Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 15

The Nkhotakota Lakeshore Catchment

Ministry of Water and Sanitation

Ministry of Water and Sanitation
Tikwere House,
City Centre,
P/Bag 390,
Lilongwe 3.
MALAWI

Tel No. (265) 1 770344
Fax No. (265) 1 773737

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

Kalin, R.M., Mleta, P., Addison, M.J., Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A., Hinton, R. (2022) *Hydrogeology and Groundwater Quality Atlas of Malawi, Nkhotakota Lakeshore Catchment, Water Resource Area 15, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-14-7 69pp*

ISBN 978-1-915509-14-7

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

1st Digital Edition (22nd March 2022)

Contents

Acronyms and Abbreviations

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

Review of Malawi Hydrogeology

Groundwater in Water Resource Area 15 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.

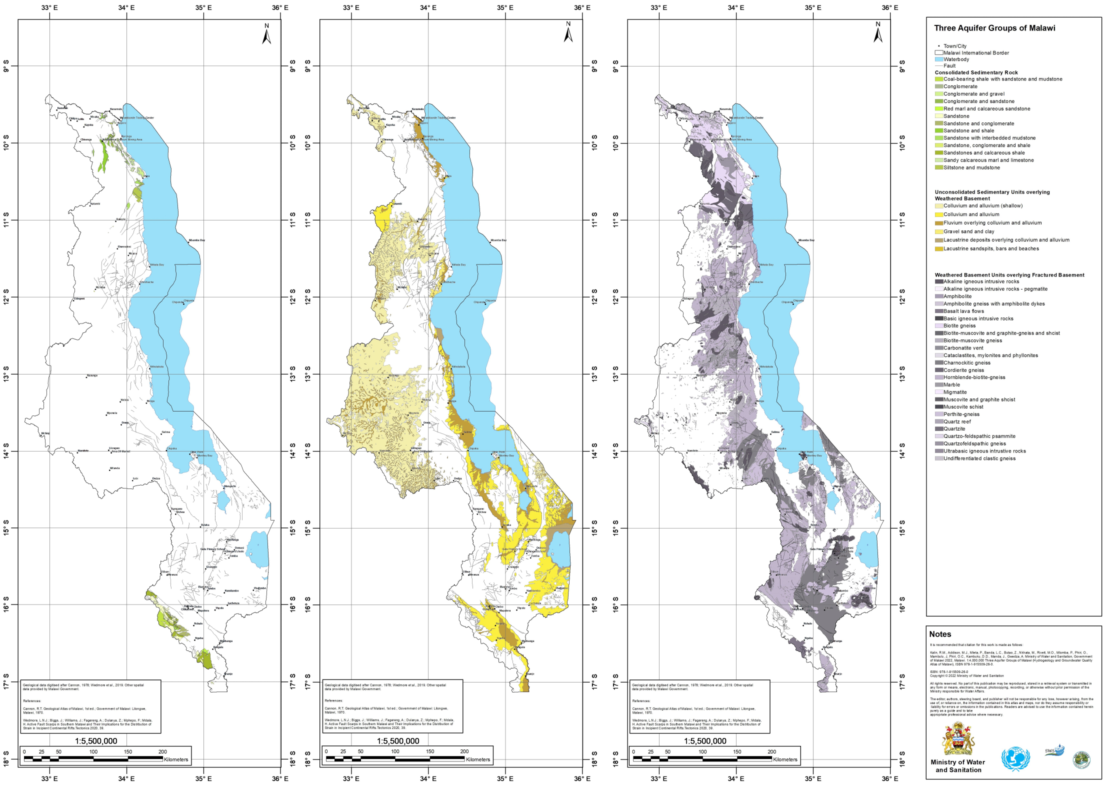


Figure 1a, b, c. Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure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

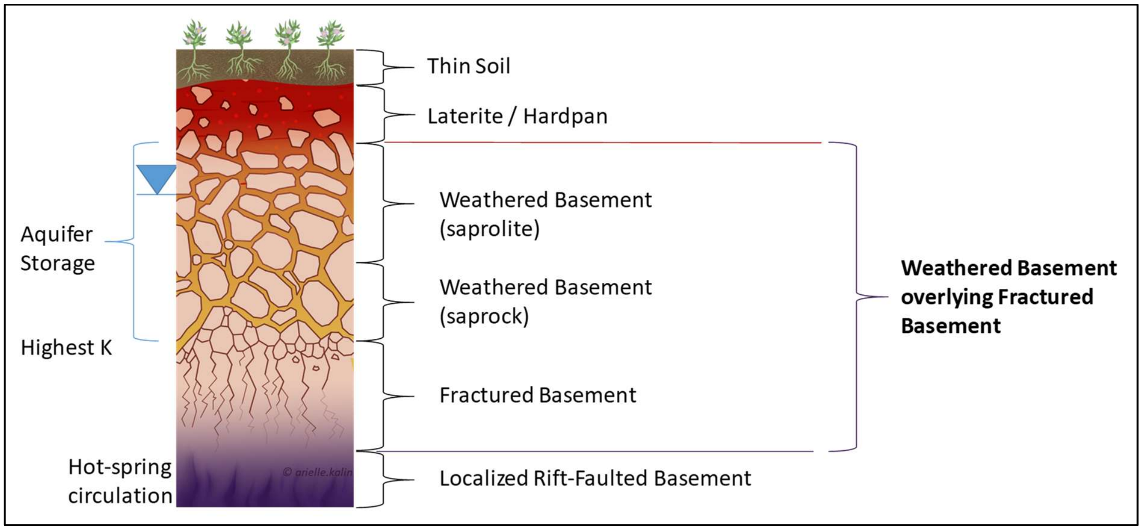


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

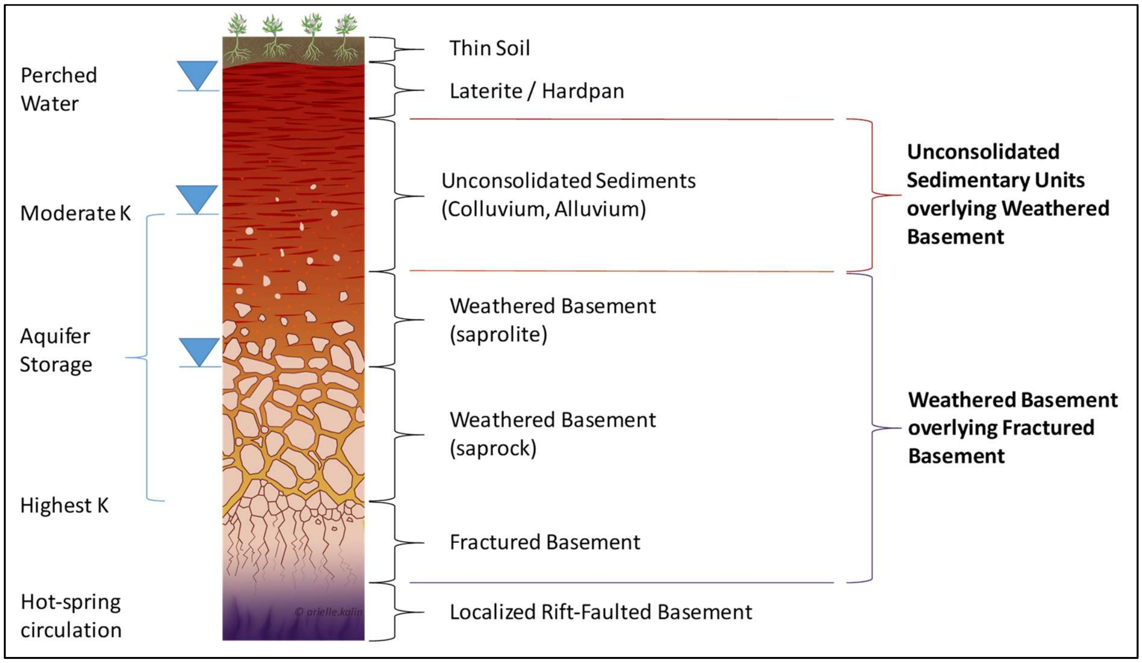


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

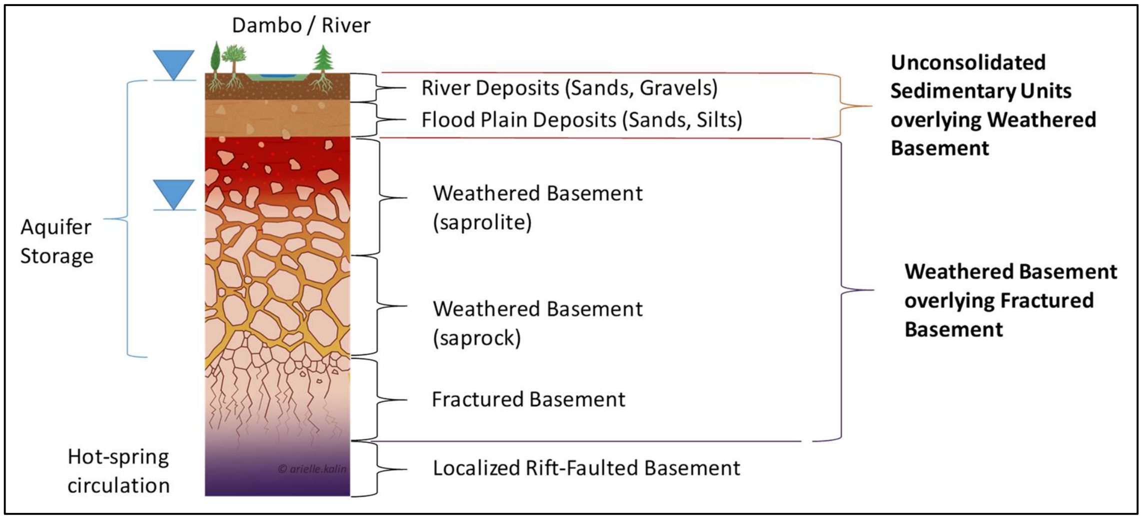


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

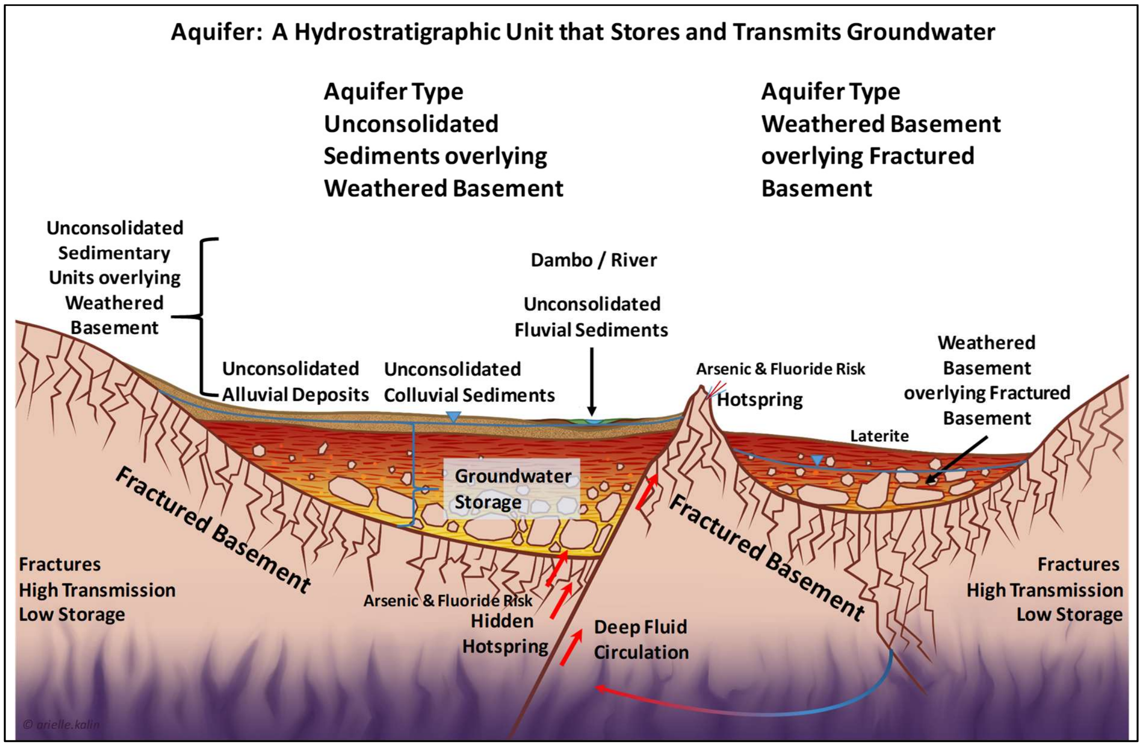


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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 15 (WRA 15): The Nkhotakota Lakeshore Catchment

The Water Resource Area (WRA) 15 in central Malawi (**Figure 2a**) constitutes four (3) Water Resource Units (WRU); WRU 15A, 15B, and 15C (**Figure 2b**). It covers an area of 4,819 Km^2 and is called the Nkhotakota Lakeshore Catchment. The catchment has seasonal flash flooding resulting from topographic setting and occurrence of seasonal tropical convergence zone precipitation and adjective storms from moisture carried from the Mozambique channel. No trans-boundary surface or groundwater bodies are found in WRA 15, but it borders on Lake Malawi which is governed by Trans-boundary water sharing agreements. The Nkhotakota Lakeshore catchment is largely drained by a network of riverine flows that include Kaombe, Lingadzi, Nkula, Lufuliza, Likoa, Rivers. Surface water flows are in a west-easterly direction, with many of the rivers deriving their headwaters from the western highlands. The Nkhotakota Lakeshore catchment occupies the country's central part of Africa's Great Rift Valley where it is separated from the country's Central African Plateau by escarpments in the uplands. The Rift Valley is characterised by a flat terrain that generally slopes near the lake. Highlands dominate the south western side while lowlands cover most of the eastern side of the catchment. The catchment covers the Salima lake shore plains southwards, extending away from the Lake Malawi to the undulating Rift Valley escarpment-foot with moderate relief.

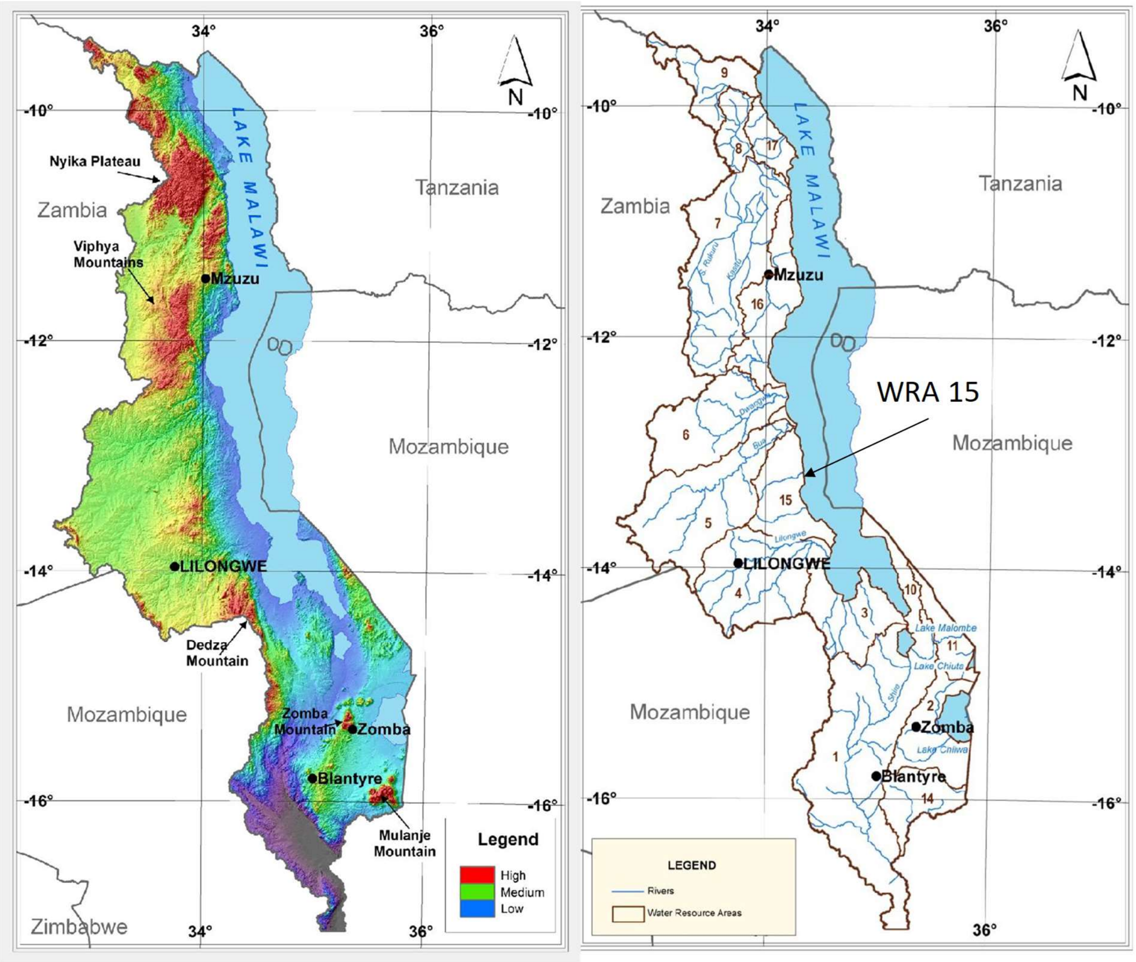


Figure 2. Location of WRA 15 with major rivers and topography shown.

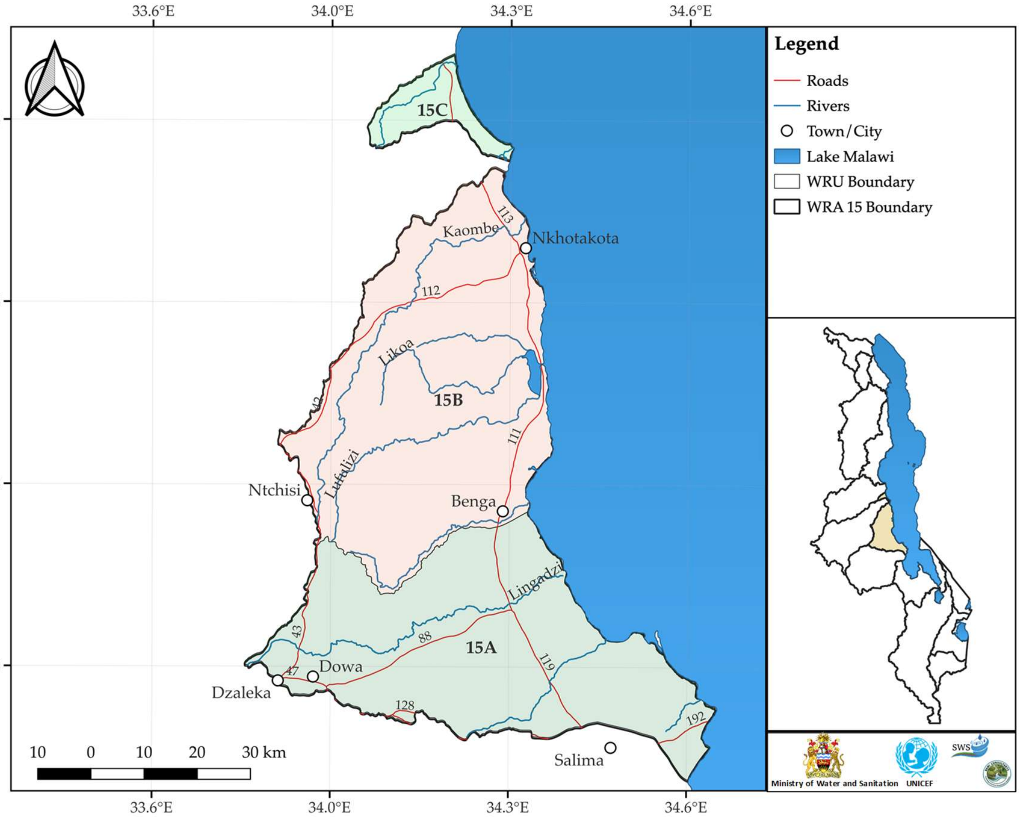


Figure 2b. Water Resource Area 15 and Water Resource Units

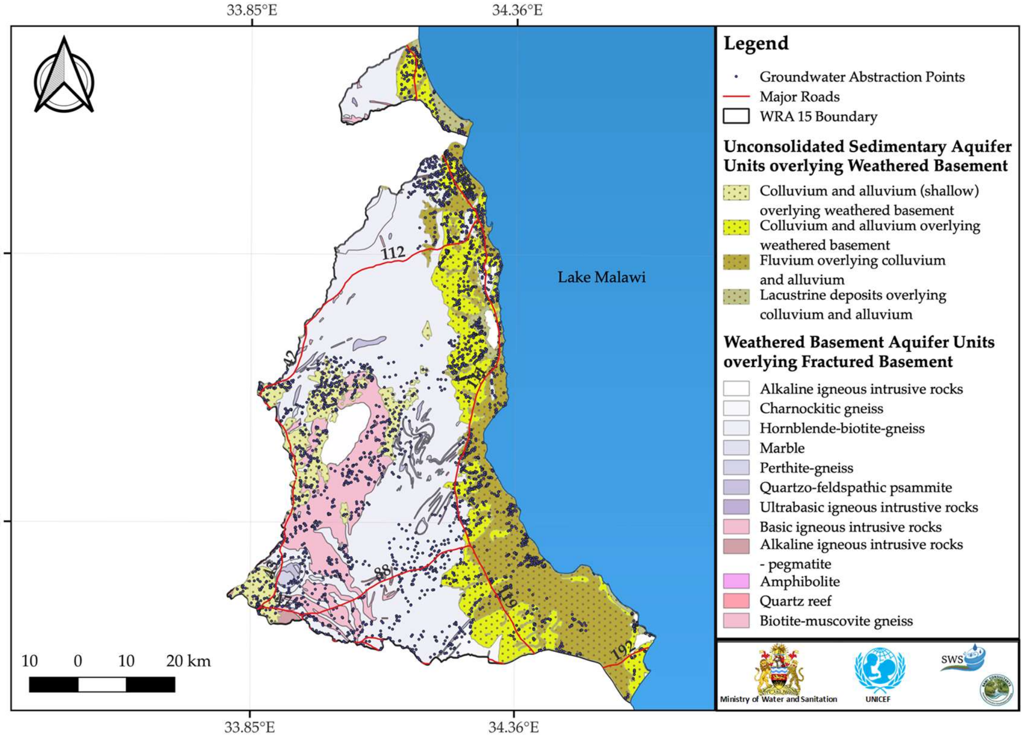


Figure 3. Distribution of groundwater abstraction points in WRA 15.

Groundwater Abstraction in WRA 15

Public abstraction points for groundwater are moderate in WRA 15 (**Figure 3, Table 2**) and it should be noted there are likely a number of unaudited private groundwater abstraction points. Of the 3,710 known groundwater abstraction points, 86.8% are improved sources. 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 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 15, only 67.5% are fully functional (defined as providing water at design specification).

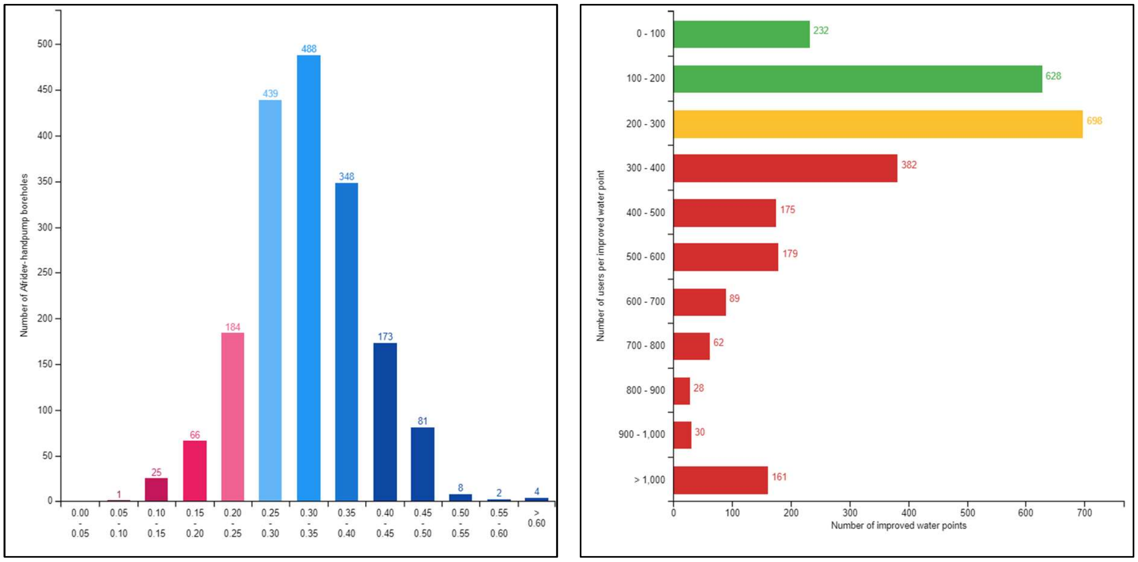


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 15 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction 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 not met and thus there is an investment need in WRA 15 from a population point of view. Most of the groundwater supply points provide water to 250 or more users per water point, and with the preponderance of dug wells which have a contamination risk and may not meet the water quality guidelines, the WRA should be considered 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, 11.4% 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. Unlike other WRAs, there is a weaker correlation between the depth of the groundwater water supplies and the decline in seasonal water availability, but is assumed this is due to the preponderance of shallow dug well supplies that are more at risk to lowering water tables resulting in lower functionality during the dry season.

