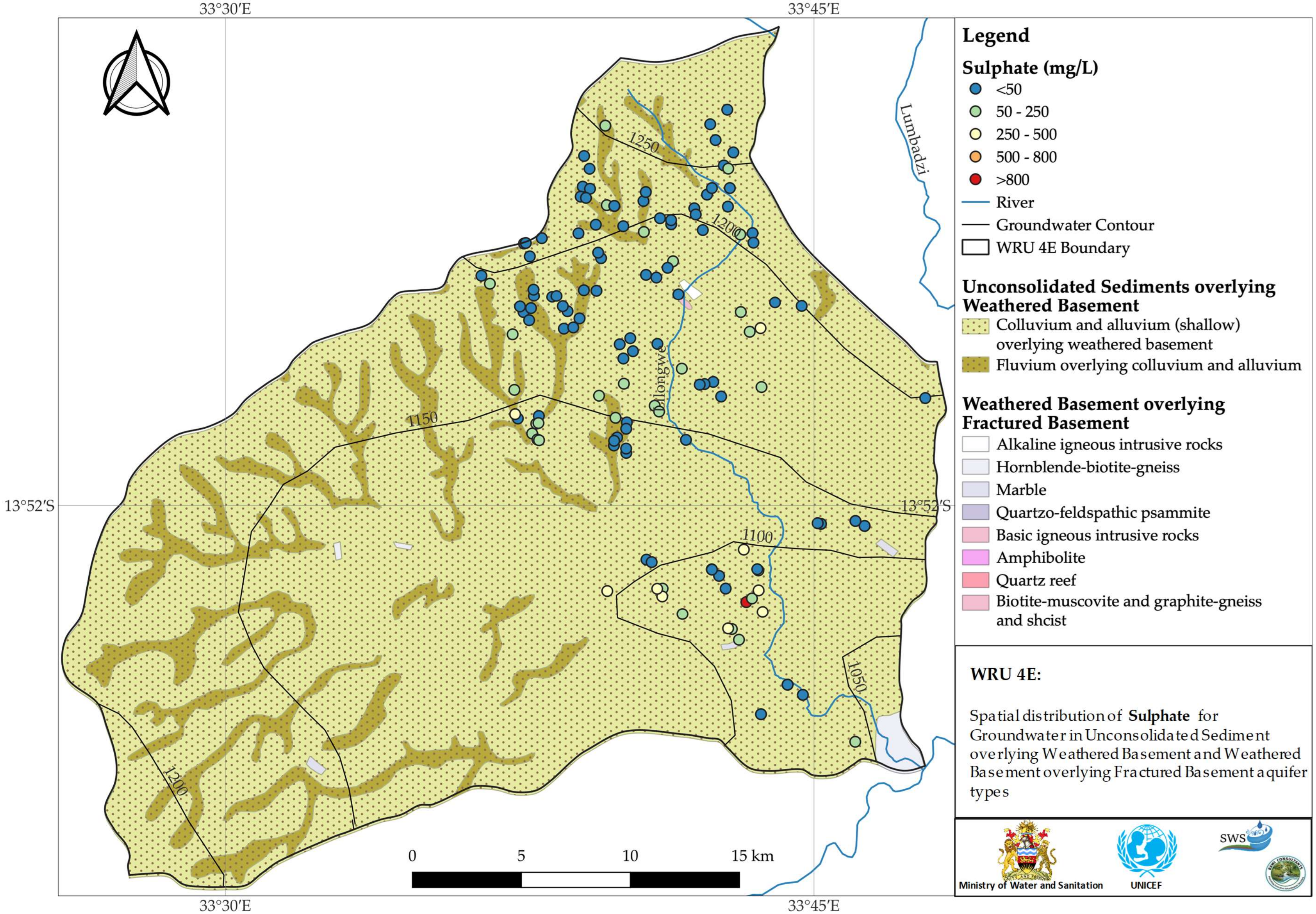


Figure WRU 4E.6 Groundwater Chemistry Distribution Chloride

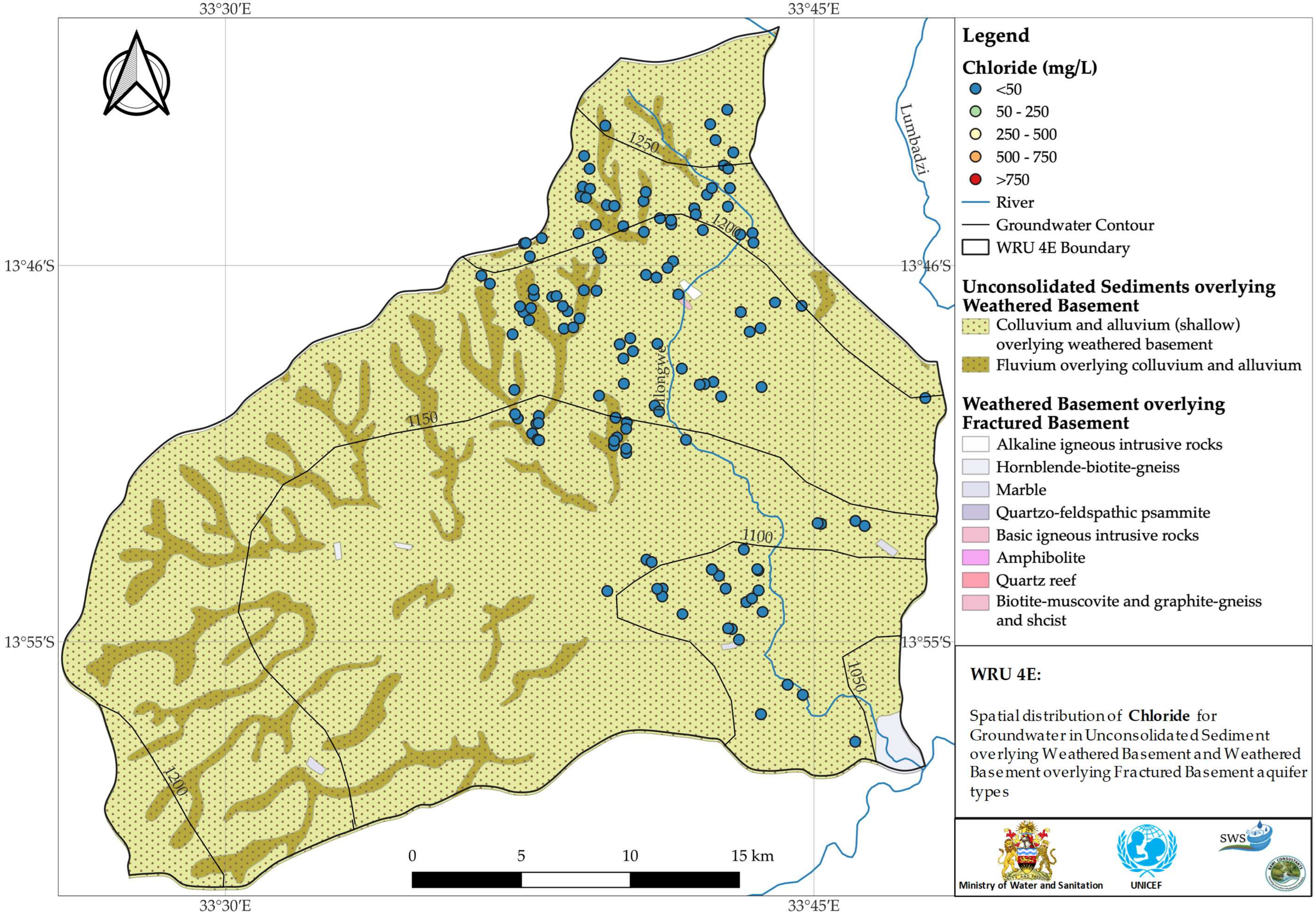


Figure WRU 4E.7 Groundwater Chemistry Distribution Sodium

