Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 2

Lake Chilwa Catchment

Ministry of Water and Sanitation

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Contents

Acronyms and Abbreviations

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

Review of Malawi Hydrogeology

Groundwater in Water Resource Area 2 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.

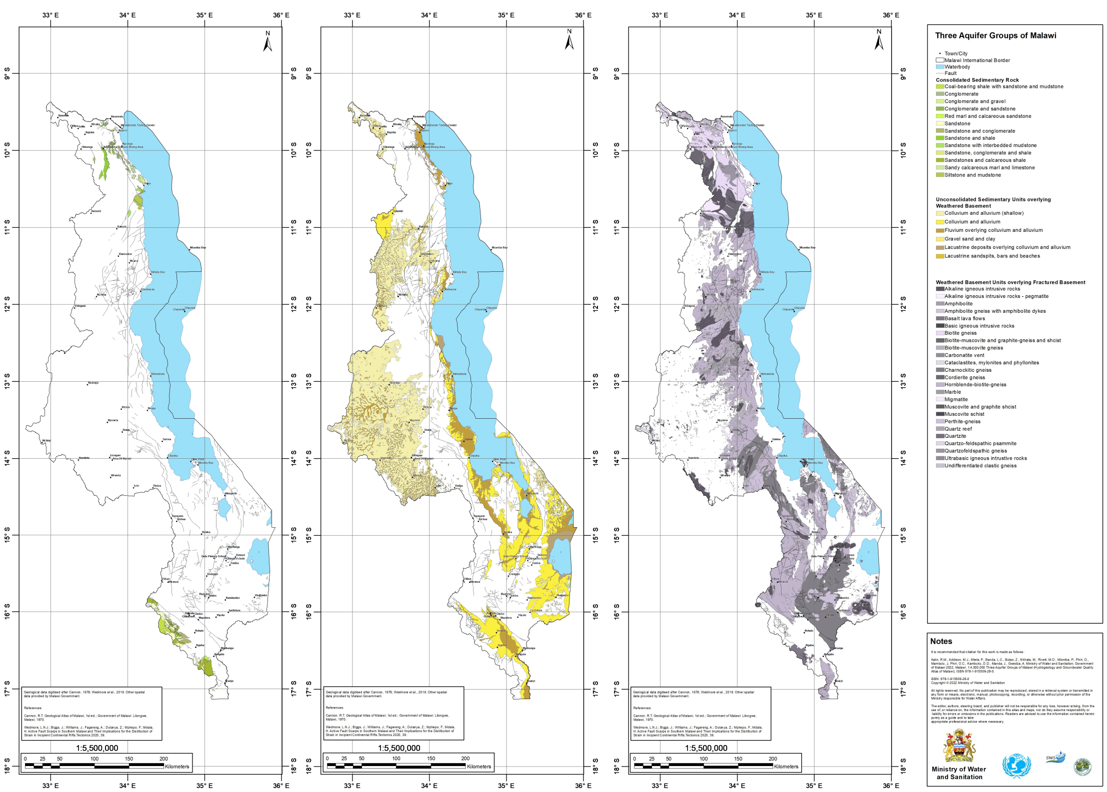


Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure 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).

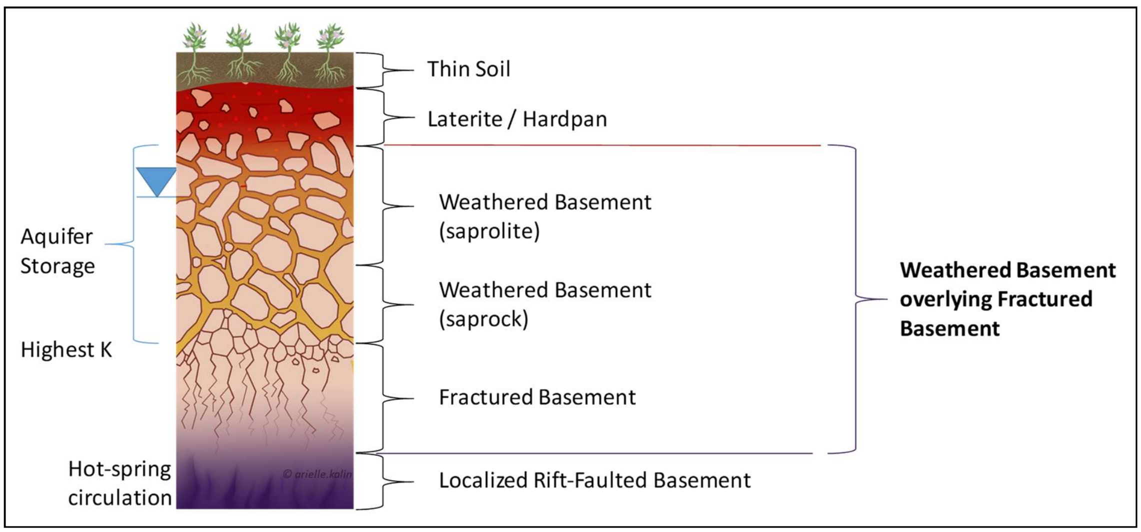


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

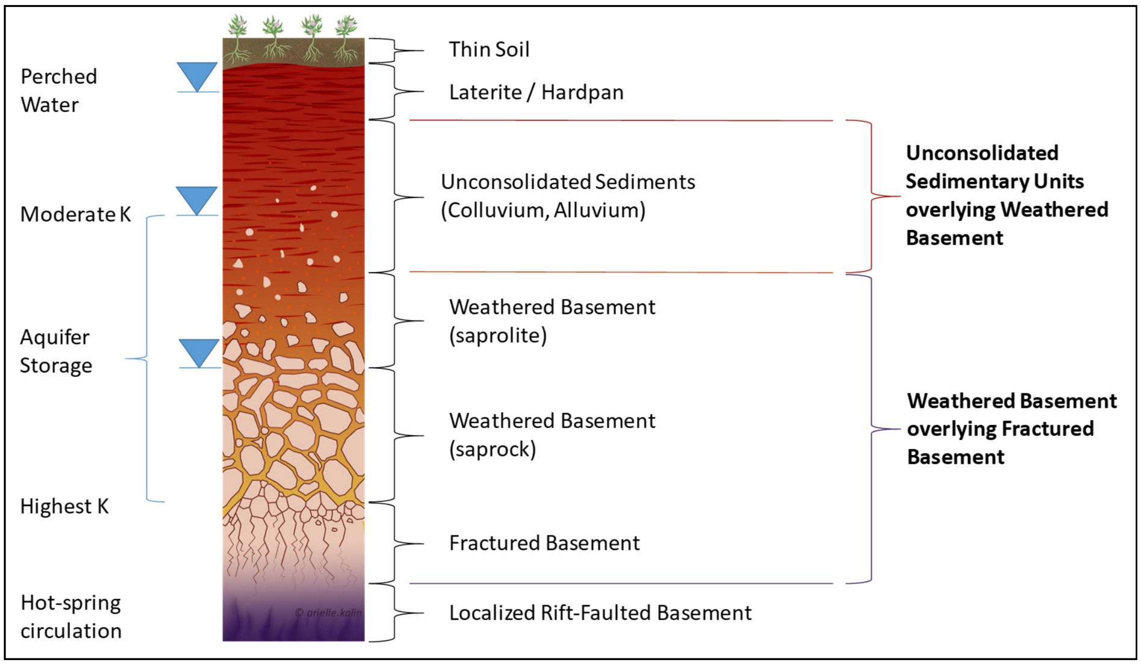


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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 (**Figure 9c**). 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.

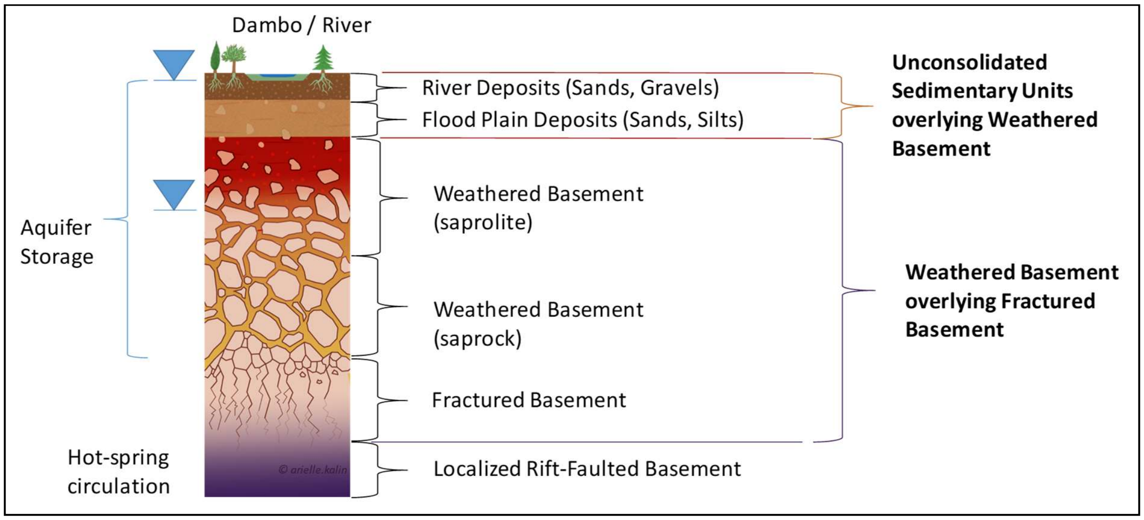


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

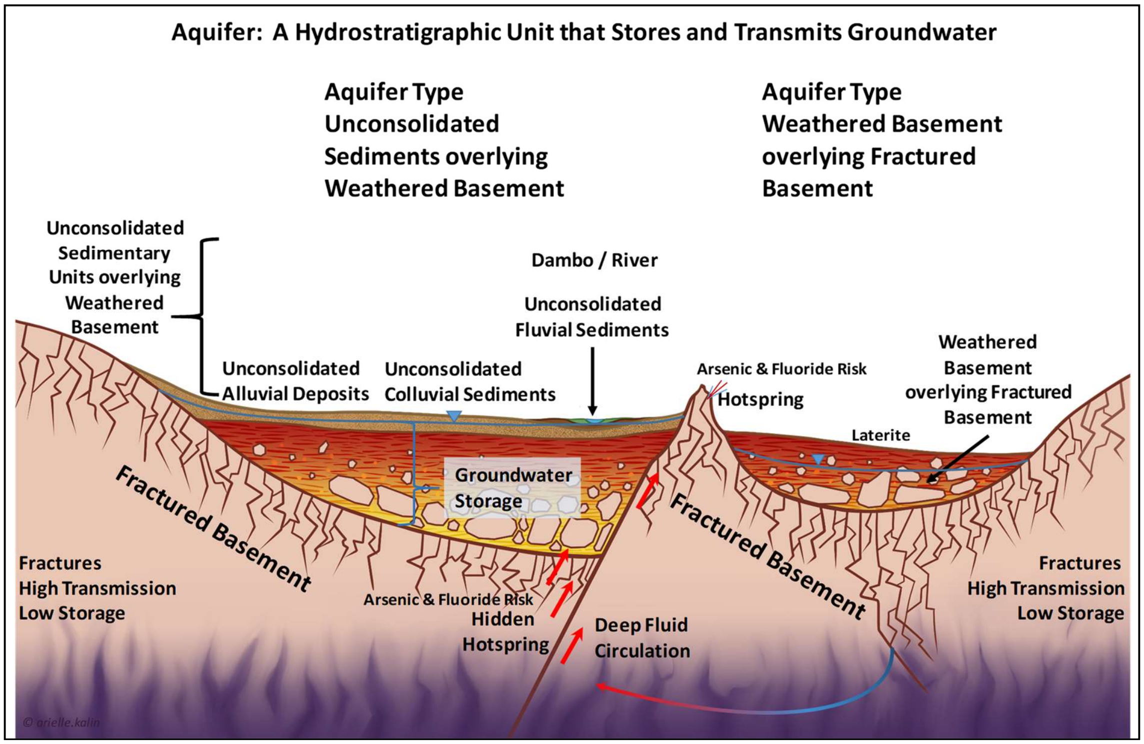


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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 2 (WRA 2): The Lake Chilwa Basin

Water Resource Area 2 (WRA 2) covers the entire Lake Chilwa Basin portion within Malawi (**Figure 2a**). Water Resource Area 2 and its component four Water Resource Units (WRU) is shown in Figure 2b. The Basin lies within a northeast-southwest trending tectonic depression in Southern Malawi at its eastern border with Mozambique. It occurs to the immediate east of the main Rift Valley and is an endorheic basin, that is without outflow with all surface waters draining into Lake Chilwa. Groundwater flow broadly follows topography. The lake is extremely shallow at just 1 to 5 m depth, but with an area of 683 km^2 and considerable wetlands, it is Malawi's second largest lake. It is a RAMSAR Convention wetland of international importance and annually contributes US$ 21 million to the Malawian economy, mostly from its fishery. The lake is vulnerable to desiccation, including complete drying out, occurrences of which spanned the last century but potentially now exacerbated by climate change. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of adjective storms from moisture carried from the Mozambique channel. WRA 2 is trans-boundary with respect to both surface and groundwater bodies. Integrated Water Resources Management (IWRM) should include provisions governed by Trans-boundary water sharing agreements.

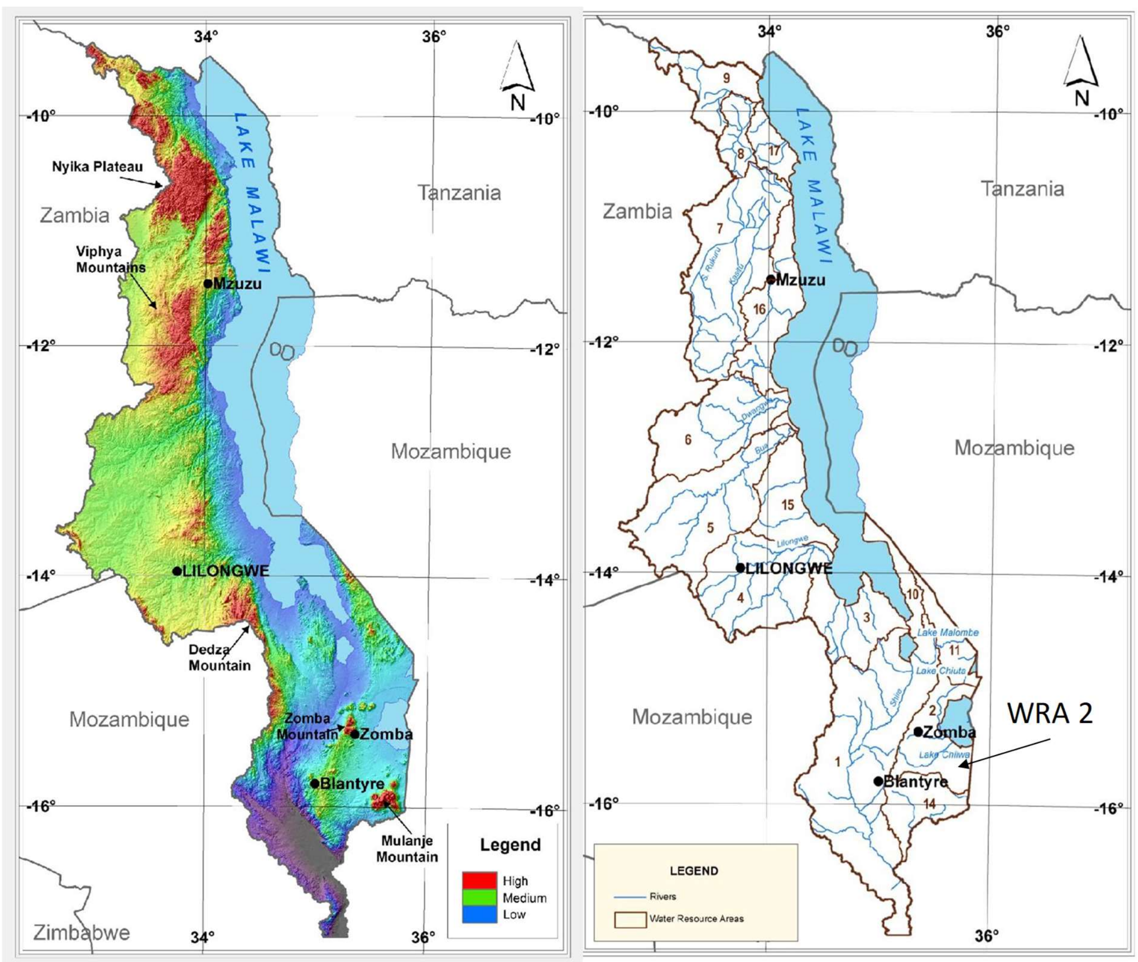


Figure 2a. Location of WRA 2 with major rivers and topography shown.

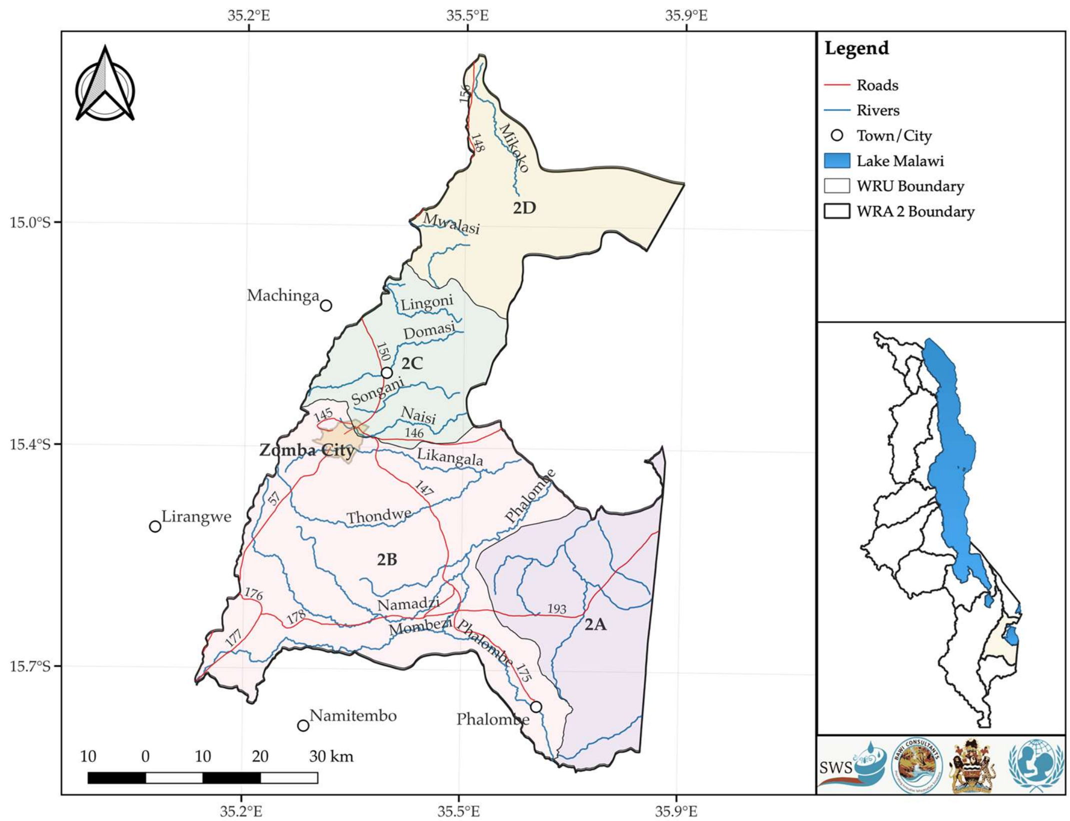


Figure 2b. Water Resource Area 2 and Water Resource Units.

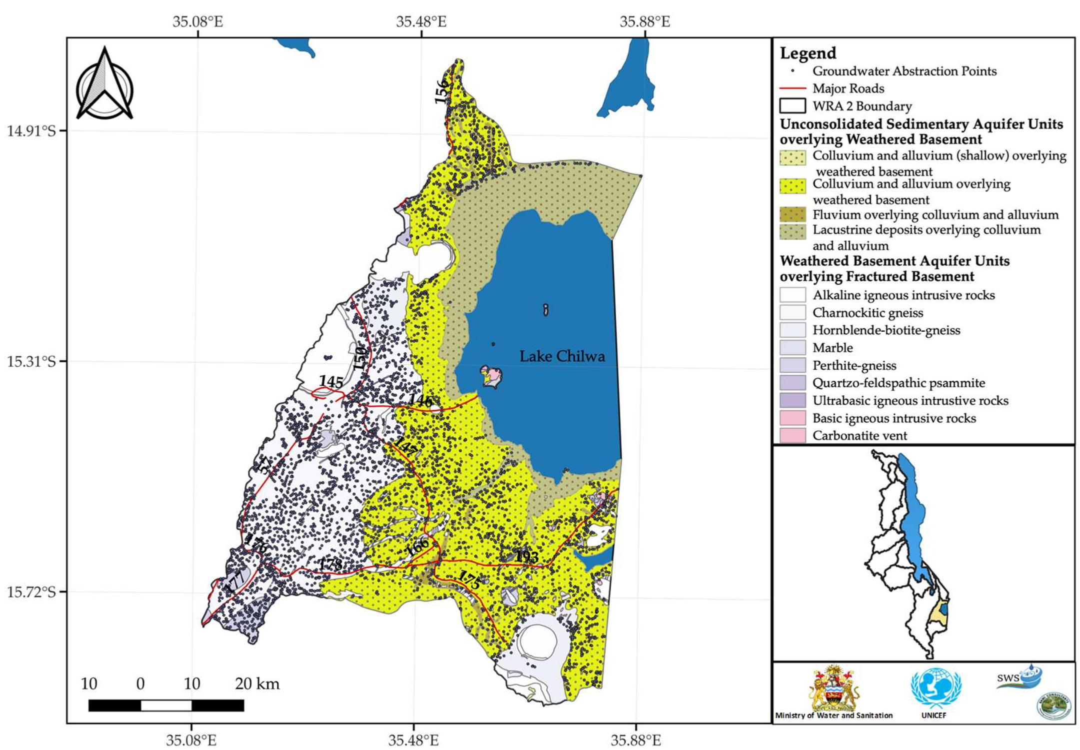
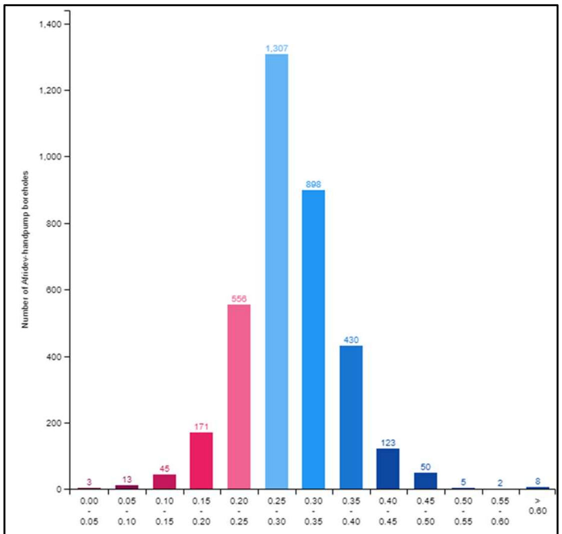


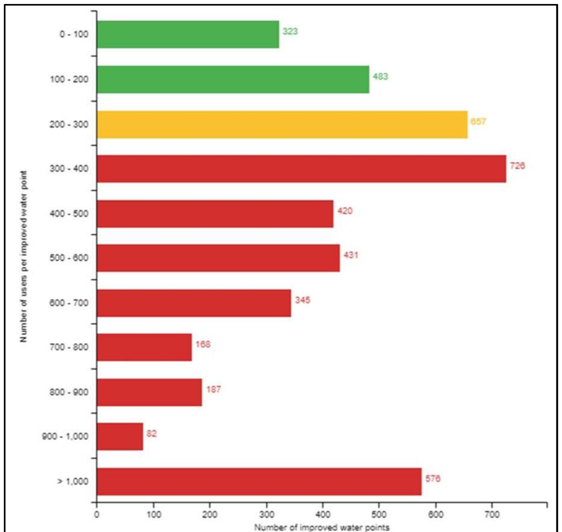
Figure 3. Distribution of groundwater abstraction points in WRA 2.

Groundwater Abstraction in WRA 2

Public abstraction points for groundwater are numerous in WRA 2 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 6,154 known groundwater abstraction points, 93.3% are improved sources (with 298 being protected dug wells and 477 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 hand-pump 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 2, only 60.1% are fully functional (defined as providing water at design specification).



Borehole Yield (l/s) Afridev Pump Borehole WRA 2



Number of users per Groundwater Supply

Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 2 (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 this target is considerably exceeded and there is an outstanding investment need in WRA2. Most of the groundwater supply points provide water to more than 250 users per water point, and with the number of dug wells and non-functional boreholes that likely 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, 26.8% of groundwater abstraction points do not provide sufficient water (September through November) due to water table declines (**Figure 5a and 5b**). Shallow boreholes and dug wells (protected and unprotected) are the most heavily impacted (see details at the end of this annex), impacting the functionality of these water supplies. In particular, there is a strong correlation between the depth of the groundwater water supplies, with shallow supplies are more at risk to lowering water tables resulting in lower functionality during the dry.

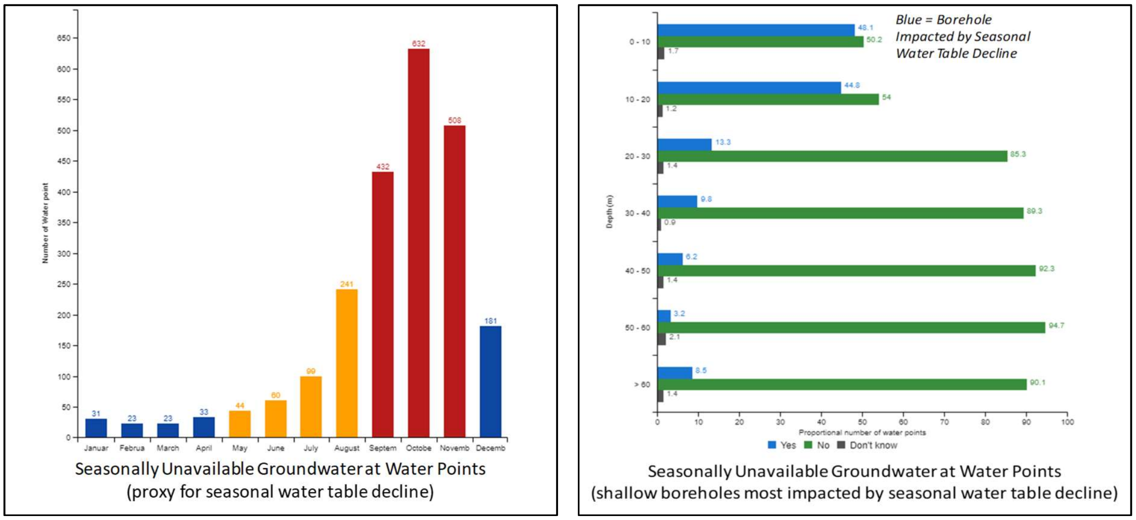


Figure 5a and 5b. Number of groundwater abstraction points in WRA 2 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

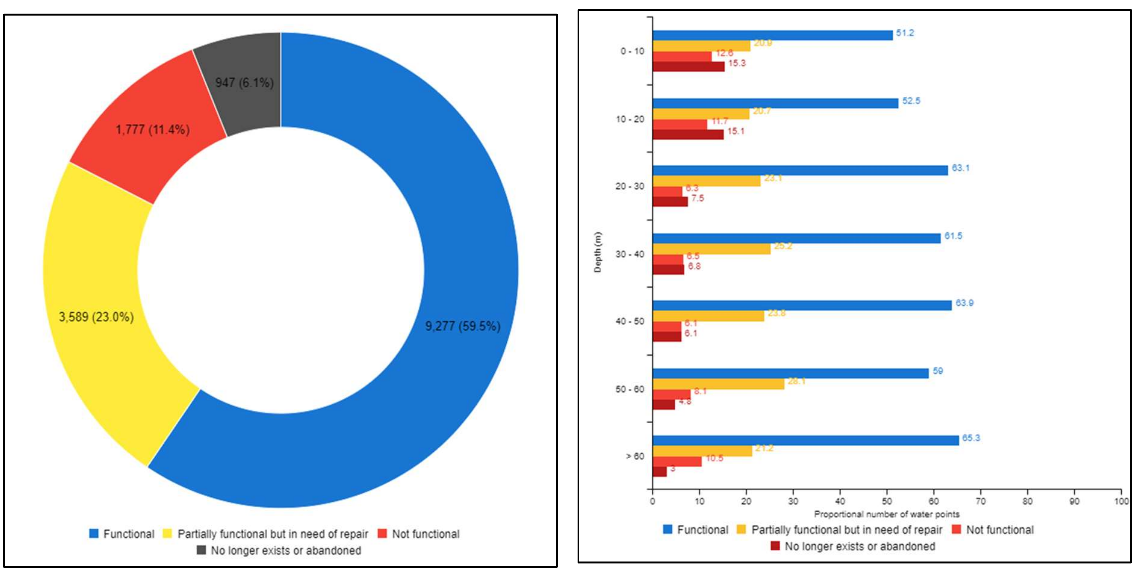


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA2 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water 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. 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 2 (after Kalin et al 2019).

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

Type	Number of Groundwater Abstraction points
Borehole or tube well	5,422
Protected dug well	298
Protected spring	20
Unprotected dug well	377
Unprotected spring	37

Description of Water Resources WRA 2

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. The Lake Chilwa basin incorporates (in Malawi) the 4 Water Resources Units: 2A, 2B, 2C, and 2D (**Figure 7a, 7b, 7d, 7e**), and it should be noted that this basin is Internationally Trans-Boundary and therefore international agreements should be in place to manage surface and groundwater for this Water Resource Area.

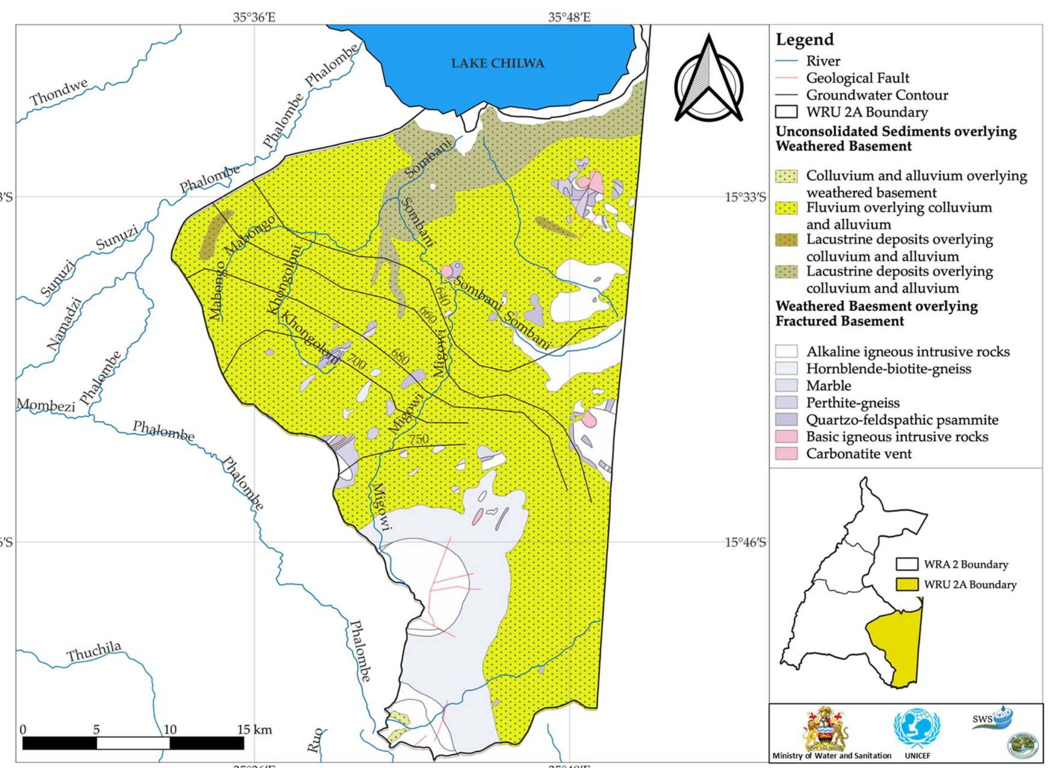


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 2A wtihin Water Resource Area 2 (Lake Chilwa Basin).