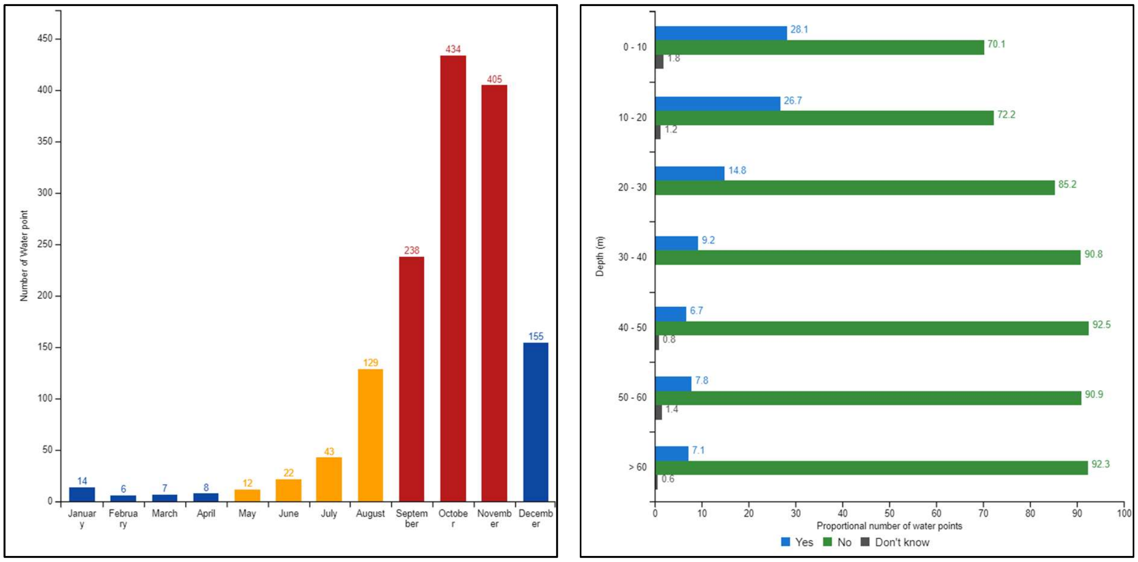


Figure 5a and 5b. Number of groundwater abstraction points in WRA 15 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

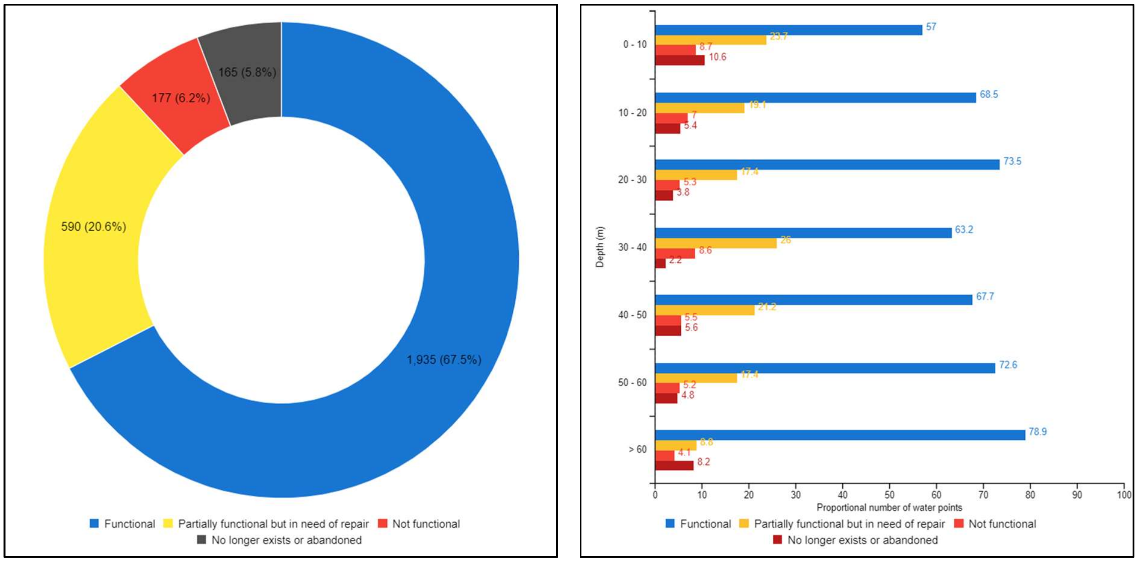


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 15 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National 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, nonfunctional 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 15 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 15 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	2,436
Protected dug well	766
Protected spring	17
Unprotected dug well	396
Unprotected spring	95

Description of Water Resources WRA 15

Water resources management according to the Water Resource Act (2013) Malawi is devolved to sub-basin Water Resource Units (WRUs), and Integrated Water Resources Management (IWRM) should be managed at this sub-basin scale. Water Resource Area (WRA) 15 in central Malawi constitutes three (3) Water Resource Units (WRU); WRU 15A, 15B, and 15C (**Figures 7a, 7b, 7c**).

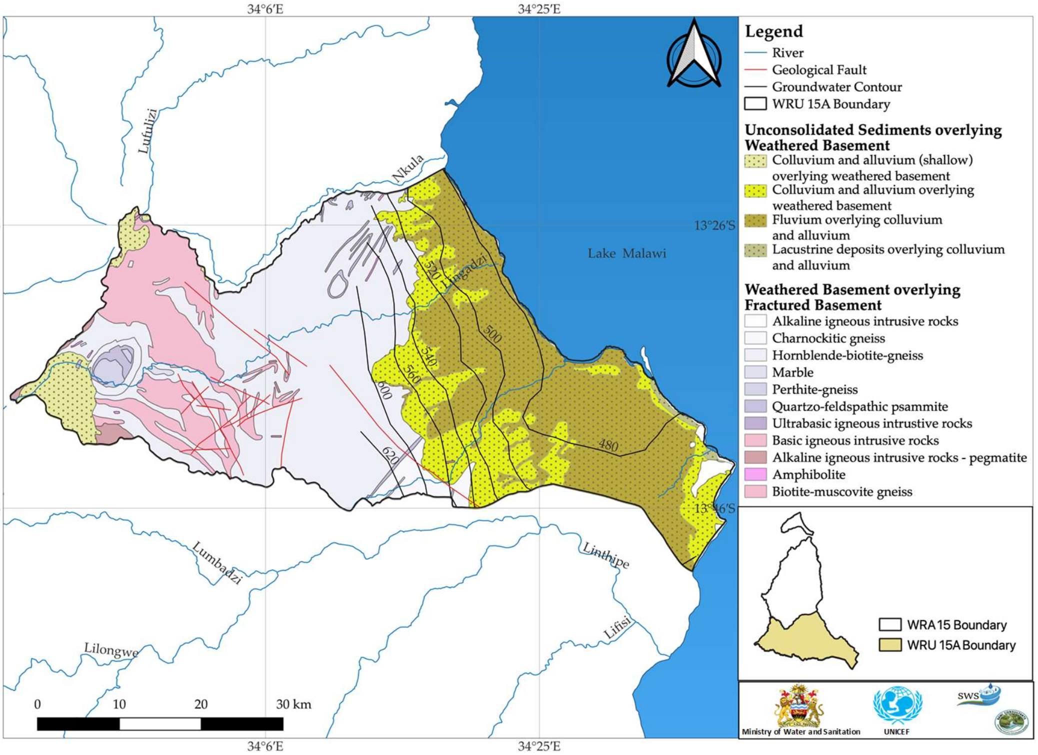


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 15A wtihin Water Resource Area 15 (Nkhotakota Lakeshore Catchment).

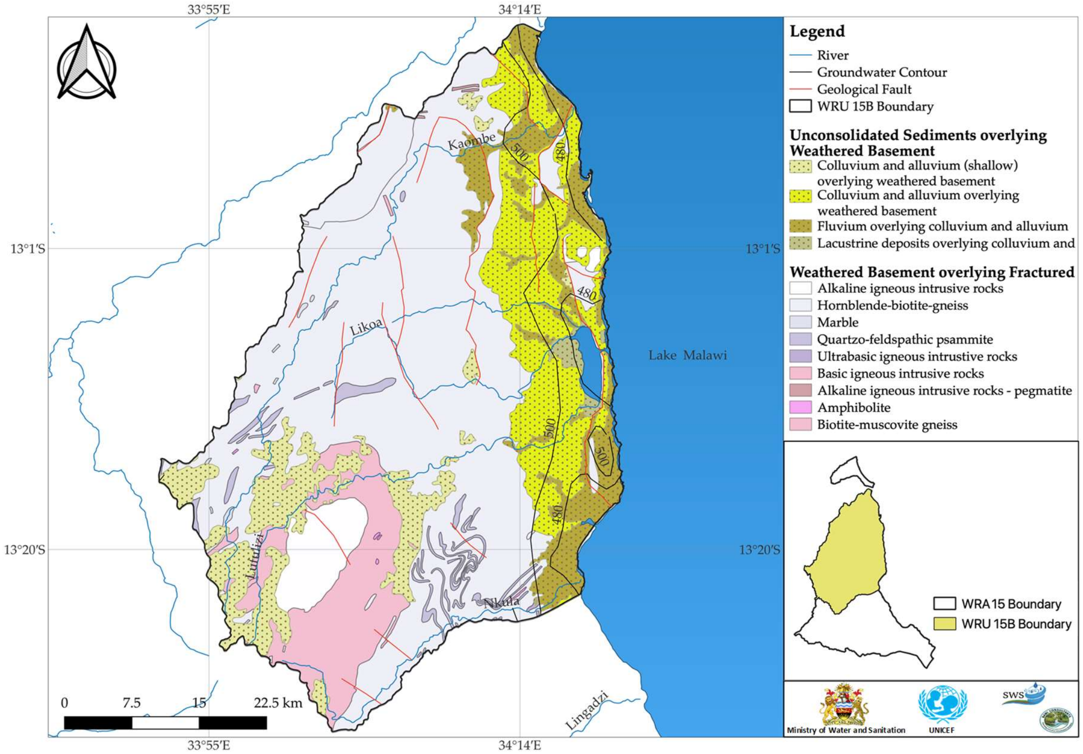


Figure 7b. Map showing the hydrogeologic units and water table for Water Resource Unit 15B wtihin Water Resource Area 15 (Nkhotakota Lakeshore Catchment).

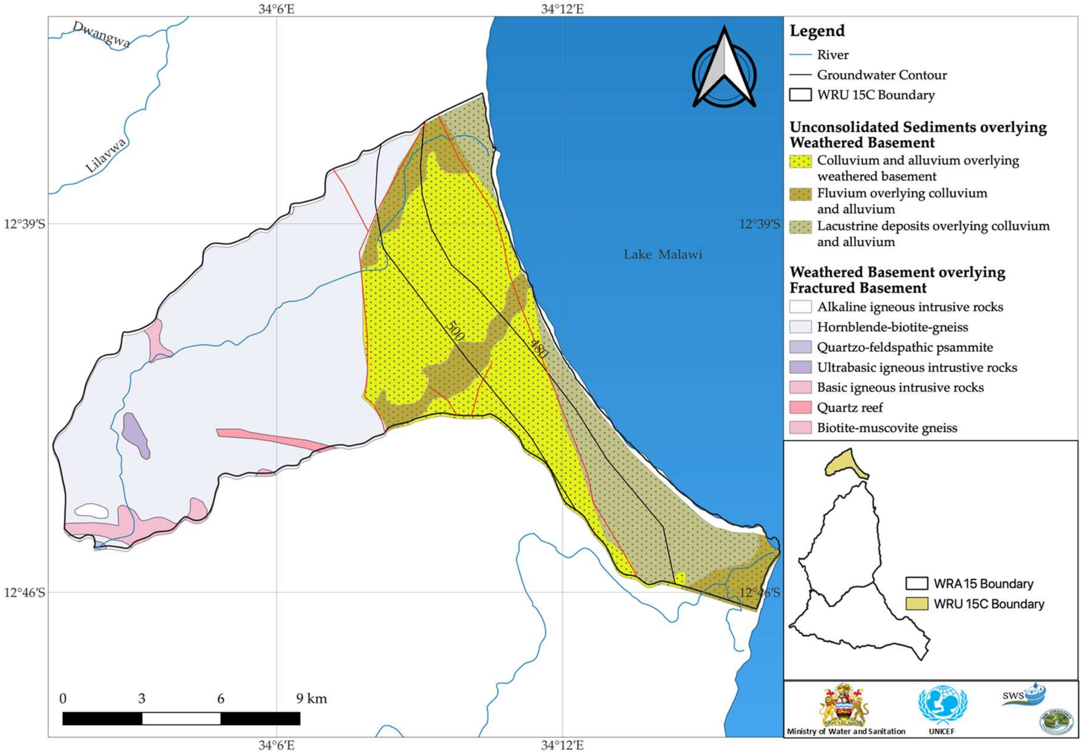


Figure 7c. Map showing the hydrogeologic units and water table for Water Resource Unit 15C wtihin Water Resource Area 15 (Nkhotakota Lakeshore Catchment).

The Nkhotakota Lakeshore catchment is largely drained by a network of riverine flows that include Kaombe, Lingadzi, Nkula, Lufuliza, Likoa, Rivers. Surface water flows are in a west-easterly direction, with many of the rivers deriving their headwaters from the western highlands.

Topography and Drainage

The topographical setting of Water Resource Area 15 is dominated by uplands of over 1,500 meters in the west of the catchment, and with lowlands dominating the eastern side of the catchment where it drains into Lake Malawi (**Figure 8**). This largely influences surface water flows eastwards to Lake Malawi and enhances the occurrence of frequent seasonal flash flooding in the Water Resource Area.

Geology – Solid

WRA 15 solid geology (**Figure 7a, 7b, 7c**) is concentrated in the west and is composed of Precambrian to Lower Palaeozoic basement rocks. The dominant lithology is biotite gneiss with folder linear sequences of quartzofeldspathic gneiss and grannulite. Other major lithologies include muscovite-biotite gneiss and schist, and perthite augen gneiss. Large-scale faulting is mostly absent from the centre of the WRA, increasing in frequency north. Major faults present are the Chamsani West Fault, the Chamsani East Fault, and the Kaombe fault which represent the eastern extent of the Malawi Rift Valley in this area.

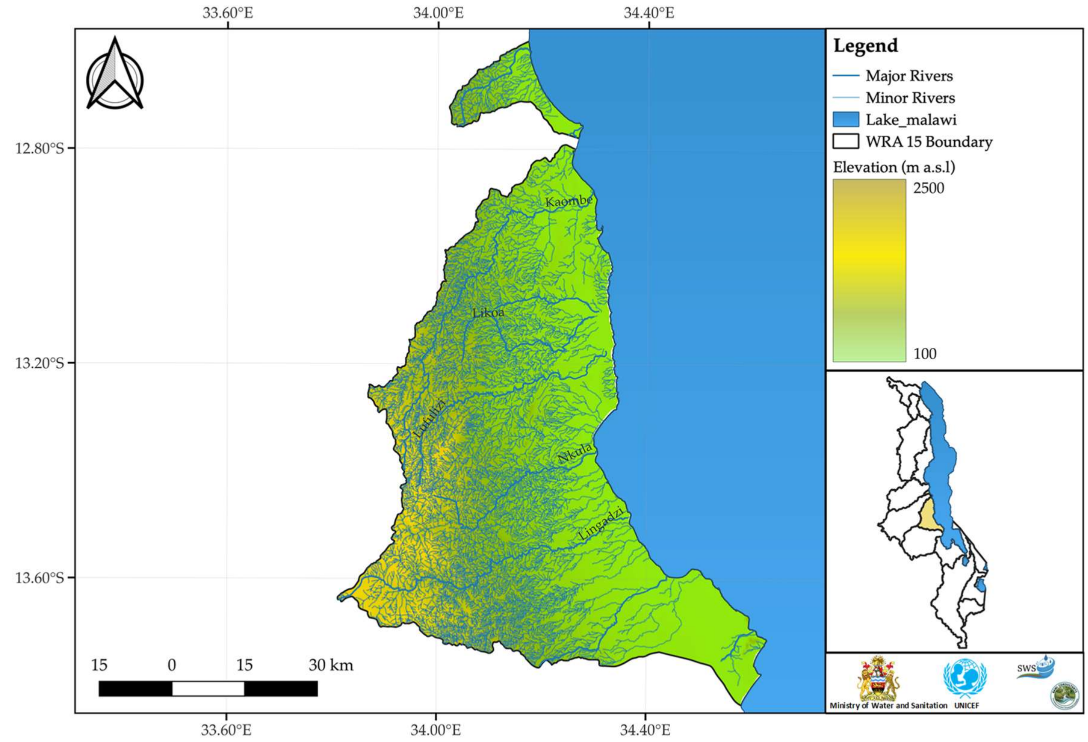


Figure 8. Drainage for the major rivers in Water Resources Area 15.

Geology – Unconsolidated deposits

Unconsolidated sediments dominate in the east. Moving west to east across the Rift zone, basement rock gives way to an extensive covering of colluvium and alluvium east toward Lake Malawi. Lacustrine deposits are common along the shores of Lake Malawi, particularly surrounding the Chia Lagoon. Fluvial deposits and small dambos are common where rivers drain eastward toward the lake.

Climate

Around 80% rainfall occurrence between September and May due to both Inter- Tropical Convergence Zone moisture and north easterly monsoon and south easterly trade wind convergence. Annual rainfall averages from is 1,089mm (with greater precipitation likely in the highlands in areas not covered by weather stations), (**Figure 9**). 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 15. 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)
15	A	Salima/Lifuwu/Dowa	1,050	968
	B	Ntchisi/Nkhotakota	1,149	1,021
	C	- No Station -		1,077

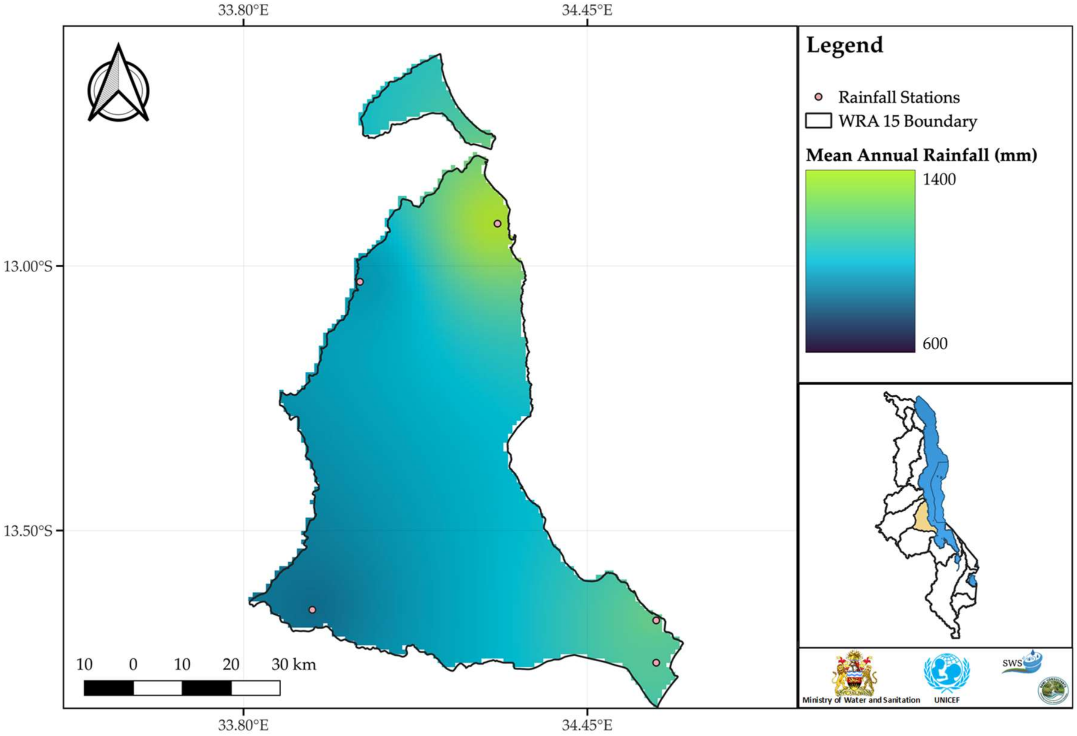


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 15 with the location of weather stations. Average rainfall measured is 1,016mm, average rainfall modelled is 1,000 +/- 115mm (range 808 to 1,384mm).

Land use

Land use is largely dominated by rain fed cultivation and open woodlands followed by open grasslands. There is also some wetland and open waters area cultivation with dimba cultivation along the lake Malawi shoreline.

The Nkhotakota Lakeshore catchment (WRA 15) is one of the productive fishing areas of the Lake Malawi basin and the Chia Lagoon Watershed where fishing remains one of the major income streams for most of the population, particularly the fishing communities along lakeshore areas. The area is well known with rice cultivation especially along the lakeshores there several rice irrigation schemes and is another major income stream in the catchment.

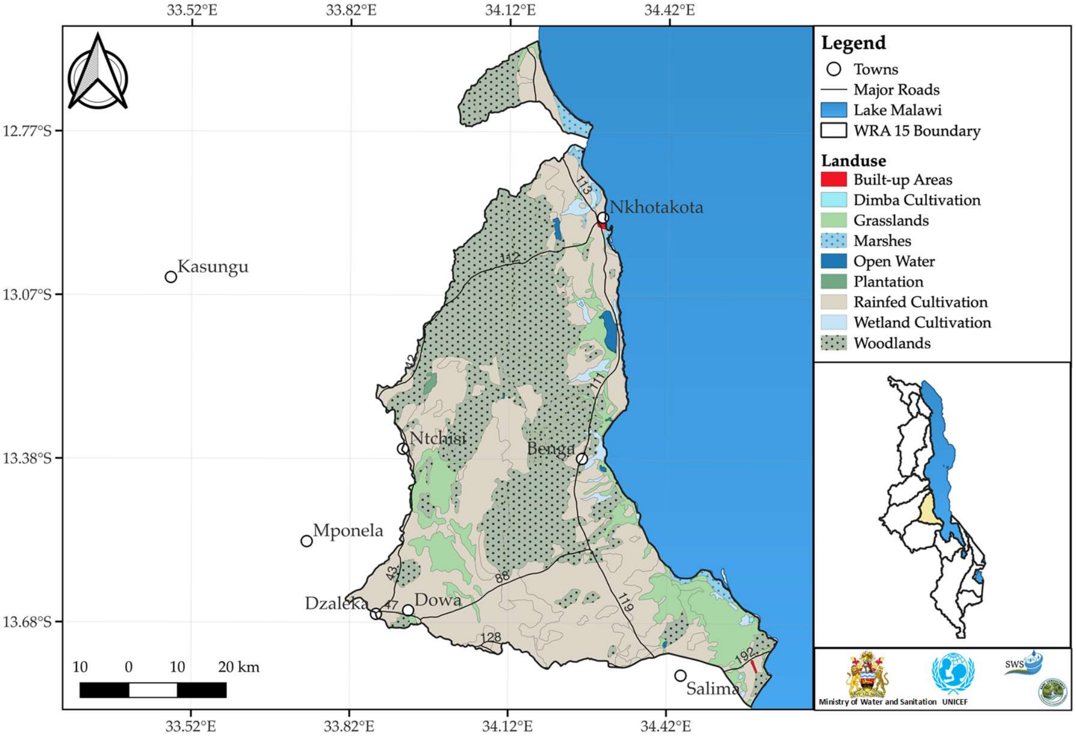


Figure 10. Land use in WRA 15 is dominated by woodlands.

