Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 7

The South Rukuru and North Rumphi River Catchment

Ministry of Water and Sanitation

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Contents

Acronyms and Abbreviations

BAWI	BAWI Consultants Lilongwe Malawi
BGS	British Geological Survey
BH	Borehole
BY	Billion Years
$^{\circ}C$	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 7 is interpreted within the same context as presented in the Hydrogeology and Water Quality Atlas Bulletin publication. A general description of the Hydrogeology of Malawi and its various units is provided here to remind the reader of the complexity of groundwater in Malawi and its nomenclature. The various basement geologic units have variable mineralogy, chemistry, and structural history that may be locally important for water quality parameters such as Fluoride, Arsenic and geochemical evolution. Therefore, translation of geologic units to potential hydrostratigraphic units was based on the 1:250,000-scale Geological Map of Malawi compiled by the Geological Survey Department of Malawi (Canon, 1978). Geological units were grouped into three main aquifer groups for simplicity.

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

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

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

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

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

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

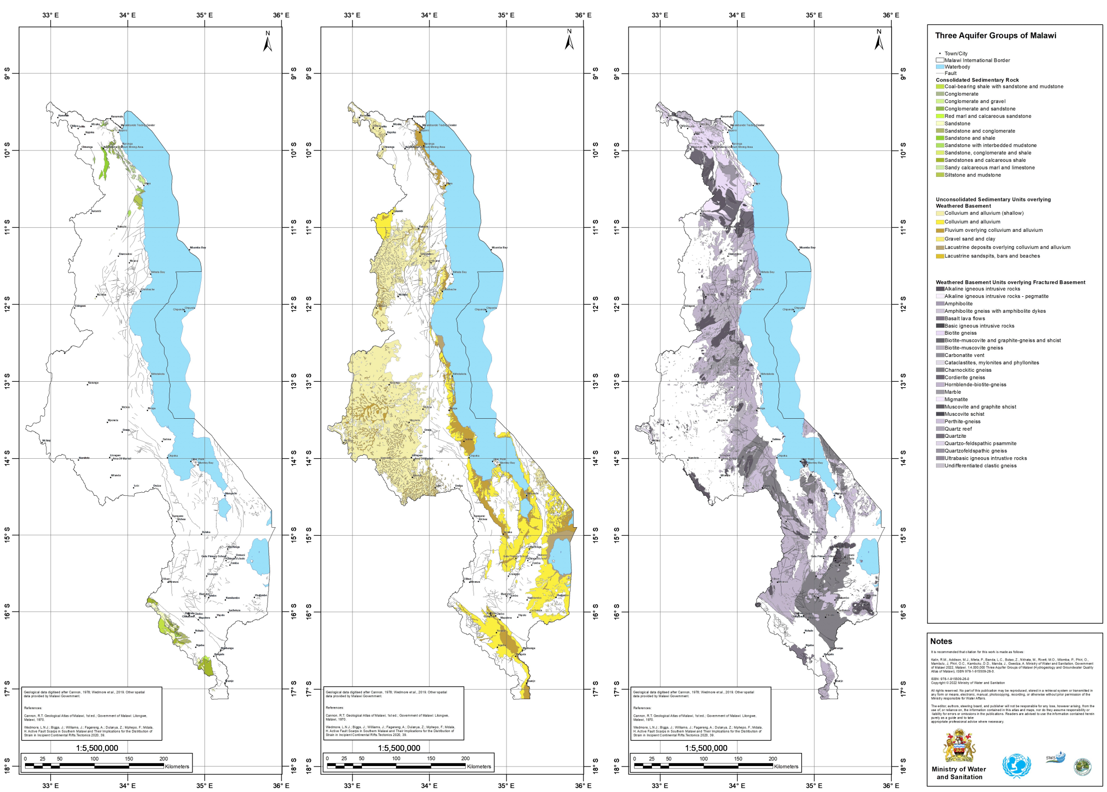


Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure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

Nomenclature: Hydrogeology of Malawi

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

Weathered Basement overlying Fractured Basement

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

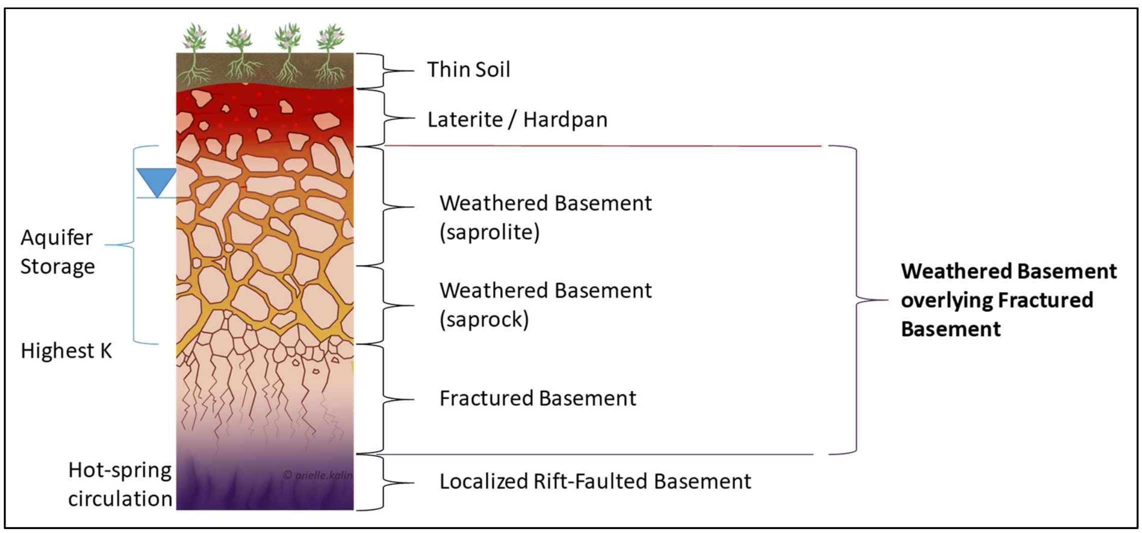


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

Unconsolidated Colluvial and Alluvial Sedimentary Units overlying Weathered Basement

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

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

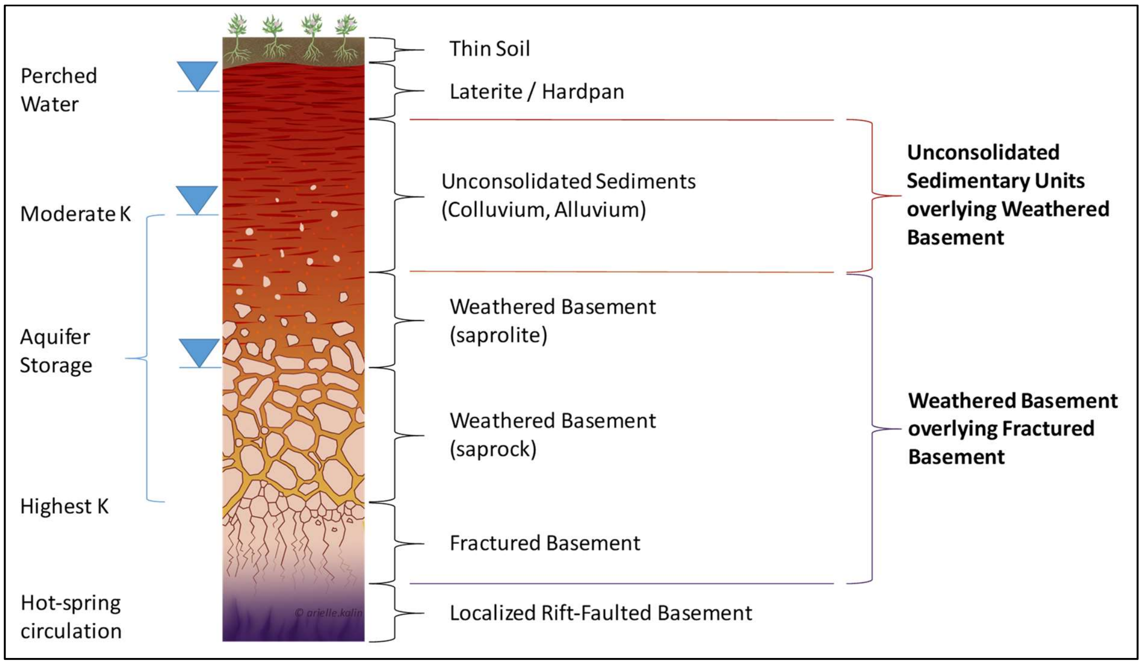


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Unconsolidated Fluvial Sedimentary Units overlying Weathered Basement

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

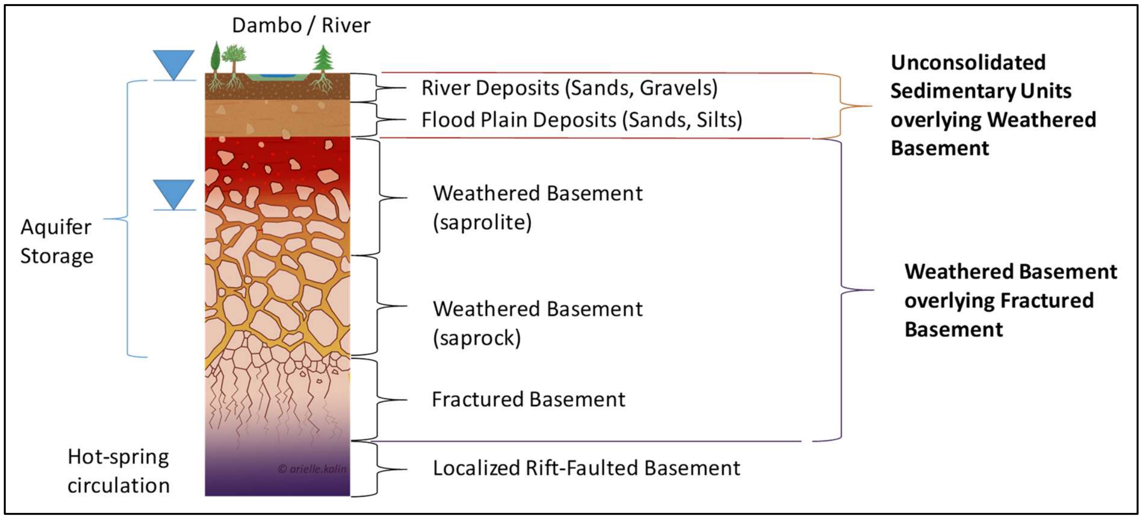


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Idealised Cross Sectional Representation of Hydrostratigraphic Units (Aquifers)

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

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

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

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

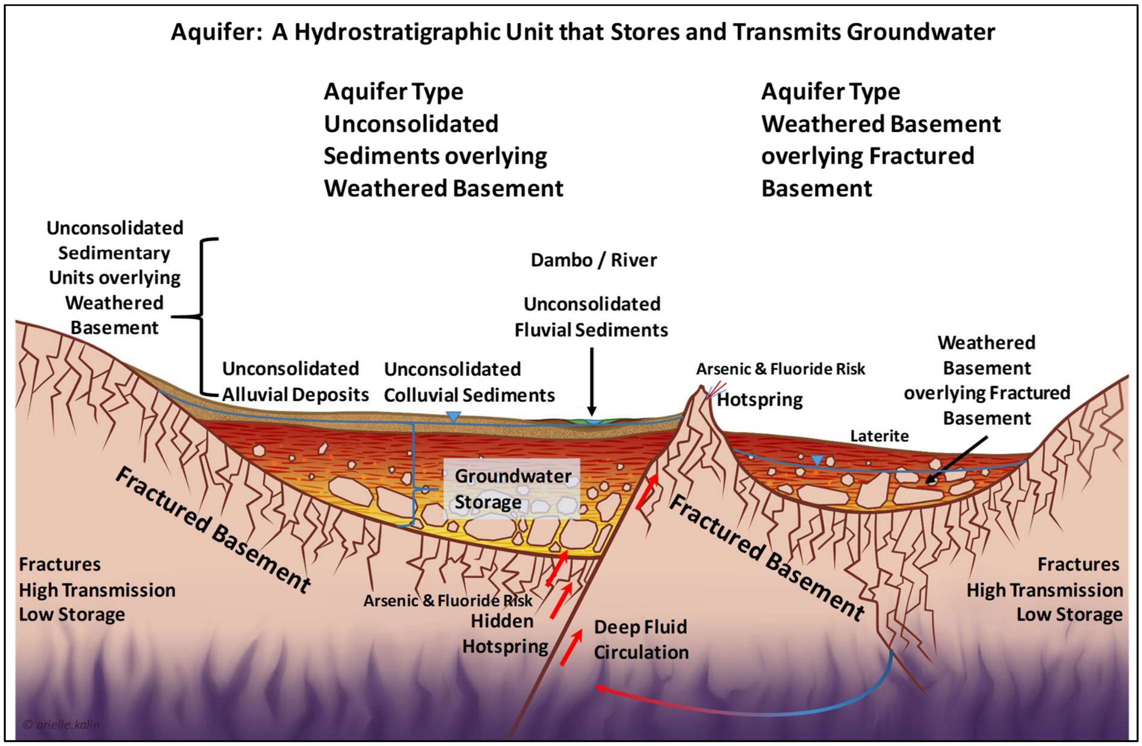


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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

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

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

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

Water Resource Area 7 (WRA 7): The South Rukuru and North Rumphi River Catchment

Water Resources Area (WRA) 7 is in northern part of Malawi (**Figure 2a**) and consists of eight (8) Water Resource Units (WRUs): WRU 7A, WRU 7B, WRU 7C, WRU 7E, WRU 7D, WRU 7E, WRU 7F, WRU 7G and WRU 7H (**Figure 2b**). It covers a vast area of 12,720 Km^2, which is largely drained by South Rukuru and North Rumphi Rivers, hence called the South Rukuru and North Rumphi River Catchment. Its riverine system also constitutes Runyina River, Rumphi River, Lunyangwa River and Mzimba River.

The catchment is mostly drained by South Rukuru River emerging from Viphya Mountains and accounting 94% of the catchment's surface water drainage to Lake Malawi. The South Rukuru River flows through meandering gorge over several rapids as it drains into Lake Malawi. Rumphi River emerging from Nyika Plateau flows through a largely uninhabited stretch of land of about 712 Km^2. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of longer seasonal tropical convergence zone precipitation and adjective storms from moisture carried from the Mozambique channel. The catchment has both surface and groundwater which are governed by Trans-boundary water sharing agreements and the transboundary nature of the water resources should be included in Integrated Water Resource Management (IWRM) planning.

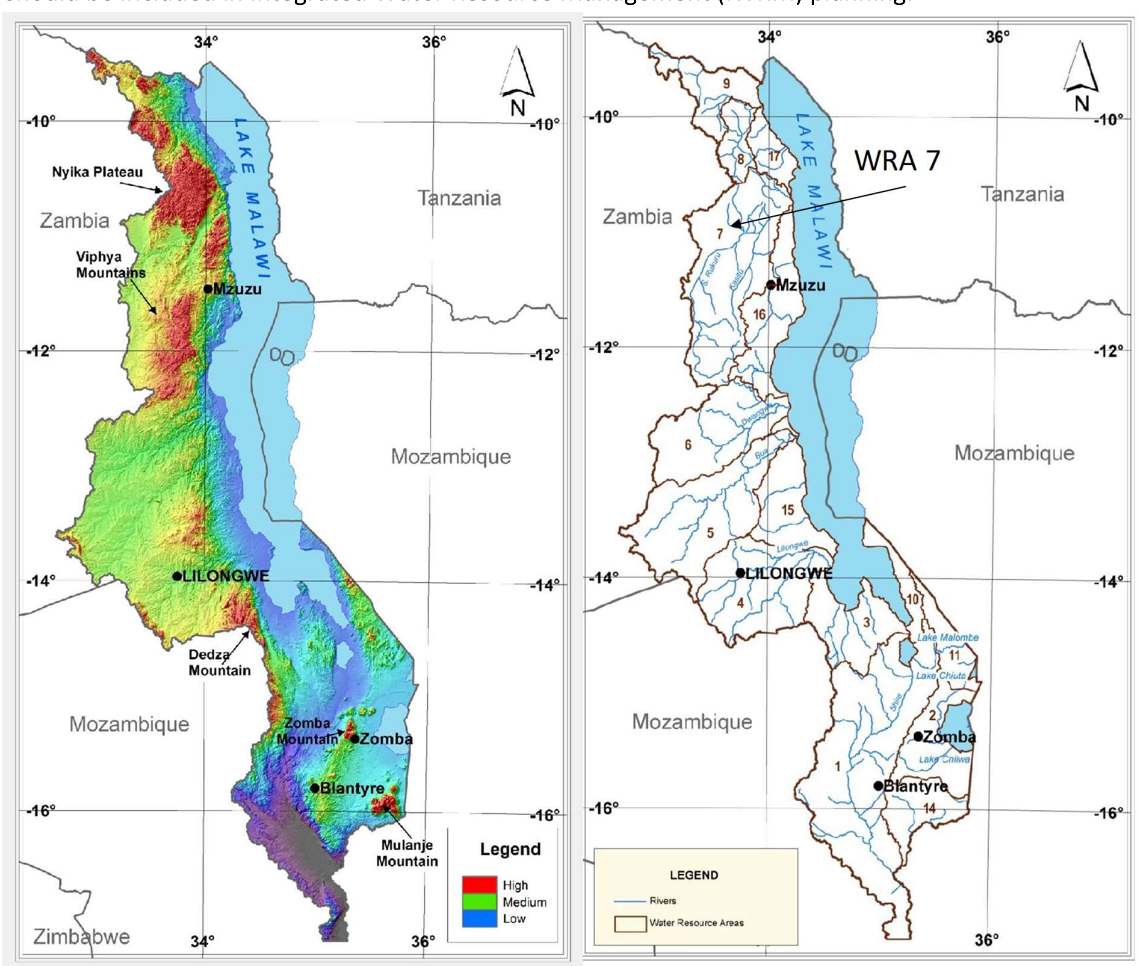


Figure 2a. Location of WRA 7 with major rivers and topography shown**.**

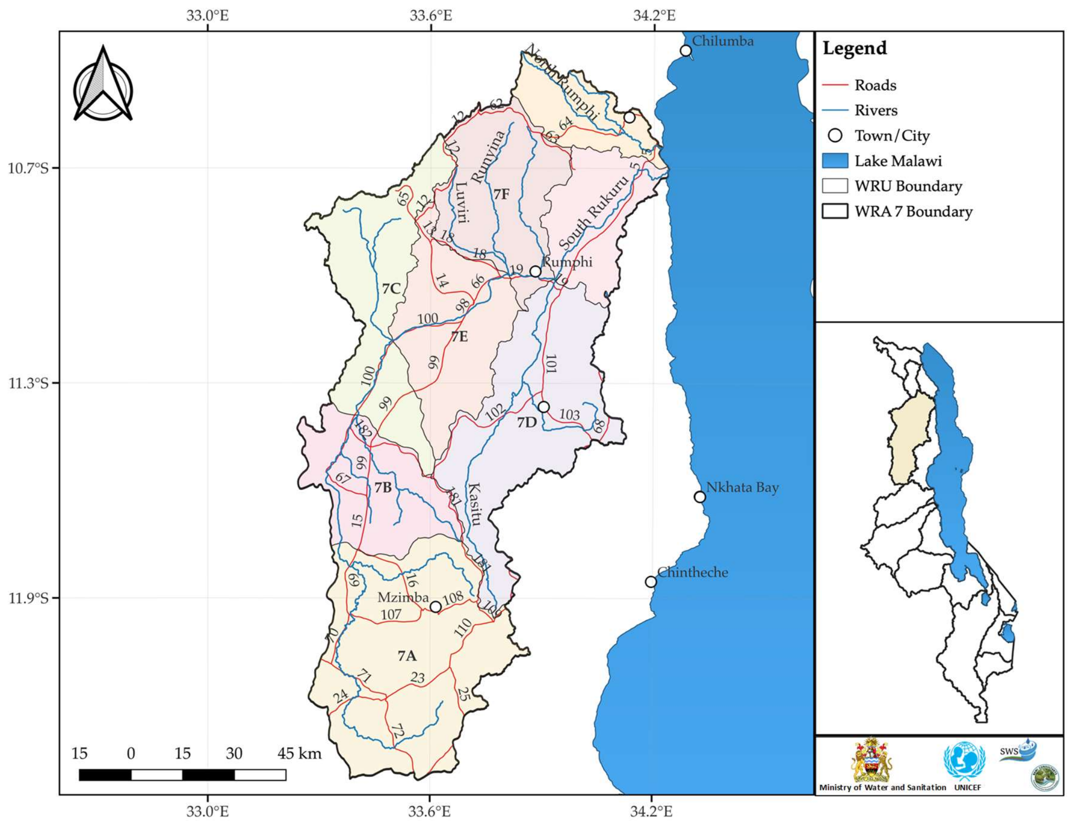


Figure 2b. Water Resource Area and Water Resource Units.

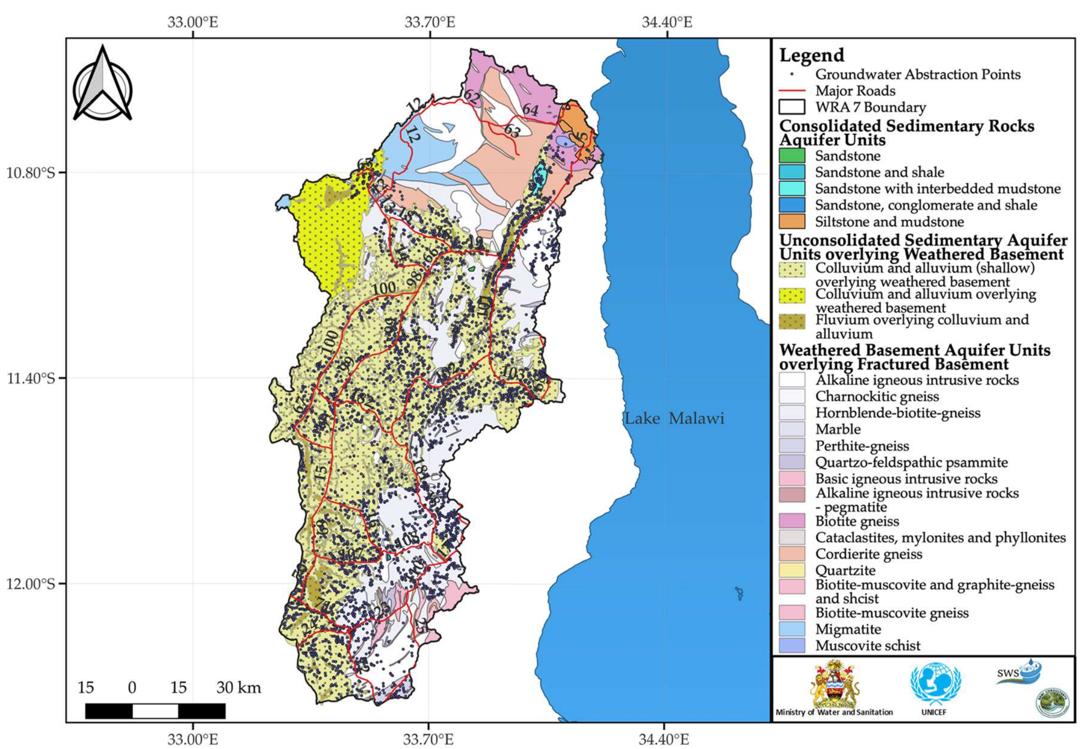


Figure 3. Distribution of groundwater abstraction points in WRA 7.

Groundwater Abstraction in WRA 7

Public abstraction points for groundwater are numerous in WRA 7 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 6,686 known groundwater abstraction points, 94.9% are improved sources (with 1,181 being protected 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 7, only 67.5% are fully functional (defined as providing water at design specification).

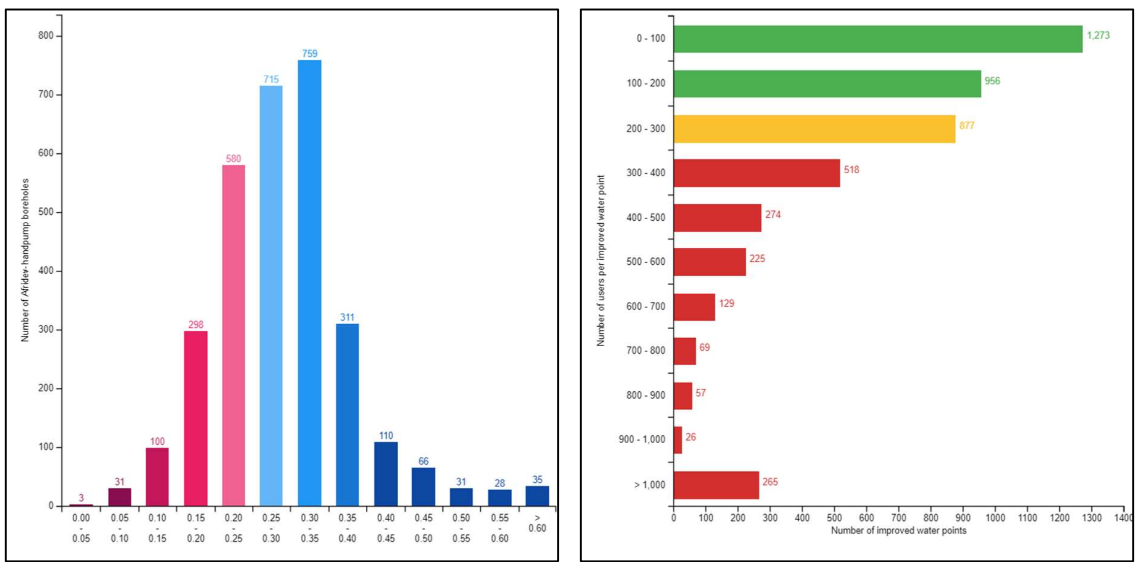
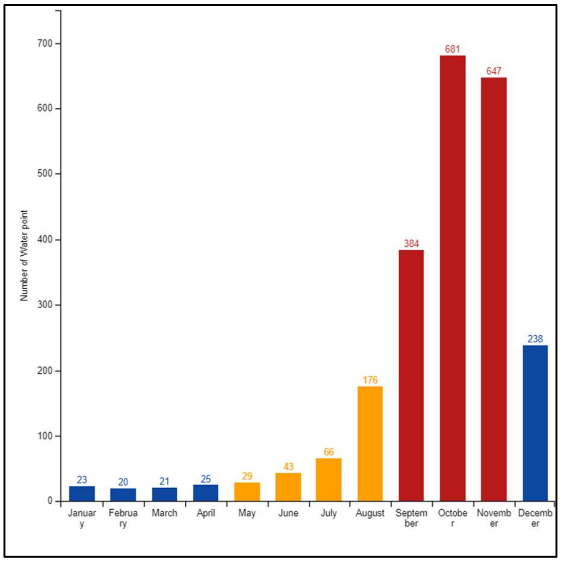


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 7 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction point. [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 7 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 (often 'self-supply' dug supplies with rope pumps which are an extreme contamination risk) may not meet the water quality guidelines, the WRA should be considered regulation of self-supplies and self-funded water quality monitoring within investment planning.

The 2020 National Water Point Survey data provides proxy information on annual water table variations as during the height of the hot-dry season, 10.2% of groundwater abstraction points do not provide sufficient water (September through November) most likely due to water table declines

(**Figure 5a and 5b**). Shallow boreholes and dug wells (protected and unprotected) are the most heavily impacted, impacting the functionality of these water supplies. There is a strong correlation between the depth of the groundwater water supplies and the decline in seasonal water availability, and is assumed this is due to shallow dug well supplies or improperly installed boreholes that are more at risk to lowering water tables resulting in lower functionality during the dry season.



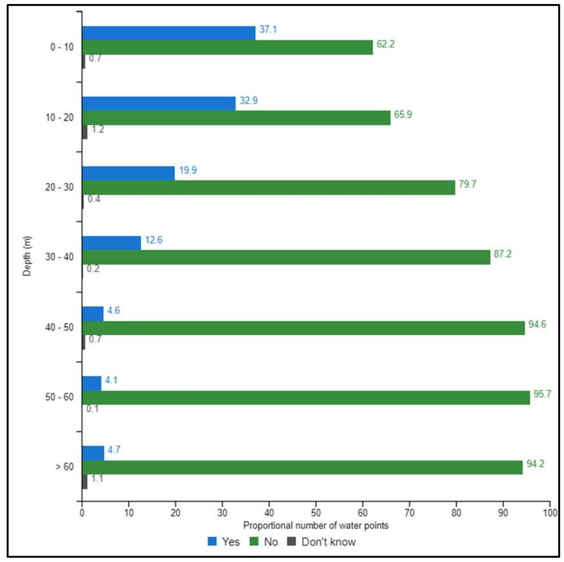
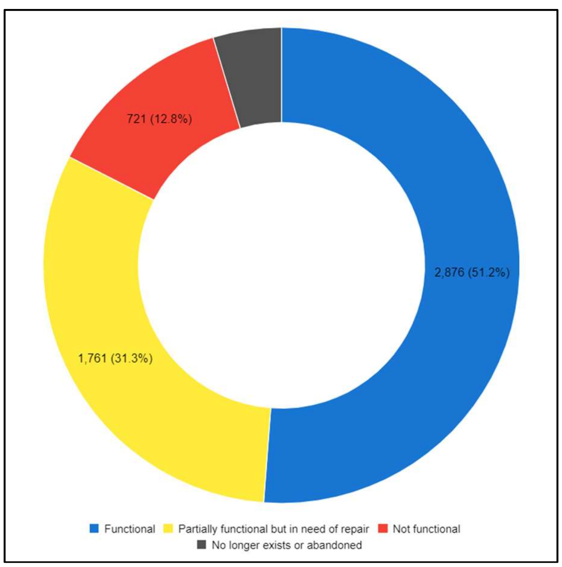


Figure 5a and 5b. Number of groundwater abstraction points in WRA 7 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].



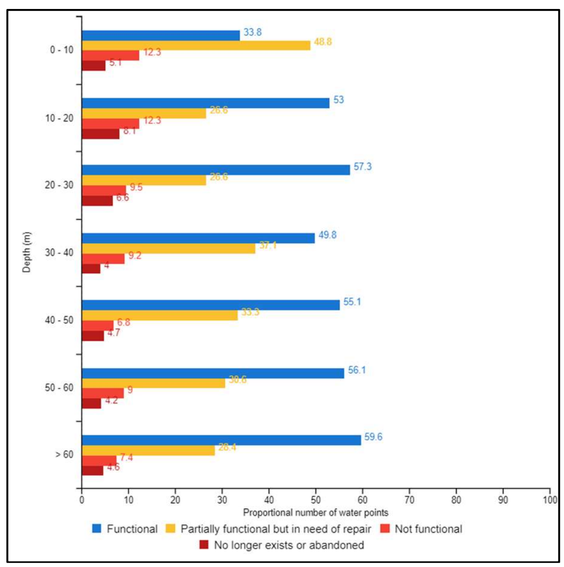


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 7 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water 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 51.2% 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 7 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 7 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tubewell	4,519
Protected dug well	1,818
Protected spring	12
Unprotected dug well	309
Unprotected spring	28

Description of Water Resources WRA 7

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 eight (8) Water Resource Units (WRUs): WRU 7A, WRU 7B, WRU 7C, WRU 7E, WRU 7D, WRU 7E, WRU 7F, WRU 7G and WRU 7H (**Figure 7a – 7h**). It covers a vast area of about 12,720 Km^2, which is largely drained by South Rukuru and North Rumphi Rivers, hence called the South Rukuru and North Rumphi River Catchment. Its riverine system also constitutes Runyina River, Rumphi River, Lunyangwa River and Mzimba River. 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.

The catchment is mostly drained by South Rukuru River emerging from Viphya Mountains and accounting 94% of the catchment's surface water drainage to Lake Malawi. The South Rukuru River flows through meandering gorge over several rapids as it drains into Lake Malawi. Rumphi River emerging from Nyika Plateau flows through a largely uninhabited stretch of land of about 712 Km^2.

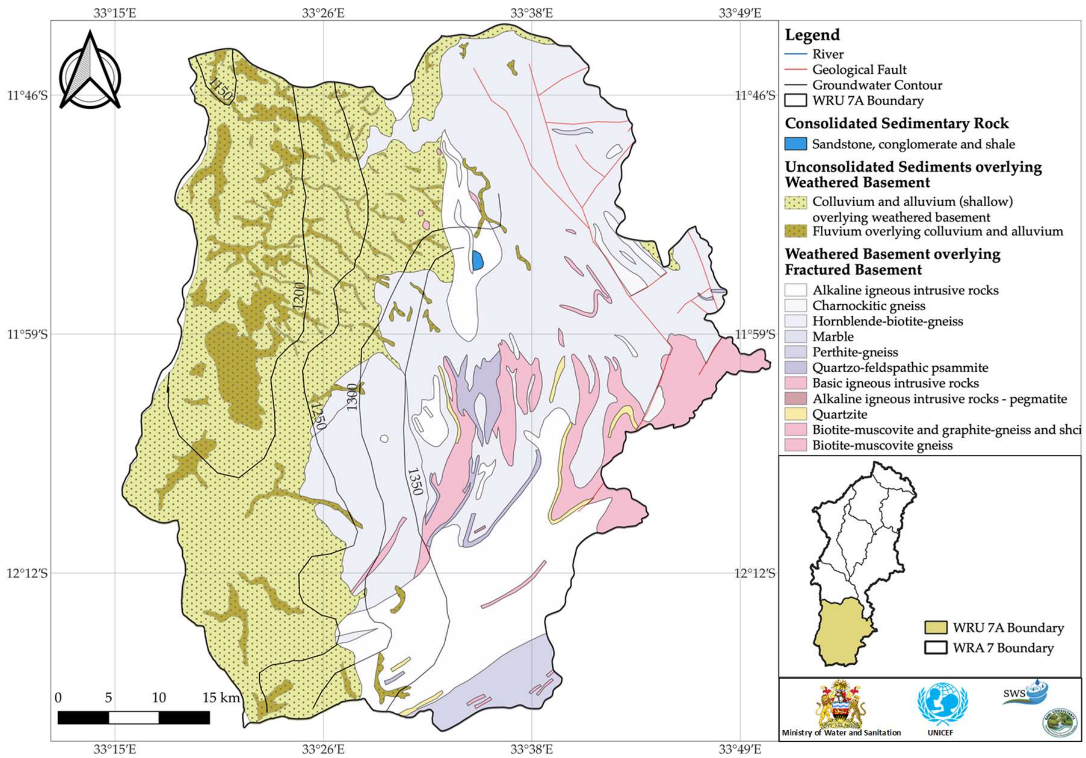


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 7A wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

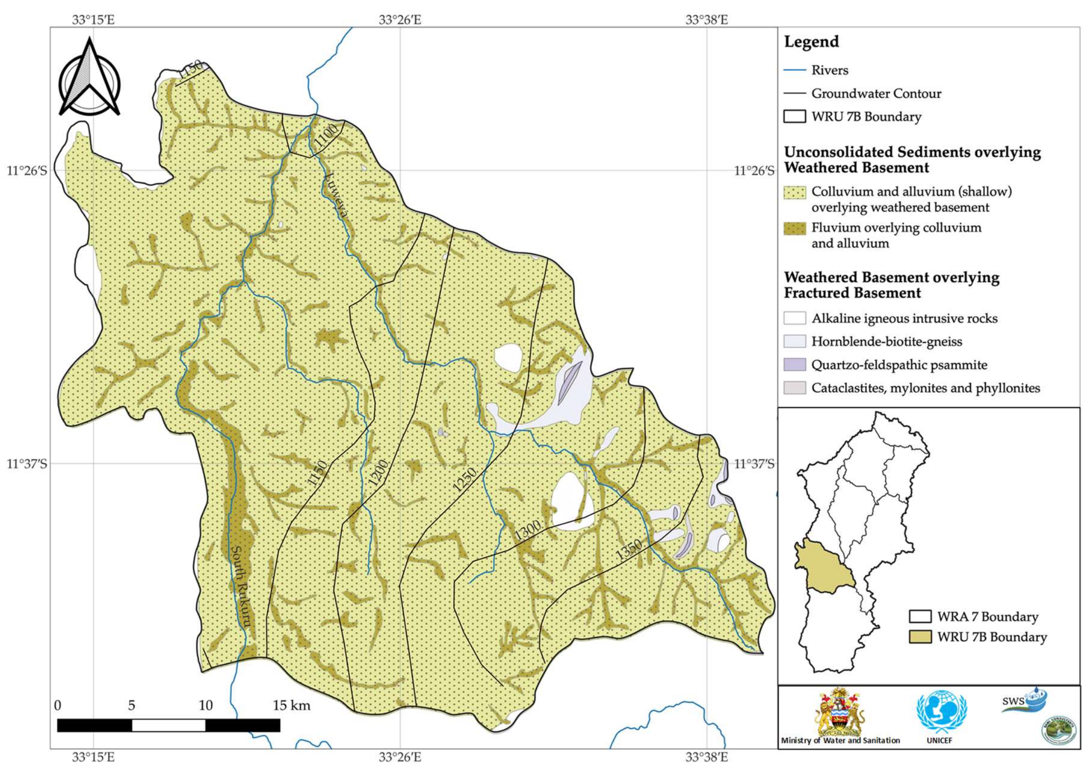


Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 7B wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

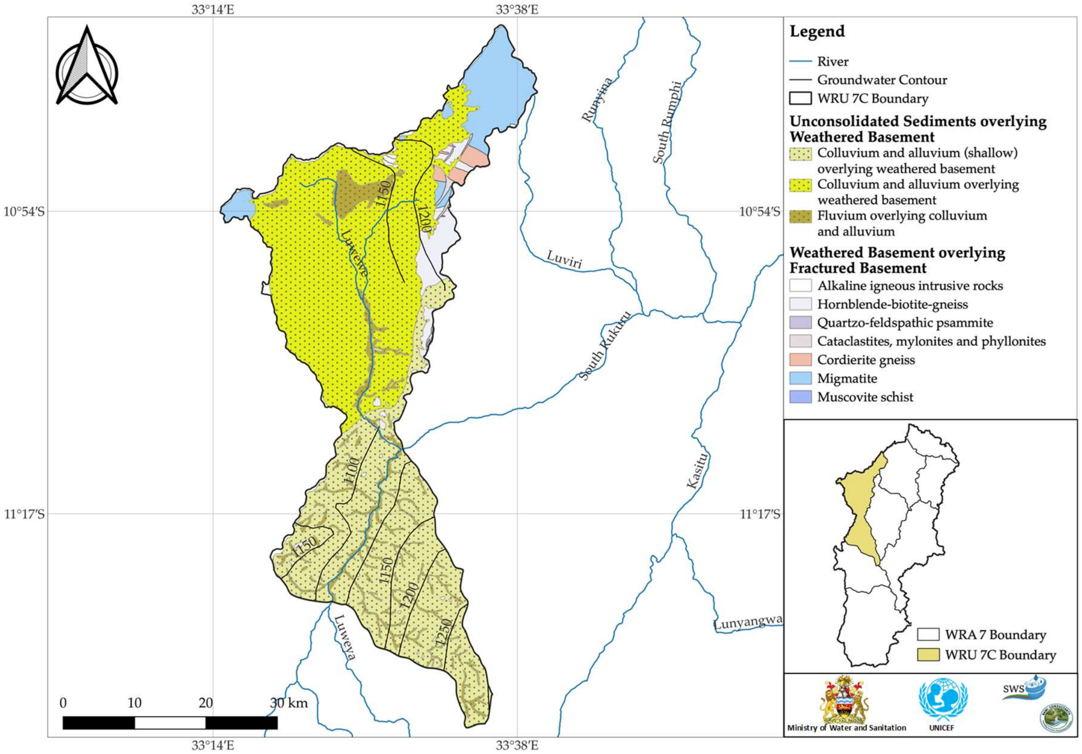


Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 7C wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

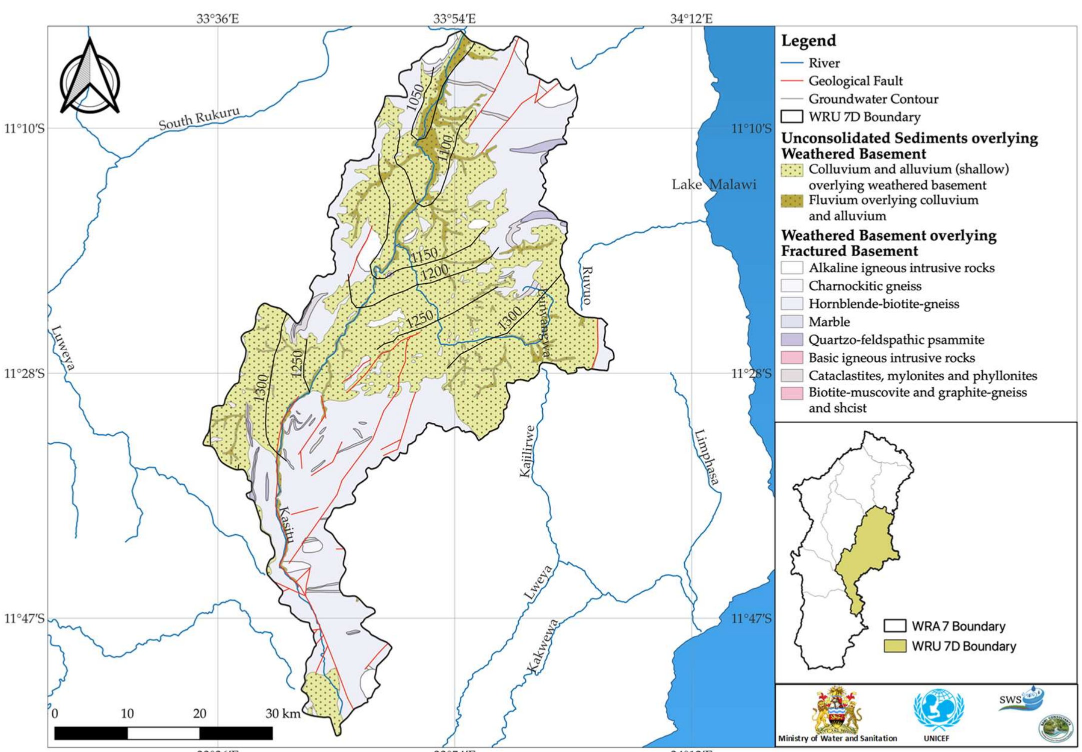


Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 7D wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

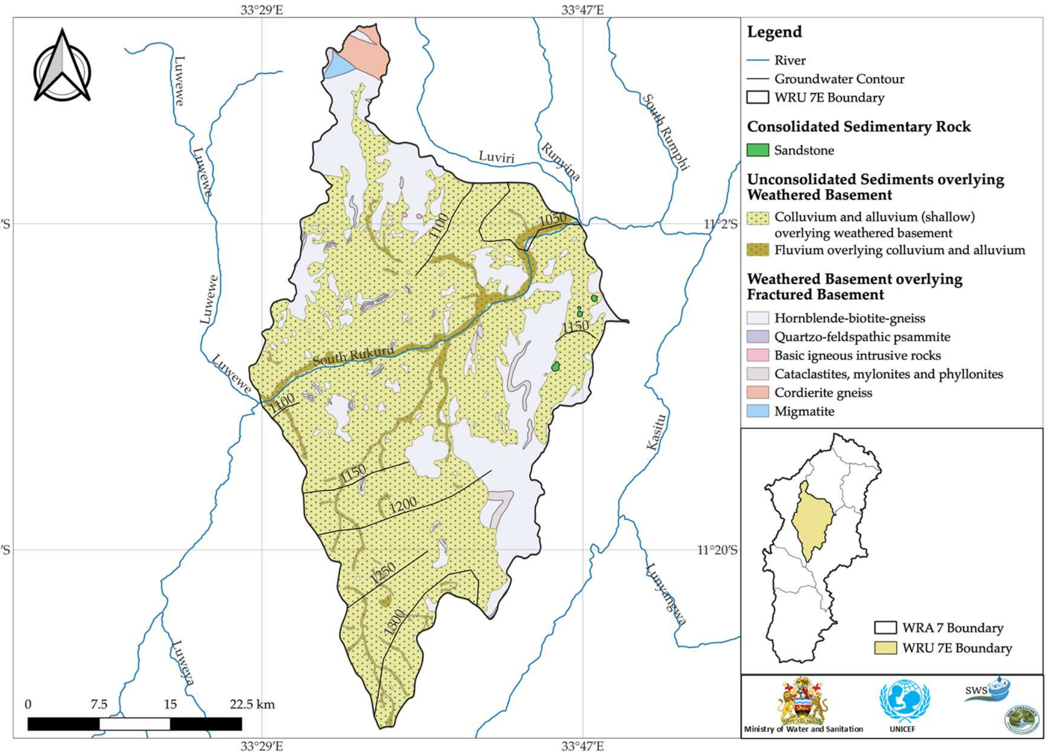


Figure 7e. Map showing the hydrogeologic units and water table for Water Resource Unit 7E wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

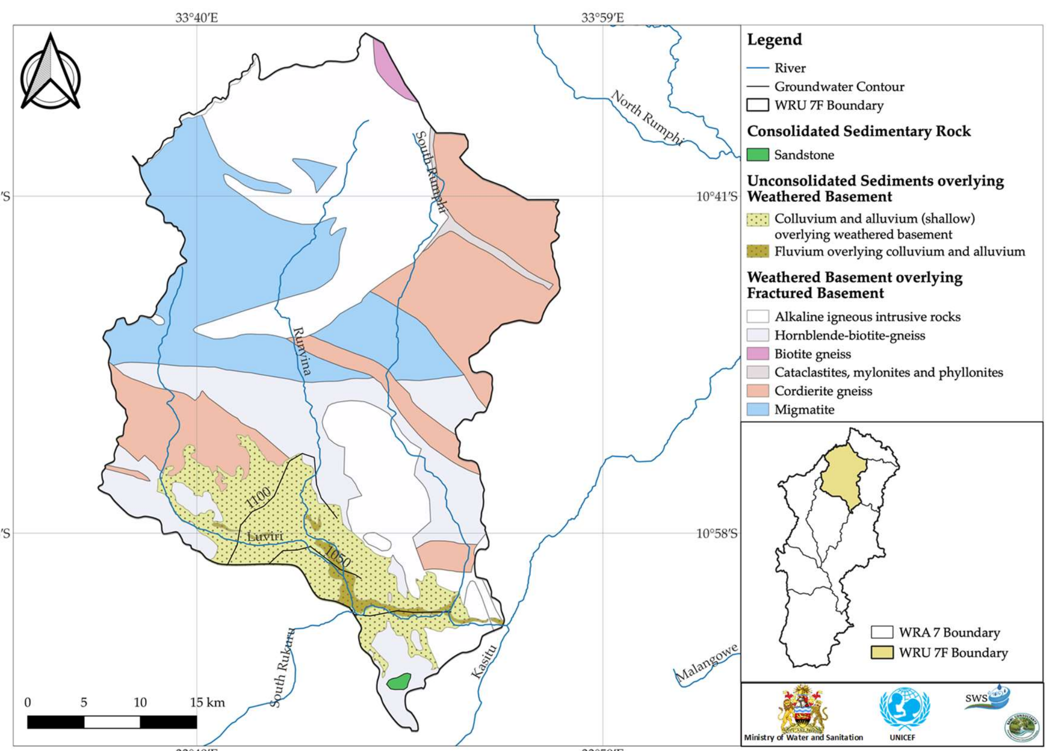


Figure 7f. Map showing the hydrogeologic units and water table for Water Resource Unit 7F wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

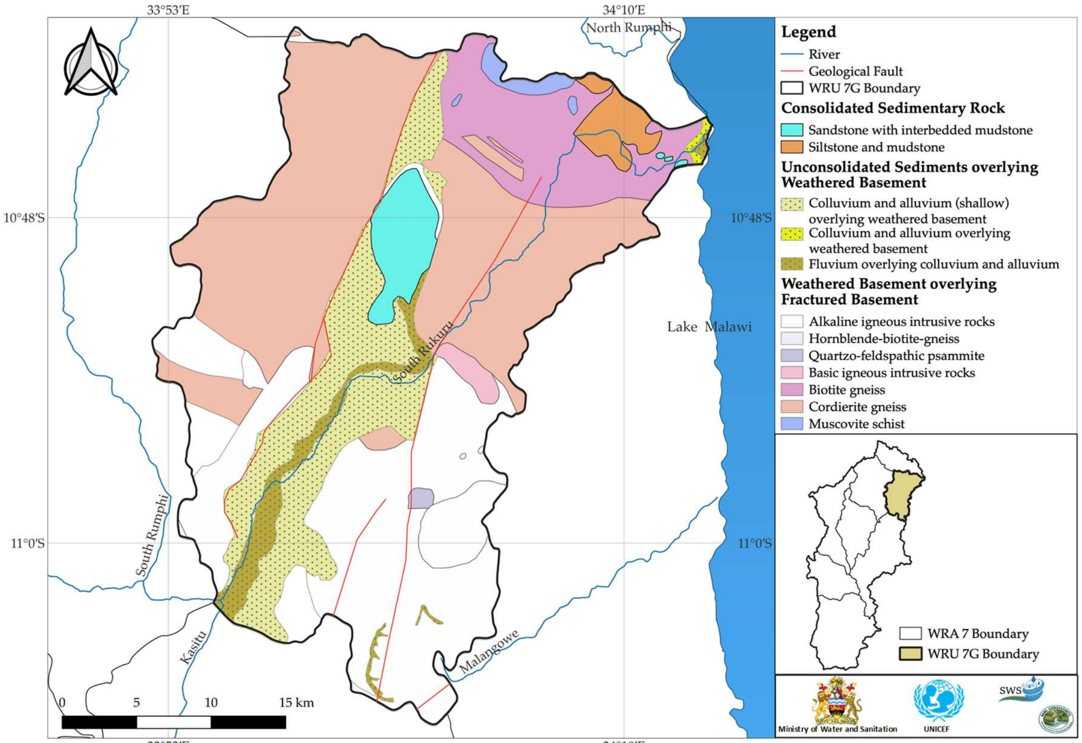


Figure 7g. Map showing the hydrogeologic units and water table for Water Resource Unit 7G wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

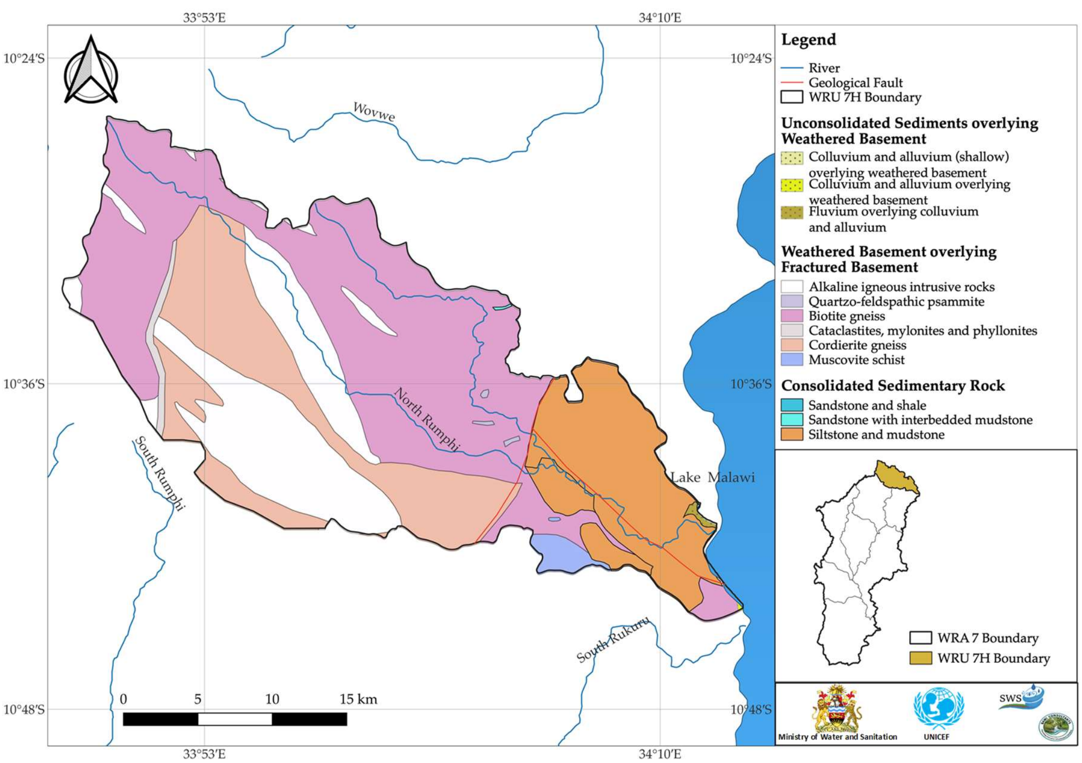


Figure 7h. Map showing the hydrogeologic units and water table for Water Resource Unit 7H wtihin Water Resource Area 7 (South Rukuru and North Rumphi River Catchment).