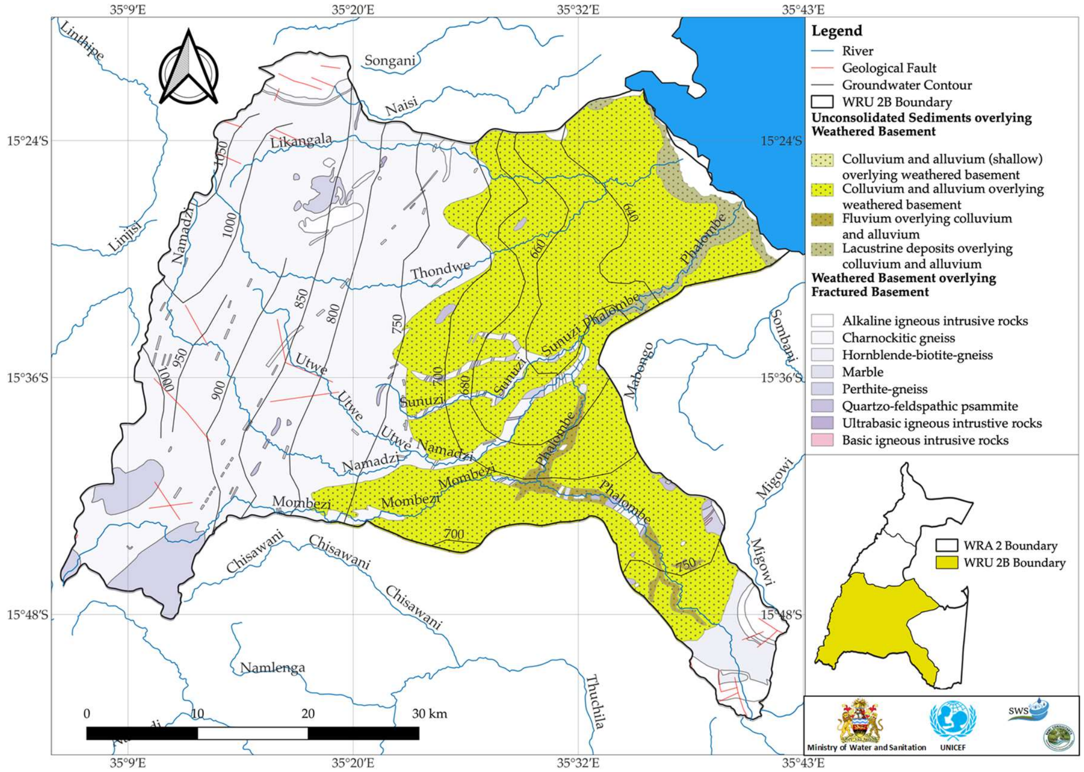


Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 2B wtihin Water Resource Area 2 (Lake Chilwa Basin).

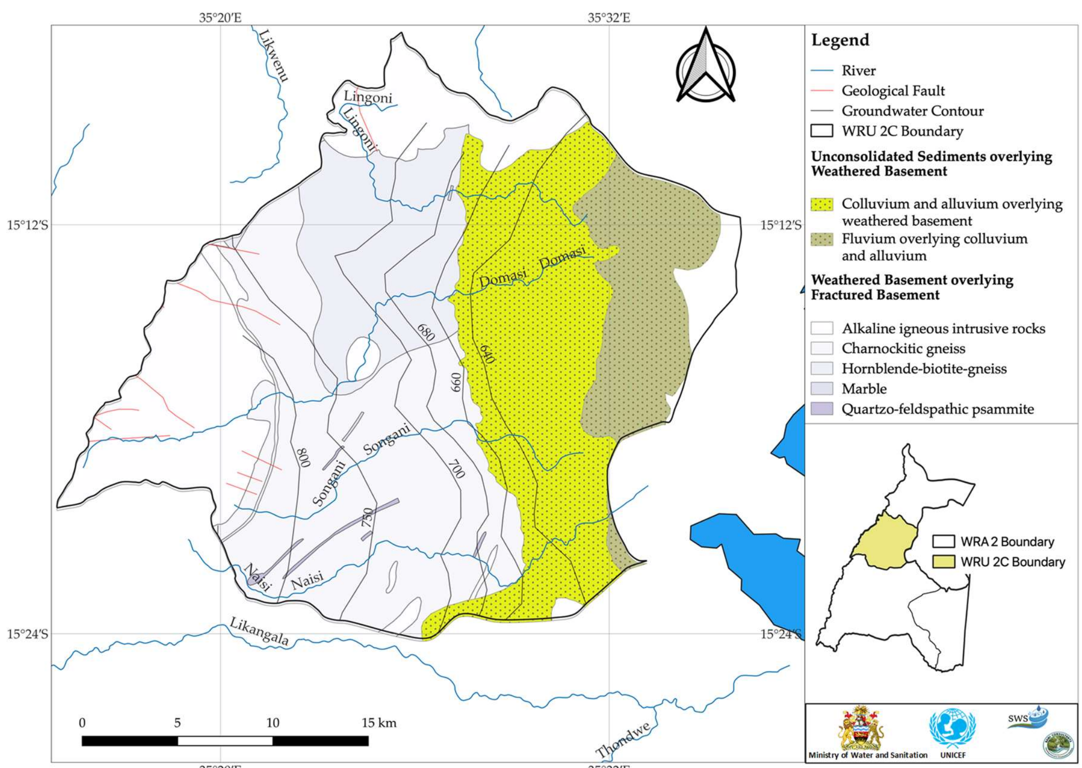


Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 2C wtihin Water Resource Area 2 (Lake Chilwa Basin).

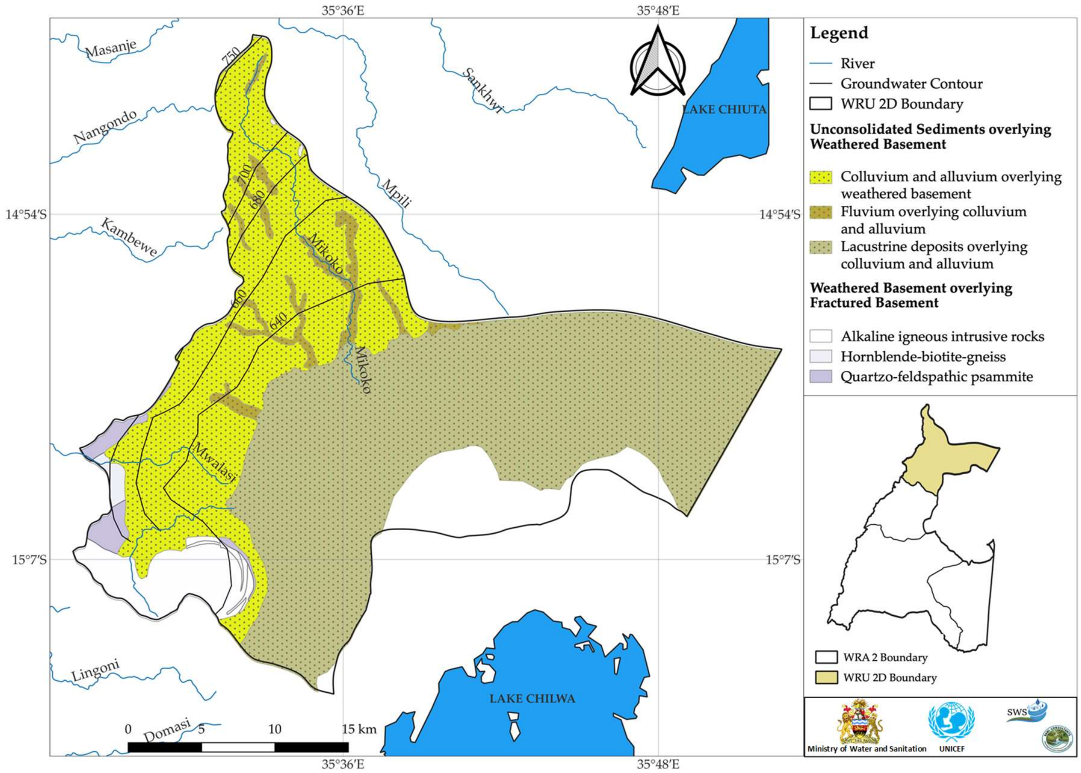


Figure 7d. Map showing the hydrogeologic units and water table for Water Resource Unit 2D wtihin Water Resource Area 2 (Lake Chilwa Basin).

Topography

The Shire Highland form the western Basin edge at 700 – 1200 m asl trending NE – SW along the edge of the Rift Valley escarpment (**Figure 2**). The Chilwa – Phalombe Plain between the Highlands and Lake Chilwa comprises gently undulating plains with isolated low rocky hills. This is subdivided by the Phalombe pediplain, an eroded platform at the foot of the Shire Highlands at 670 – 940 m asl. An area of broad convex divides separating marshy valleys which locally merges with colluvium eroded from the slopes of the Mulanje Massif that forms the southern Basin edge at 200 - 3000 m asl. The southern margins of the basin are mostly flat and sometimes marshy with areas of indeterminate drainage between the Thuchira and Phalombe rivers, cognisant that most drainage from the Massif is not into the Basin but southwards to the Ruo River. Lake Chilwa itself is immediately surrounded by Chilwa – Phalombe terrace deposits at 630 – 660 m asl.

Geology – Solid

The basin is underlain by the Precambrian–Lower Palaeozoic Malawi Basement Complex of metamorphic and igneous rocks, exposed in Shire Highlands to the west, and dipping below the lacustrine and alluvial deposits of the Chilwa–Phalombe Plain (**Figure 7a – 7d**). The Shire Highlands Basement of high-grade metamorphic rocks comprising predominantly charnokitic granulites of quartz and feldspar are replaced around the Mulanje Massif in the south by coarse-grained biotite gneisses rock derived from granite that weathers to sandy soils. The Basement is intruded by Upper Jurassic to Lower Cretaceous alkaline igneous rocks comprising intrusions, volcanic vents and radial dykes. Intrusions typically comprise granites and syenites and form the prominent Mulanje Massif that rises precipitously to over 3000 m asl in the south. Distinctive volcanic vents occur to the immediate south of Lake Chilwa at Tundulu as a complex of alkaline silicate rocks, carbonatites rich in sodium and calcium carbonates. Alkaline dyke swarms are widespread, particularly to the north east of the Mulanje Massif. Hot springs at Mpyupyu to the west of Lake Chilwa and off Chisi (Nchisi) Island in Lake Chilwa represent the final remnants of this period of igneous activity.

Geology – Unconsolidated deposits

Unconsolidated (Superficial) deposits extensively cover the basin from weathering of surrounding highland and underlying Basement rock within a post Cretaceous tectonic depression. A complex mix of Quaternary fluvial (alluvial) and lacustrine deposits exist from spatial/temporal influences of open and closed Lake Chilwa paleo-environments. Colluvium foothills surround the Massif to around 700 m asl incised by small stream gorges. The Phalombe Plain of predominantly lacustrine deposits slopes gradually northwards, merging with the Lake Chilwa depression. The apparently flat plain comprises several terrace levels associated with successive changes in the lake level. Island-like hills occasionally rise above the plain and colluvial pediments provide good agricultural land around isolated inselbergs. Otherwise, lowland plains comprise treeless lacustrine (clay) flats with some dambo wetland in marshy alluvial deposits in the lower areas that now mostly seasonal in occurrence.

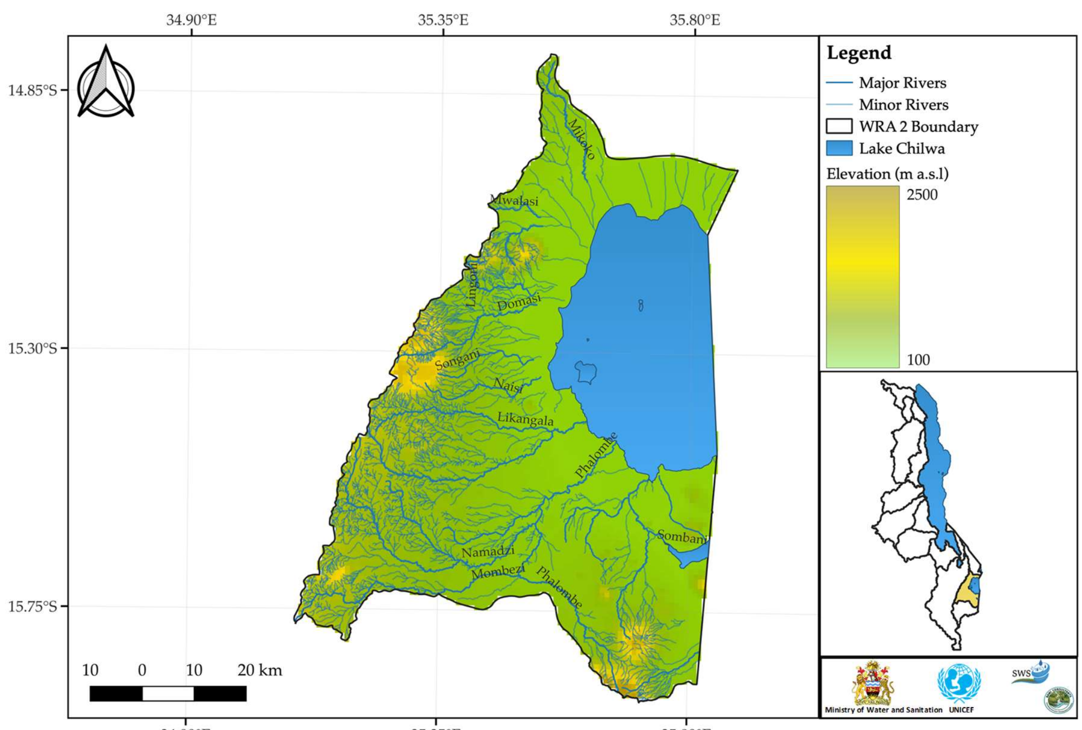


Figure 8. Drainage for the major rivers in Water Resources Area 2.

Drainage – Current

The Lake Chilwa wetland comprises the open lake surrounded by Typha swamps, marshes and seasonally inundated grassland floodplain. WRA 2 accounts for 68% of the 8350 km^2 area watershed the remainder being in Mozambique (**Figure 8**). The endorheic drainage pattern to Lake Chilwa is broadly evident from its four component WRU sub-catchment distributions. Perennial rivers include the Phalombe and Sombani draining the Massif northwards and Domasi, Likangala, Thondwe, and Namadzi draining the Shire Highlands eastwards. These account for 70% of lake inflow. Distinctive features, besides shallowness, are that Chilwa is a large East African lake that lies close to, but not within, the Rift Valley and it is one of only two of these lakes likely to have formerly drained into the Indian Ocean prior to lake enclosure by the Chilwa–Chiuta arcuate sandbar to the immediate north of the present lake during the Holocene. Paleo-lake levels were much higher then, with even higher levels under open lake conditions in the Pleistocene.

Drainage – Paleo-environment

The paleo-environment is not only significant in it control of predominantly lacustrine deposits within the lake terraces, but also fluvial sediment contributions. For instance, fluvial sediments deposited around the western side of paleo-lake Chilwa, especially from the Sumulu and Domasi Rivers, that form the lower terrace deposits of coarse to medium sands. Also, fluvial sediments within the deepest channel and probable course of the ancestral Phalombe–Lugenda River projected to occur on a northeast–southwest-trending down-warp of structural weakness that extends from Nayuchi to the northeast of the Chilwa–Chiuta sandbar to the Phalombe River estuary area.

Drainage – Lake Chilwa dynamics

The dynamic nature of Lake Chilwa is not restricted to modern times and requires recognition in assessing modern climate change influences. Whilst modern lake level seasonal fluctuation of around 1 m is expected, Lake Chilwa levels regularly fluctuate by 2 to 3 m and result in partial or complete lake desiccation during successive droughts, as inflows become low relative to lake evaporation. Chilwa is reported to have dried up completely on nine occasions during the last century (1903, 1913–1916, 1922, 1934, 1943–1944, 1967, 1973, 1975, and 1995–1996. Continuing lake dynamics, with complete desiccation in 2018, followed by flood in 2019, motivate the need for understanding the complexity of natural and anthropogenic dynamic factors involved.

Climate

Around 80% rainfall occurrence between November and April due to north easterly monsoon and south easterly trade wind convergence drives Basin hydrology. Annual rainfall averages from 1100 to 1600 mm, but may vary from 800 mm in the lowland plains to over 2000 mm in the mountains (**Figure 9**). Sporadic winter rainfall (May to October) only occurs in the highlands. The mean annual temperature is 21–24 °C, with a climate described as tropical wet and dry.

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 2. 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)
2	A	- No Station -	-	1,142
	B	Chanco/Makoka/Mombeza/Ntaja/Zomba	1,016	1,052
	C	- No Station -	-	1,054
	D	- No Station -	-	984

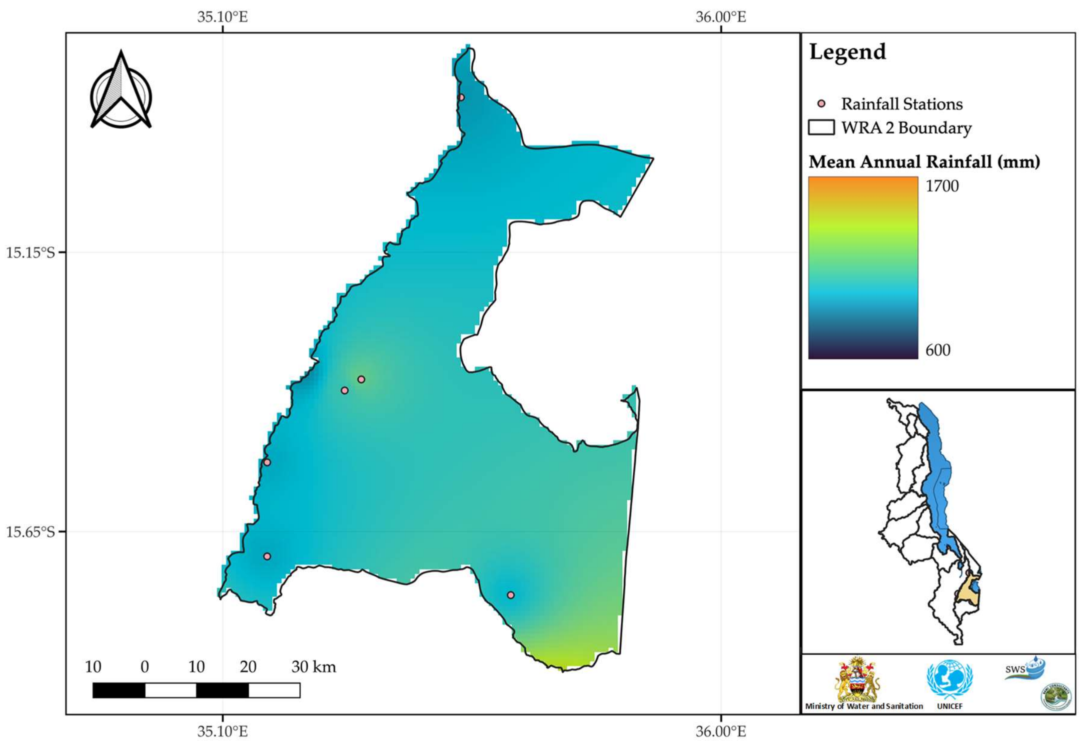


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 2 with the location of weather stations. Average rainfall measured is 1,016mm, average rainfall modelled is 1,057 +/- 65mm (range 876 to 1,418mm).

Land use

51% in forest, but increases of 62% in cultivation and 69% in grassland over the 40-year period of 1973–2013 (**Figure 10**). These accord with observations of livestock holdings and forest cover decrease, and cultivation increase including rice production. Intensified use of stream banks and wetlands for agriculture poses basin-wide erosion risks that continue. Such land-use changes will have significantly perturbed the basin water cycle from around the 1960s onwards.

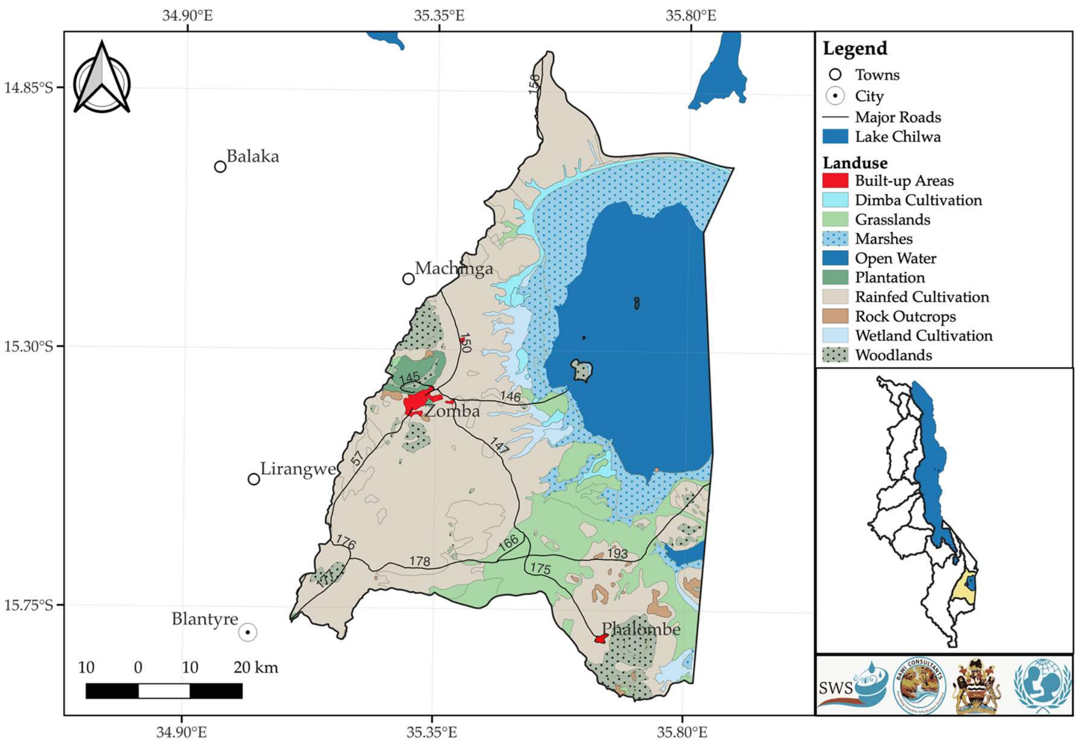


Figure 10. Land use in WRA 2 is dominated by rain fed cultivation.

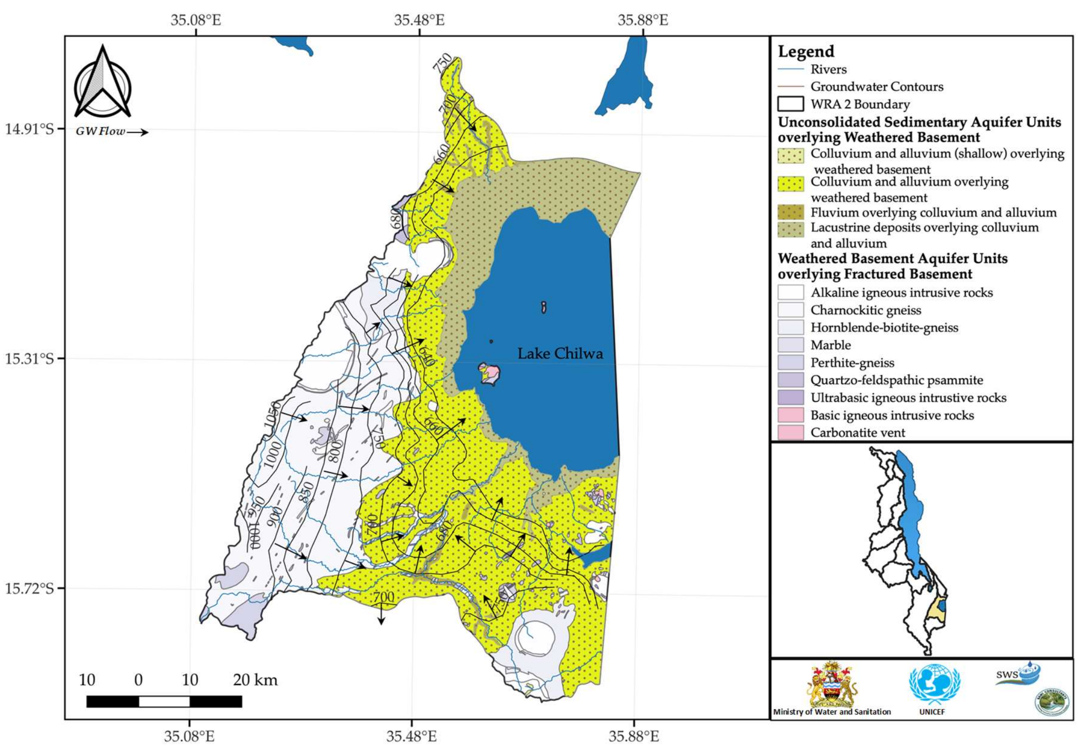


Figure 11. Groundwater level contours and flow direction in WRA 2 [1987 Hydrogeological Reconnaissance data] [water level contour interval 20m]

Hydrogeology of WRA 2

Aquifer properties

The Chilwa system location perched on the eastern edge of the Rift Valley with associated potential for increased clayey lithologies renders it distinct from other alluvial areas in Malawi located in the Rift Valley floor. Lacustrine deposits of low-energy deposition that comprise predominantly finer-grained lithologies and more common across the basin generally may be expected to be of modest aquifer potential. Layered unconsolidated, anisotropic aquifer systems may be expected, individual layers tending to an aquitard nature where very fine-grained silt/clay lacustrine deposits are thick and laterally extensive. Better aquifer units for water supply in the Chilwa Basin are most likely associated with former paleo-riverine environments where fluvial deposit accumulations are more extensive. Smith-Carrington and Chilton (1983).

Accordingly note the sediments in the Lake Chilwa Basin appear to be dominantly very fine-grained ascribed to the very low energy environment of deposition with internal drainage to the lake. Their expectation of coarser sediments derived from Mulanje or Zomba Mountains was not apparent from lithological records for existing boreholes except in Domasi Valley where there are some coarse sands (**Figure 11**).

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 data, therefore groundwater level data for WRA2 is based on prior hydrogeological reconnaissance and confirm Basin groundwater flows are convergent on Lake Chilwa generally following topography (see **Figure 10**). Steepest gradients occur in the uplands with gradients becoming shallower in areas covered by the high-level deposits and shallowest beneath the lake terrace deposits nearing Lake Chilwa. Groundwater divides at the basin boundary mimic those for surface-water drainage.

Groundwater in the northwest of the basin drains towards the Lake Chilwa wetland side of the Chilwa–Chiuta sandbar (separating the lake from Lake Chiuta in adjacent WRA 11). High gradients around 0.015 occur near Nanyumbu giving way to shallow gradients around 0.003 closer to the sandbar/wetland edge (**Figure 11**). Similar variability occurs in WRUs 2C and 2B to the west of the lake where gradients are much steeper in 2C at around 0.012 than in 2B at around 0.007. Differences are attributed to the restricted lowland area and highland proximity in 2C compressing gradients in contrast to the more extensive lake plain in the latter ever widening to the south. Groundwater flows in 2A towards the southern Lake Chilwa wetland area where steep gradients in the Mount Mulanje foothills of 0.012 give way to relatively even gradients of 0.008 in the lowland plain. Recent gradients there observed by Rivett et al. (2020) of 0.0063 towards the Lake over a 16 km distance infer a groundwater velocity of around 7 m/y applies for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.3.

Variation in river influent – effluent conditions expected across the widening lake plain may cause some gradient variability. Head contours are often convergent on rivers, especially in their mid- to upper reaches suggesting significant groundwater base flow contributions, for instance the Domasi, Thondwe and Phalombe. Head contours also convexly bow away from rivers towards Lake Chilwa and infer those reaches are influent, losing flows to groundwater below, e.g. some mid to lower reaches of the Thondwe, Songani southern tributaries and Phalombe where rivers can carve into and incise soft sediments.

Aquifer / Borehole Yield

As with most WRA's in Malawi, borehole yields do not appear to follow the anticipated distribution based on aquifer lithology. **Figure 12** provides the distribution of the data held by the Ministry of Water and Sanitation, and it is clear the distribution is skewed toward values of < 0.25l/s. This is suspect and likely represents substandard well construction for nearly 70% of the 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.

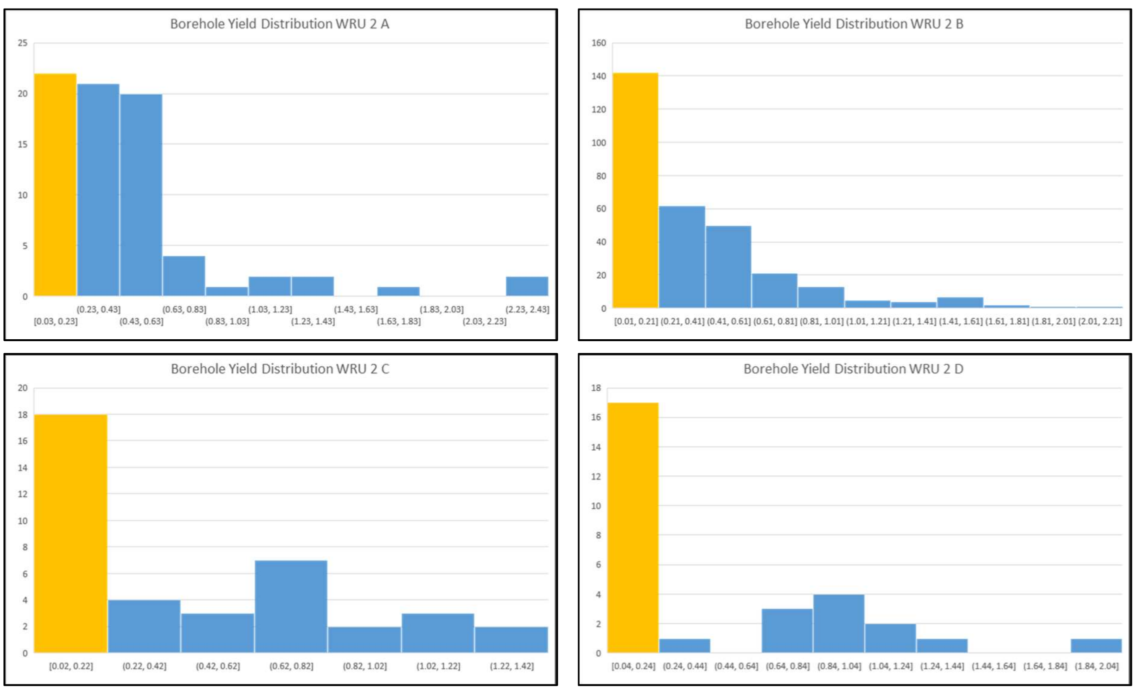


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 2 (y axis = *n* observations)

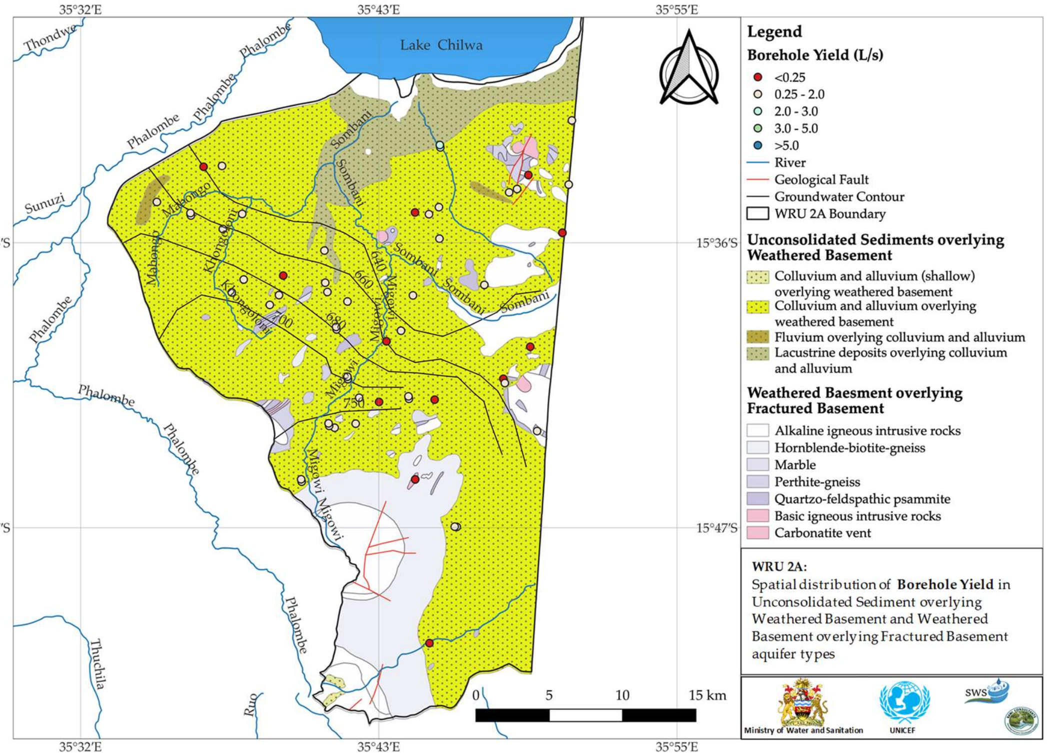


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 2A.