Hydrogeology of WRA 15

Aquifer properties

WRA 15 is located along the western African rift with a dominance of fluvial and lacustrine deposits that comprise predominantly finer-grained lithologies along the lake boundary; generally, these may be expected to be of modest aquifer potential and potential salinity from evaporative enrichment. Layered unconsolidated, anisotropic aquifer systems may be expected where very fine-grained silt/clay lacustrine deposits are thick and laterally extensive. Better aquifer units for water supply in are most likely associated with paleo-riverine environments where fluvial deposit accumulations are more extensive.

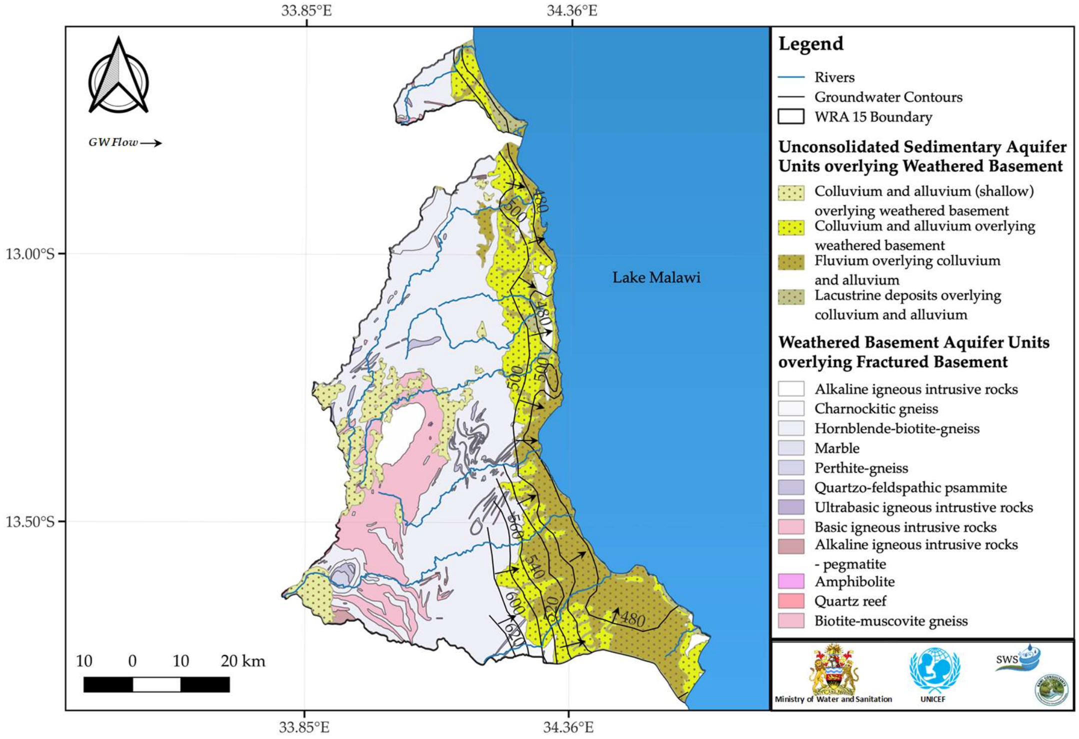


Figure 11. Groundwater level contours and flow direction in WRA 15 [1987 Hydrogeological Reconnaissance data] showing location of groundwater monitoring points. [water level contour interval 20m]

One can extrapolate coarser sediments to be deposited nearer to the escarpment, but given the paucity of detailed particle size distribution and lithological records provided to this work, it is can only be assumed that fluvial and colluvium channels may provide locally productive aquifer units (**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 this data, therefore groundwater level data for WRA 15 is based on prior hydrogeological reconnaissance and it can be confirmed that basin groundwater flows are convergent on the Lake Shore generally following topography with indication of groundwater discharge to rivers (see **Figure 11**).

Groundwater level data for WRA 15 based on prior hydrogeological reconnaissance confirm groundwater flows follow topographic drainage (**Figure 11**). Head data are restricted to the Lake Malawi lakeshore unconsolidated sediments and escarpment Basement in the south that would generally be expected to recharge the western flank of lakeshore unconsolidated deposits. Head contours in the lakeshore plains approximately parallel the shoreline with gradients towards the lake, but with some inflections inland around some of the river – dambo wetland lowland area signifying groundwater discharges to these near shoreline surface-water features. For instance, in mid-basin WRU 15B arcuate contours inflected inland approaching Nkhotakota, nearing the Chia Lagoon and local wetland area, around Mtachi and Mtosa to the south. Also in WRU 15A in the basin south inflect, inland just south of Domira Bay. Hydraulic gradients in the shoreline aquifer somewhat vary. Gradients in 15B and 15C in the central to the north of the WRA generally vary between 0.005 and 0.012 with groundwater velocities estimated at 9 to 22 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2. Extensive lakeshore plains occur in WRU 15A reaching over 30 km inland from Domira Bay and 40 km from Senga Bay. Excepting very shallow hydraulic gradients on the lake promontory with flows northward towards the near shoreline Chigolo Dambo, gradients are towards the lower end of the range for 15B and 15C above, around 0.006.

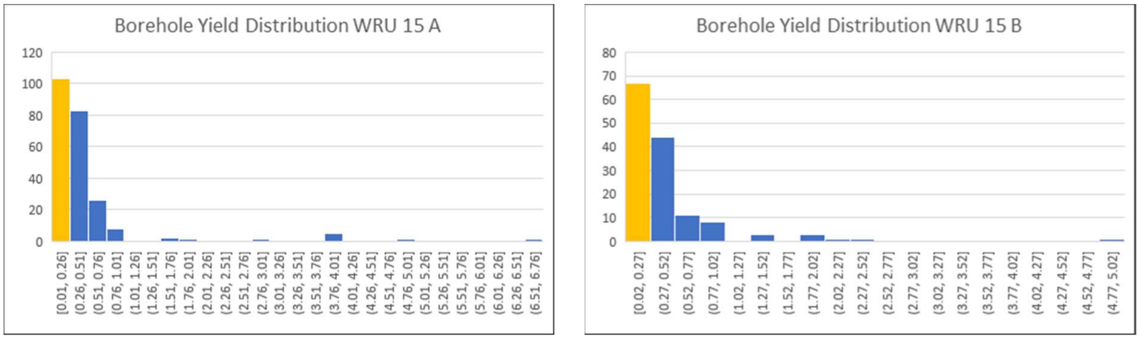


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 15 (note: limited data in WRU 15C) (y axis = *n* observations)

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, 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 WRU 15A and WRU 15B there appears to be a trend to higher borehole yields related to alluvium aquifer units. There are boreholes with yields at or above 4 l/s across WRU15A and WRU. In WRA 15 (**Figures 13a, 13b and 13c**) the high average rainfall and potential for recharge suggests there is some potential in the lower elevations for higher yielding boreholes, in particular there are reported yields as high as 5l/s, and for artesian confined systems along the escarpment but detailed hydrogeological on-site mapping should be undertaken to confirm.

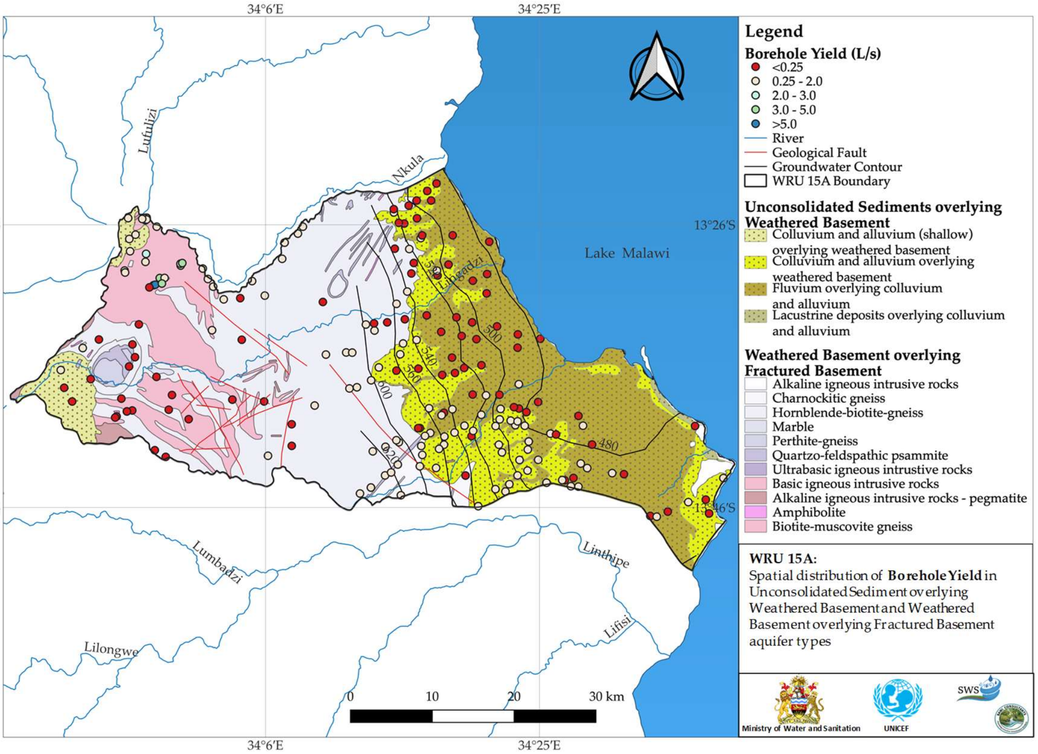


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 15A.

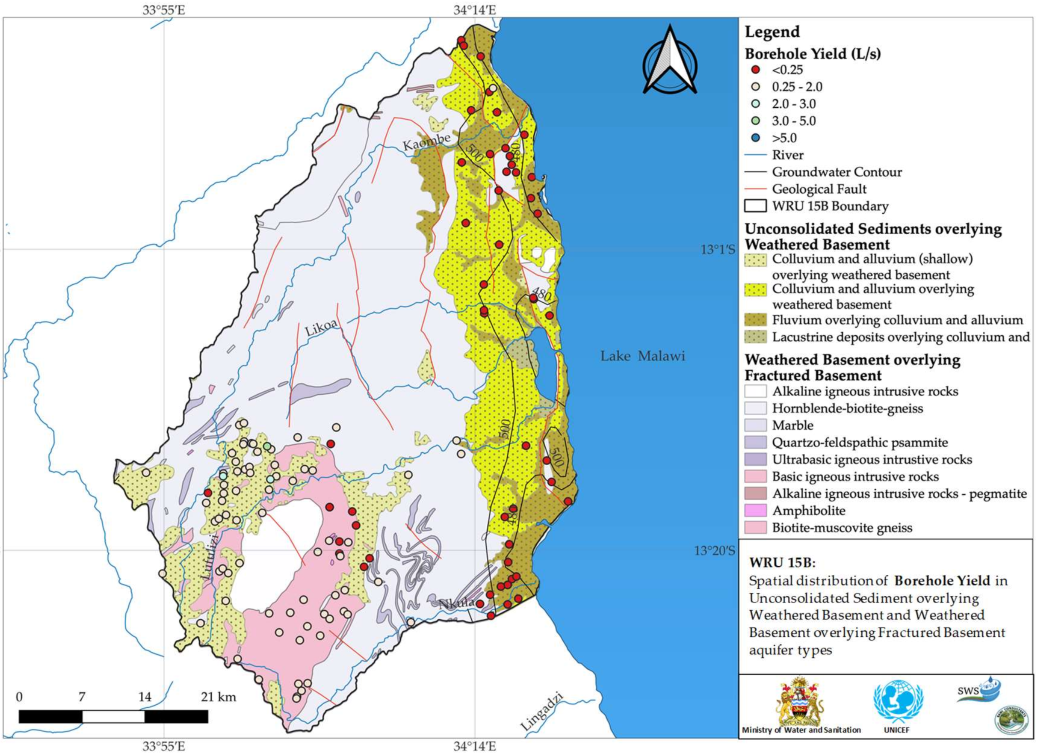


Figure 13b. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 15B.

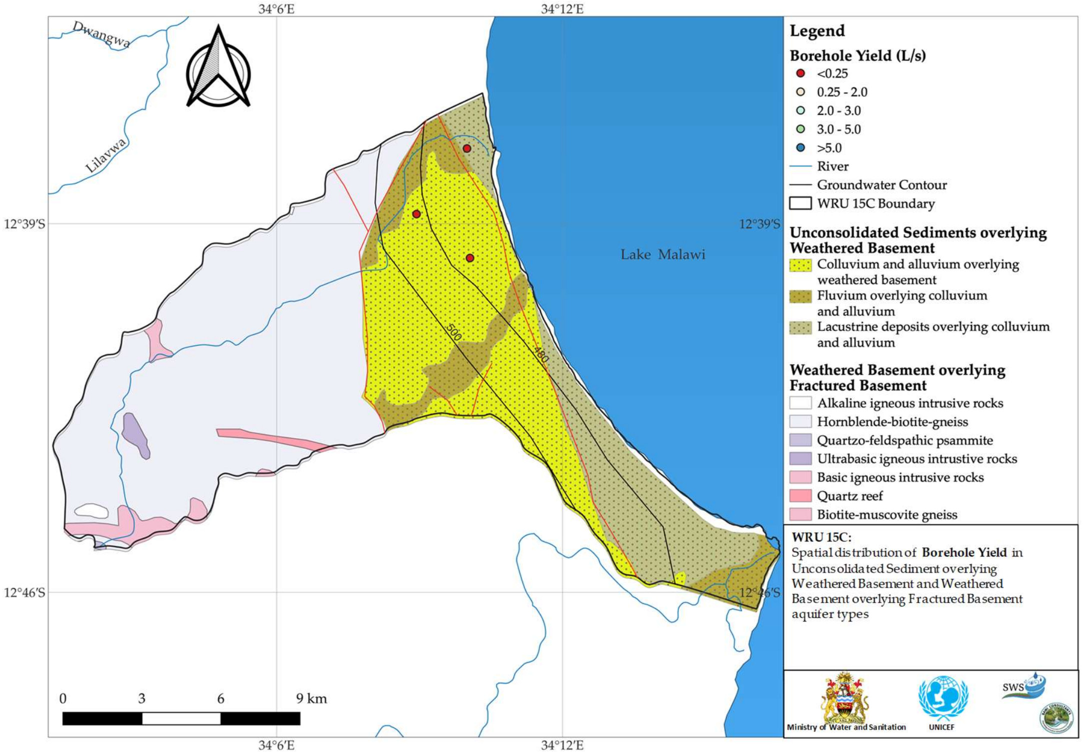


Figure 13c. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 15C.

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

There is one operational groundwater monitoring stations within WRA 15 at the Nkhotakota Water Office (see **Figure 14a** for location of groundwater monitoring points), the data is not complete but it does show a few continuous (annual) readings. Data from the 2020 National Survey suggested seasonal water table declines, supported by the data in **Figure 14b**. From the data that is held by the Ministry of Water and Sanitation, there is about a 5-meter annual change in groundwater table, but it is not possibly to determine any long-term trends that may relate to climate variability (rainfall and recharge relationships). 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 are placed into each hydrostratigraphic unit is an area for future investment.

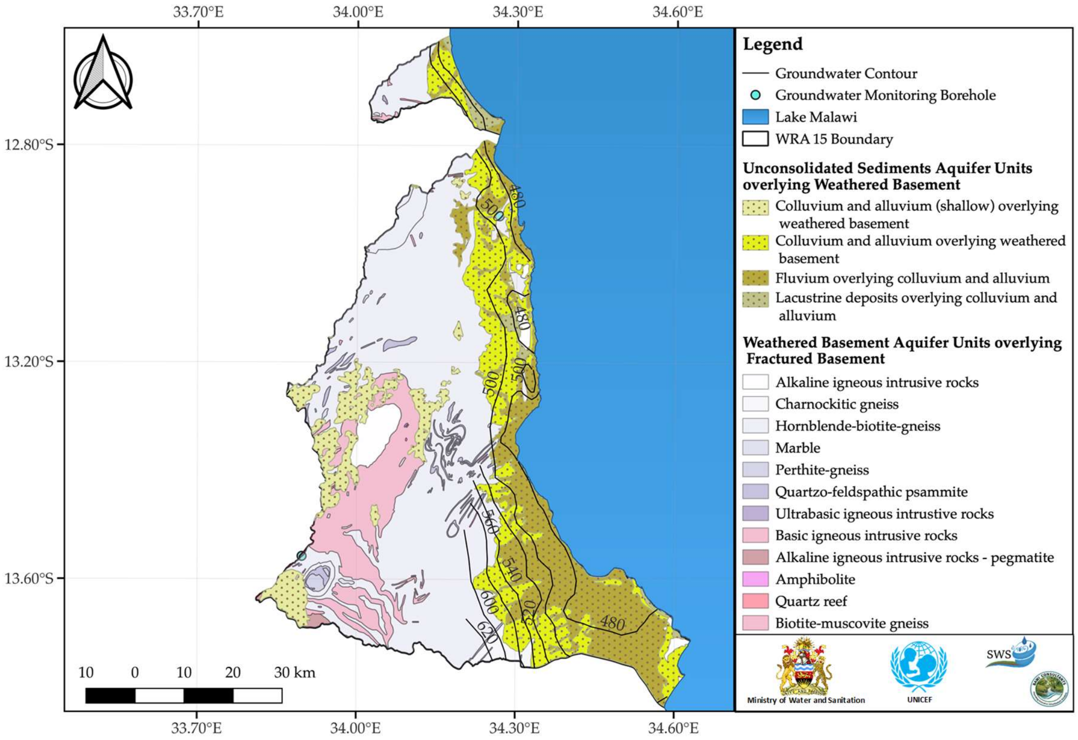


Figure 14a. Location of groundwater monitoring stations in WRA 15.

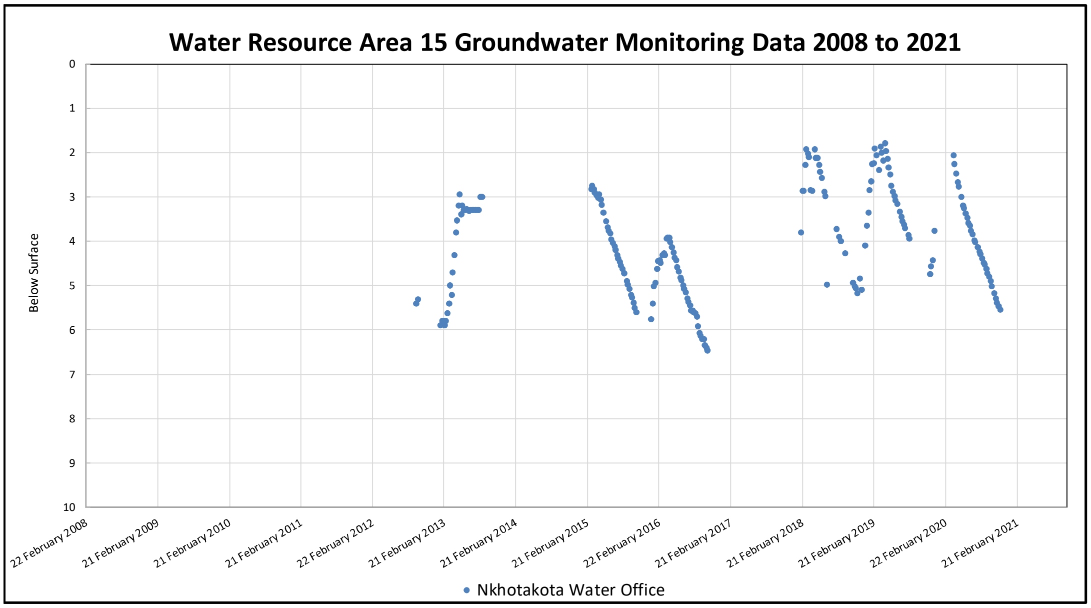


Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 15. (units assumed to be meters below ground level).

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 15 ranges between 47.9 Million Cubic Meters (MCM) and 359.3 MCM per year, with a mean age of groundwater of 122 years across the Water Resource Area **(Tables 4a, 4b, 4c**). 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 15A, 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	580.4	10%	35%	0.02	0.10	1,160.8	20,313.2	
Lacustrine units	6.7	10%	35%	0.02	0.03	13.3	70.1	
Colluvial etc.	384.7	10%	30%	0.02	0.06	769.4	6,924.4	
W & F Basement	1,174.3	1%	10%	0.02	0.03	234.9	3,522.8	
	Area of WRU (km^2)	15A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*2,178.3*	*30,830.4*	*Total Volume Groundwater*
	2,146.0	968	Average Rainfall in WRU	9.68	72.6	20.8	155.8	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]						105	198	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 15B, 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	212.8	10%	35%	0.02	0.10	425.5	7,447.0	
Lacustrine units	18.2	10%	35%	0.02	0.03	36.4	191.1	
Colluvial etc.	552.4	10%	30%	0.02	0.06	1,104.7	9,942.6	
W & F Basement	1,656.7	1%	10%	0.02	0.03	331.3	4,970.0	
	Area of WRU (km^2)	15B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*1,898.0*	*22,550.8*	*Total Volume Groundwater*
	2,440.0	1021	Average Rainfall in WRU	10.21	76.575	24.9	186.8	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]						76	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 15C, 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	17.6	10%	35%	0.02	0.10	35.2	616.3	
Lacustrine units	27.3	10%	35%	0.02	0.03	54.7	287.0	
Colluvial etc.	55.6	10%	30%	0.02	0.06	111.1	1,000.1	
W & F Basement	106.3	1%	10%	0.02	0.03	21.3	318.9	
	Area of WRU (km^2)	15C	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*222.3*	*2,222.2*	*Total Volume Groundwater*
	206.8	1077	Average Rainfall in WRU	10.77	80.775	2.2	16.7	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						100	133	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

Table 5. Distribution of dissolved species in groundwater WRA 15. 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 15	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	7.1	214	10.5	18.3	0.5	0.6	16.3	3.9	15.4	7.3	1.1
Std Dev	0.6	169	7	27	0.3	0.4	17	2.4	13.4	7.5	2.4
Median	7.3	174	8.7	10.8	0.6	0.7	11.0	3.6	12.1	5.8	0.6
Max	8.3	1,281	31	202	1	1.1	100	10	91	46	14.2
Min	6.0	84.0	0.2	0.4	0.1	0.1	5.5	0.6	2.9	1.4	0.0
n	76	76	76	76	48	25	76	32	76	76	68

Groundwater quality WRA 15

Groundwater major-ion water quality in WRA 15 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**).

Piper plots of the WRA 15 water quality data suggest most water has limited geochemical changes from water-rock interactions dominated by Ca-Mg-HCO$_3$ type waters with just a few analyses that trend to increasing Na-Cl-SO$_4$ likely due to fault-related fluid flow (**Figure 15a and 15b**). The average groundwater age, the high precipitation rate and calculated recharge rates together with the relatively low electrical conductivity points to recent meteoric recharge of much of the groundwater with limited water-rock interactions. There are a number of known hot springs and a detailed reconnaissance survey of fault related groundwater movement is advised, in particular geolocation of all known and suspected groundwater samples influenced by hot springs and fault zones.

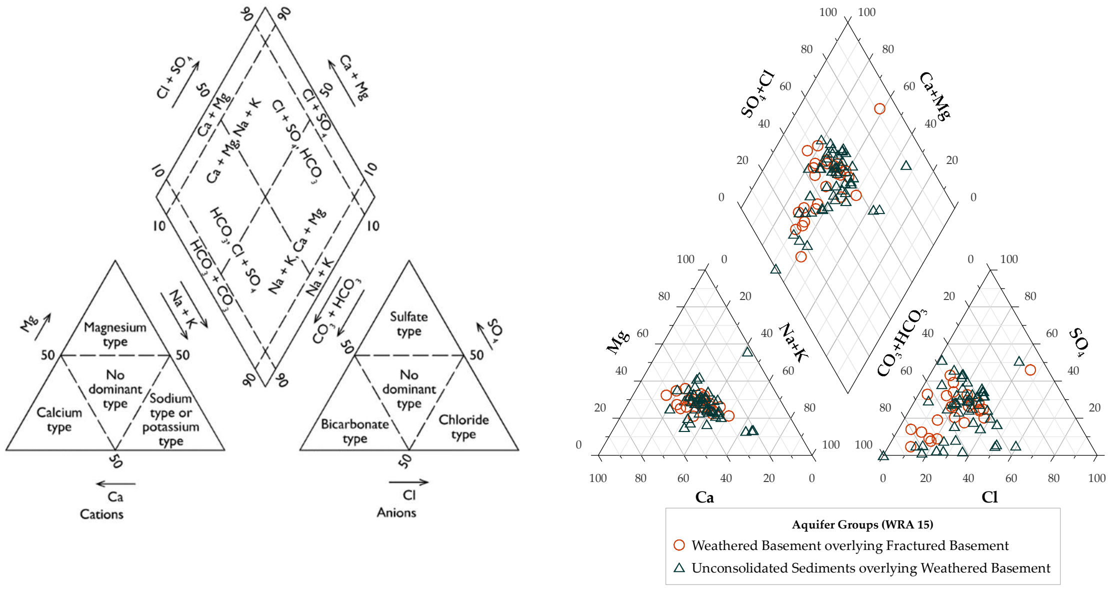


Figure 15a, 15F. Piper Diagrammes of Groundwater Samples in WRA 15 and for each Aquifer Type in WRA 15.