Topography and Drainage

The catchment is occupied by flat plains, broad dambos and swamps in the southern part that lies between 1,070 and 1,830 m asl in altitude, whereas Vwaza March Wildlife Reserve and Nkhamanga plains occupying the central part lies between 1,000 and 1,100 m asl. Nyika Plateau, harbouring natural flora and fauna, lies between 2,000 and 2,600 m asl and bears headwaters of Runyina and Rumphi Rivers. (**Figure 8**).

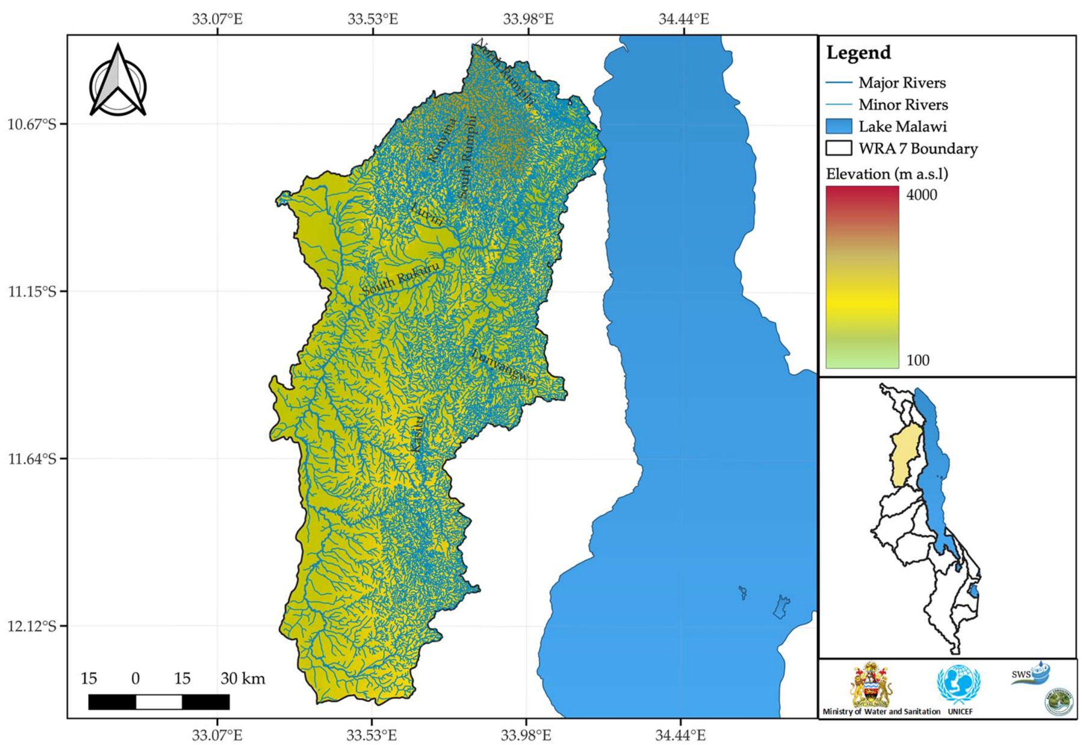


Figure 8. Drainage for the major rivers in Water Resources Area 7.

Geology – Solid

Solid geology in WRA 7 is limited to small isolated exposures of hornblende-biotite gneiss and micaceous phyllonites in the south, and regional-scale outcrops of Precambrian - Lower Palaeozoic granites, biotite gneisses, and cordierite-silliconite gneisses of the Pre-Mafingi group. The extent of basement outcrops south of the Nyika Plateau is unknown due to extensive sediment cover (**Figure 7a – 7h**).

Geology – Unconsolidated deposits

WRA 7 is dominated by Tertiary - Recent unconsolidated sediments which overlie weathered basement rock from the Pre-Mafingi Group. The area is a regional sedimentary basin truncated by the Malawi Rift escarpment to the east, and the Nyika Plateau to the north. It is predominantly composed of colluvium and alluvium from surrounding highlands. The basin hosts the South Rukuru River which drains the area north to the Nkhamanga Plain, then east over the rift escarpment and into Lake

Malawi. Fluvial sediments and isolated dambos are present where rivers and ephemeral streams occur within the basin.

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 such as Viphya and Nyika Plateaus spans between 1,200 – 1,600 mm annually (long-term data not available for modelling) (**Figure 9**), peak rainfall occurs between December and March. High rainfall in the mountain region results in periodic and severe flooding in the catchment.

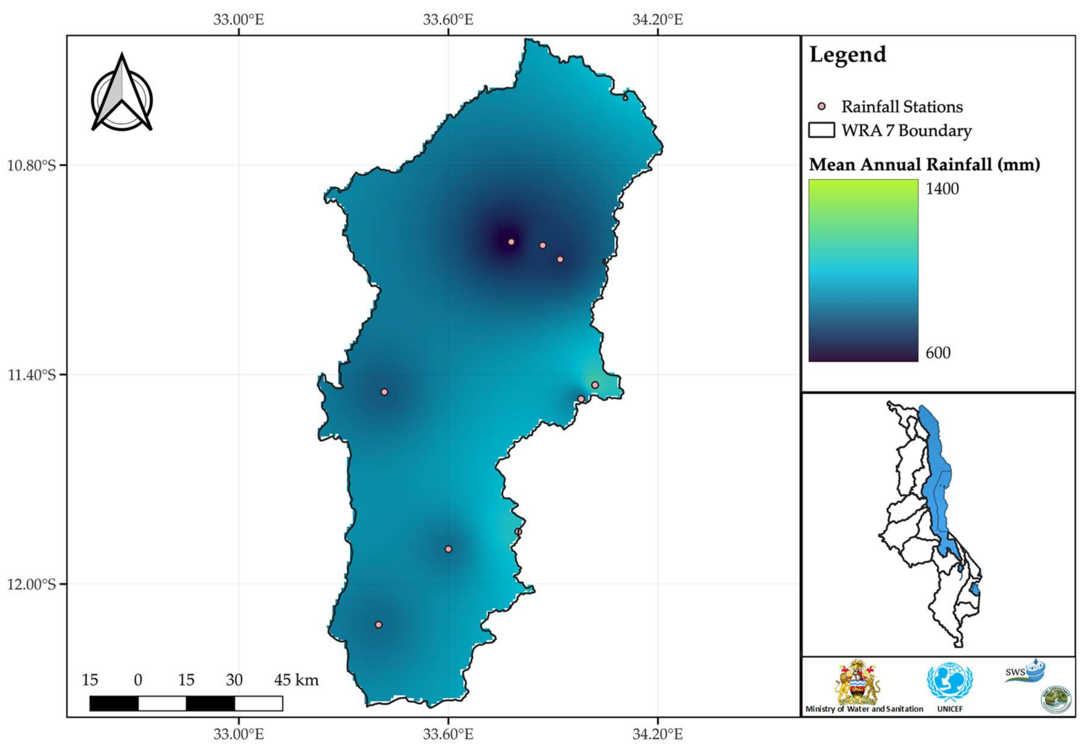


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 7 with the location of weather stations. Average rainfall measured is 822mm, average rainfall modelled is 853 +/- 75mm (range 623 to 1,118mm).

Land use

The WRA 7 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.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 7. 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)
7	A	Mbawa/Mzimba	809	881
	B	Euthini	768	853
	C	- No Station -	-	833
	D	Zombwe/Mzuzu/Bwengu	879	905
	E	Bolero	622	795
	F	Rumphi	714	783
	G	- No Station -	-	810
	H	- No Station -	-	939

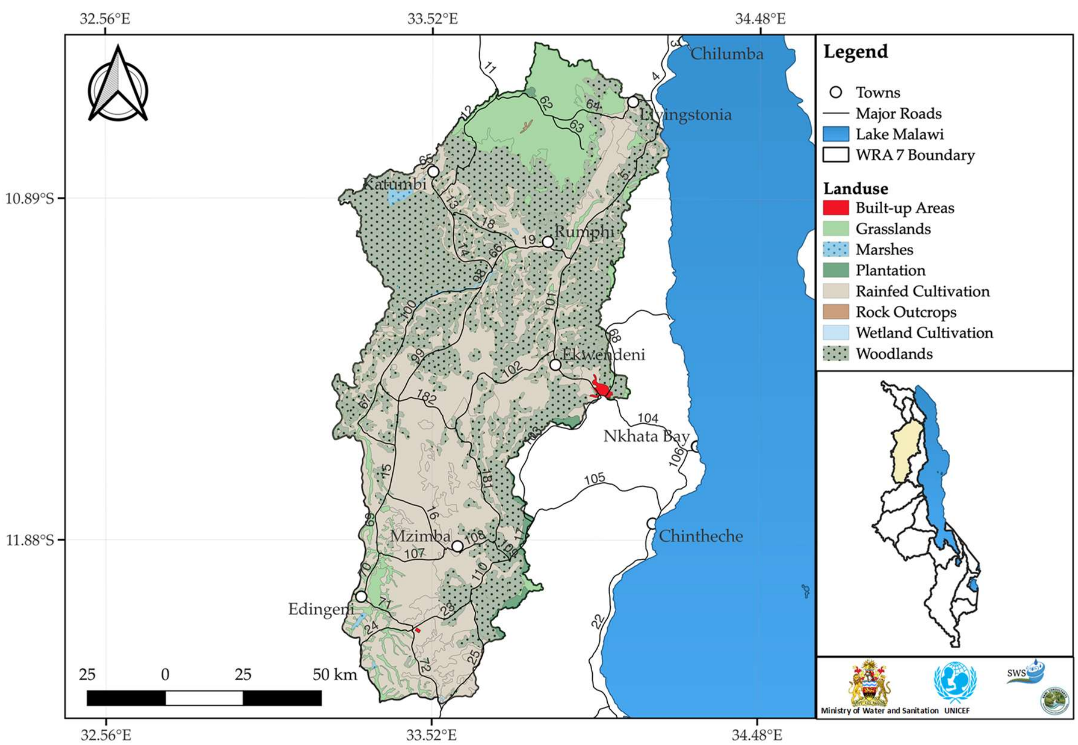


Figure 10. Land use in WRA 7 is dominated by woodlands, grasslands and rain fed agriculture.

Hydrogeology of WRA 7

Aquifer Properties

The dominant aquifer type in WRA 7 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.

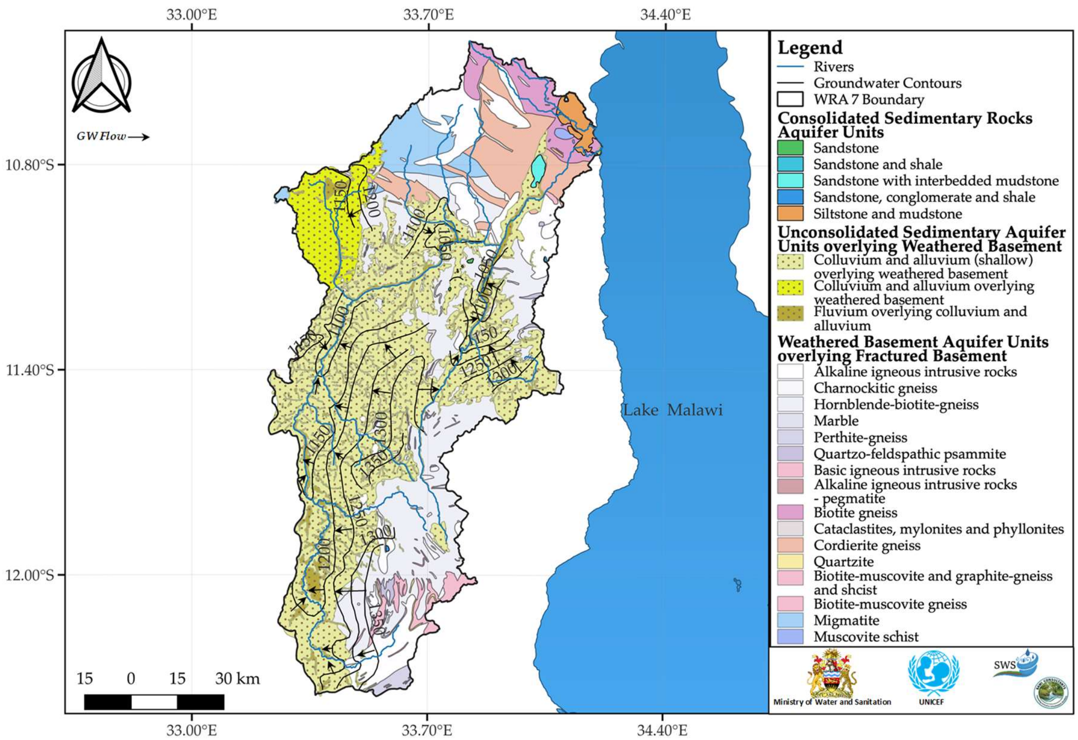


Figure 11. Groundwater level contours and flow direction in WRA 7 [1987 Hydrogeological Reconnaissance data] [water level contour interval 50m]

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 7 is based on prior hydrogeological reconnaissance.

Groundwater level data for WRA 7 based on prior hydrogeological reconnaissance confirm a system flow regime closely following topographic drainage (Figure 11). Groundwater flows in the unconsolidated deposits aquifer tend to closely follow the valley topography, draining down the valley length or locally towards rivers and other water features such as dambo or larger lakes/lagoons. The valleys will drain the adjoining, often steeply sloping fractured Basement rock. Groundwater flows in WRU 7A in the southwest catchment headwaters are overall northwards along and towards the South Rukuku River that tracks the western national boundary surface-water divide flowing northwards. Within this overall flow regime, significant flow components to the west exist as groundwater migrates from the eastern valley flanks to discharge at the river or dambo wetlands that extensively occur along or near to the national boundary. Hydraulic gradients from the valley flanks towards the Rukuku are moderate to high at around 0.01 declining somewhat further north in WRU 7B to 0.007 where the valley opens out with decreased topographic relief. These gradients calculate velocities of 13 – 18 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2.

A groundwater flow divide occurs around the intersection of WRUs 7A, 7B and 7D around the centre of the basin mirroring the local surface-water divides. The more easterly groundwater migrates along the eastern limb of weathered Basement tracking northeast along the narrow Kasitu River valley. The greater majority of groundwater though migrates along the wider South Rukuku valley to the north that also trends north east, moving away from the western national boundary. Groundwater flows into the valley are augmented by groundwater north of the Rukuku migrating south-eastwards from WRU catchment 7E and south from 7C located at the national north-east boundary of WRA 7. Hydraulic gradients are quite variable at entry and within both the South Rukuku and Kasitu valleys due to the contorted flow lines within the complex valley intersection with gradients approximately varying over 0.002 to 0.01. Head contours though generally strongly converge on both rivers inferring groundwater base flows are significant.

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 7 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 7 (**Figures 13a to 13g**) there is some potential in the colluvium, alluvial and fluvial units for higher yielding boreholes, in particular where there are reported yields over 2l/s, and there is potential for artesian confined systems along the escarpment but detailed hydrogeological on-site mapping should be undertaken to confirm.

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 7 (note: limited data in WRU 7G and no data 7H) (y axis = *n* observations).

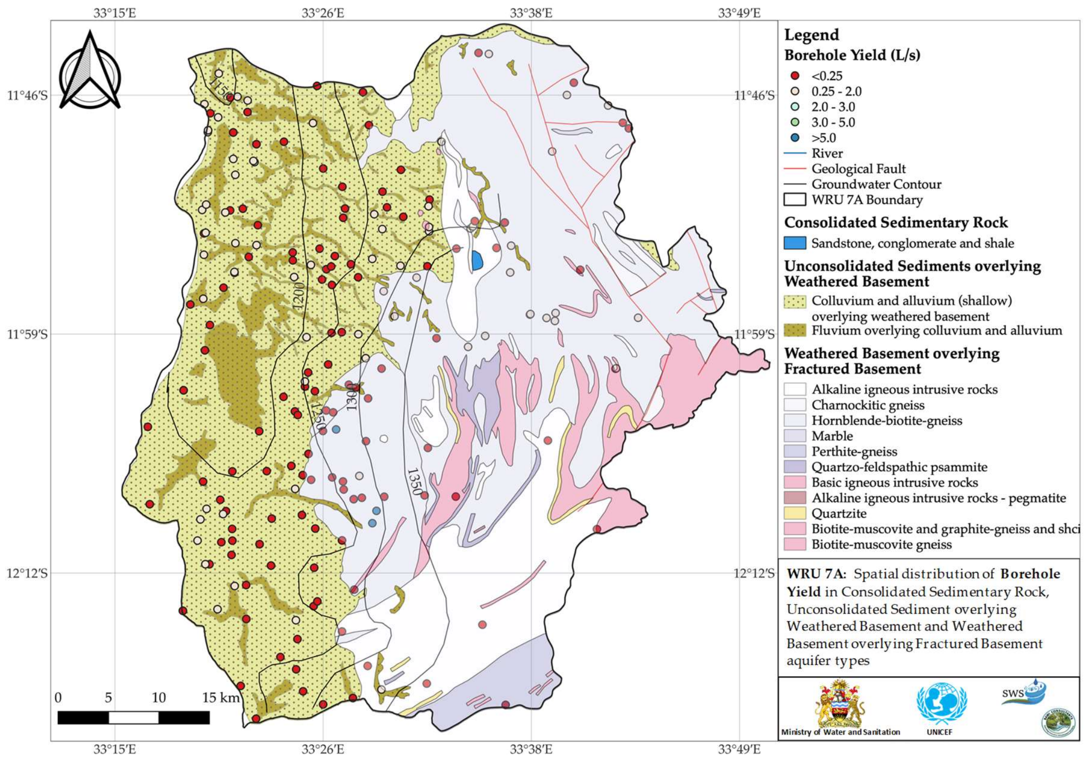


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7A.

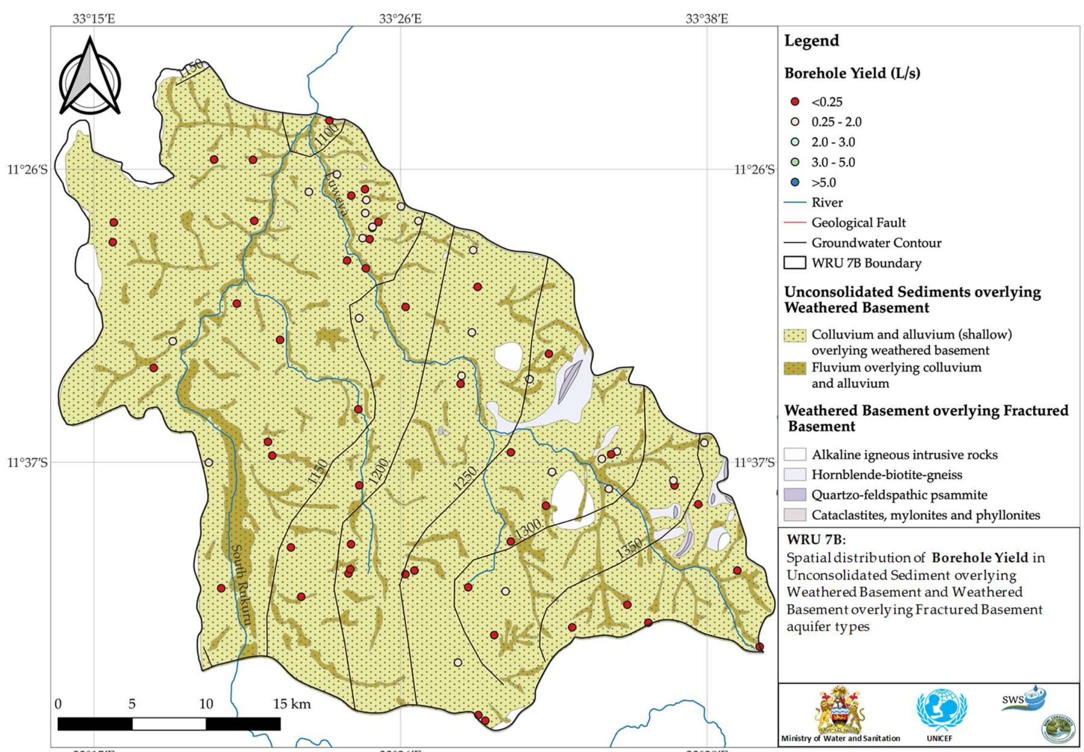


Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7B.

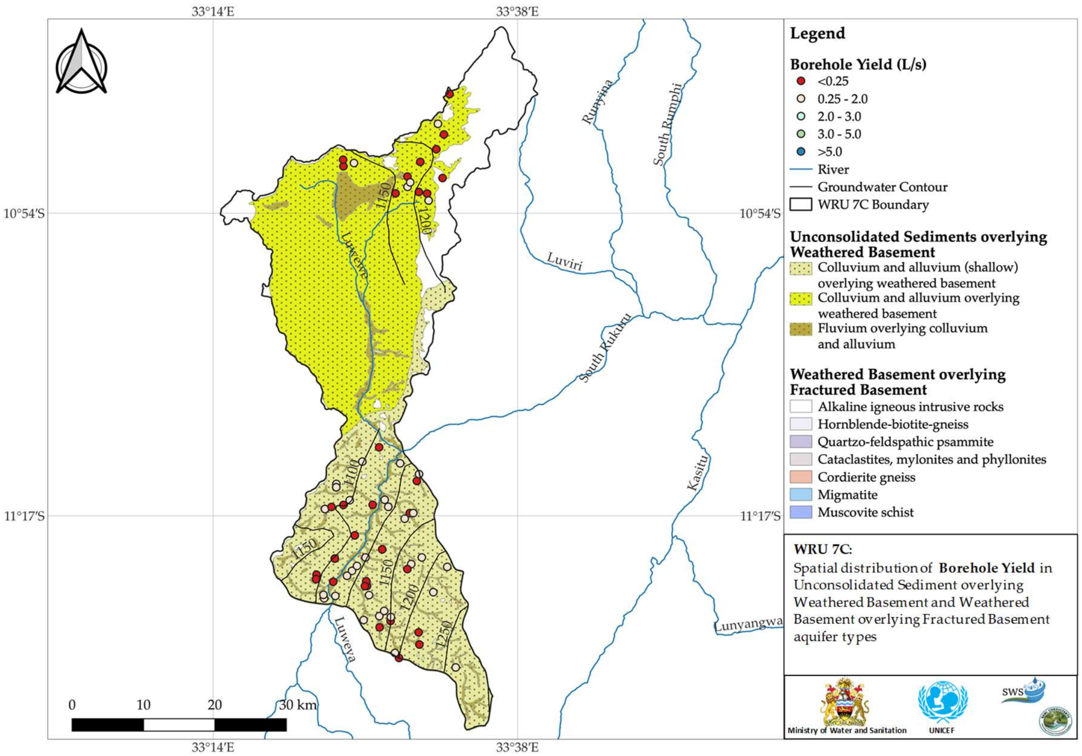


Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7C.

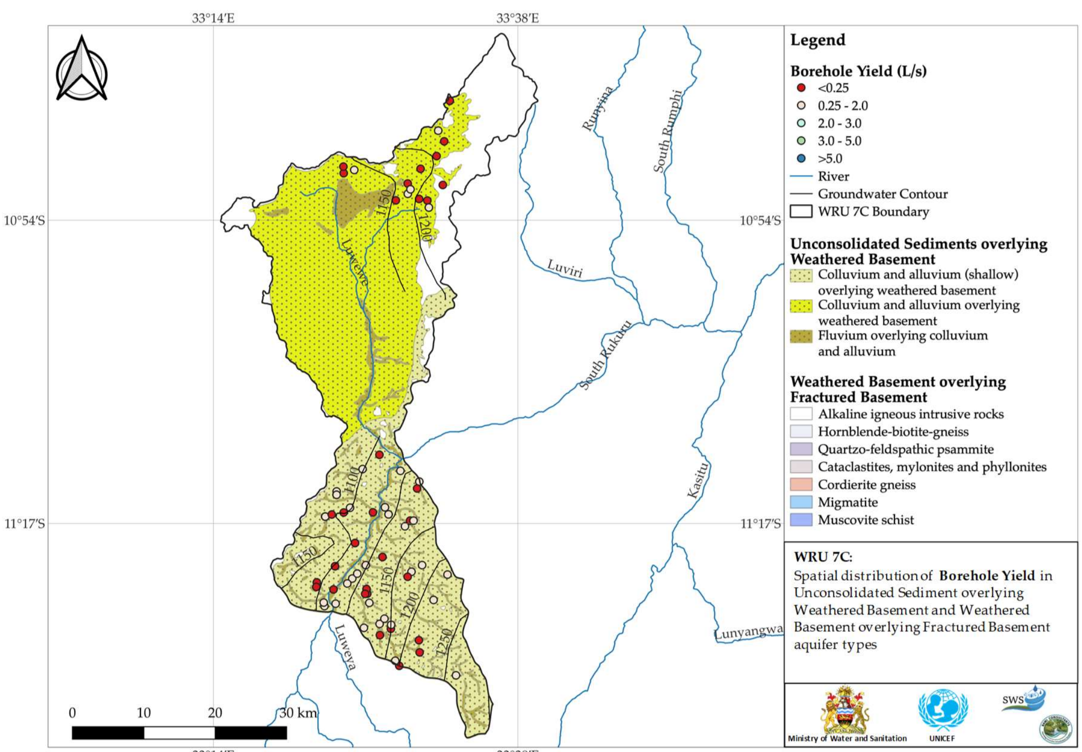


Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7D.

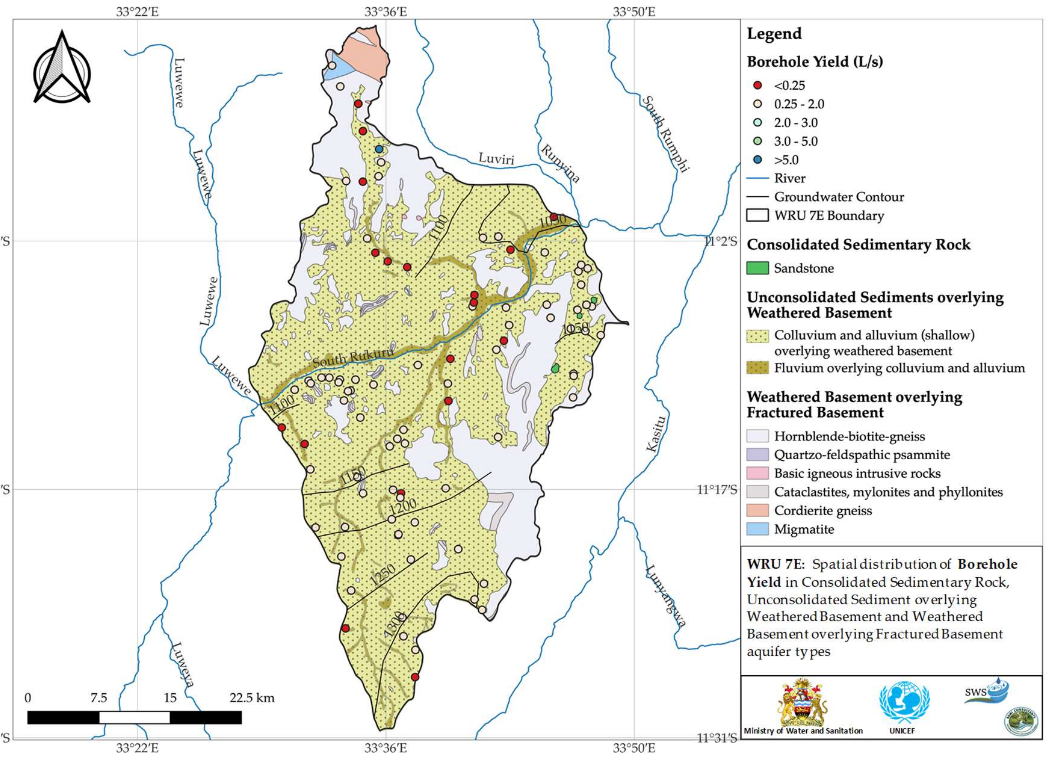


Figure 13e. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7E.

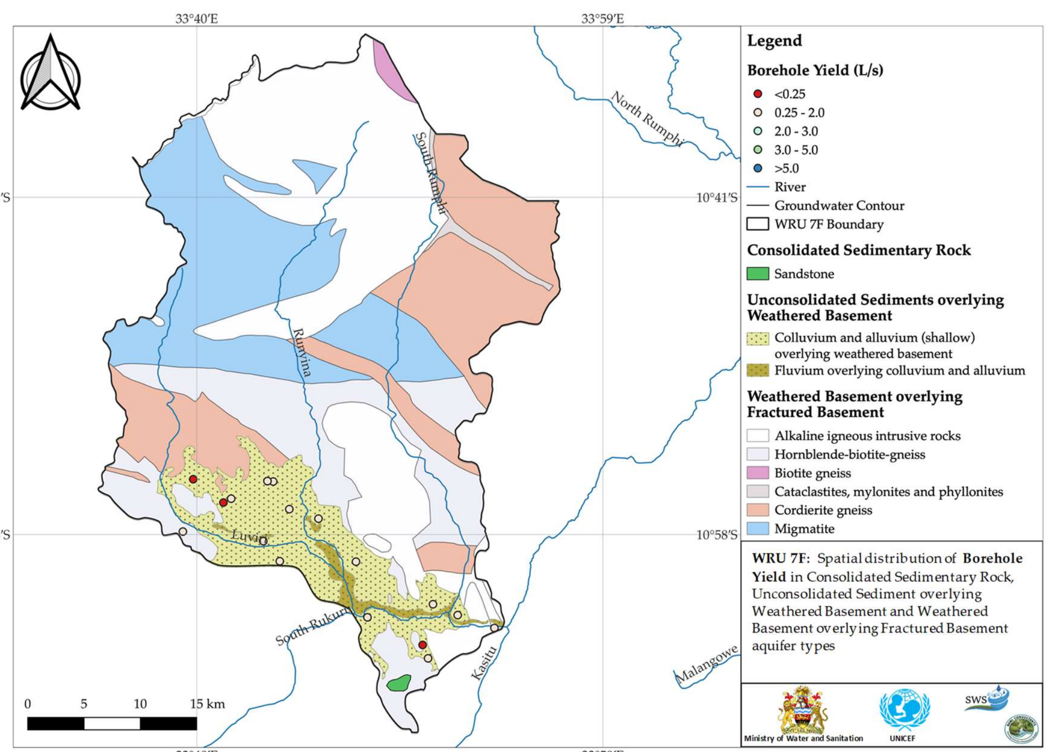


Figure 13f. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7F.

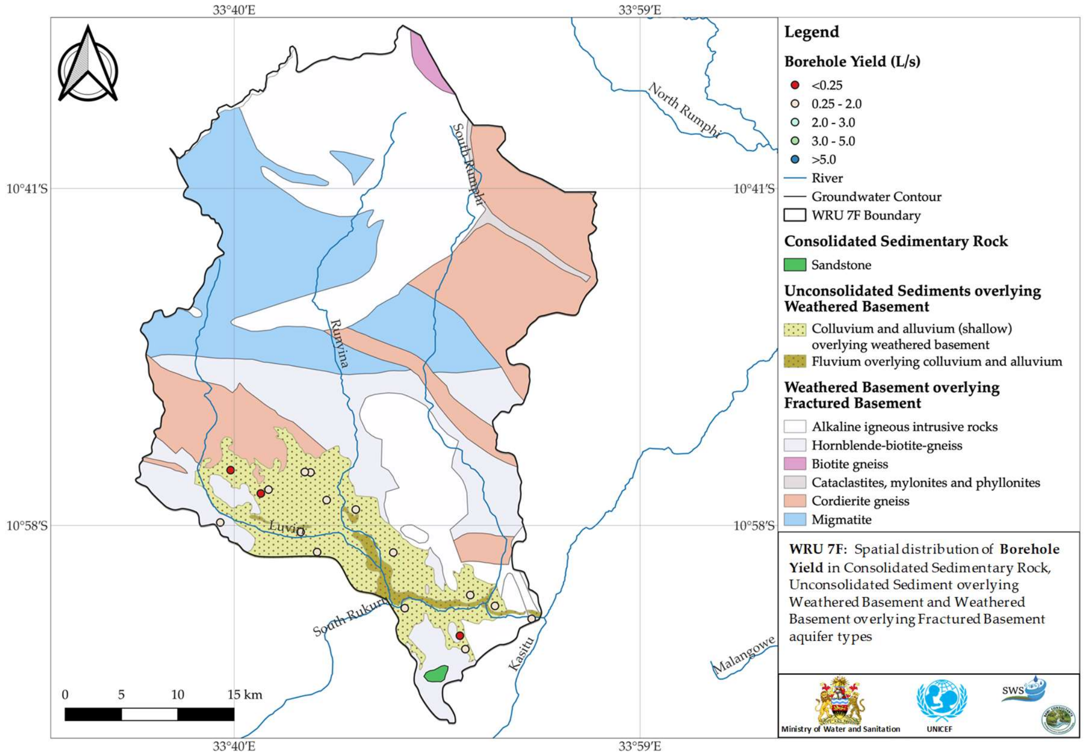


Figure 13g. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 7G.

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

Groundwater Table Variations

No groundwater monitoring data in WRA 7 was provided by the Ministry of Water and Sanitation for analysis.

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 7A, 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	1.7	3%	15%	0.02	0.10	1.0	24.9	
Fluvial Units	212.4	10%	35%	0.02	0.10	424.9	7,435.3	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	1,023.9	10%	30%	0.02	0.06	2,047.8	18,429.8	
W & F Basement	1,695.0	1%	10%	0.02	0.03	339.0	5,085.0	
	Area of WRU (km^2)	7A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,812.6*	*30,975.0*	*Total Volume Groundwater*
	2,933.0	881	Average Rainfall in WRU	8.81	66.075	25.8	193.8	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]						109	160	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 7B, 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	140.0	10%	35%	0.02	0.10	280.1	4,901.4	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	1,056.0	10%	30%	0.02	0.06	2,112.0	19,007.8	
W & F Basement	38.4	1%	10%	0.02	0.03	7.7	115.3	
	Area of WRU (km^2)	7B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,399.7*	*24,024.5*	*Total Volume Groundwater*
	1,234.5	853	Average Rainfall in WRU	8.53	63.975	10.5	79.0	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]						228	304	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 7C, 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	122.0	10%	35%	0.02	0.10	243.9	4,268.9	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	1,289.1	10%	30%	0.02	0.06	2,578.1	23,203.3	
W & F Basement	222.0	1%	10%	0.02	0.03	44.4	665.9	
	Area of WRU (km^2)	7C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,866.5*	*28,138.0*	*Total Volume Groundwater*
	1,633.0	833	Average Rainfall in WRU	8.33	62.475	13.6	102.0	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]						211	276	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 7D, 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	125.0	10%	35%	0.02	0.10	250.0	4,374.8	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	1,075.1	10%	30%	0.02	0.06	2,150.1	19,351.1	
W & F Basement	1,068.7	1%	10%	0.02	0.03	213.7	3,206.2	
	Area of WRU (km^2)	7D	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,613.9*	*26,932.2*	*Total Volume Groundwater*
	2,268.8	905	Average Rainfall in WRU	9.05	67.875	20.5	154.0	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]						127	175	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 7E, 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	1.2	3%	15%	0.02	0.10	0.7	18.5	
Fluvial Units	73.6	10%	35%	0.02	0.10	147.3	2,577.6	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	980.1	10%	30%	0.02	0.06	1,960.1	17,641.3	
W & F Basement	408.8	1%	10%	0.02	0.03	81.8	1,226.3	
	Area of WRU (km^2)	7E	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,189.9*	*21,463.8*	*Total Volume Groundwater*
	1,463.7	795	Average Rainfall in WRU	7.95	59.625	11.6	87.3	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						188	246	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 7F, 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	2.1	3%	15%	0.02	0.10	1.3	31.3	
Fluvial Units	16.9	10%	35%	0.02	0.10	33.9	592.5	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	168.3	10%	30%	0.02	0.06	336.7	3,030.3	
W & F Basement	1,293.6	1%	10%	0.02	0.03	258.7	3,880.8	
	Area of WRU (km^2)	7F	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*630.5*	*7,534.9*	*Total Volume Groundwater*
	1,481.0	783	Average Rainfall in WRU	7.83	58.725	11.6	87.0	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]						54	87	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 7G, 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	51.1	3%	15%	0.02	0.10	30.6	765.8	
Fluvial Units	31.5	10%	35%	0.02	0.10	62.9	1,100.8	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	141.6	10%	30%	0.02	0.06	283.2	2,548.5	
W & F Basement	732.8	1%	10%	0.02	0.03	146.6	2,198.4	
	Area of WRU (km^2)	7G	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*523.3*	*6,613.5*	*Total Volume Groundwater*
	956.9	810	Average Rainfall in WRU	8.1	60.75	7.8	58.1	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]						68	114	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 7H, 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	114.1	3%	15%	0.02	0.10	68.5	1,711.6	
Fluvial Units	1.0	10%	35%	0.02	0.10	2.0	35.7	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	0.1	10%	30%	0.02	0.06	0.3	2.6	
W & F Basement	593.6	1%	10%	0.02	0.03	118.7	1,780.7	
	Area of WRU (km^2)	7H	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*189.5*	*3,530.8*	*Total Volume Groundwater*
	708.9	939	Average Rainfall in WRU	9.39	70.425	6.7	49.9	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]						28	71	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 7 ranges between 108.1 Million Cubic Meters (MCM) and 811.1 MCM per year, with a mean age of groundwater of 153 years across the Water Resource Area **(Tables 4a to 4h)**. 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 7

Groundwater major-ion water quality in WRA 7 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 7. 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 7	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	7.5	435	55.3	12.5	25.6	5.3	35.7	4.7	89.6	60.7	8.5
Std Dev	0.7	557	110	36	51.3	14.1	39	10.6	103.4	86.4	12.0
Median	7.6	260	19.9	4.6	3.1	1.0	20.5	3.2	50.0	13.6	0.3
Max	9.3	3,720	689	452	444	140.0	224	123	695	563	90.0
Min	5.0	16.0	2.0	1.0	0.0	0.0	6.8	0.0	7.3	1.0	0.0
n	208	278	206	165	165	201	128	131	204	205	195

Piper plots of the WRA 7 water 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 (**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 there are zones of high EC groundwater that might be related to evaporative enrichment.

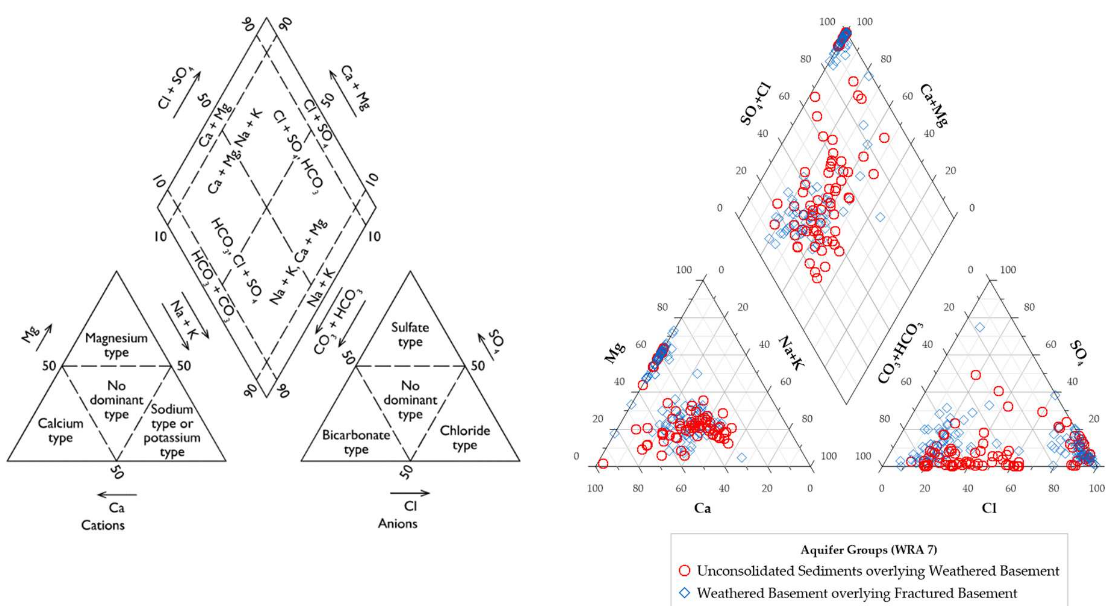


Figure 14a, 14b. Piper Diagrammes of Groundwater Samples in WRA 7 and for each Aquifer Type in WRA 7.

The distribution of key dissolved water quality species in groundwater of WRA 7 is provided however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine in WRA 7, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

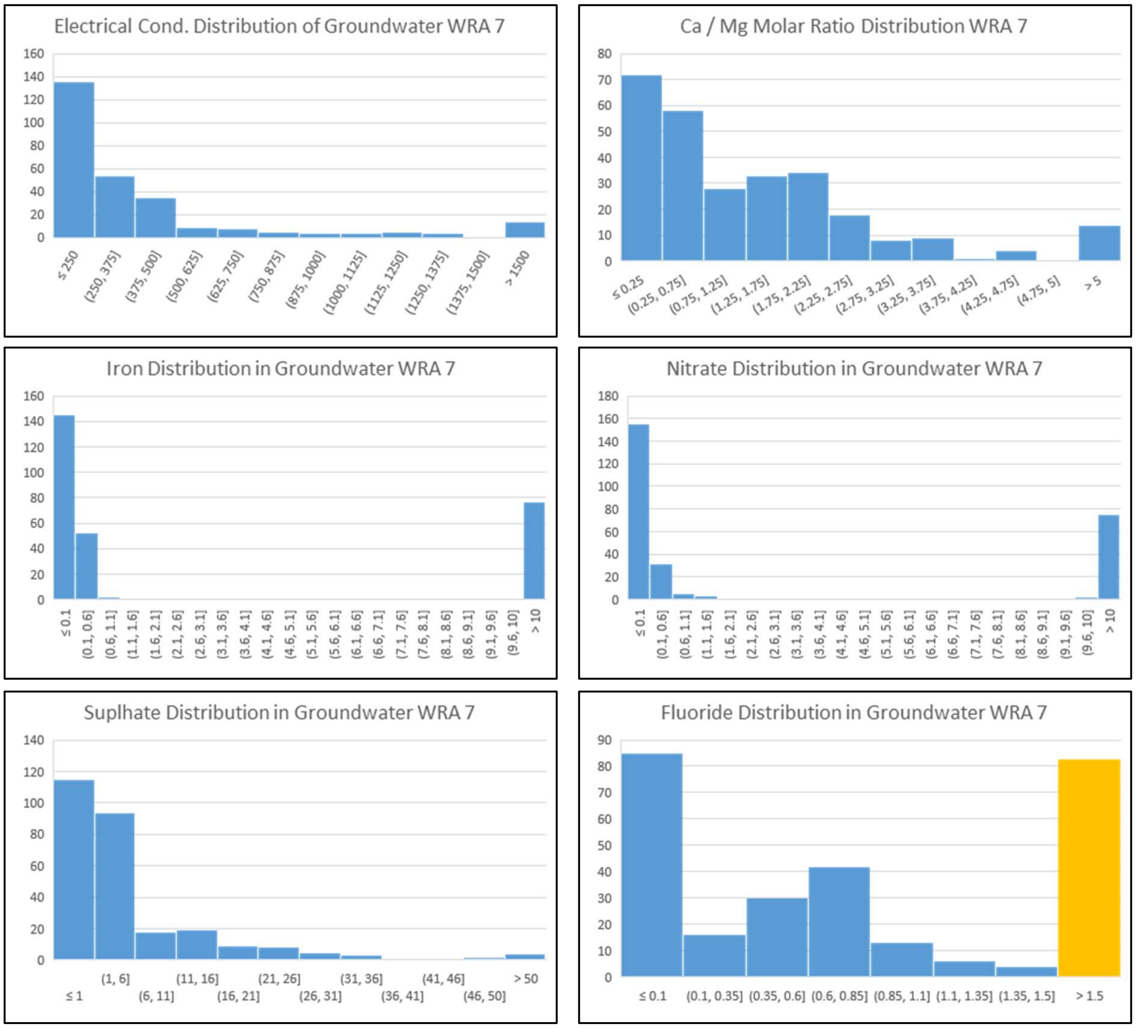


Figure 15 Distribution of chemical species in groundwater within WRA 7 (y axis = *n* observations).