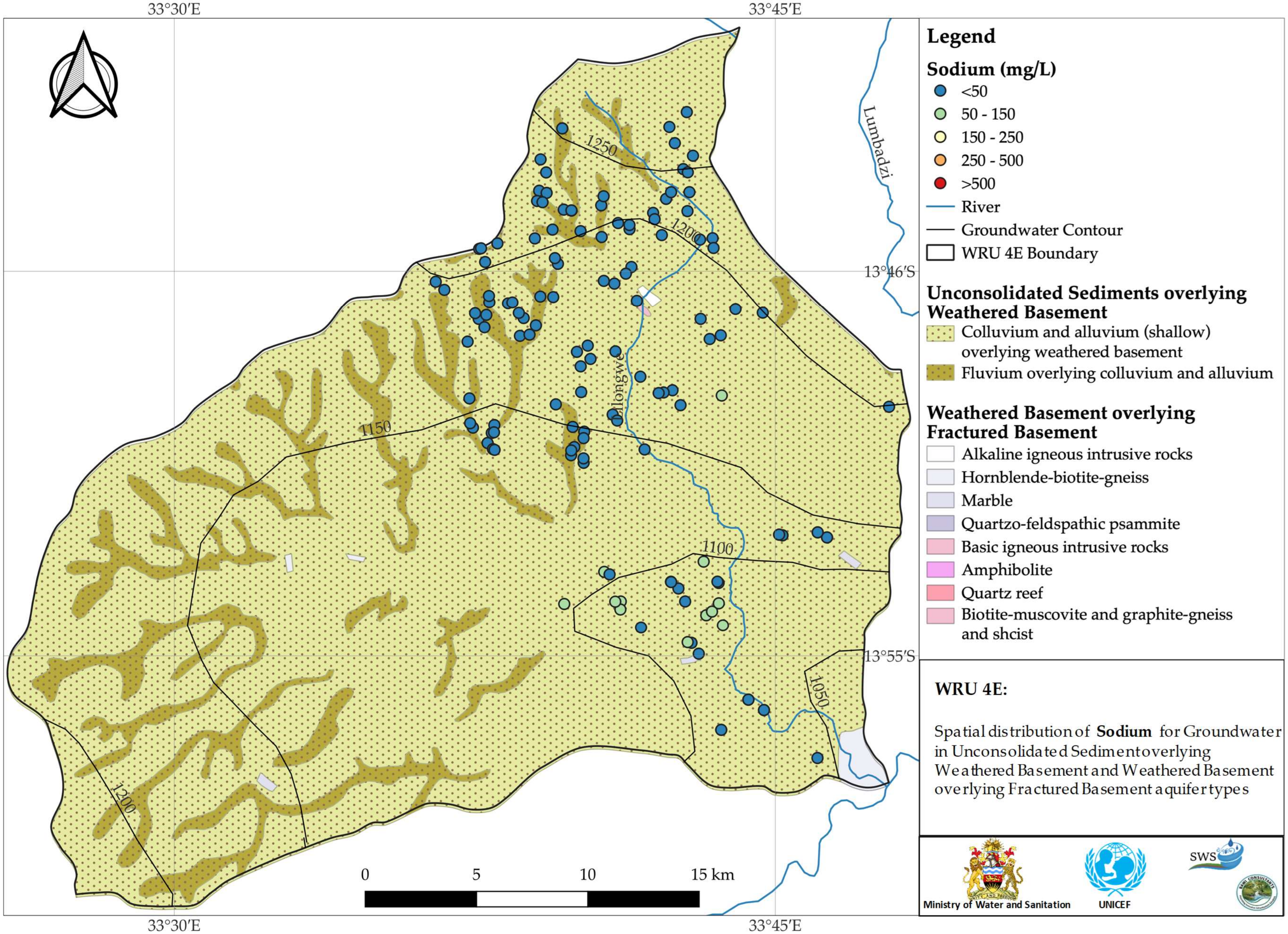


Figure WRU 4E.8 Groundwater Chemistry Distribution Calcium

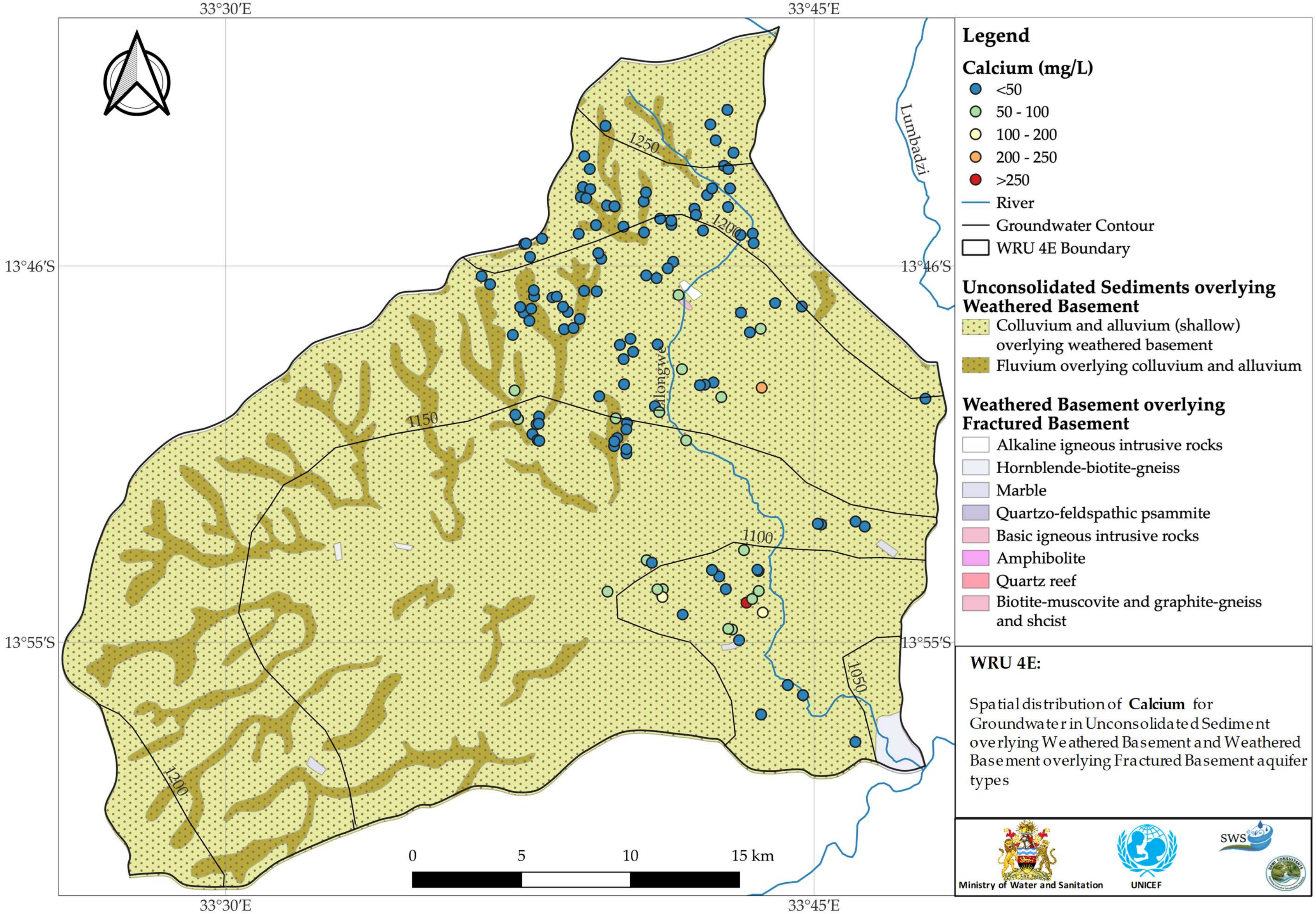


Figure WRU 4E.9 Piper Diagram of water quality results with respect to the major aquifer type