The distribution of key dissolved water quality species in groundwater of WRA 15 is provided however caution for over interpretation is advised due to the limited data held by the Ministry of Water and Sanitation in the WRA. Water quality results with geospatial coordinates were rare in WRA 15 and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 15 (**Figure 16**) 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. Given the number of hot springs and the likely relationship of groundwater abstraction points to fault zone water movement, it is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation, especially for 'solar pumped' boreholes.

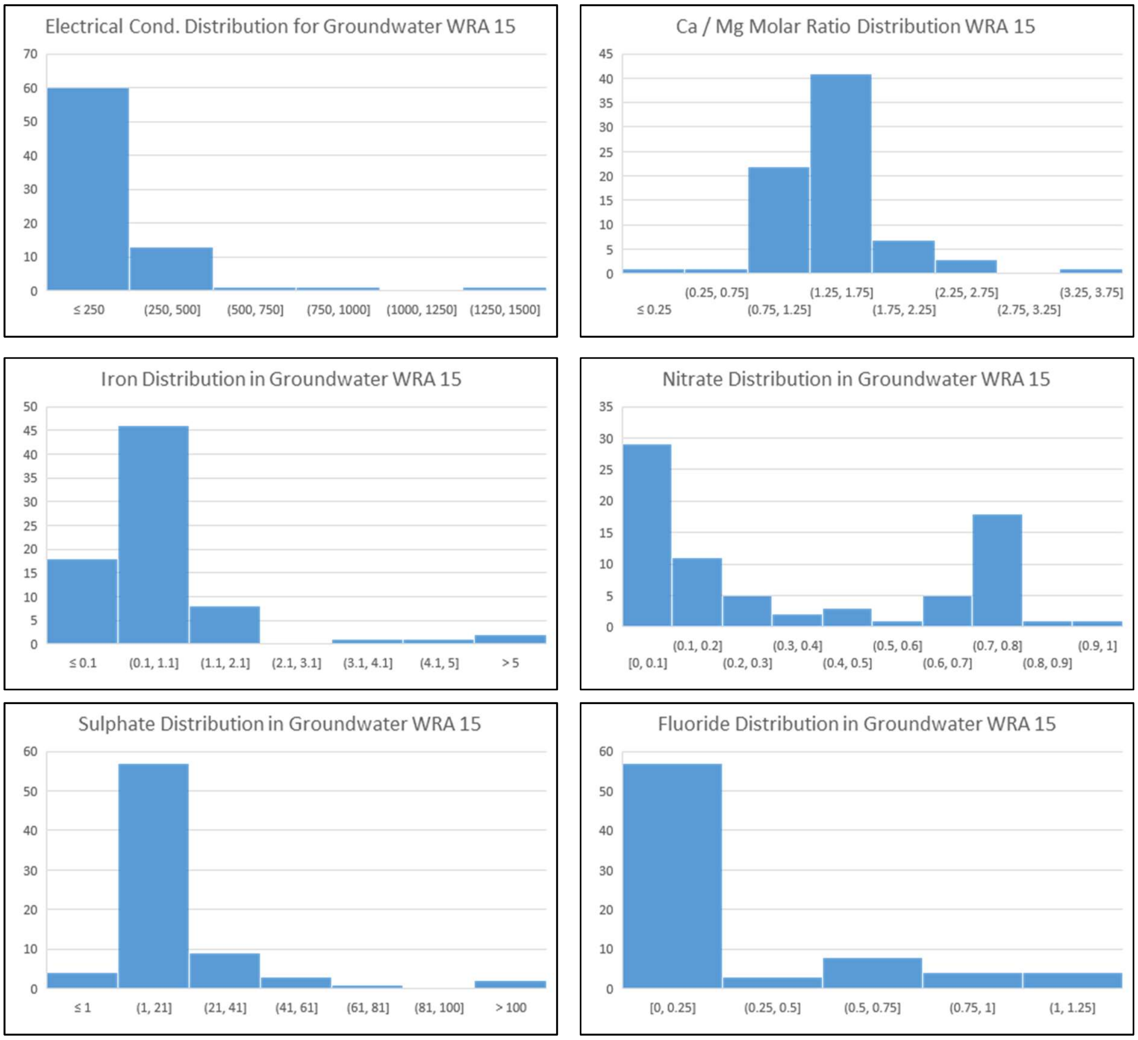
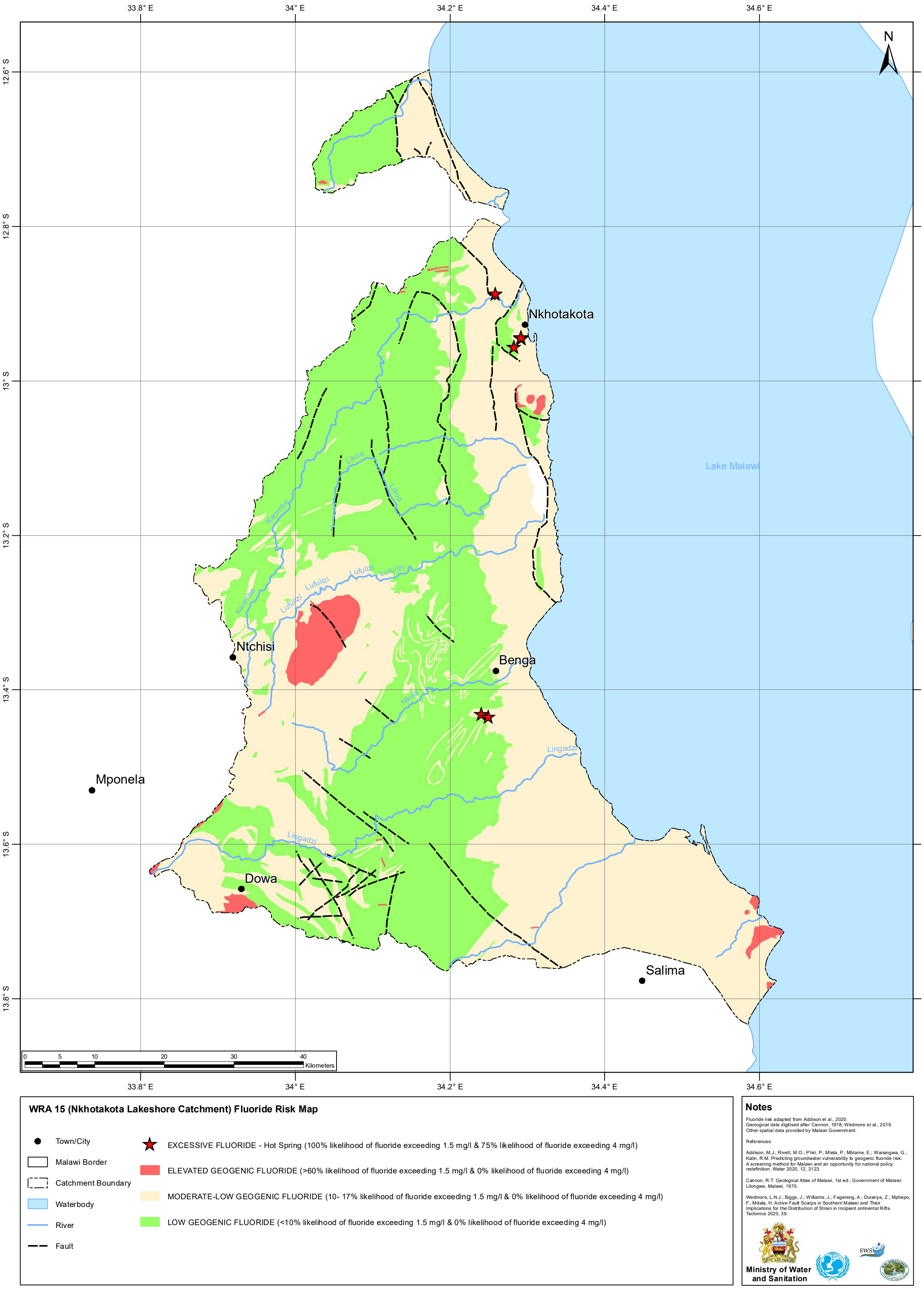


Figure 16 Distribution of chemical species in groundwater within WRA 15 (y-axis = *n* observations).

Fluoride

The prevalence of hot springs resulting from rift faulting places WRA 15 into the **Median Risk** category for fluoride in groundwater. Groundwater data drawn from the recent national-scale assessments (**Figure 17**) reveals though existing analyses are not above 1.5mg/l, hot springs 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. 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 15 is planned and implemented.



WRA 15 (Nkhotakota Lakeshore Catchment) Fluoride Risk Map

Notes

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

References:

Addison, M.J.; Rivett, M.O.; Phiri, P.; Mleta, P.; Mblame, E.; Wanangwa, G.; Kalin, R.M. Predicting groundwater vulnerability to geogenic fluoride risk: A screening method for Malawi and an opportunity for national policy redefinition. Water 2020, 12, 3123.

Cannon, R.T. Geological Atlas of Malawi, 1st ed.; Government of Malawi: Lilongwe, Malawi, 1970.

Wedmore, L.N.J.; Biggs, J.; Williams, J.; Fagereng, A.; Dulanya, Z.; Mphepo, F.; Mdala, H. Active Fault Scarps in Southern Malawi and Their Implications for the Distribution of Strain in Incipient ontinental Rifts. Tectonics 2020, 39.

Figure 17. Groundwater Fluoride Risk Map WRA 15 (after Addison et. al. 2021).

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 not sample WRA 15 where arsenic risks may exist due to the presence of hot springs, but 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 15 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 15.

	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**
15A	289,432	313,301	338,829	364,931	392,462	358,718	1,111,143,277	1,333,372
15B	241,874	258,078	278,085	297,441	316,615	305,601	916,754,620	1,100,106
15C	20,601	21,161	22,108	22,901	23,365	28,195	74,698,381	89,638
WRA 15	**551,907**	**592,540**	**639,021**	**685,273**	**732,442**	**692,514**	**2,102,596,277**	**2,523,116**

Modelled results for water resource unit 15 (**Table 6**) show a calculated total of 2,523,116 metric tonnes of faecal matter loading over the 10-year period (2012-2022). Over the 10-year period the modelled number of pit latrine users in the region increased by 140,607.

WRA 15 covers roughly 3.89% 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, 7,896 metric tonnes of fertiliser would be used in WRA 15 per year, the modelled results suggest there is 32 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

References

Geological Bulletins

Walter MJ, 1972. The Geology of the Lilongwe-Dowa area, Bulletin No. 26

Bellingham KS, Bromley J, 1973. The Geology of the Ntchisi-Middle Bua area, Bulletin No. 27

Walter MJ, 1972. The Geology of the Salima-Mvera Mission area, Bulletin No. 30

Relevant Hydrogeological Reconnaissance Maps

Chilton PJ, Magulu W, 1987. Hydrogeological Reconnaissance Map: Sheet 3 - Mzuzu

Mauluka LH, Phiri G, 1987. Hydrogeological Reconnaissance Map: Sheet 4 - Nkhotakota

Bibliography WRA 15

Boke-Olén, N., Abdi, A., Hall, O. et al. High-resolution African population projections from radiative forcing and socio-economic models, 2000 to 2100. Sci Data 4, 160130 (2017). https://doi.org/10.1038/sdata.2016.130

Donga TK, Eklo OM. Environmental load of pesticides used in conventional sugarcane production in Malawi. Crop protection 2018; 108, 71-77. https://doi.org/10.1016/j.cropro.2018.02.012

Hurtt, G. C., Chini, L., Sahajpal, R., Frolking, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinimann, A., Humpenöder, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krisztin, T., Lawrence, D., Lawrence, P., Ma, L., Mertz, O., Pongratz, J., Popp, A., Poulter, B., Riahi, K., Shevliakova, E., Stehfest, E., Thornton, P., Tubiello, F. N., van Vuuren, D. P., and Zhang, X.: Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, Geosci. Model Dev., 13, 5425–5464, https://doi.org/10.5194/gmd-13-5425-2020

Kalin, R.M.; Mwanamveka, J.; Coulson, A.B.; Robertson, D.J.C.; Clark, H.; Rathjen, J.; Rivett, M.O. Stranded Assets as a Key Concept to Guide Investment Strategies for Sustainable Development Goal 6. Water 2019, 11, 702. https://doi.org/10.3390/w11040702

Kanyerere T. *Assessment of groundwater management for domestic use from IWRM perspective in upper Limphasa river catchment, Malawi*. Doctoral dissertation, University of the Western Cape; 2012. http://hdl.handle.net/11394/4055 .

Kanyerere T, Levy J, Xu Y, Saka J. Assessment of microbial contamination of groundwater in upper Limphasa River catchment, located in a rural area of northern Malawi. *Water SA*, 2012; *38(4)*, 581-596. https://doi.org/10.4314/wsa.v38i4.14

Alan M MacDonald *et al* 2021 *Environ. Res. Lett.* **16** 034012 https://doi.org/10.5285/45d2b71c-d413-44d4-8b4b-6190527912ff.

Nyirenda TM, Mapoma HW, Msiska A, Dzonzi-Undi J, Jumbo S. Hydrogeochemical assessment of groundwater quality in Salima and Nkhotakota Districts, Malawi. International Journal of Science and Research 2015; 14, 1568-76. https://www.academia.edu/16281830/Hydrogeochemical_Assessment_of_Groundwater_Quality_in_Salima_and_Nkhotakota_Districts_Malawi

Rivett, MO; HL Robinson, LM Wild, J Melville, L McGrath, P Phiri, J Flink, GJ Wanangwa, P Mlwta, SSP MacLeod, AVM Miller, RM Kalin (2018), Arsenic occurrence in Malawi groundwater, Journal of Applied Sciences and Environmental Management, Vol 22, No 11, http://dx.doi.org/10.4314/jasem.v22i11.16

Rivett, Micheal O., Laurent-Charles Tremblay-Levesque, Ruth Carter, Rudi C.H. Thetard, Morris Tengatenga, Ann Phoya, Emma Mbalame, Edwin Mchilikizo, Steven Kumwenda, Prince Mleta, Marc J. Addison, Robert M. Kalin, Acute health risks to community hand-pumped groundwater supplies following Cyclone Idai flooding, Science of The Total Environment, Volume 806, Part 2, 2022, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.150598

Stevens FR, Gaughan AE, Linard C, Tatem AJ (2015) Disaggregating Census Data for Population Mapping Using Random Forests with Remotely-Sensed and Ancillary Data. PLoS ONE 10(2): e0107042. https://doi.org/10.1371/journal.pone.0107042

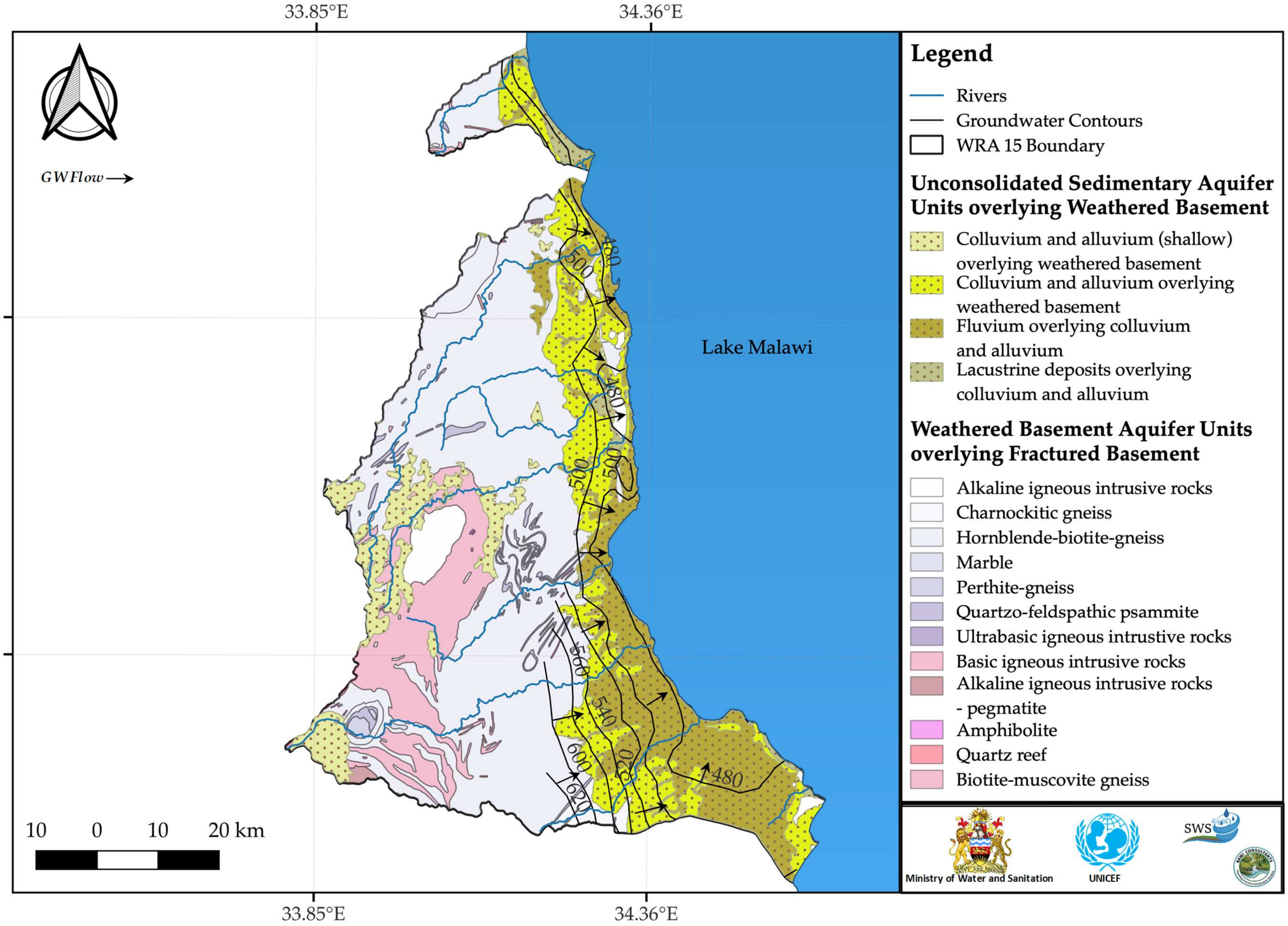
World bank 2022. https://data.worldbank.org/indicator/AG.CON.FERT.ZS?locations=MW. Accessed 28/02/2022

WorldPop. Malawi 100m Population, Version 2. University of Southampton. www.worldpop.org. Accessed 28/02/2022

Water Resource Unit (WRA) 15 Figures

Figure WRA 15.0: Aquifer Units and Groundwater Level Contours Water Resources Area 15