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 7 (**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 7 (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.

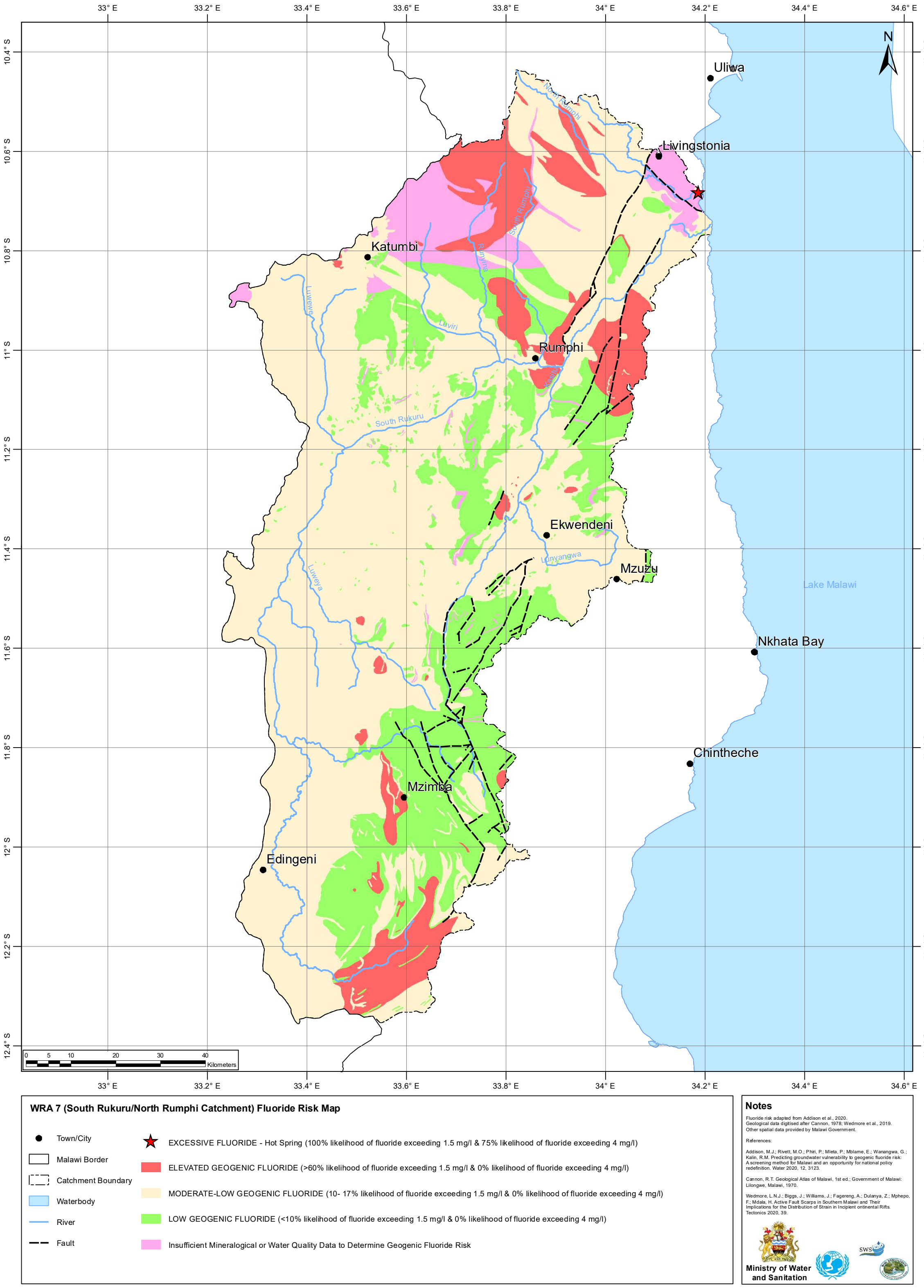


Figure 16. Groundwater Fluoride Risk Map WRA 7 (after Addison et. al. 2021).

Fluoride

There is little prevalence of hot springs in WRA 7, placing **Lower Risk** category for fluoride in groundwater but numerous fault zones to exist. Groundwater data drawn from the recent national-scale assessments (**Figure 16**) reveals 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 7 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 7 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 7 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 7.

	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**
7A	244,829	260,887	277,190	293,484	310,133	299,554	910,482,011	1,092,578
7B	94,972	101,630	107,988	114,682	121,693	110,782	351,943,709	422,332
7C	55,285	58,934	63,032	67,025	71,138	65,584	205,738,521	246,886
7D	251,230	267,828	284,219	308,486	317,387	342,457	956,668,006	1,148,002
7E	76,752	81,289	86,063	90,330	94,407	89,836	280,085,089	336,102
7F	53,620	56,747	59,915	63,298	66,814	76,490	203,517,643	244,221
7G	54,893	58,145	61,839	65,637	69,365	63,146	201,432,911	241,719
7H	14,763	15,506	16,222	17,150	18,019	19,377	54,559,748	65,472
WRA 7	**846,343**	**900,966**	**956,469**	**1,020,090**	**1,068,956**	**1,067,226**	**3,164,427,638**	**3,797,313**

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 3,797,313 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 220,883. WRA14 covers roughly 10.3% 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, 20,841 metric tonnes of fertiliser would be used in WRA1 per year which is 84 less than faecal matter was added to this WRA this 10-year period.

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Water Resource Unit (WRA) 7 Figures

Figure WRA 7.0: Aquifer Units and Groundwater Level Contours Water Resources Area 7

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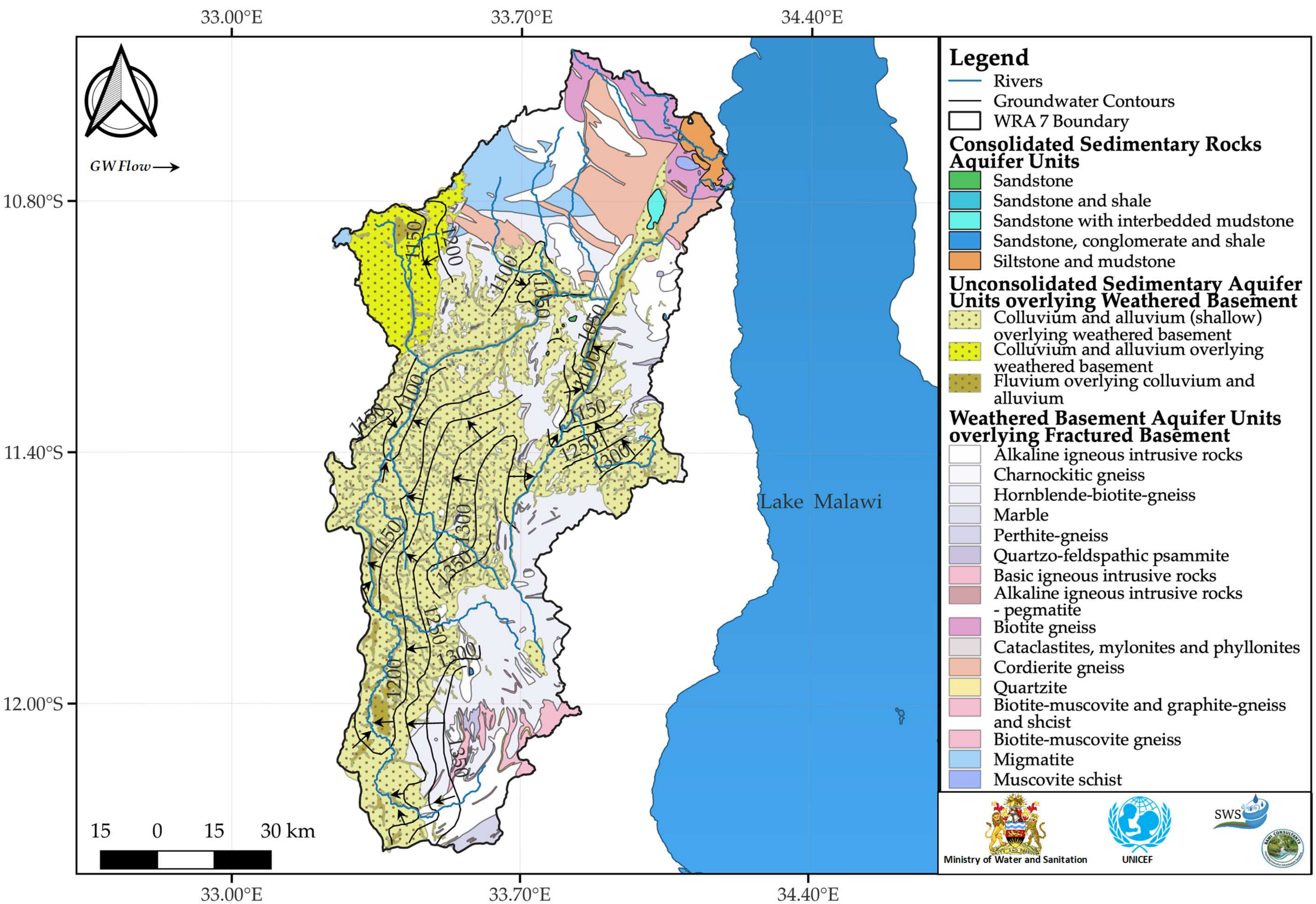


WRU 7A Figures

Figure WRU 7A.1 Land Use and Major Roads

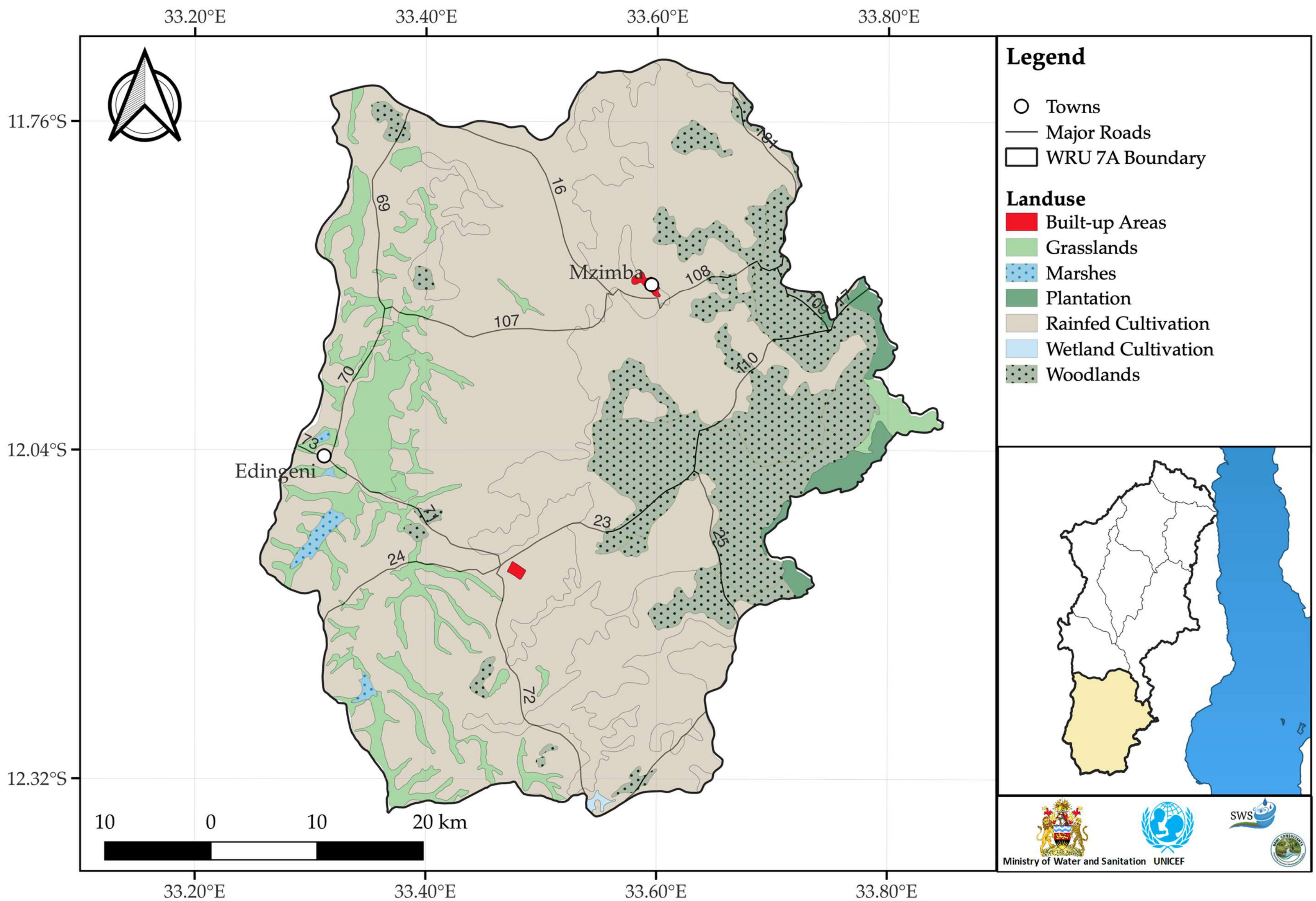


Figure WRU 7A.2 Rivers and Wetlands

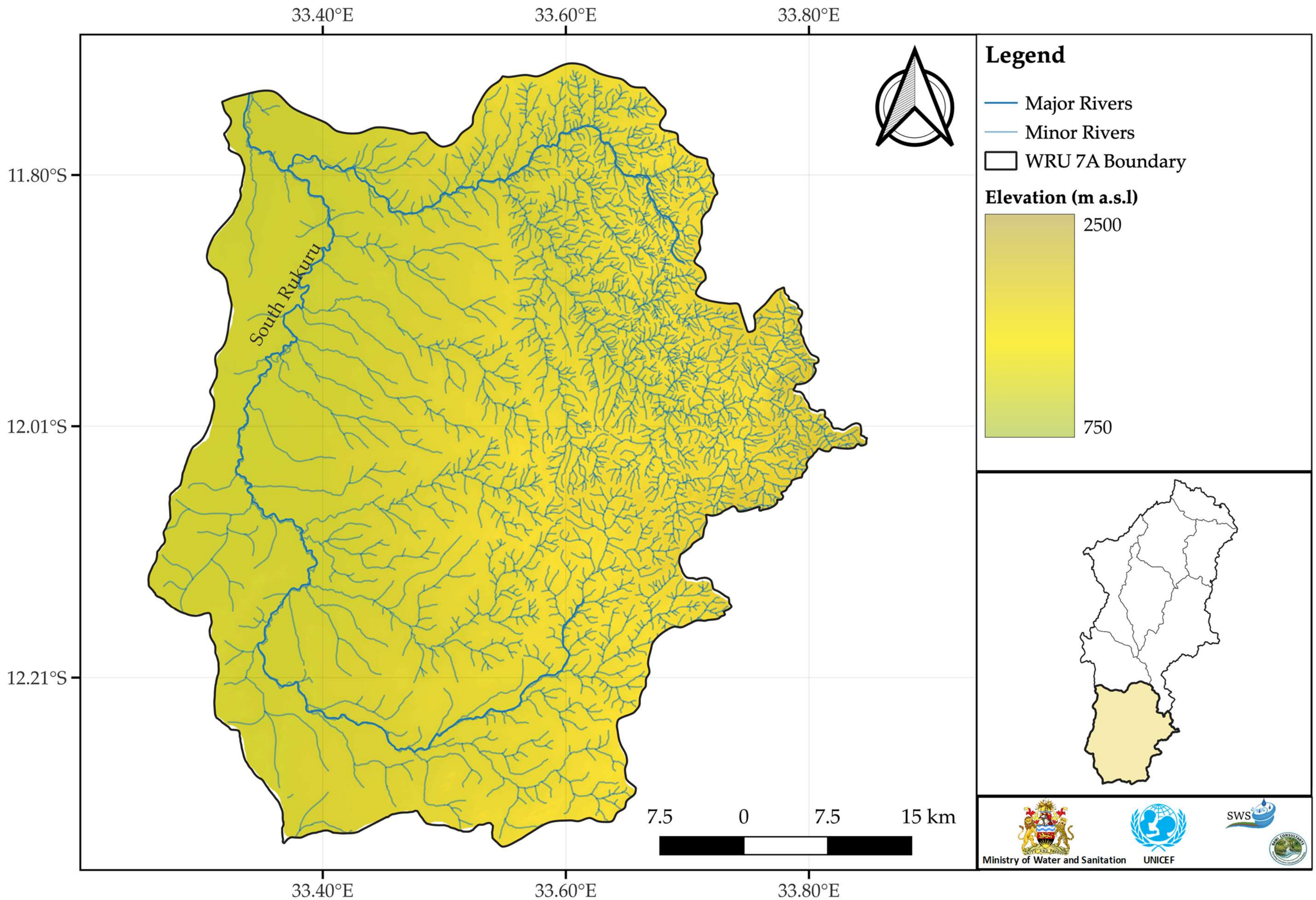


Figure WRU 7A.3 Hydrogeology Units and Water Table

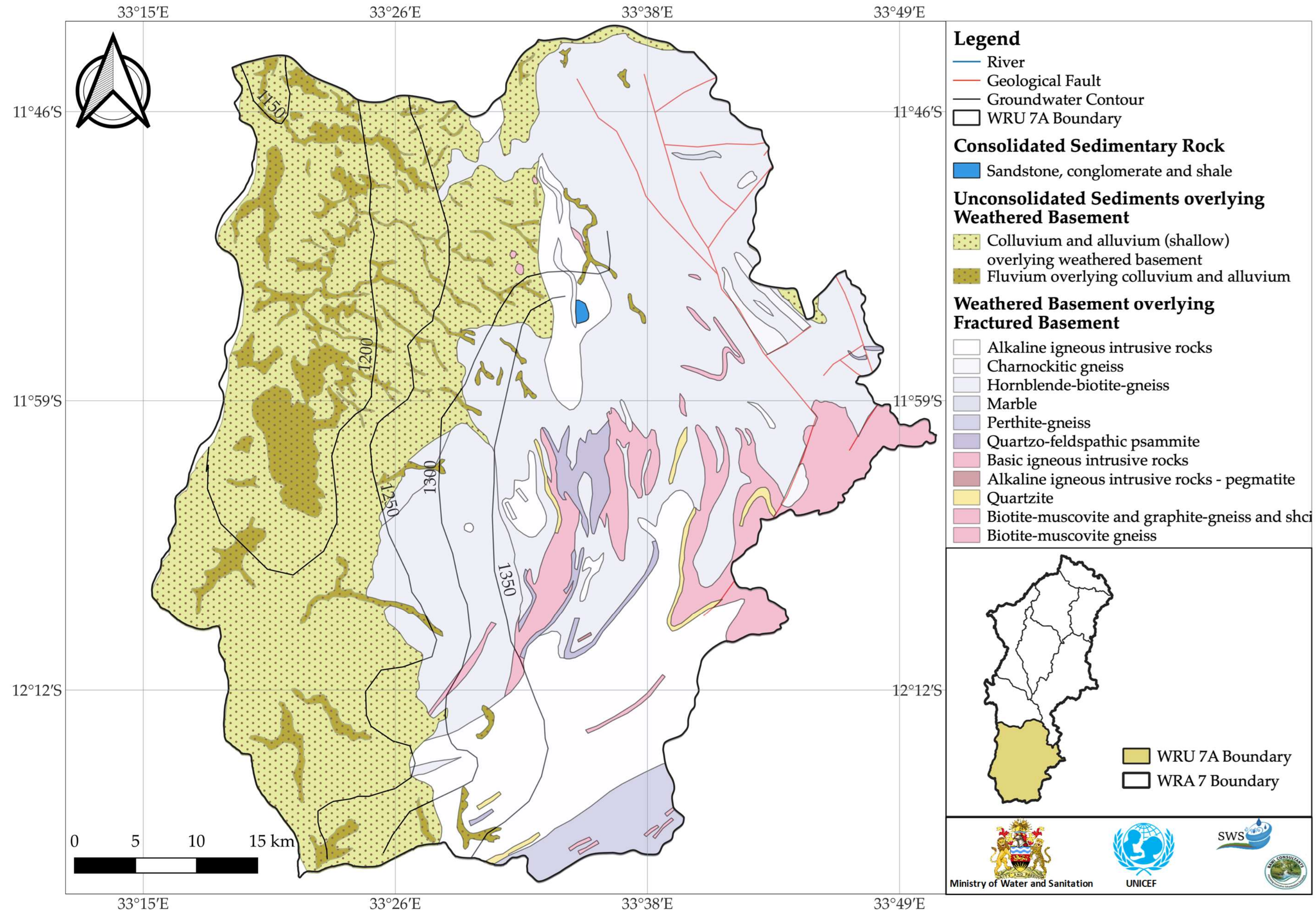


Figure WRU 7A.4 Groundwater Chemistry Distribution Electrical Conductivity

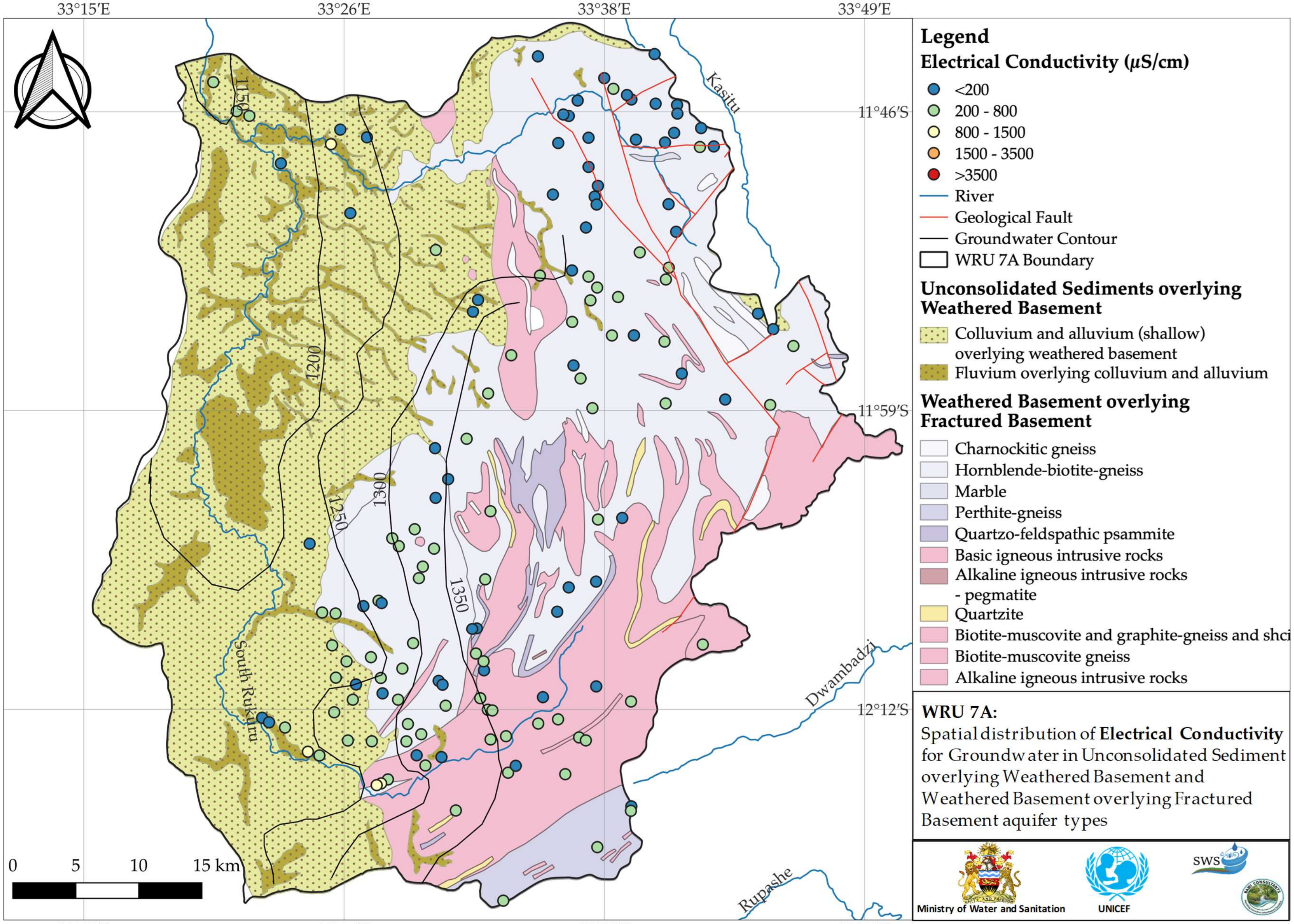


Figure WRU 7A.5 Groundwater Chemistry Distribution Sulphate

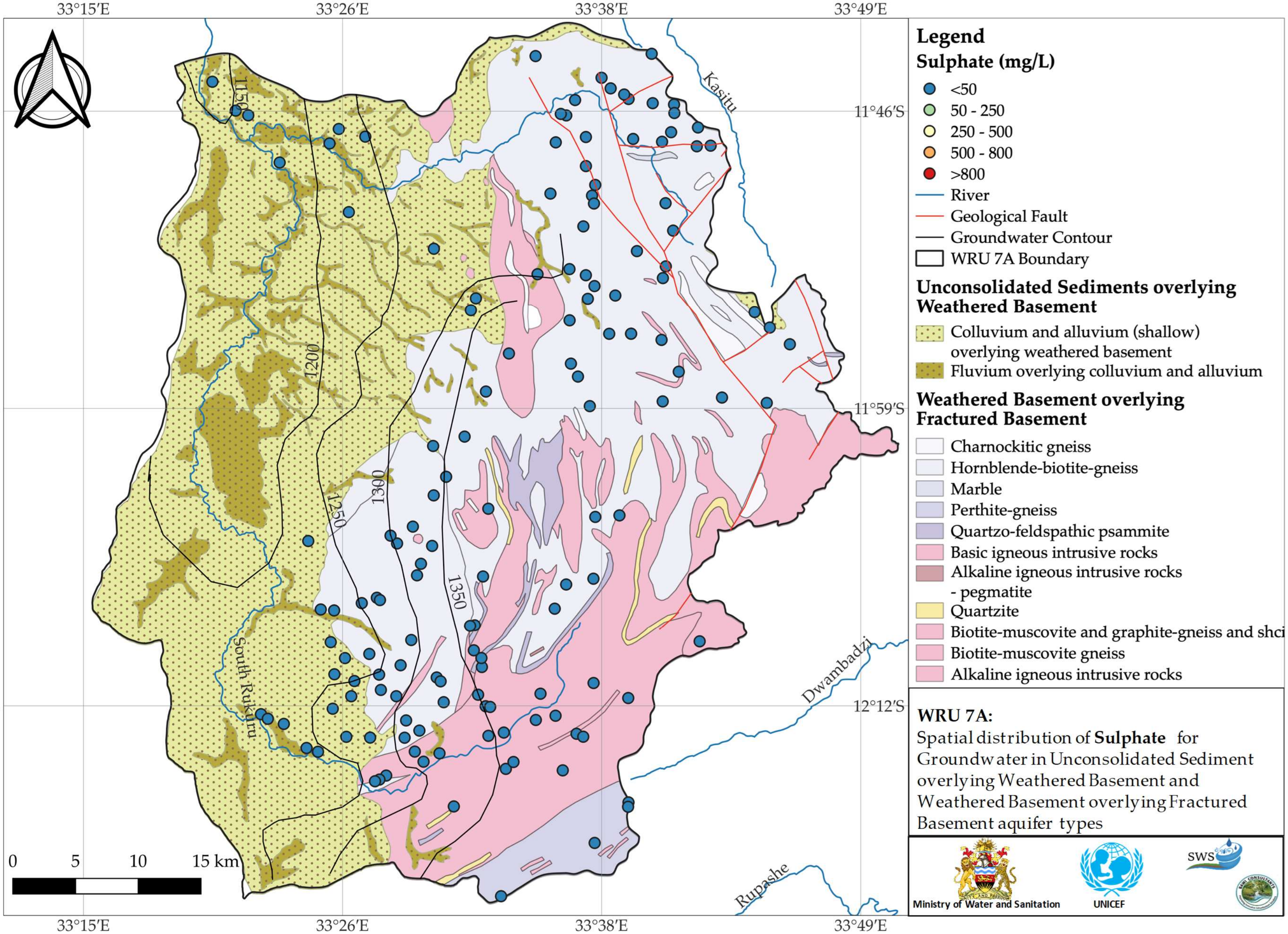


Figure WRU 7A.6 Groundwater Chemistry Distribution Chloride

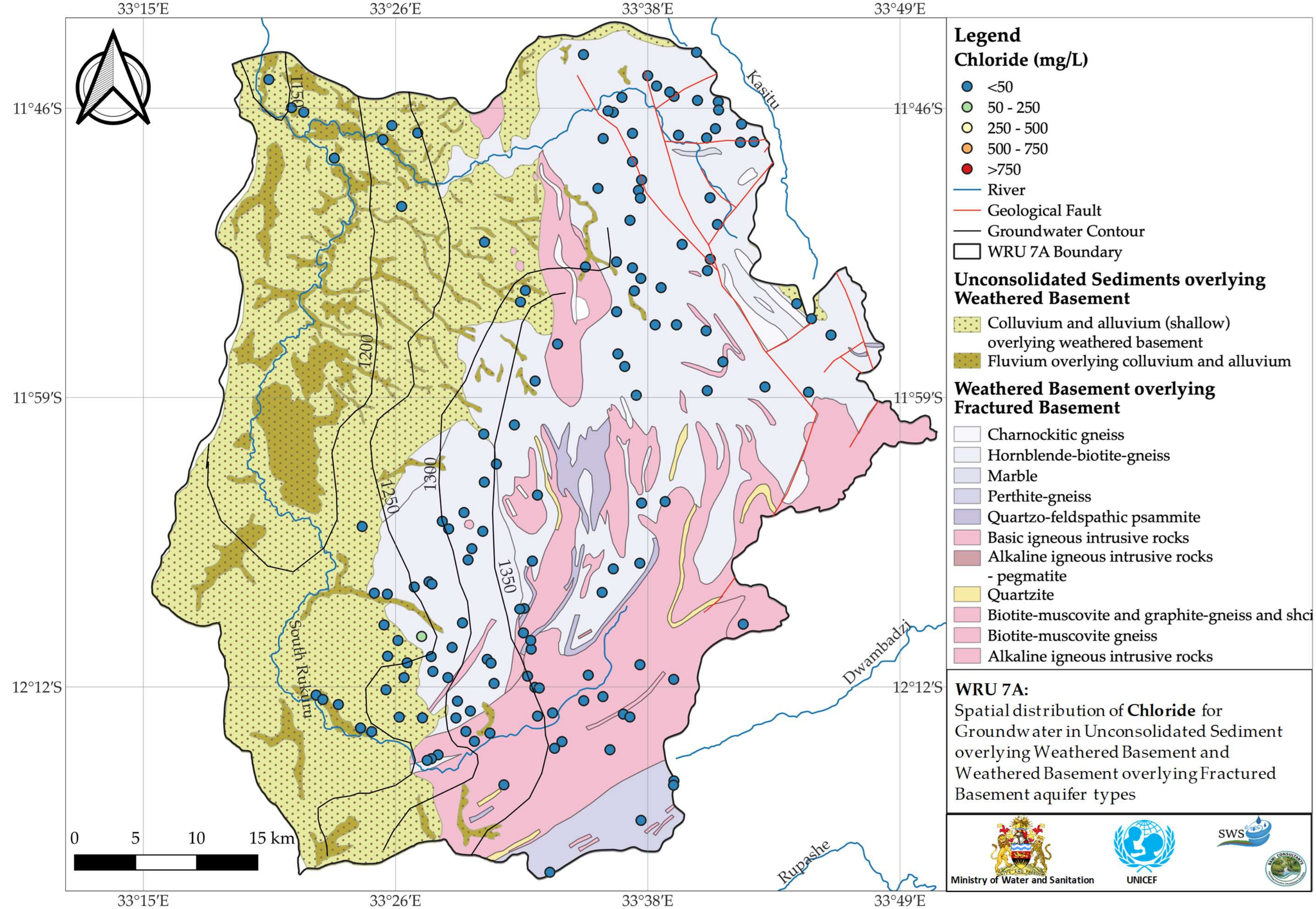


Figure WRU 7A.7 Groundwater Chemistry Distribution Sodium

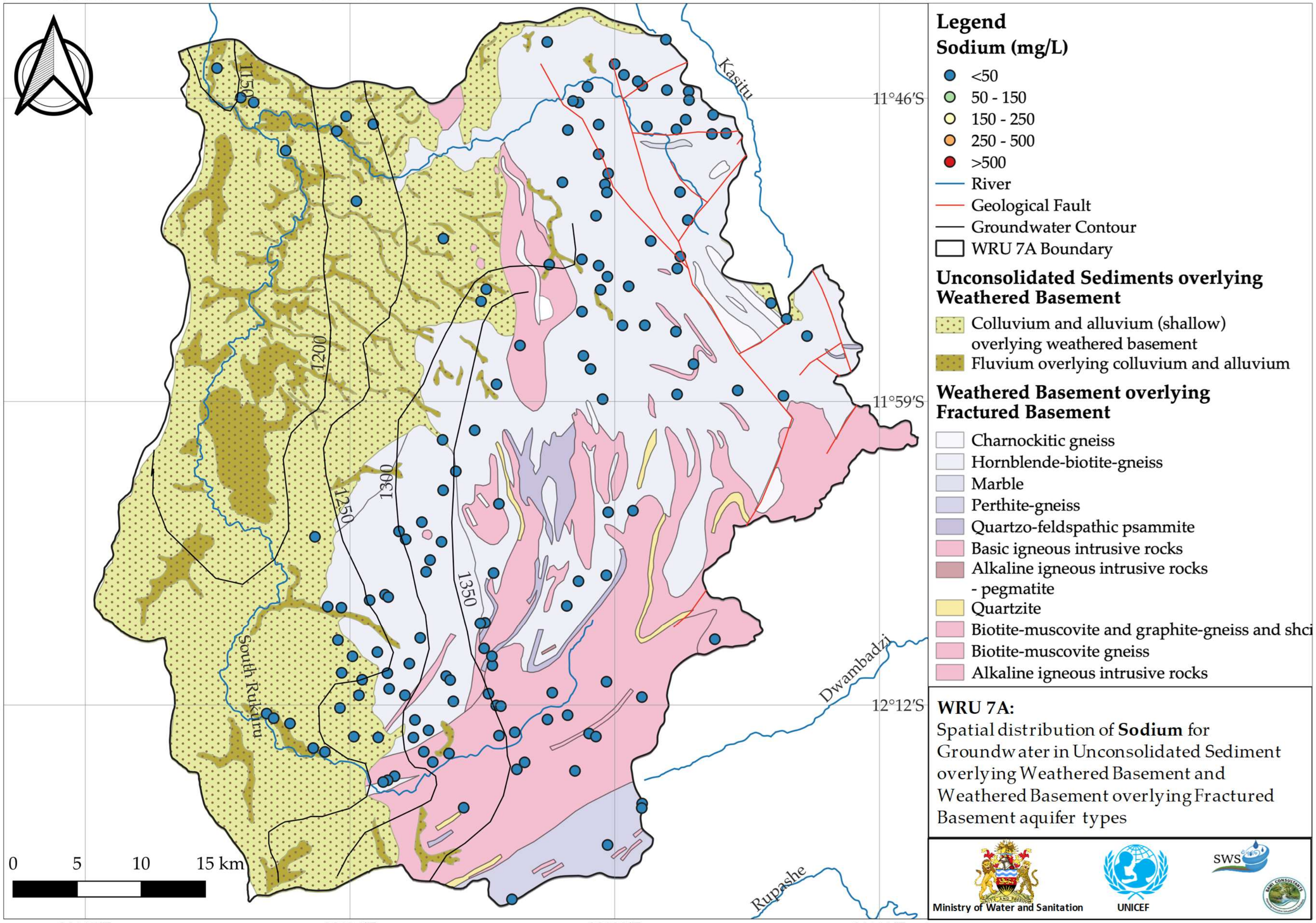


Figure WRU 7A.8 Groundwater Chemistry Distribution Calcium

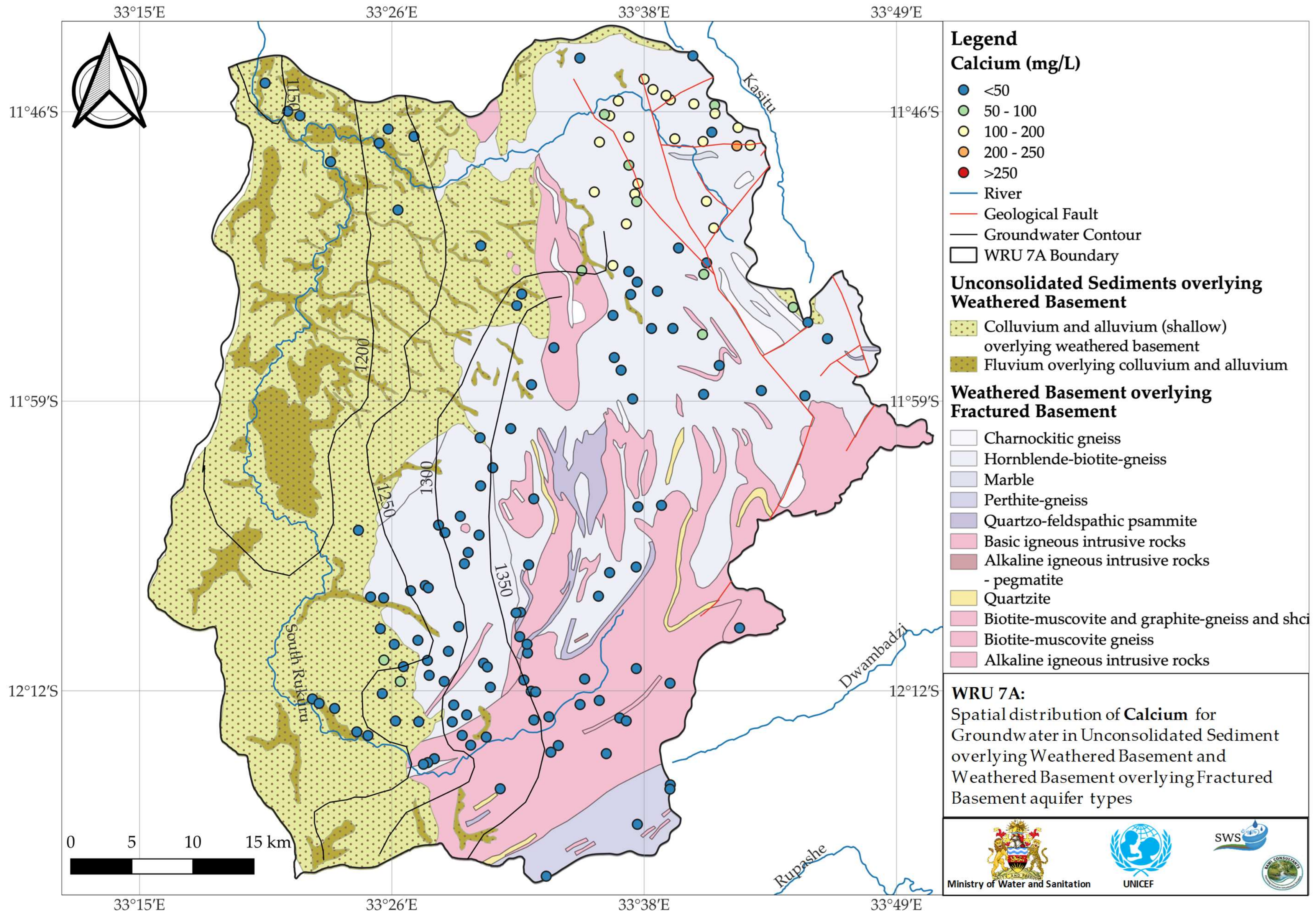


Figure WRU 7A.9 Piper Diagram of water quality results with respect to the major aquifer type

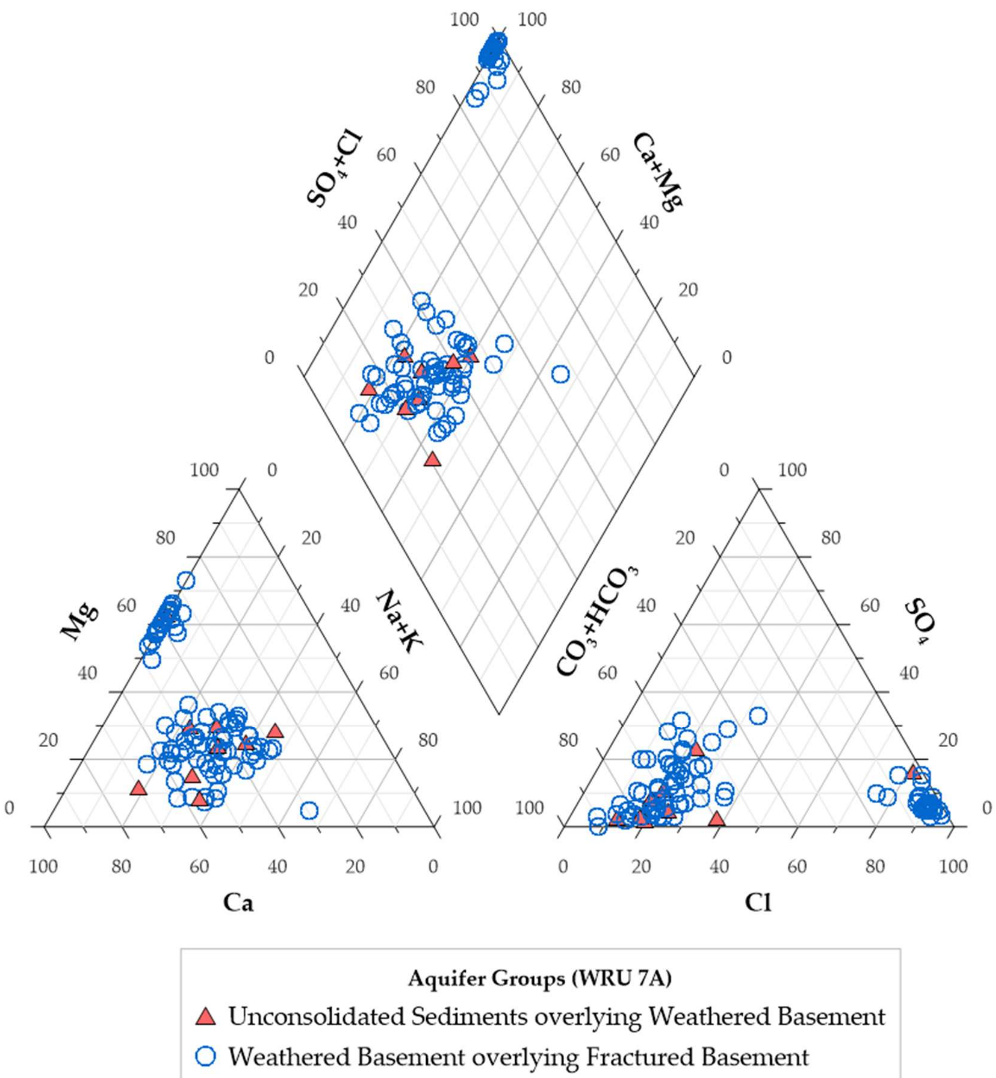
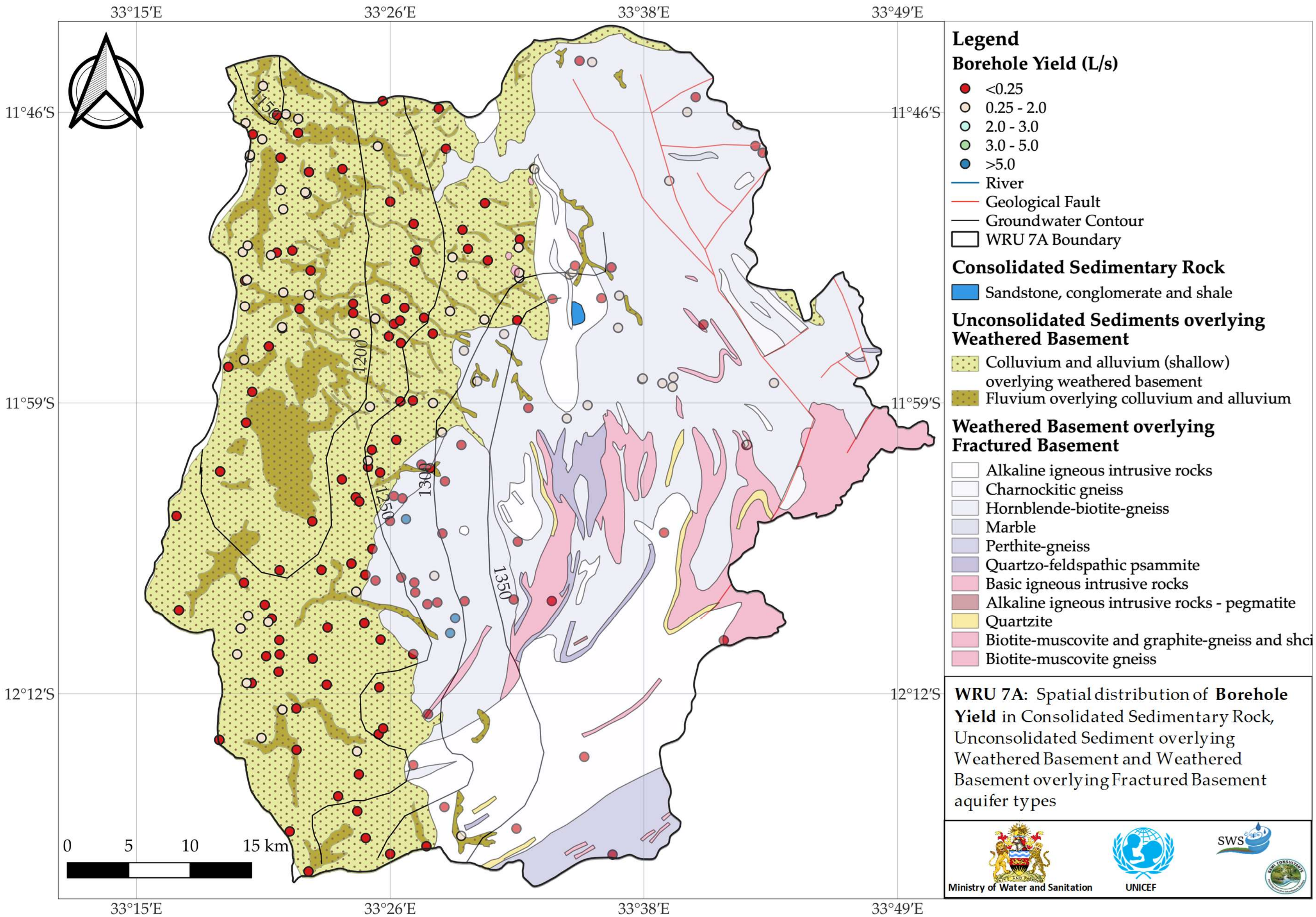