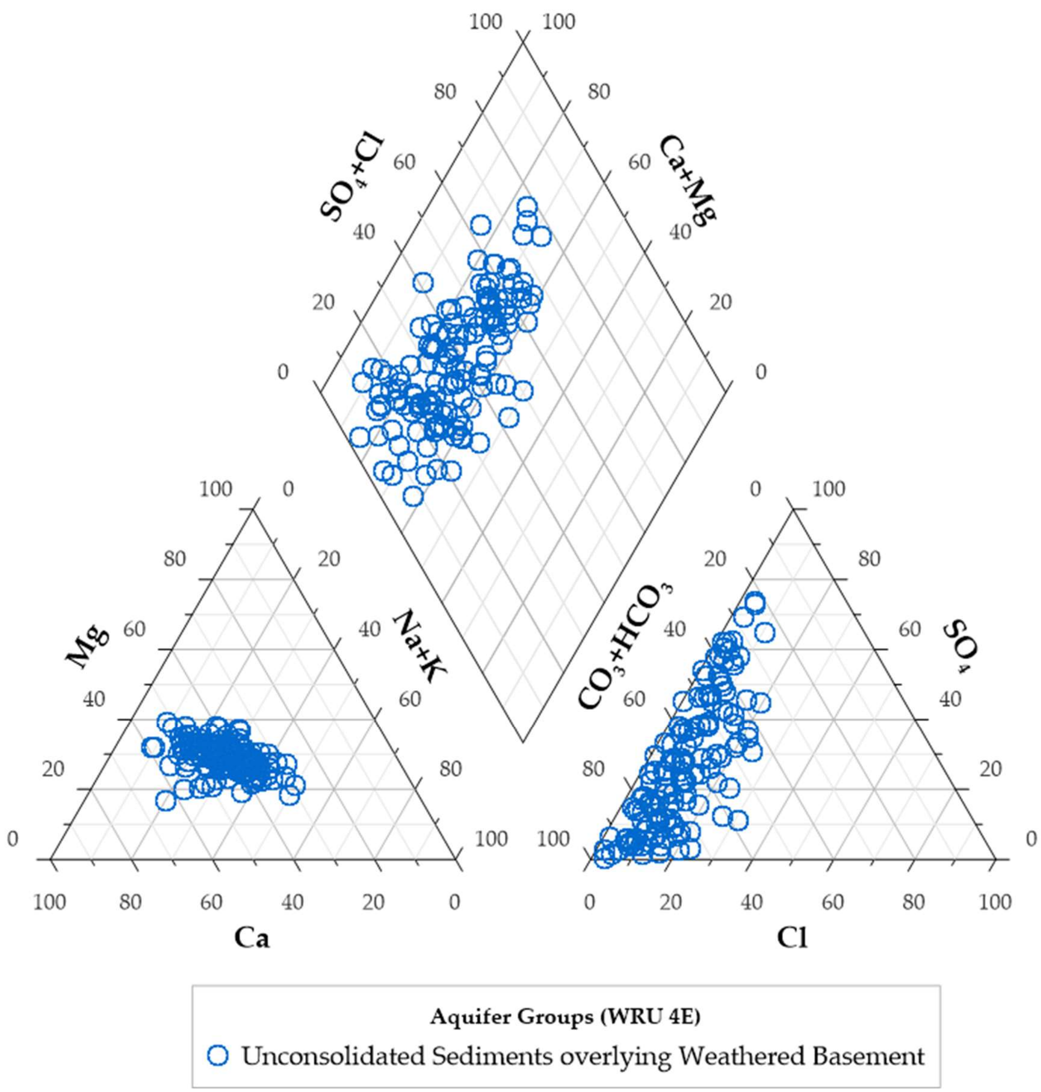
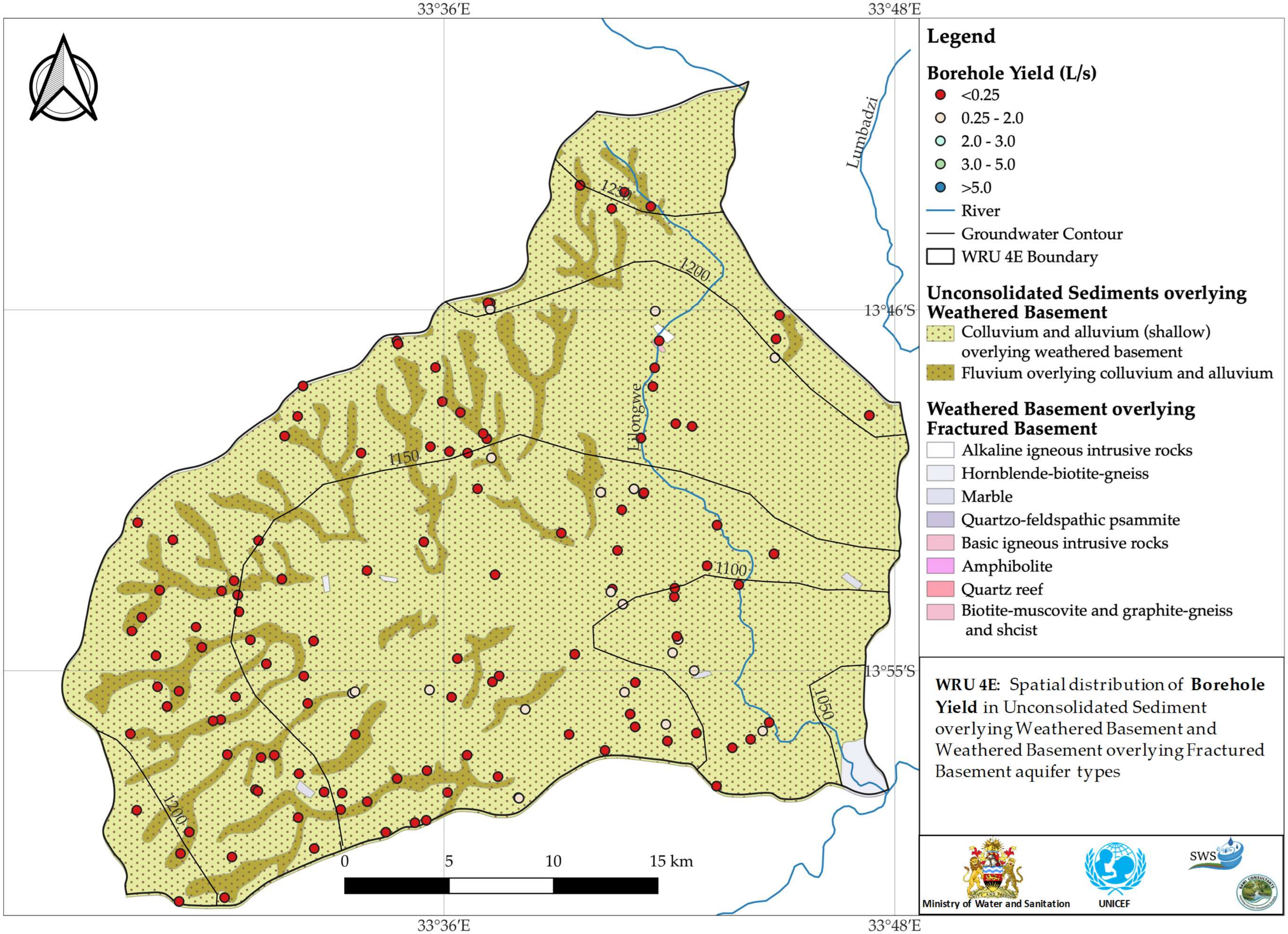