Figure WRA 15.0: Aquifer Units and Groundwater Level Contours WRA 15



WRU 15A Figures

Figure WRU 15A.1 Land Use and Major Roads

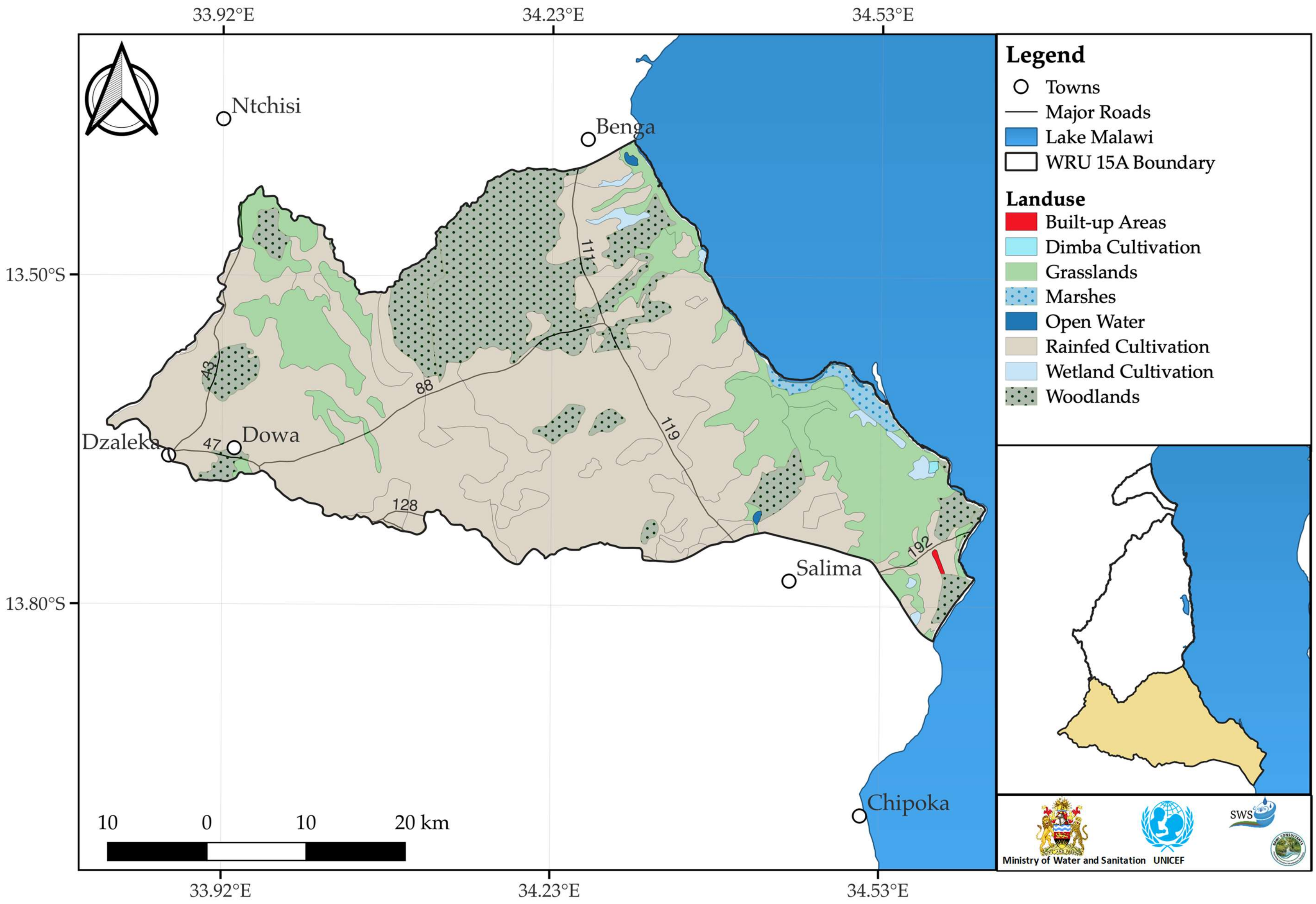


Figure WRU 15A.2 Rivers and Wetlands

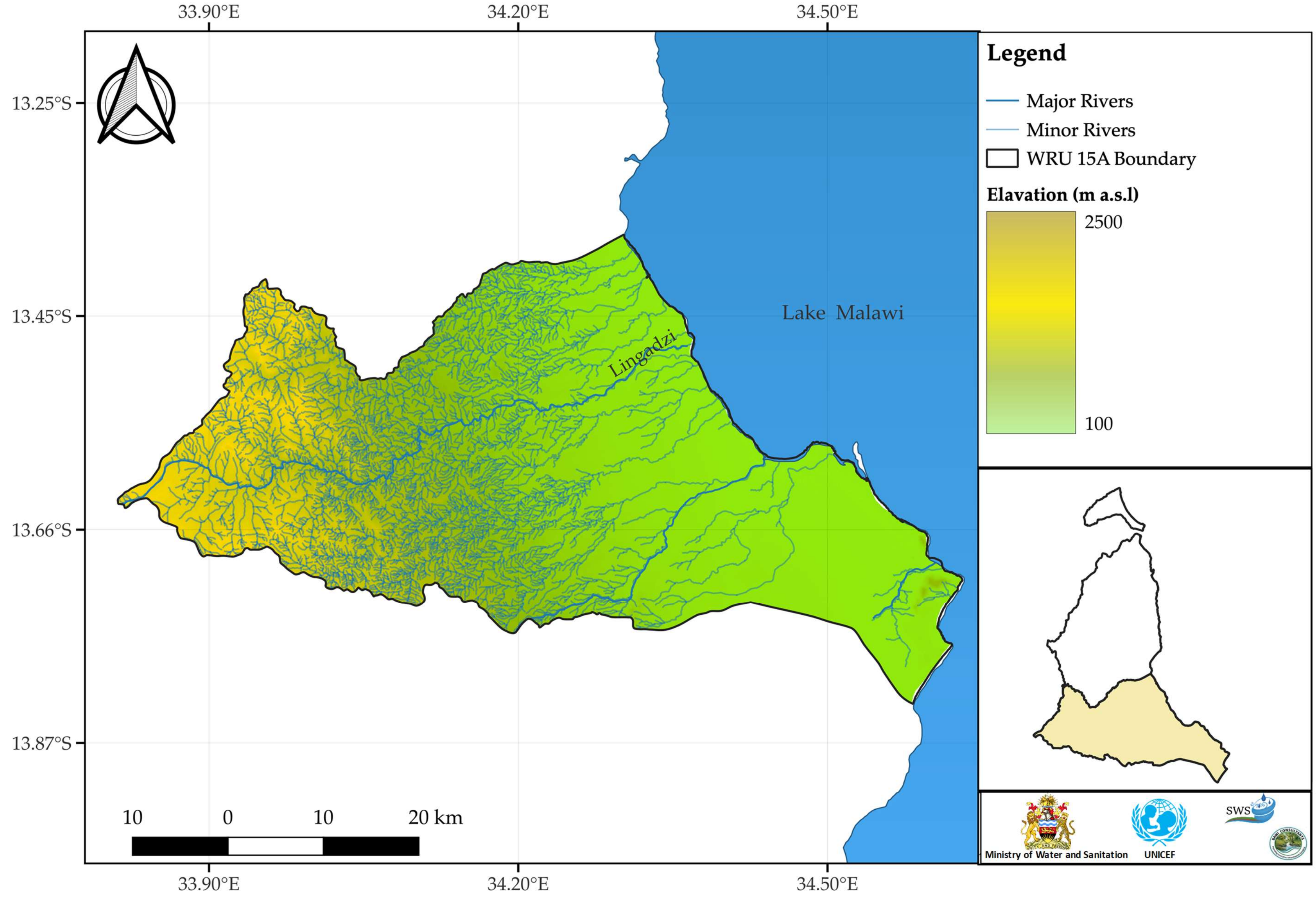


Figure WRU 15A.3 Hydrogeology Units and Water Table

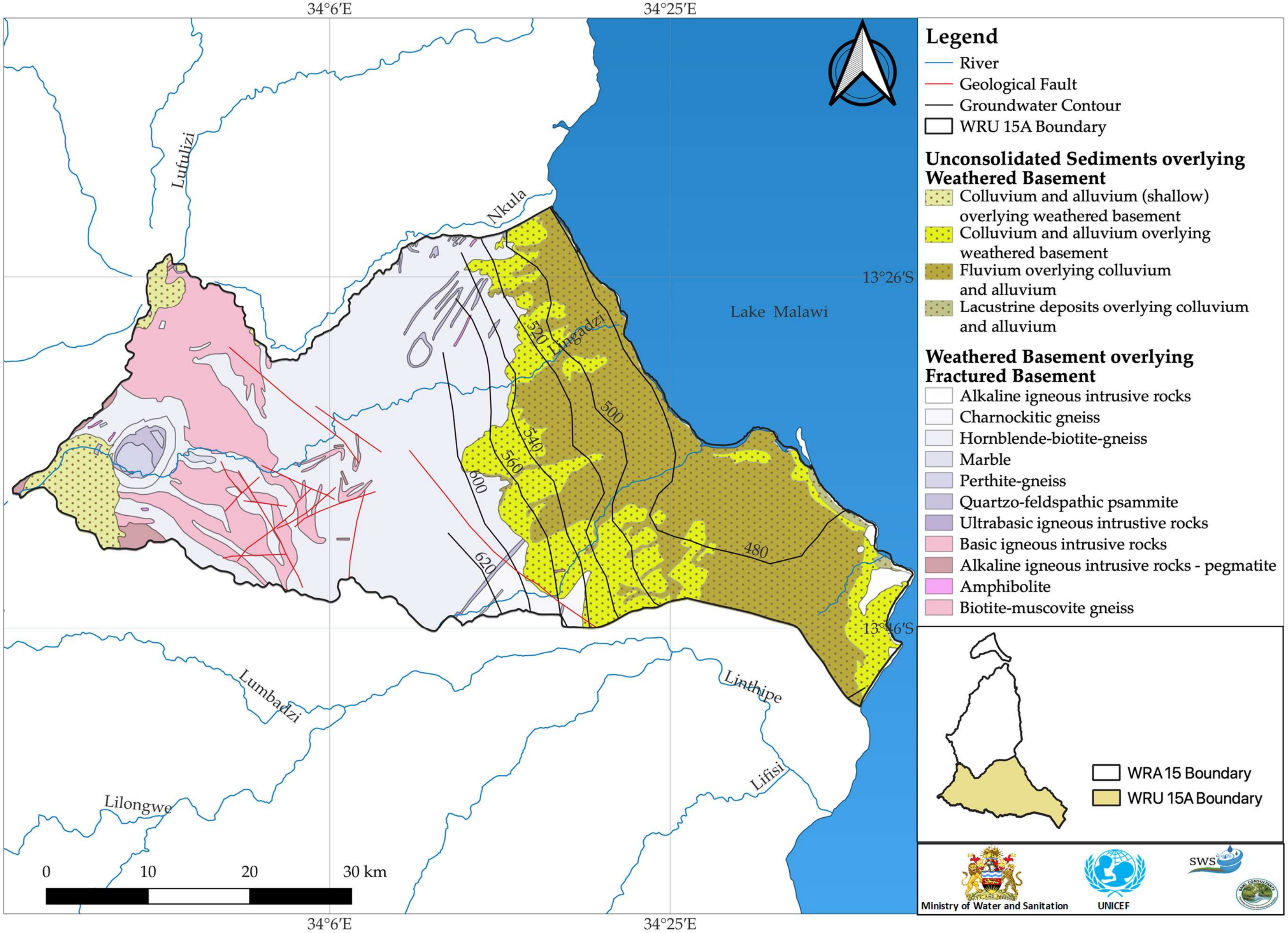


Figure WRU 15A.4 Groundwater Chemistry Distribution Electrical Conductivity

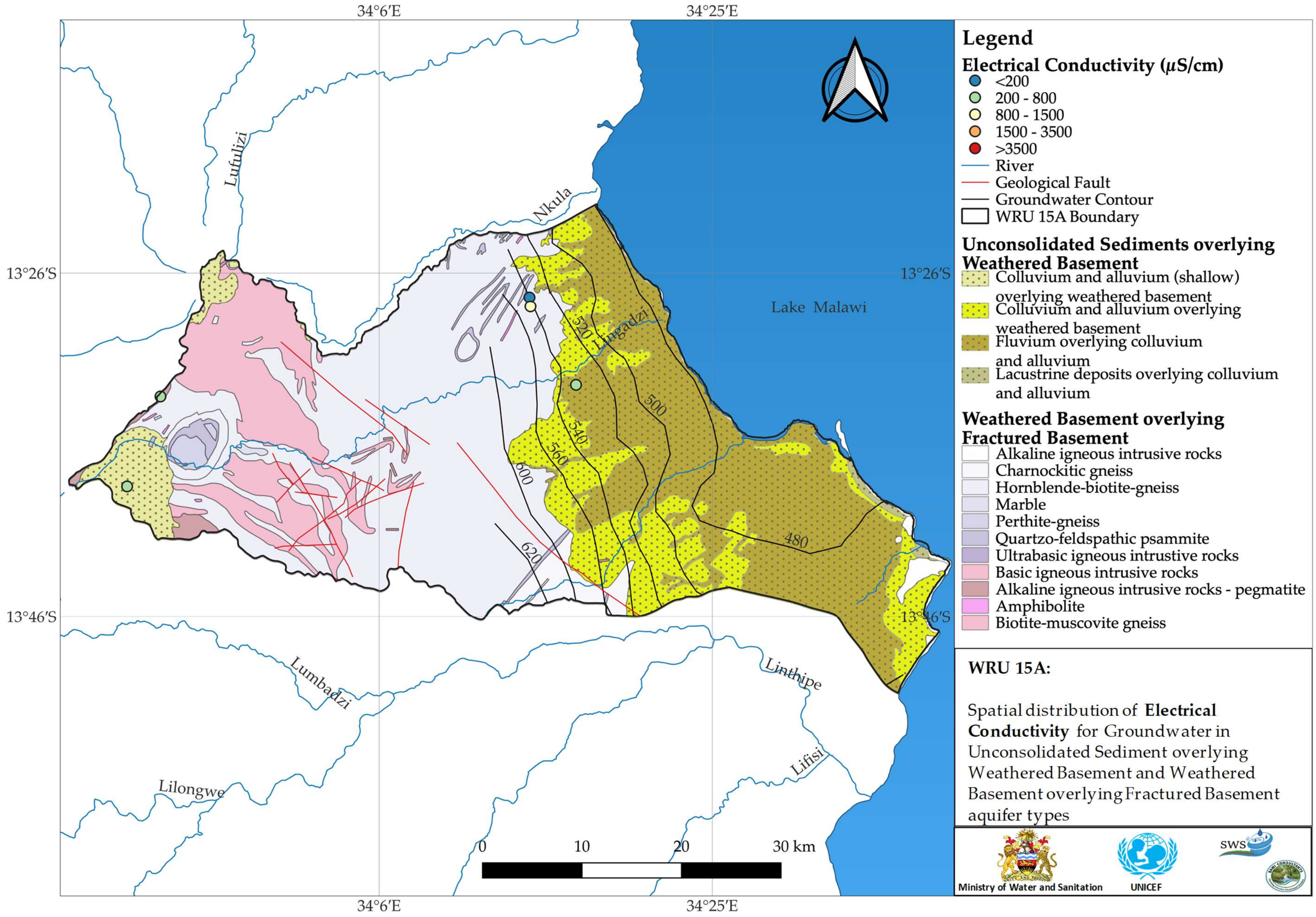


Figure WRU 15A.5 Groundwater Chemistry Distribution Sulphate

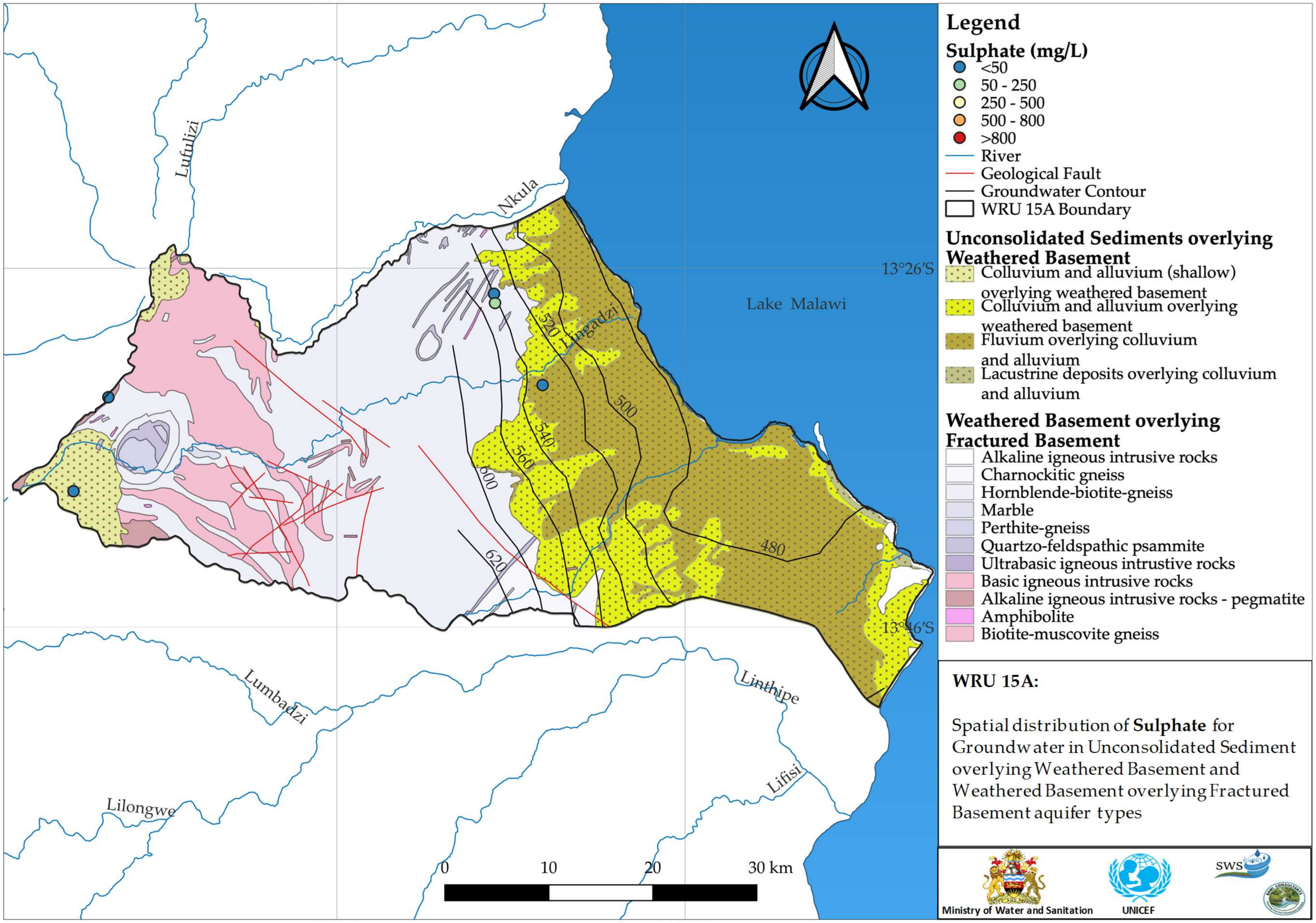
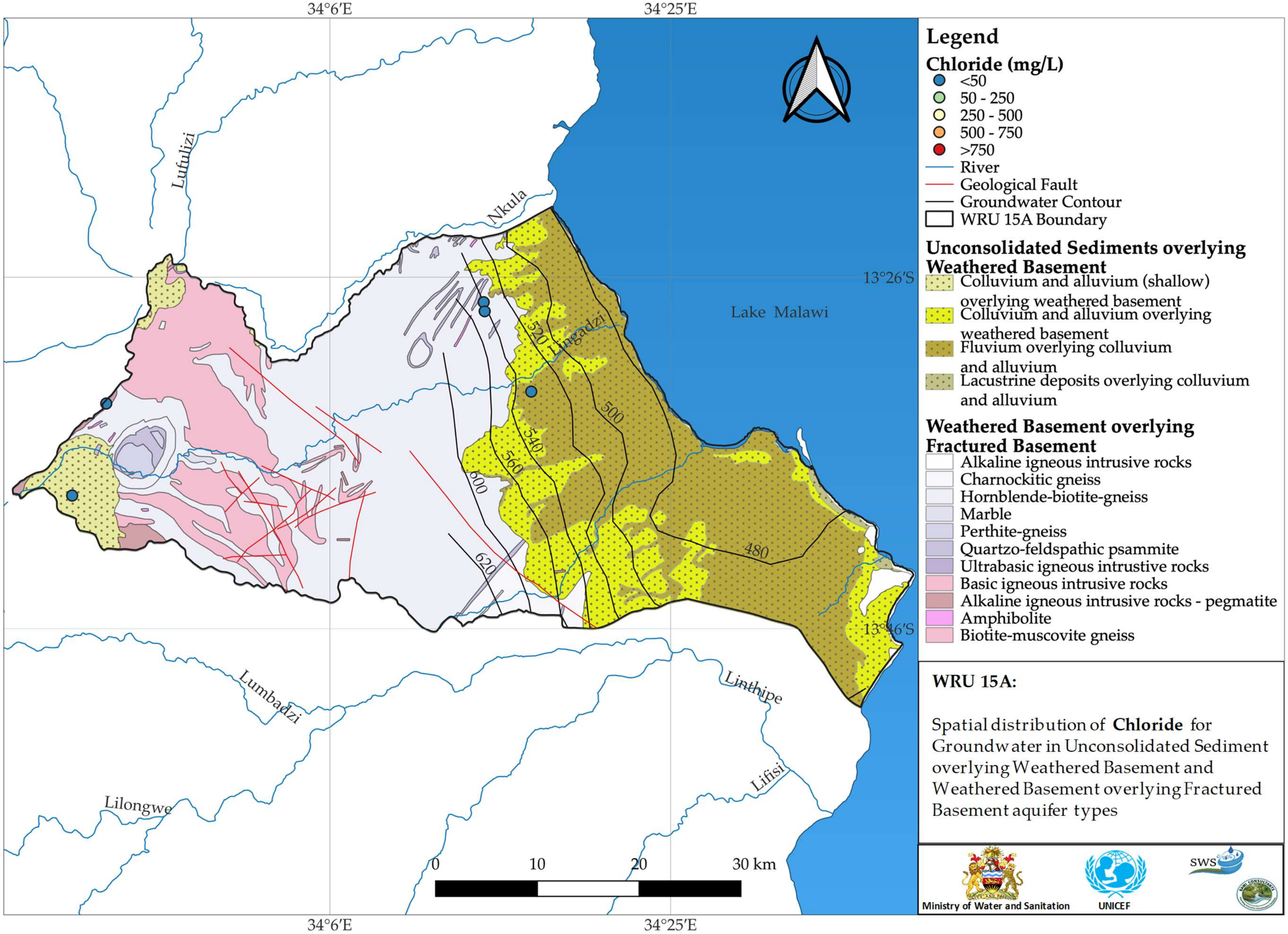


Figure WRU 15A.6 Groundwater Chemistry Distribution Chloride



WRU 15A:

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

Figure WRU 15A.7 Groundwater Chemistry Distribution Sodium

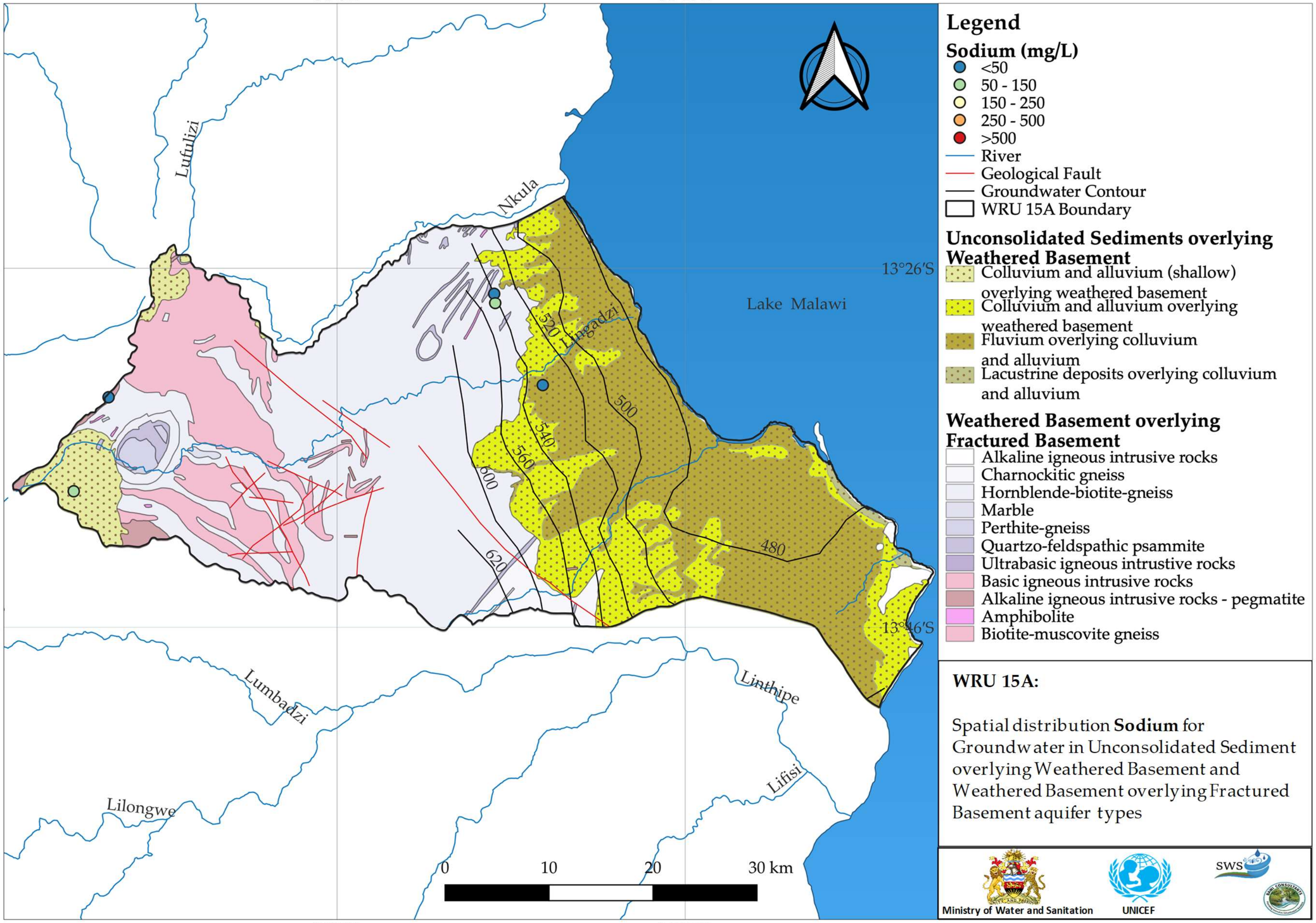
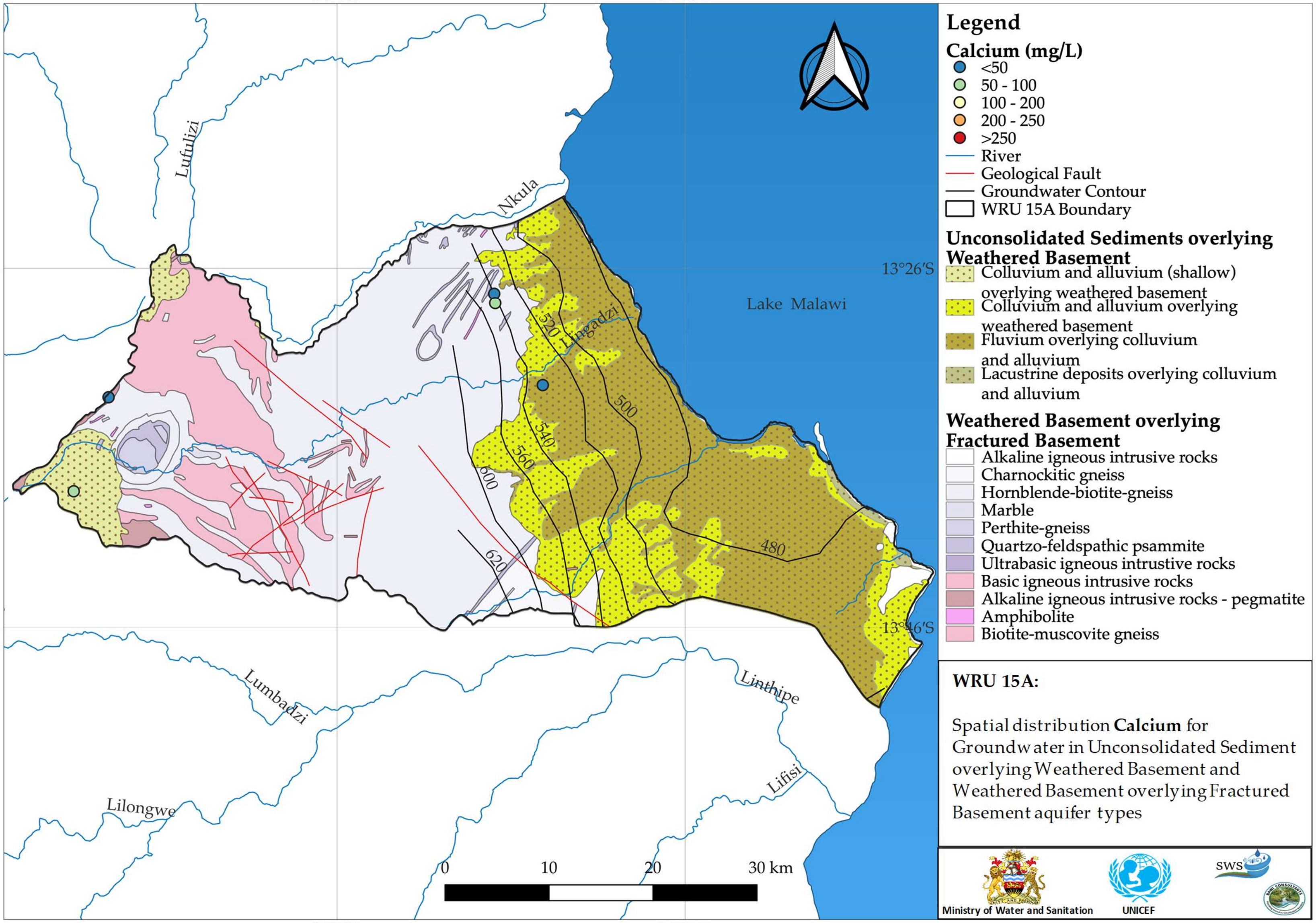