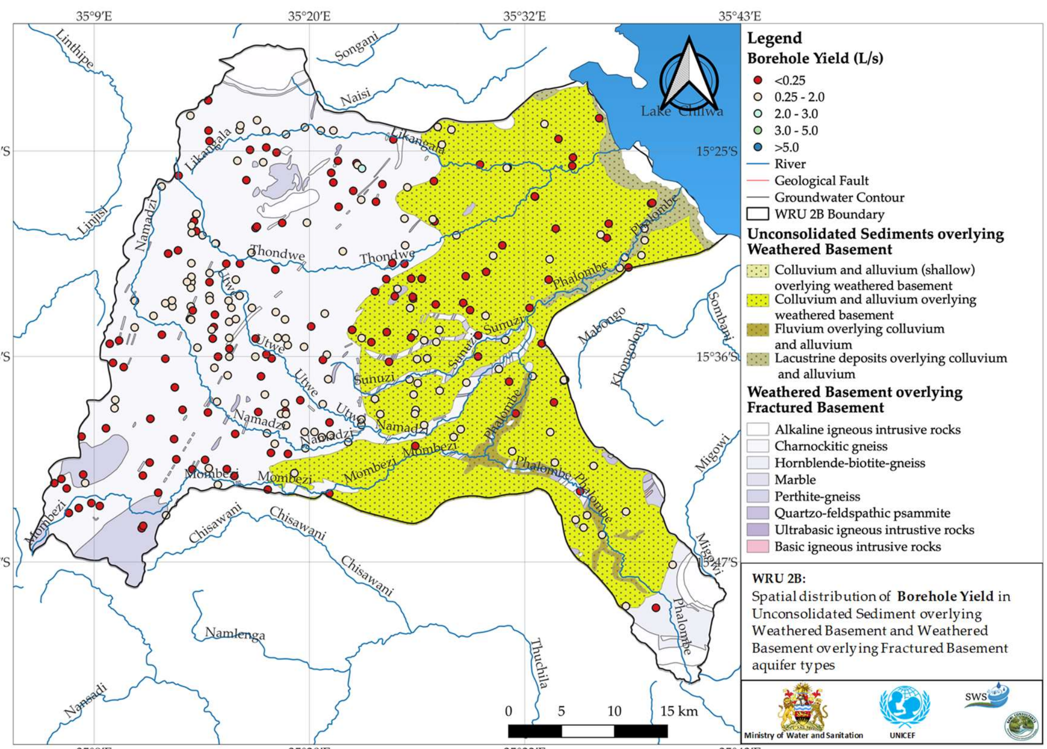


Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 2B.

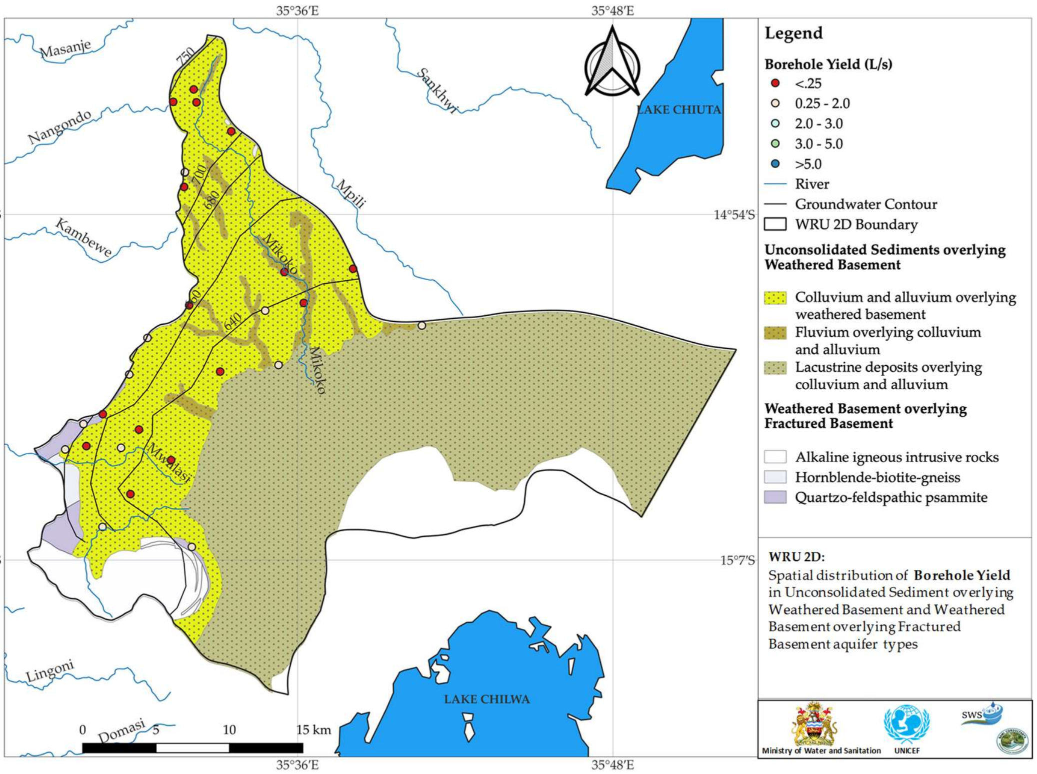


Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 2C.

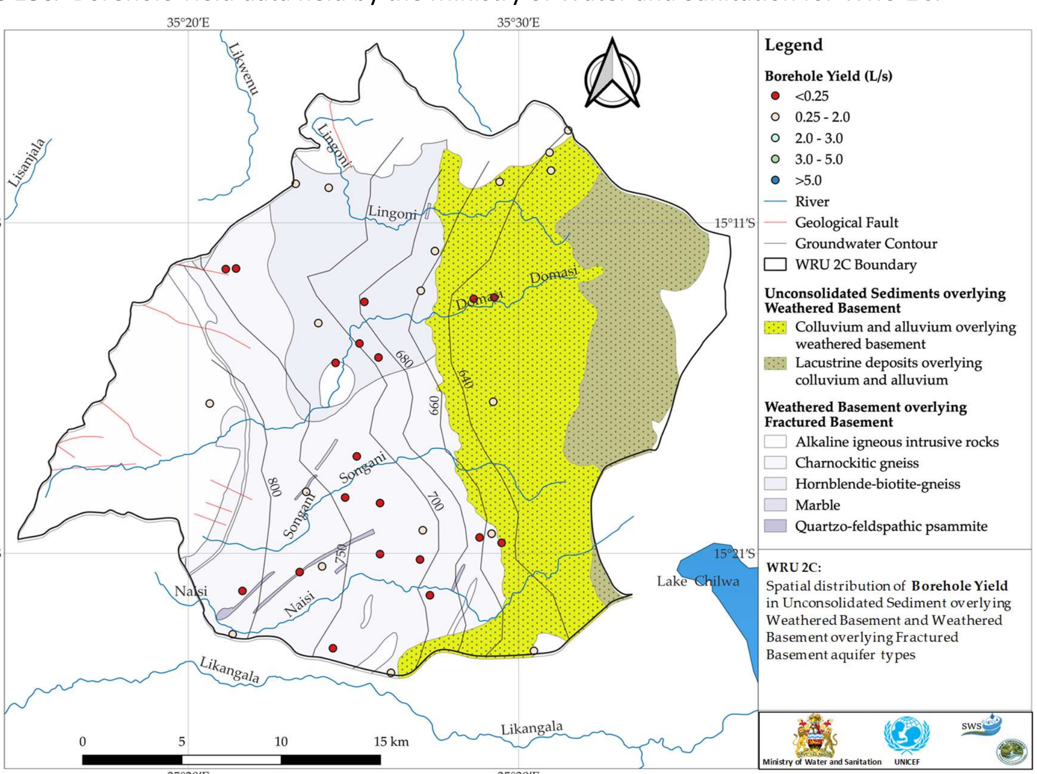


Figure 13d. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 2D.

There are general trends which suggest the highest borehole yields are found in alluvial aquifers in the order of 26 l/s, whereas in weathered and fractured aquifers, the highest yields are 15 l/s and 2 l/s respectively (see **Figures 13a, 13b, 13c, and 13d**). The highest yielding boreholes in basement aquifers are located mainly along linear structures and main streams and near contacts between different aquifers.

Groundwater Table Variations

There are three operational groundwater monitoring stations within WRA 2 (**Figure 14a**), however there has not been a continuous record of water table fluctuations over the period 2008 to 2021 (**Figure 14b**). Data from the 2020 National Survey suggested seasonal water table declines, supported by the data in **Figure 14**. From the data that is held by the Ministry of Water and Sanitation, there is between a 2- and 6-meter annual change in groundwater table. The magnitude of the seasonal variation suggests the aquifers these monitoring points intersect are unconfined and receive annual seasonal recharge. However, there are no borehole logs or multi-level installations that separate different hydro-stratigraphic units and it is recommended that multi-level installations into each unit is an area for future investment.

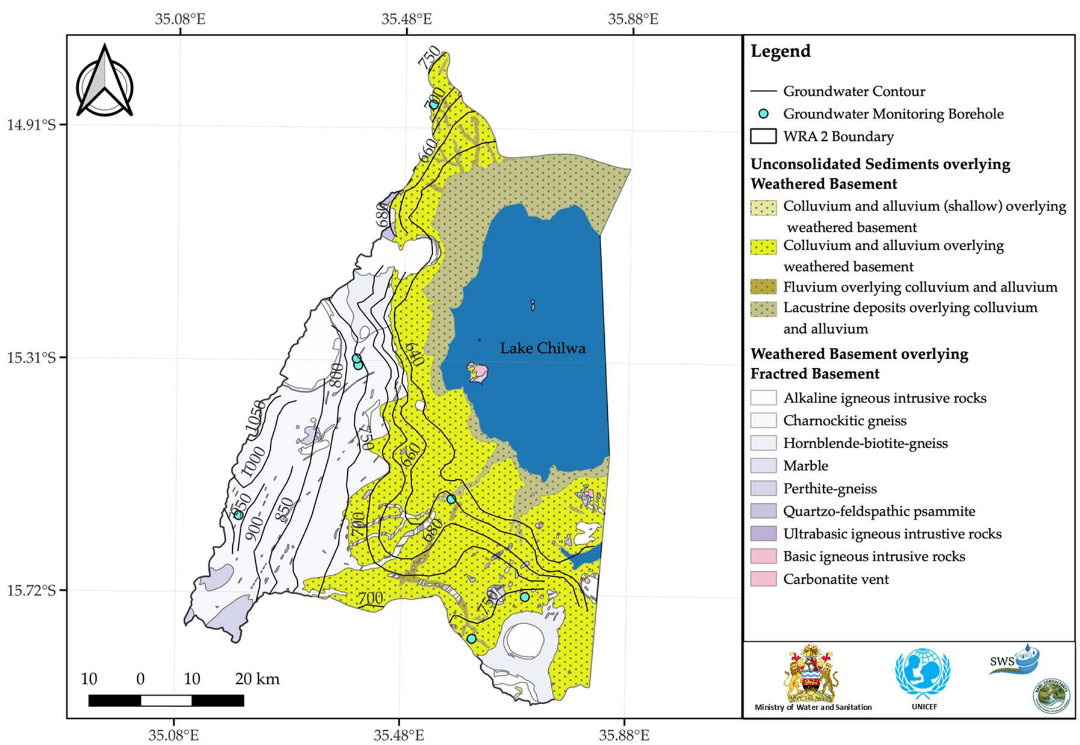


Figure 14a. Location of Groundwater Monitoring points in WRA 2

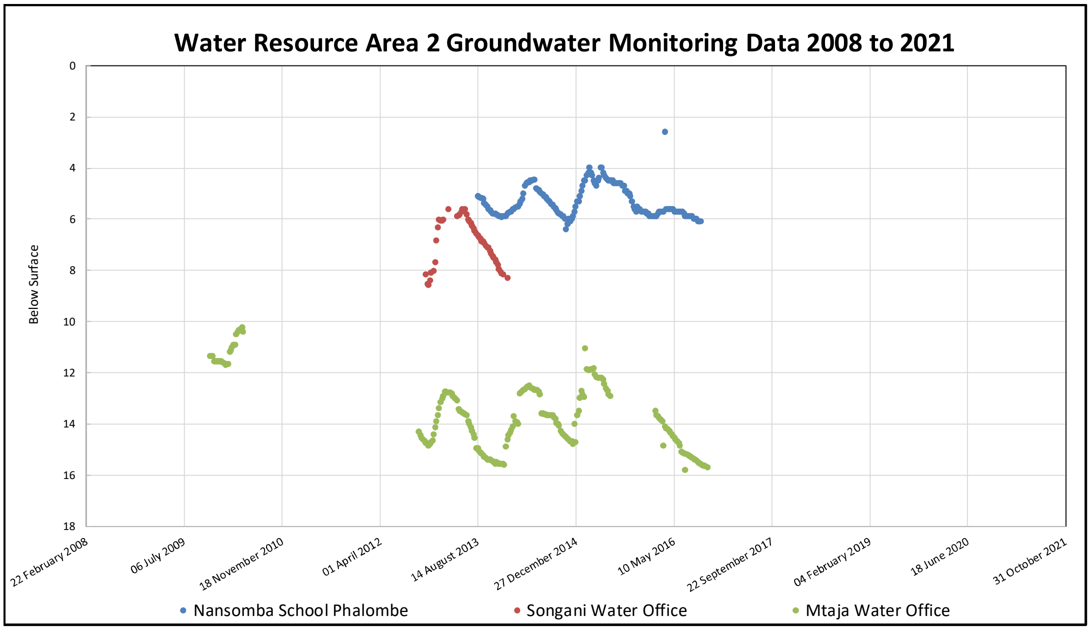


Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 2. (units assumed to be meters below ground level).

Groundwater recharge

The groundwater volume in each WRU was calculated using the estimated range of porosities published by McDonald et al. (2021) and the range of saturated thickness for each aquifer type (based on the depth of boreholes and water strikes per agreement with the Ministry of Water and Sanitation). The calculated volume of groundwater recharge in WRA 2 ranges between 25.4 Million Cubic Meters (MCM) and 266 MCM per year, with a mean age of groundwater of 178 years across the Water Resource Area **(Tables 4a, 4b, 4c, 4d**). There is a need to better constrain water volume/balance aspects of the Basin.

Table 4a. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 2A, 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	4.4	10%	35%	0.02	0.10	8.7	152.6	
Lacustrine units	68.0	10%	35%	0.02	0.03	135.9	713.7	
Colluvial etc.	642.8	10%	30%	0.02	0.06	1,285.7	11,570.9	
W & F Basement	189.7	1%	10%	0.02	0.03	37.9	569.1	
	Area of WRU (km^2)	2A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,468.2*	*13,006.2*	*Total Volume Groundwater*
	904.9	1142	Average Rainfall in WRU	11.42	85.65	10.3	77.5	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]						142	168	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 2B, 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	27.8	10%	35%	0.02	0.10	55.6	973.8	
Lacustrine units	41.1	10%	35%	0.02	0.03	82.1	431.0	
Colluvial etc.	819.8	10%	30%	0.02	0.06	1,639.7	14,757.1	
W & F Basement	1,176.5	1%	10%	0.02	0.03	235.3	3,529.6	
	Area of WRU (km^2)	2B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,012.7*	*19,691.6*	*Total Volume Groundwater*
	2,065.3	1052	Average Rainfall in WRU	10.52	78.9	21.7	162.9	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]						93	121	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 2C, using these calculations the mean residence time of groundwater has been calculated.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	0.0	10%	35%	0.02	0.10	0.0	0.0	
Lacustrine units	72.0	10%	35%	0.02	0.03	143.9	755.7	
Colluvial etc.	165.8	10%	30%	0.02	0.06	331.6	2,984.2	
W & F Basement	431.7	1%	10%	0.02	0.03	86.3	1,295.1	
	Area of WRU (km^2)	2C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*561.9*	*5,035.0*	*Total Volume Groundwater*
	669.4	1054	Average Rainfall in WRU	10.54	79.05	7.1	52.9	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]						80	95	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 2D, 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	27.8	10%	35%	0.02	0.10	55.5	972.0	
Lacustrine units	436.7	10%	35%	0.02	0.03	873.4	4,585.5	
Colluvial etc.	266.4	10%	30%	0.02	0.06	532.8	4,795.3	
W & F Basement	61.4	1%	10%	0.02	0.03	12.3	184.3	
	Area of WRU (km^2)	2D	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,474.1*	*10,537.1*	*Total Volume Groundwater*
	792.3	984	Average Rainfall in WRU	9.84	73.8	7.8	58.5	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]						189	180	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Stable Isotope Insights

Stable isotopes are a key tool for Integrated Water Resource Management. Basin-scale stable isotope surface water (river) signatures plot close to the Global Meteoric Water Line (GMWL) defined by the relationship of $\delta^2H = 8\delta^{18}O + 10$ (**Figure 15** after Rivett et al. 2020).

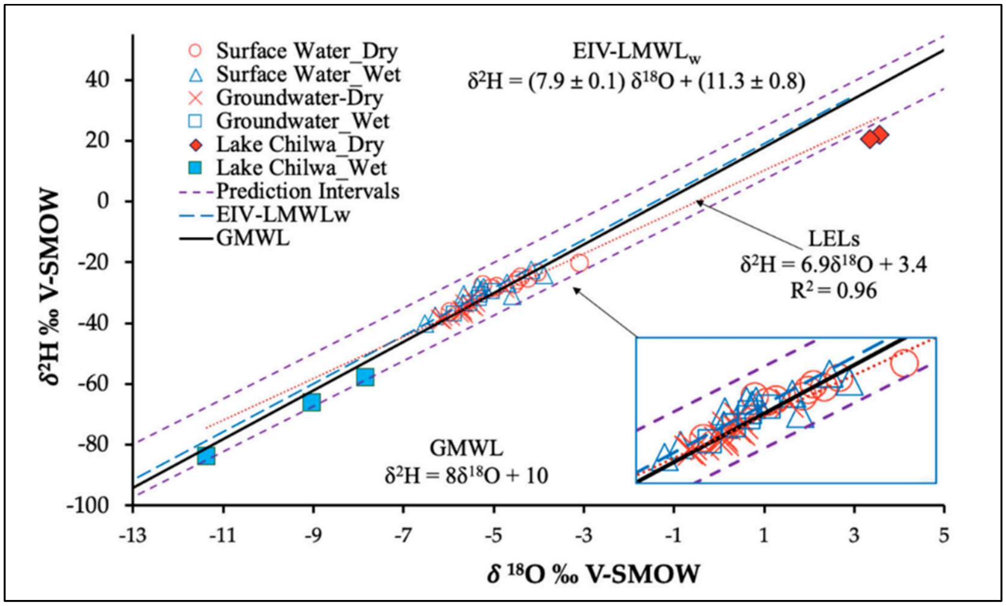


Figure 15. Stable isotope values for groundwater and surface water in WRA 2 plotted against the global meteoric water line and the local meteoric water line.

All surface-water samples plot along meteoric water lines providing strong evidence of non-evaporated precipitative recharge input into surface-water bodies. During the dry season all surface water samples plot along meteoric water lines and within the prediction intervals except for Lake Chilwa that has a significant enrichment due to evaporative fractionation of lake water. The lake water shows progressive evaporative enrichment along a Local Evaporation Line (LEL) calculated of $\delta^2H = 6.9\ \delta^{18}O + 3.4$. Surface water isotopic signatures comprise current precipitation and groundwater (base flow / interflow) contributions, the latter primarily sustaining dry-season river flows.

Groundwater quality WRA 2

Groundwater major-ion water quality in WRA 2 show lowest concentrations occur in the rivers followed by groundwater, with highest concentrations (except for nitrate) found in Lake Chilwa. Differences approach an order of magnitude with median (and interquartile ranges) in Total Dissolved Solids (TDS) for rivers (n = 29) of 40 mg/L (24–95 mg/L) and groundwater (n = 276) of 564 mg/L (294–958 mg/L) and Lake Chilwa (n = 3) of median 3120 mg/L (**Table 5**). The 95th percentile TDS for groundwater of 2384 mg/L approaches, and its maximum of 3200 mg/L exceeds the Lake Chilwa TDS found near the lakeshore of approximately 3‰ salinity, at the lower hyposaline lake threshold. Literature lake perimeter salinity is comparable at 2.5‰ in the dry season with diluted wet-season salinities of c. 1.5‰ and a recessed central lake salinity reaching 10–12‰.

Table 5. Distribution of dissolved species in groundwater WRA 2. 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 2	pH	EC	Cl (mg/l)	SO_4 (mg/l)	NO_3 (mg/l)	F (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	Fe (mg/l)
Mean	7.4	754	61	19	1.1	0.6	54	2.1	65	26	0.5
Std Dev	0.8	849	111	35	2.2	0.4	73	2.6	82	36	0.4
Median	7.3	505	21	8	0.4	0.6	27	1.5	39	14	0.4
Max	9.1	5,300	897	360	22	3.0	600	24	680	298	1.7
Min	5.0	6.0	1.1	1.0	0.0	0.0	1.4	0.1	1.0	0.1	0.0
n	595	575	559	533	439	237	560	560	554	532	213

A key observation is paleo-Lake deposit extent control on current groundwater TDS and hydrochemistry in WRU 2a. Virtually all groundwater points located at higher elevation than the High Level lacustrine deposit extent have a TDS < 1000 mg/L, with most having a TDS < 600 mg/L. Groundwater will be drawn from either the colluvium where present or underlying weathered basement. Hence good drinking water quality groundwater at <600 mg/L TDS predominantly occurs in the mid-to-upland basin and may also discharge as good-quality freshwater base flow to upper stream reaches and support the surface-water based gravity-fed supplies. Groundwater at 600–1000 mg/L TDS still of reasonable quality occurs at mid to lower Basin elevations. Groundwater generally of higher TDS, becoming brackish increasingly occurs at lower basin elevations as Lake Chilwa is approached. Groundwater nearing the lake may be semi-confined and slow moving and hence prone to high TDS. Boreholes of highest salinity (>1500–4300 mg/L TDS) track close to the 652 m elevation contour and terrace 5 deposit line. Closer to the lake salinity was somewhat lower, but remained significant at 1000–1500 mg/L TDS.

A notable exception to increased TDS groundwater nearing the Lake is the observation of some low TDS (< 600 mg/L) boreholes close to the Phalombe and Sombani rivers in their mid-to-lower river reaches crossing the high-level and terrace deposits in their approach to Lake Chilwa. This is postulated to arise from river infiltration of low-TDS surface water to groundwater, more probable where reaches are incised into the lacustrine deposits. Such infiltration may potentially provide important useful near-Lake, shallow, low TDS groundwater resource.

Piper plots largely fall within a mixed-type domain with a linear trend in composition from Ca (and Mg) water to Na (and K) attributed to increased cation exchange of Ca in recent recharge groundwater with sodium from clay-based lithologies progressively encountered along flow lines to the lake **(Figure 16a and 16b**). Anions exhibit a predominant HCO_3-type water with a trend to increased Cl content. Data confirm anticipations of recent recharge waters associated with the basement rock–colluvium–superficial deposits and the influence of acidic conditions from soil CO_2 and rock mineralogy that promote dissolution of Ca (and Mg) carbonates leading to the predominant Ca-HCO_3 water type at 46% of sites.

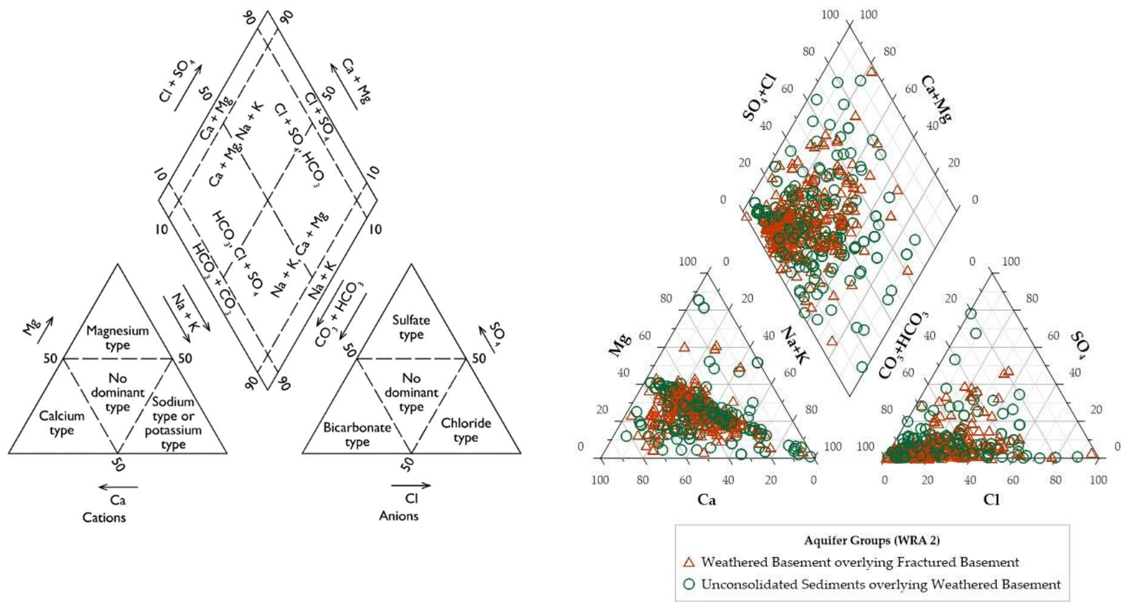


Figure 16a, 16b. Piper Diagrammes of Groundwater Samples in WRA 2 and for each Aquifer Type in WRA 2.

Increased groundwater residence times and influence by clay lithologies in the terrace lacustrine deposits providing cation exchange opportunity and Na exchange for Ca and greater Ca-Na-HCO_3-type waters (38% of sites) with increased sodium in groundwater. Exchange may be associated with montmorillonites formed from alteration of silicates. Evaporitic enrichment (including mixing with evaporated water) is probable and promotes increased sodium and chloride and occurrence of Ca-Na-HCO_3-Cl-type waters accounting for 10% of sites, Na-HCO_3-Cl at 5% and Ca-HCO_3-Cl at 1% of sites.

The distribution of key dissolved water quality species in groundwater of WRA 2 are shown in **Figure 17a through 17f**. In general, the water quality is good to fair, and shows indications of weathering of aquifer minerals and evaporative concentration of dissolved salts.

Groundwater quality - Health relevant / aesthetic criteria

Salinity

The controls on distribution of TDS in WRU 2a has been indicated above with similar controls anticipated across the wider basin. WRU 2a contains n= 285 boreholes of which 55 % of sites > 2000 mg/L TDS (Figure 17). Further understanding of the near surface geology is needed to provide in-depth understanding of the circulation of water and management of groundwater water sources to reduce human health impact.

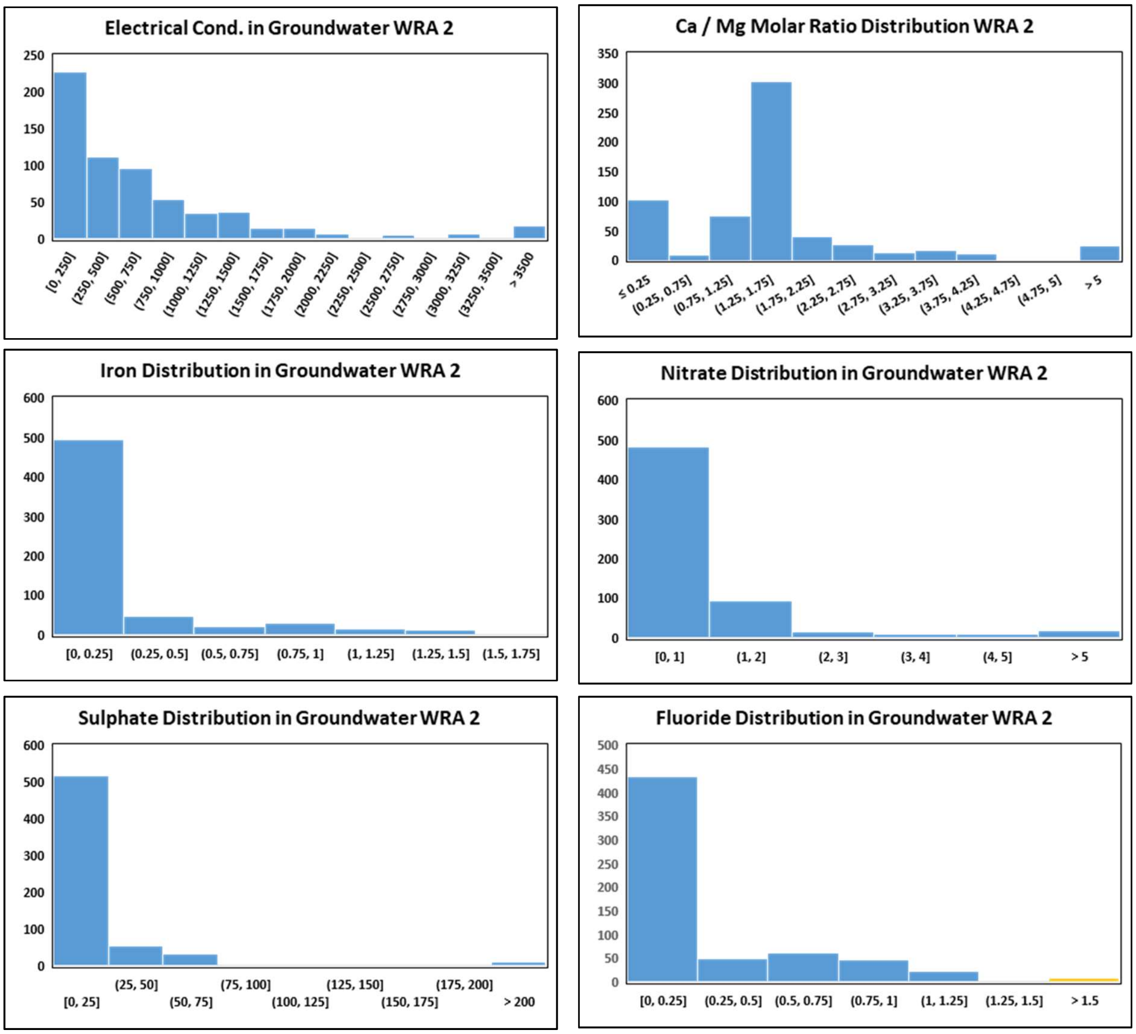


Figure 17a, 17b, 17c, 17d, 17e, 17f. Distribution of chemical species (EC [uS], Ca/Mg [molar ratio], NO_3 [ppm as N], SO_4 [ppm], F [ppm] and Fe [ppm]) in groundwater within WRA 2. Note: Fluoride measurements above WHO 1.5ppm limit are shown in yellow. (y axis = *n* observations)

Fluoride

Fluoride Basin groundwater data drawn from the recent national-scale assessments (**Figure 18**) reveals only the Mpyupyu Hot Spring exceeds the current Malawi drinking water 6 mg/L with all but one sample in the WRU's 2B, C, D below the current WHO 1.5 mg/L guideline. In WRU 2A, a mix of concentrations occur below 1.5 mg/L and between 1.5 and 4 mg/L. This relatively low occurrence accords with national expectations of predicted risk. Fluoride <1.5 mg/L is anticipated for basin/lacustrine sediments, and where increased is probably ascribed to thinning sediments and boreholes penetrating weathered granite or syenite beneath. Increased 1.5–4 mg/L fluoride may be expected in supplies in alkaline igneous intrusions (granite, syenite, carbonatite). Hot springs may display fluoride >6 mg/L, but their lateral influence as shown for Mpyupyu is restricted with low fluoride in surrounding boreholes.