Figure WRU 4E.10 Borehole Yield Map for data held by the Ministry



WRU 4F Figures

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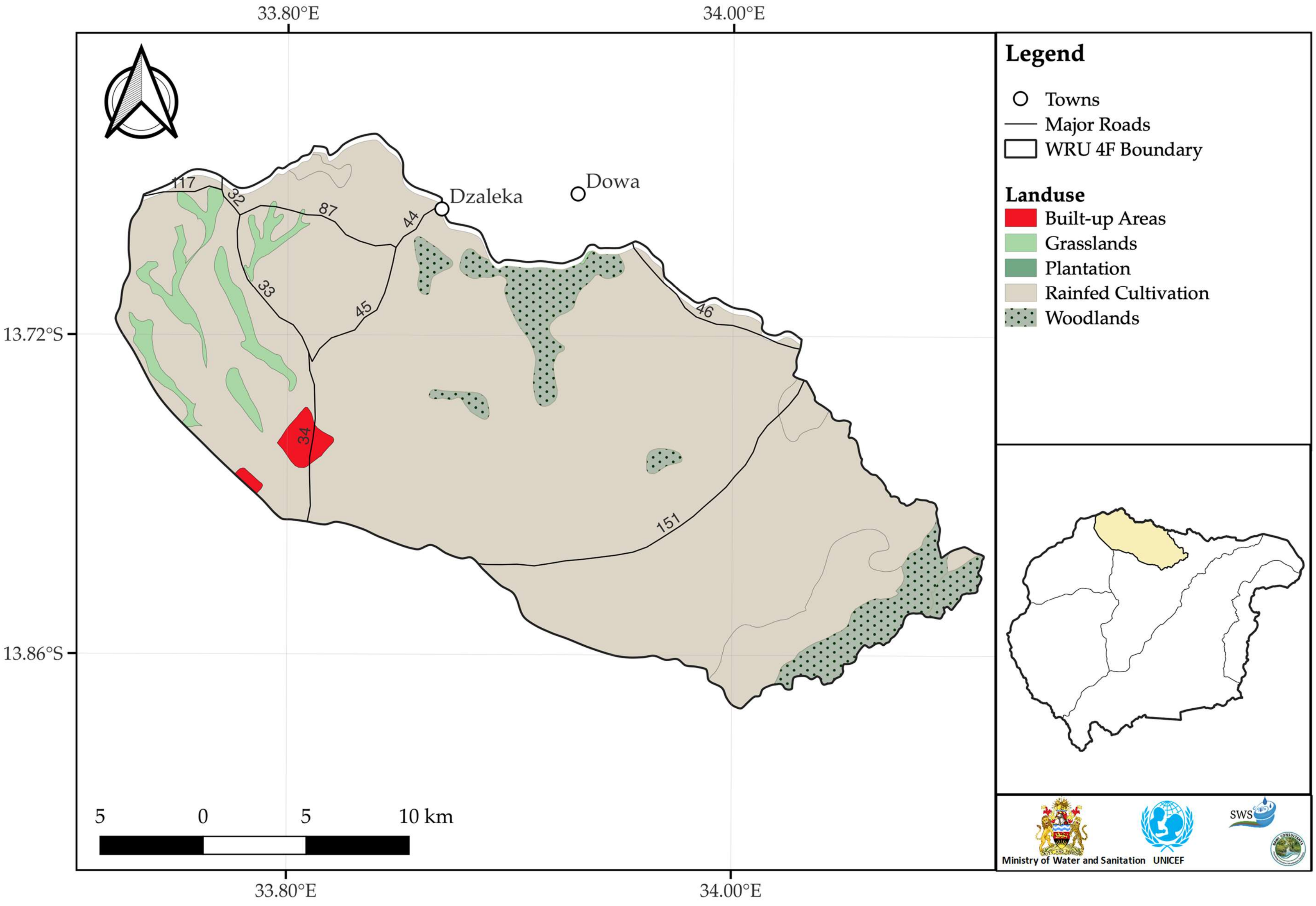