Figure WRU 7A.10 Borehole Yield Map for data held by the Ministry



WRU 7B Figures

Figure WRU 7B.1 Land Use and Major Roads

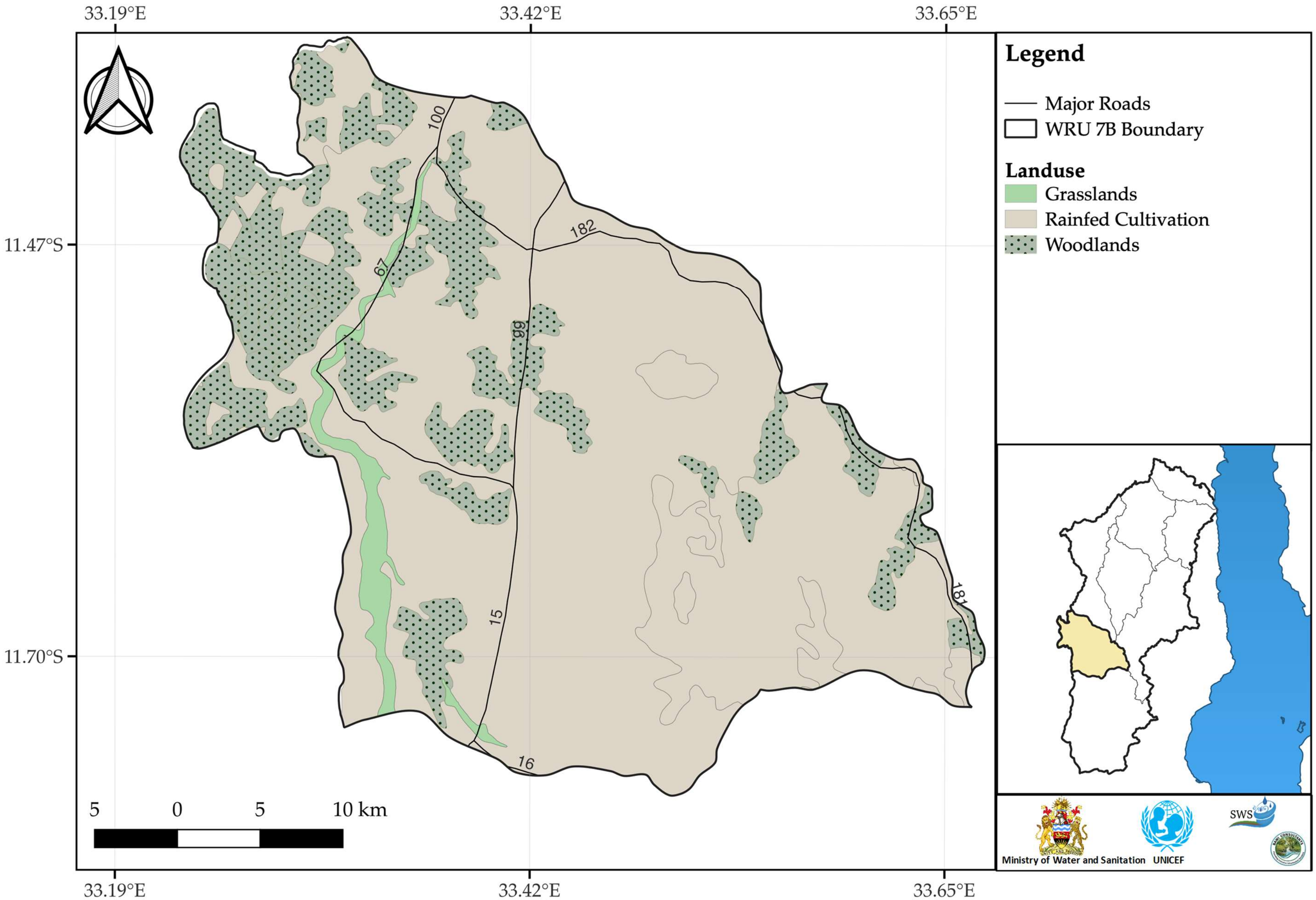
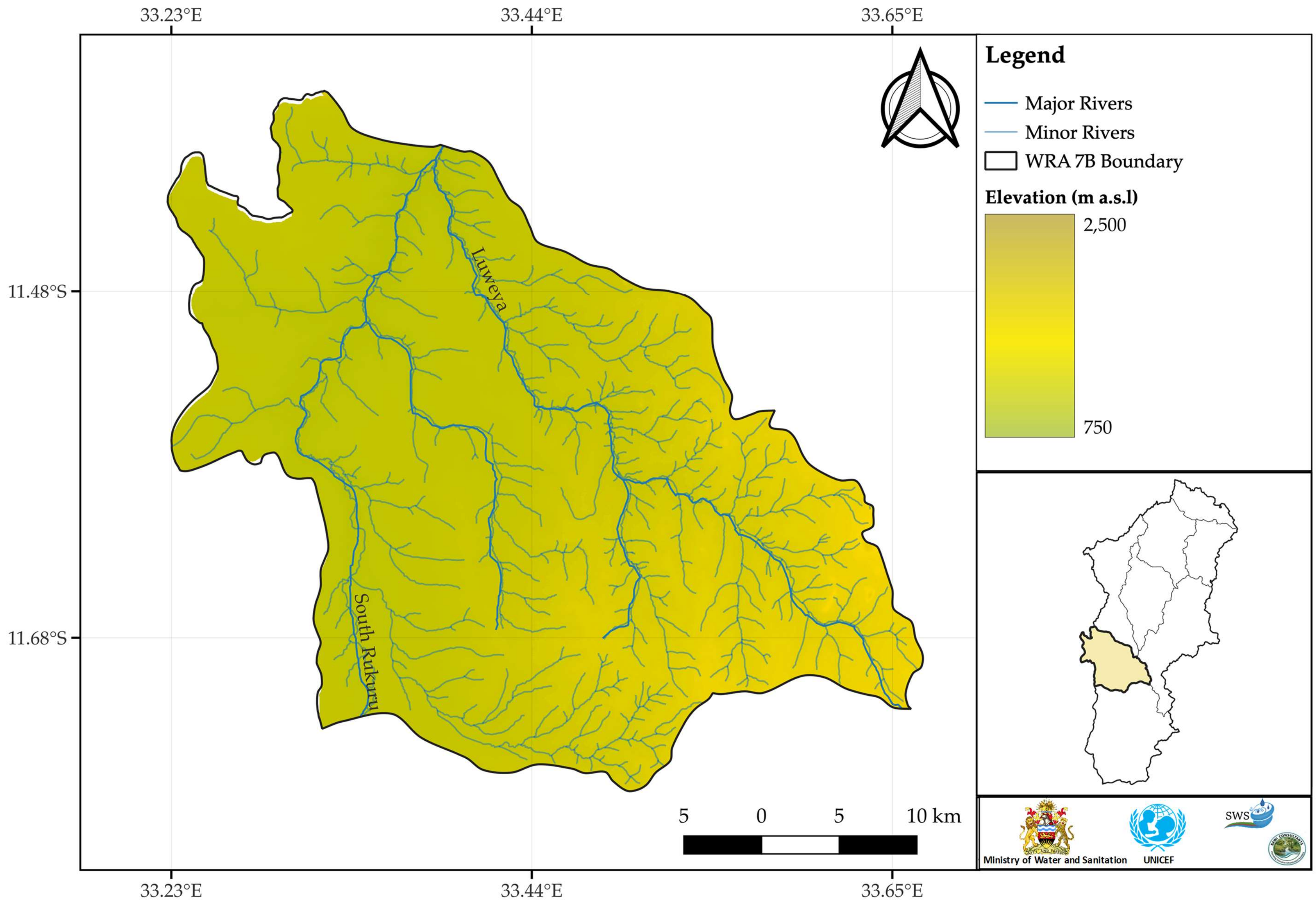


Figure WRU 7B.2 Rivers and Wetlands



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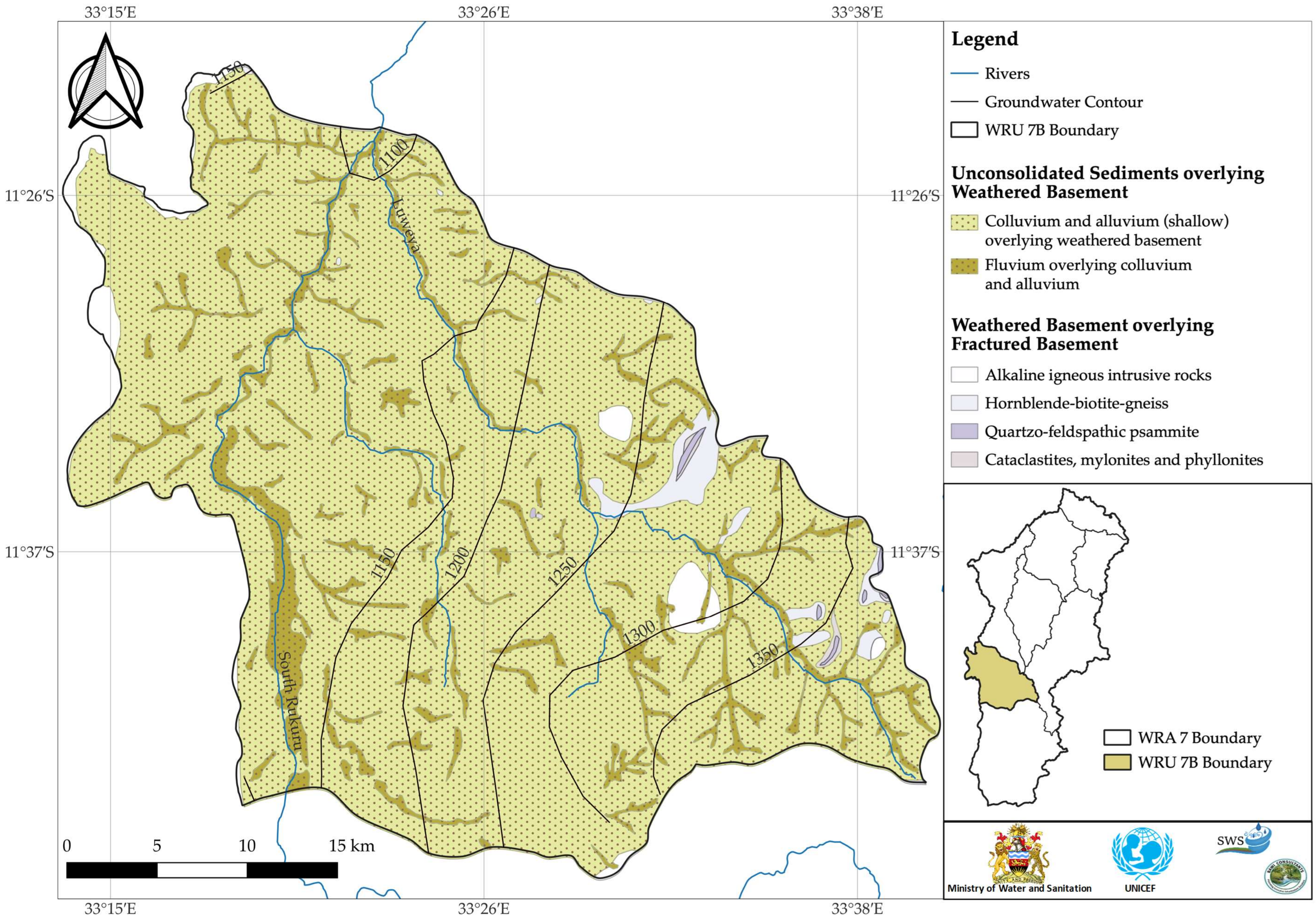
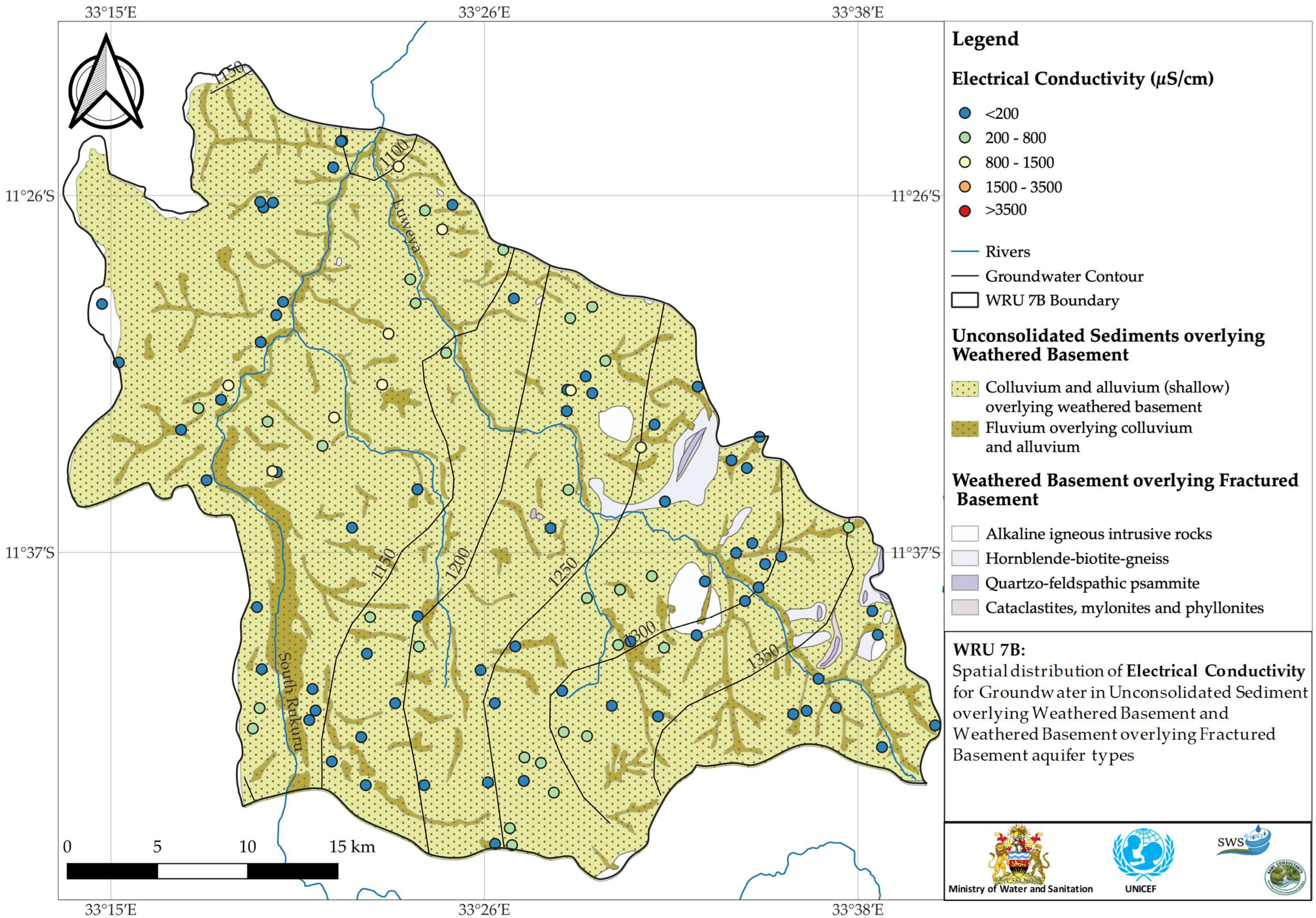


Figure WRU 7B.4 Groundwater Chemistry Distribution Electrical Conductivity



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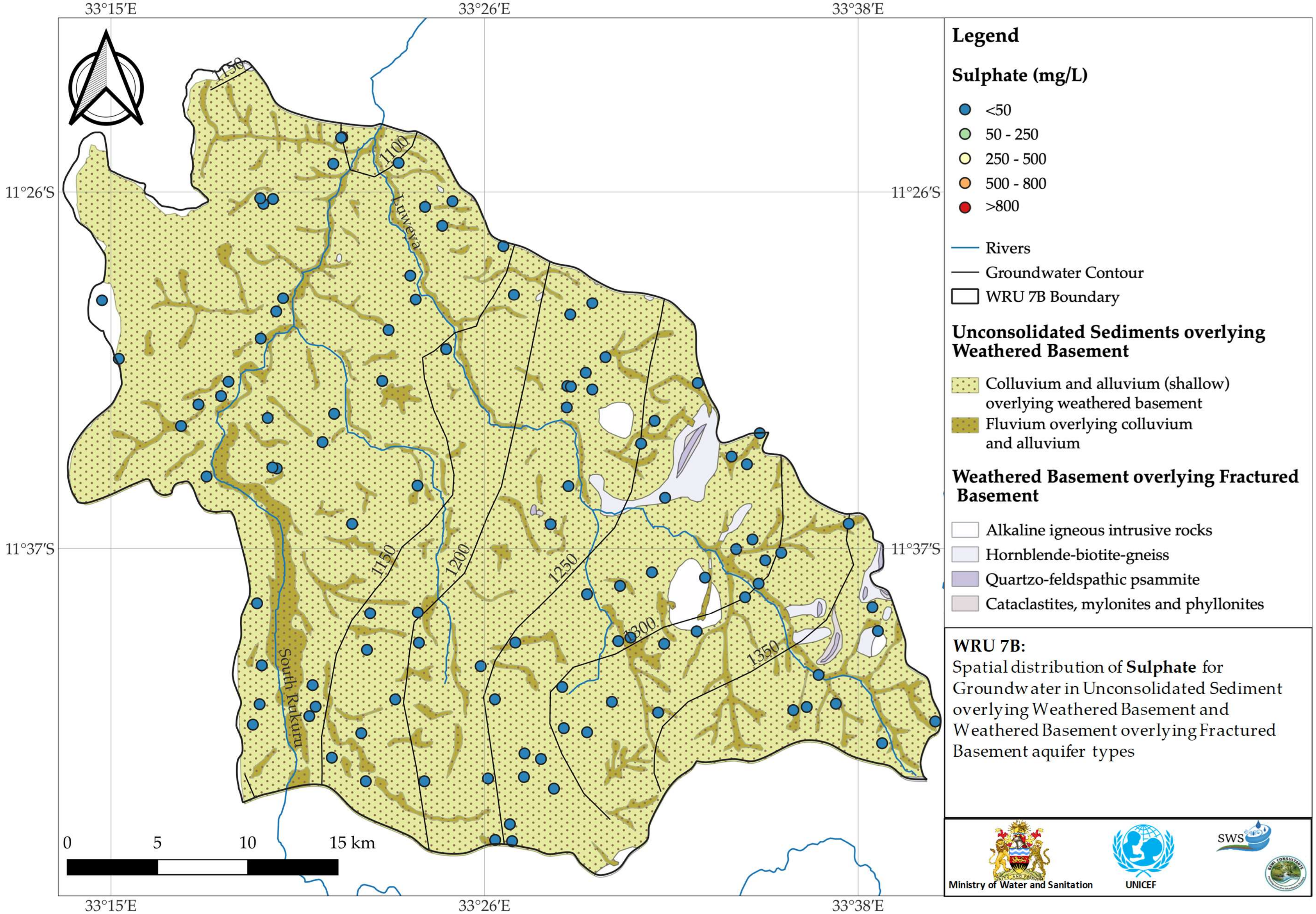
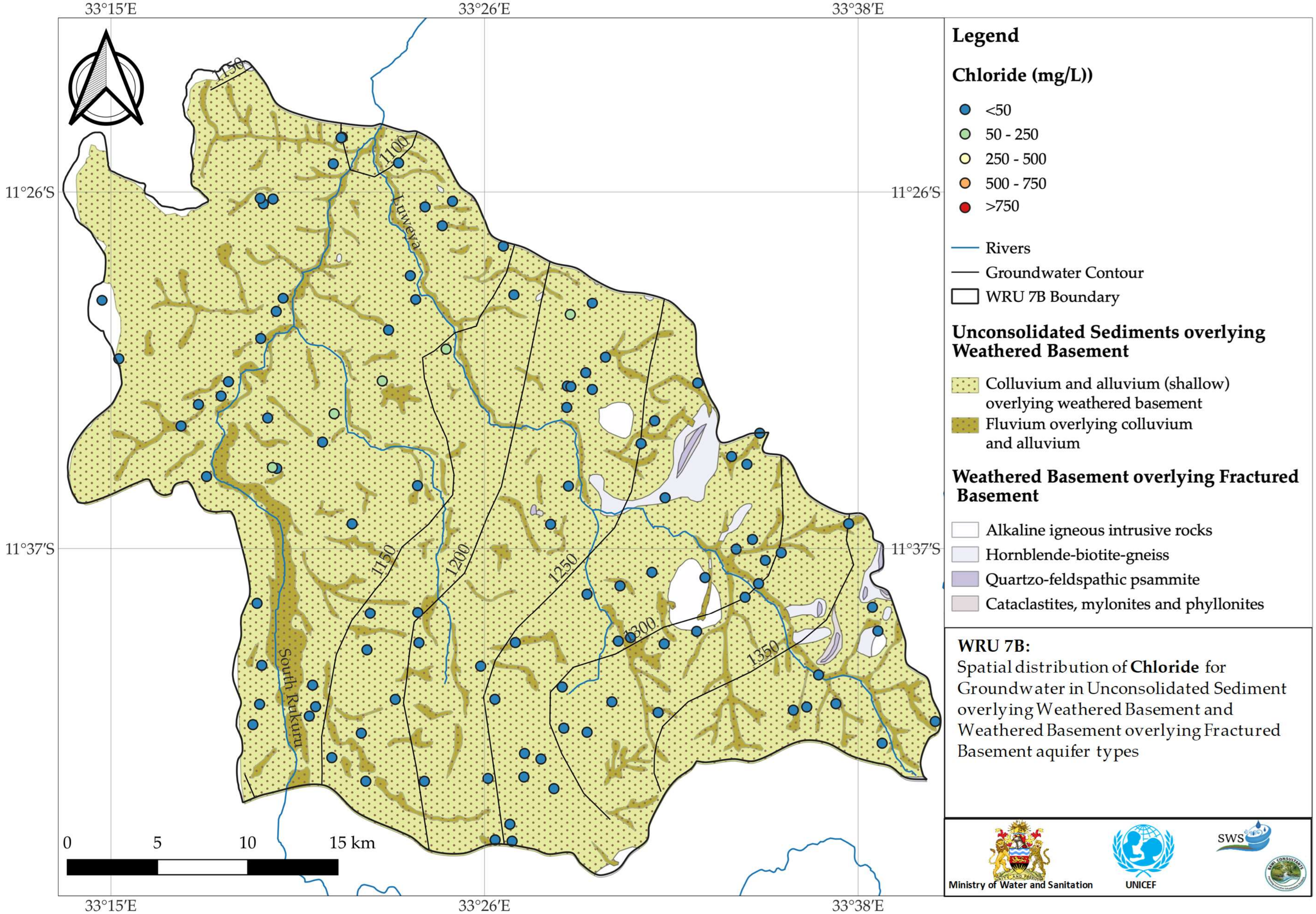


Figure WRU 7B.6 Groundwater Chemistry Distribution Chloride



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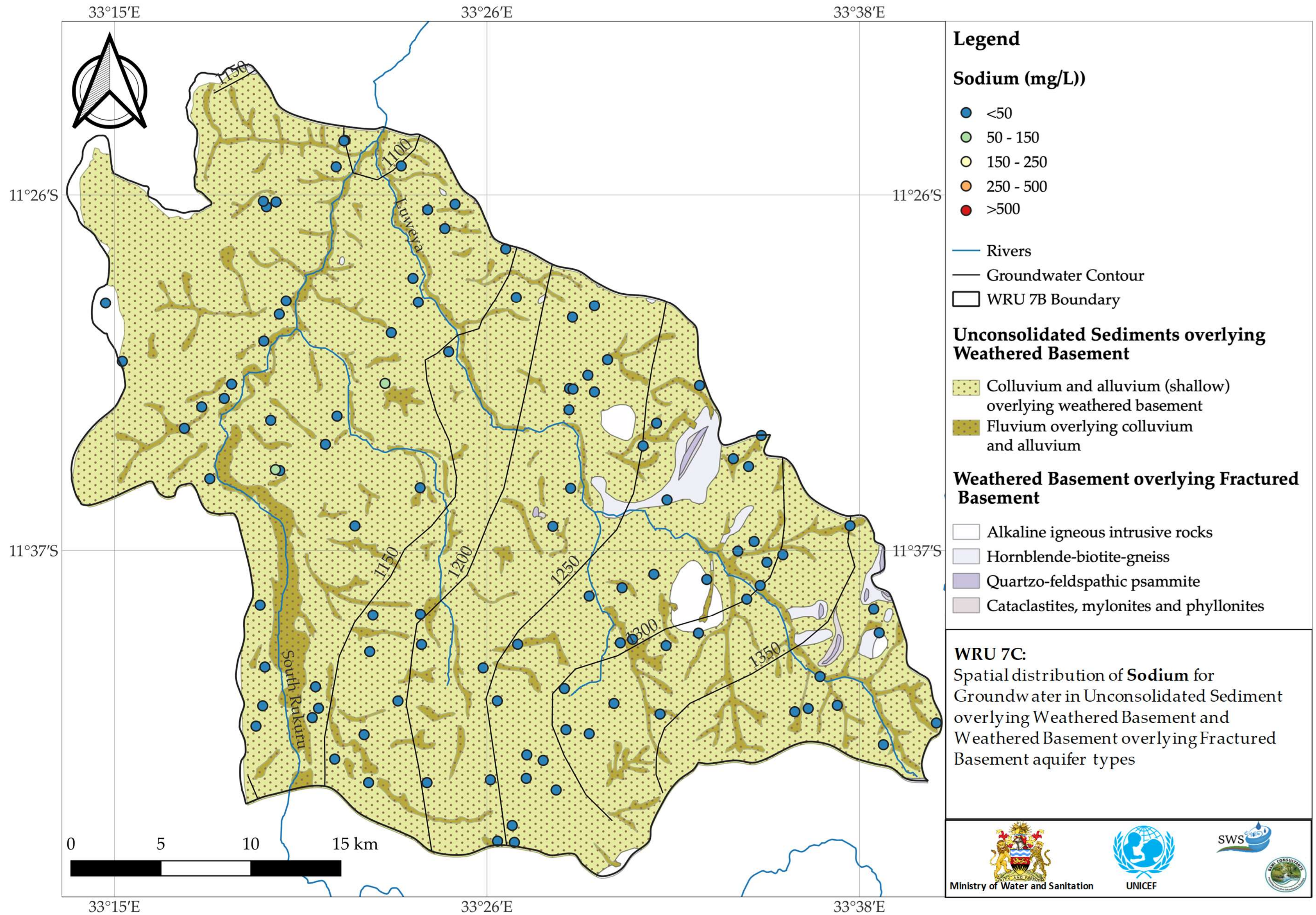

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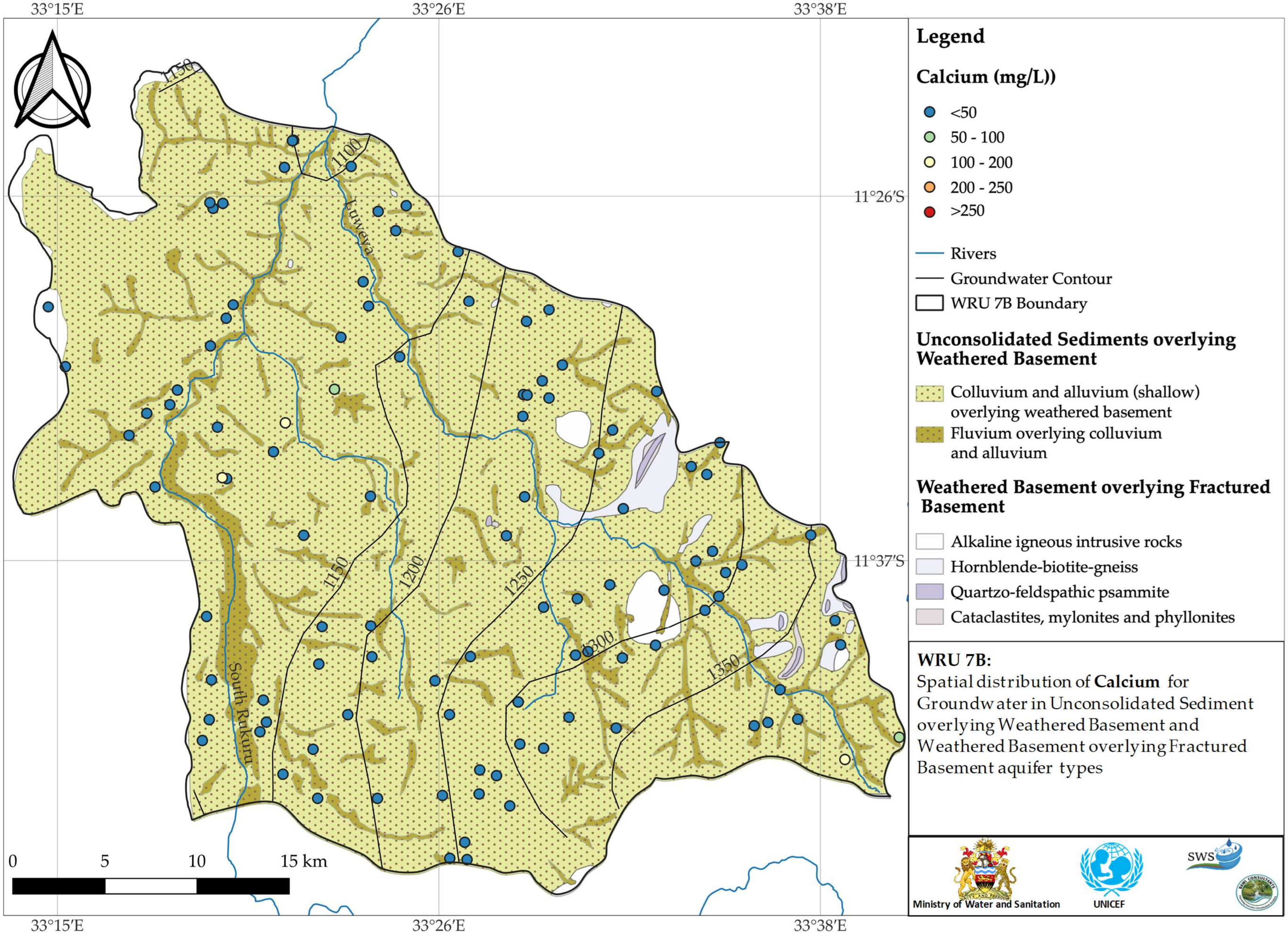


Figure WRU 7B.9 Piper Diagram of water quality results with respect to the major aquifer type

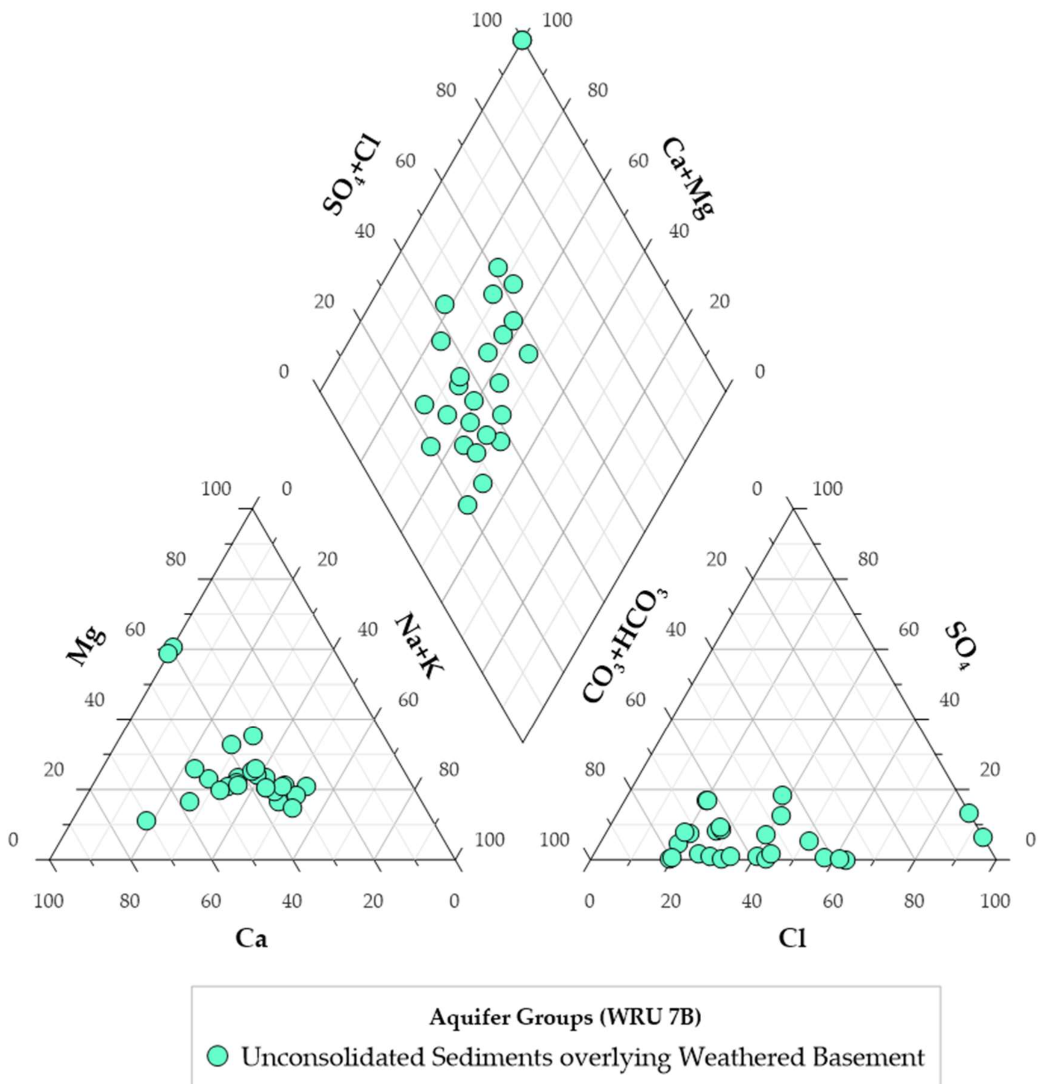
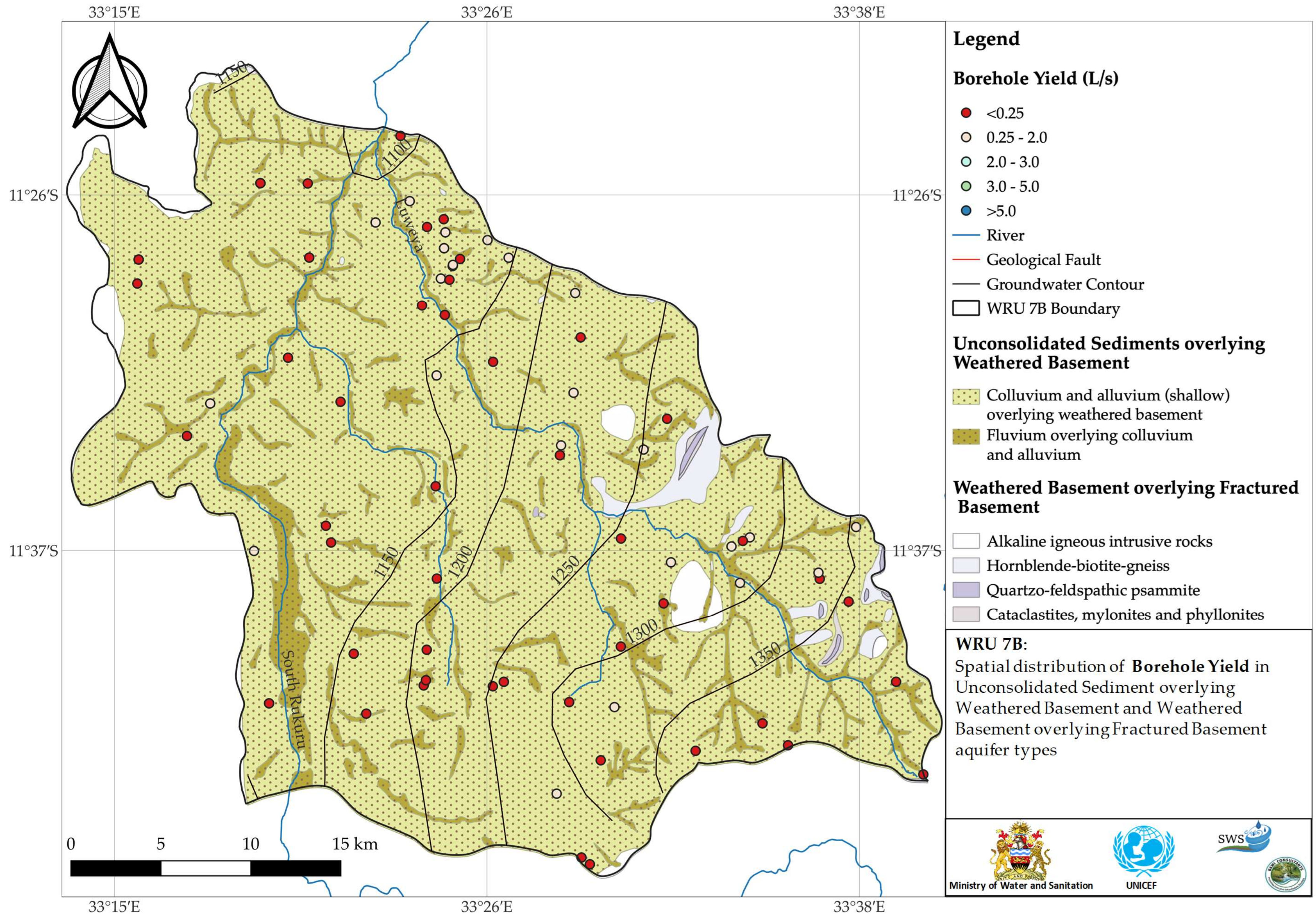