Absence of major faulting suggests that hot springs are using vertical boundaries between the alkaline intrusions and host rock as conduits to transport deep-seated groundwater upwards to the surface, or else the steep geothermal gradient present in the thin crust Rift Valley resulting from shallow heating from active rifting is causing convective vertical transport of meteoric water/shallow groundwater via intrusion-country rock boundaries acting as vertical conduits. The latter is more probable, both Mpyupyu and Chisi Island hot springs are adjacent to alkaline intrusions.

Arsenic

A recent national collation of arsenic groundwater survey data found widespread low concentrations but with only a few above the WHO 10 µg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. This national dataset did not sample the Lake Chilwa Basin where arsenic risks are perceived low, but remain unproven.

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.

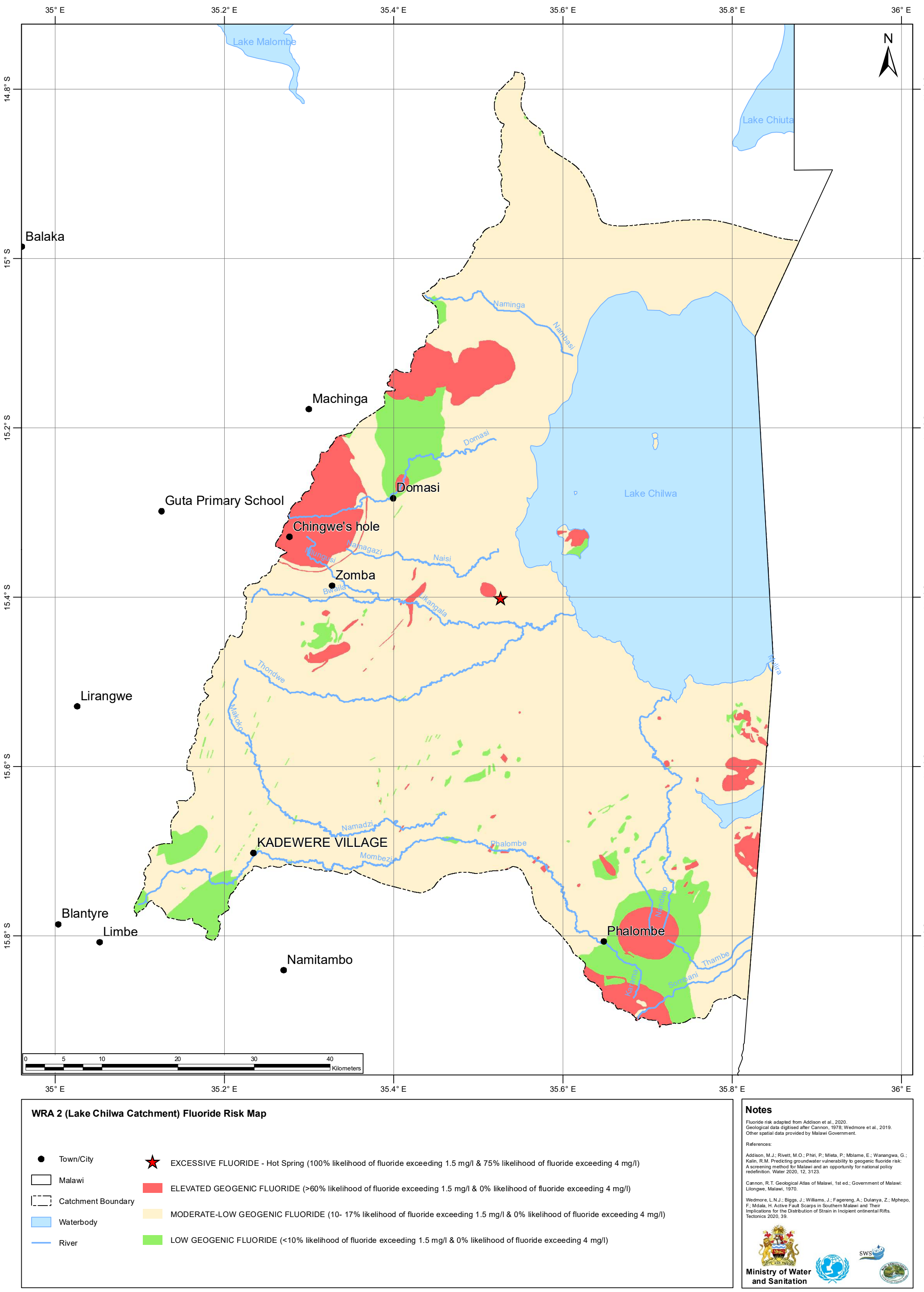


Figure 18. Groundwater Fluoride Risk Map WRA 2 (after Addison et. al. 2021).

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 2.

	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**
2A	188,570	197,680	206,704	215,633	224,365	130,290	628,150,810	753,781
2B	627,114	654,091	682,656	716,785	733,536	743,400	2,245,094,241	2,694,113
2C	165,876	172,606	179,299	187,590	190,999	198,858	591,423,291	709,708
2D	105,953	113,719	121,556	129,709	138,069	122,666	395,103,167	474,124
WRA 2	**1,087,513**	**1,138,096**	**1,190,216**	**1,249,717**	**1,286,970**	**1,195,214**	**3,859,771,508**	**4,631,726**

Table 6 presents model results that show Water Resource Unit 2 has a calculated total of 4,631,726 metric tonnes of faecal matter loading over the 10-year period (2012-2022). Over the 10-year period the number of pit latrine users in the region increased by 107,701.

WRA 2 covers roughly 3.69% 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, therefore 7,484 metric tonnes of fertiliser would be used in WRA2 per year. Almost 62 times more faecal matter was loaded to the subsurface as a groundwater threat in this WRA than fertiliser over this 10-year period. This risk, along with detailed aquifer vulnerability and borehole source-pathway-receptor modelling requires further study.

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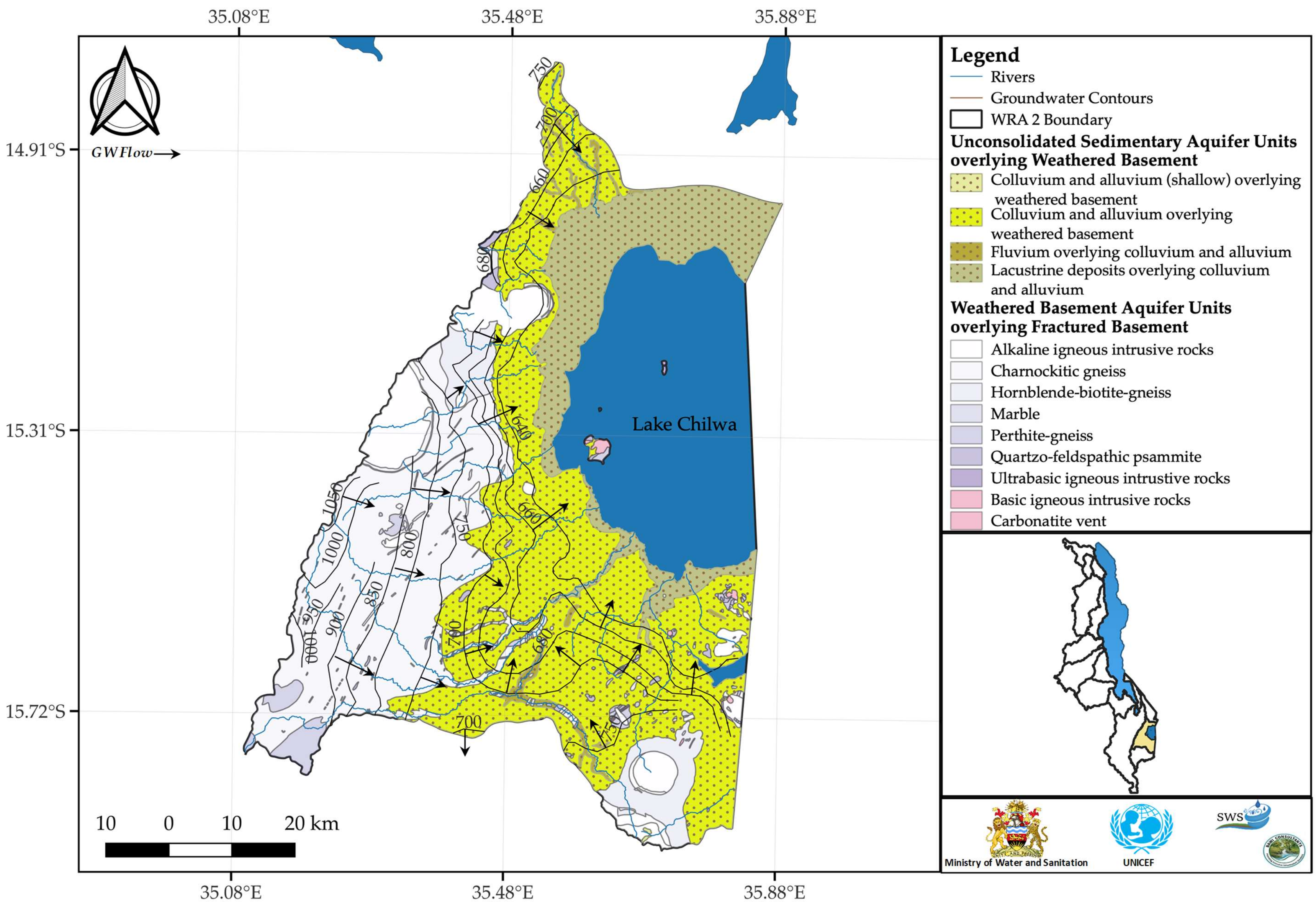
Water Resource Unit (WRA) 2 Figures

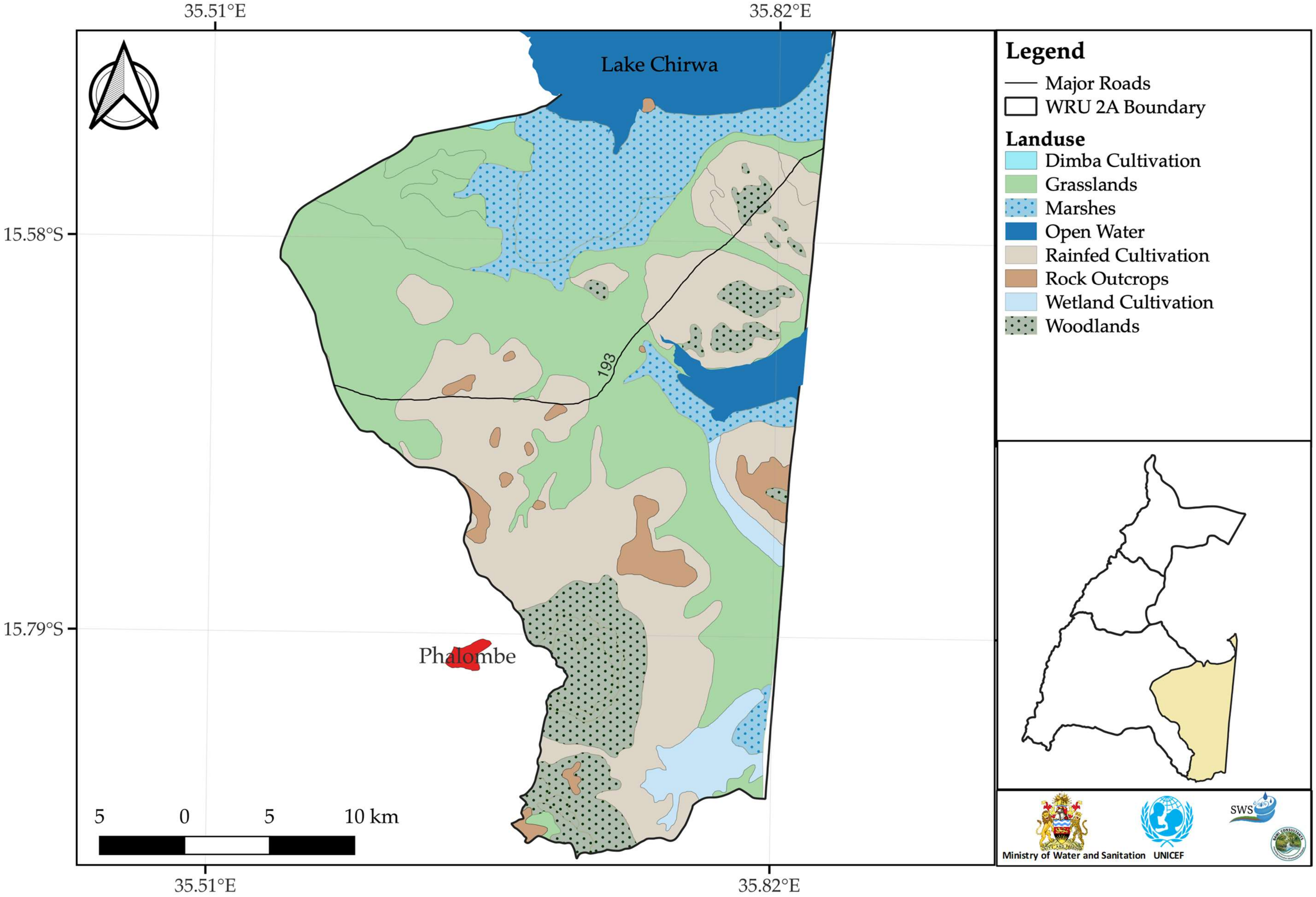
Figure WRA 2.0: Aquifer Units and Groundwater Level Contours Water Resources Area 2

Figure WRA 2.0: Aquifer Units and Groundwater Level Contours WRA 2



WRU 2A Figures

Figure WRU 2A.1 Land Use and Major Roads



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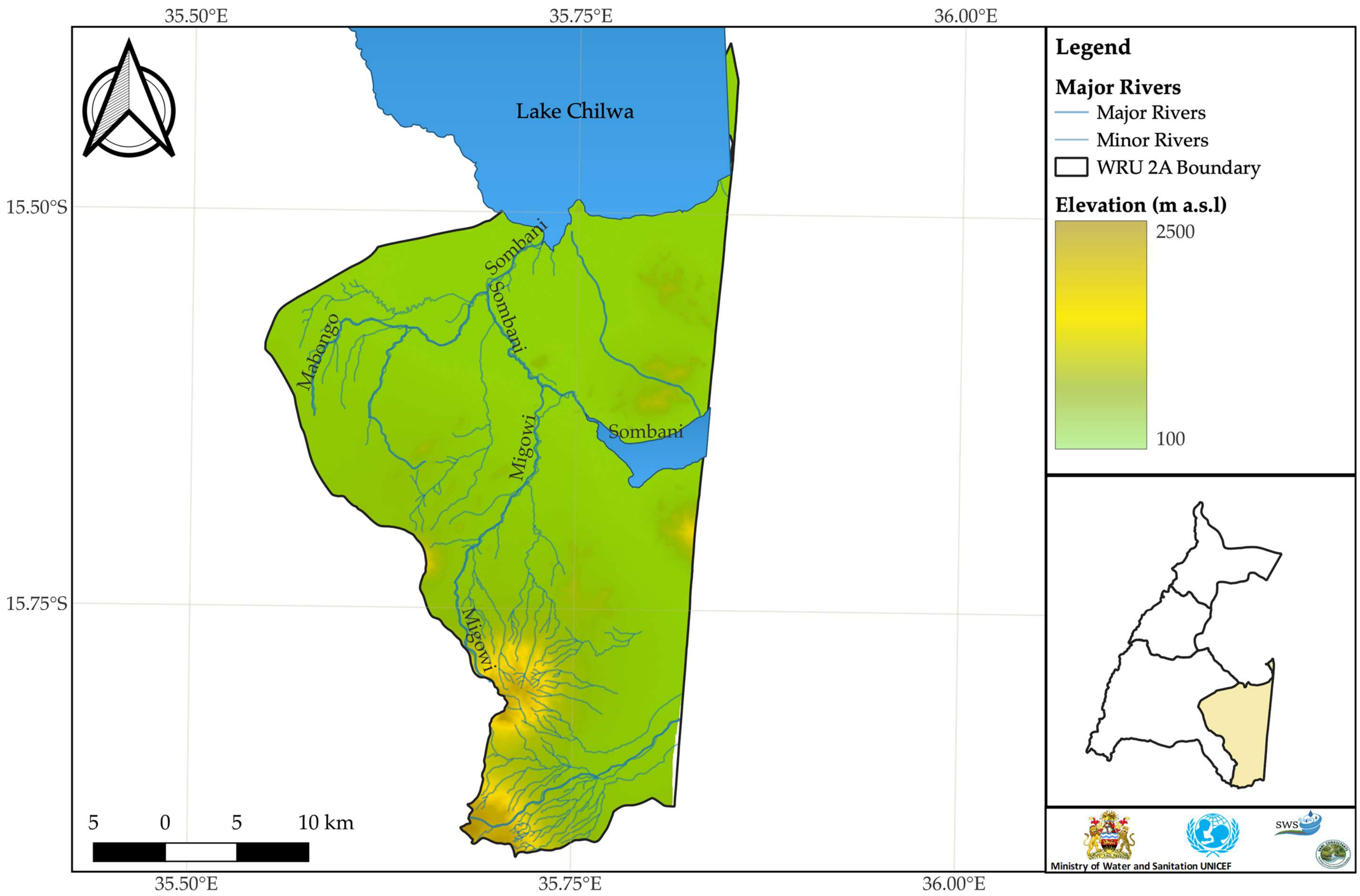