Figure WRU 4F.2 Rivers and Wetlands

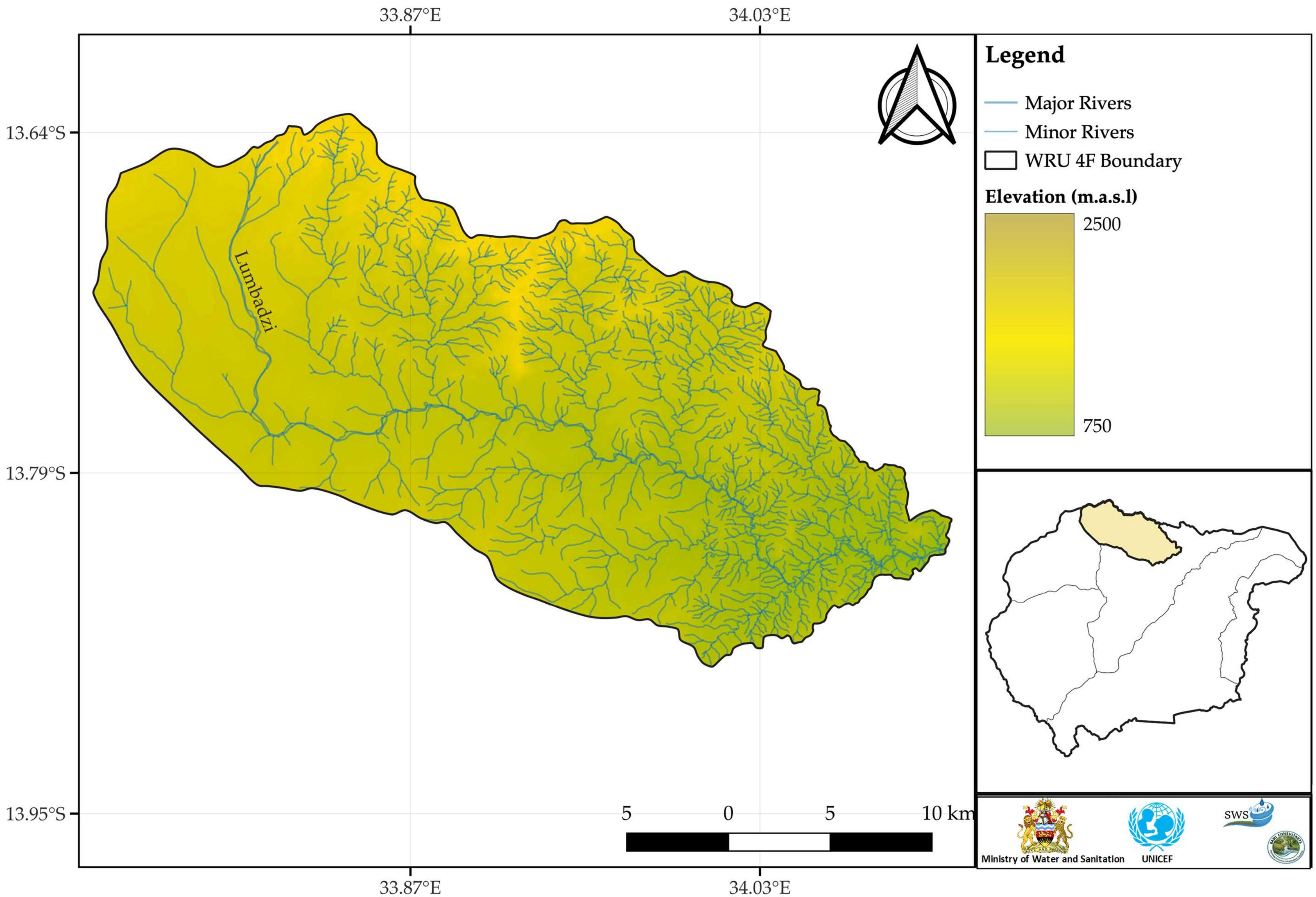


Figure WRU 4F.3 Hydrogeology Units and Water Table

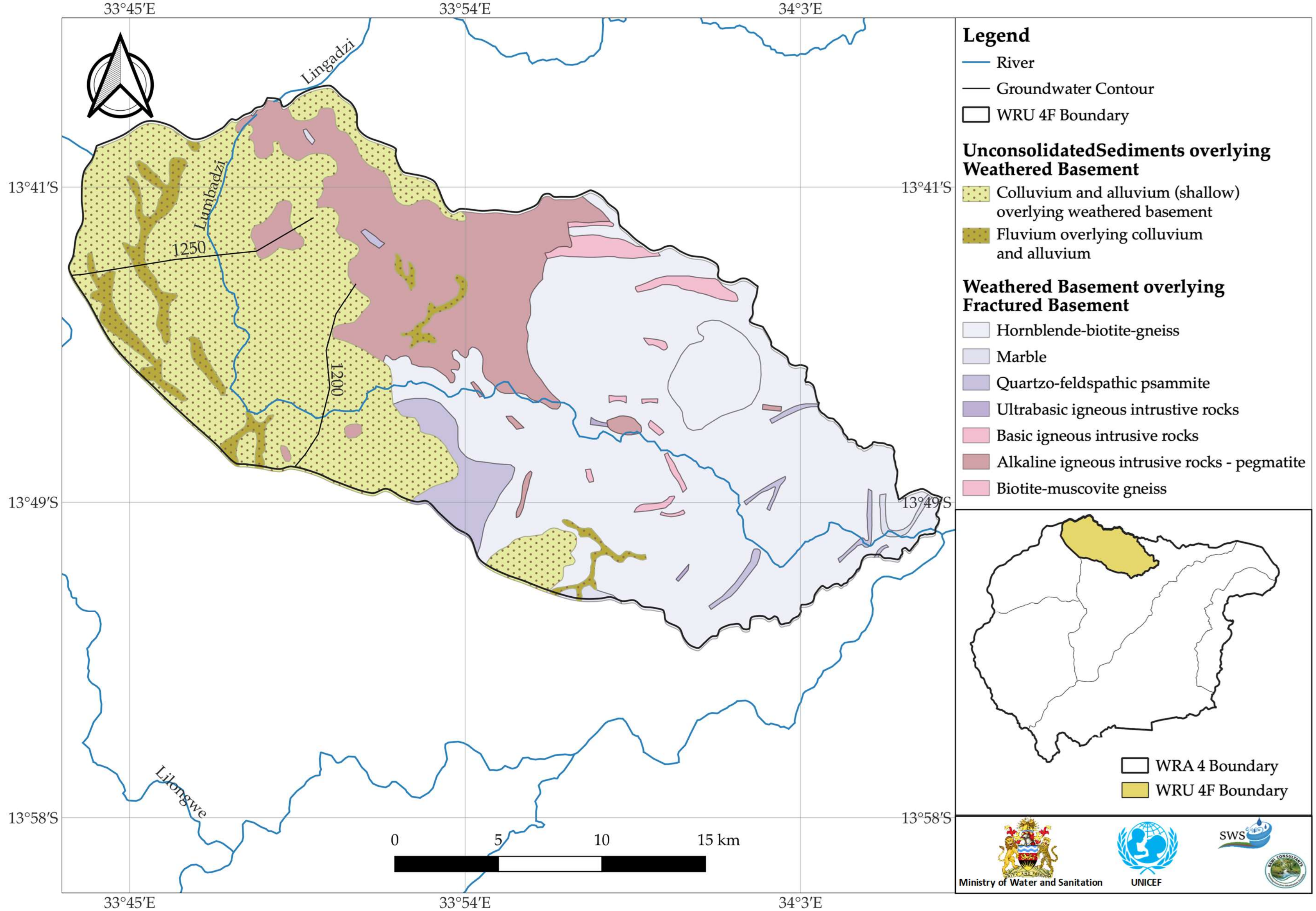


Figure WRU 4E.4 Groundwater Chemistry Distribution Electrical Conductivity