Figure WRU 7B.10 Borehole Yield Map for data held by the Ministry



WRU 7C Figures

Figure WRU 7C.1 Land Use and Major Roads

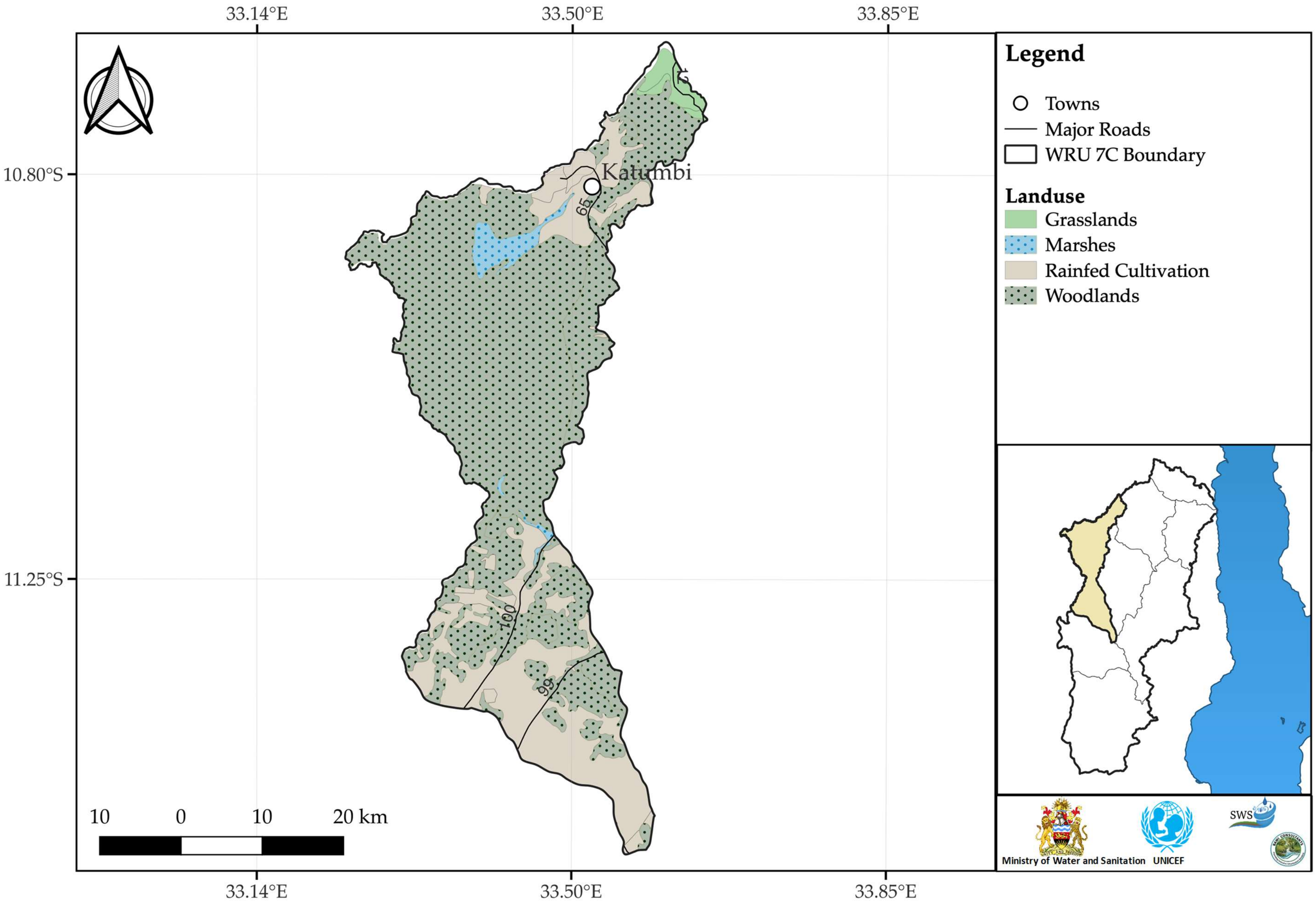


Figure WRU 7C.2 Rivers and Wetlands

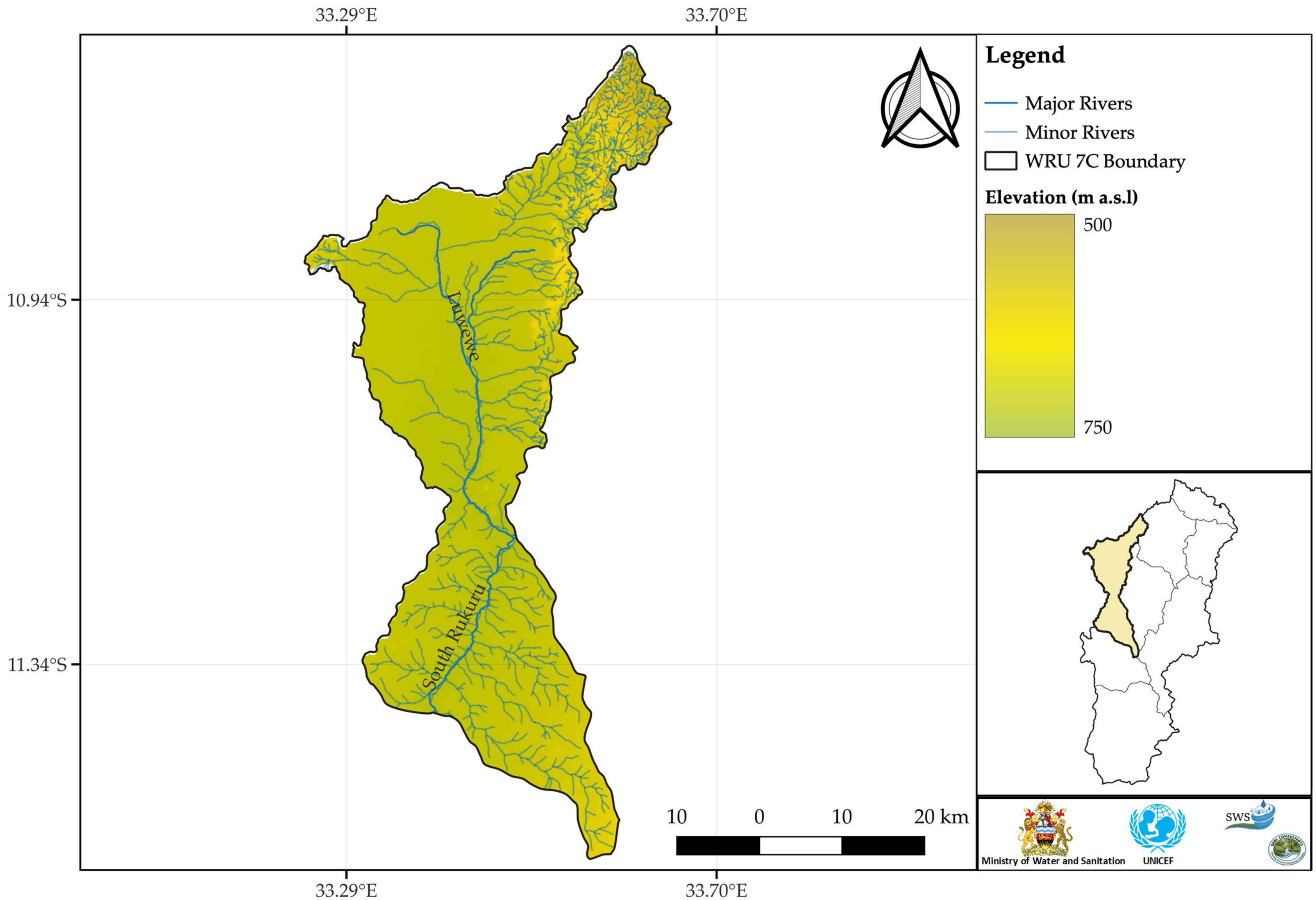


Figure WRU 7C.3 Hydrogeology Units and Water Table

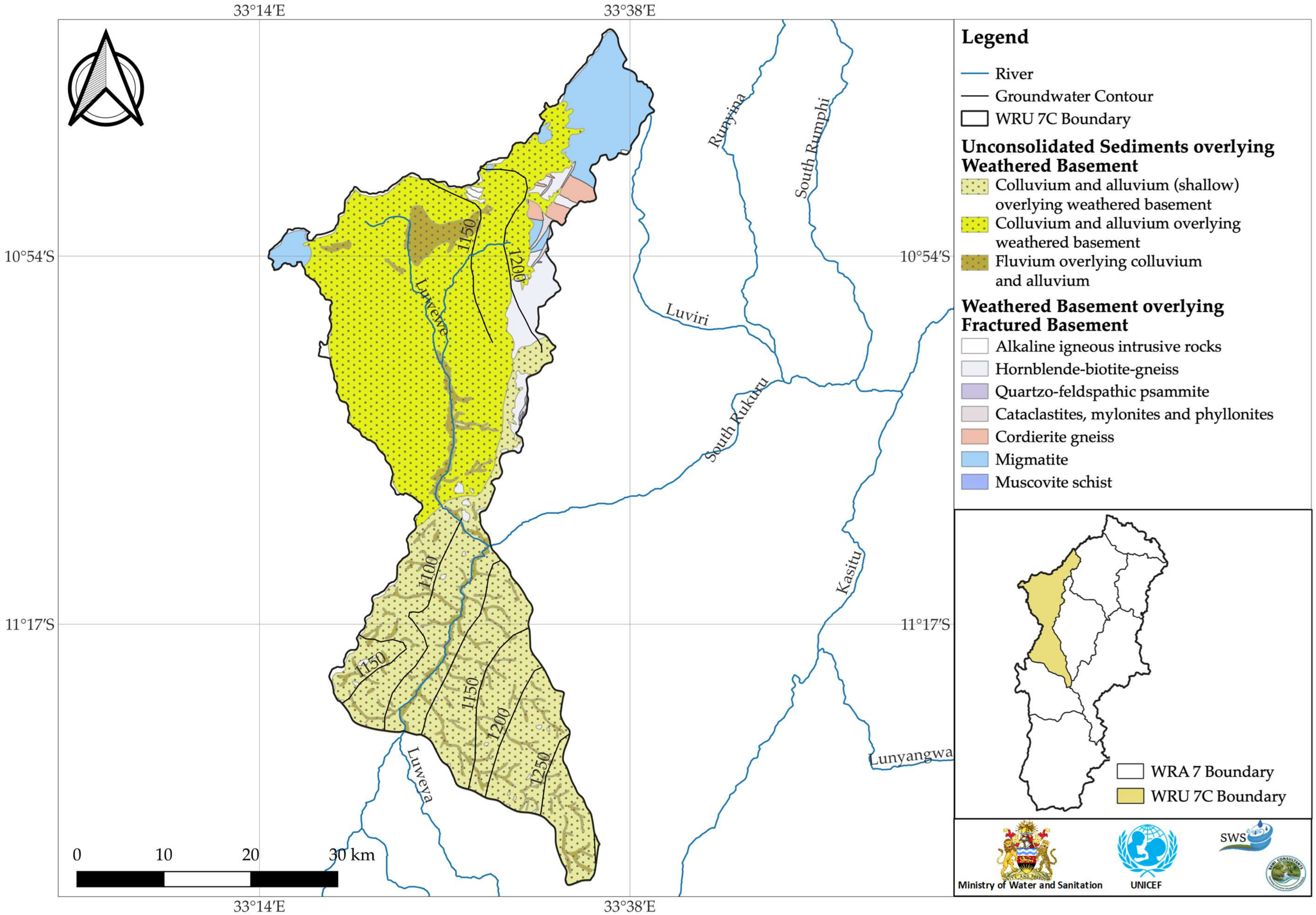


Figure WRU 7C.4 Groundwater Chemistry Distribution Electrical Conductivity

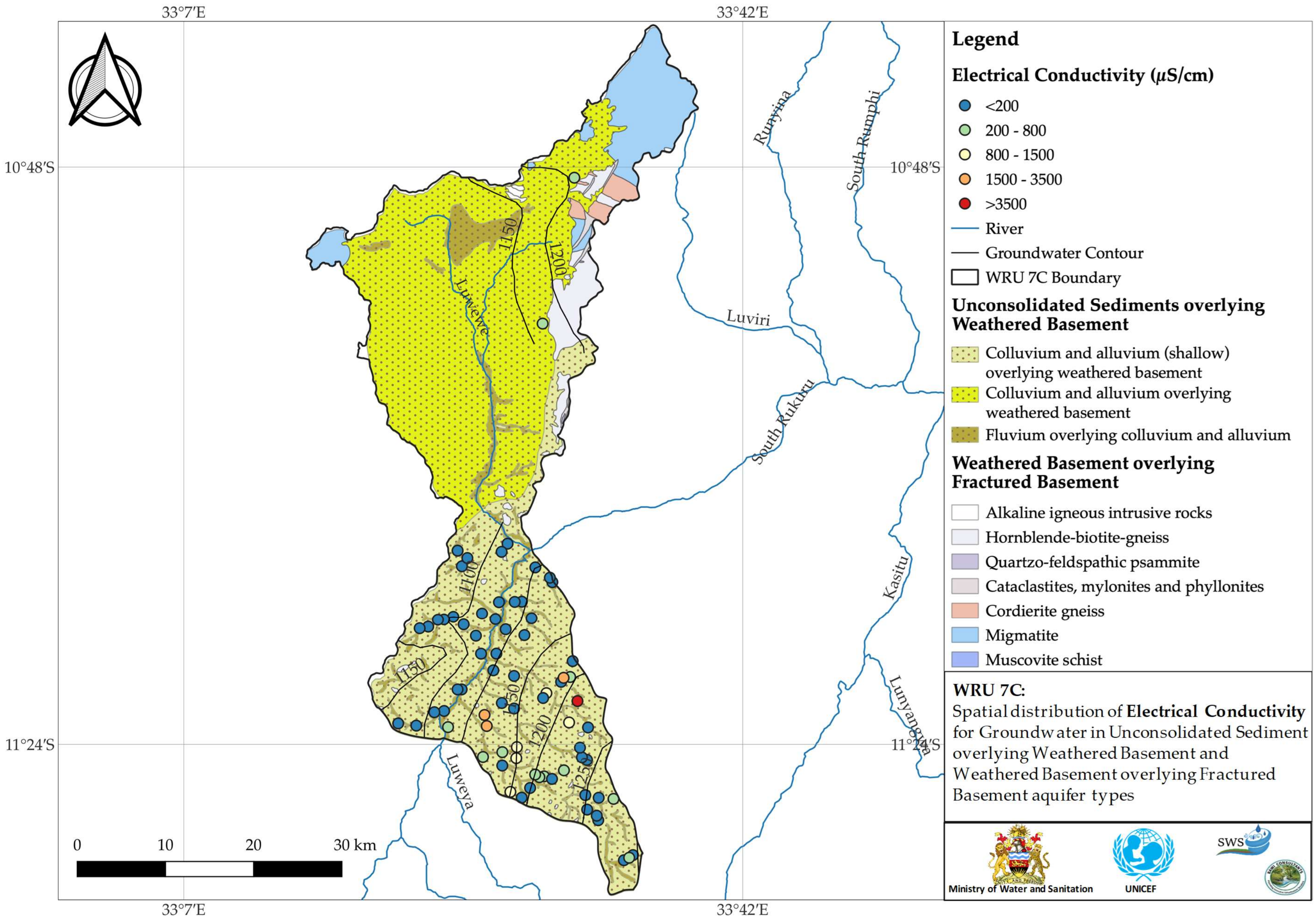


Figure WRU 7C.5 Groundwater Chemistry Distribution of Sulphate

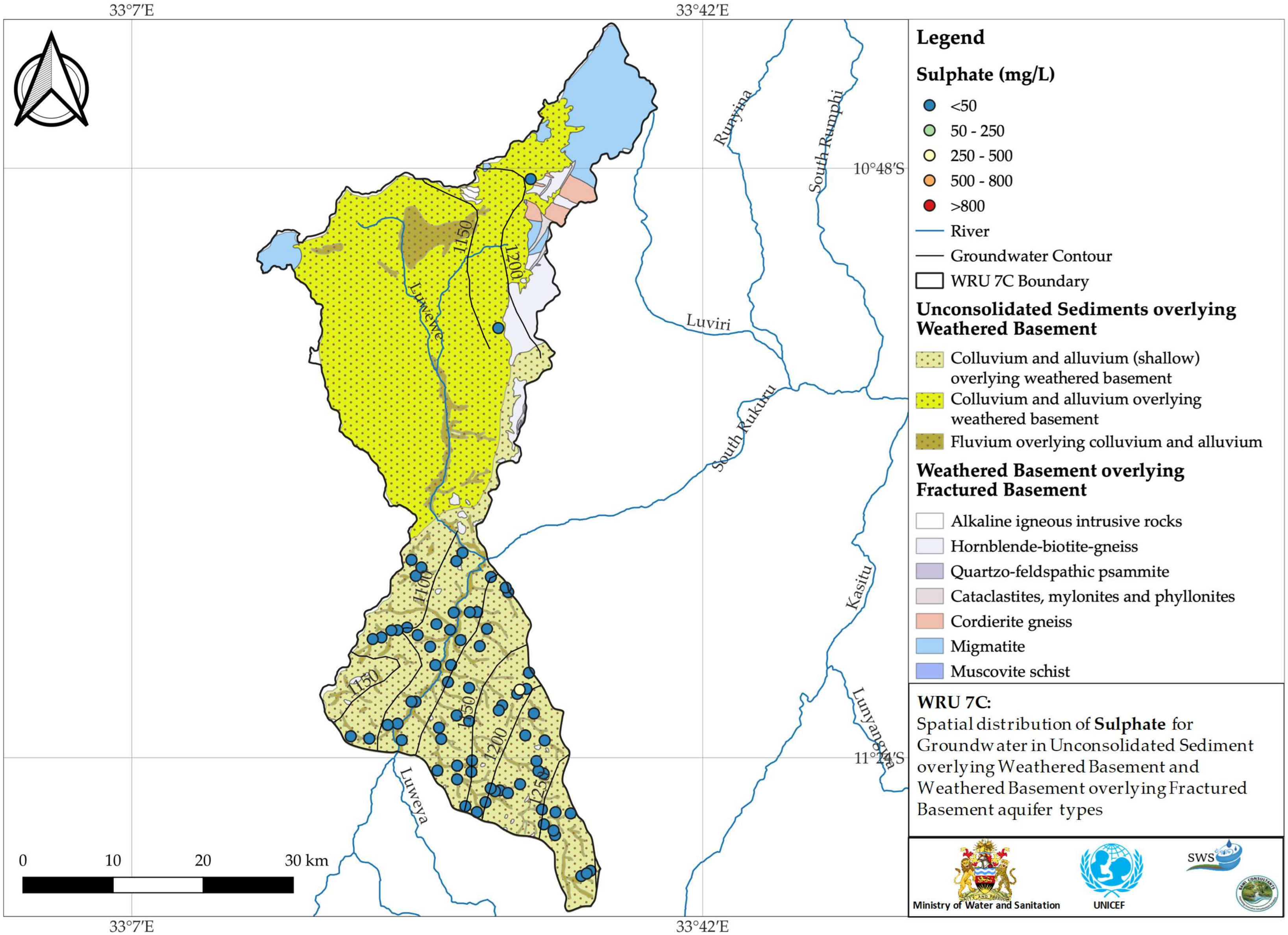


Figure WRU 7C.6 Groundwater Chemistry Distribution Chloride

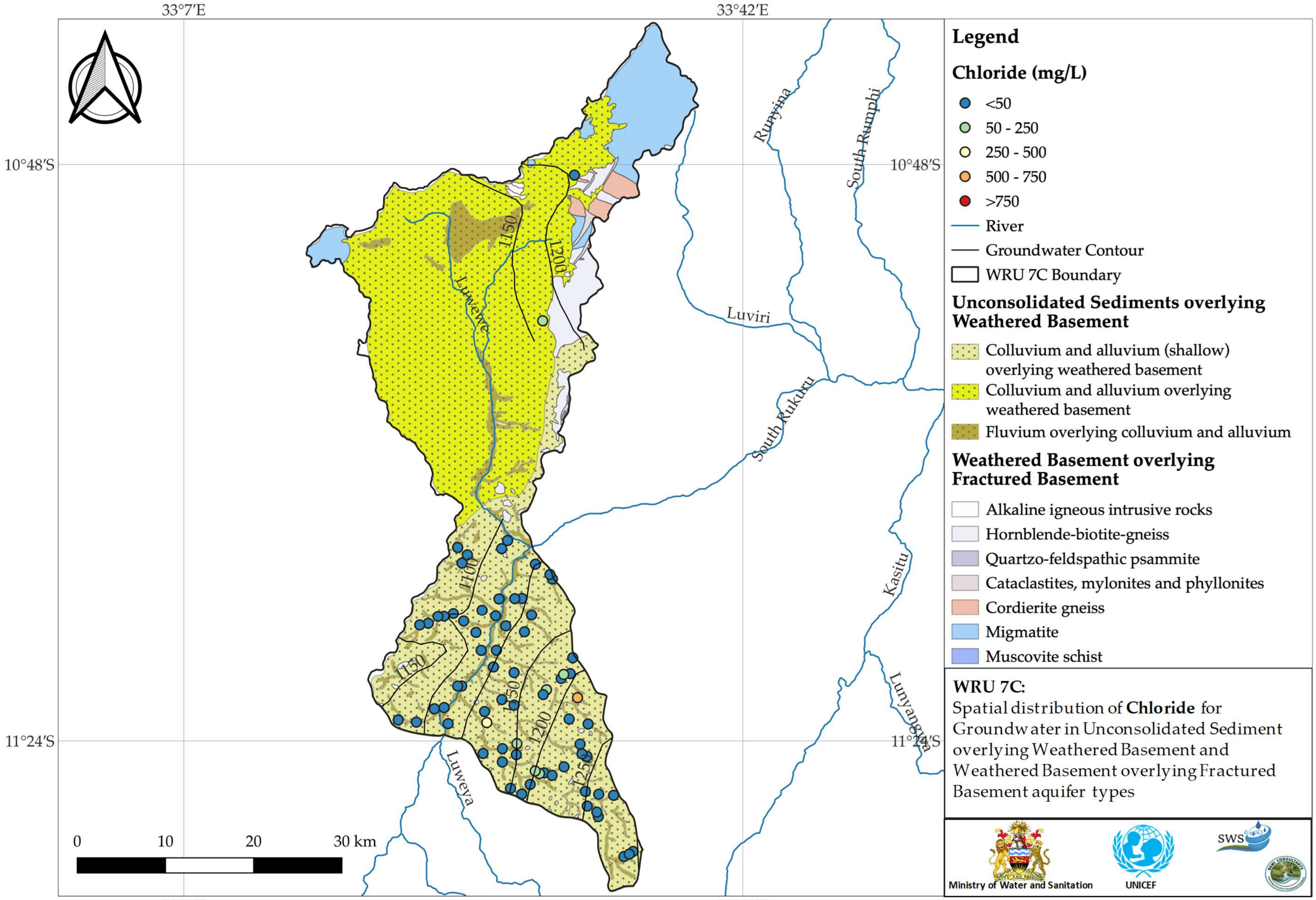


Figure WRU 7C.7 Groundwater Chemistry Distribution Sodium

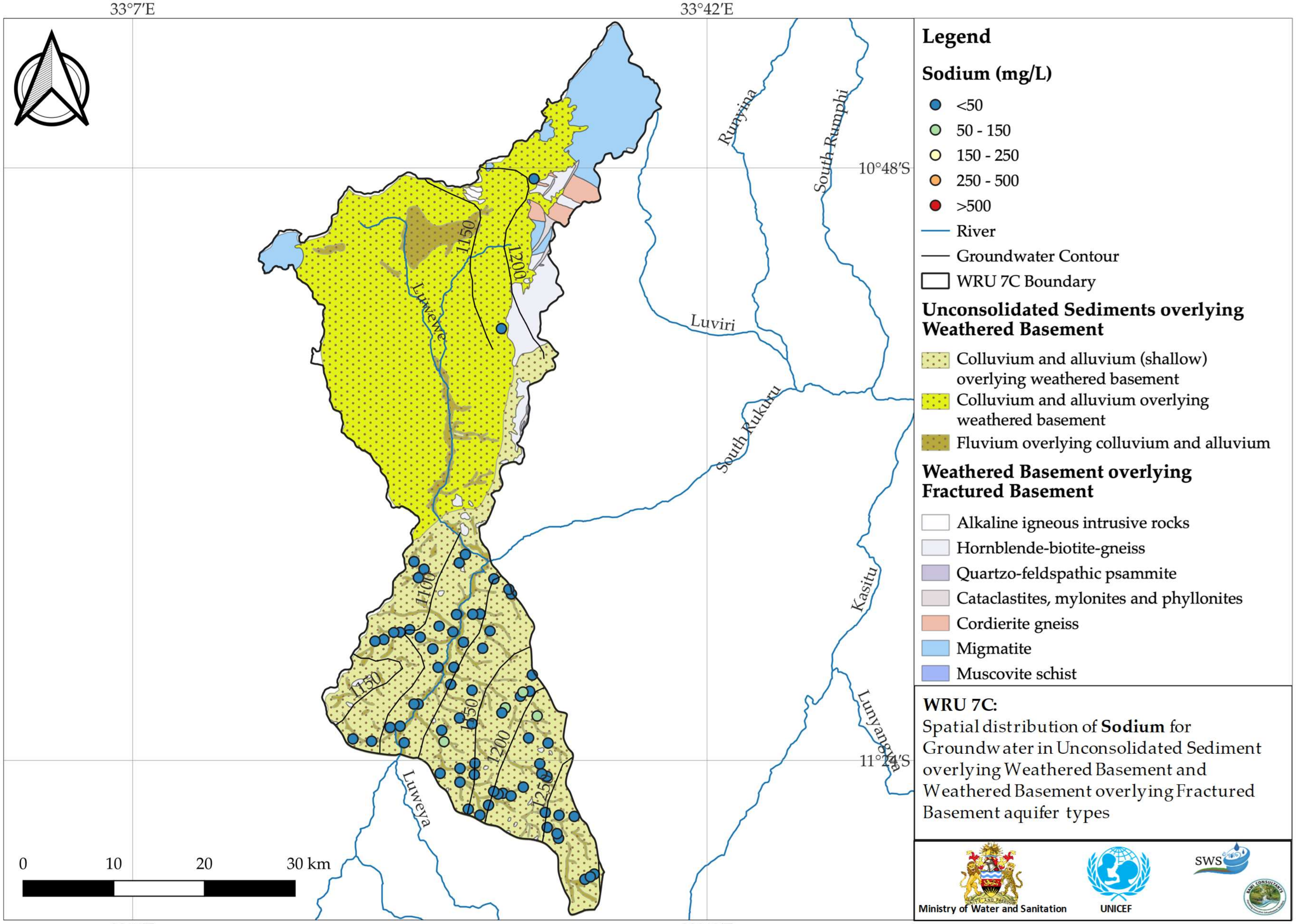


Figure WRU 7C.8 Groundwater Chemistry Distribution Calcium

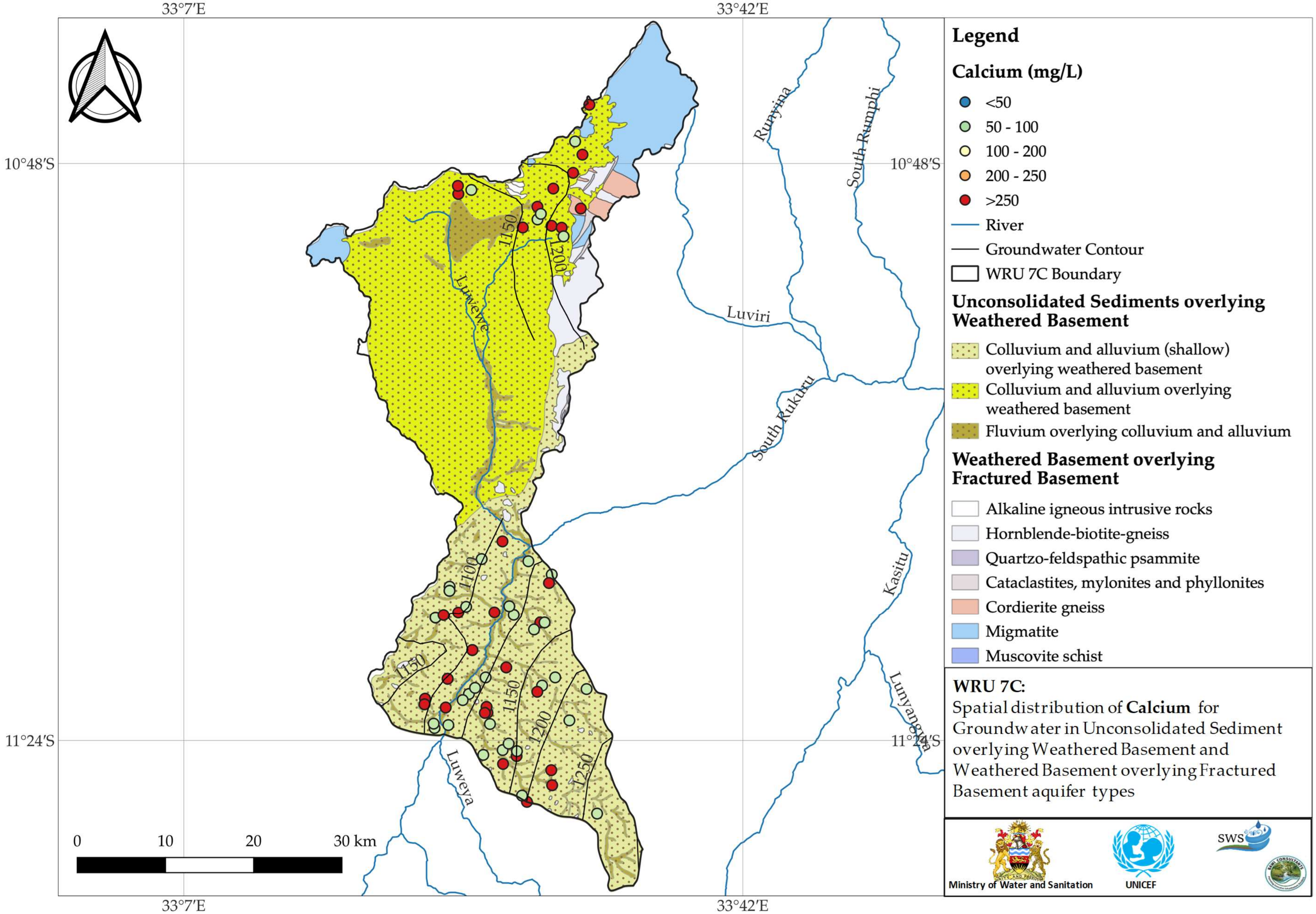


Figure WRU 7C.9 Piper Diagram of water quality results with respect to the major aquifer type

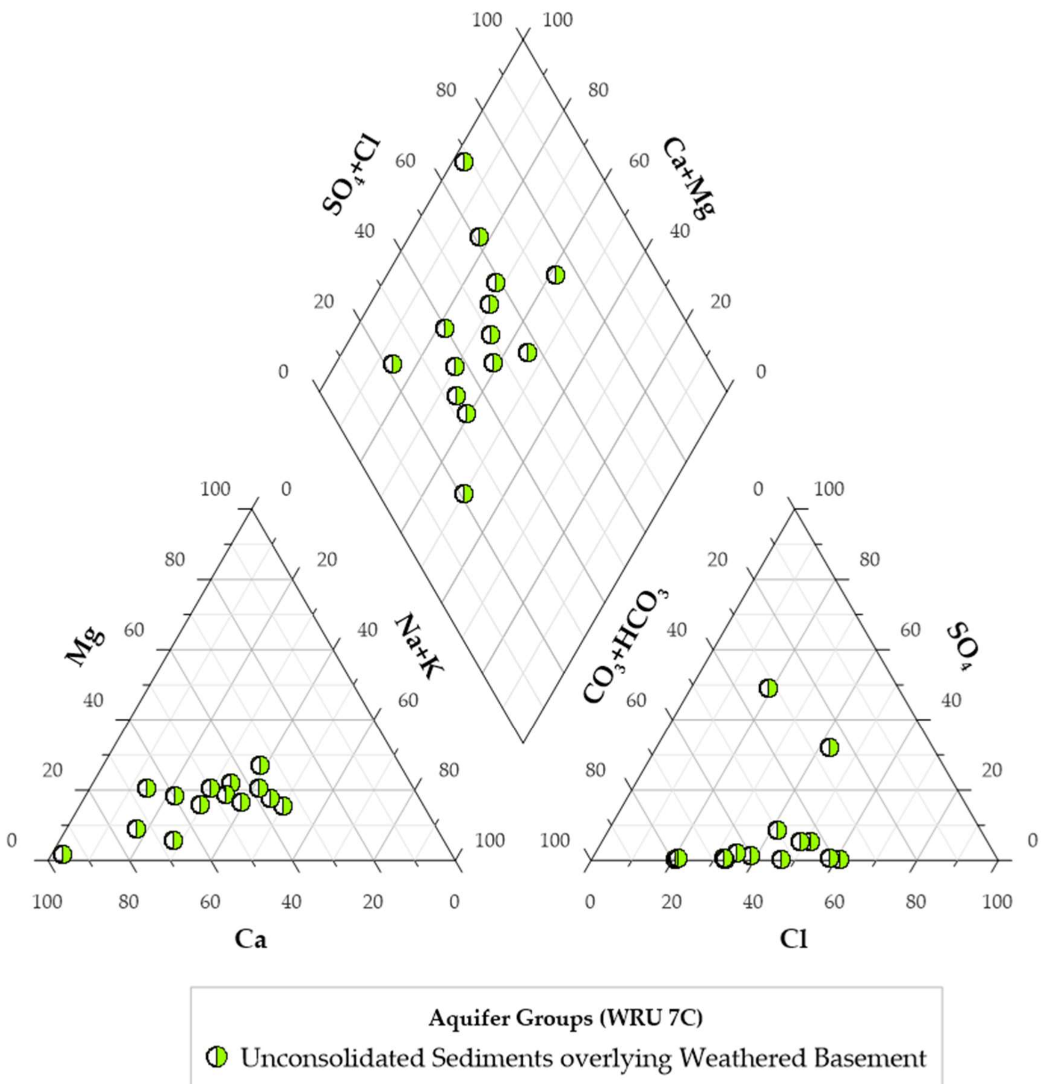
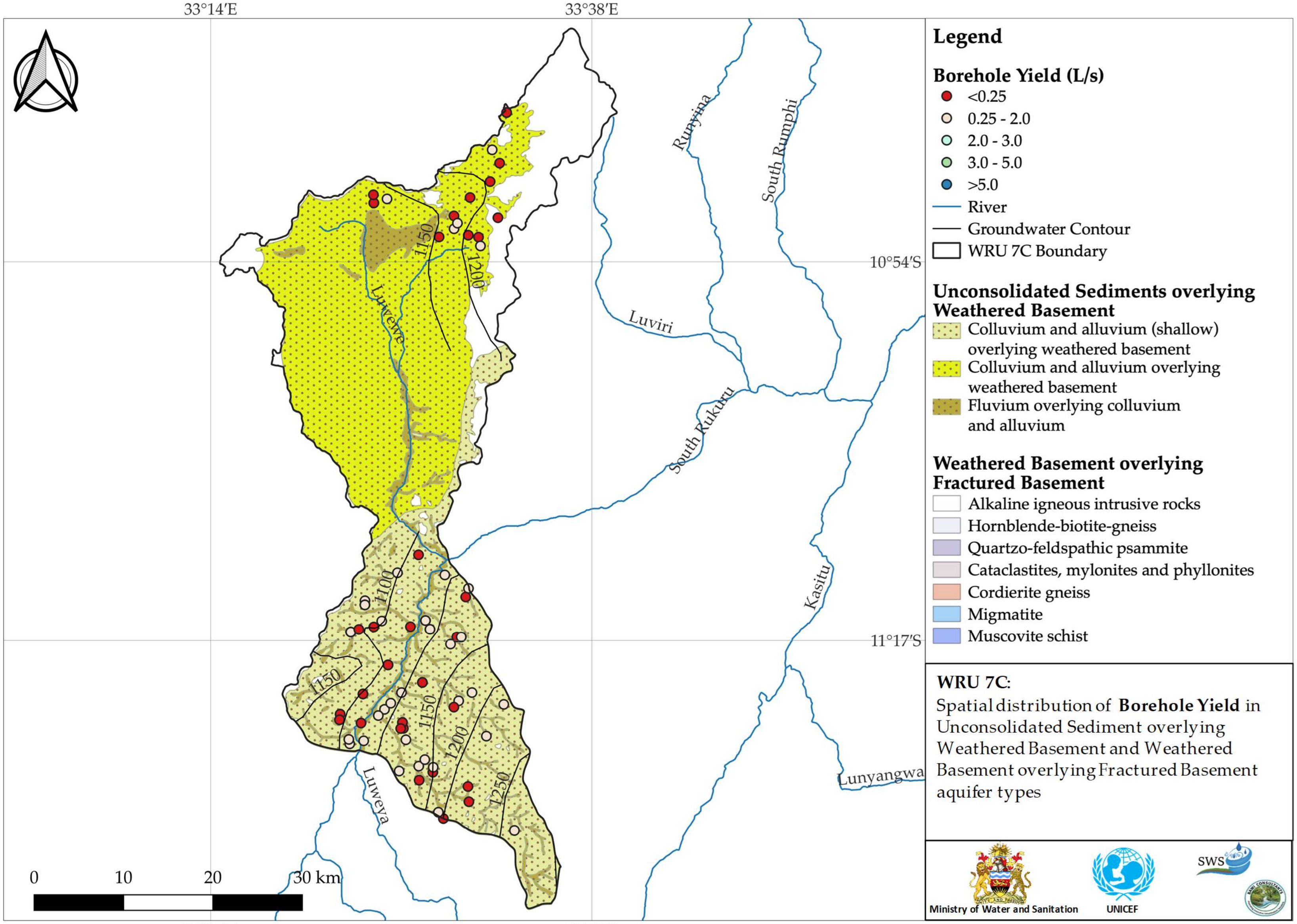