Figure WRU 2A.3 Hydrogeology Units and Water Table

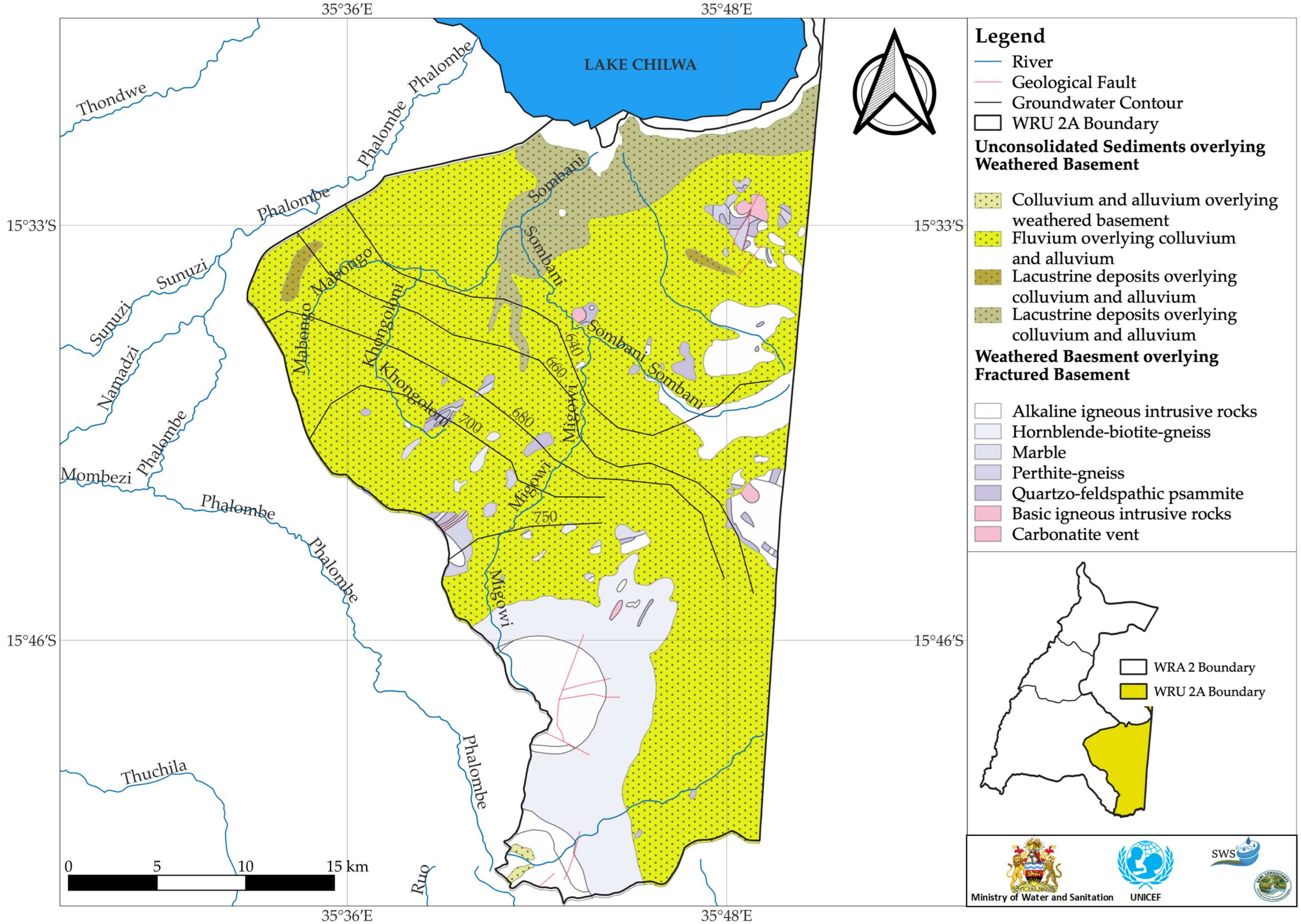


Figure WRU 2A.4 Groundwater Chemistry Distribution Electrical Conductivity

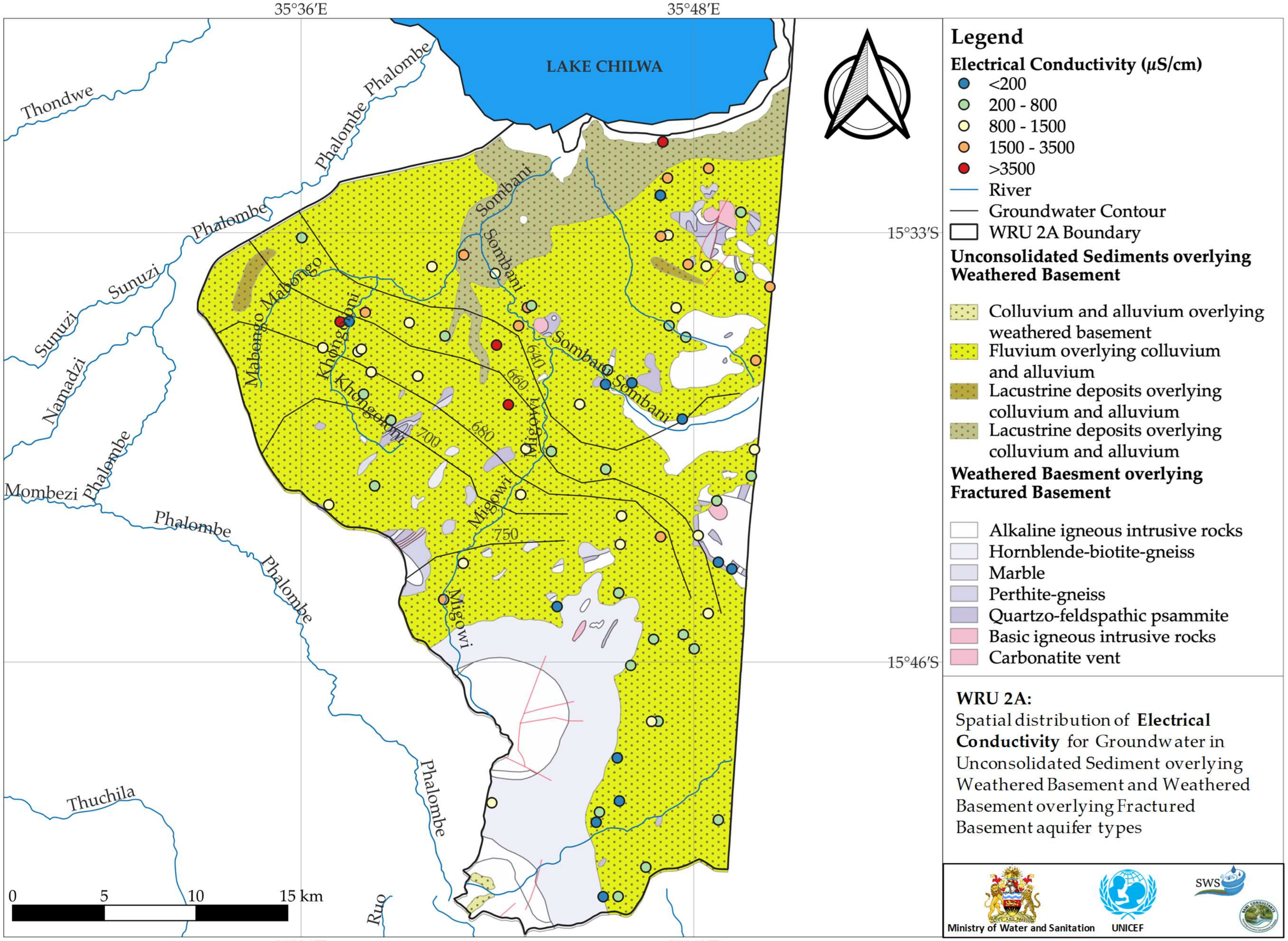


Figure WRU 2A.5 Groundwater Chemistry Distribution of Sulphate

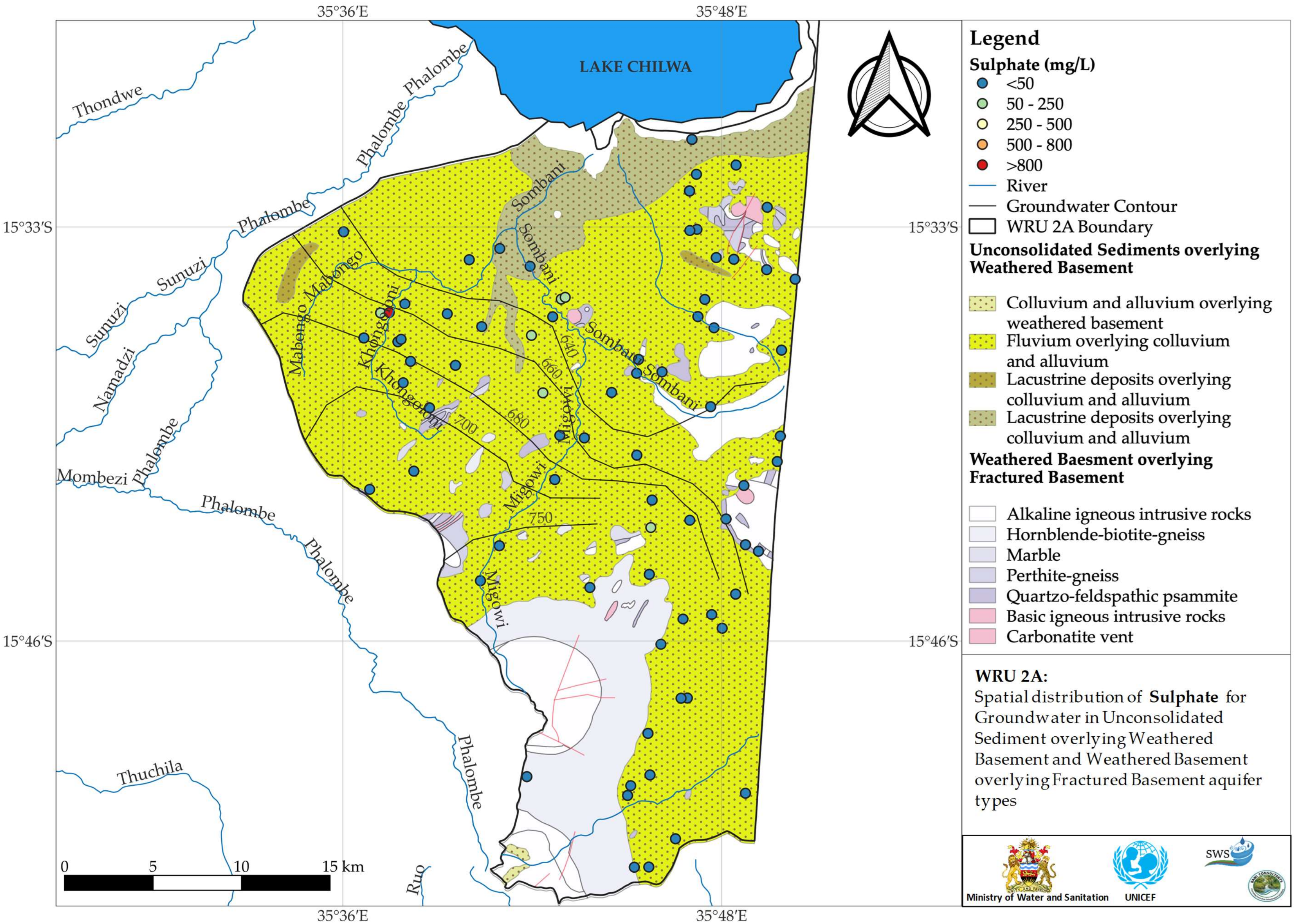


Figure WRU 2A.6 Groundwater Chemistry Distribution Chloride

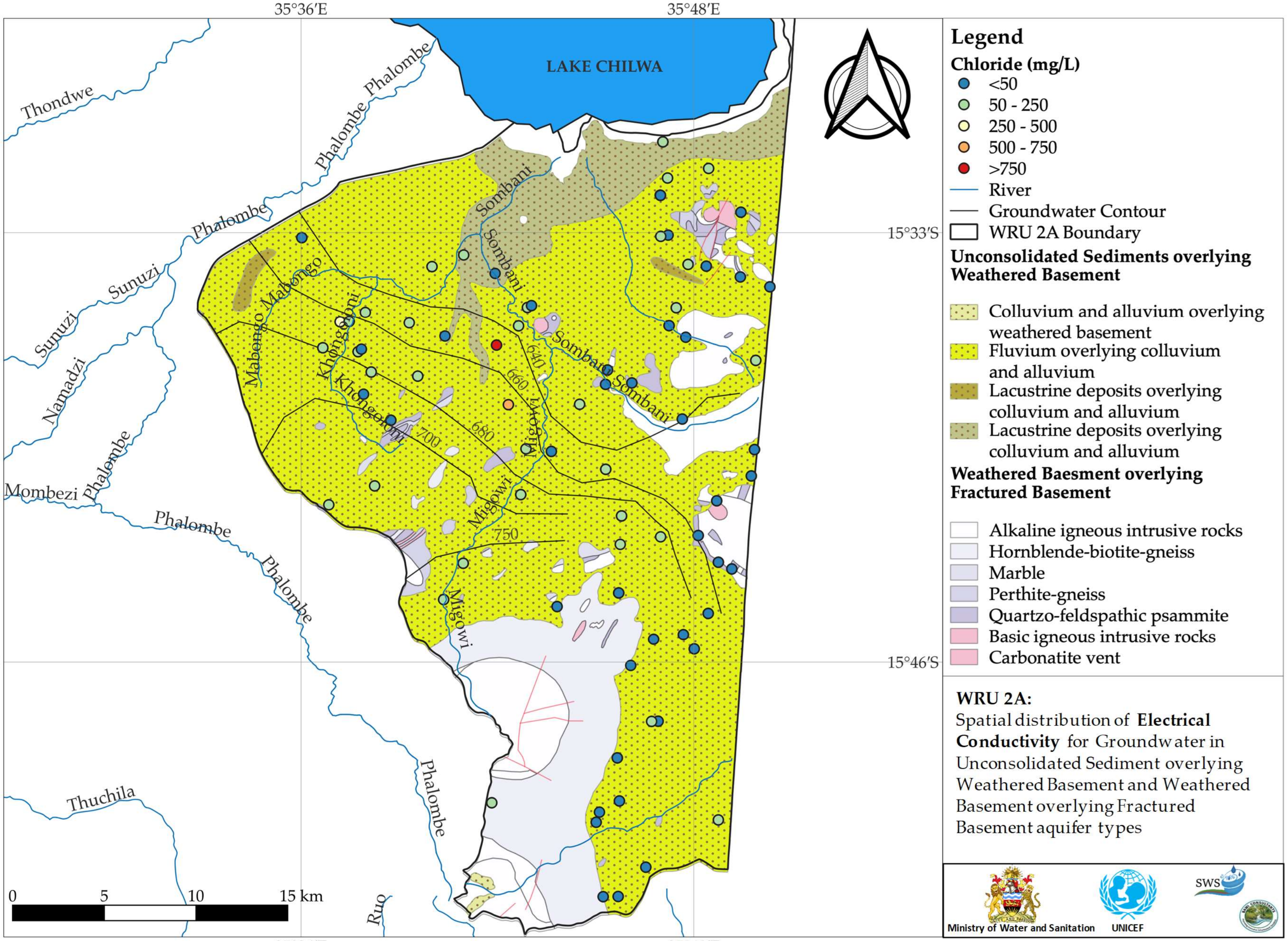


Figure WRU 2A.7 Groundwater Chemistry Distribution Sodium

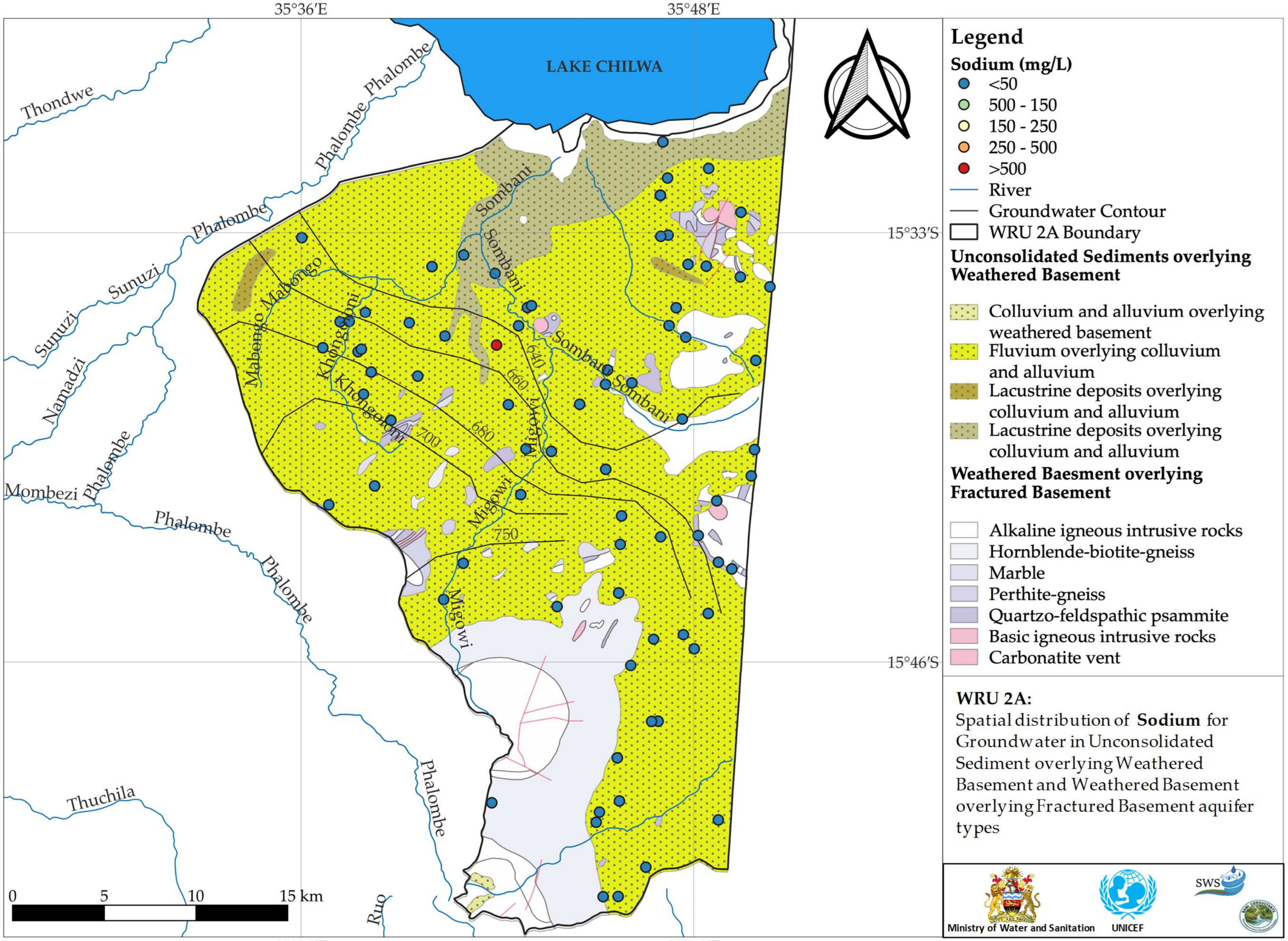


Figure WRU 2A.8 Groundwater Chemistry Distribution Calcium

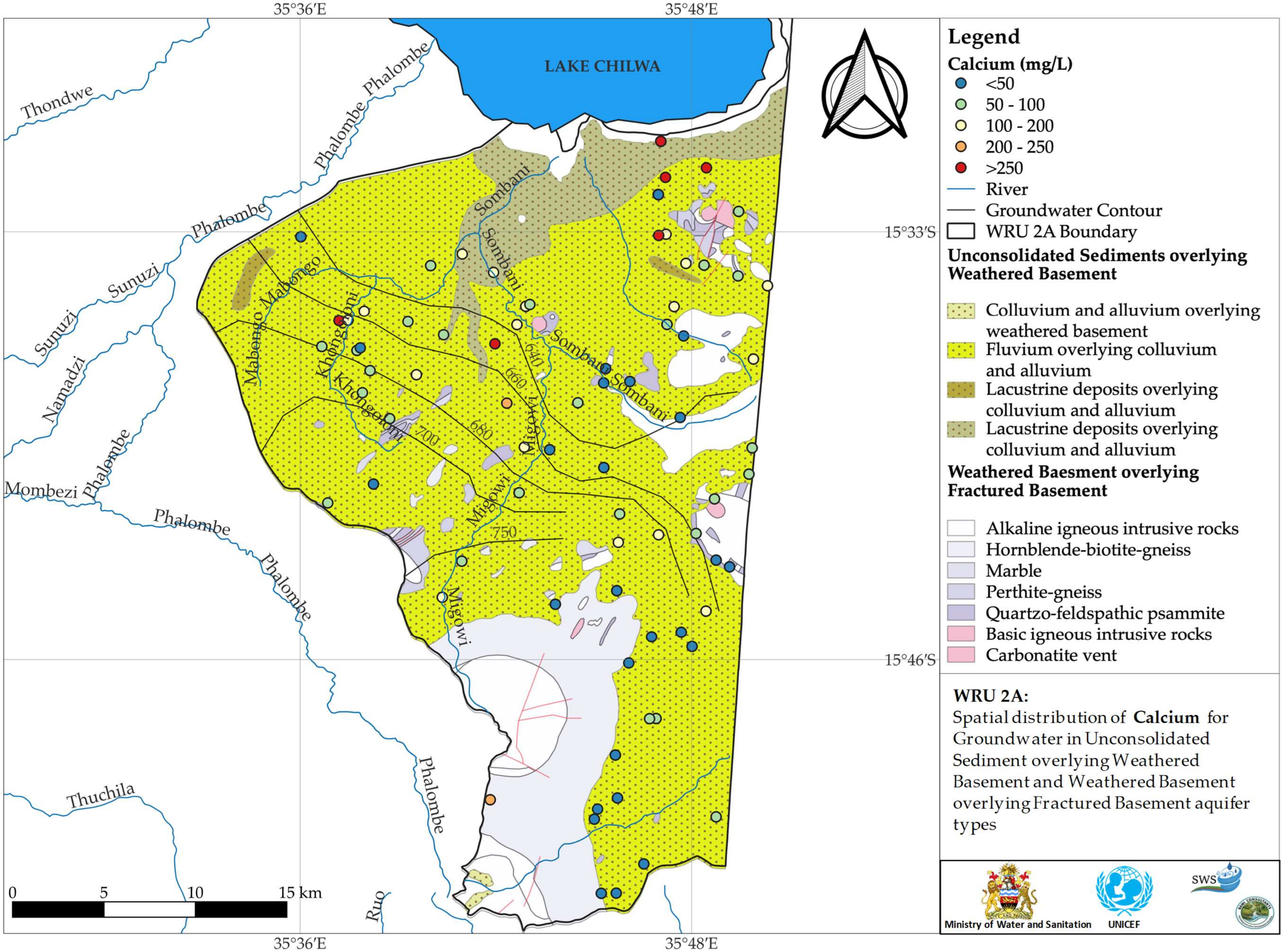


Figure WRU 2A.9 Piper Diagram of water quality results with respect to the major aquifer type

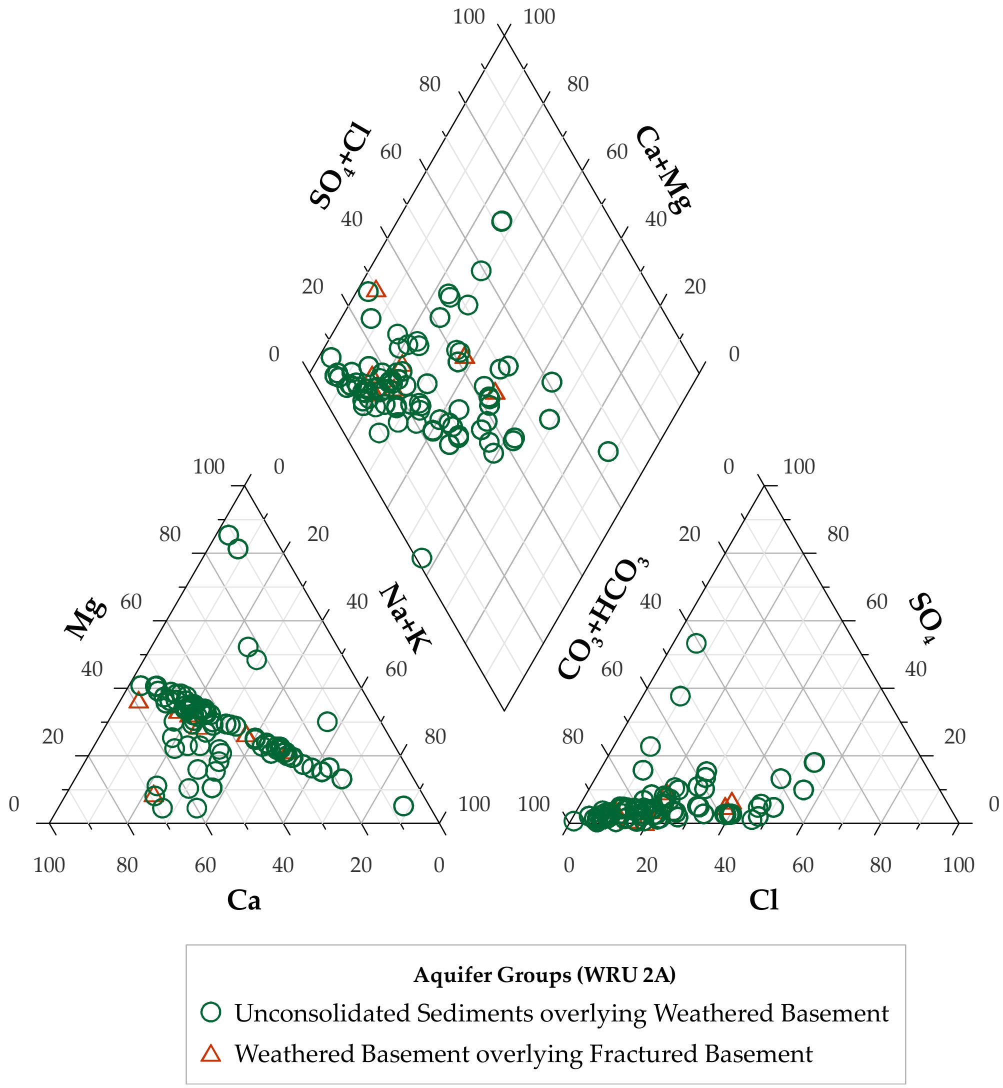
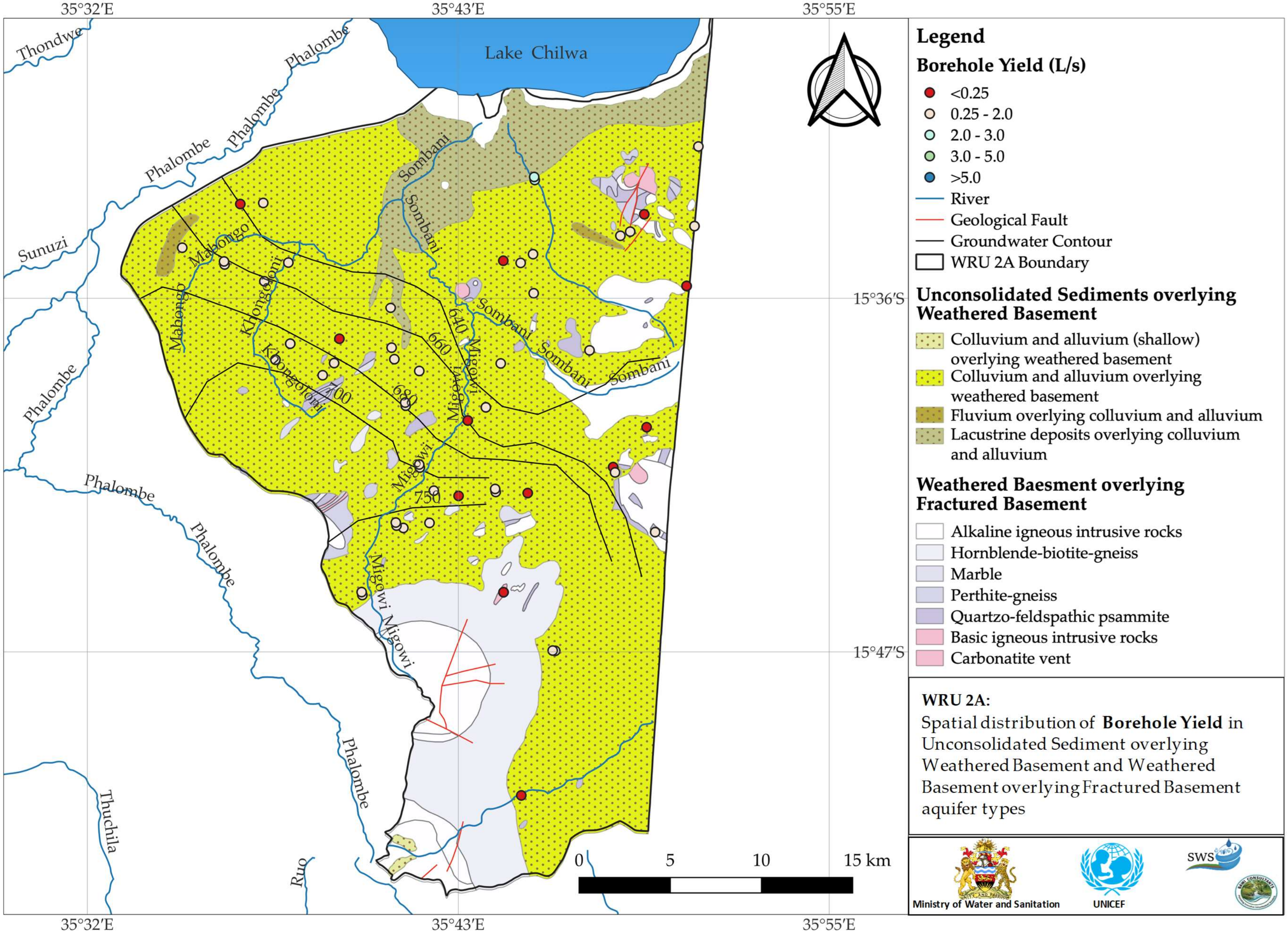


Figure WRU 2A.10 Borehole Yield Map for data held by the Ministry



WRU 2B Figures

Figure WRU 2B.2 Rivers and Wetlands

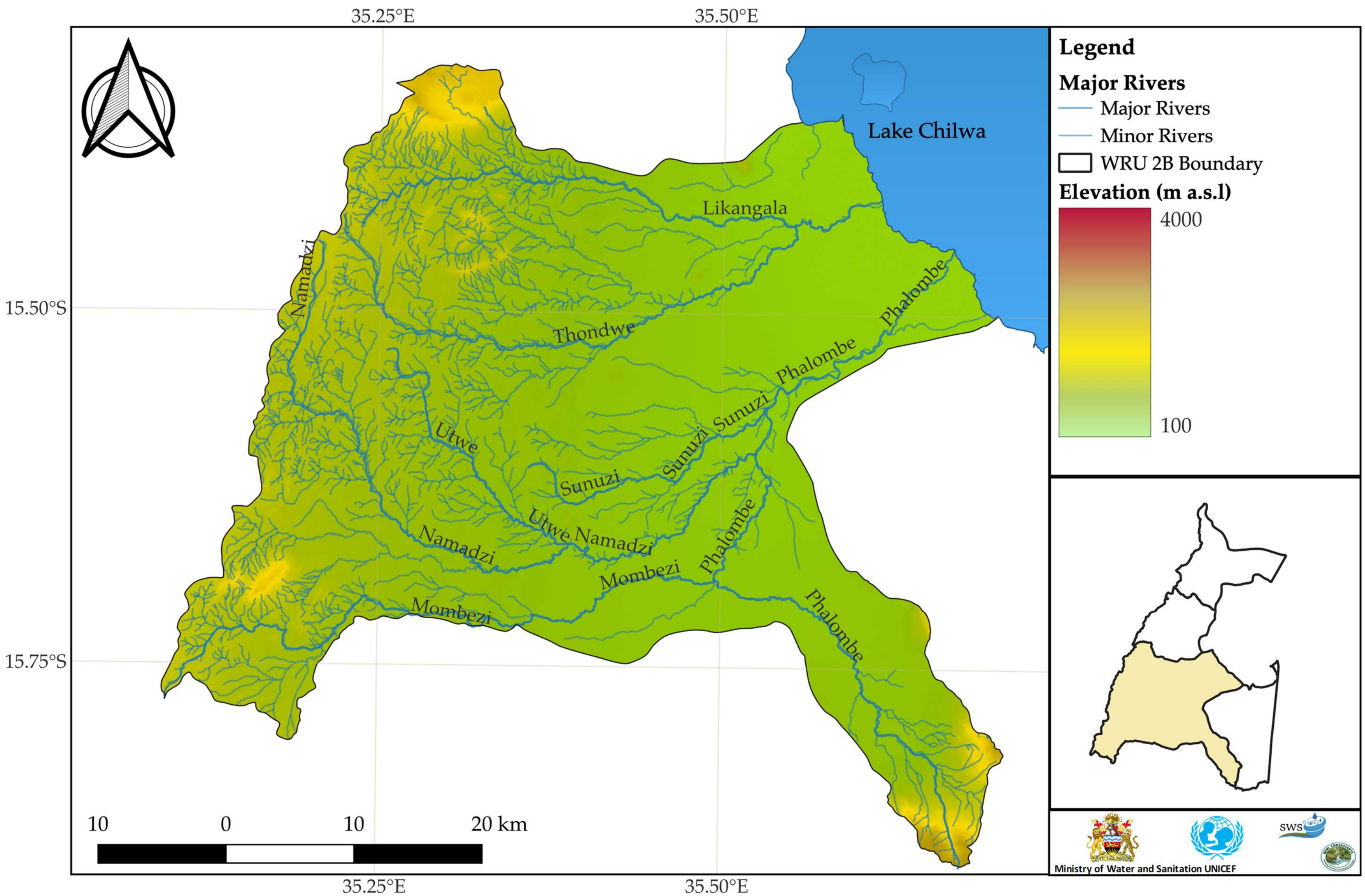
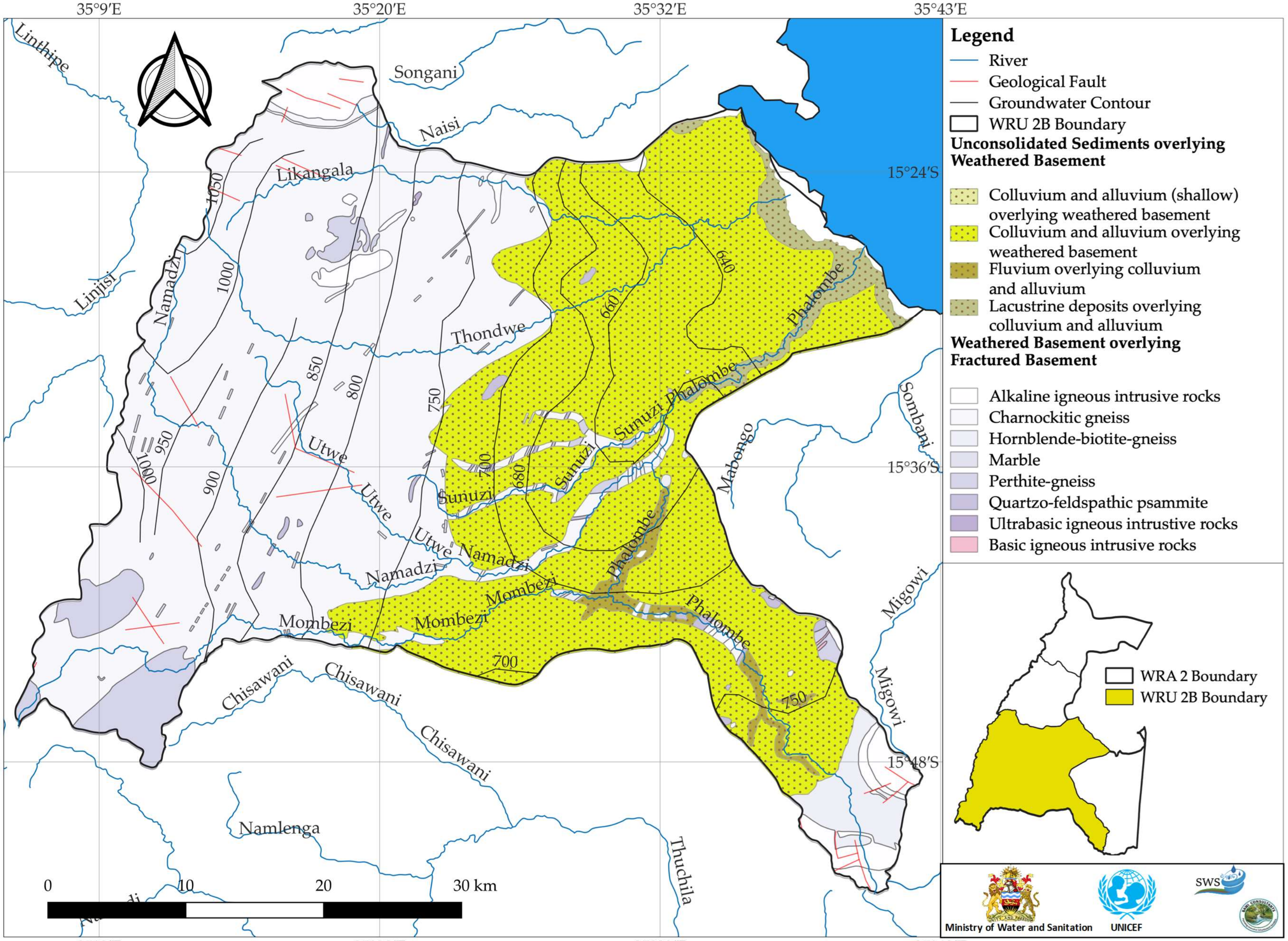


Figure WRU 2B.3 Hydrogeology Units and Water Table



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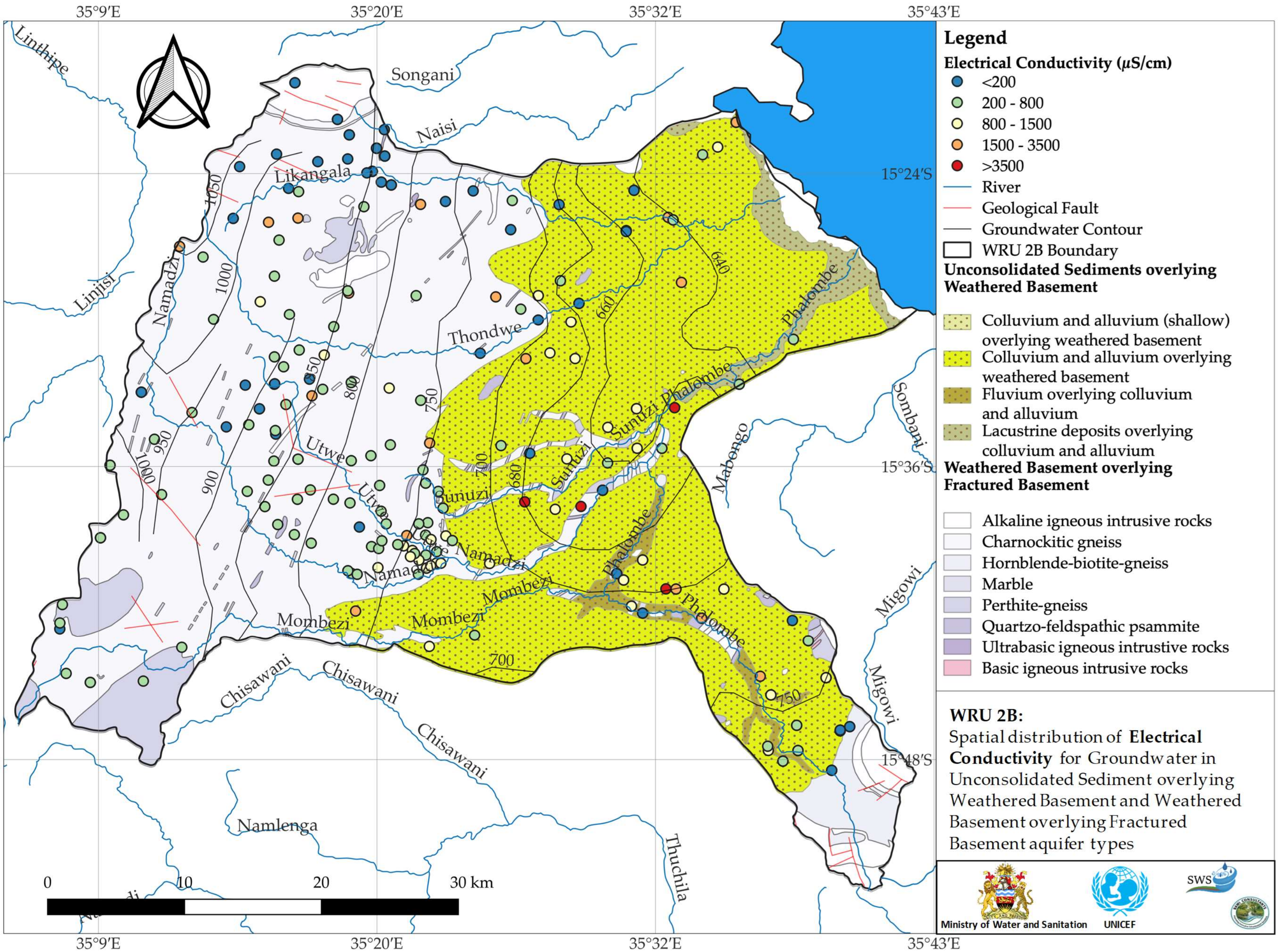

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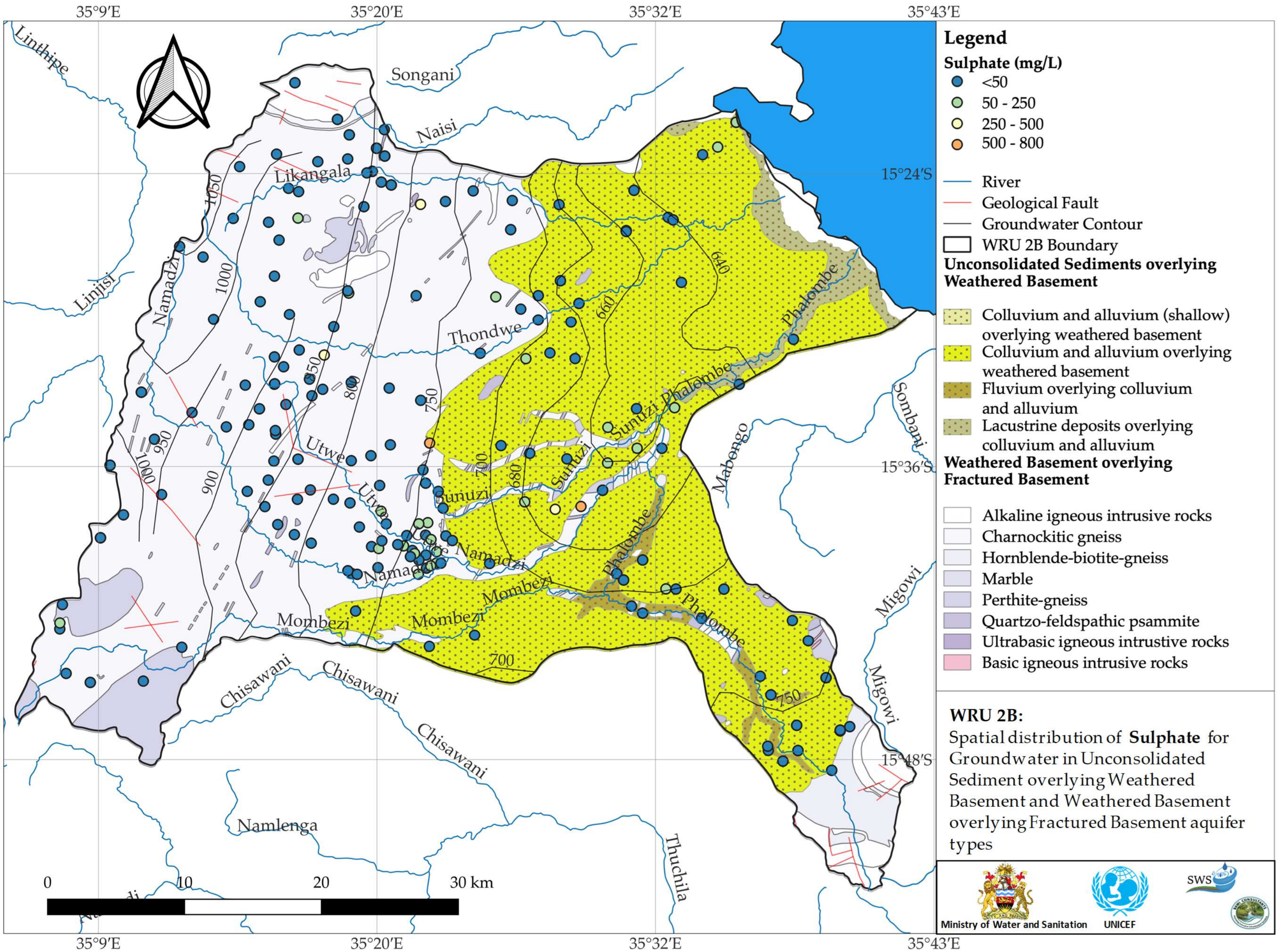