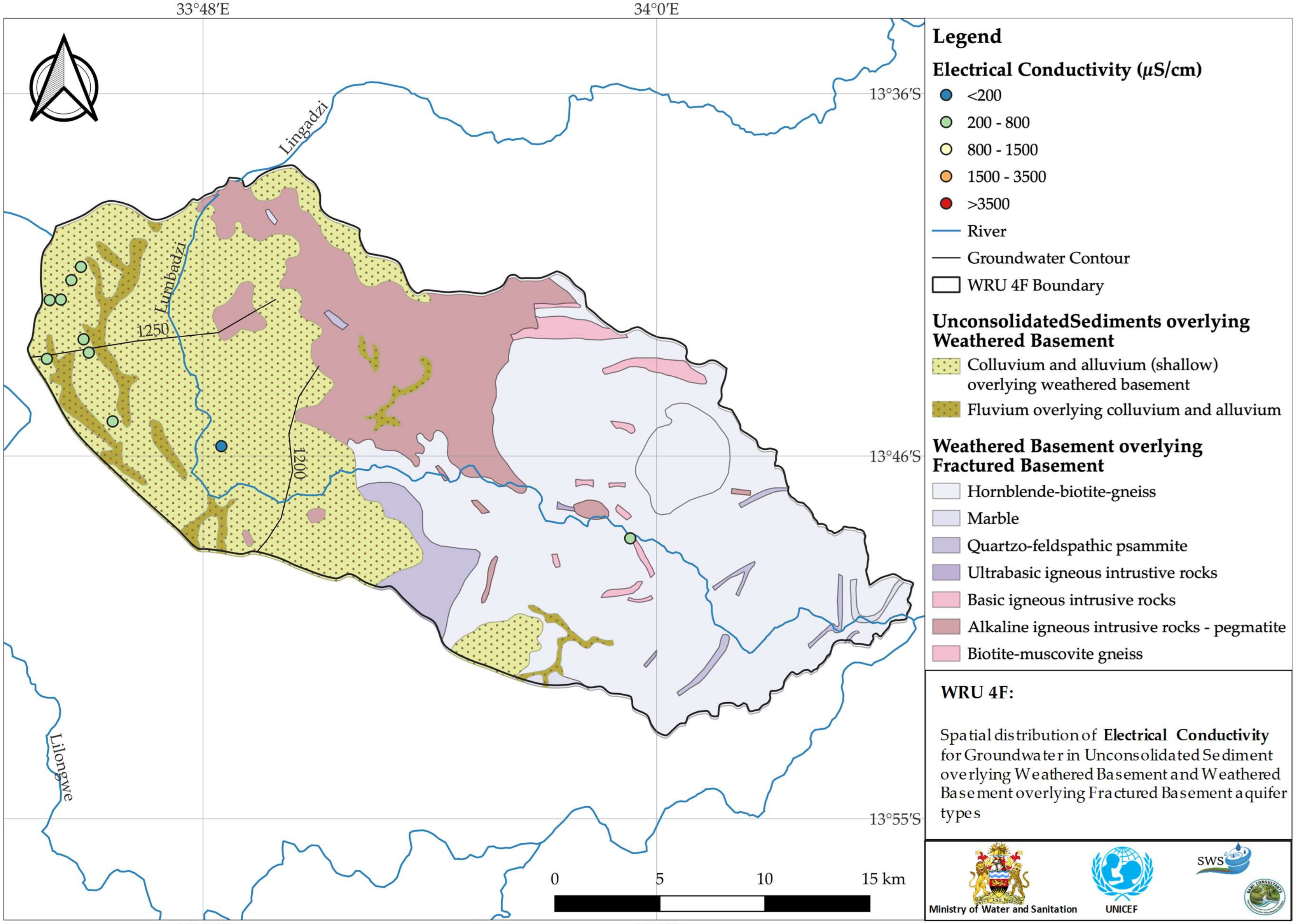


Figure WRU 4F.5 Groundwater Chemistry Distribution of Sulphate

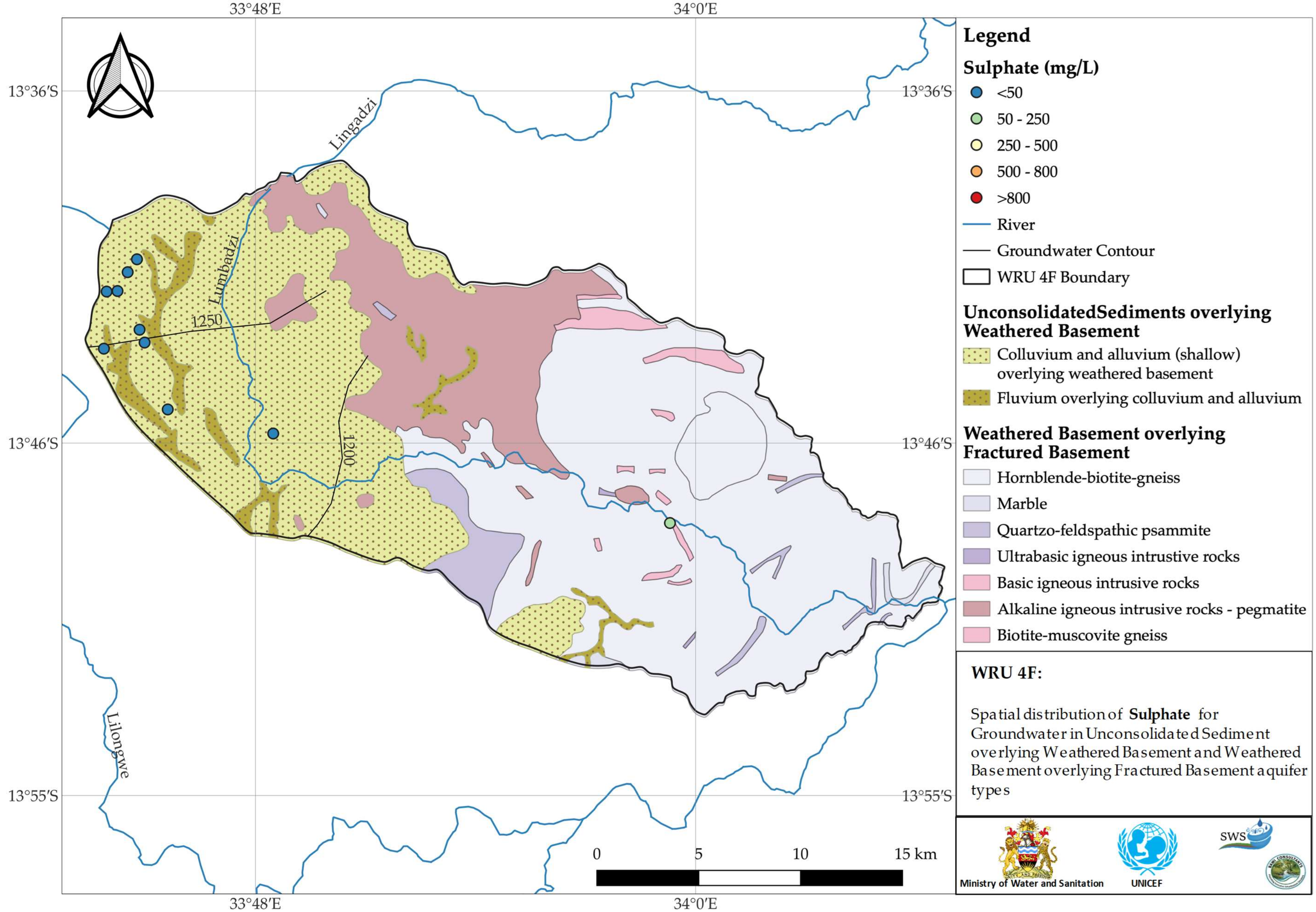
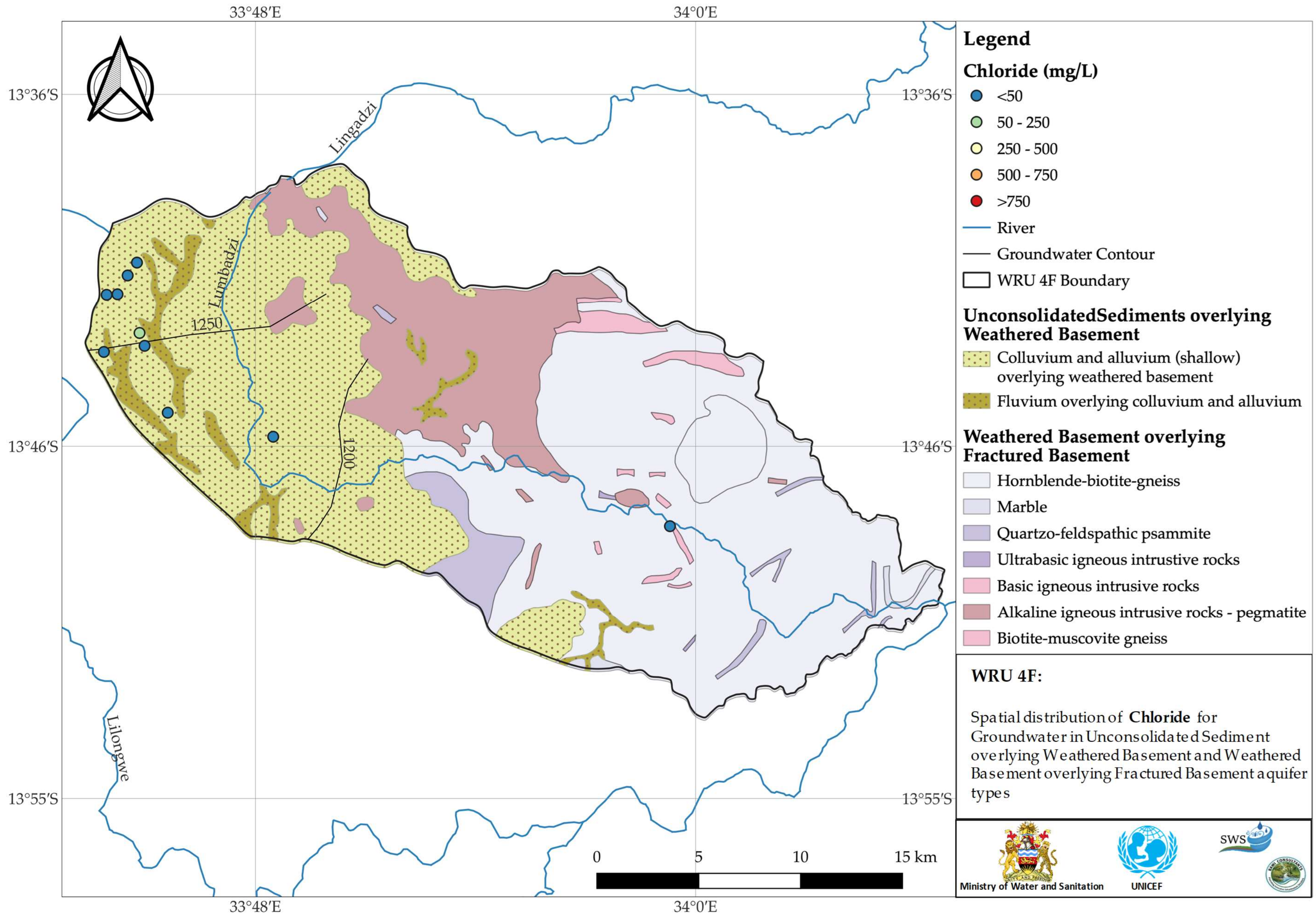