Figure WRU 7C.10 Borehole Yield Map for data held by the Ministry



WRU 7D Figures

Figure WRU 7D.1 Land Use and Major Roads

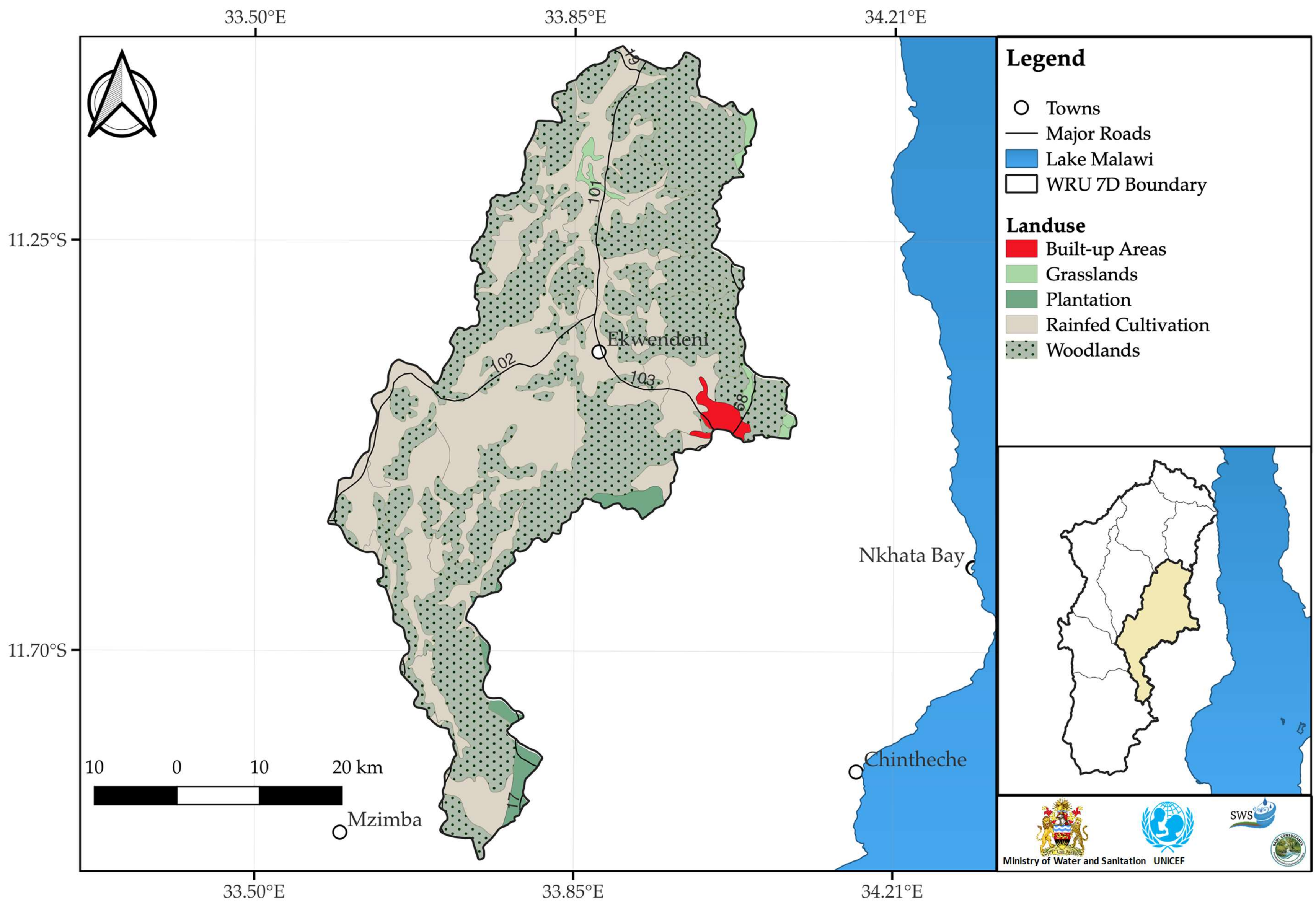


Figure WRU 7D.2 Rivers and Wetlands

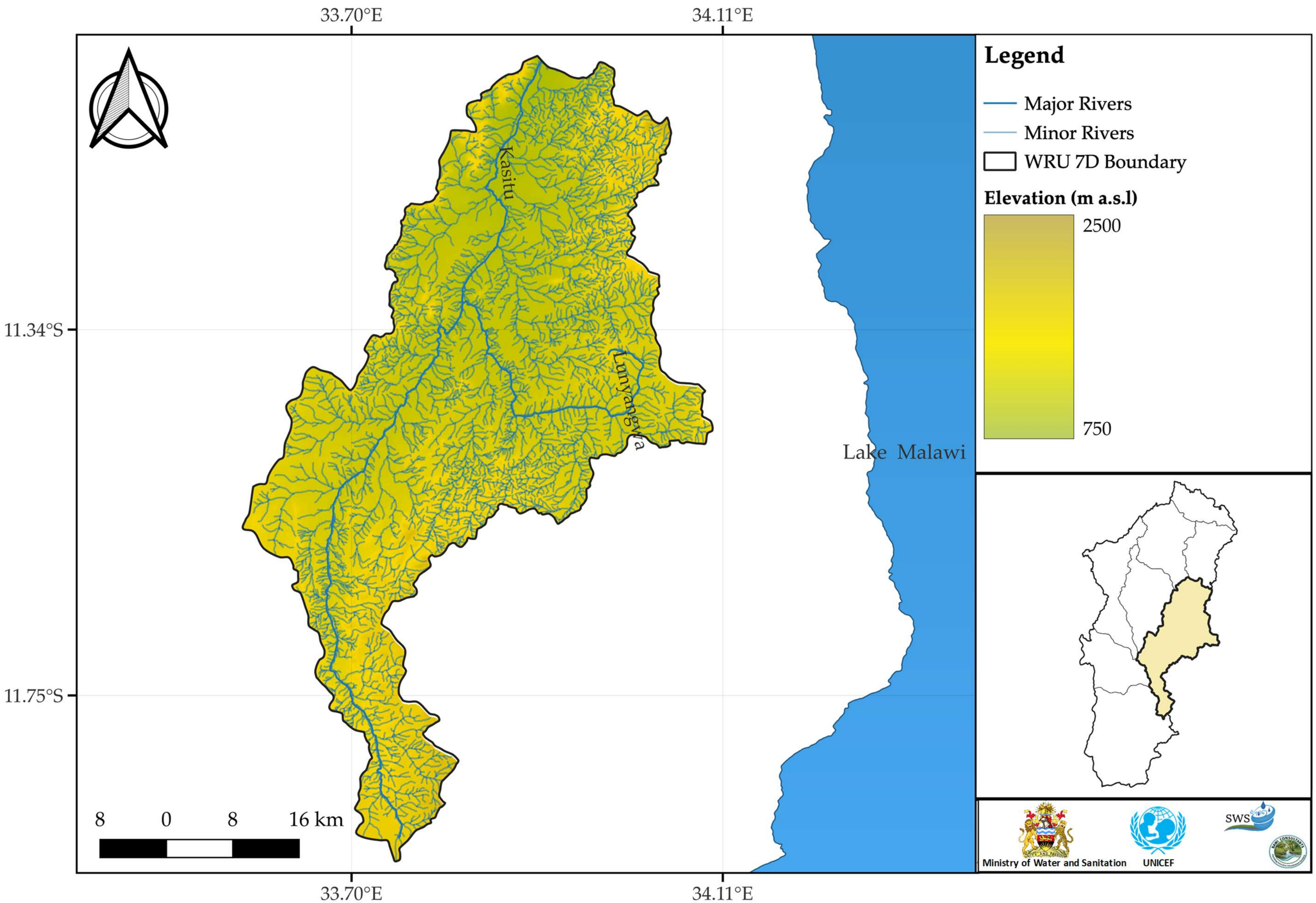


Figure WRU 7D.3 Hydrogeology Units and Water Table

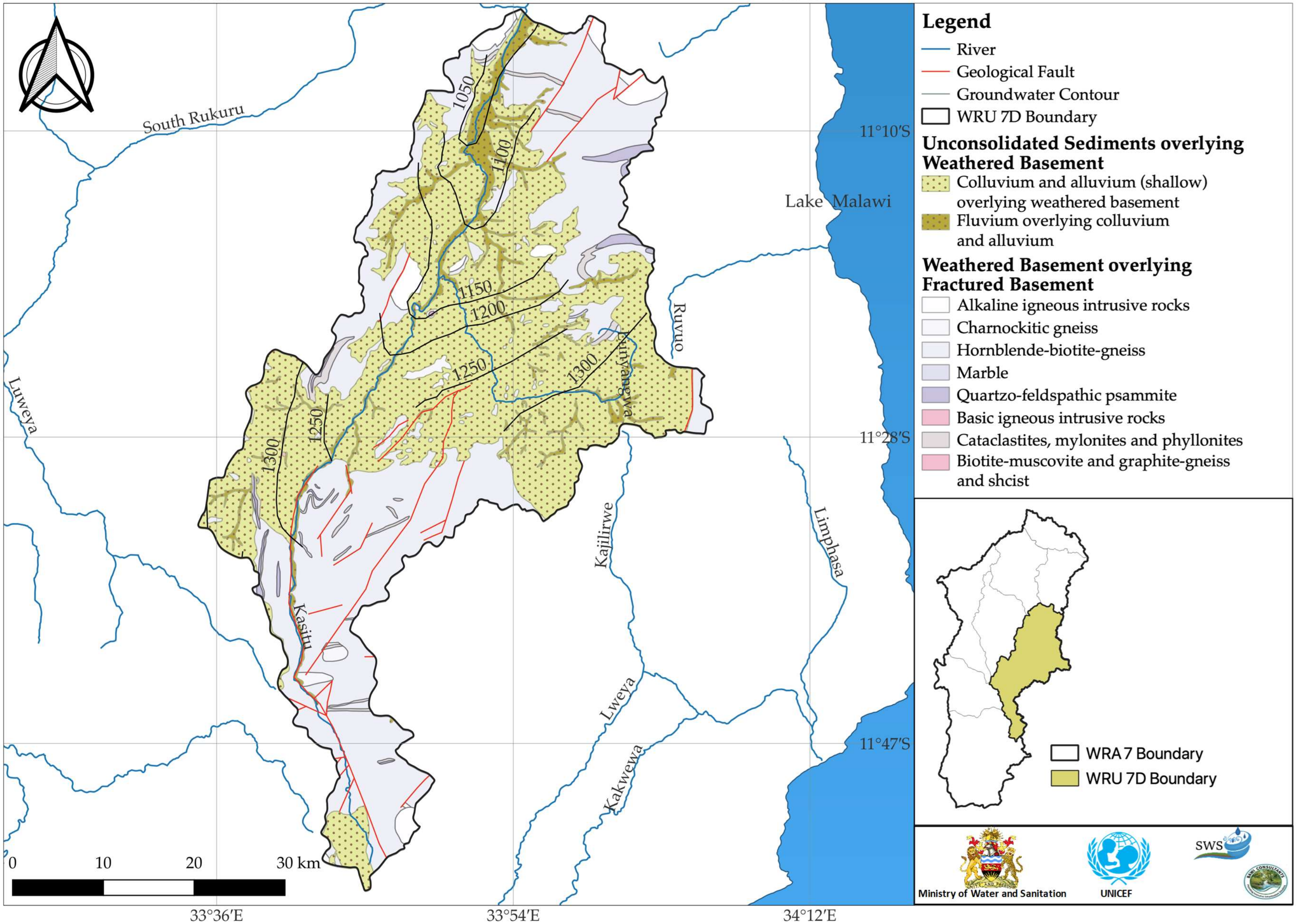


Figure WRU 7D.4 Groundwater Chemistry Distribution Electrical Conductivity

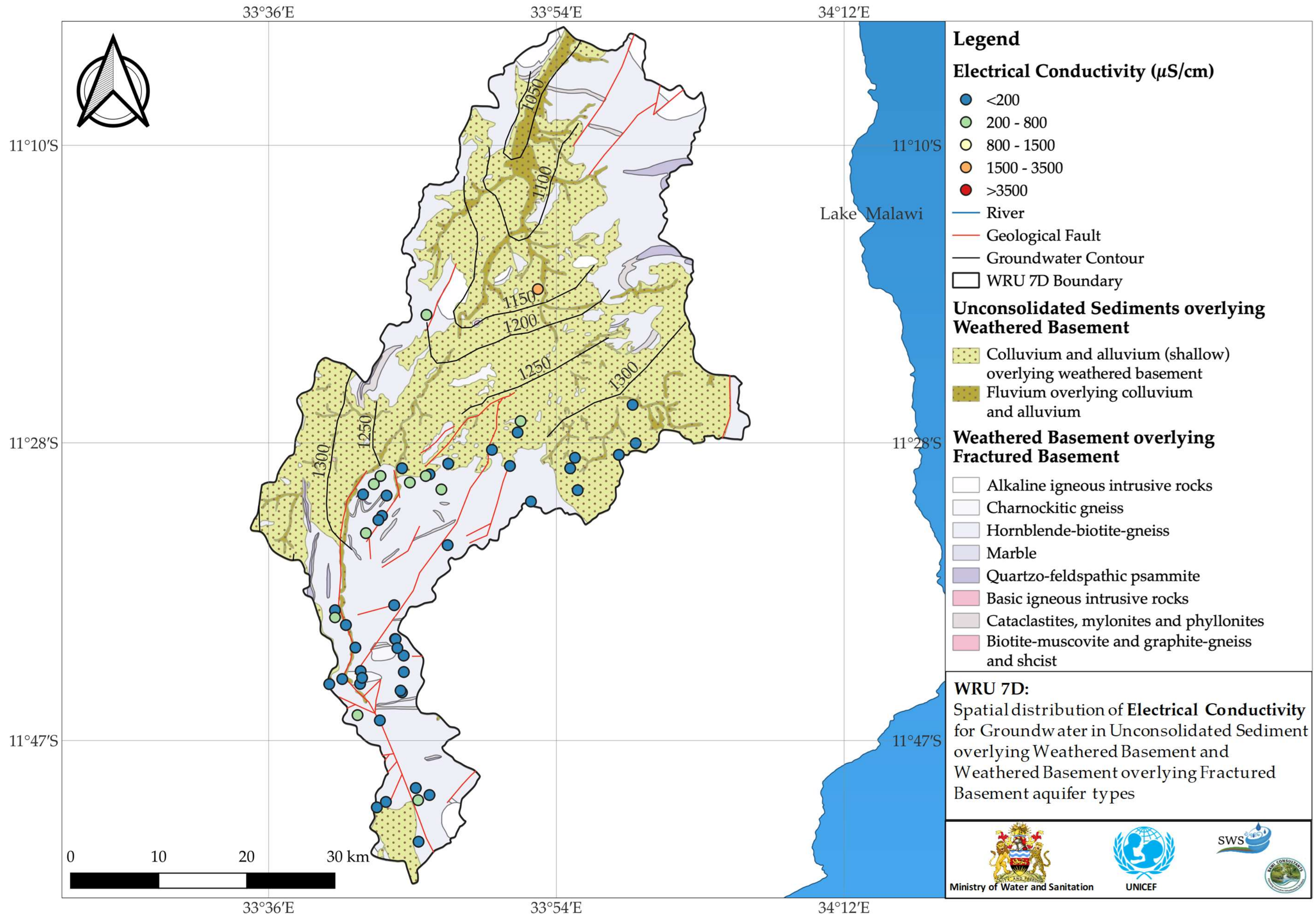


Figure WRU 7D.5 Groundwater Chemistry Distribution of Sulphate

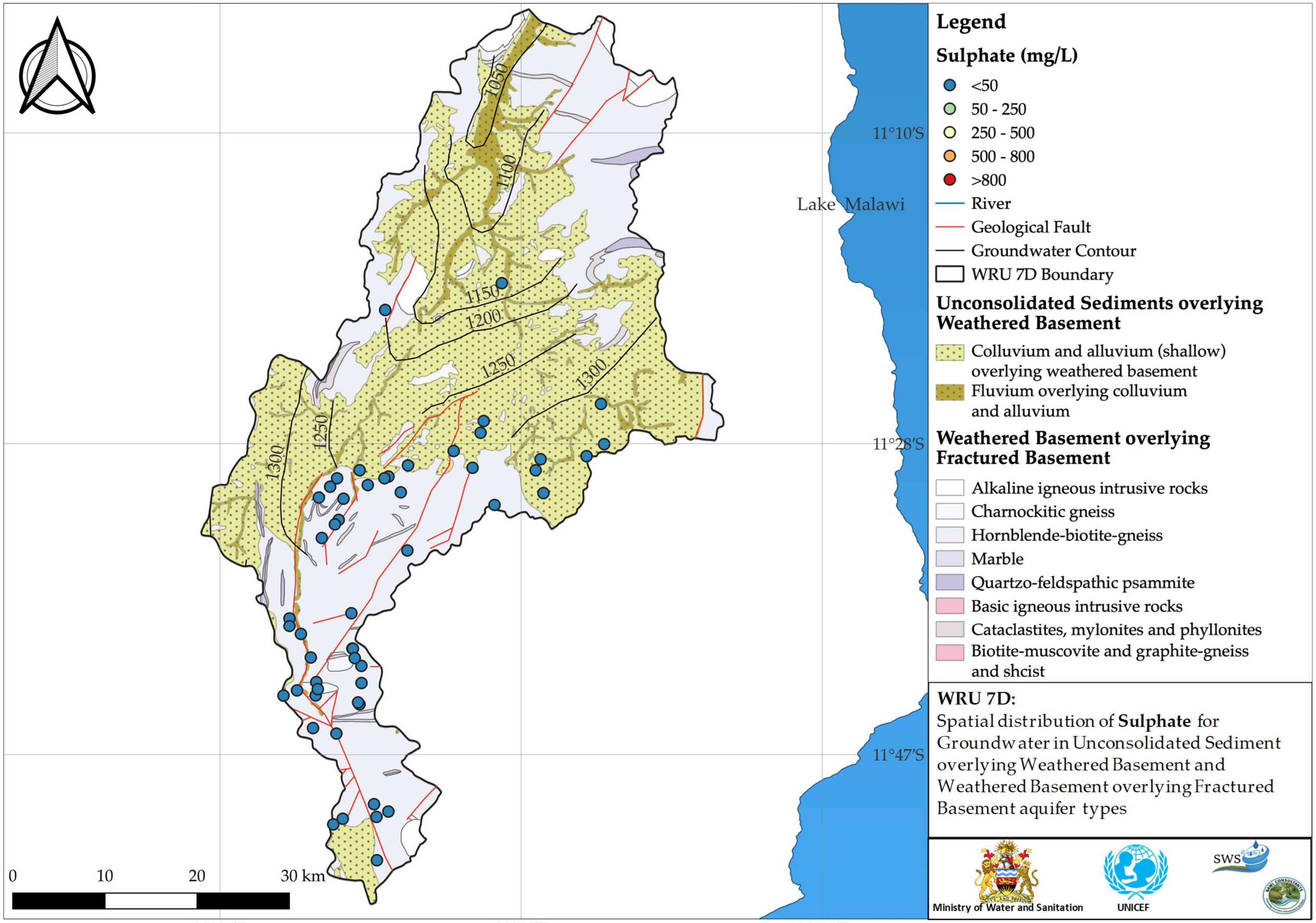


Figure WRU 7D.6 Groundwater Chemistry Distribution Chloride

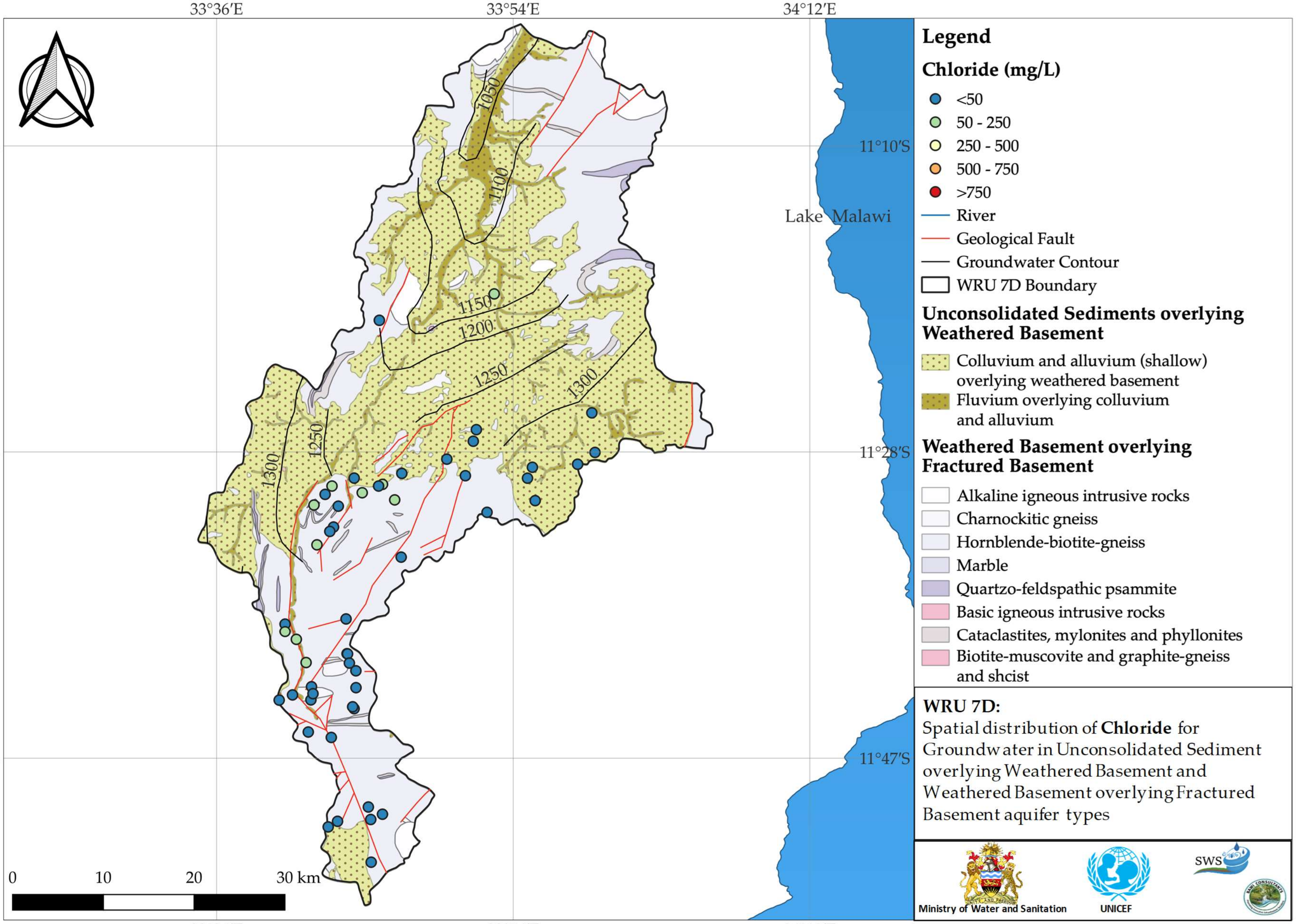


Figure WRU 7D.7 Groundwater Chemistry Distribution Sodium

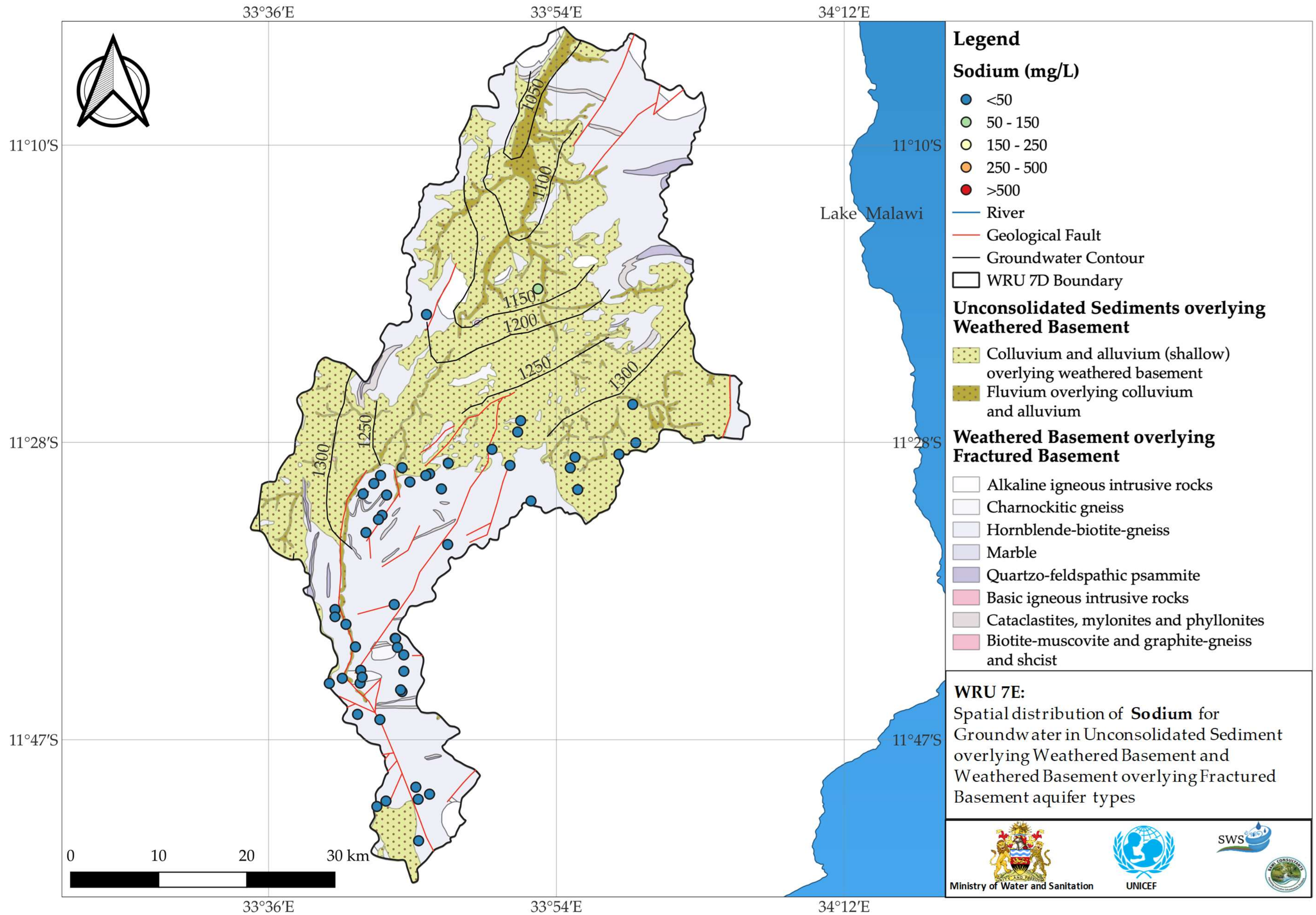


Figure WRU 7D.8 Groundwater Chemistry Distribution Calcium

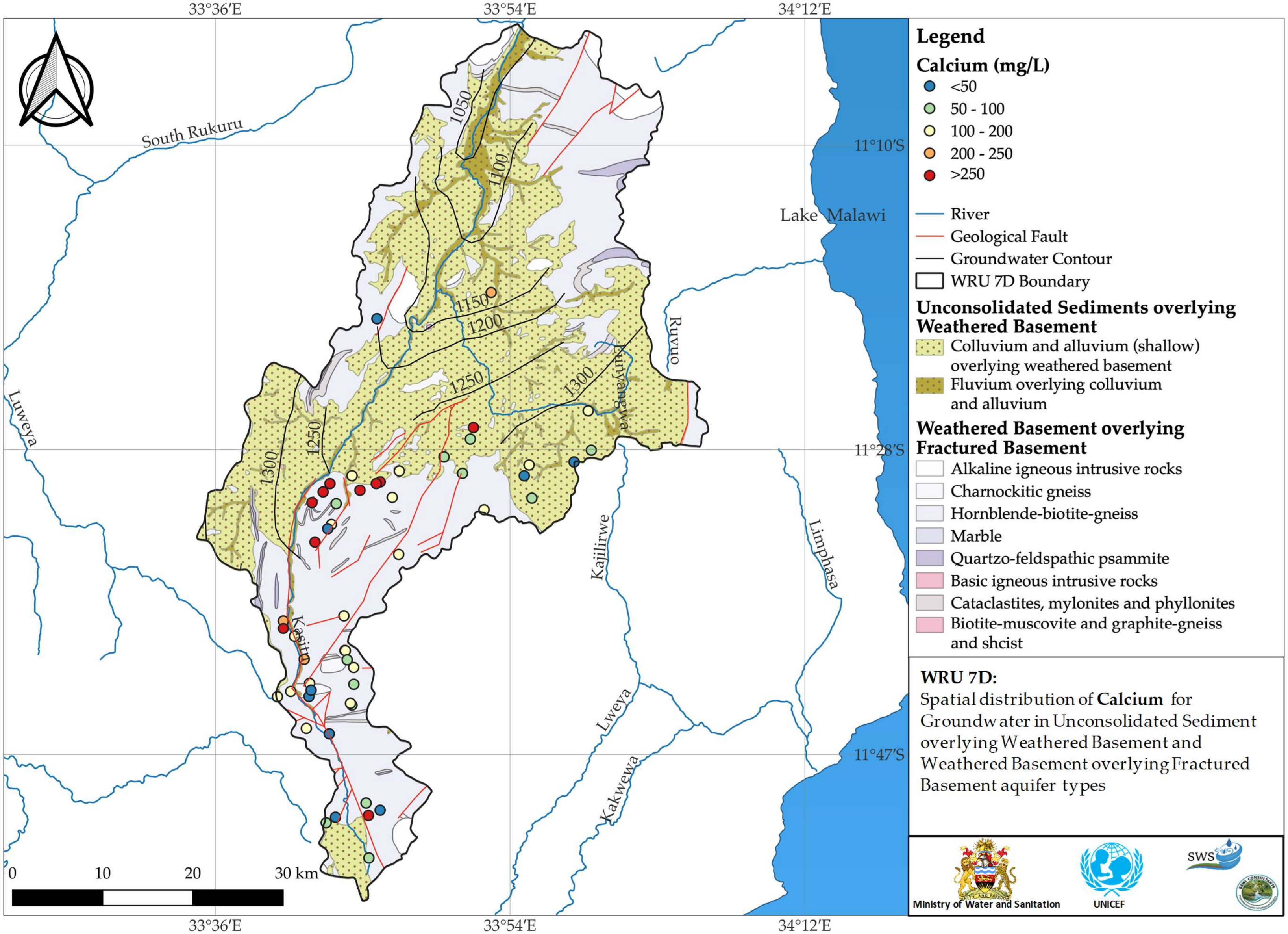


Figure WRU 7D.9 Piper Diagram of water quality results with respect to the major aquifer type

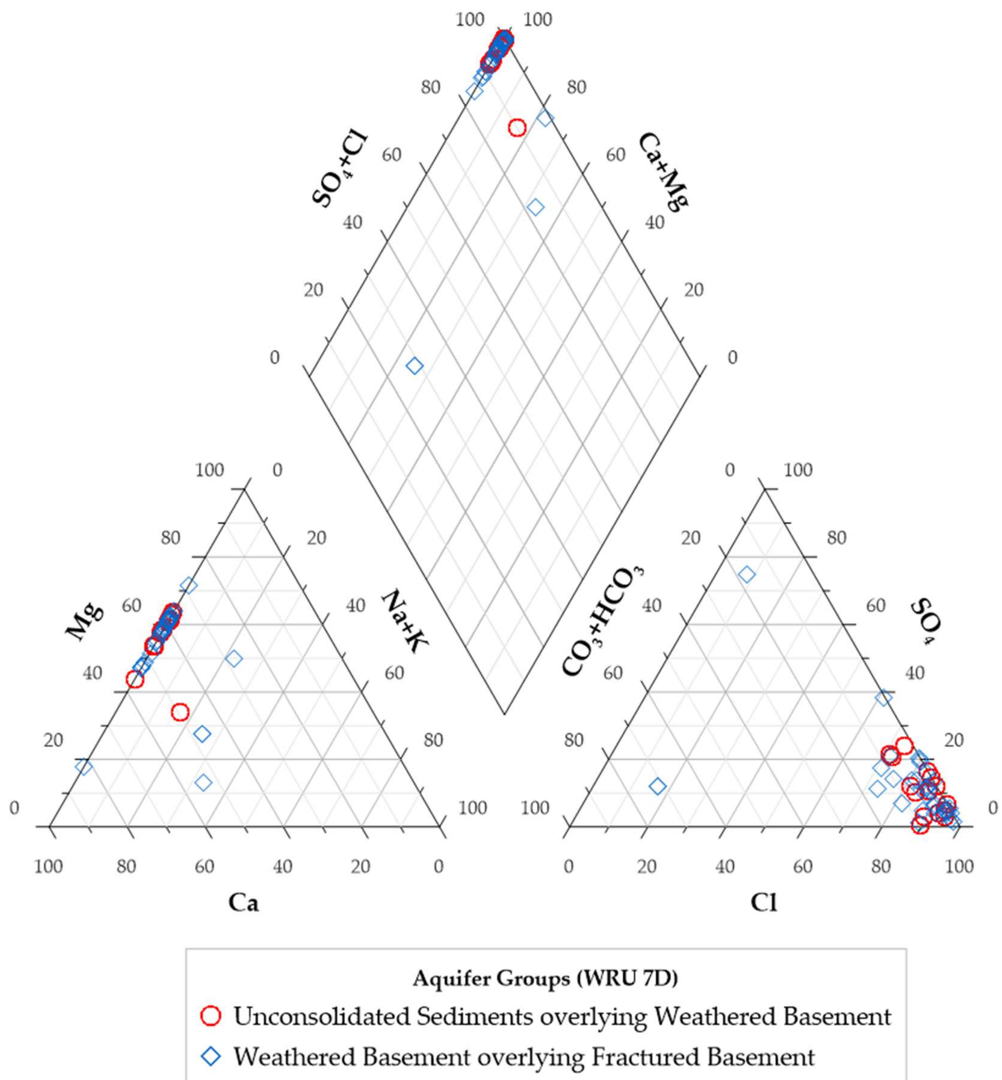
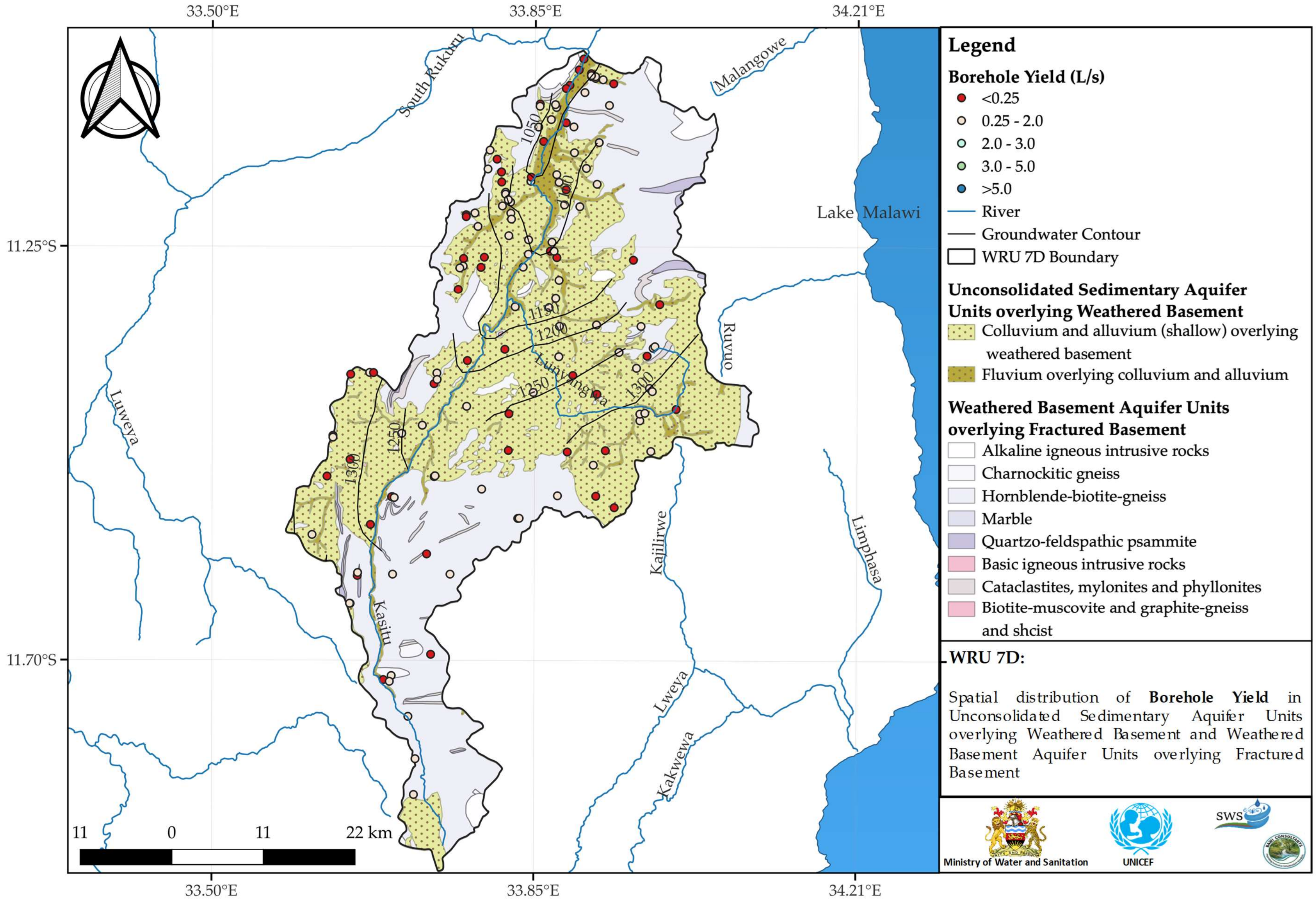


Figure WRU 7D.10 Borehole Yield Map for data held by the Ministry



WRU 7E Figures

Figure WRU 7E.1 Land Use and Major Roads

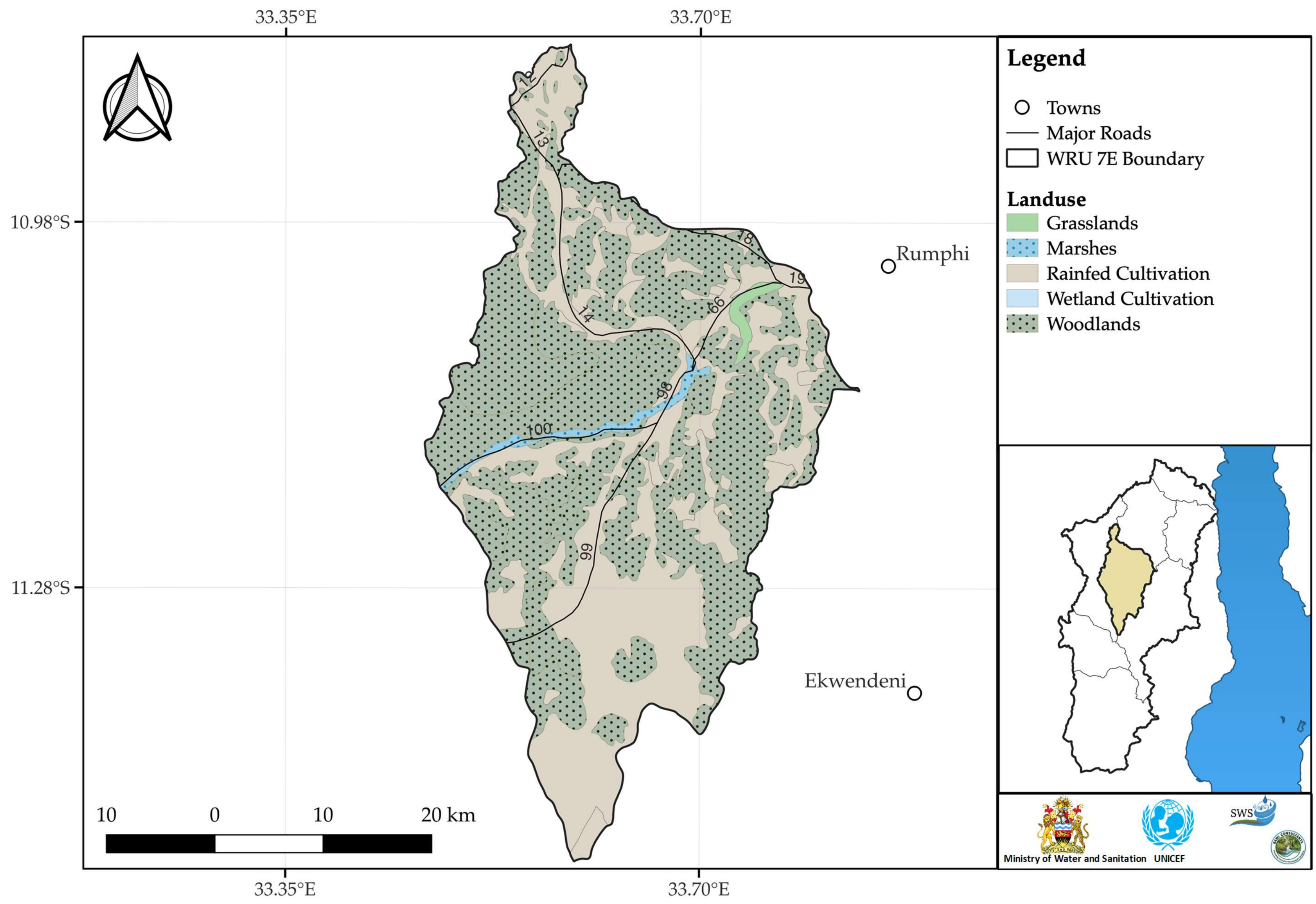


Figure WRU 7E.2 Rivers and Wetlands

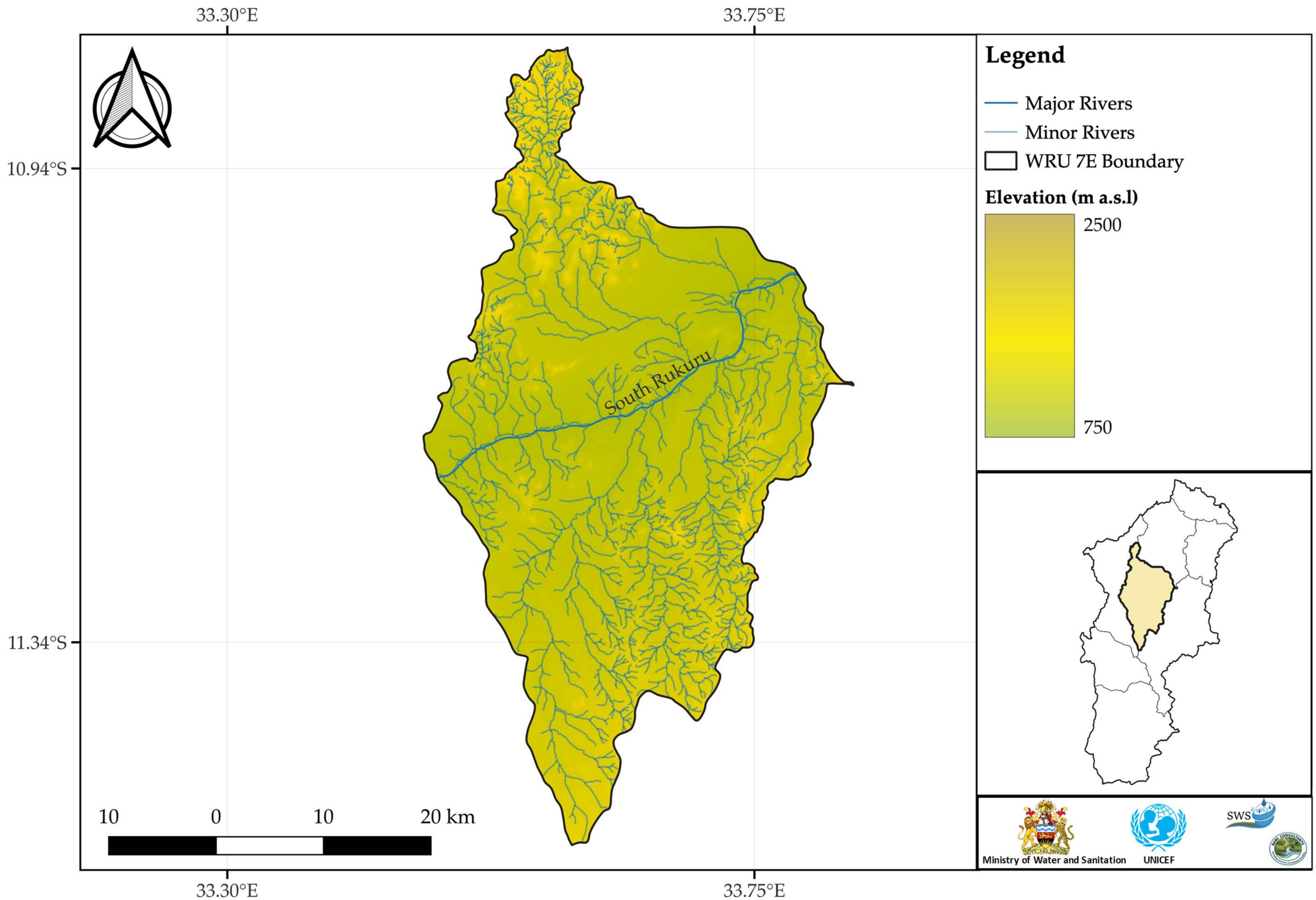


Figure WRU 7E.3 Hydrogeology Units and Water Table

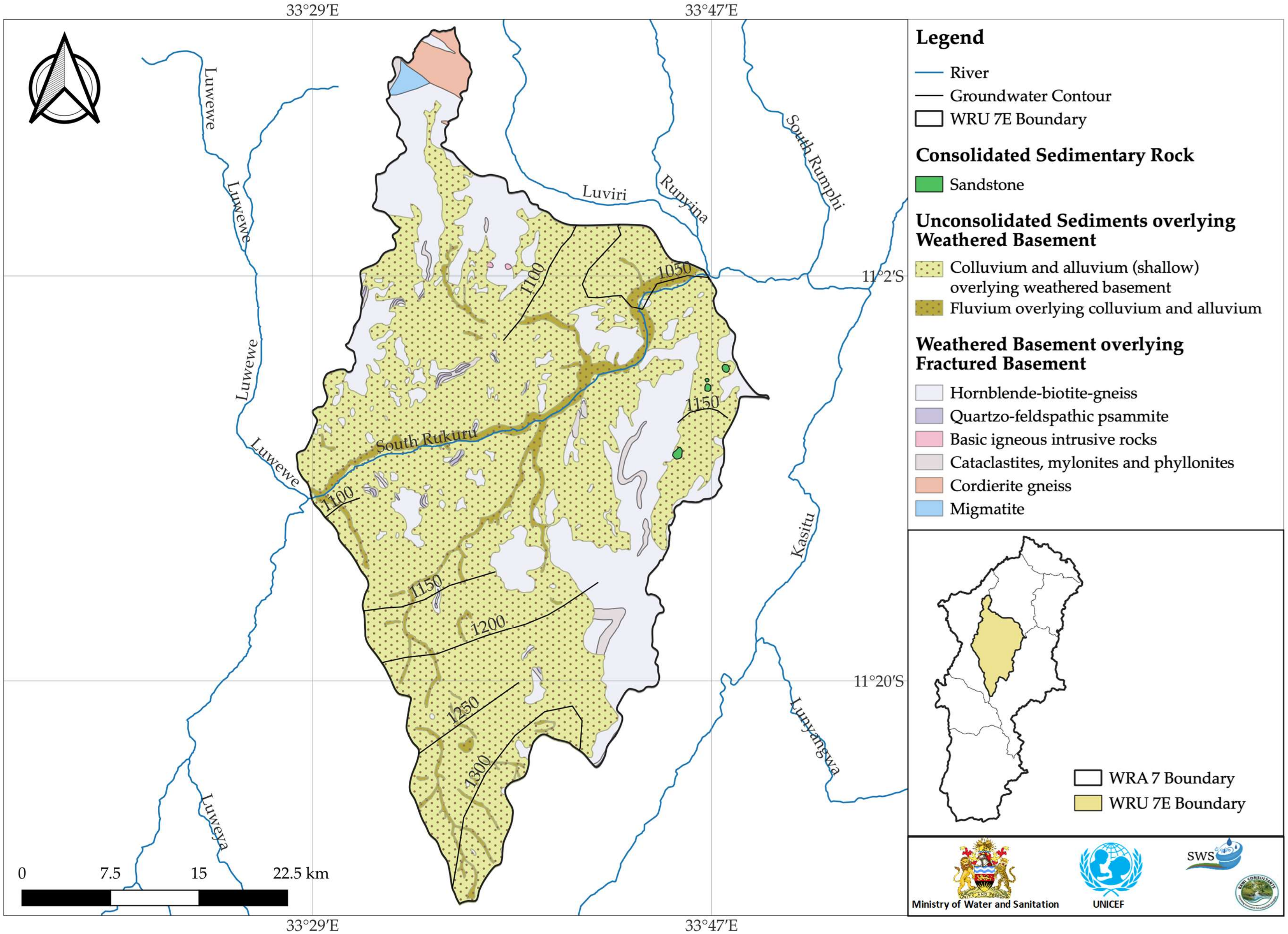


Figure WRU 7E.4 Groundwater Chemistry Distribution Electrical Conductivity

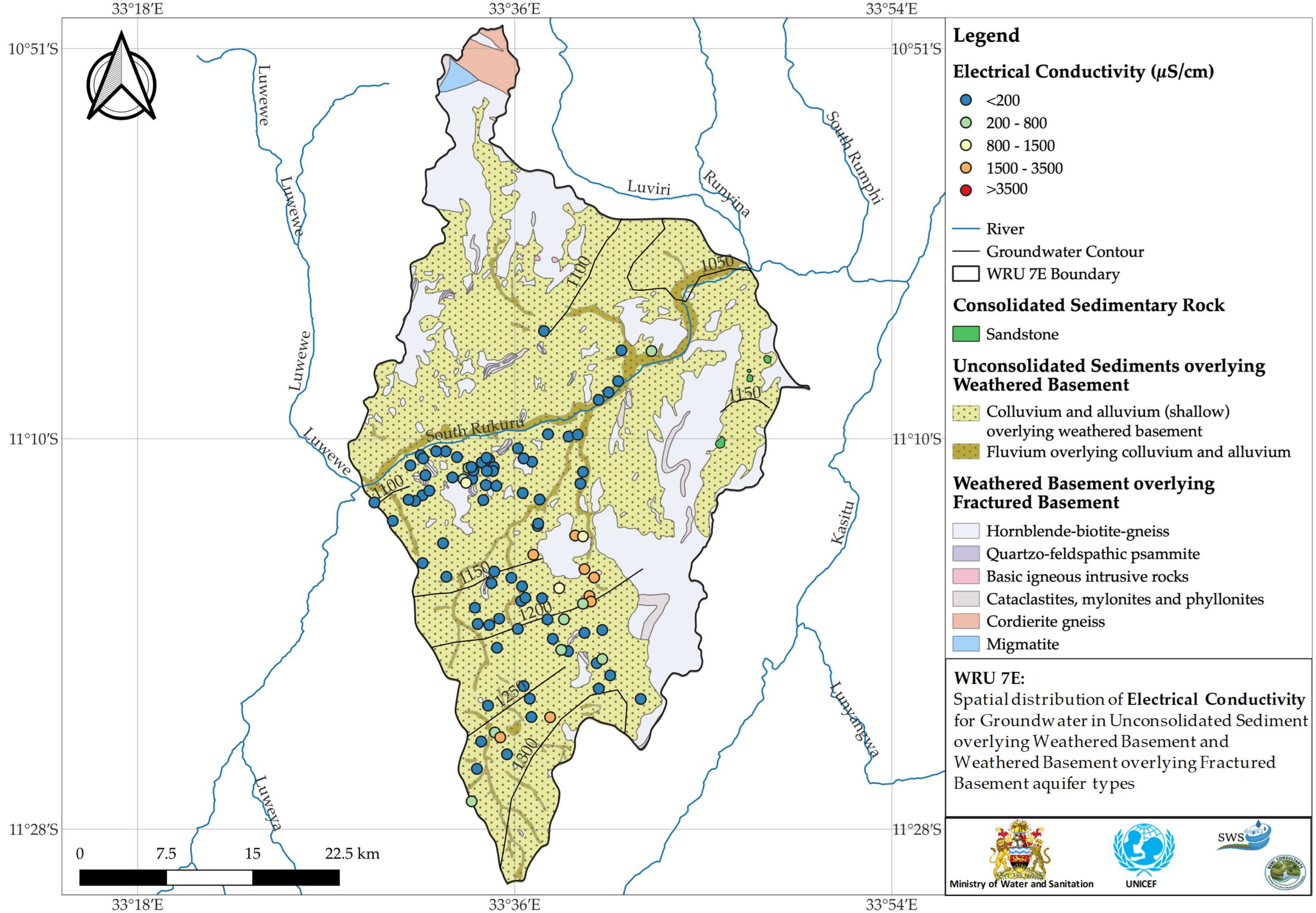


Figure WRU 7E.5 Groundwater Chemistry Distribution of Sulphate

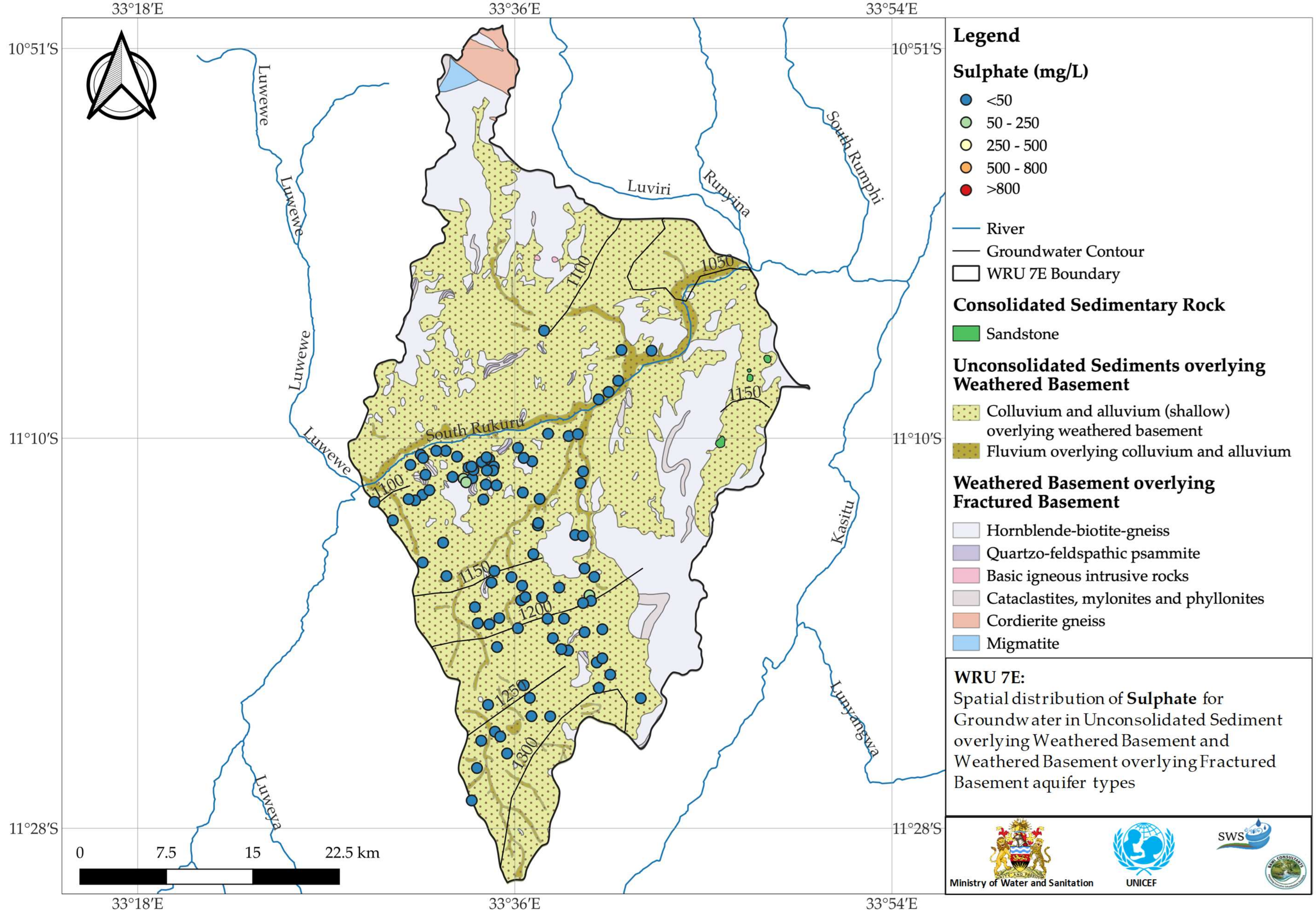


Figure WRU 7E.6 Groundwater Chemistry Distribution Chloride

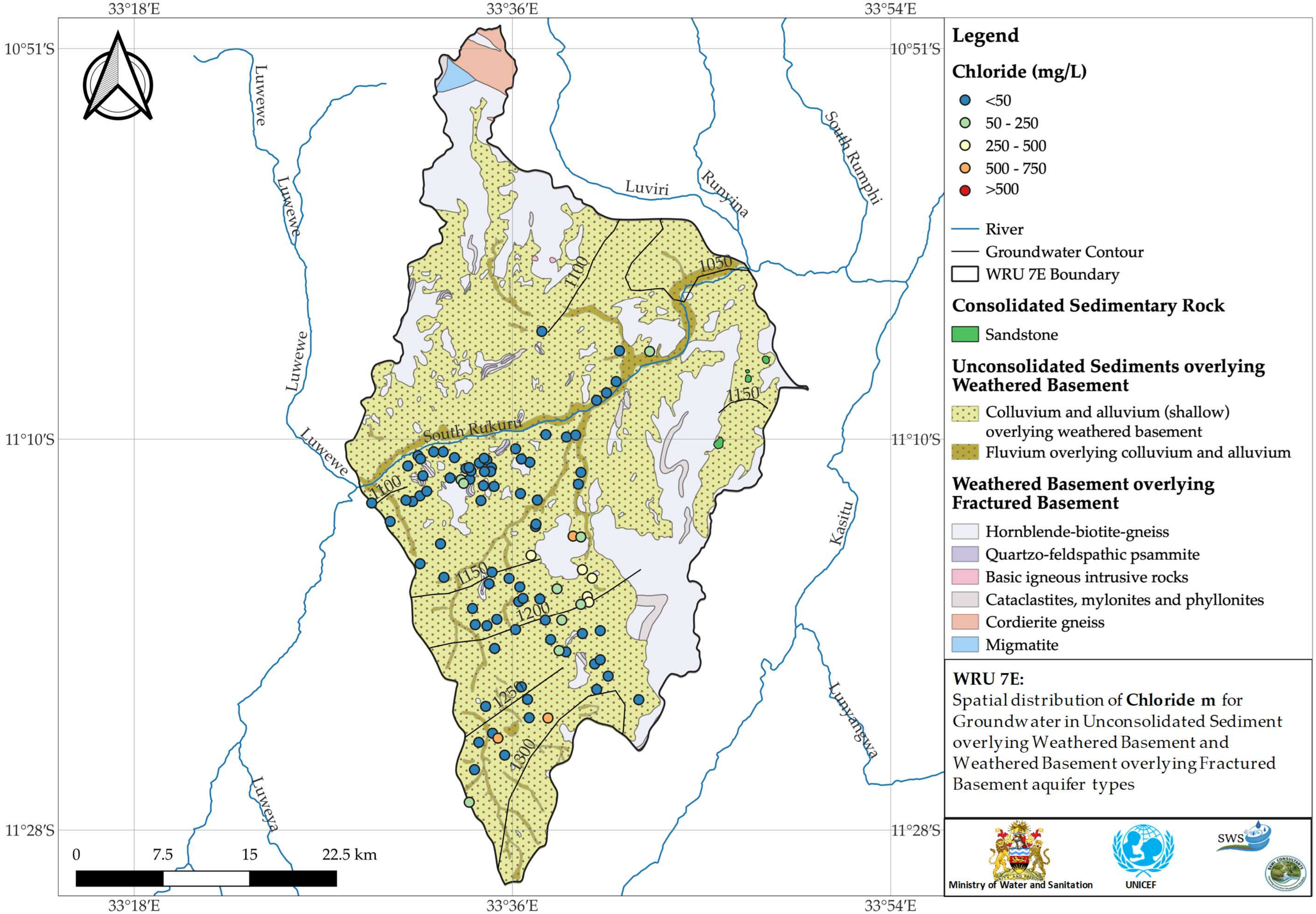


Figure WRU 7E.7 Groundwater Chemistry Distribution Sodium

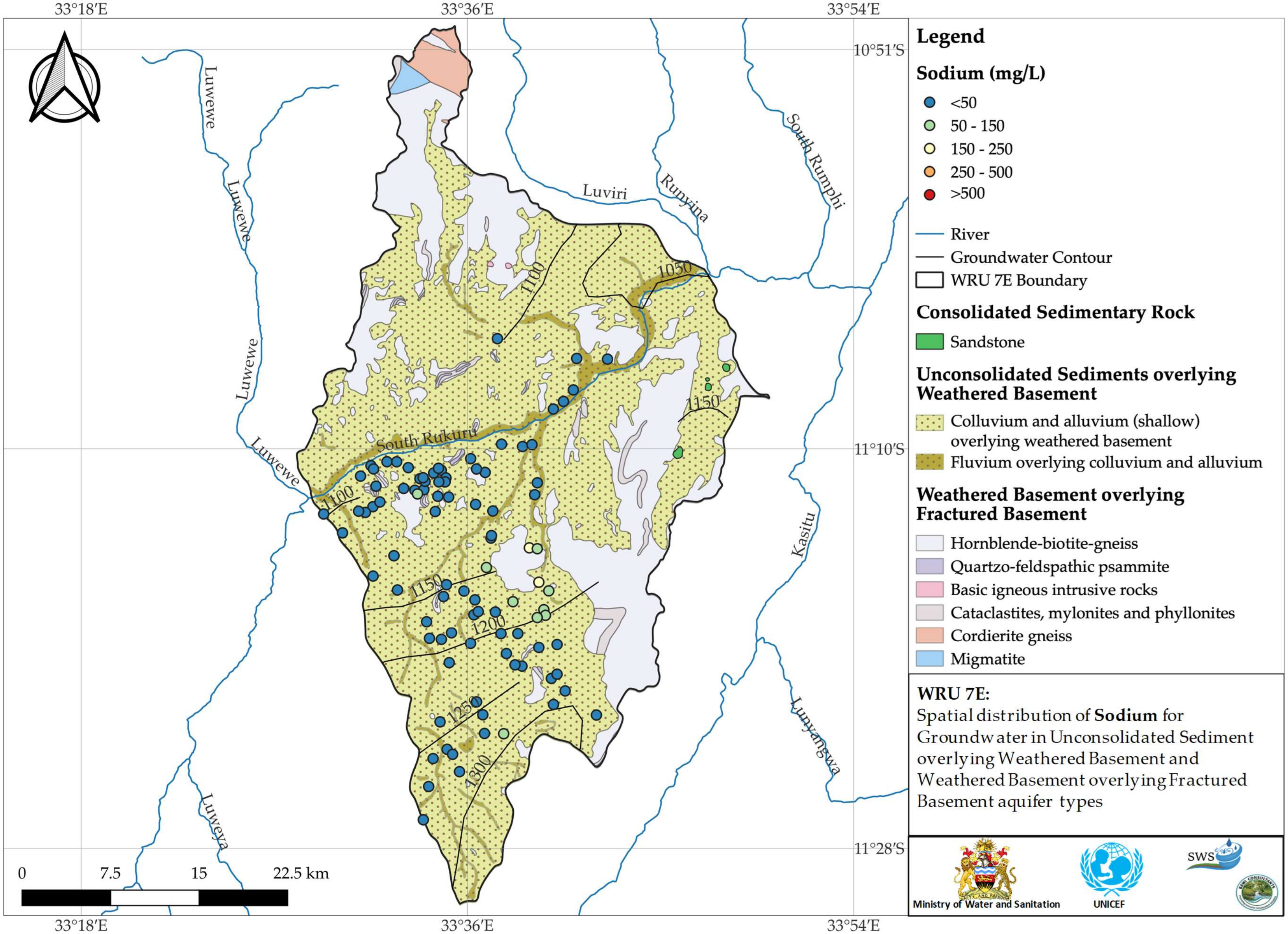


Figure WRU 7E.8 Groundwater Chemistry Distribution Calcium

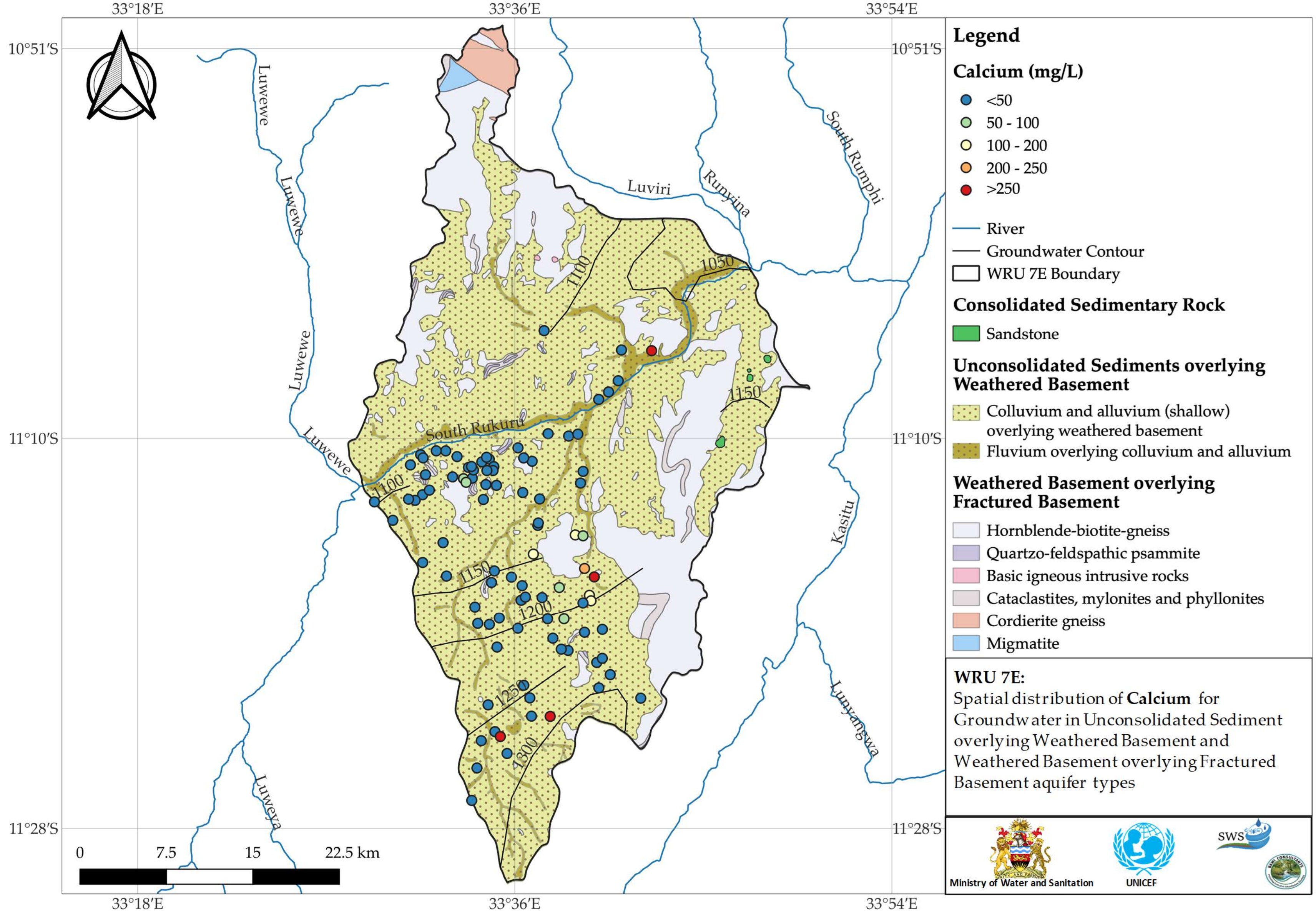


Figure WRU 7E.9 Piper Diagram of water quality results with respect to the major aquifer type