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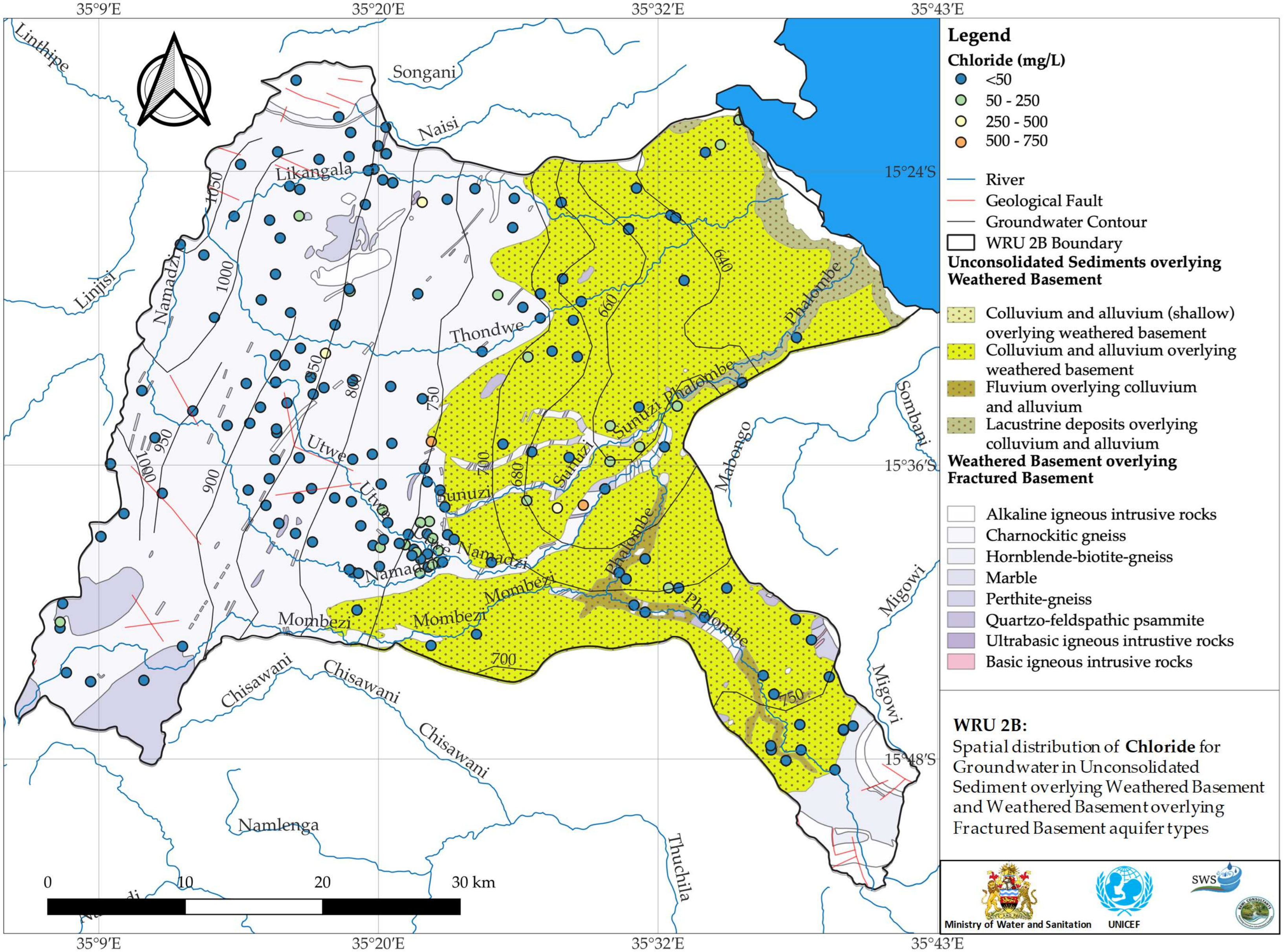

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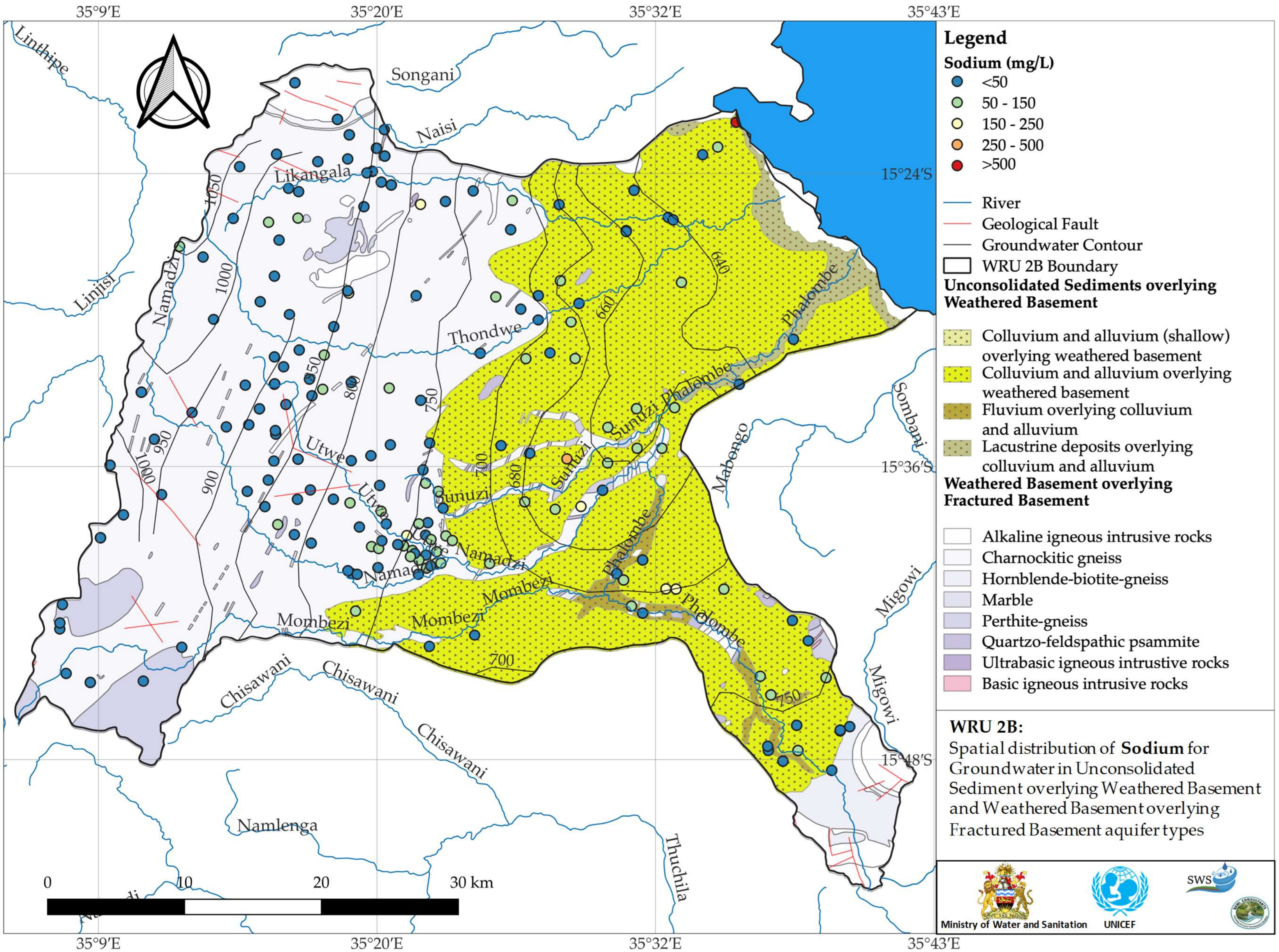

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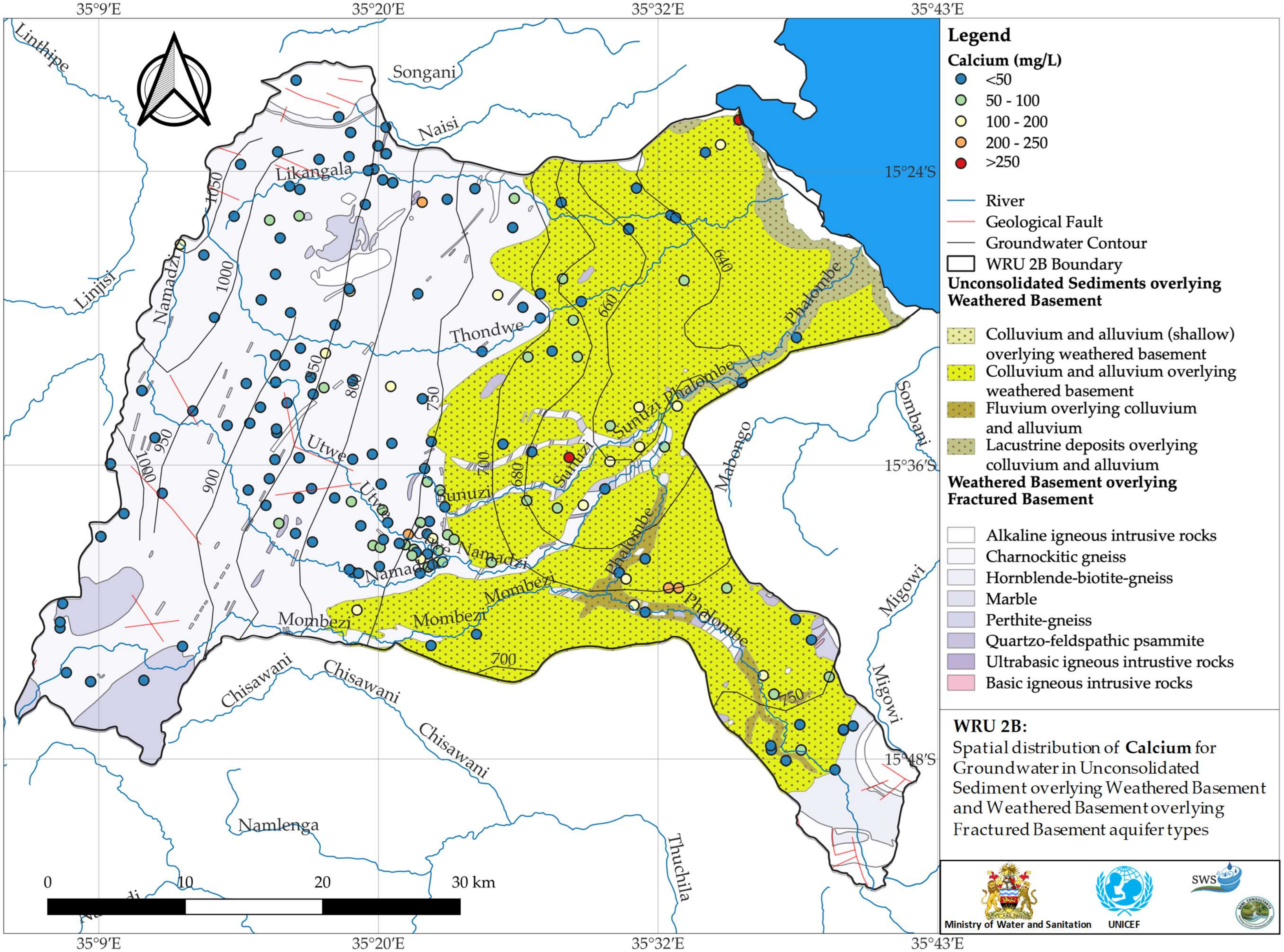


Figure WRU 2B.9 Piper Diagram of water quality results with respect to the major aquifer type

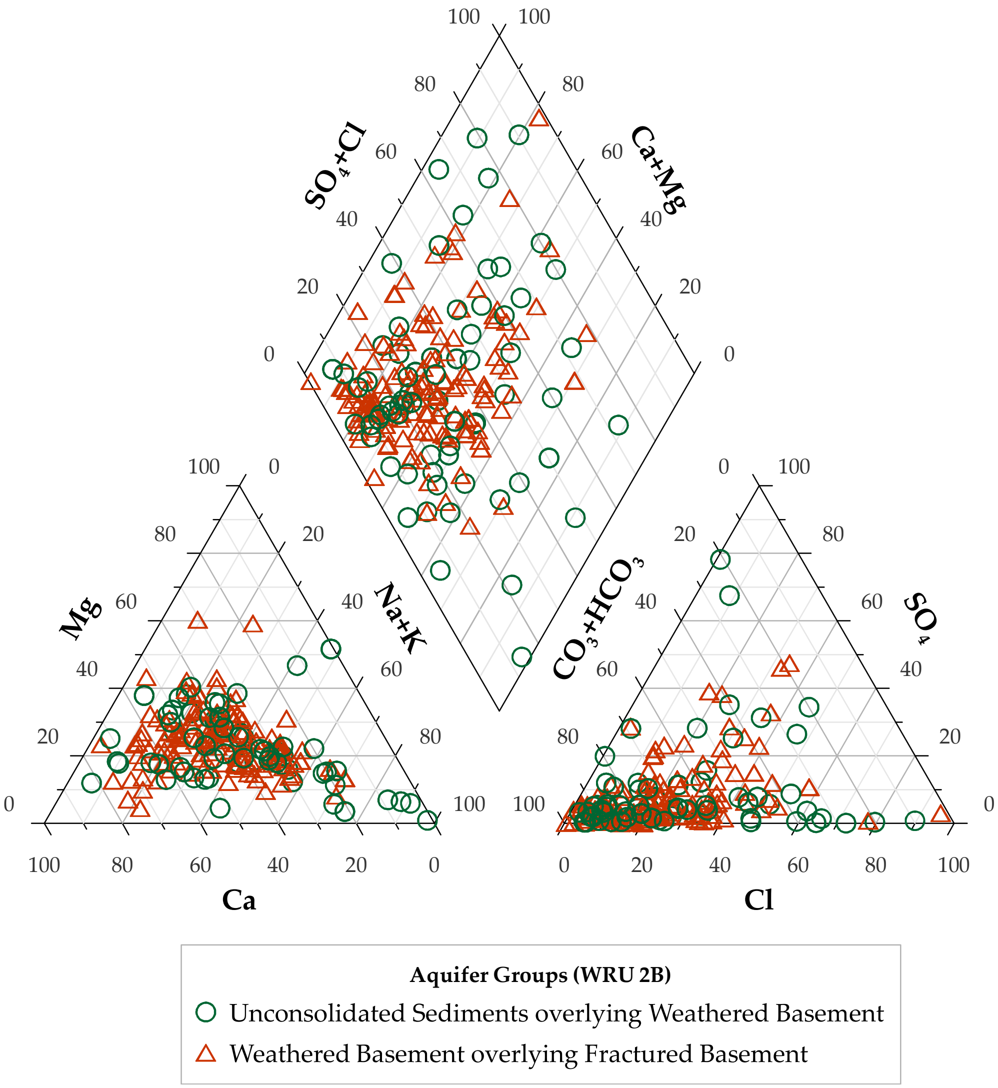
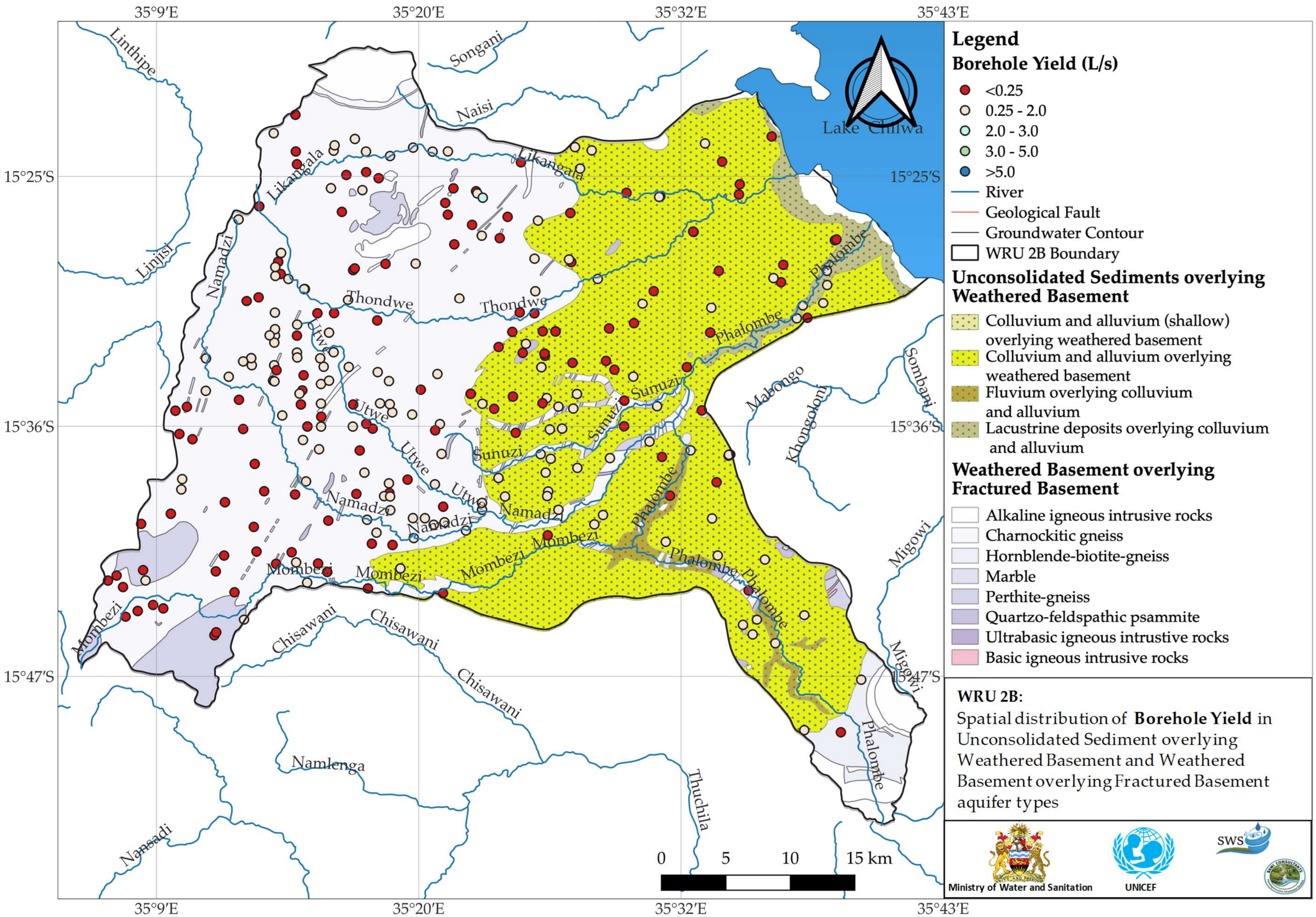


Figure WRU 2B.10 Borehole Yield Map for data held by the Ministry



WRU 2C Figures

Figure WRU 2C.1 Land Use and Major Roads

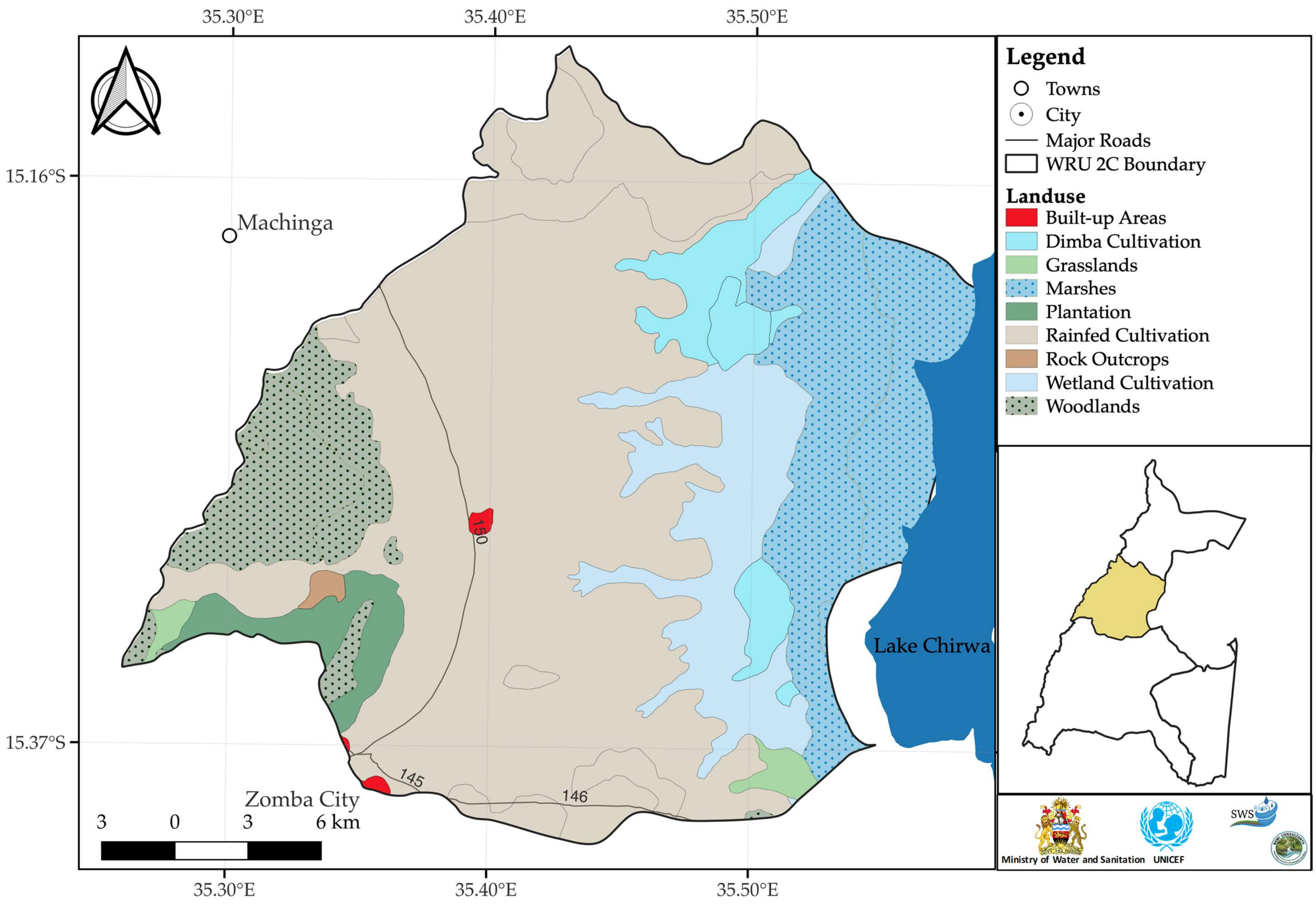


Figure WRU 2C.2 Rivers and Wetlands

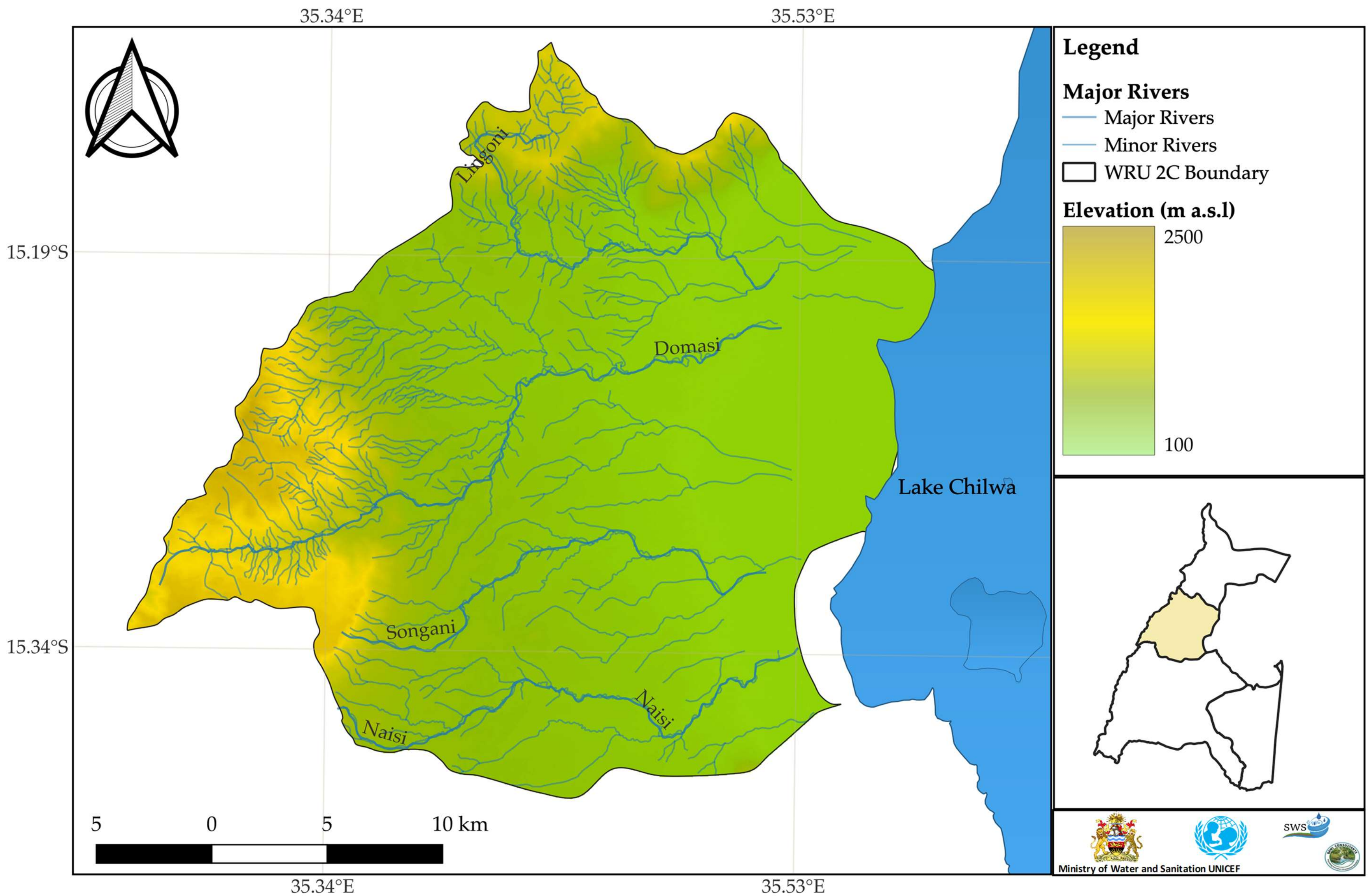
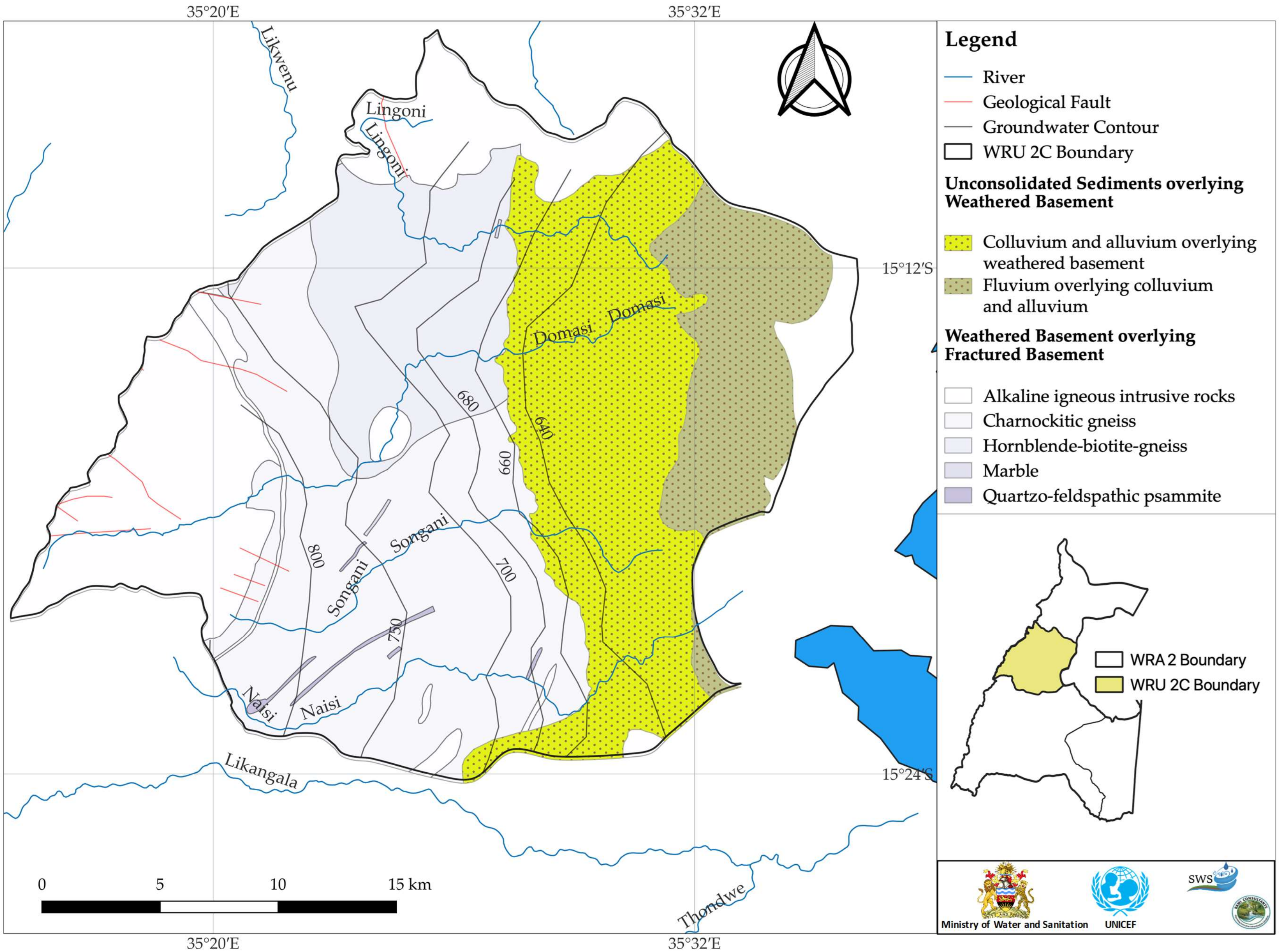