Figure WRU 15A.8 Groundwater Chemistry Distribution Calcium



WRU 15A:

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

Figure WRU 15A.9 Piper Diagram of water quality results with respect to the major aquifer type

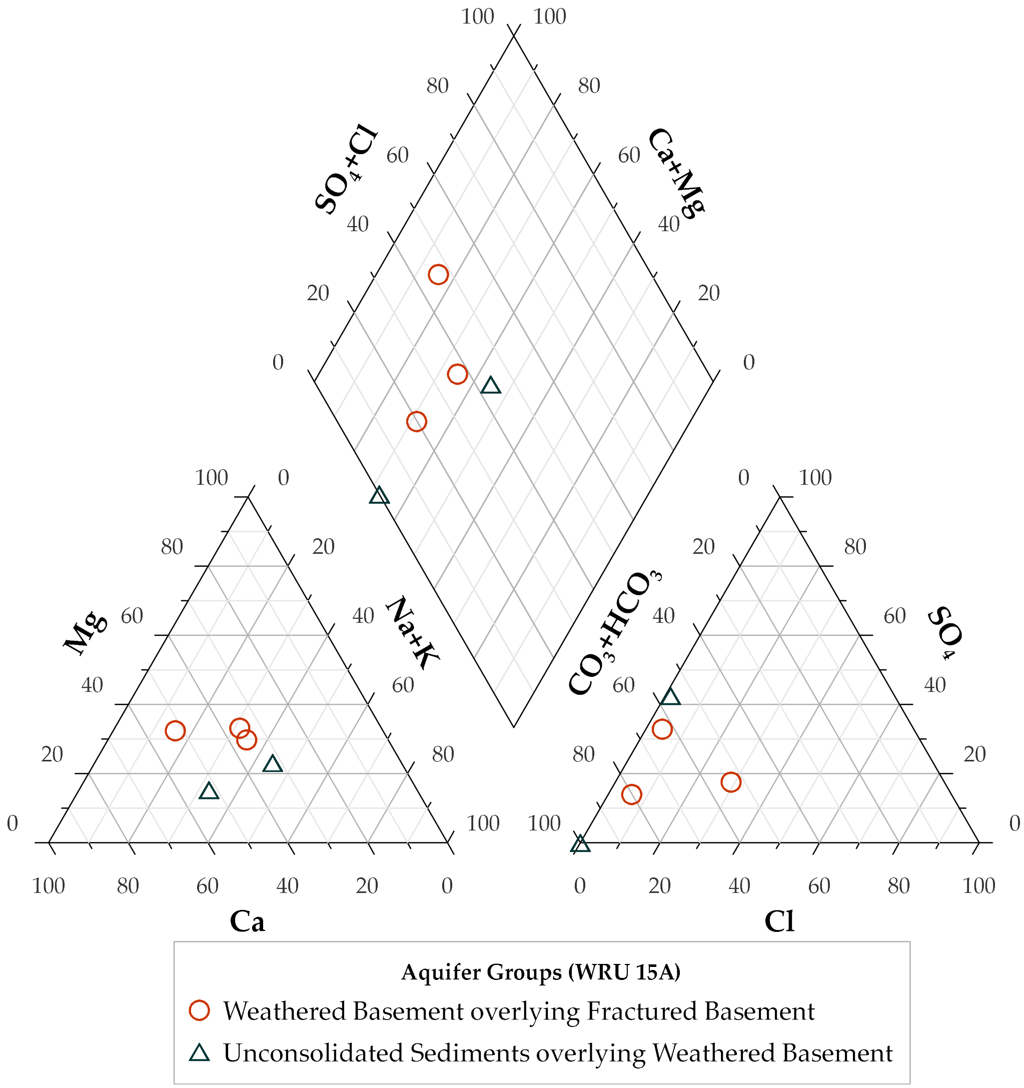
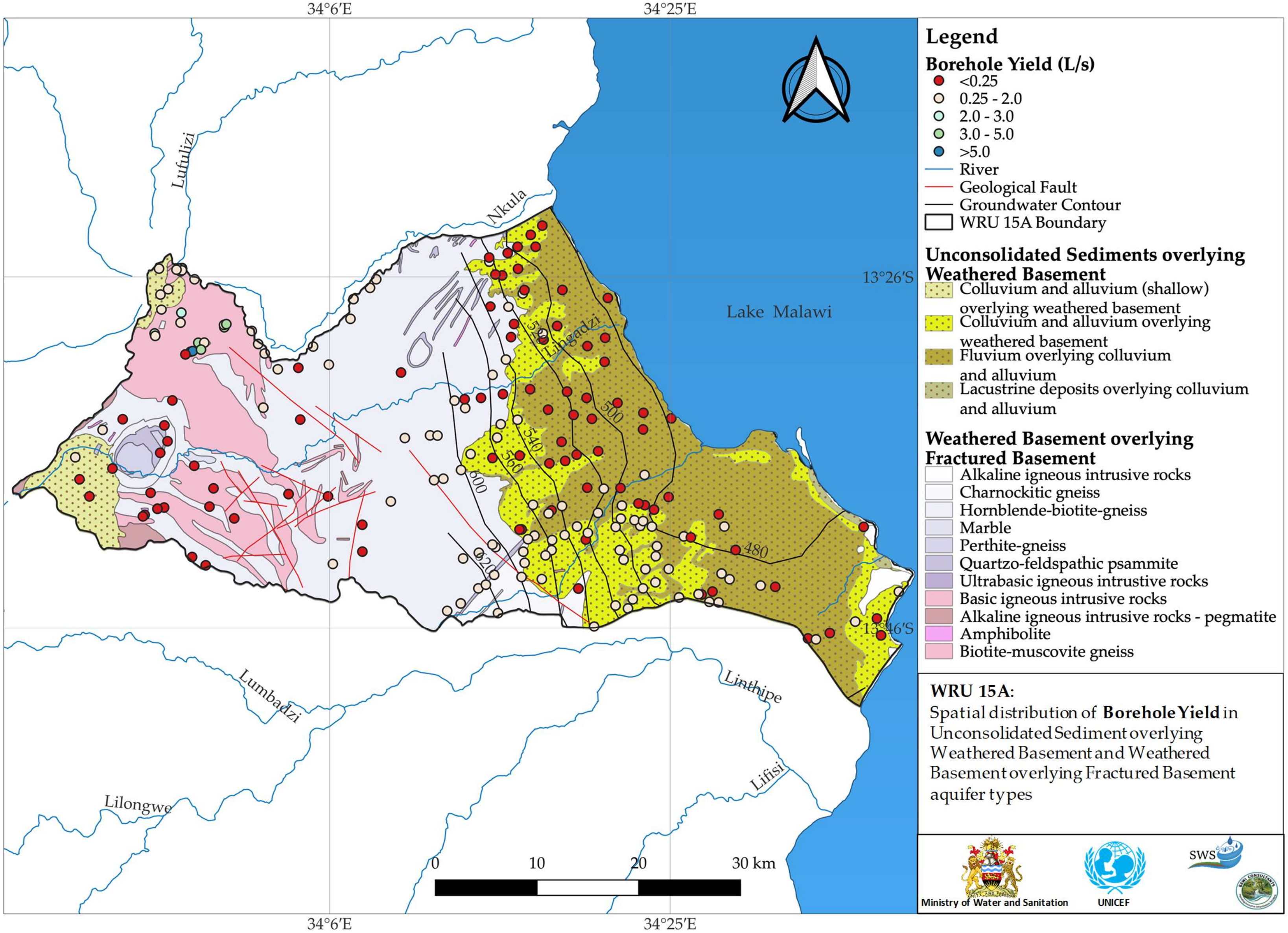


Figure WRU 15A.10 Borehole Yield Map for data held by the Ministry



WRU 15B Figures

Figure WRU 15B.1 Land Use and Major Roads

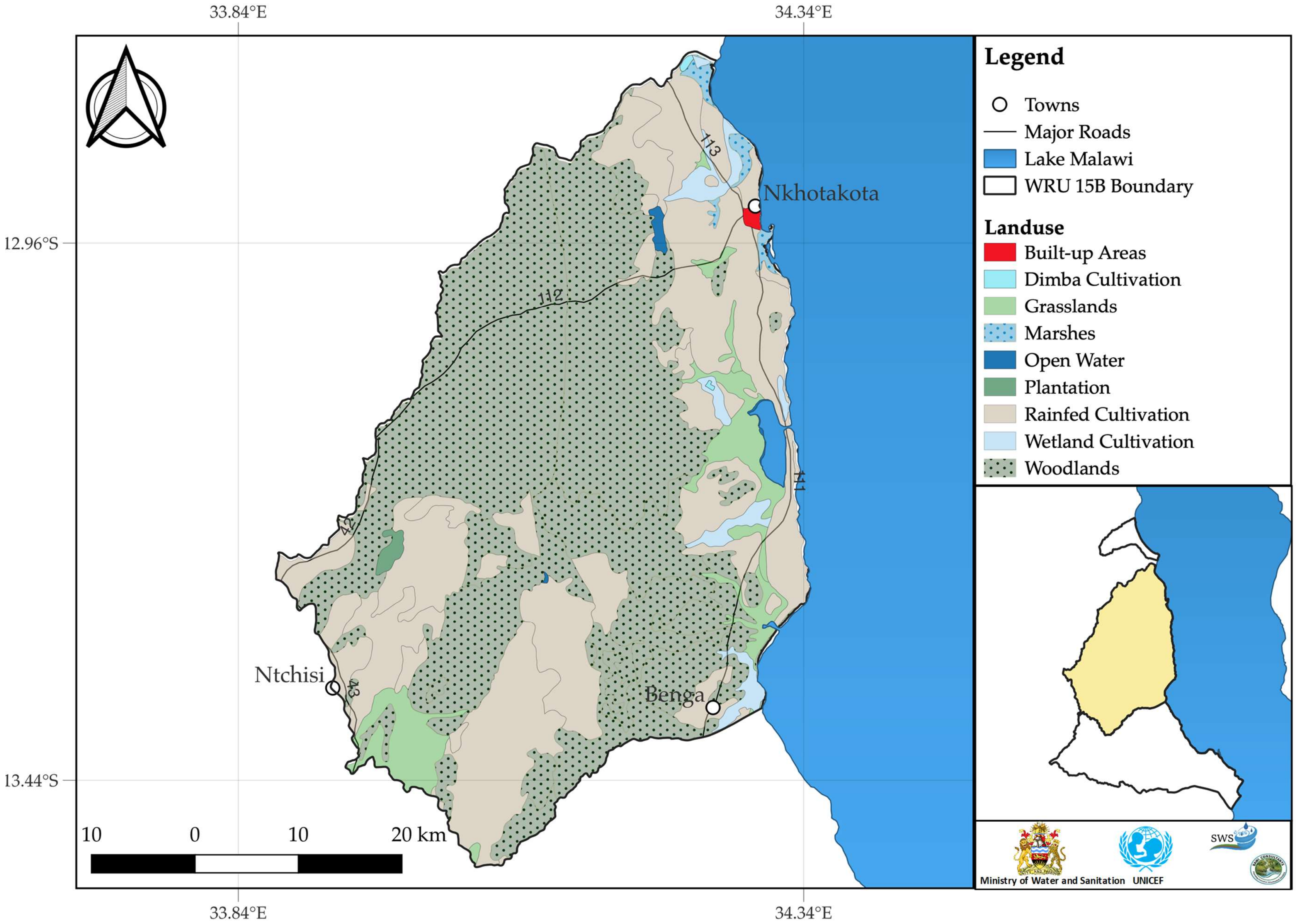


Figure WRU 15B.2 Rivers and Wetlands

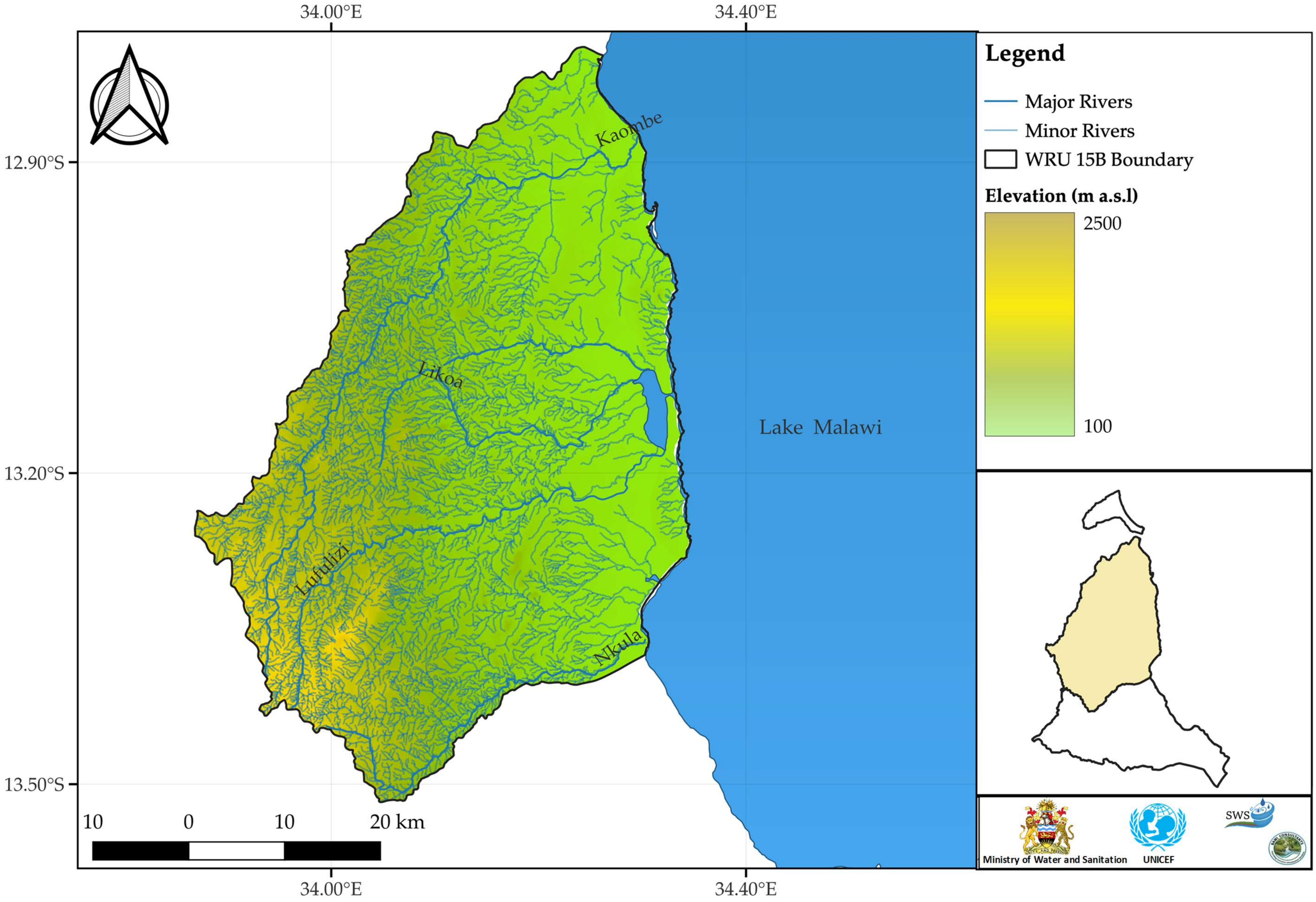


Figure WRU 15B.3 Hydrogeology Units and Water Table

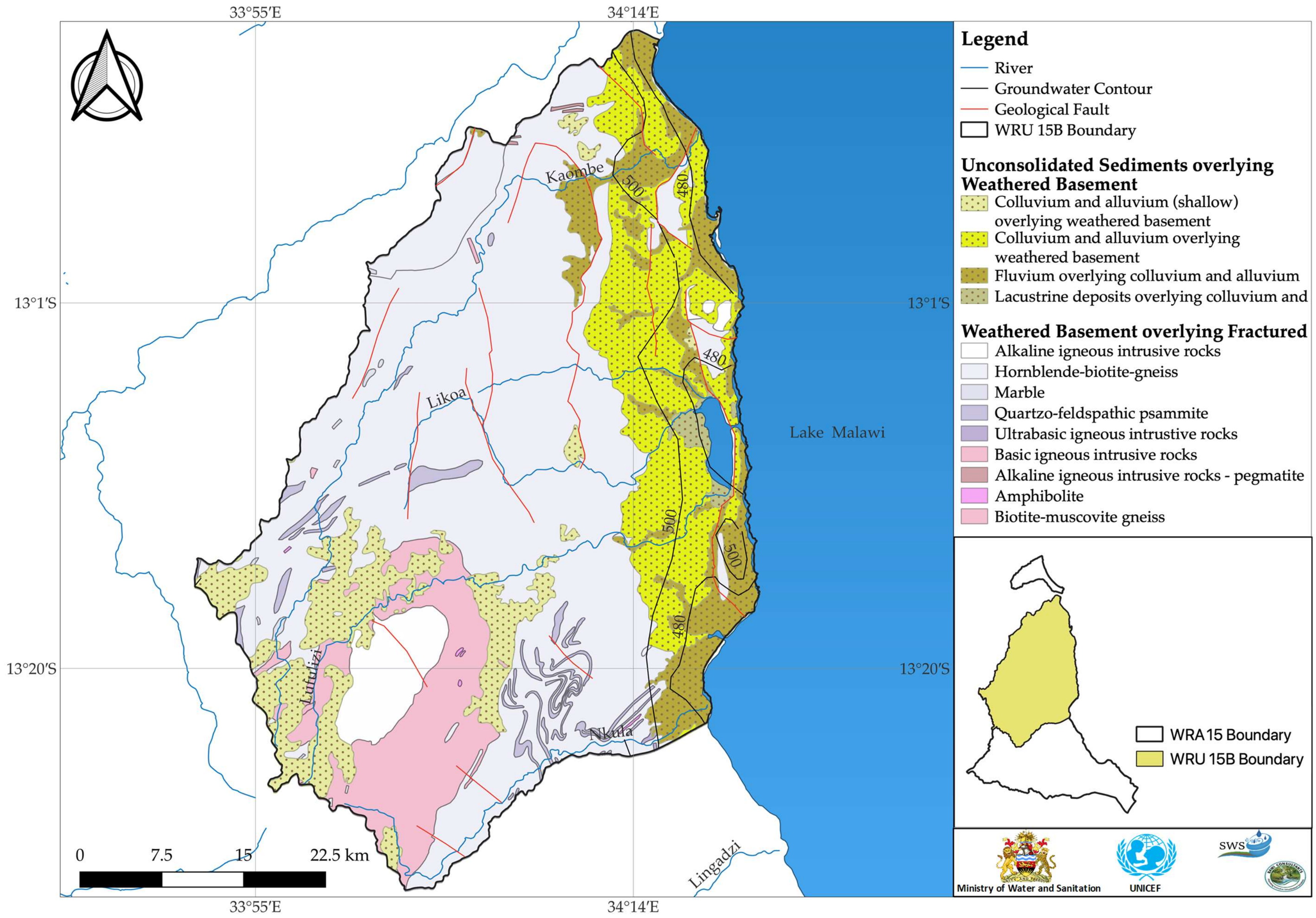


Figure WRU 15B.4 Groundwater Chemistry Distribution Electrical Conductivity

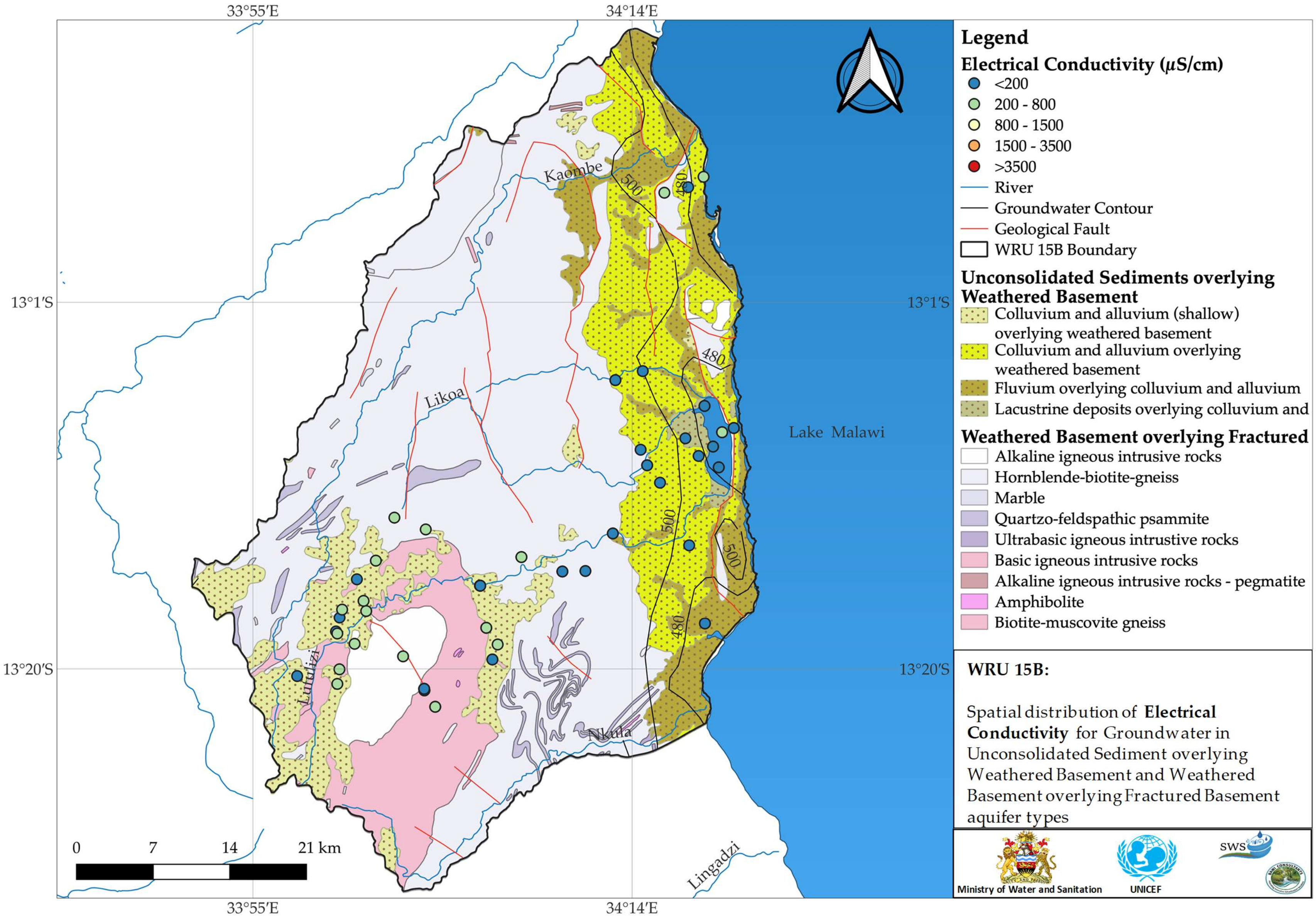
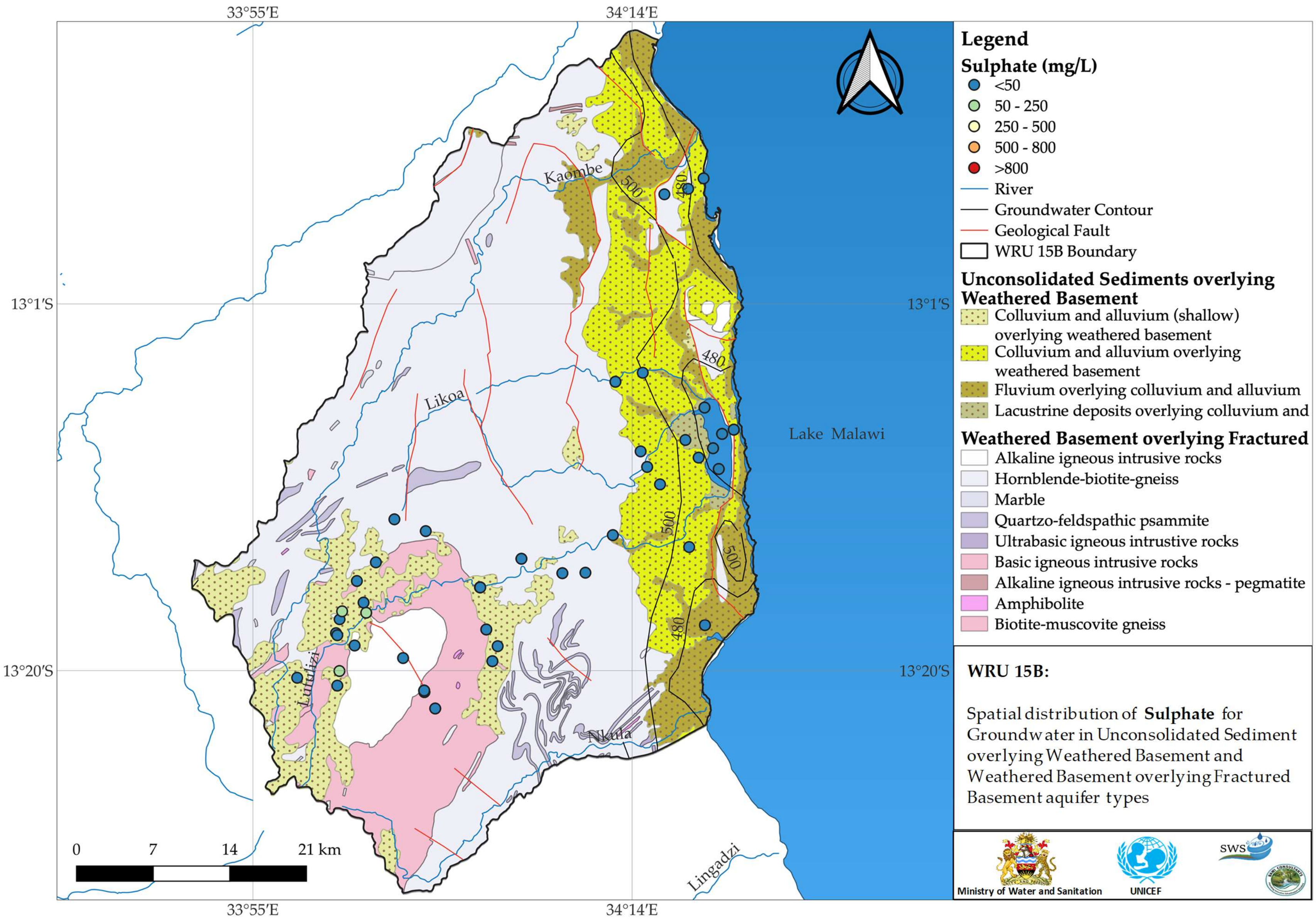