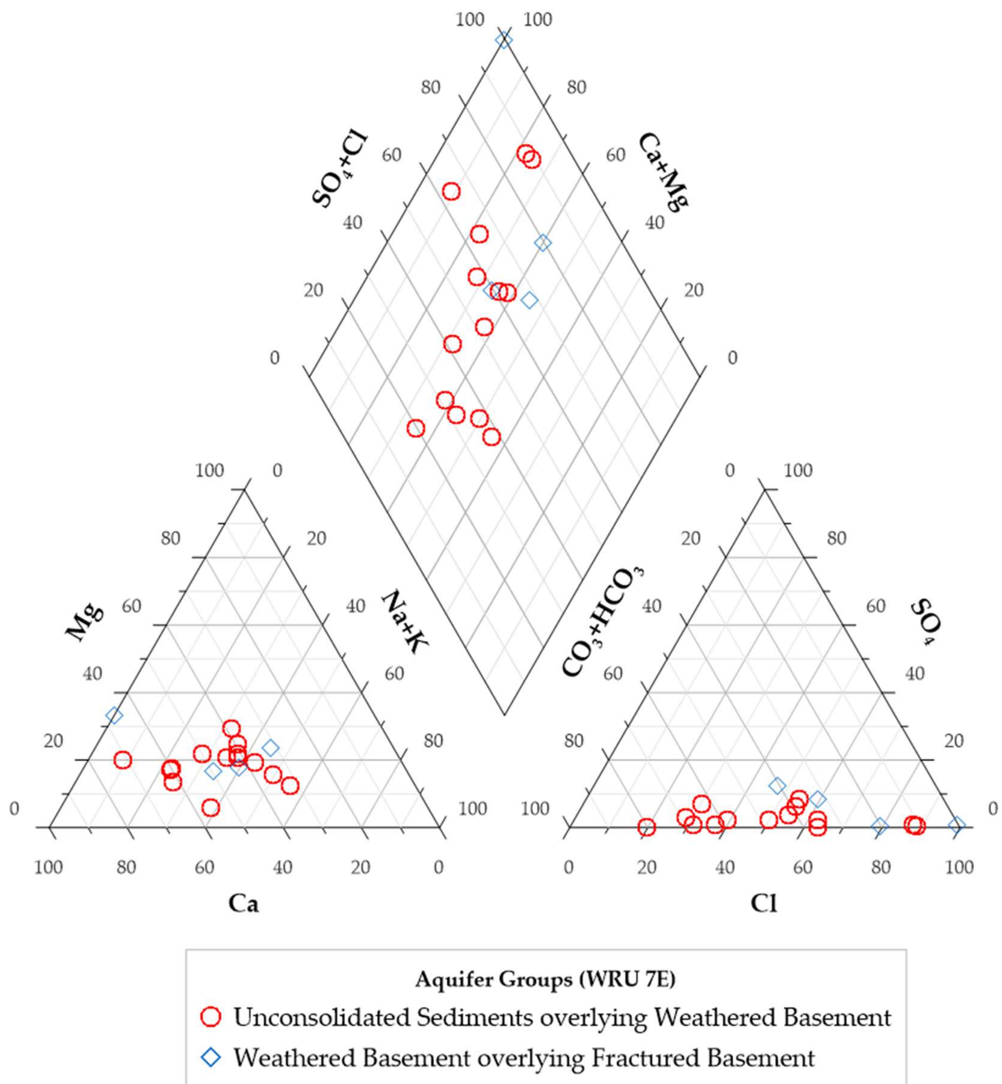
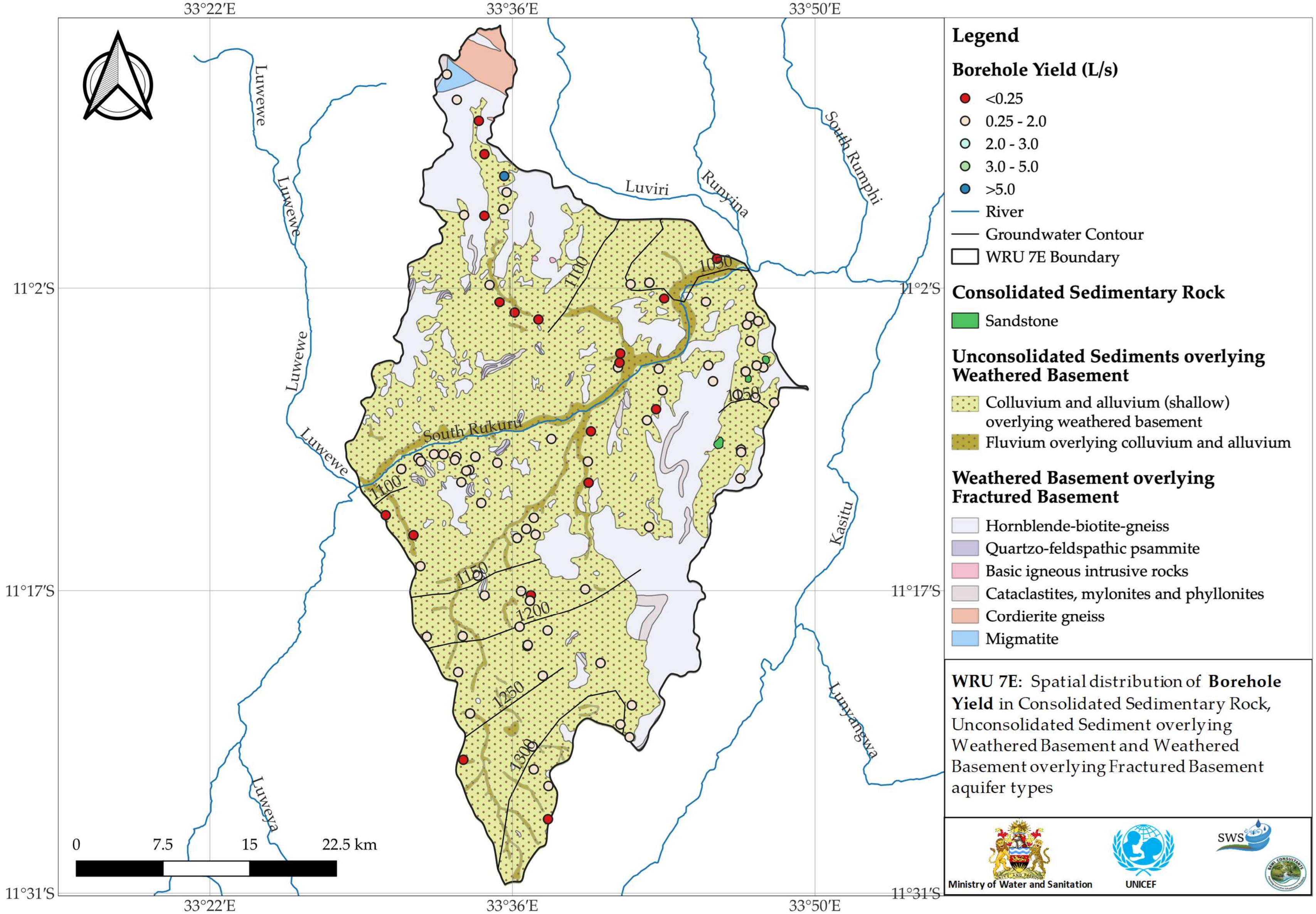


Figure WRU 7E.10 Borehole Yield Map for data held by the Ministry



WRU 7F Figures

Figure WRU 7F.1 Land Use and Major Roads

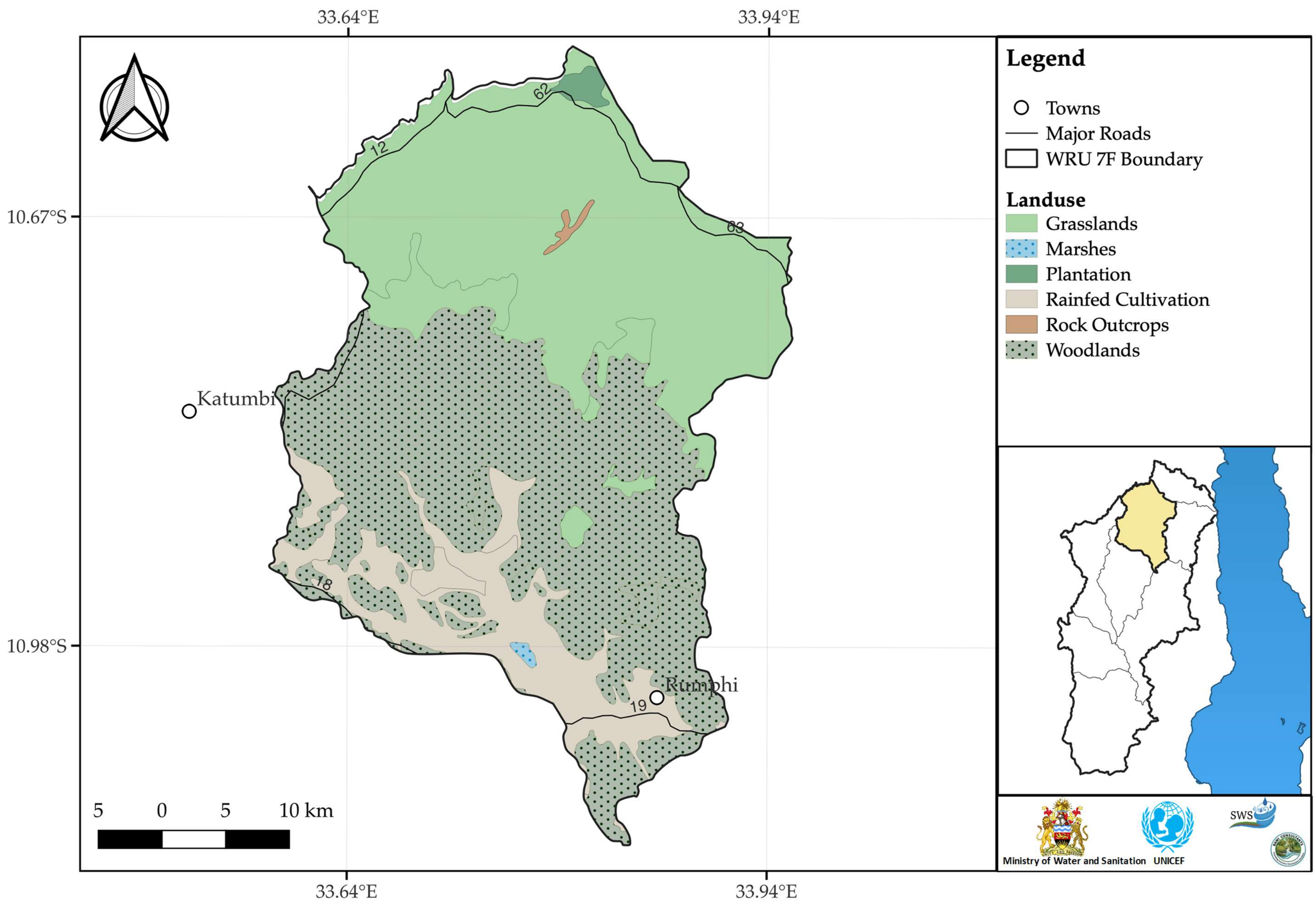


Figure WRU 7F.2 Rivers and Wetlands

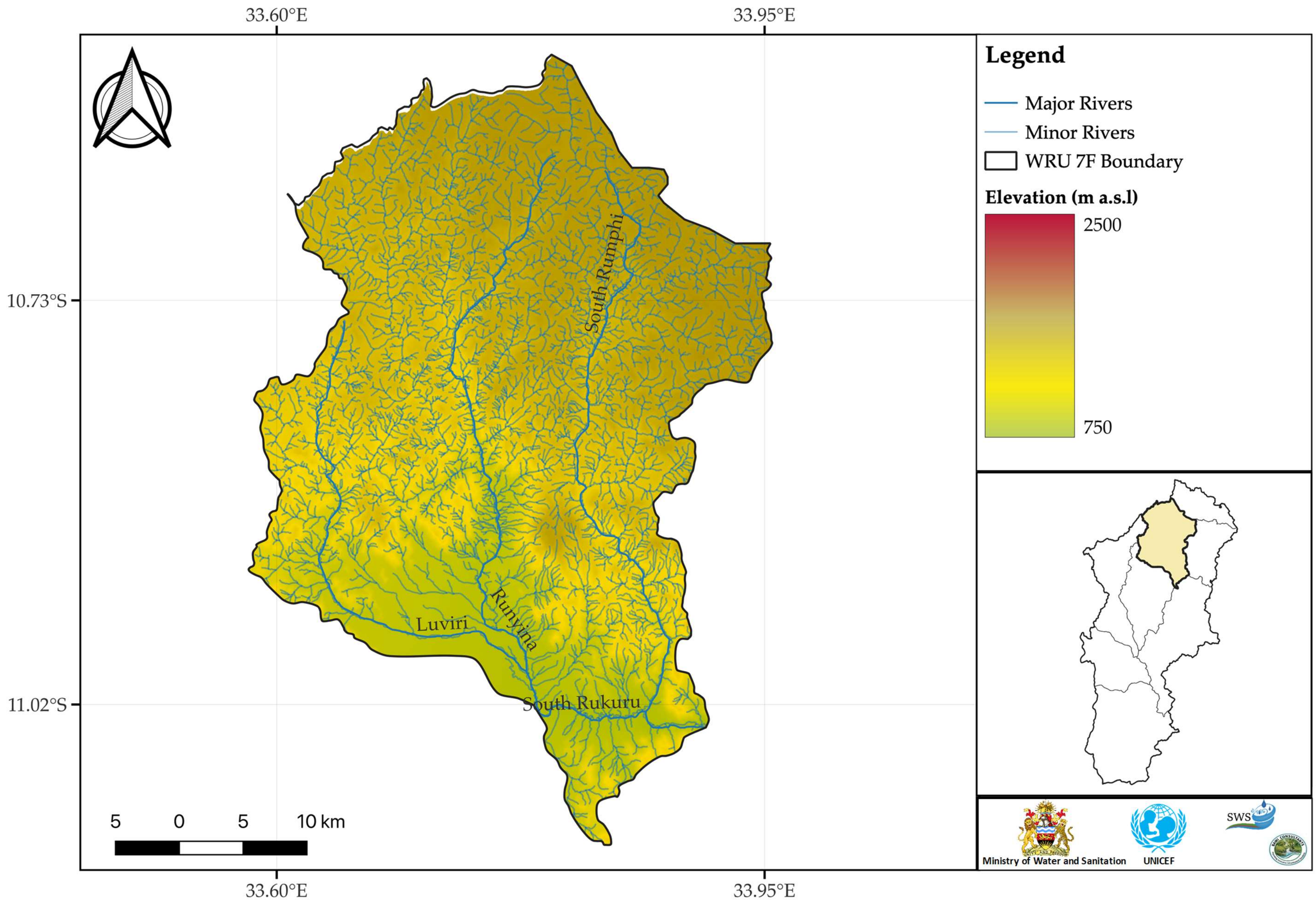


Figure WRU 7F.3 Hydrogeology Units and Water Table

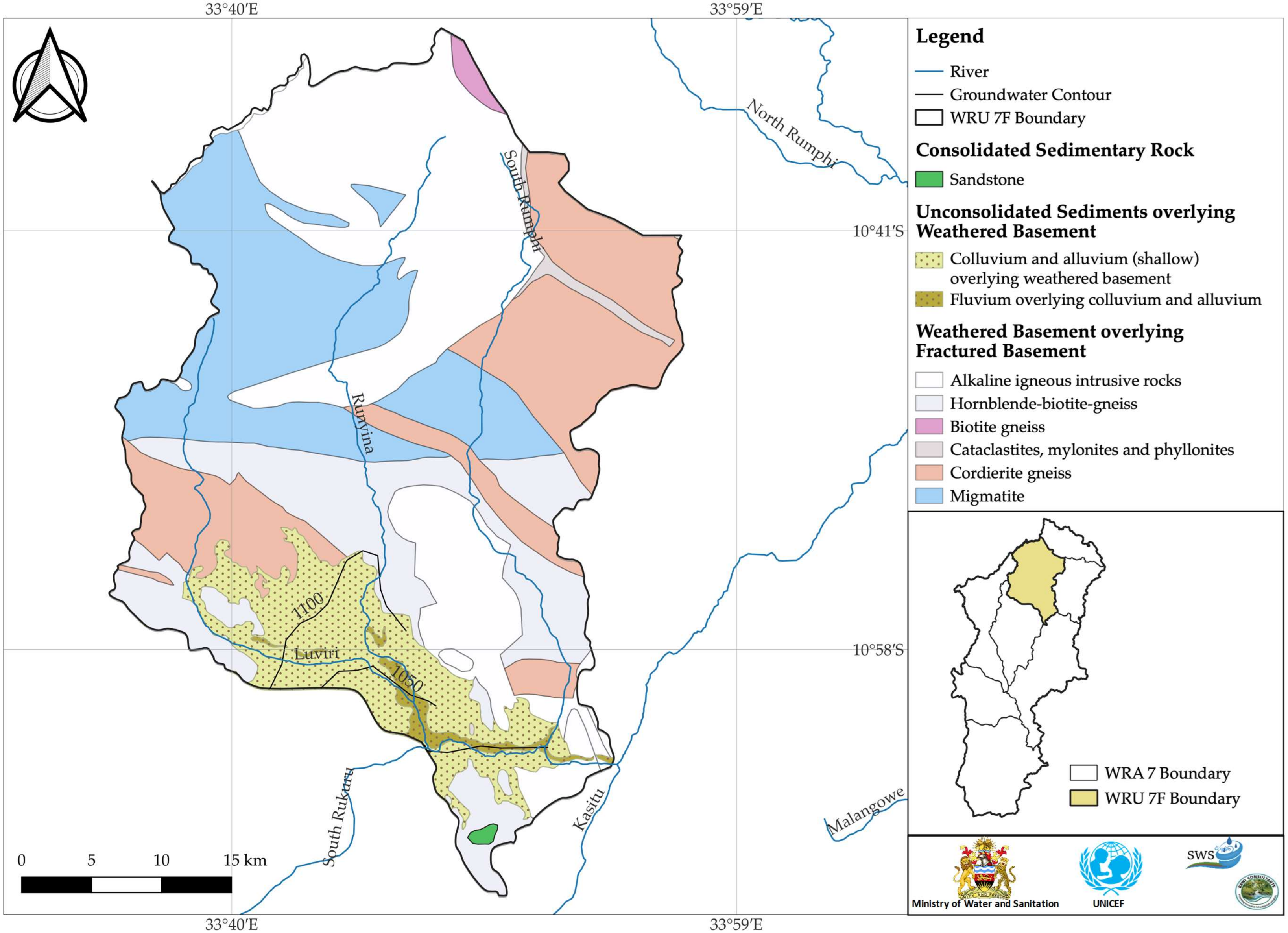


Figure WRU 7E.4 Groundwater Chemistry Distribution Electrical Conductivity

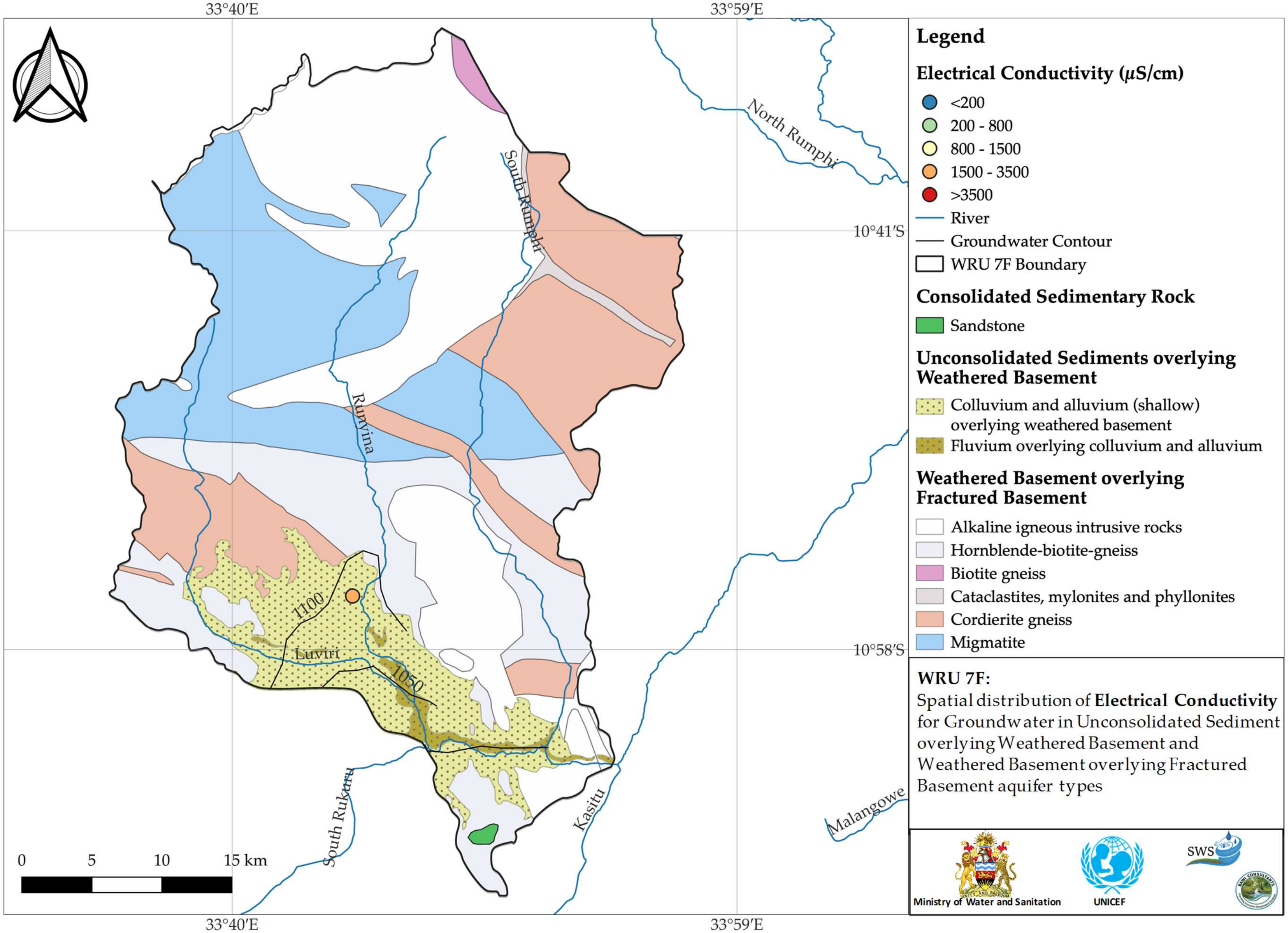


Figure WRU 7F.5 Groundwater Chemistry Distribution of Sulphate

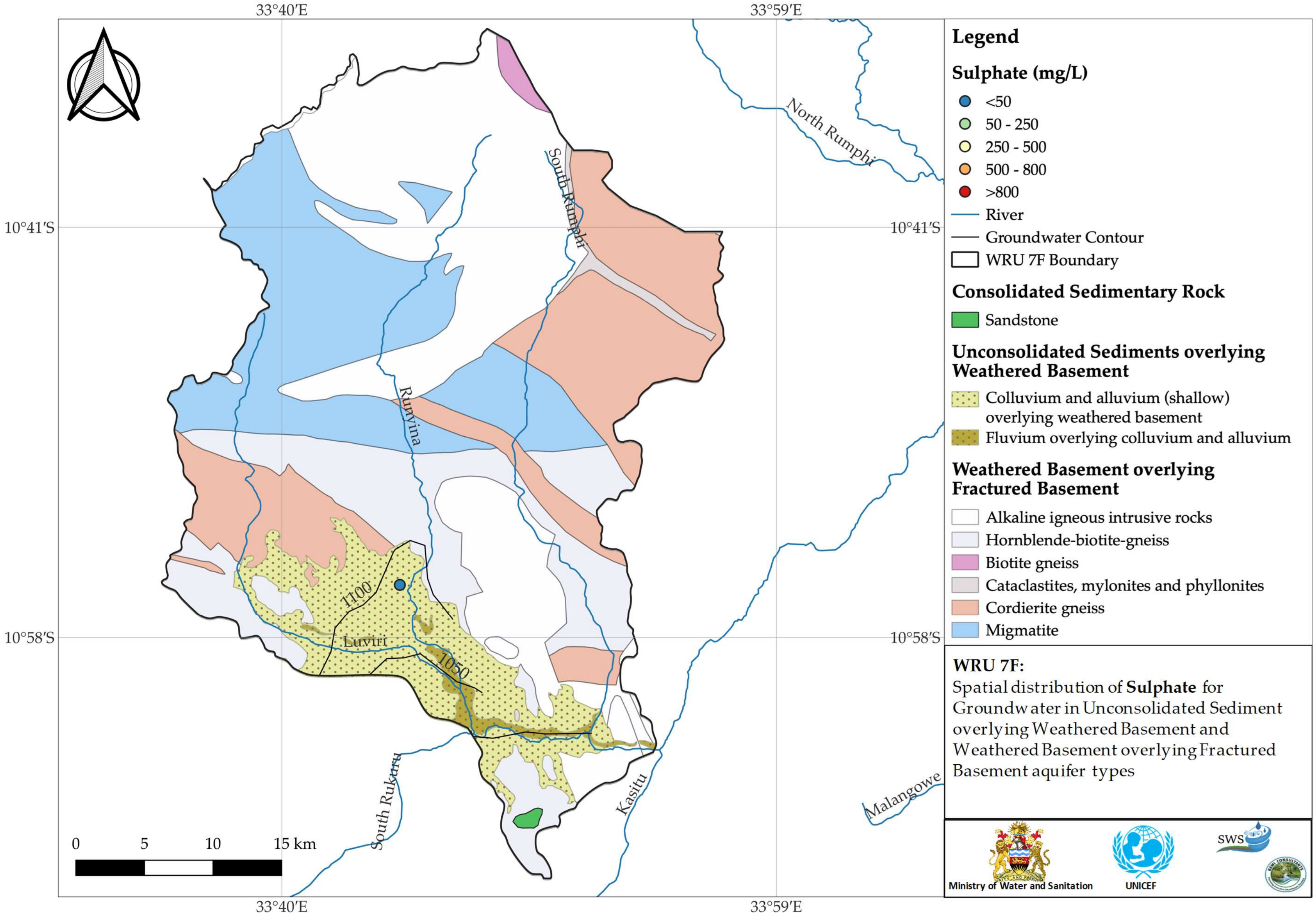


Figure WRU 7F.6 Groundwater Chemistry Distribution Chloride

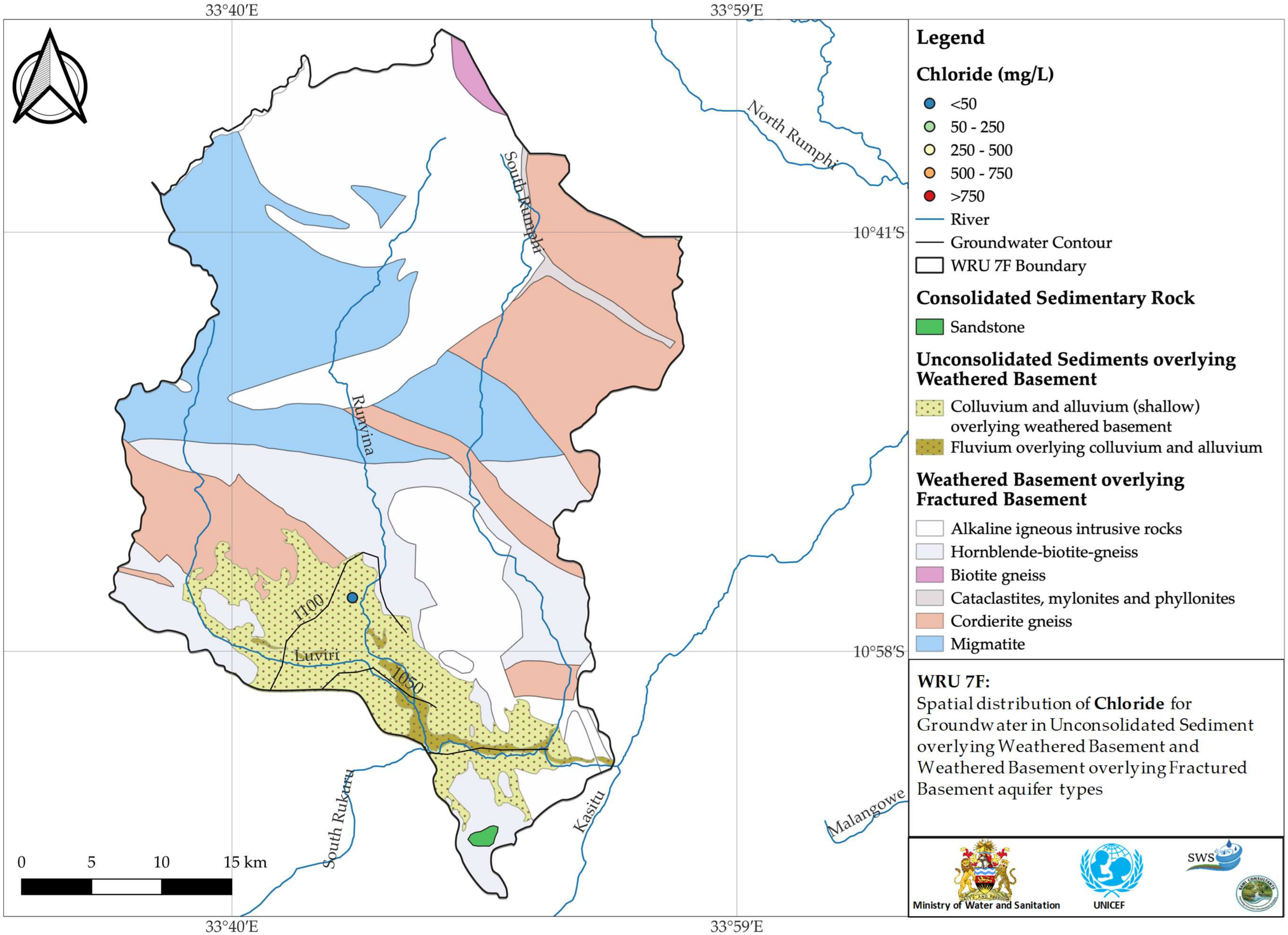


Figure WRU 7F.7 Groundwater Chemistry Distribution Sodium

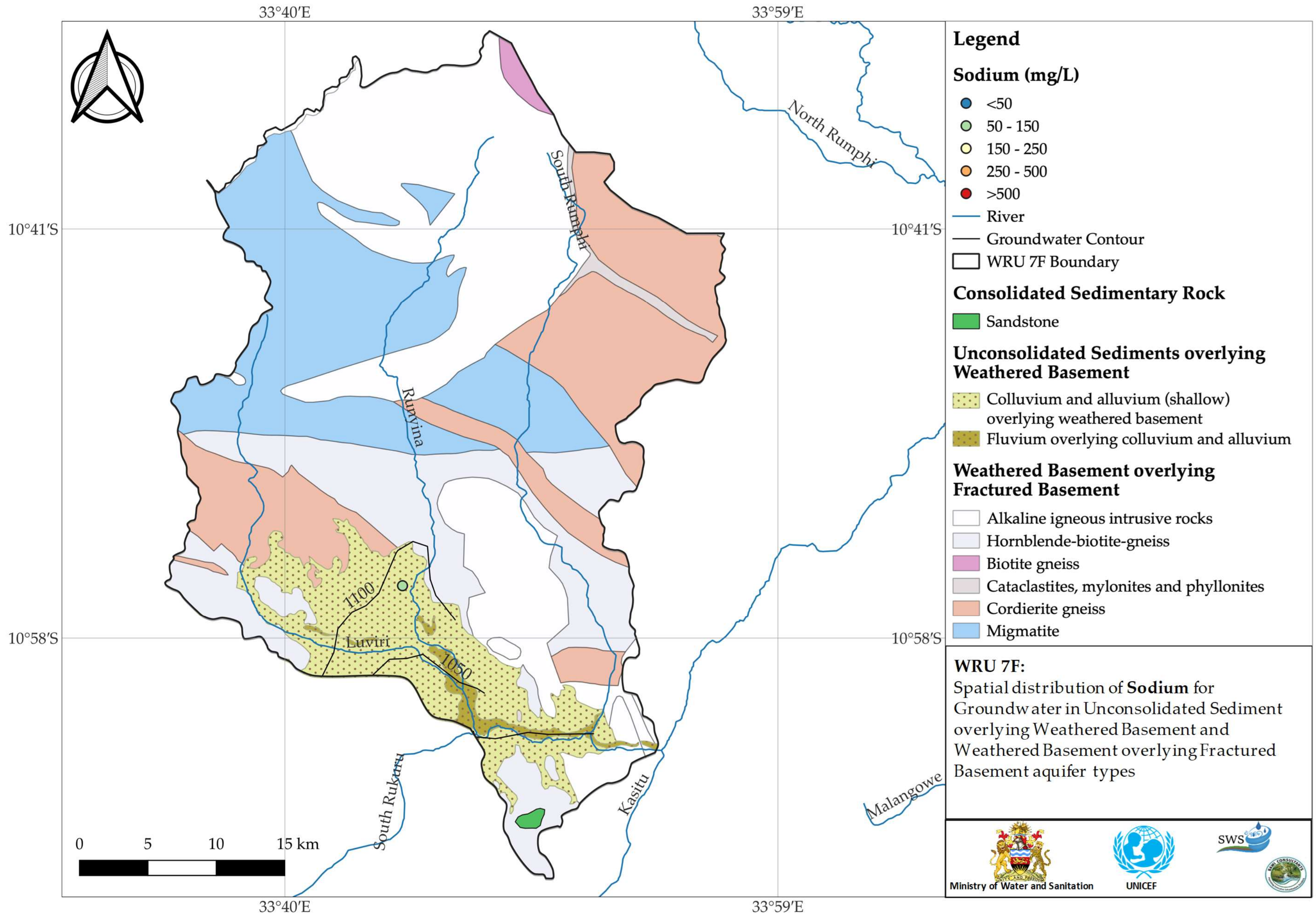


Figure WRU 7F.8 Groundwater Chemistry Distribution Calcium

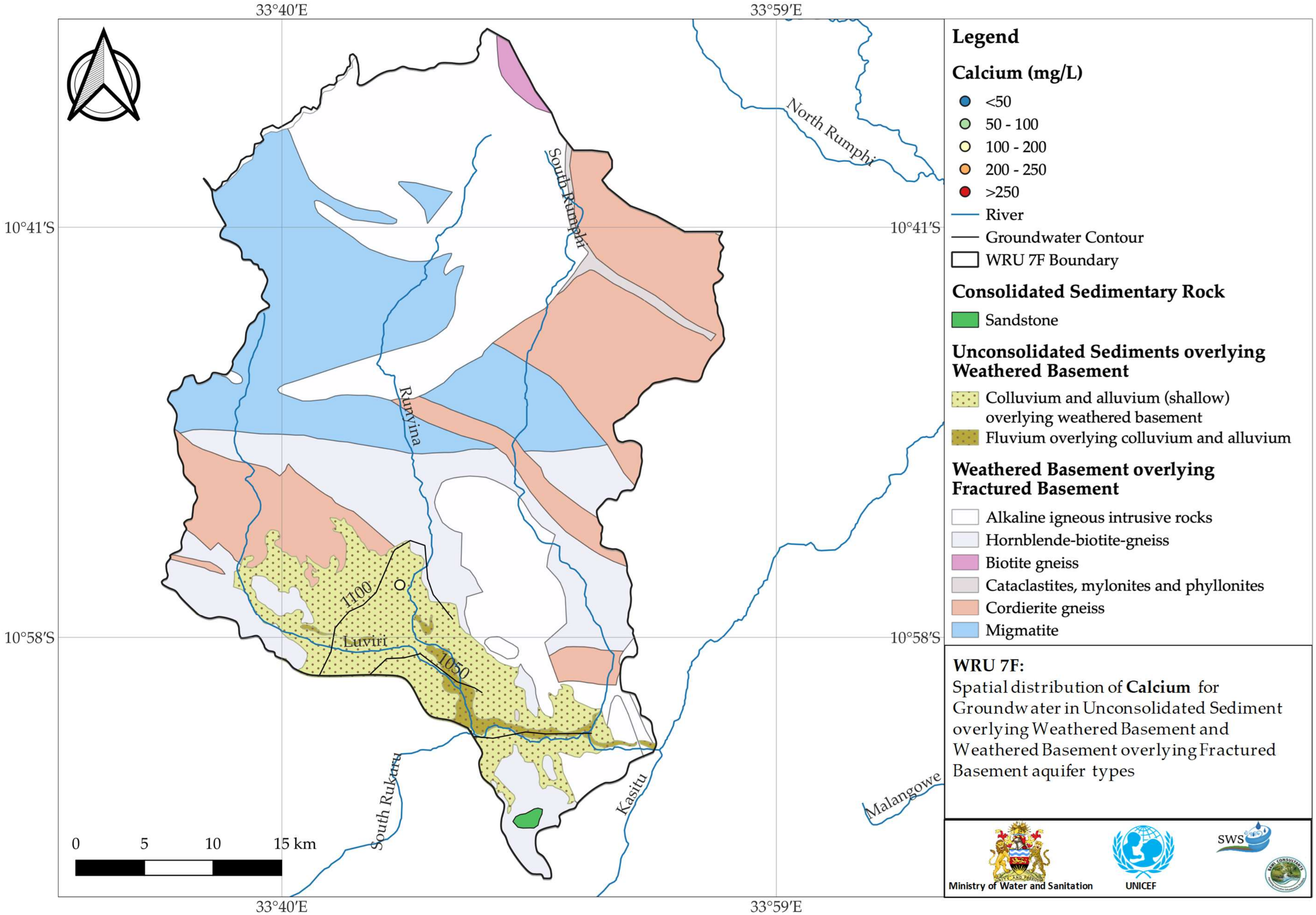


Figure WRU 7F.9 Piper Diagram of water quality results with respect to the major aquifer type

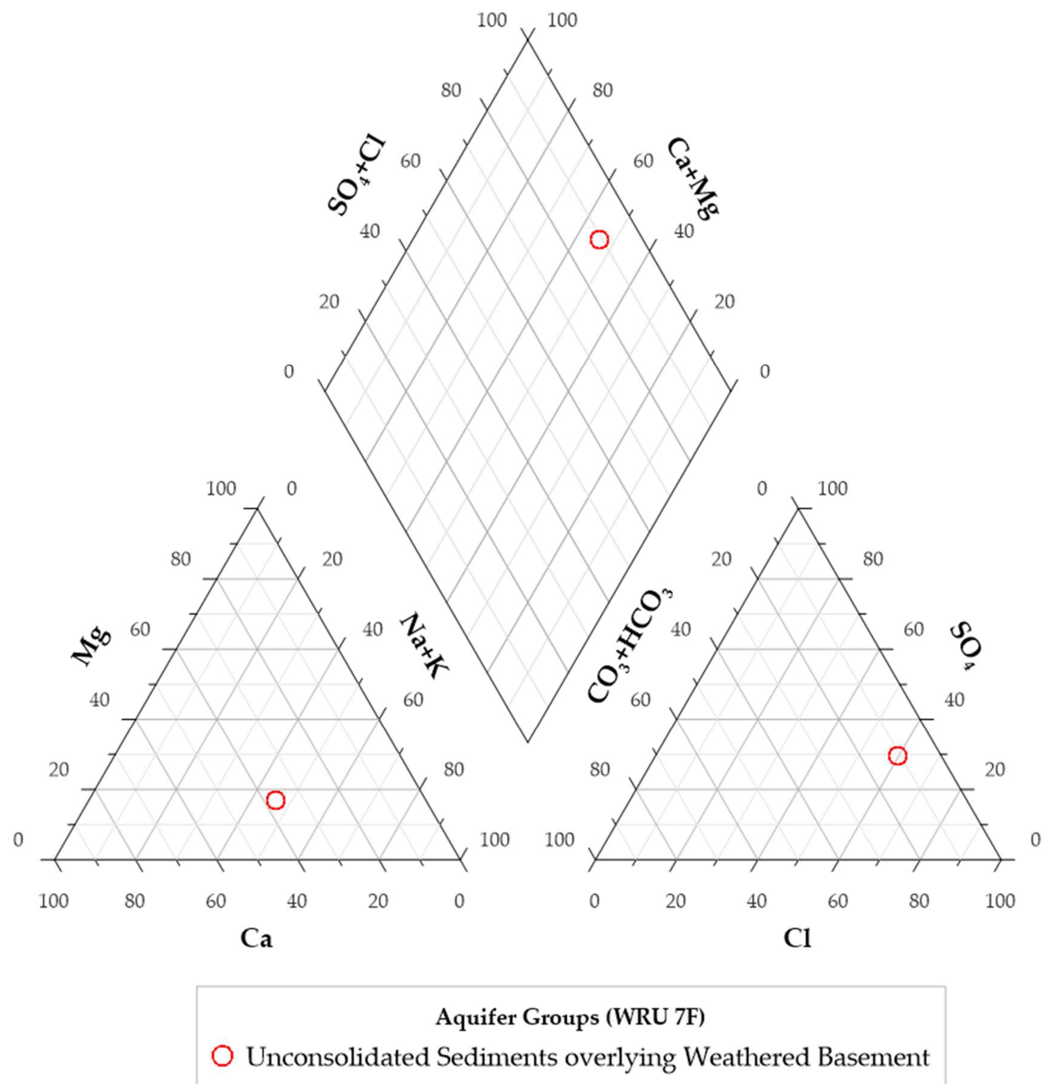
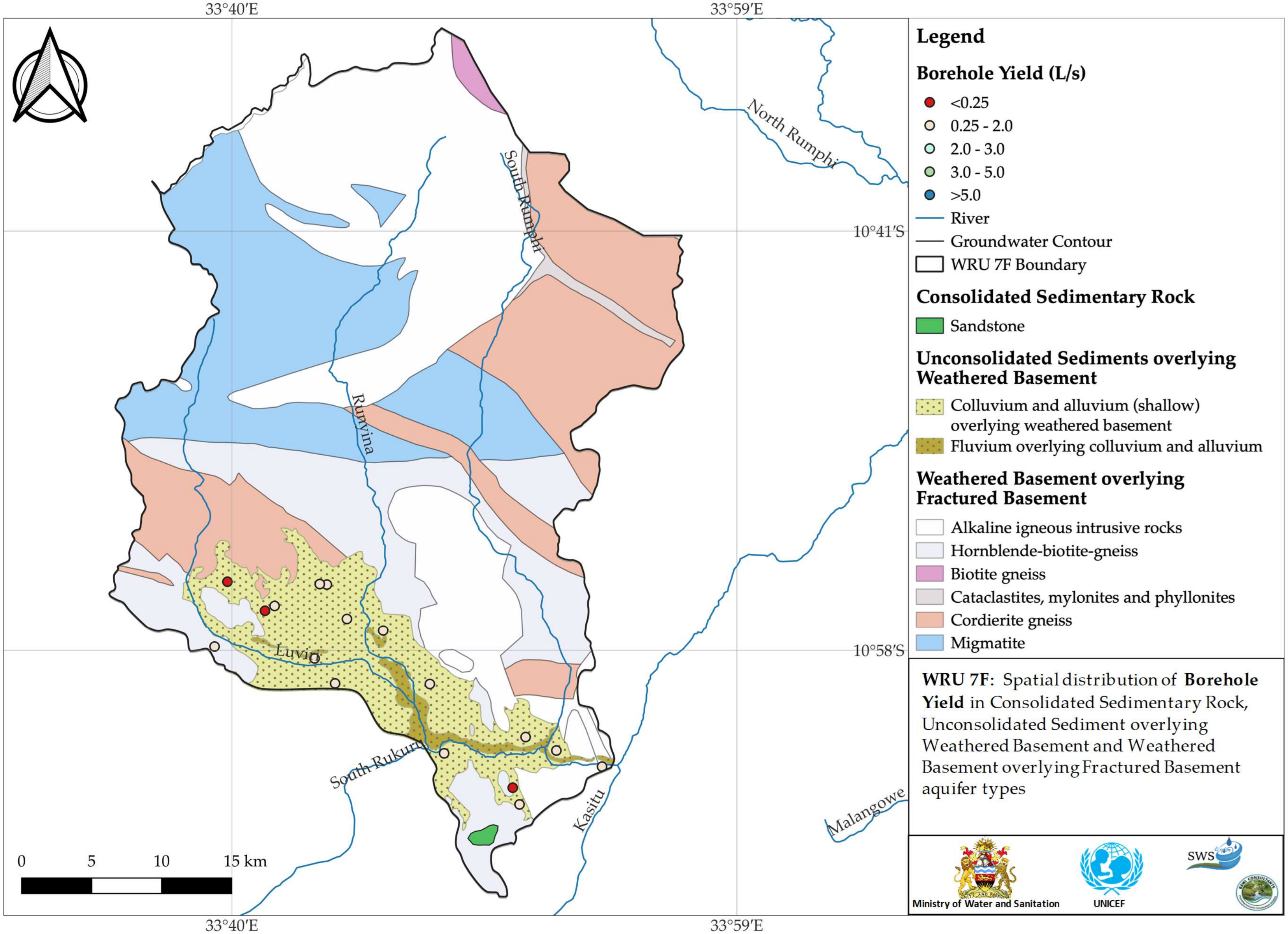