Figure WRU 2C.3 Hydrogeology Units and Water Table



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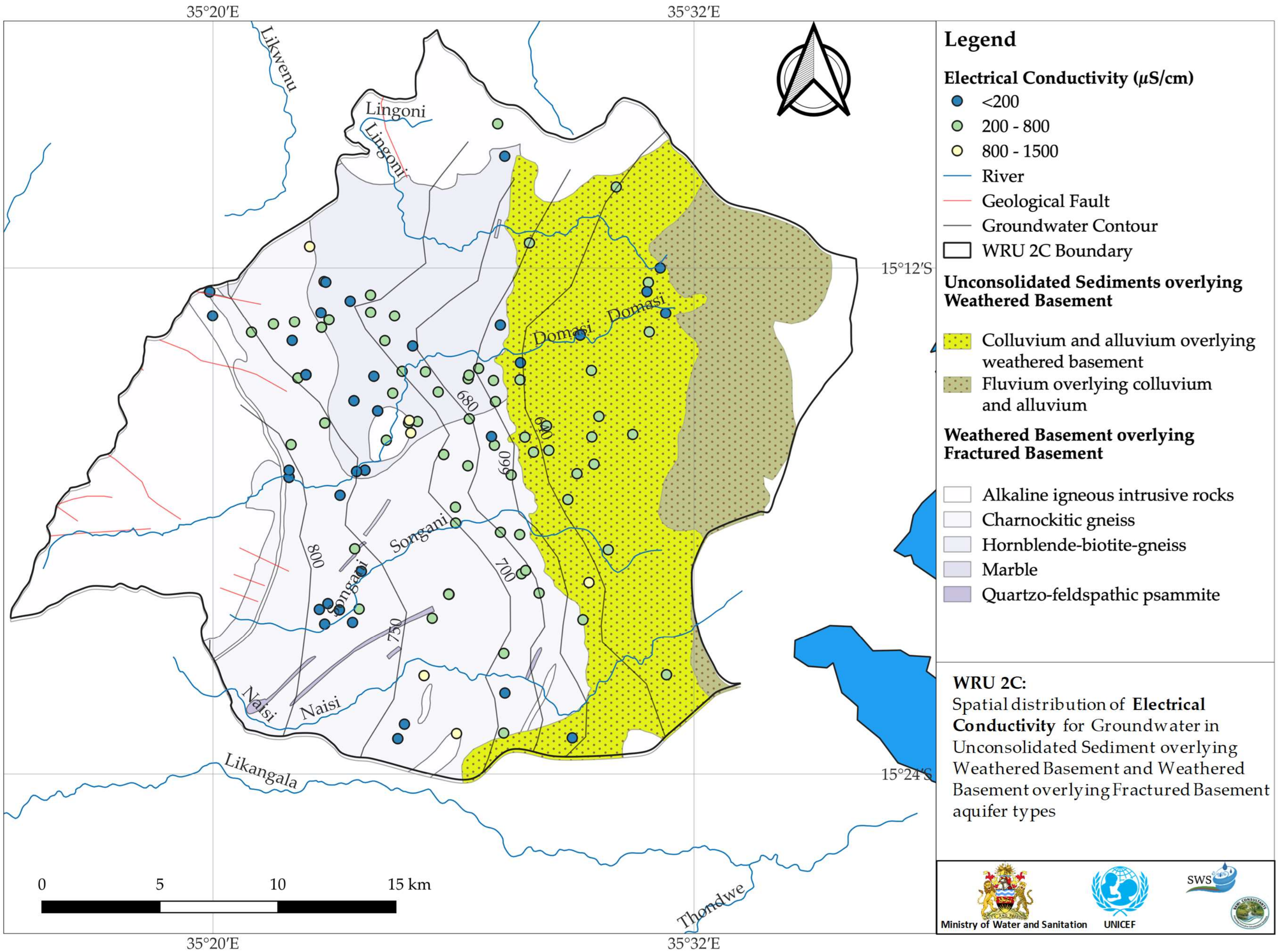


Figure WRU 2C.5 Groundwater Chemistry Distribution of Sulphate

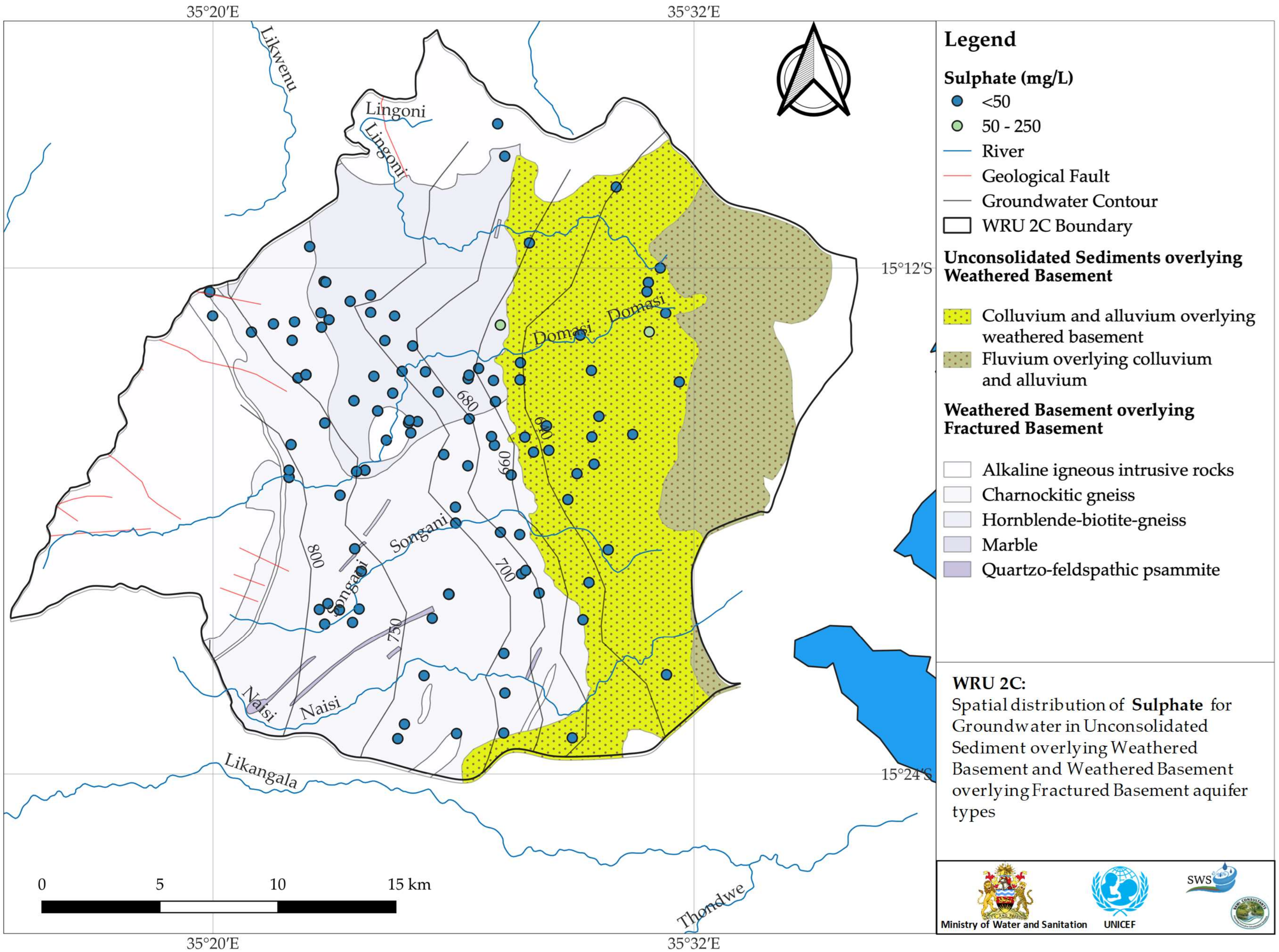


Figure WRU 2C.6 Groundwater Chemistry Distribution Chloride

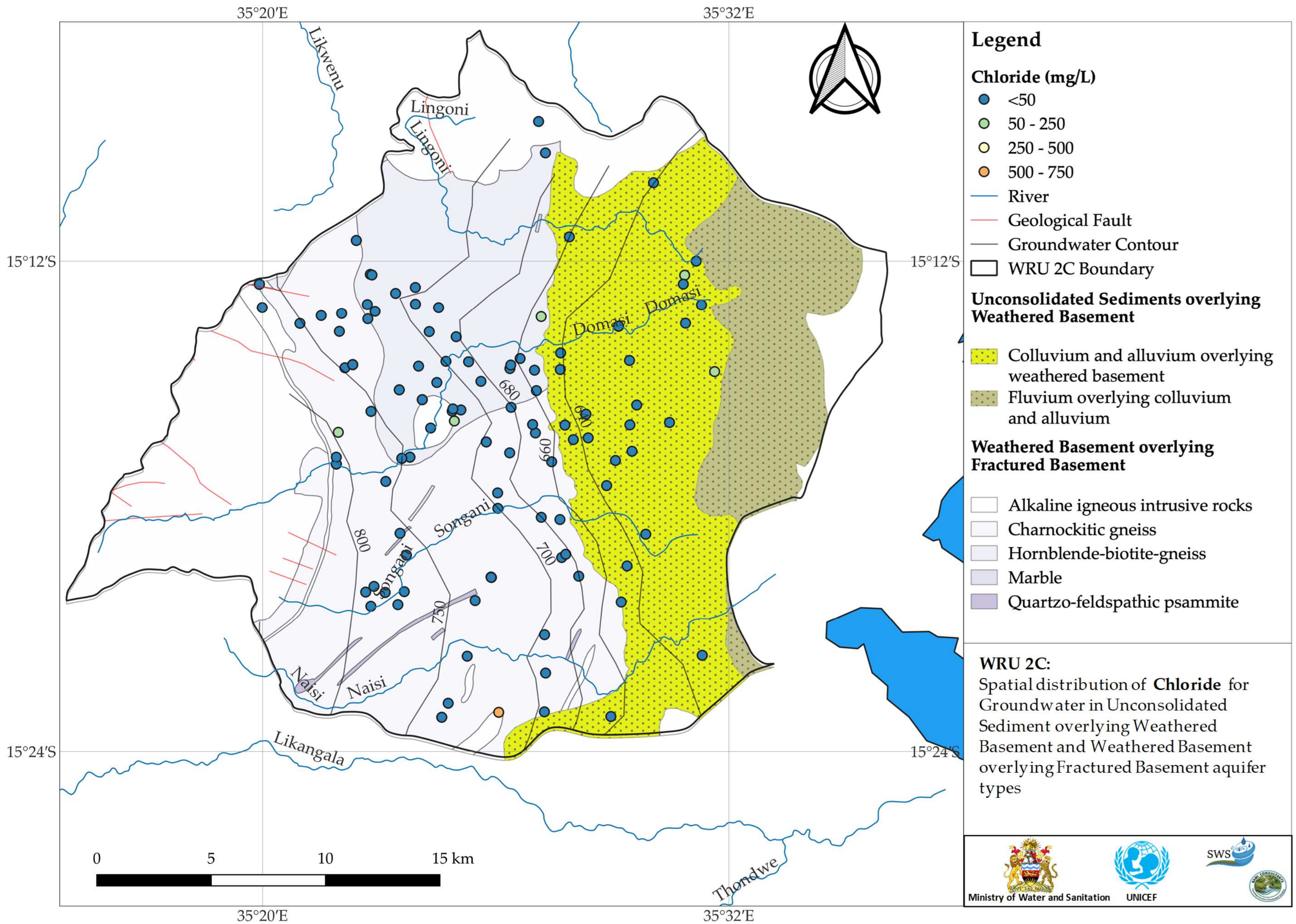


Figure WRU 2C.7 Groundwater Chemistry Distribution Sodium

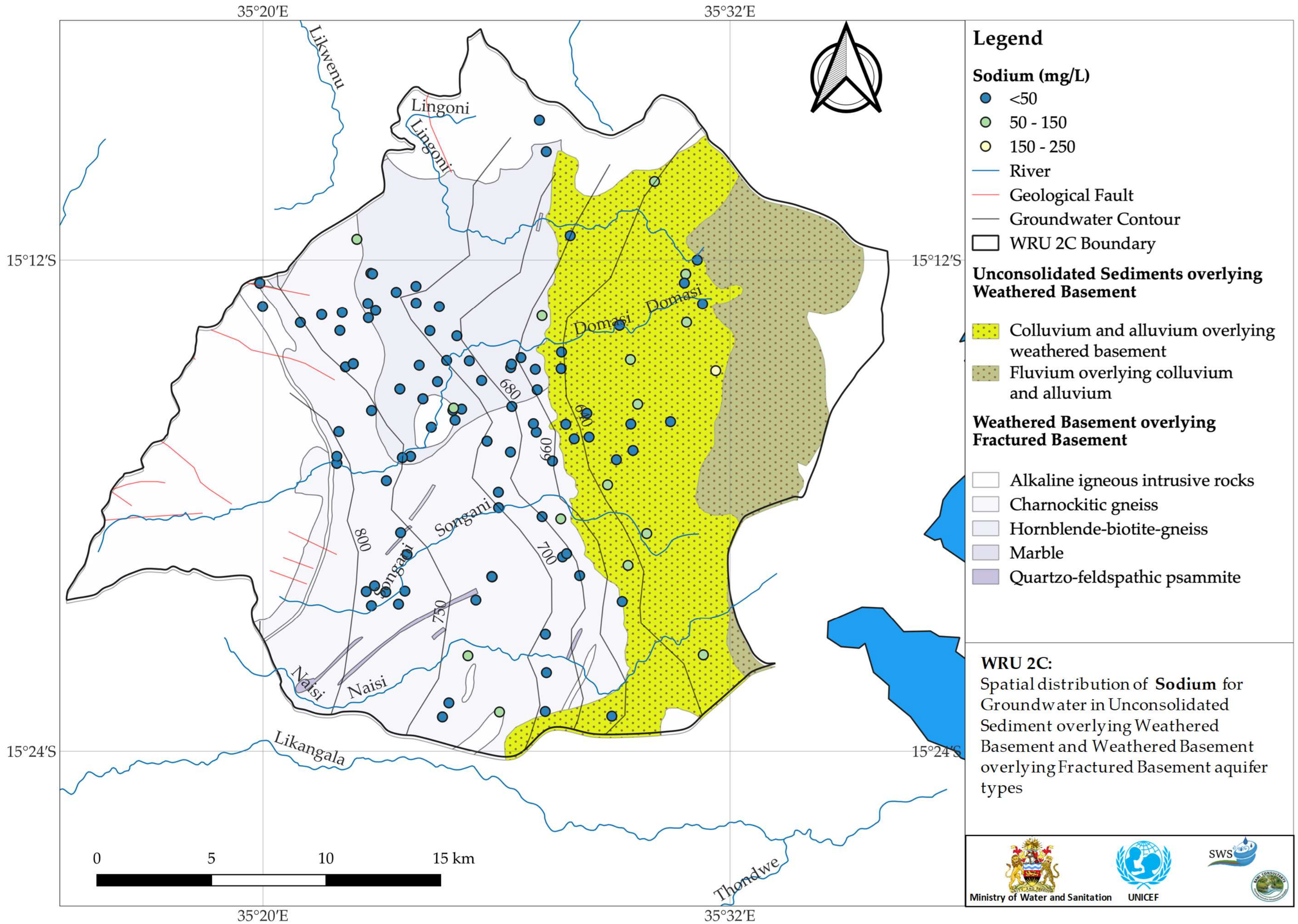


Figure WRU 2C.8 Groundwater Chemistry Distribution Calcium

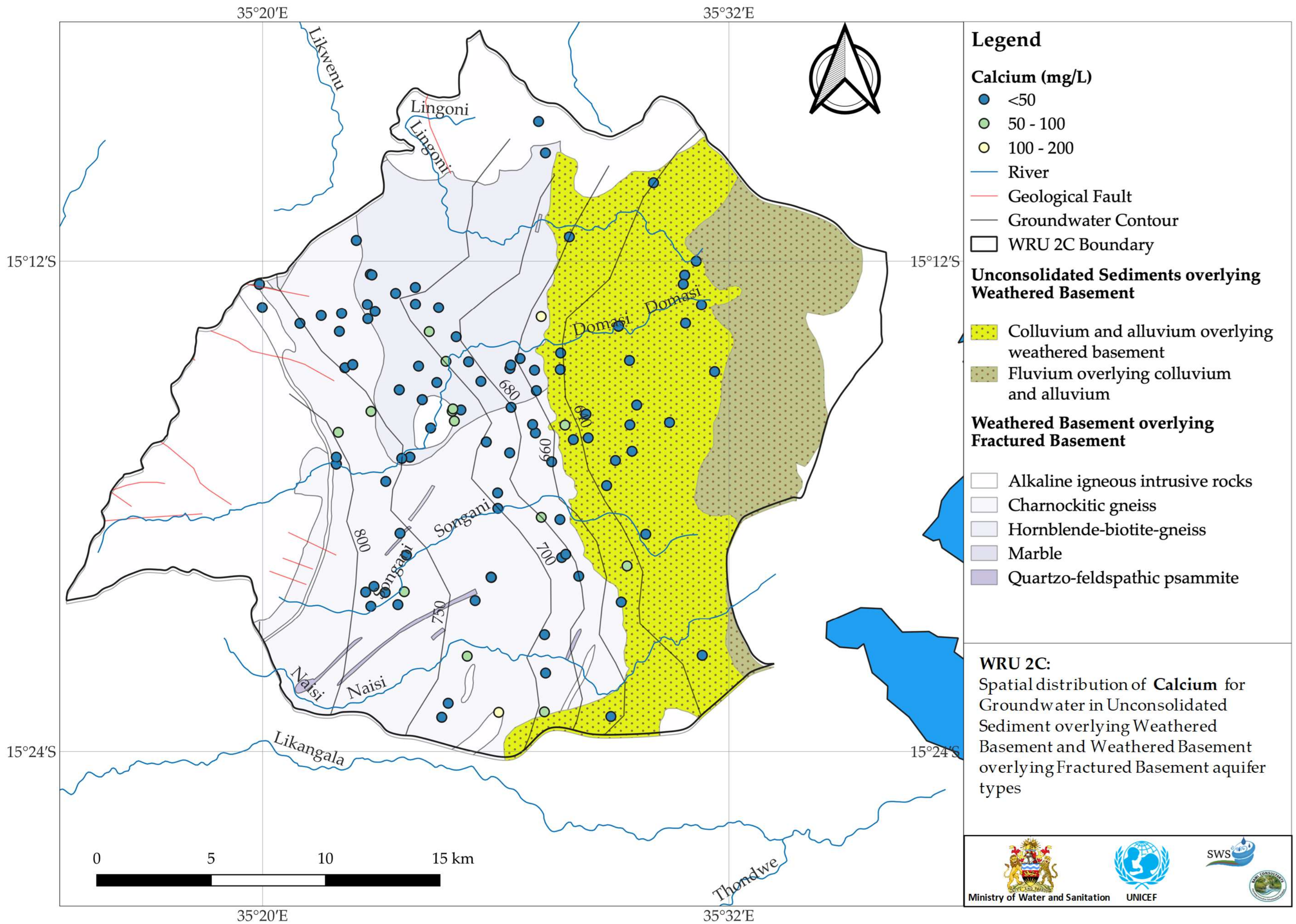


Figure WRU 2C.9 Piper Diagram of water quality results with respect to the major aquifer type

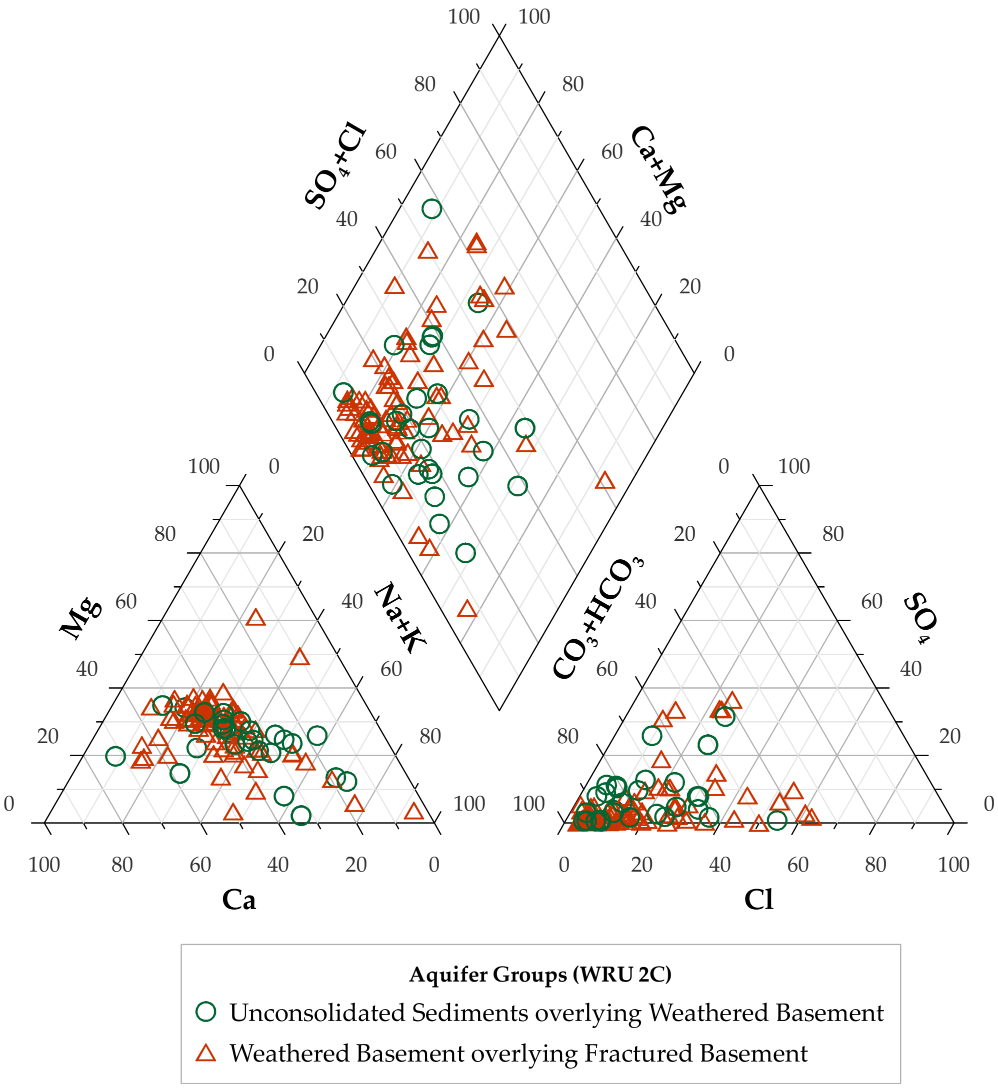
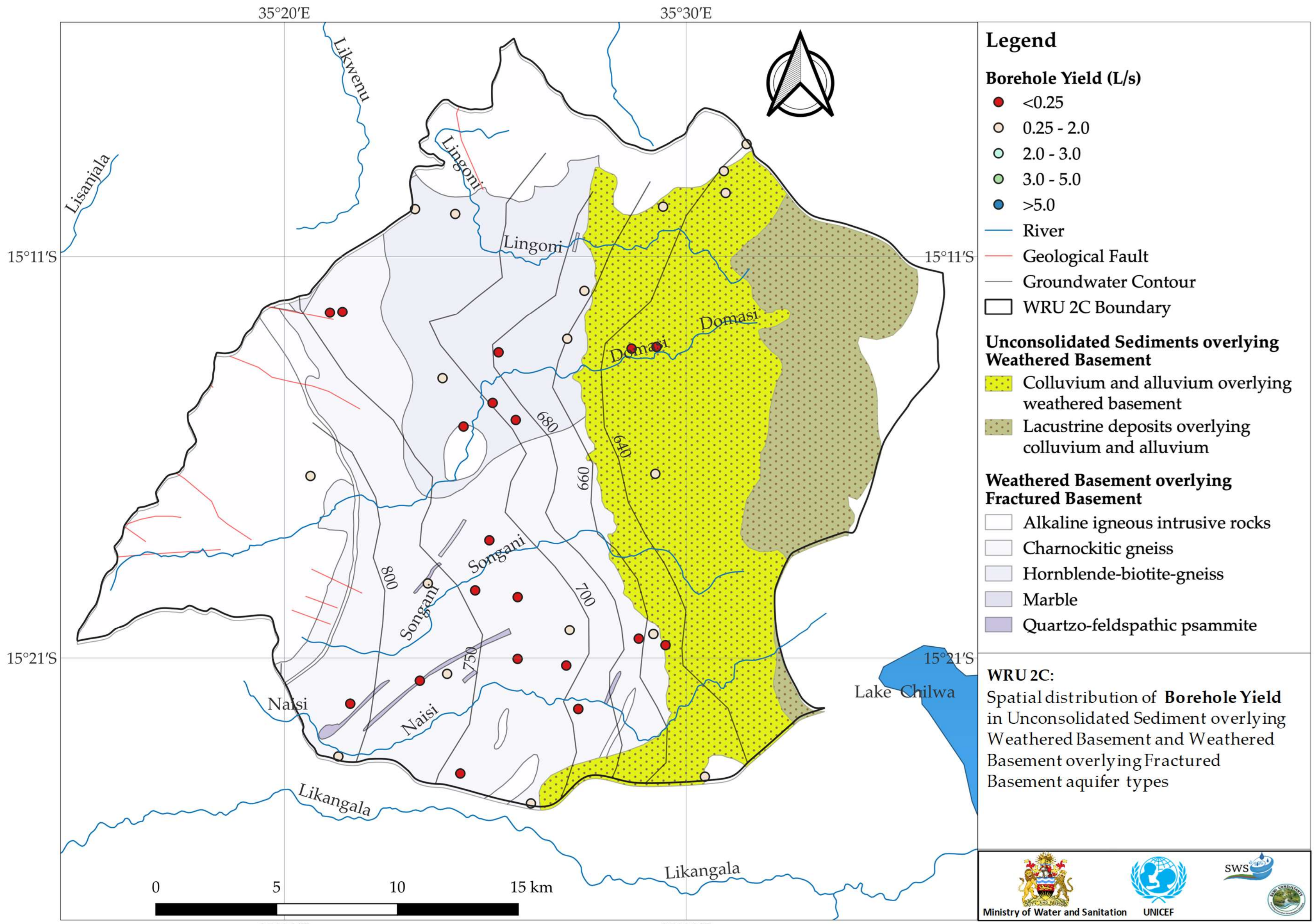