Figure WRU 15B.5 Groundwater Chemistry Distribution of Sulphate



WRU 15B:

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

Figure WRU 15B.6 Groundwater Chemistry Distribution Chloride

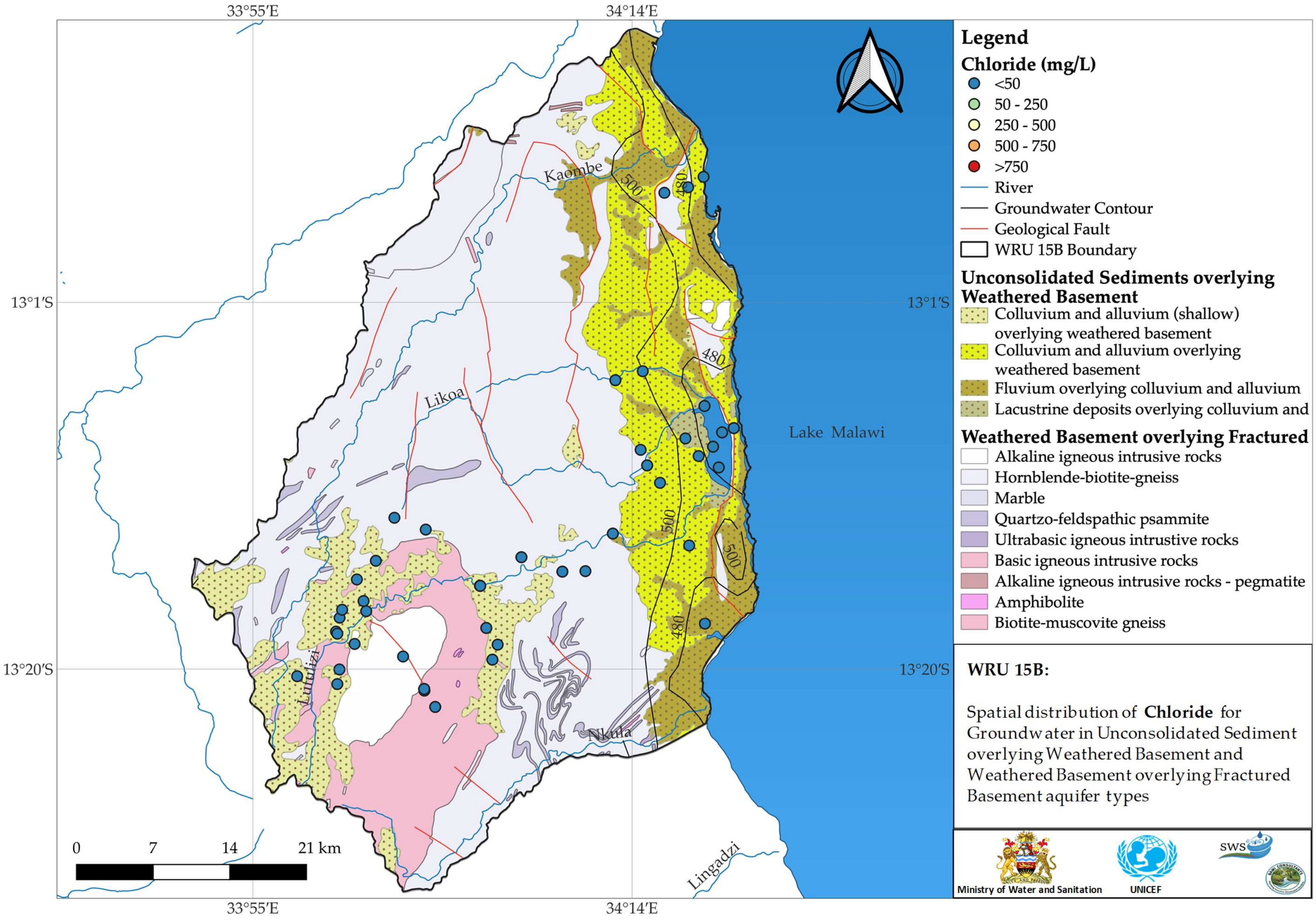


Figure WRU 15B.7 Groundwater Chemistry Distribution Sodium

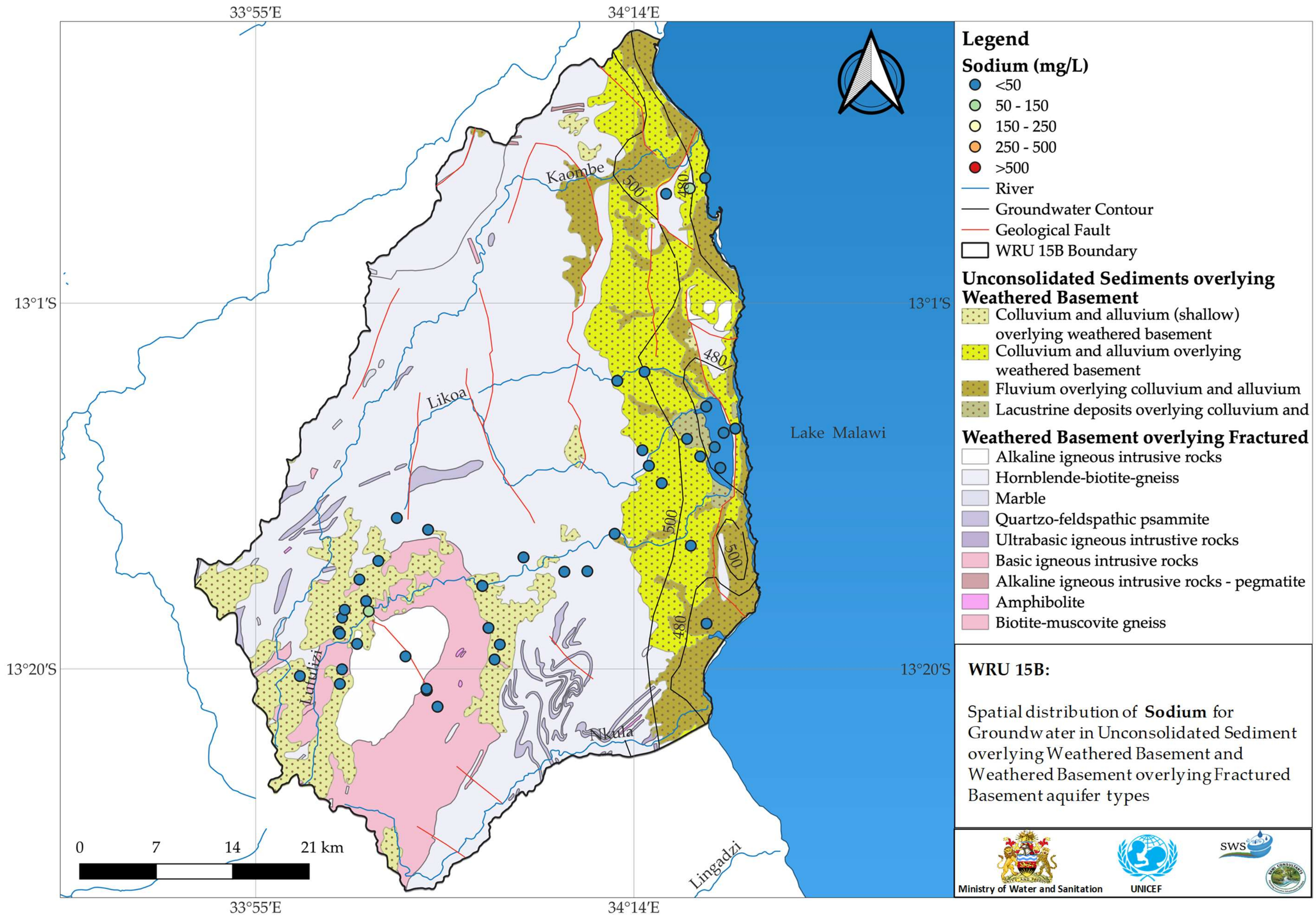
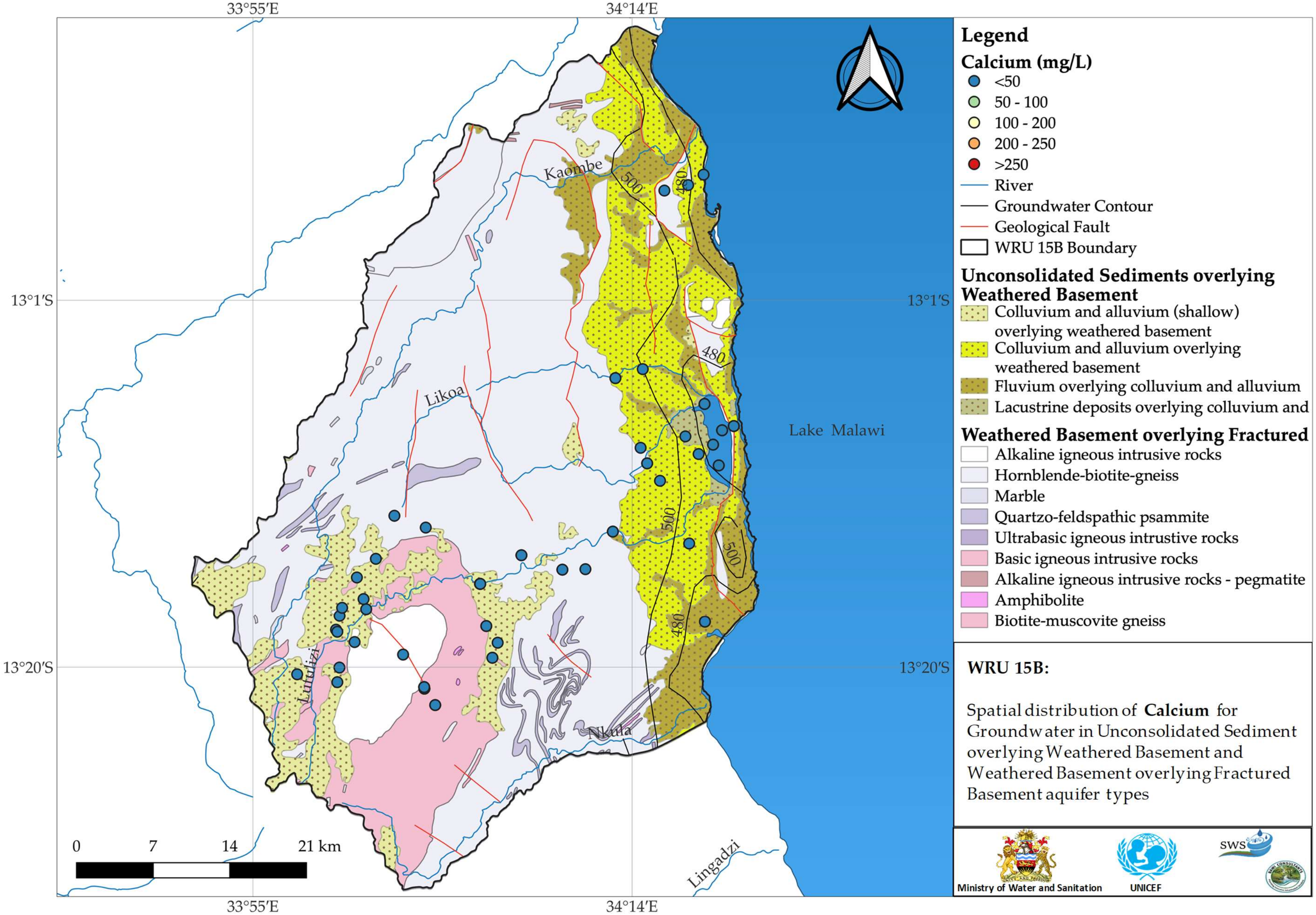


Figure WRU 15B.8 Groundwater Chemistry Distribution Calcium



WRU 15B:

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

Figure WRU 15B.9 Piper Diagram of water quality results with respect to the major aquifer type

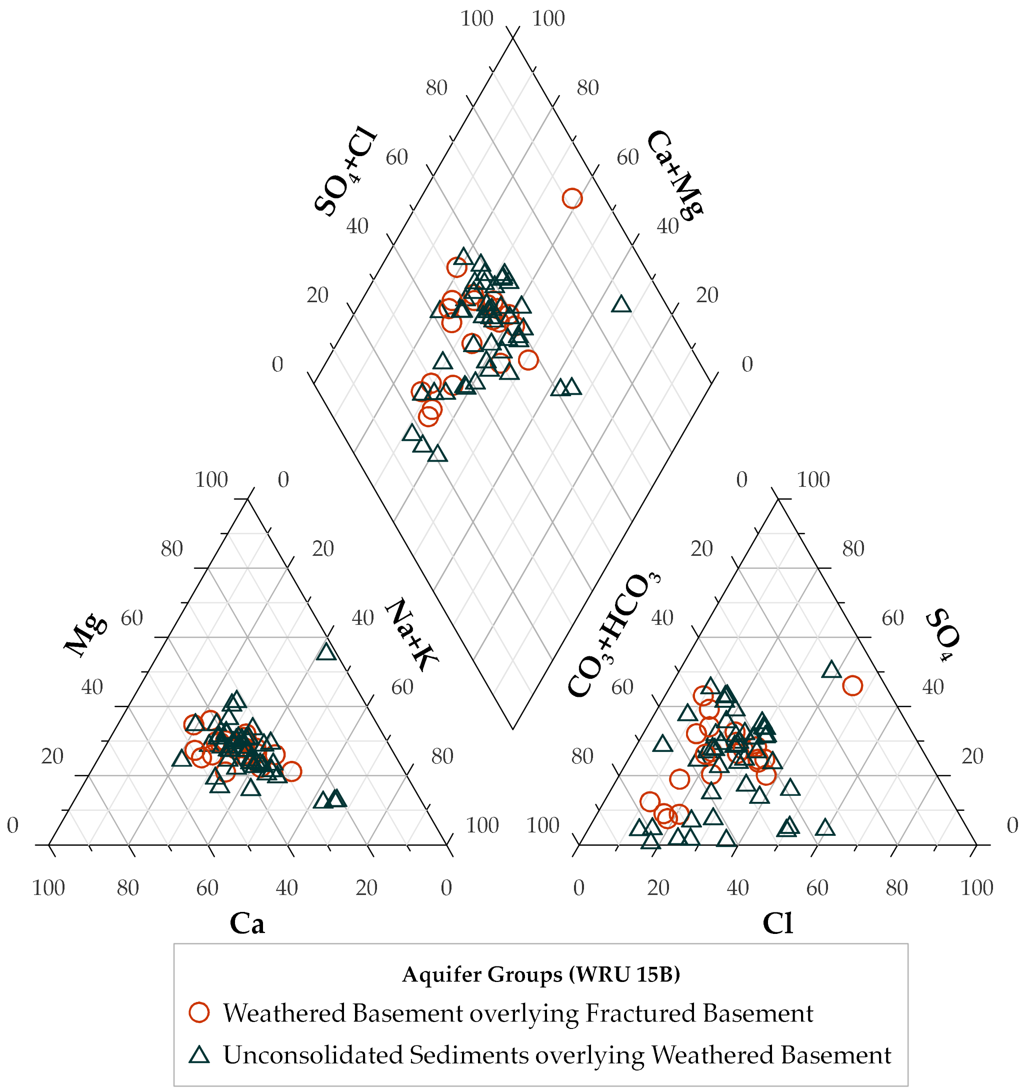
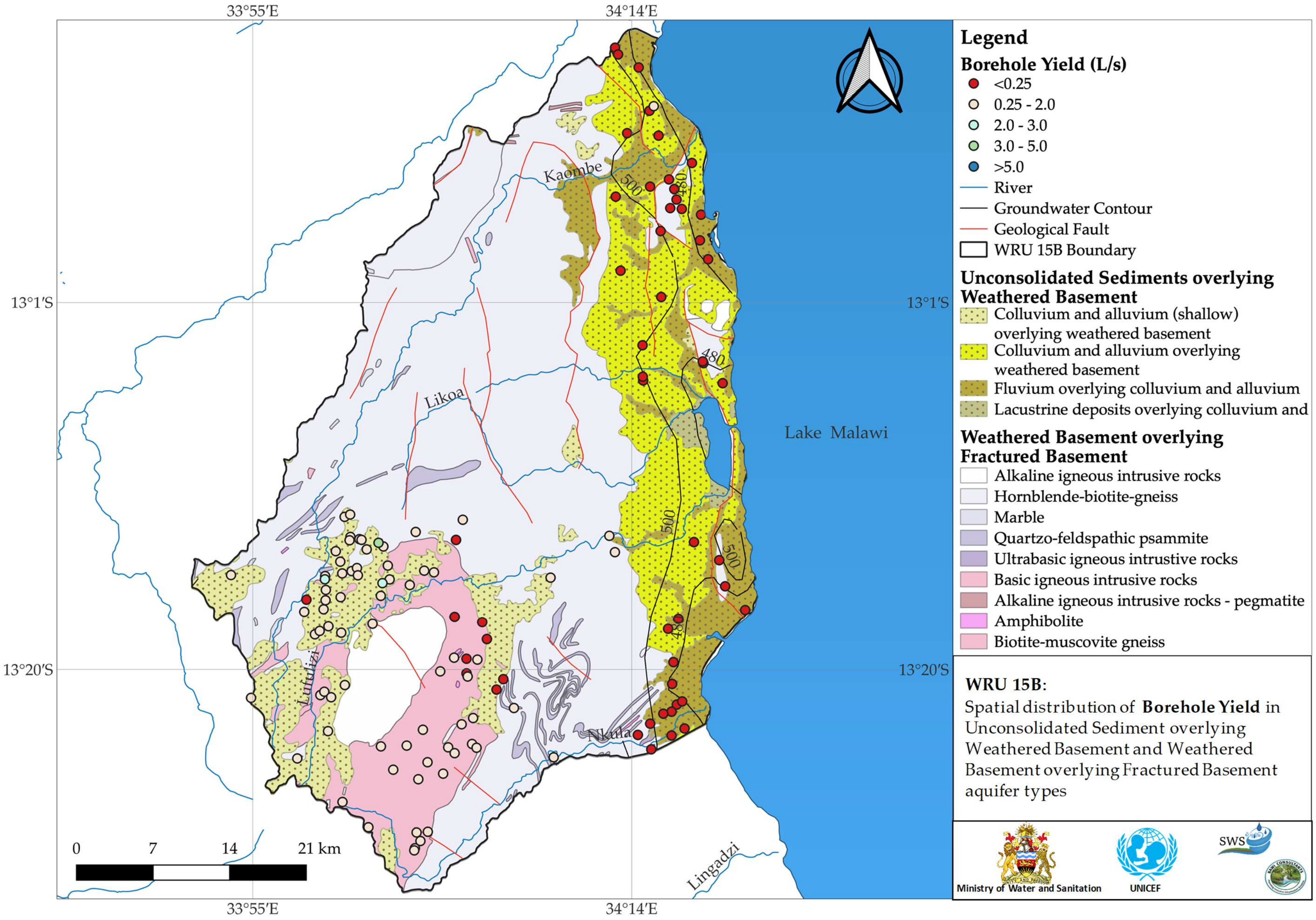