Figure WRU 7F.10 Borehole Yield Map for data held by the Ministry



WRU 7G Figures

Figure WRU 7G.1 Land Use and Major Roads

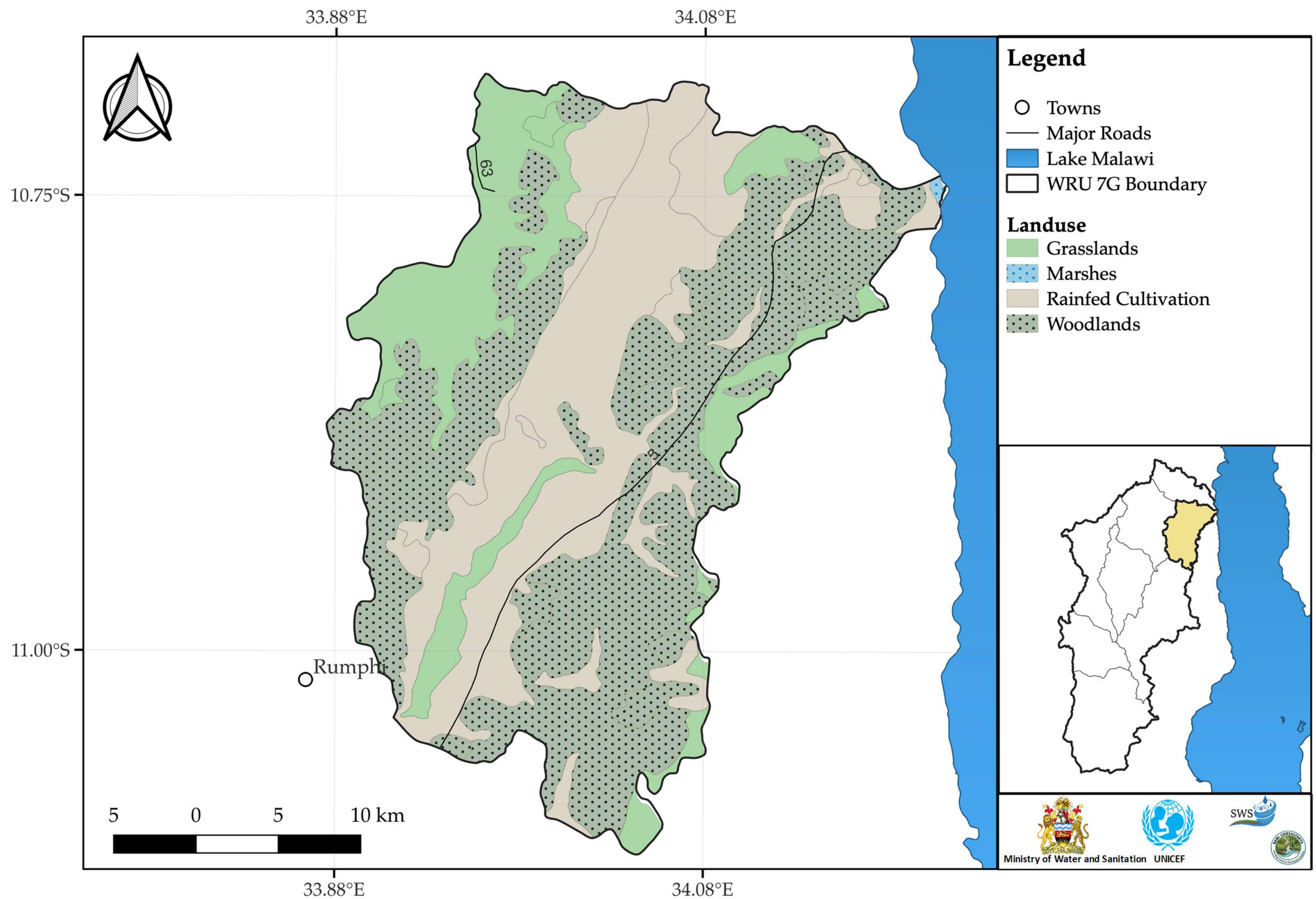


Figure WRU 7G.2 Rivers and Wetlands

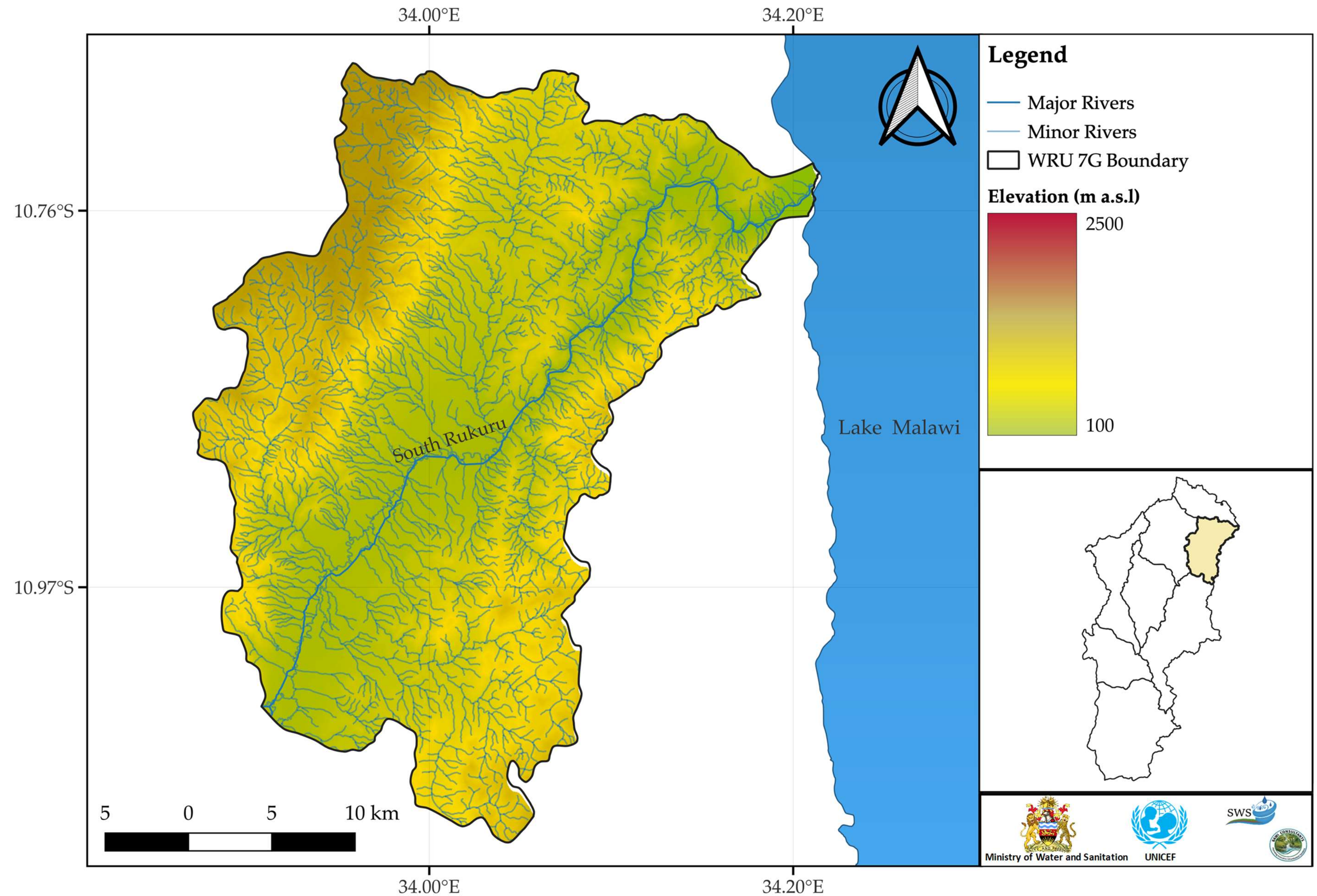


Figure WRU 7G.3 Hydrogeology Units and Water Table

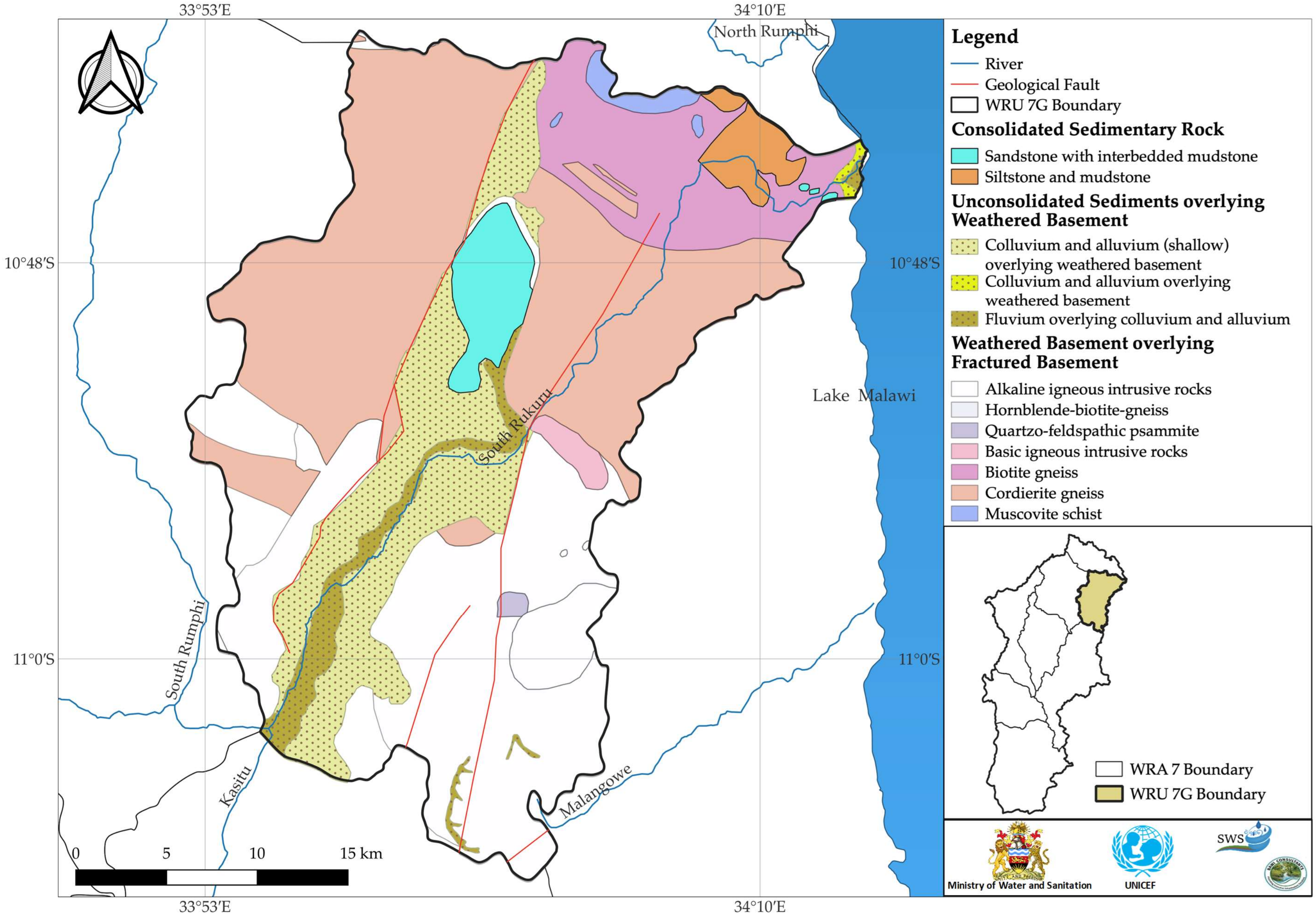


Figure WRU 7G.4 Groundwater Chemistry Distribution of Electrical Conductivity

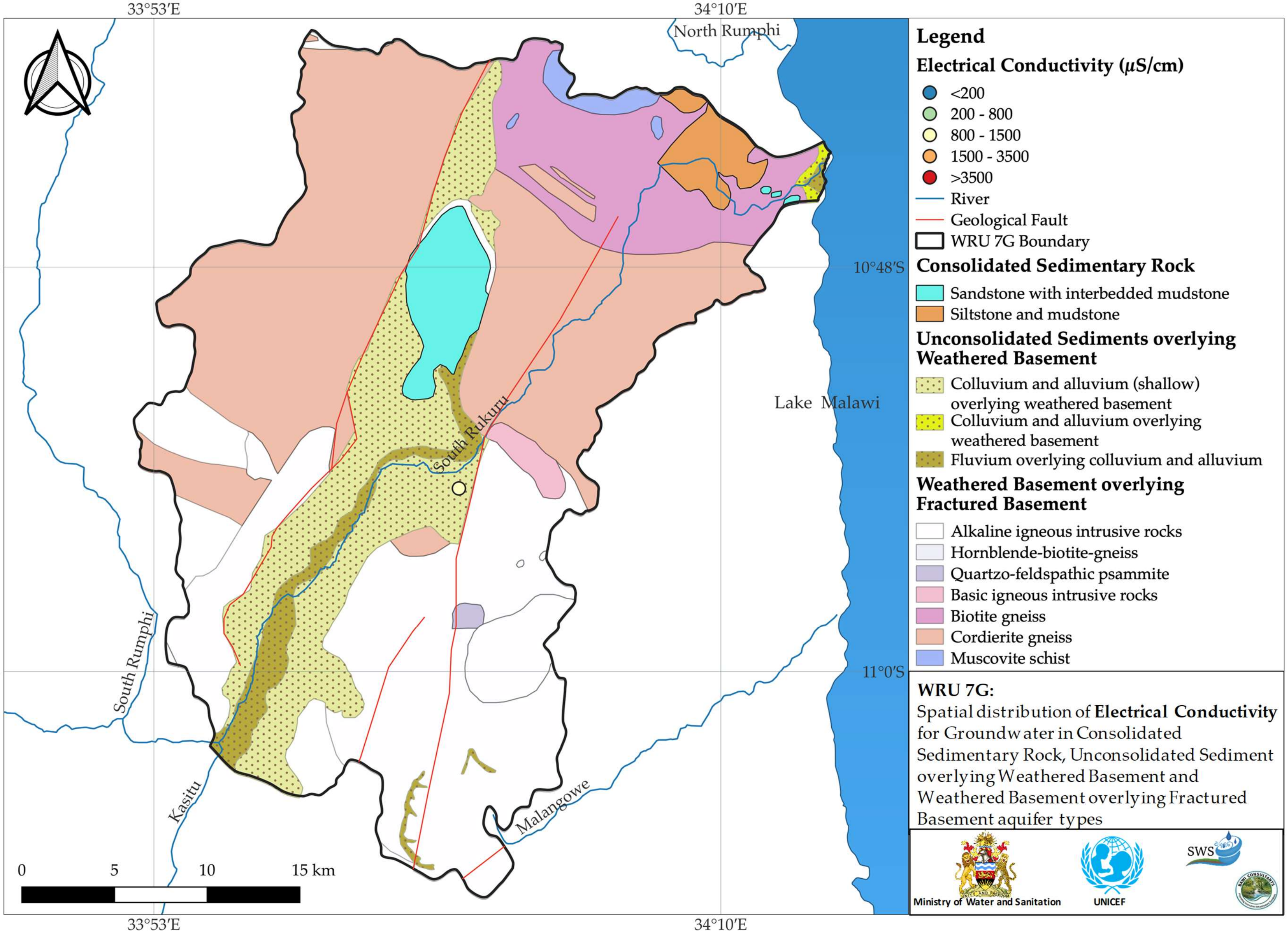


Figure WRU 7G.5 Groundwater Chemistry Distribution of Sulphate

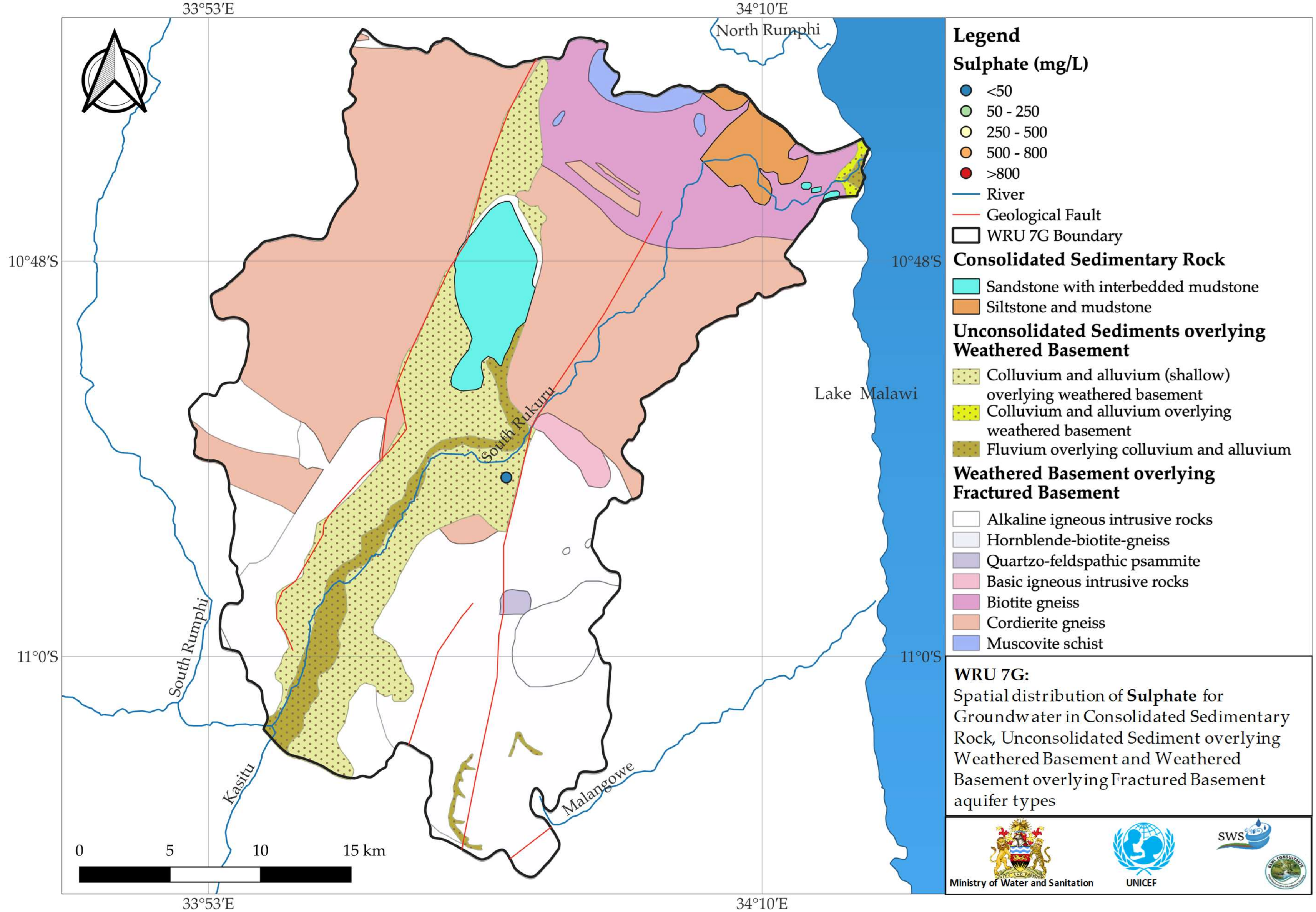


Figure WRU 7G.6 Groundwater Chemistry Distribution Chloride

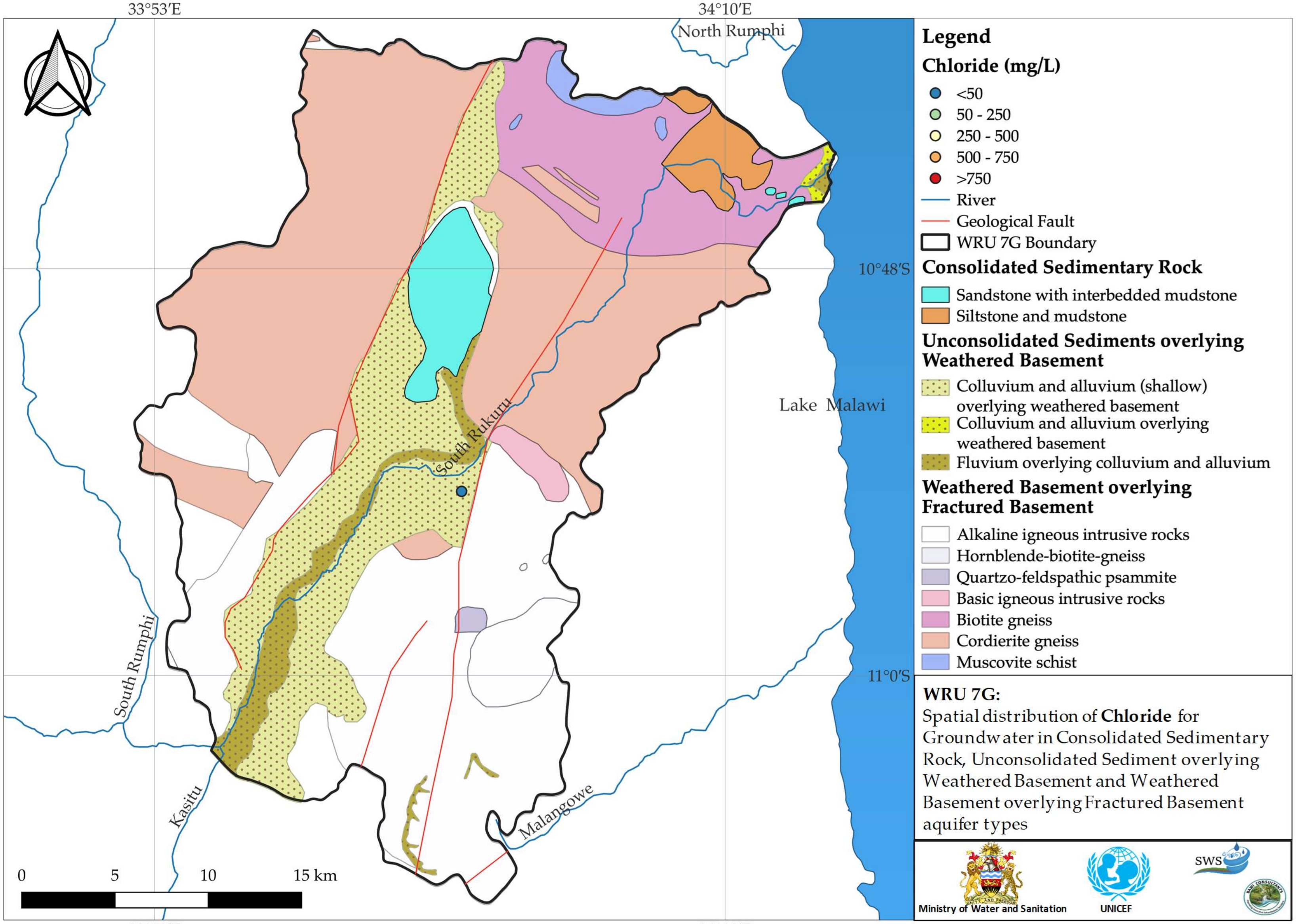


Figure WRU 7G.7 Groundwater Chemistry Distribution Sodium

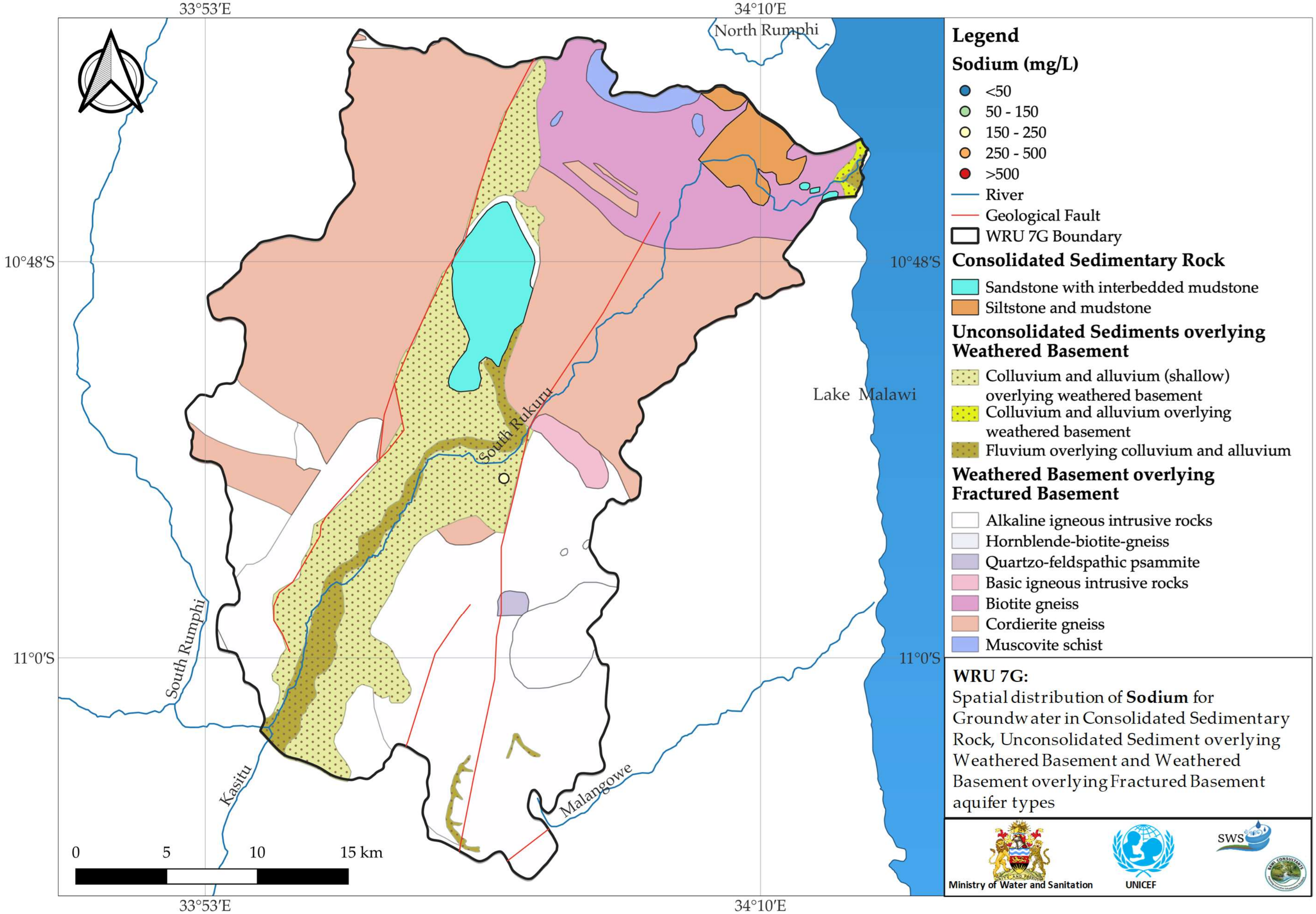


Figure WRU 7G.8 Groundwater Chemistry Distribution Calcium

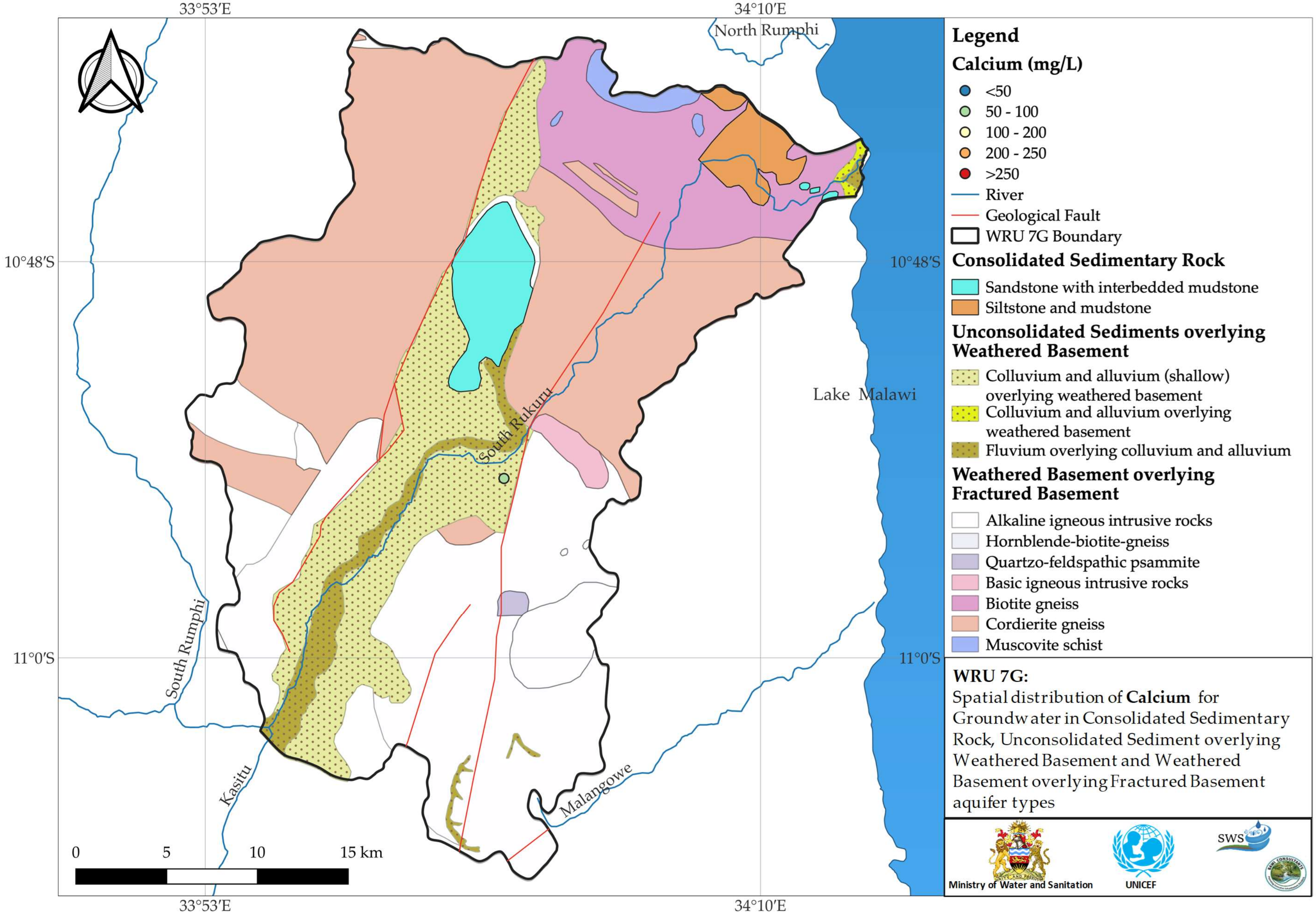


Figure WRU 7G.9 Piper Diagram of water quality results with respect to the major aquifer type

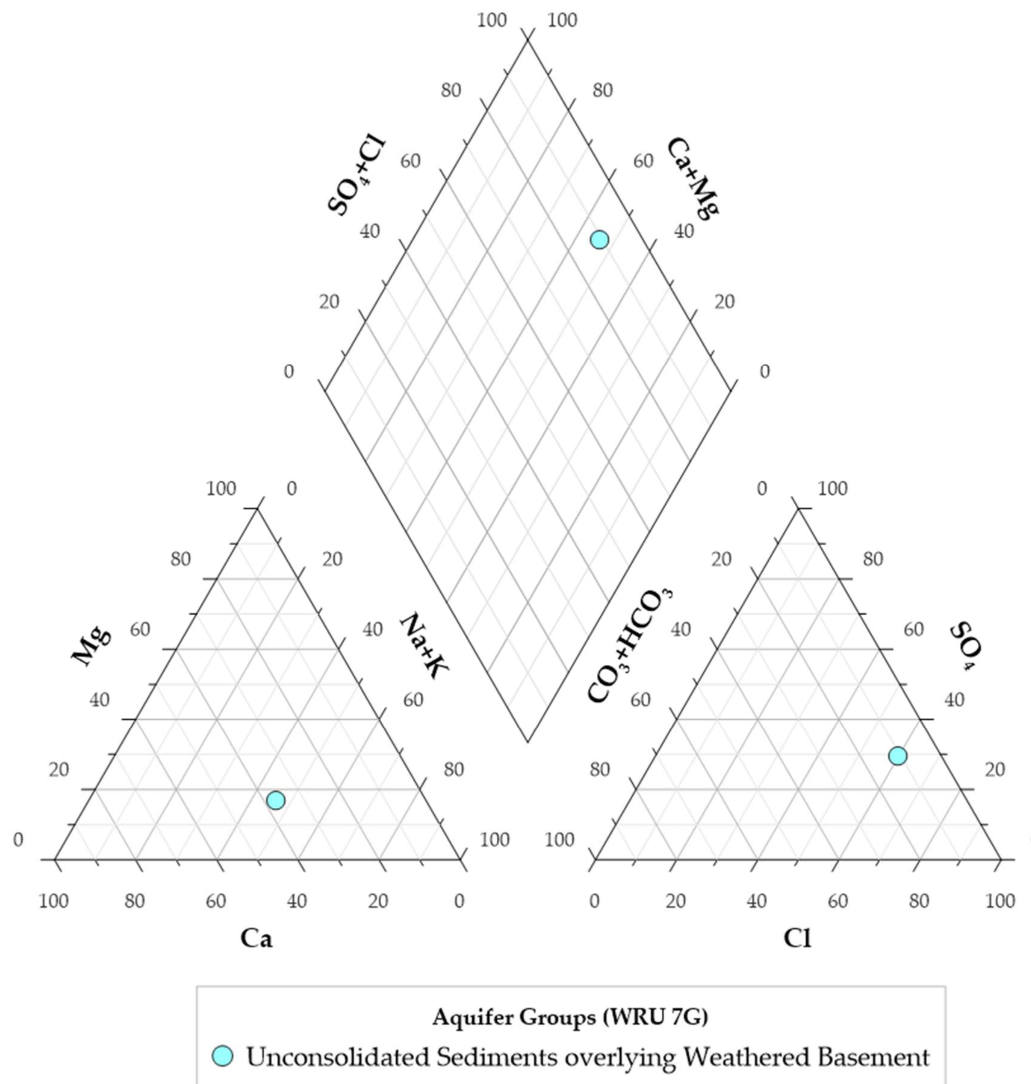
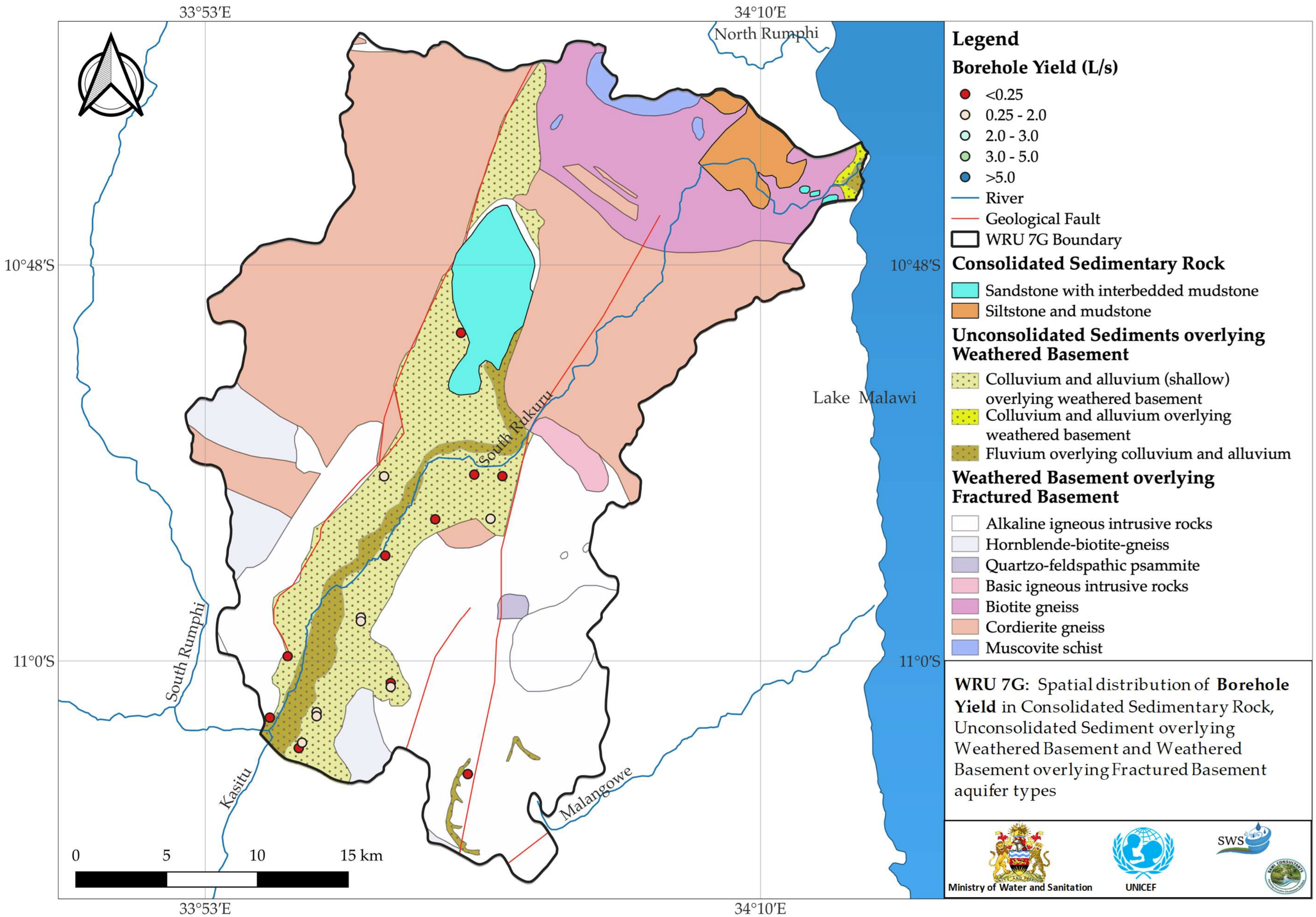


Figure WRU 7G.10 Borehole Yield Map for data held by the Ministry



WRU 7H Figures

Figure WRU 7H.1 Land Use and Major Roads

Figure WRU 7H.2 Rivers and Wetlands

Figure WRU 7H.3 Hydrogeology Units and Water Table

Note: There is no chemistry or borehole yield data held by the Ministry for WRU 7H

Figure WRU 7H.1 Land Use and Major Roads

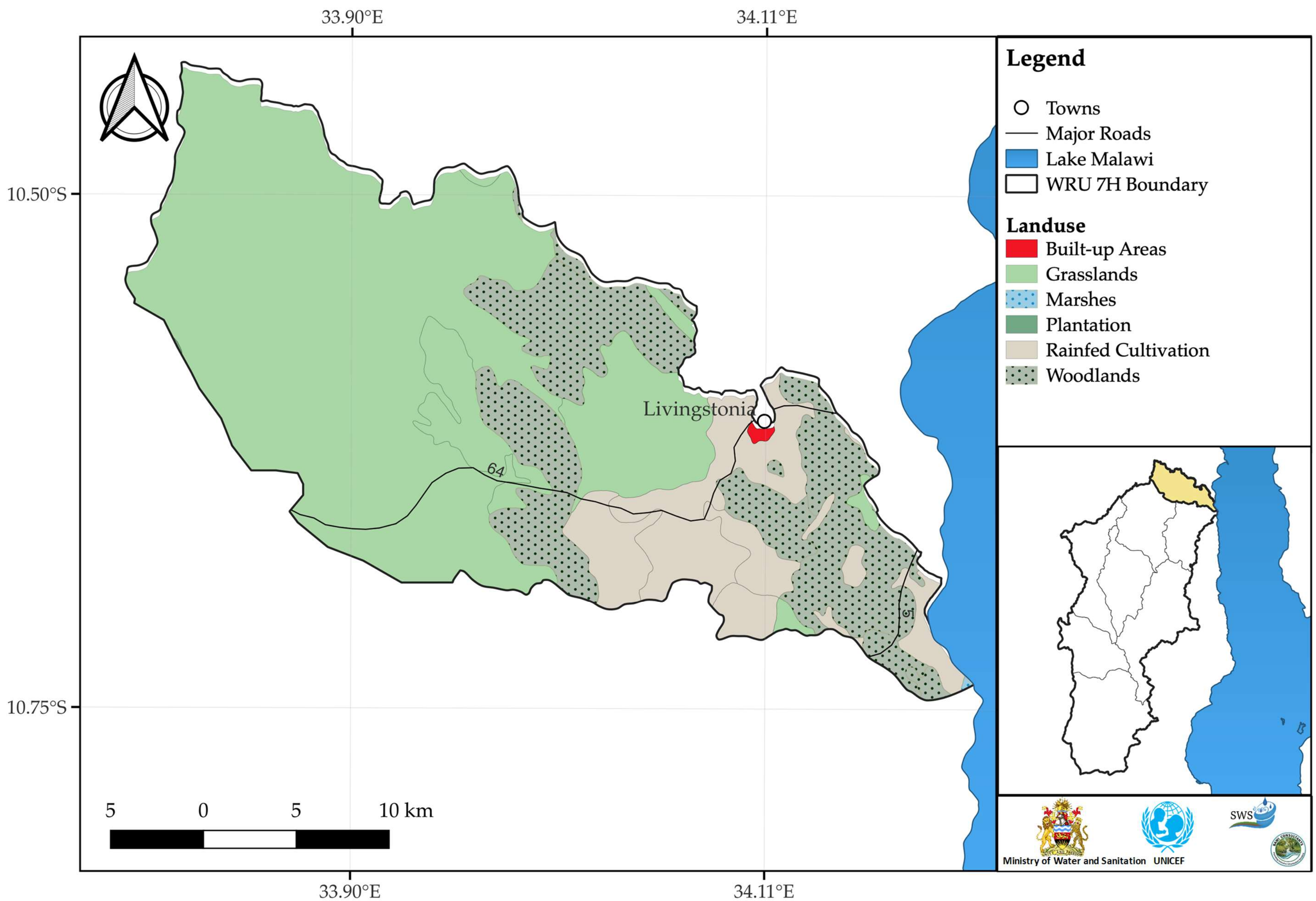


Figure WRU 7H.2 Rivers and Wetlands

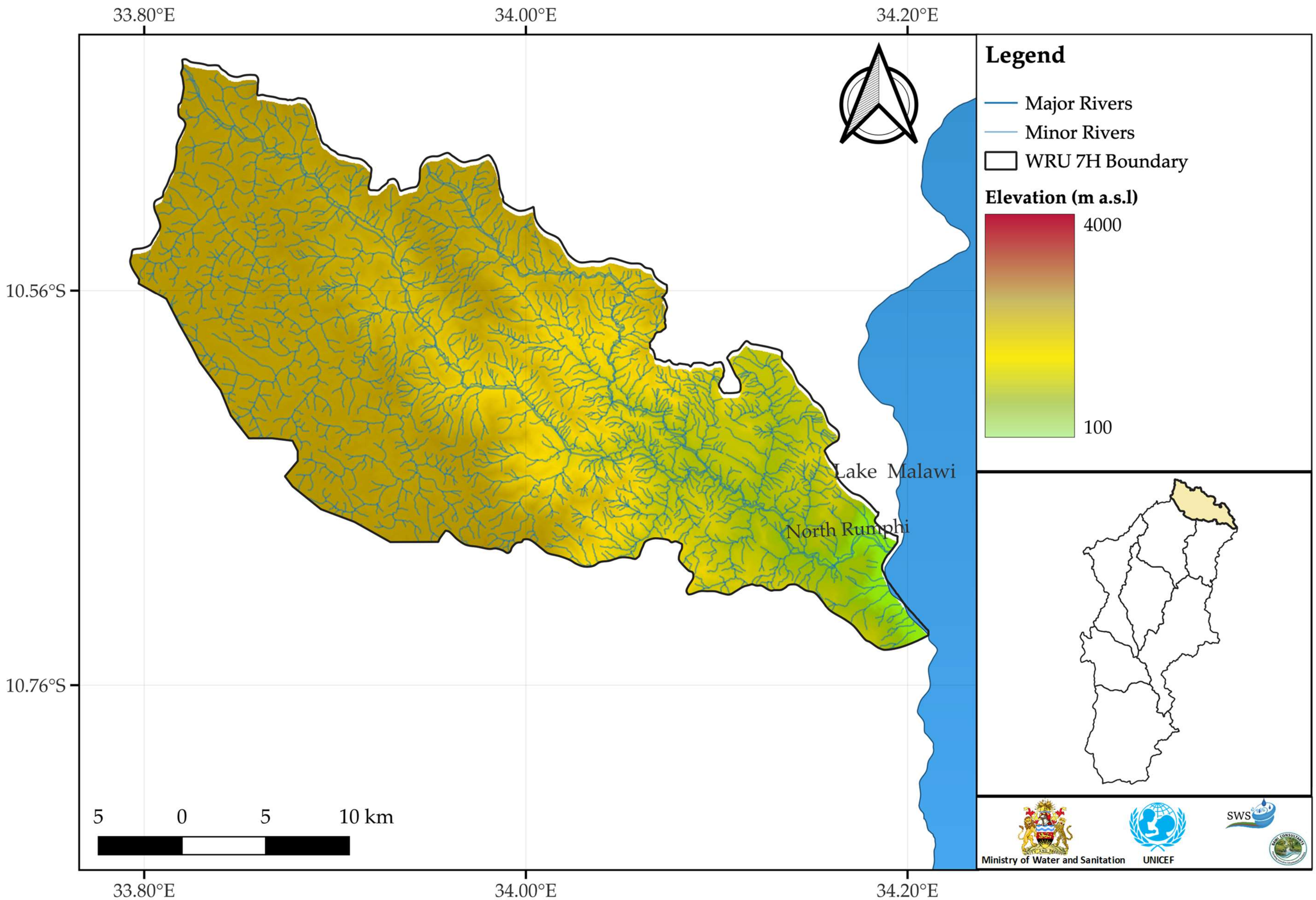
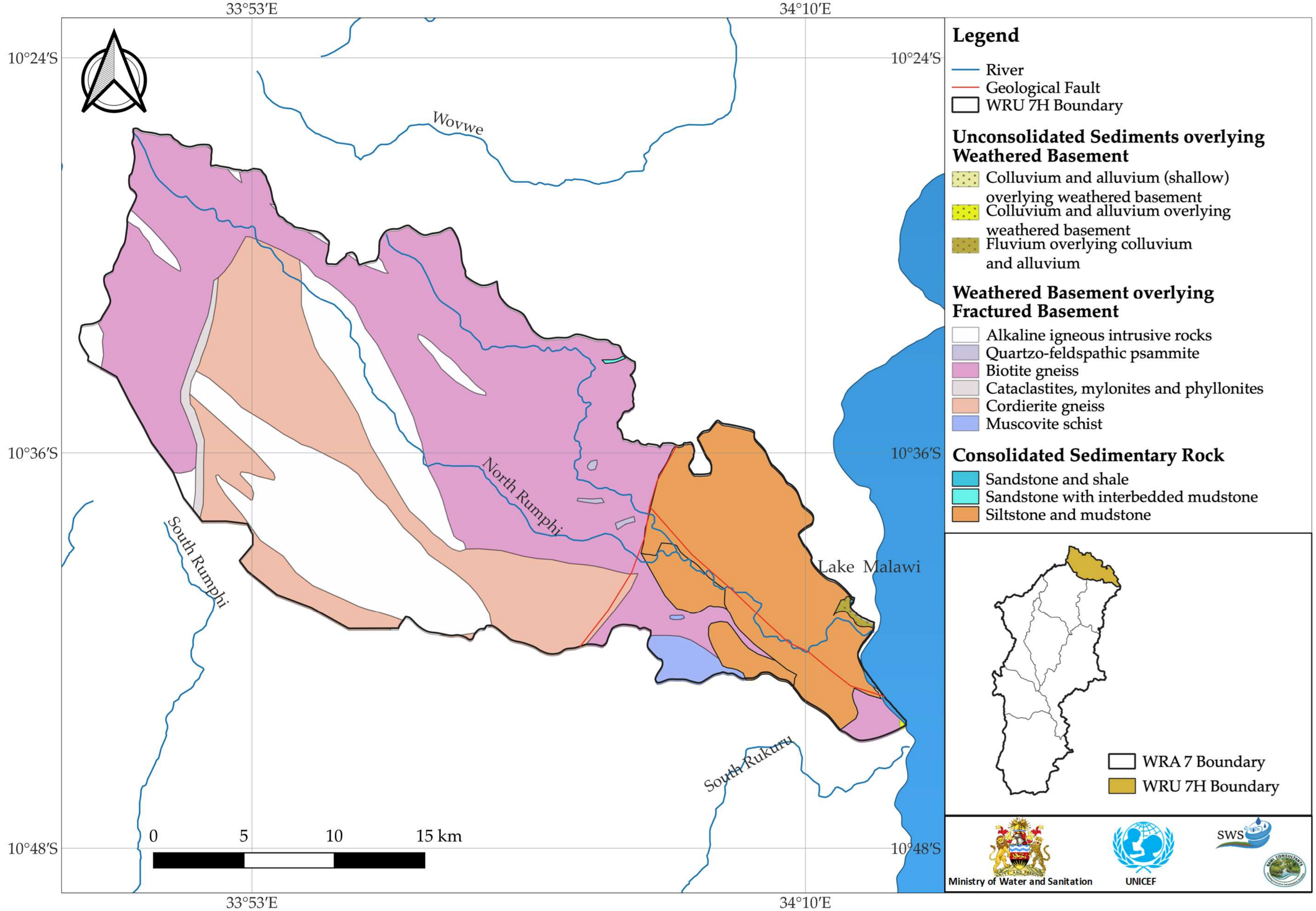


Figure WRU 7H.3 Hydrogeology Units and Water Table



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, South Rukuru and North Rumphi River Catchment, Water Resource Area 7, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-08-6 125pp*