Figure WRU 4F.6 Groundwater Chemistry Distribution Chloride



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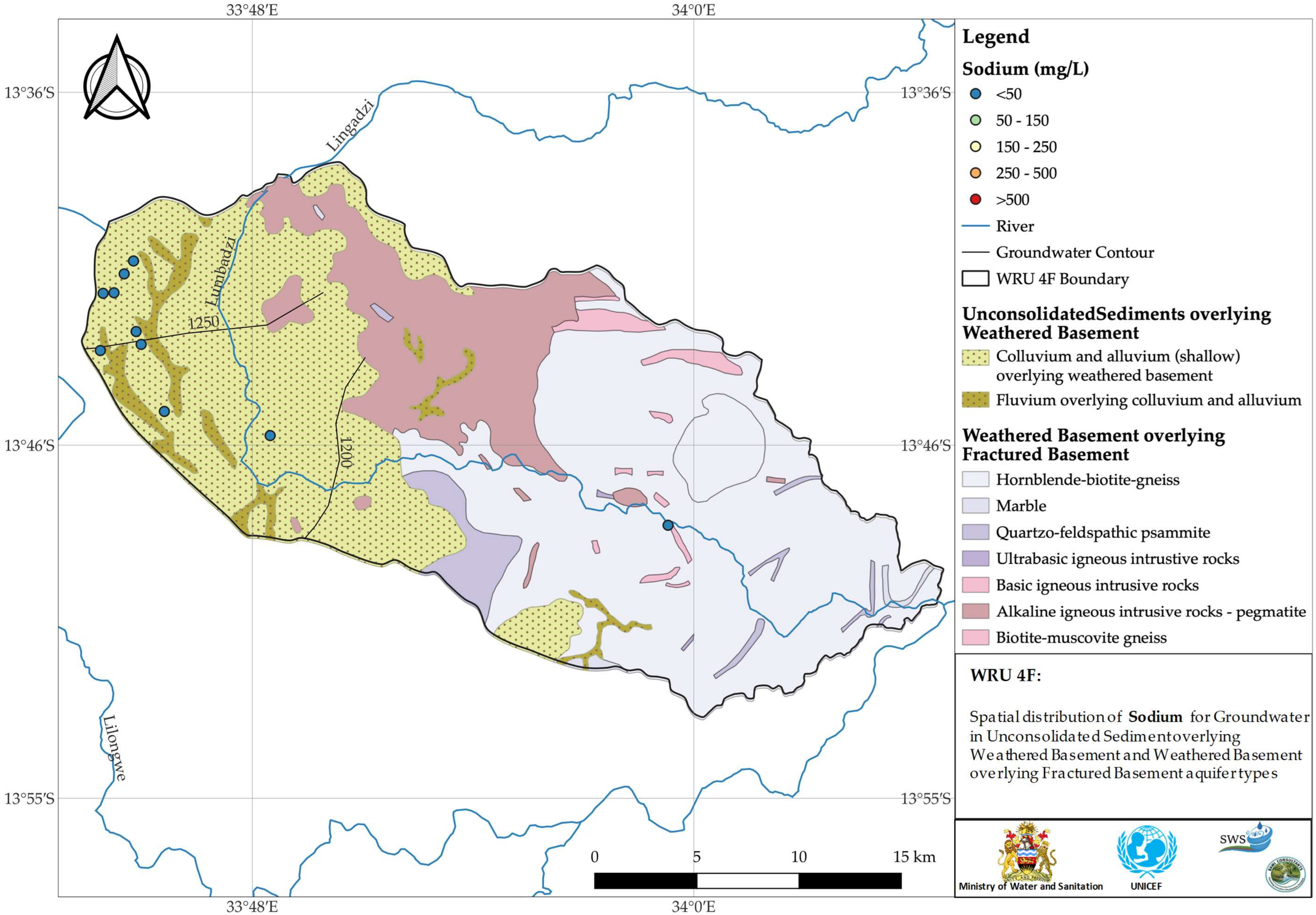


Figure WRU 4F.8 Groundwater Chemistry Distribution Calcium

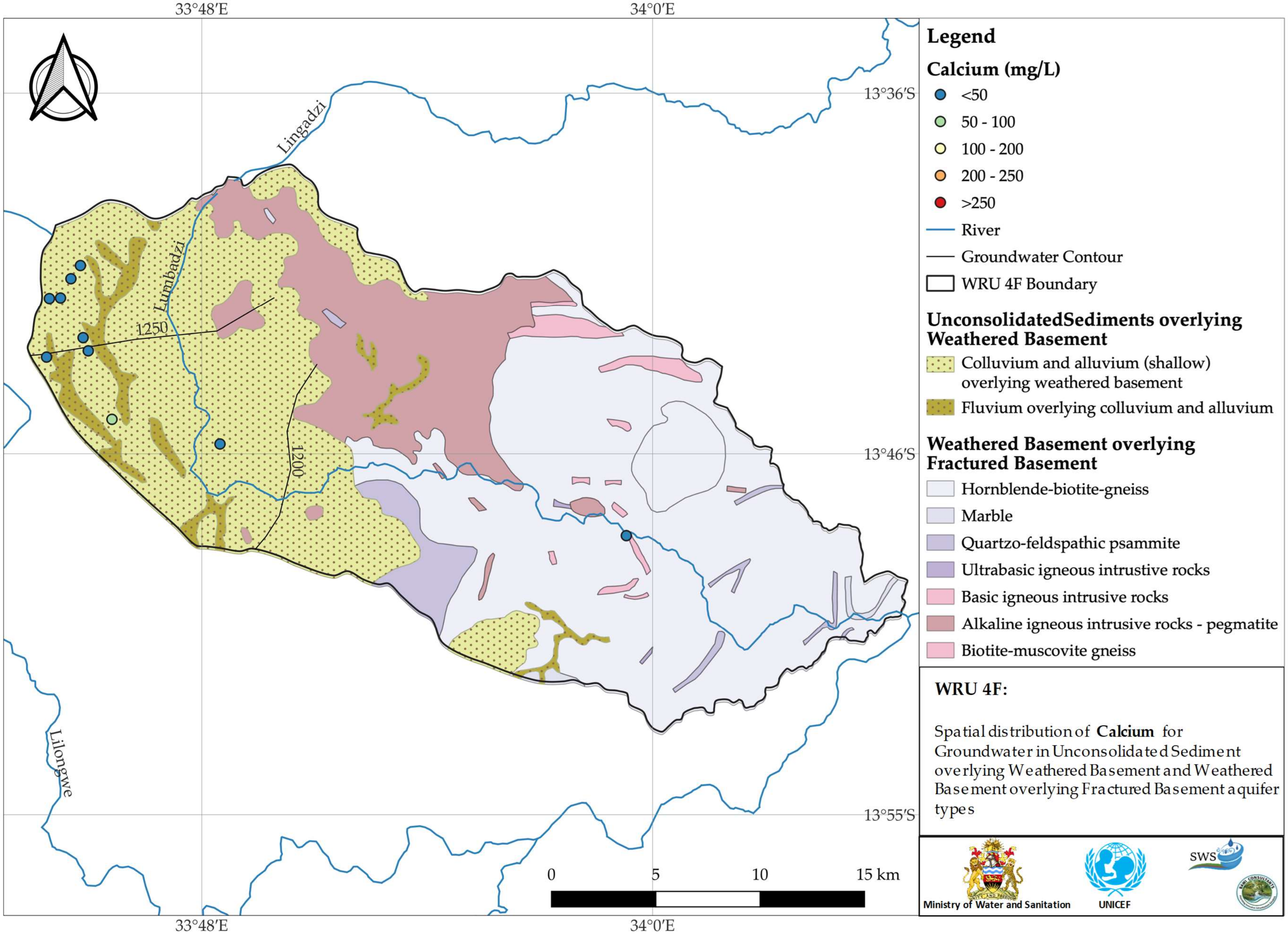


Figure WRU 4F.9 Piper Diagram of water quality results with respect to the major aquifer type