Figure WRU 2C.10 Borehole Yield Map for data held by the Ministry



WRU 2D Figures

Figure WRU 2D.1 Land Use and Major Roads

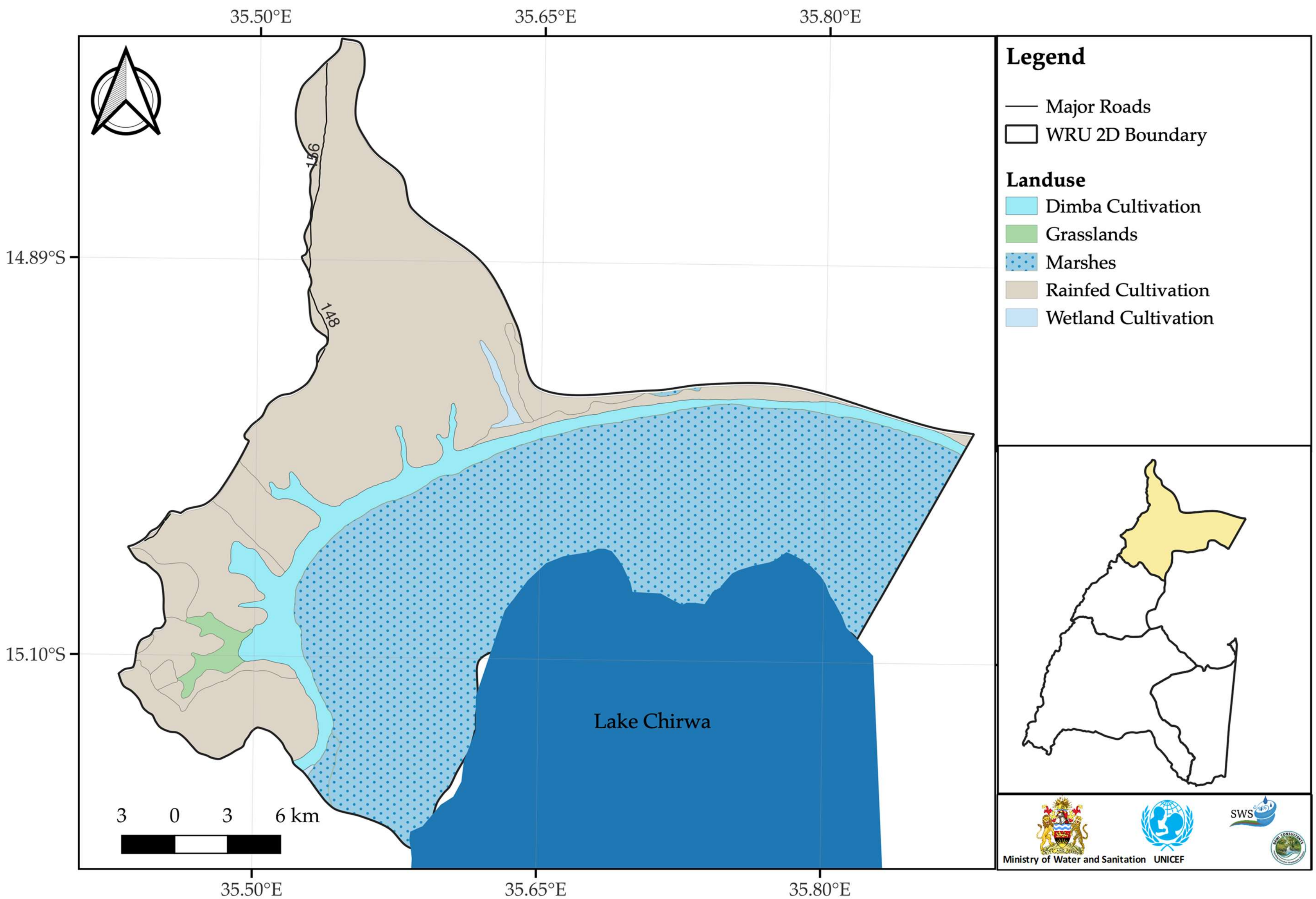


Figure WRU 2D.2 Rivers and Wetlands

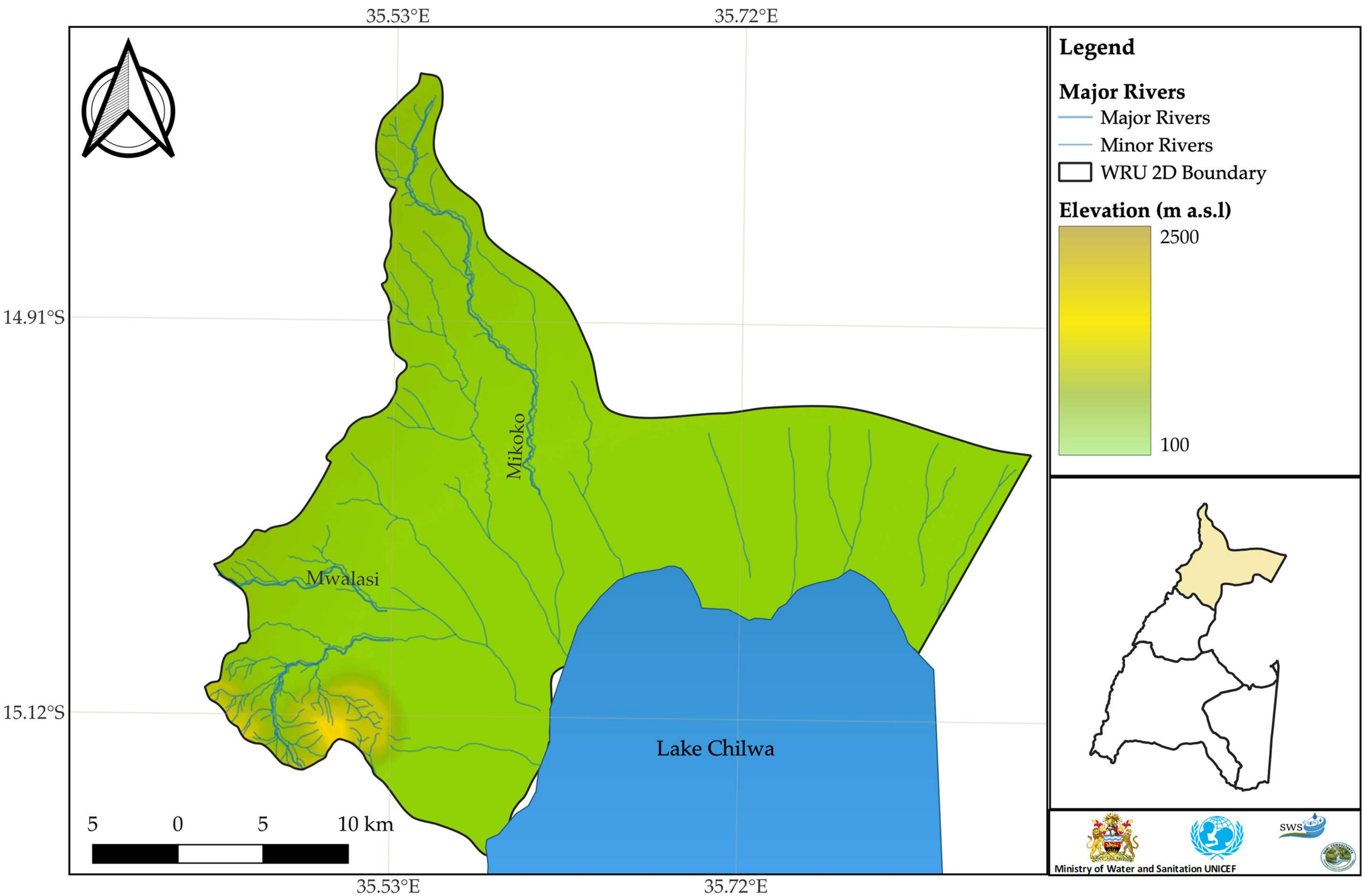


Figure WRU 2D.3 Hydrogeology Units and Water Table

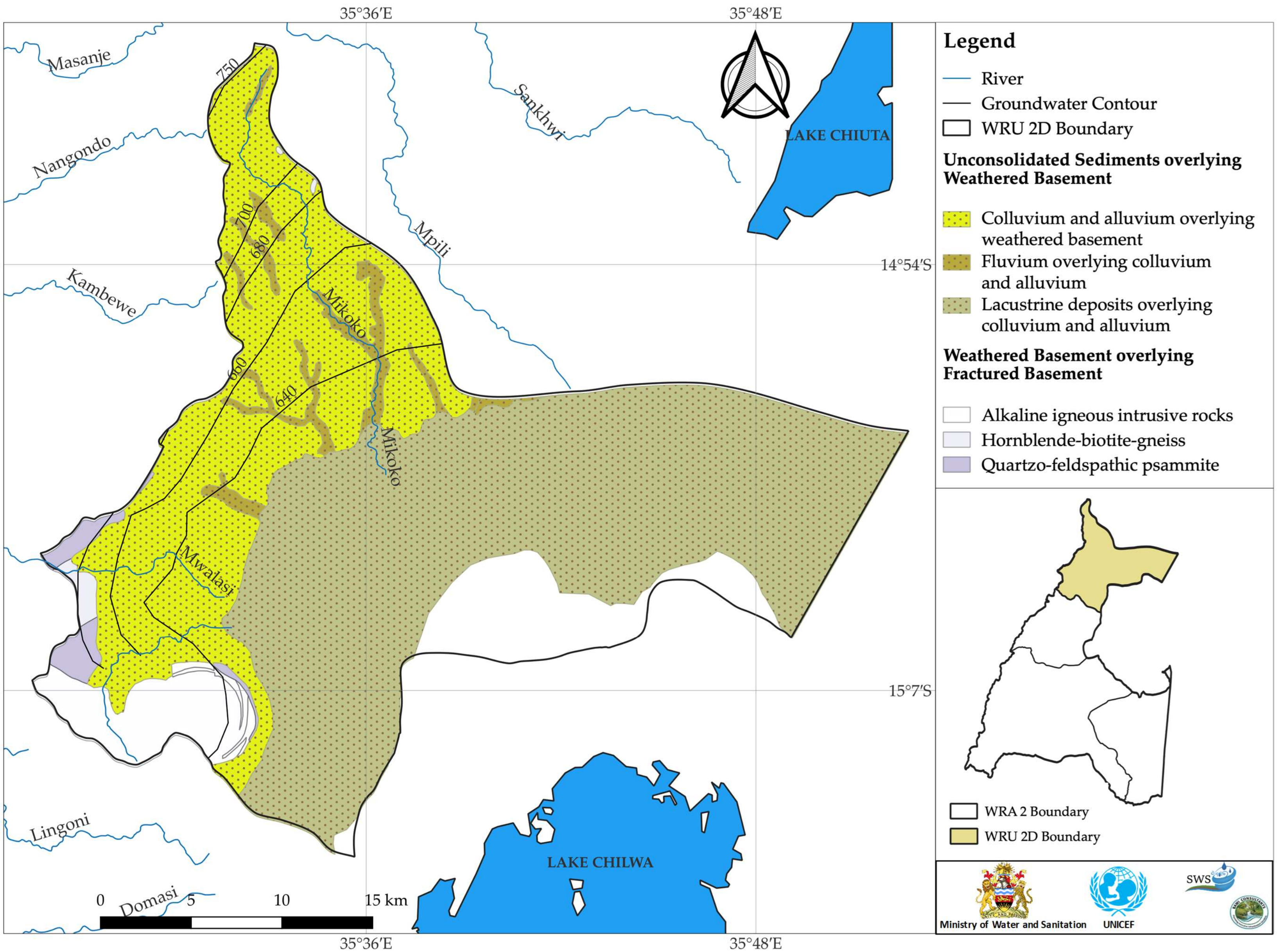
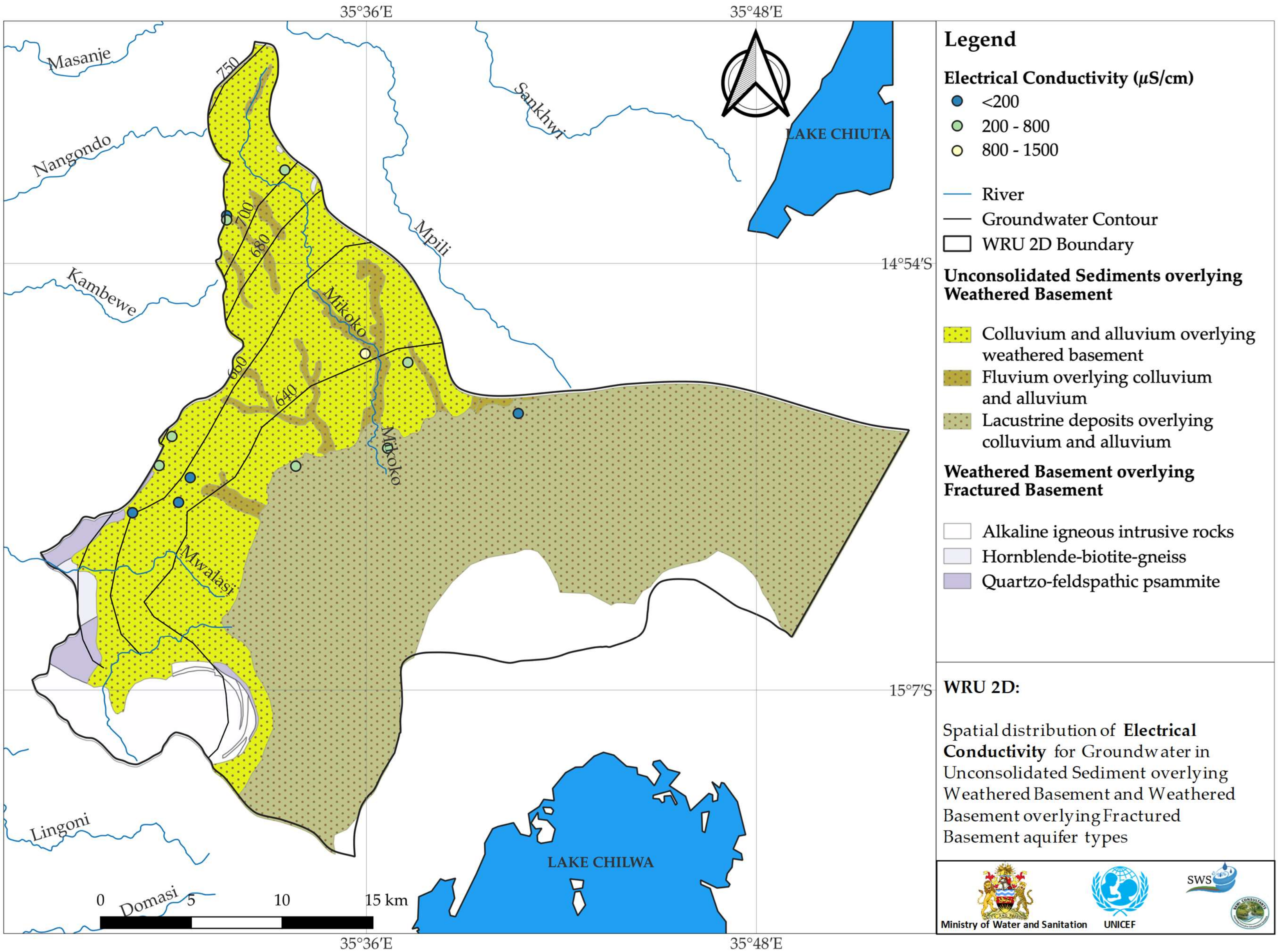


Figure WRU 2D.4 Groundwater Chemistry Distribution Electrical Conductivity



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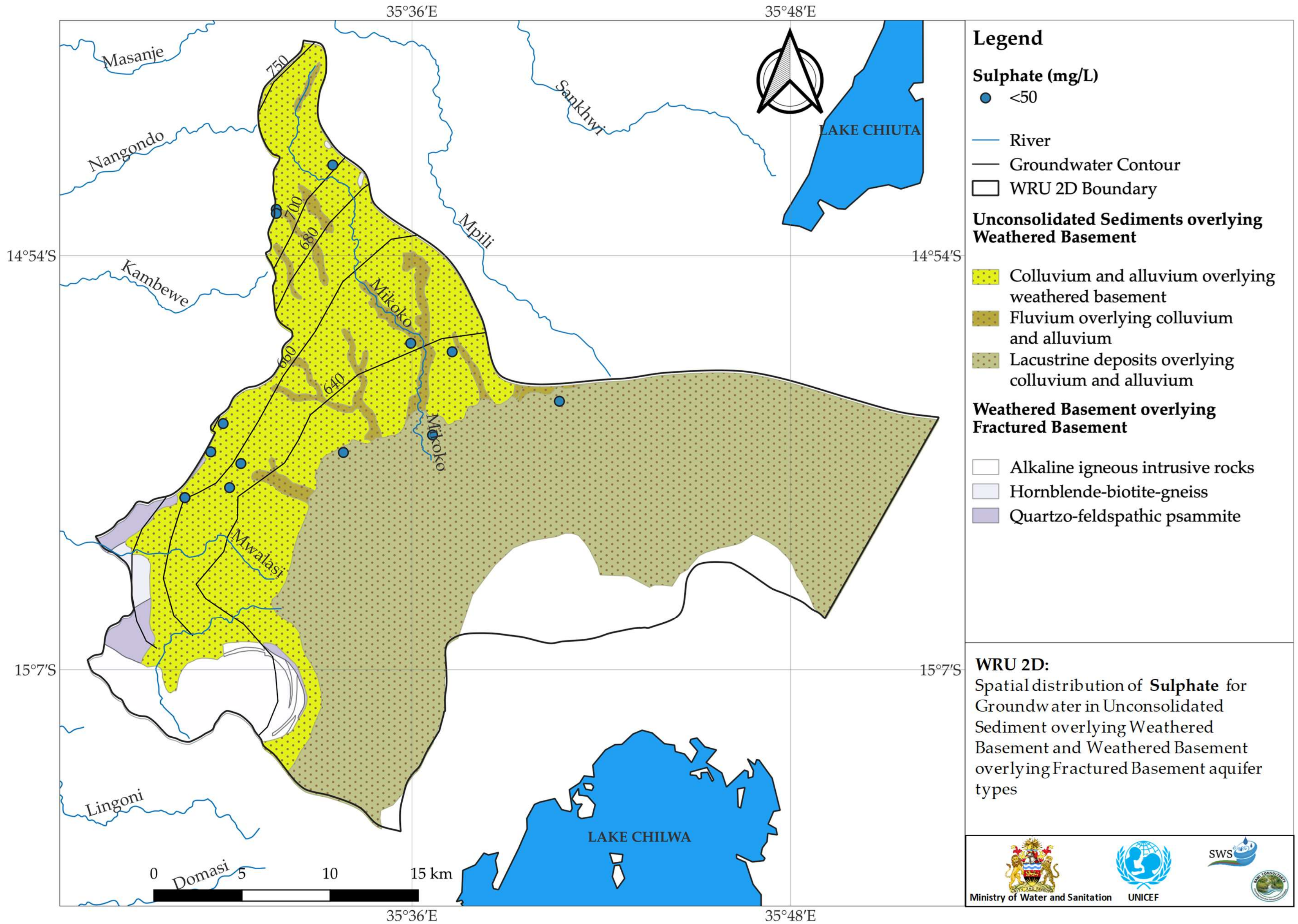


Figure WRU 2D.6 Groundwater Chemistry Distribution Chloride

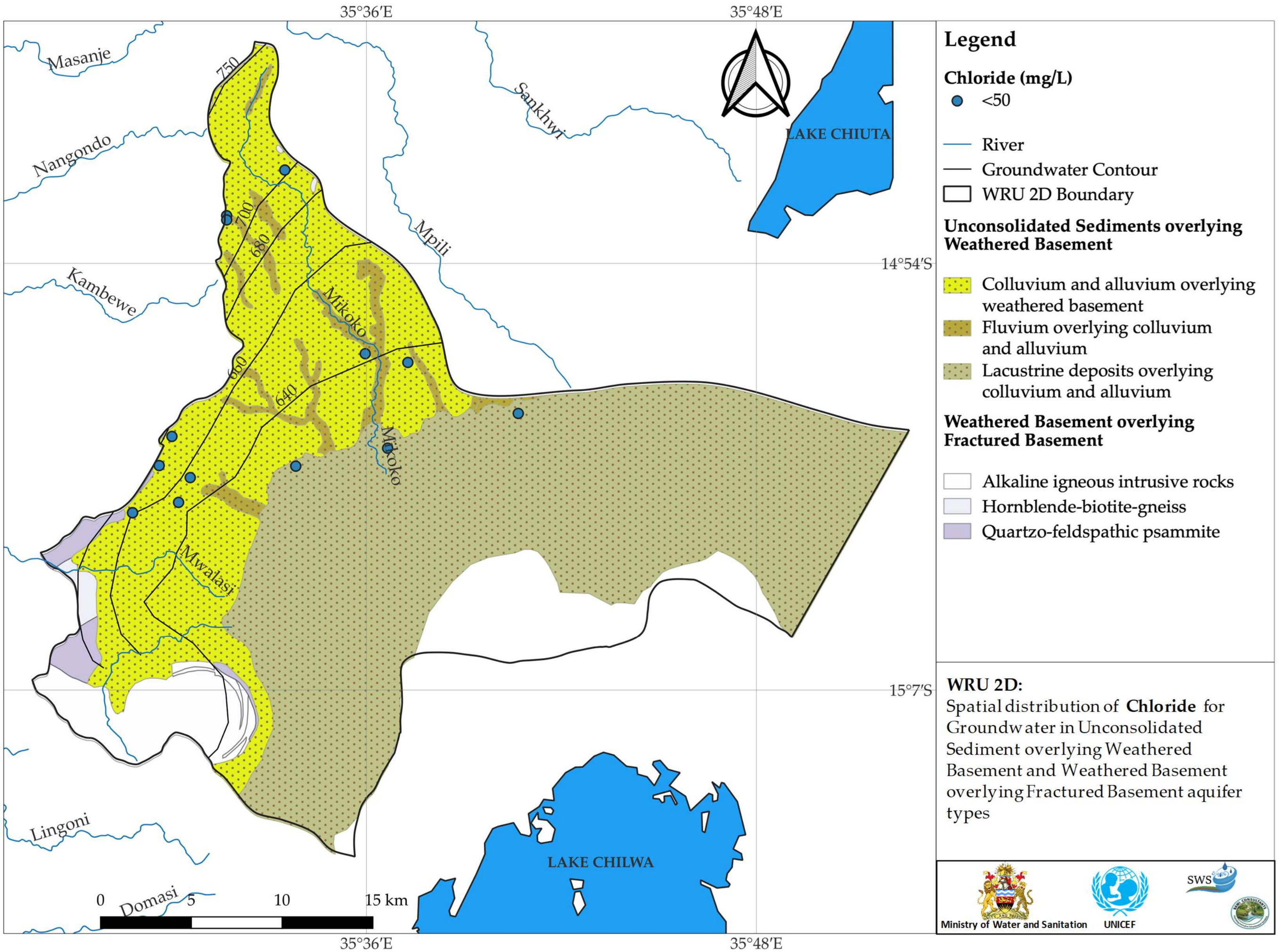


Figure WRU 2D.7 Groundwater Chemistry Distribution Sodium

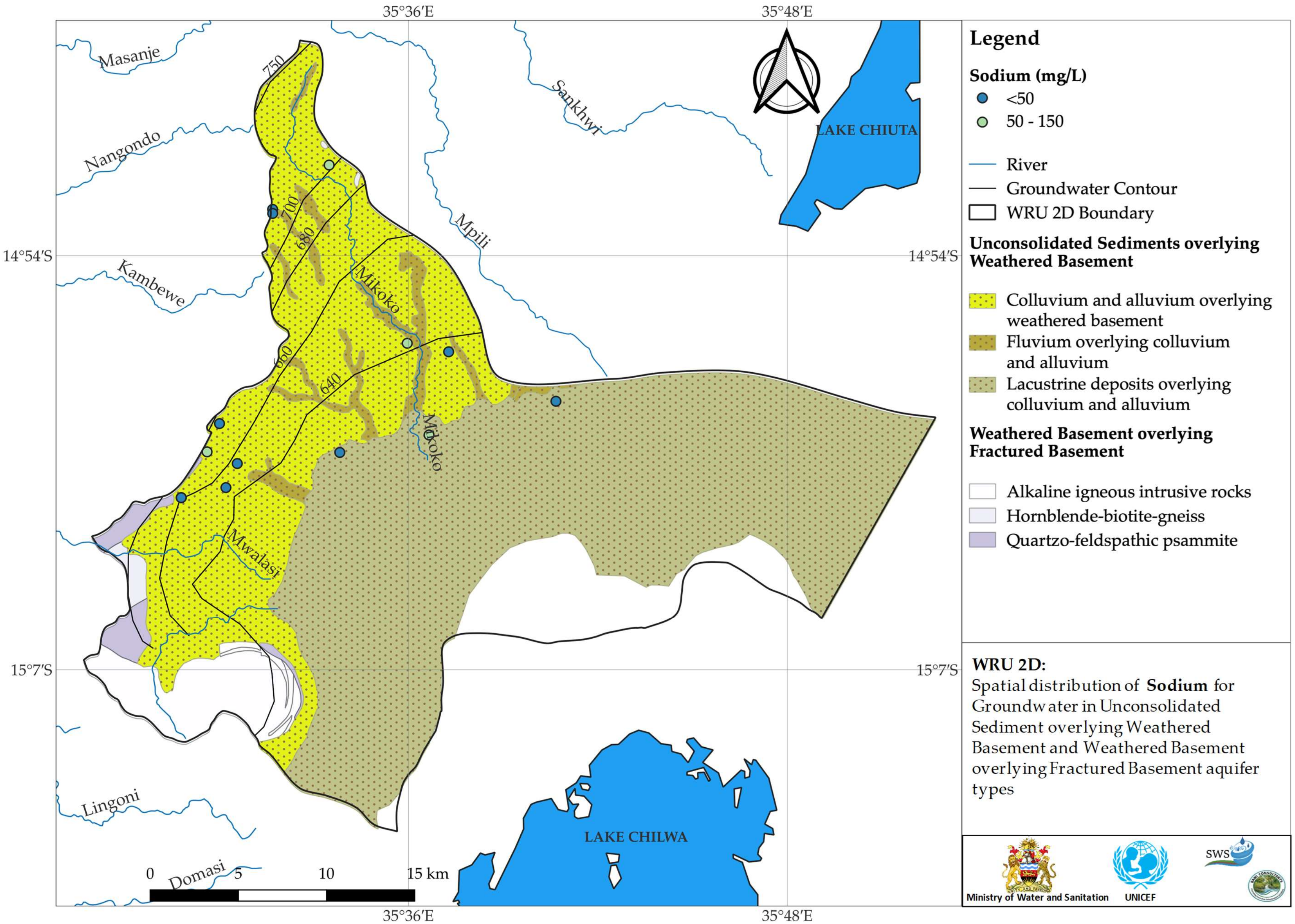


Figure WRU 2D.8 Groundwater Chemistry Distribution Calcium

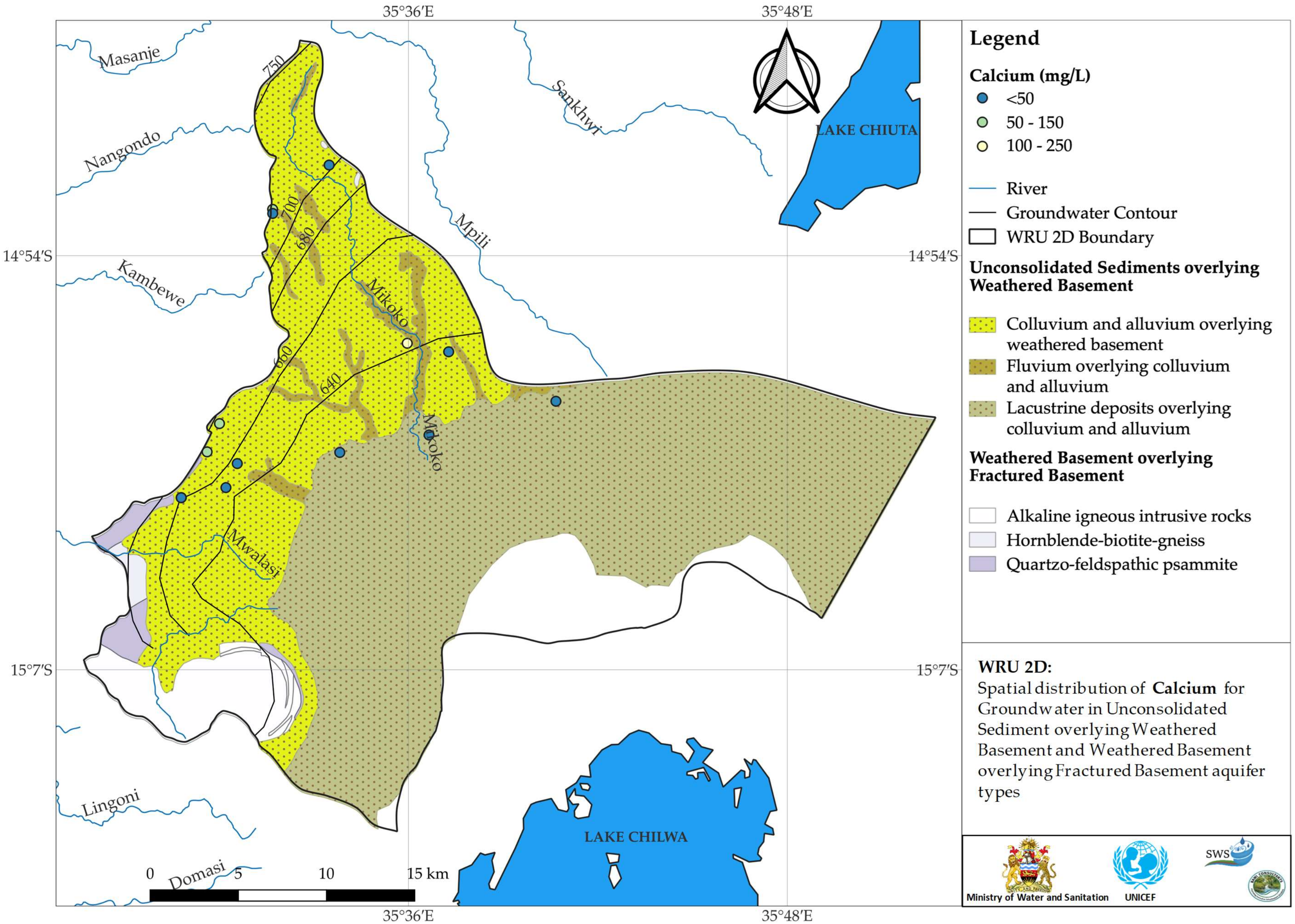


Figure WRU 2D.10 Piper Diagram of all water quality results

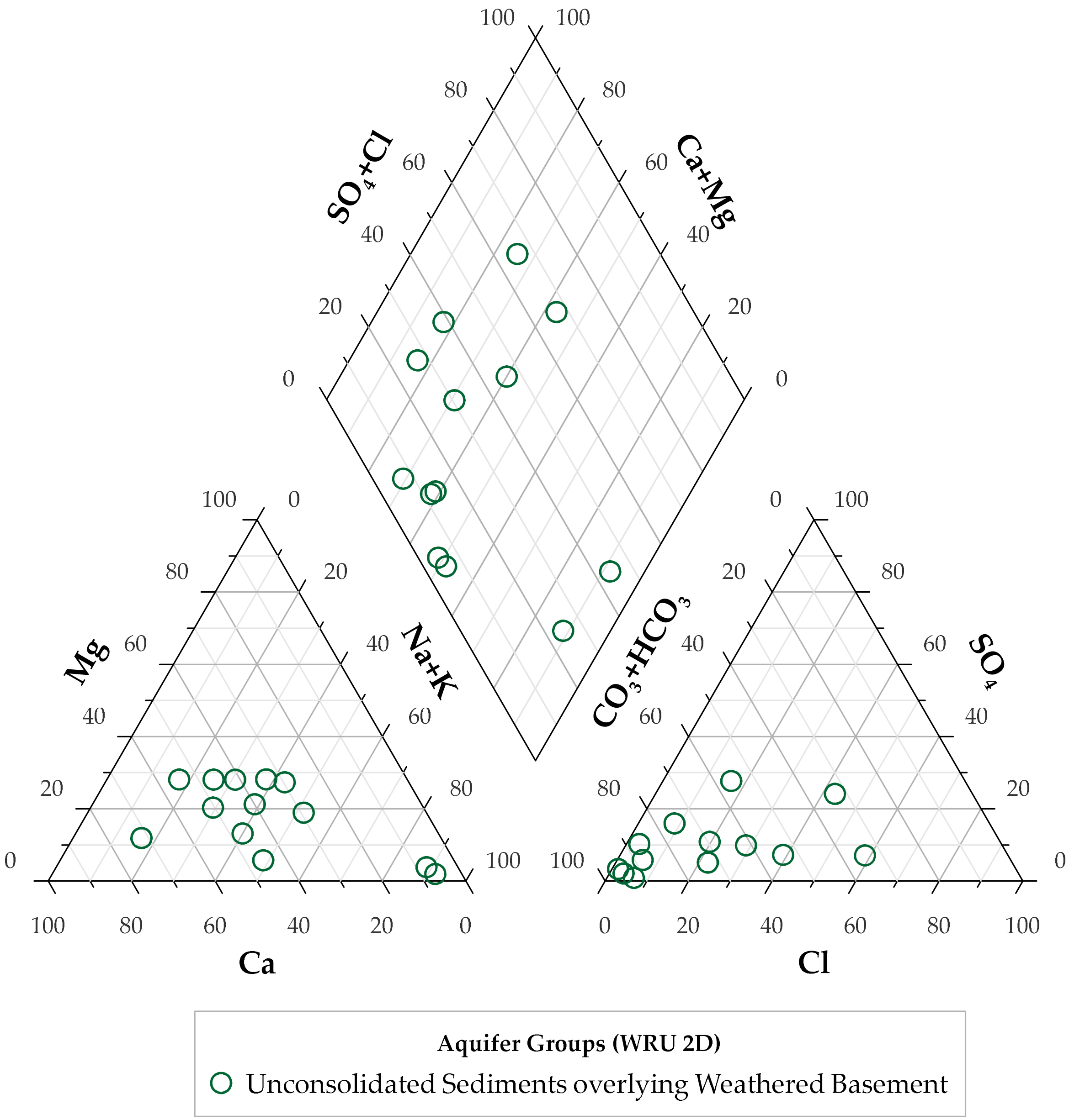
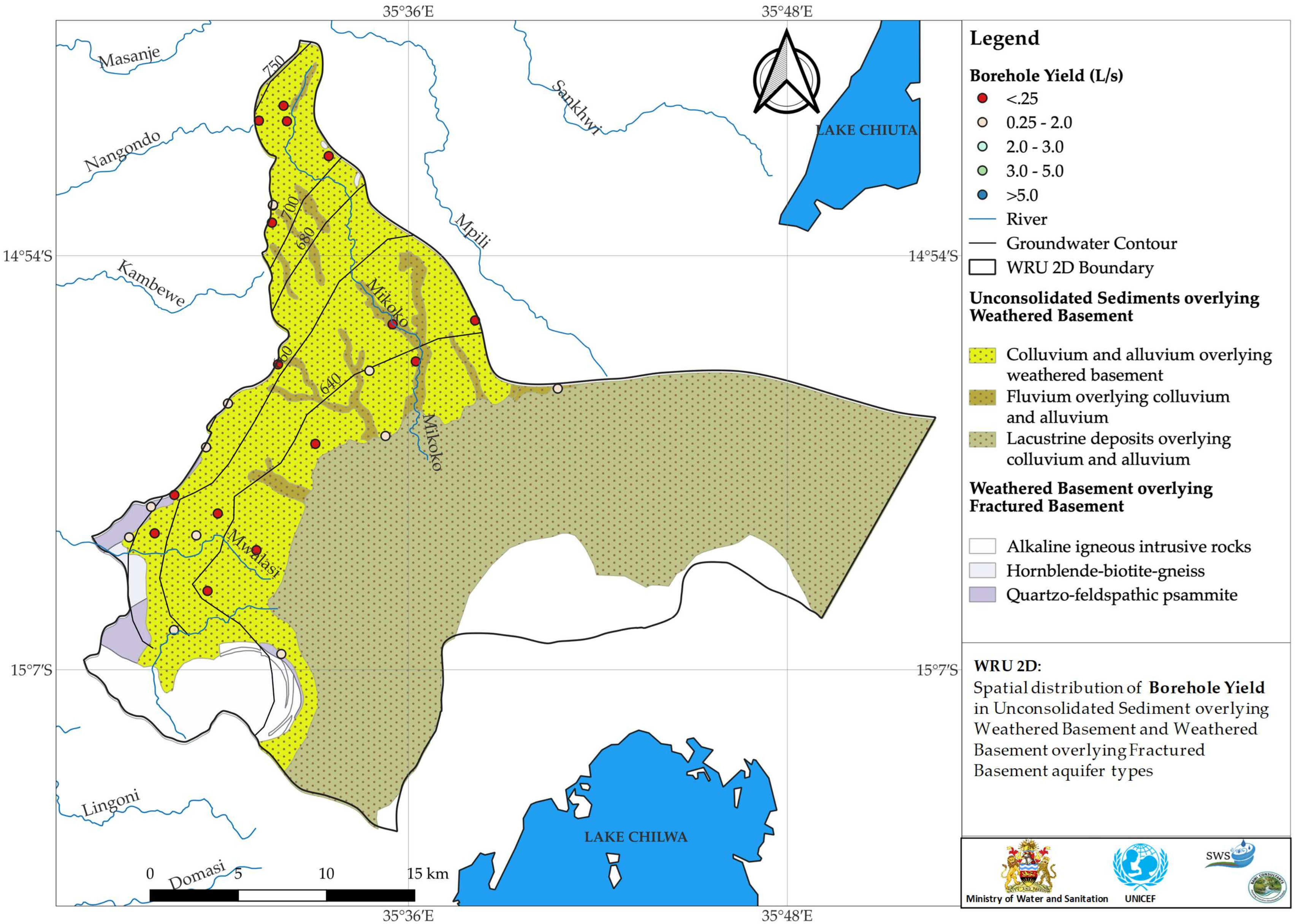


Figure WRU 2D.10 Borehole Yield Map for data held by the Ministry



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, Lake Chilwa Catchment, Water Resource Area 2, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-03-1 85pp*