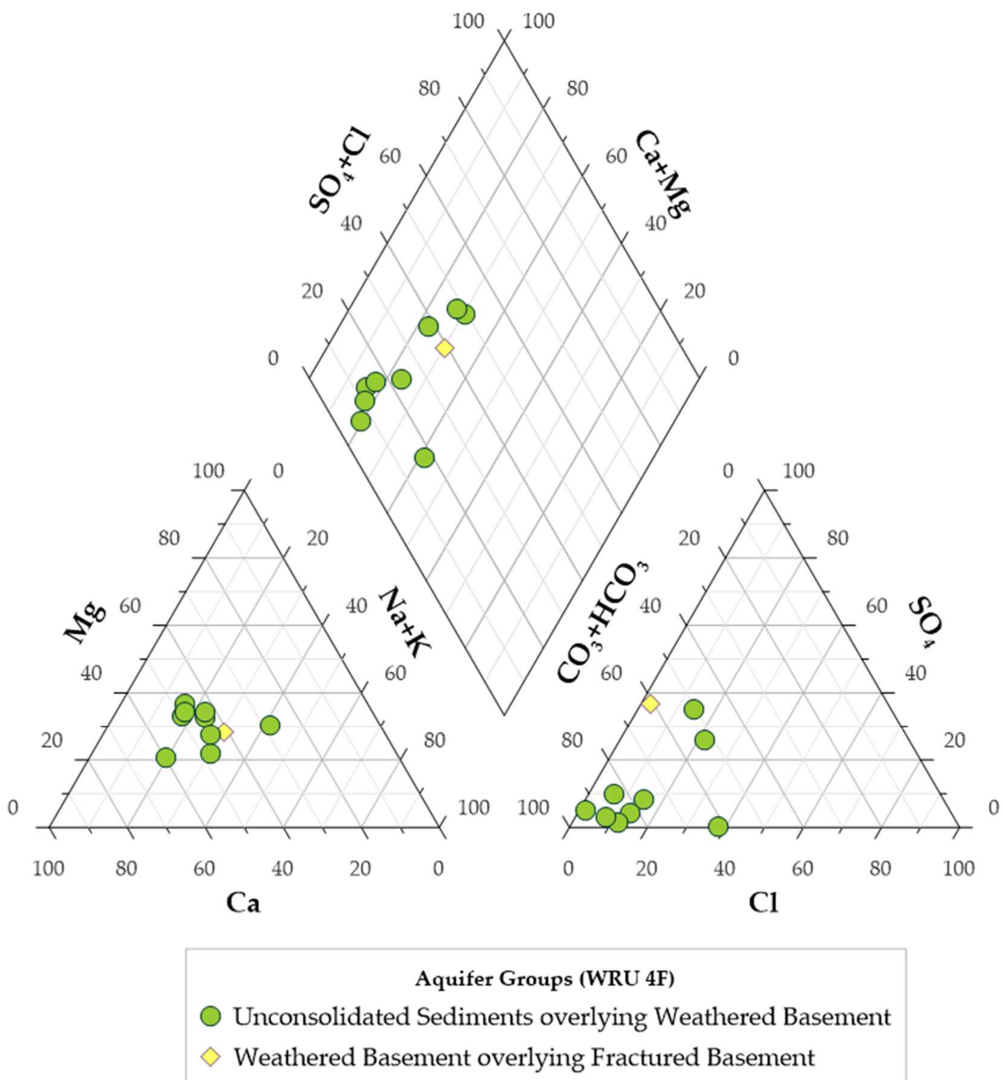
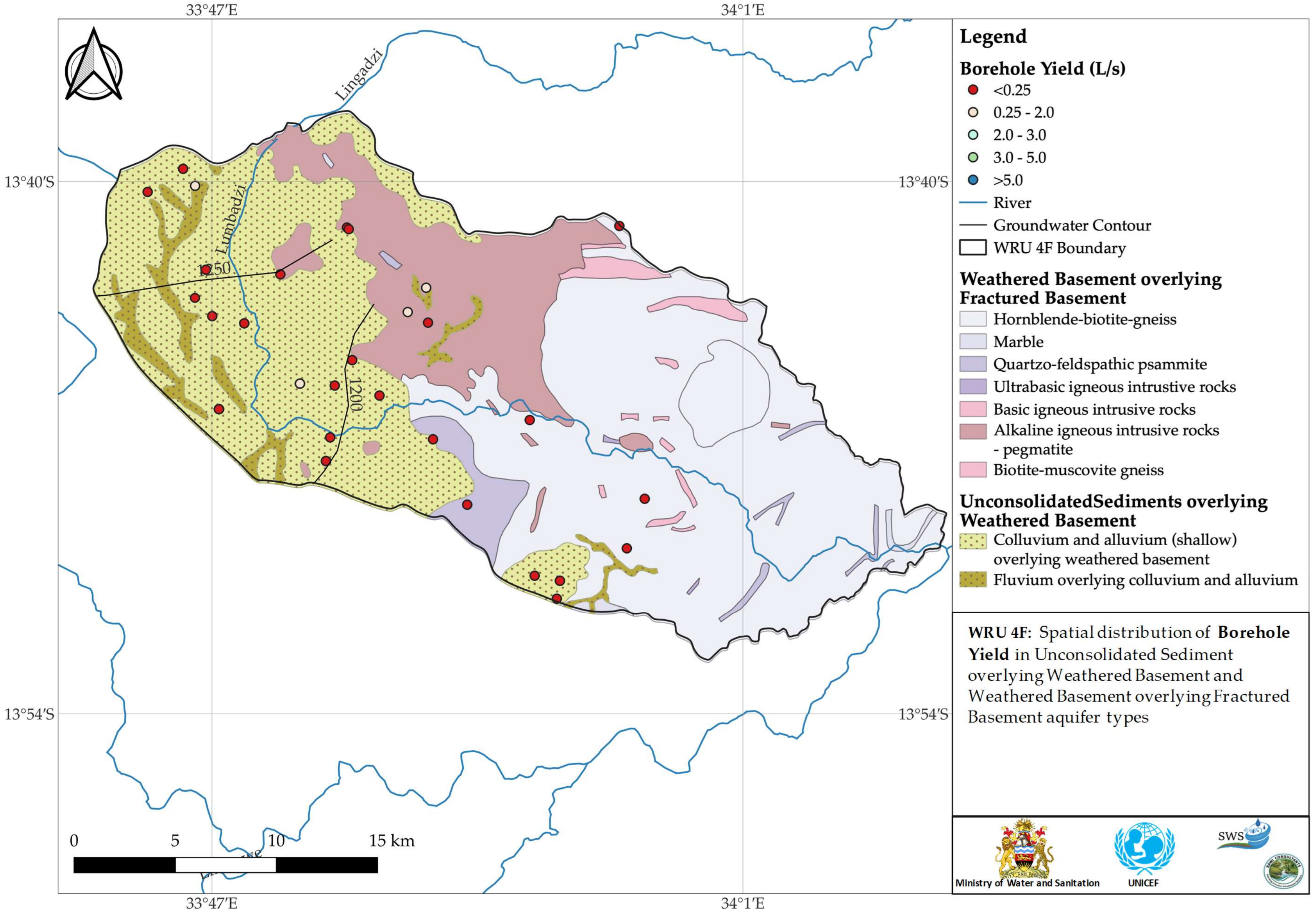


Figure WRU 4F.10 Borehole Yield Map for data held by the Ministry



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, Linthipe River Catchment, Water Resource Area 4, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-05-5 110pp*