Figure WRU 15B.10 Borehole Yield Map for data held by the Ministry



WRU 15C Figures

Figure WRU 15C.1 Land Use and Major Roads

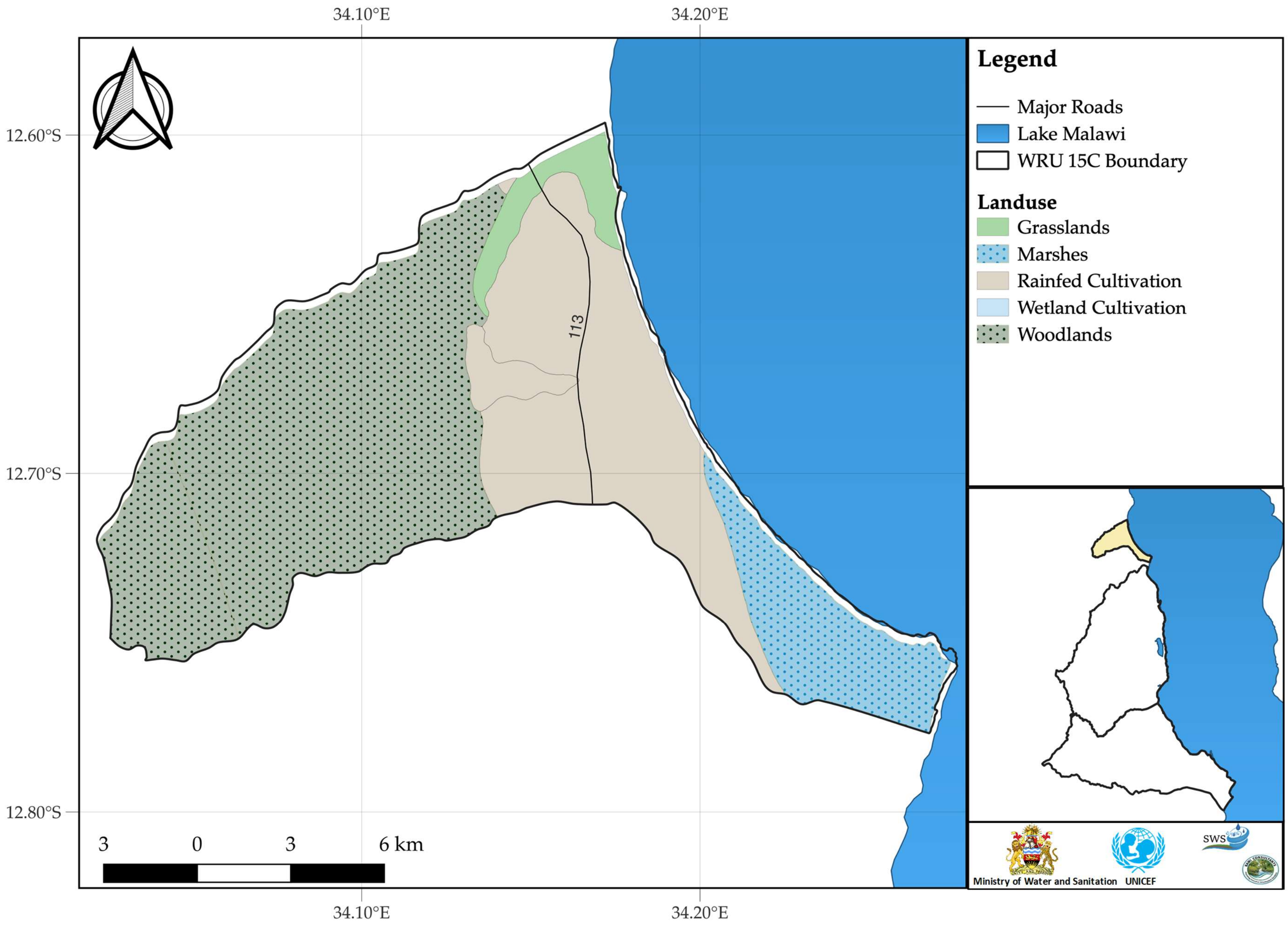


Figure WRU 15C.2 Rivers and Wetlands

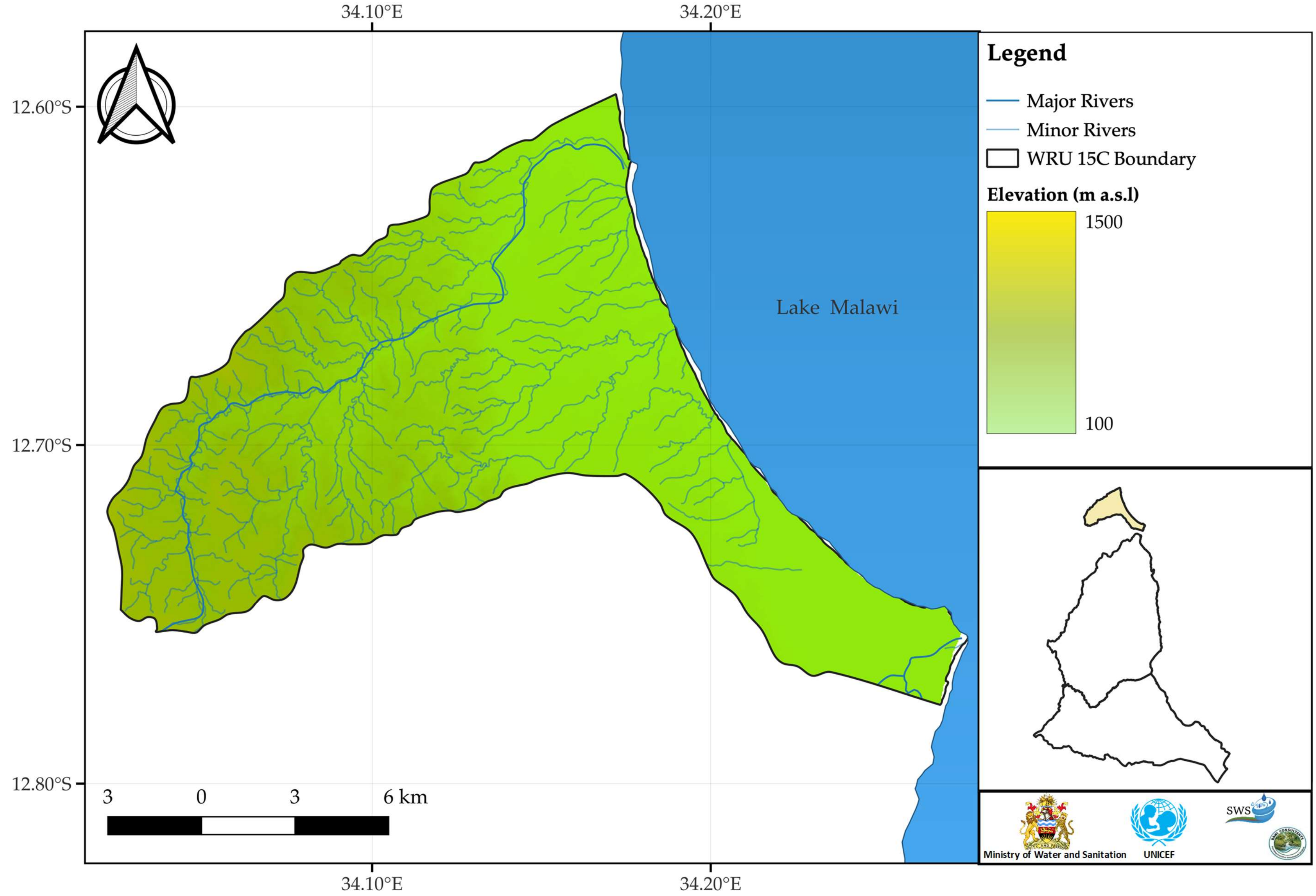


Figure WRU 15C.3 Hydrogeology Units and Water Table

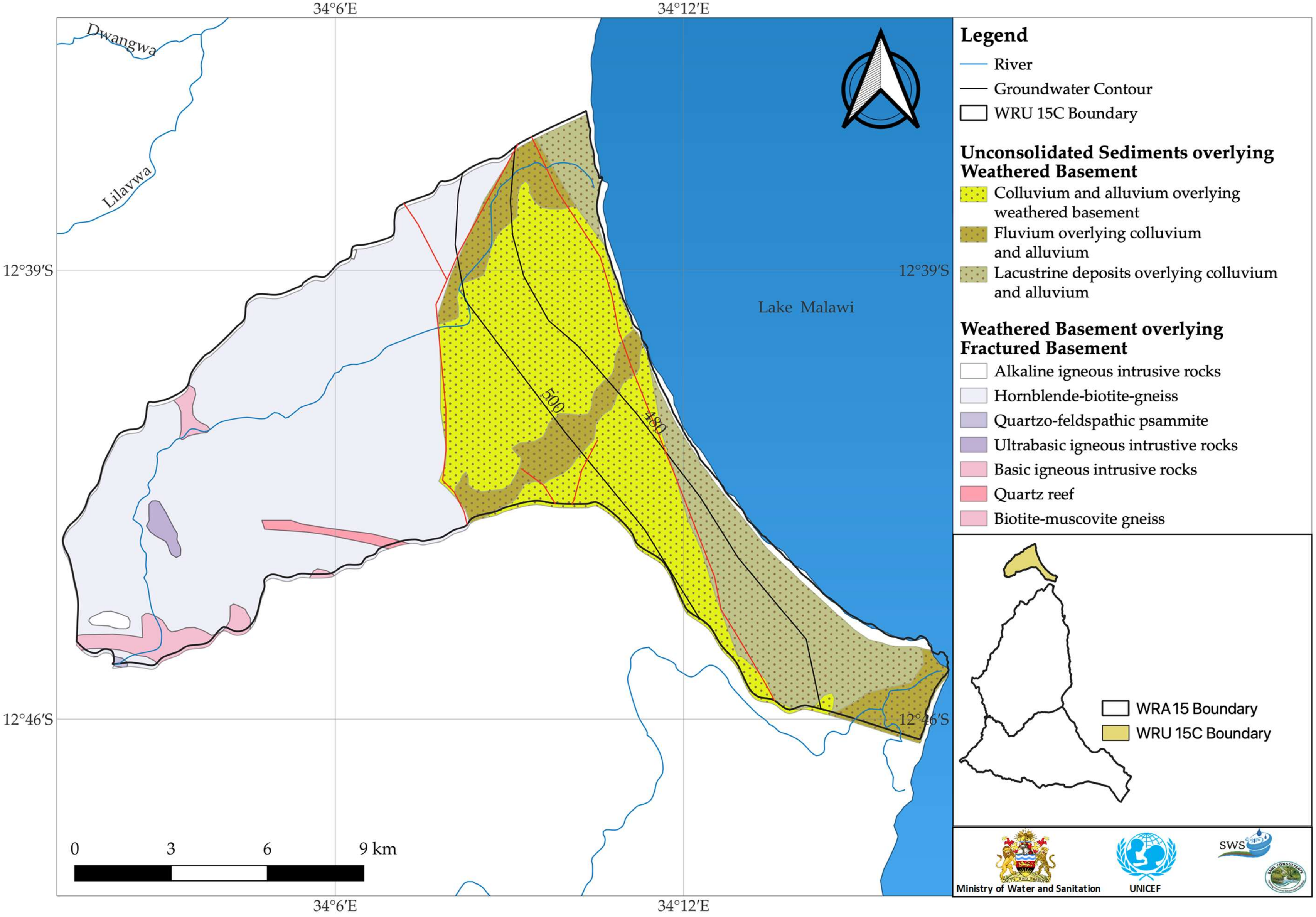


Figure WRU 15C.4 Groundwater Chemistry Distribution Electrical Conductivity

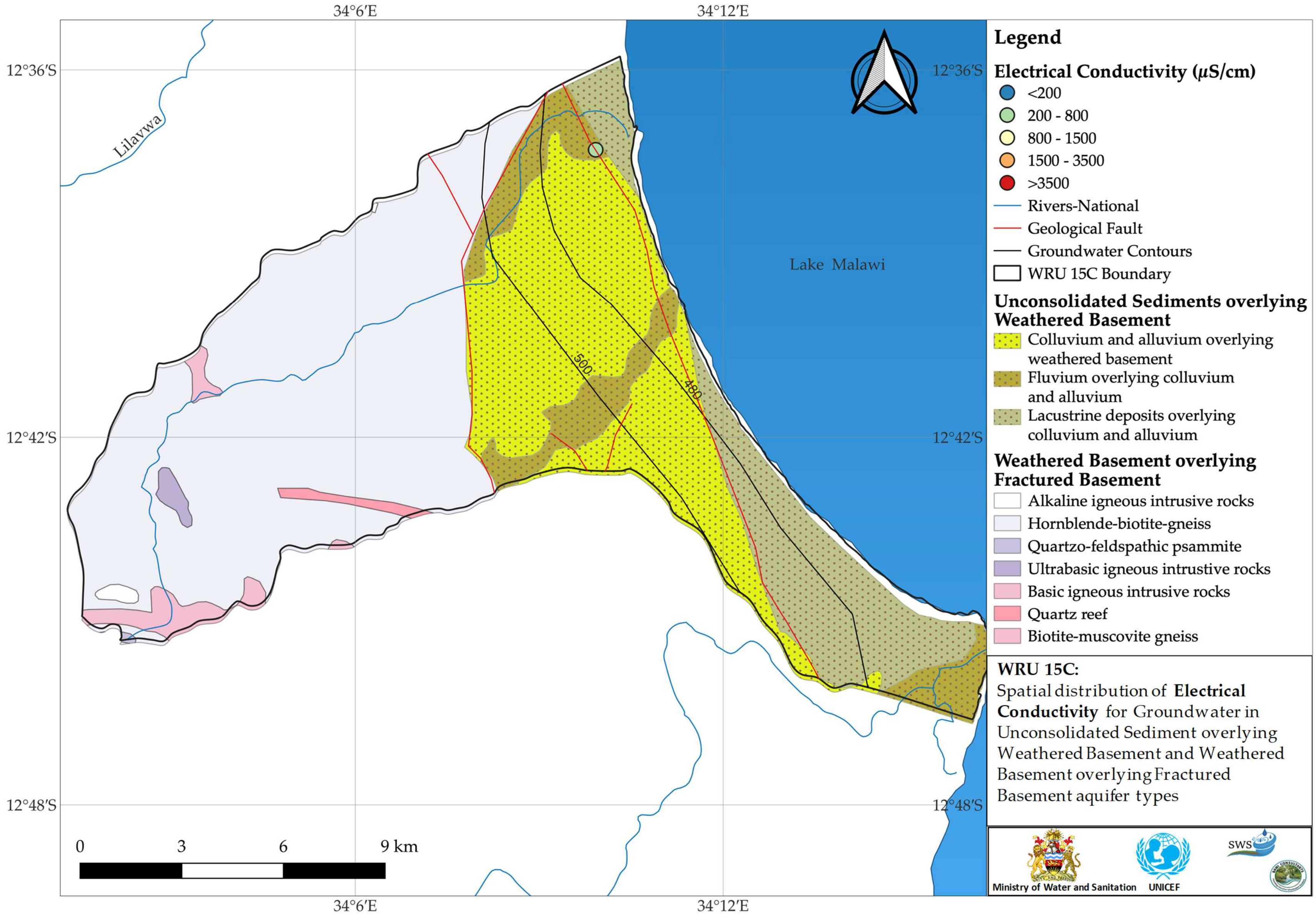


Figure WRU 15C.5 Groundwater Chemistry Distribution of Sulphate

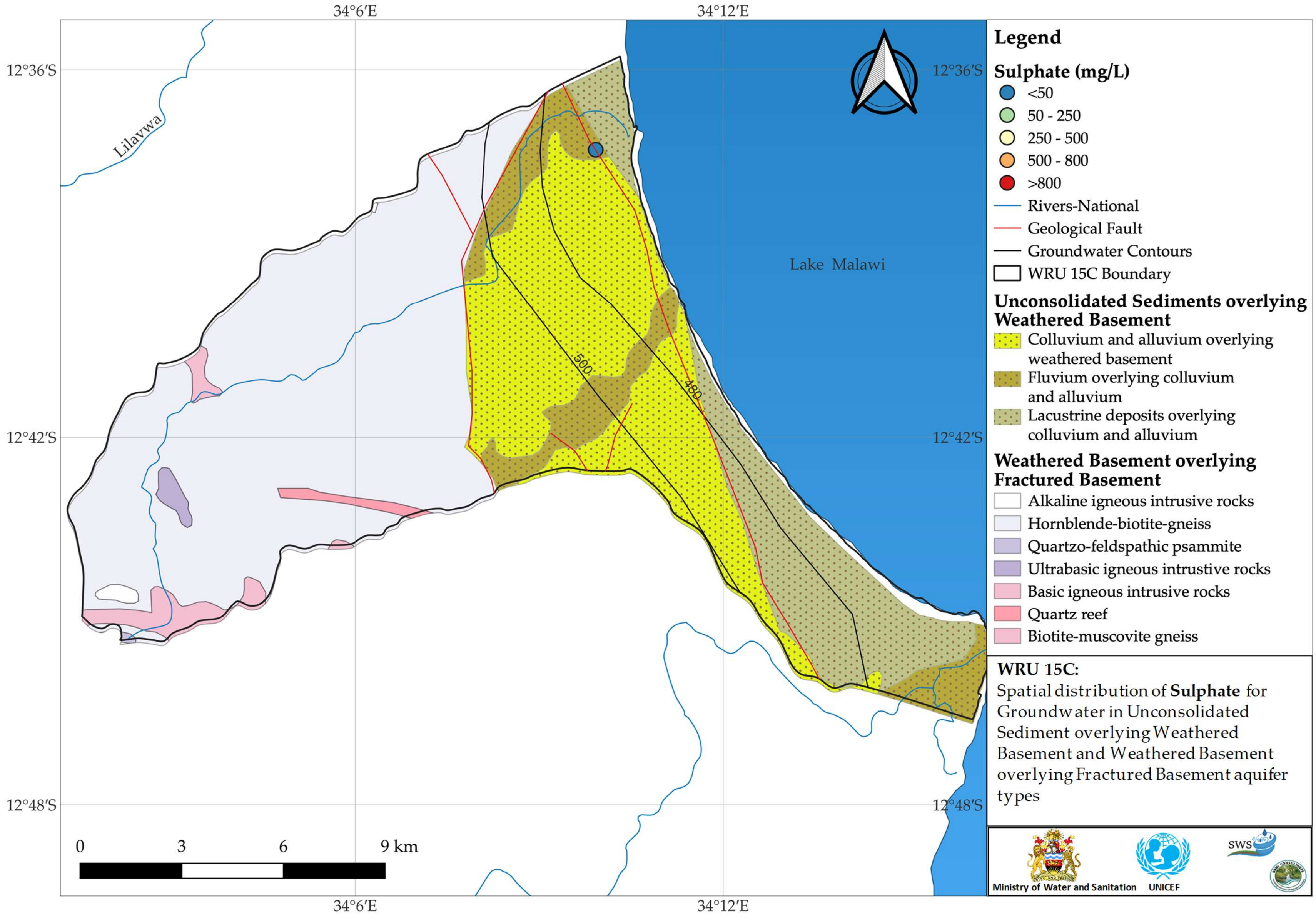


Figure WRU 15C.6 Groundwater Chemistry Distribution Chloride

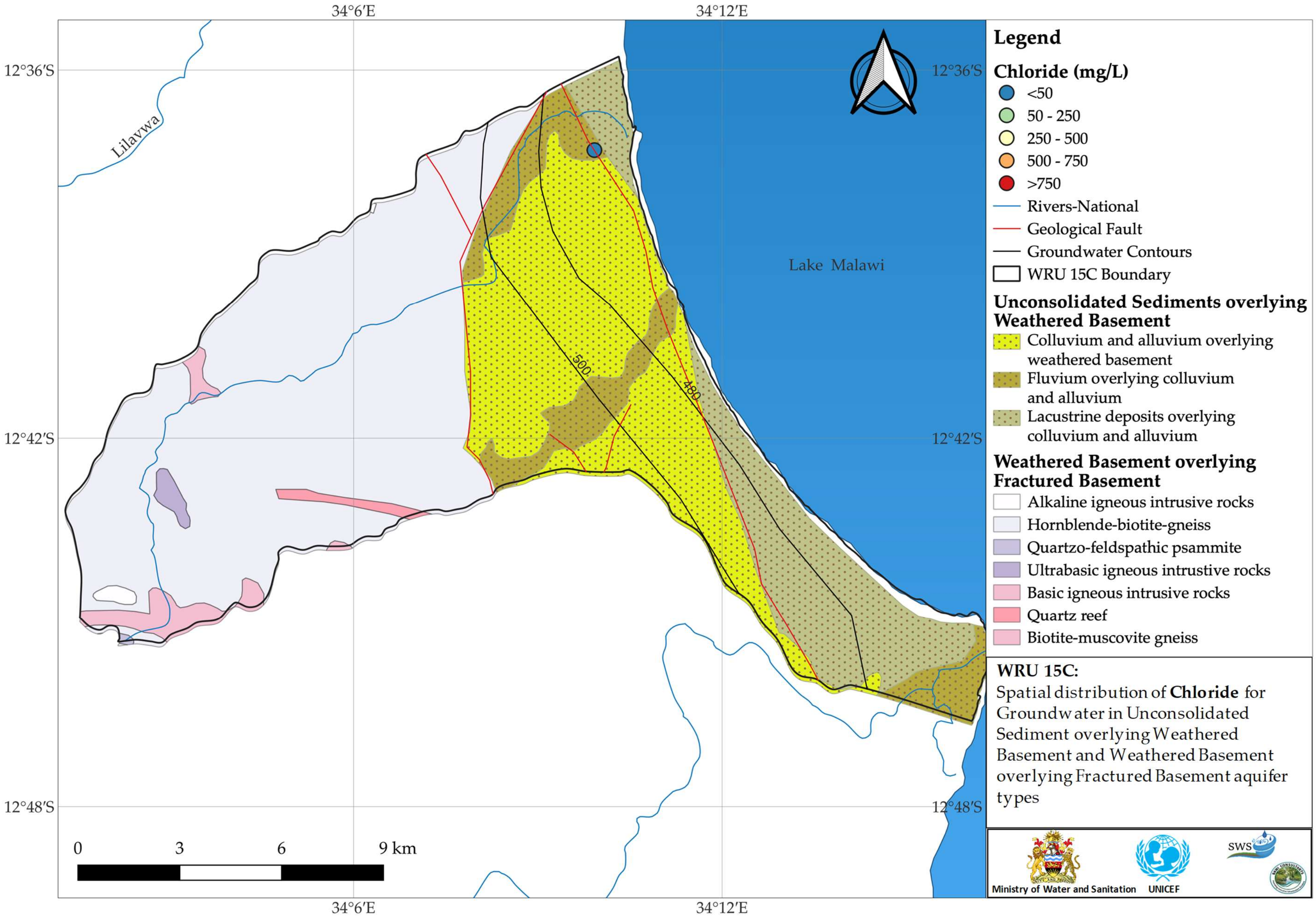


Figure WRU 15C.7 Groundwater Chemistry Distribution Sodium

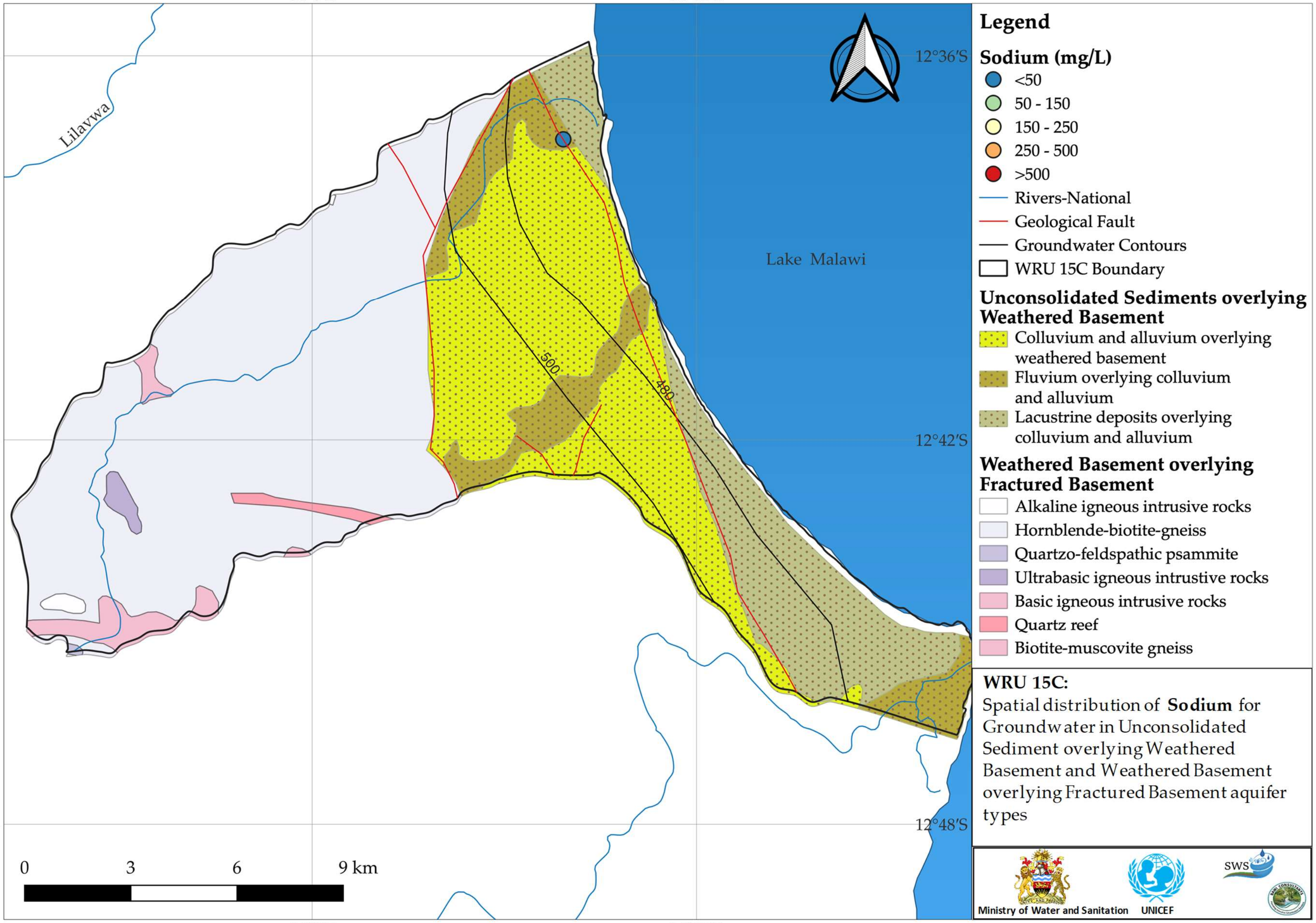
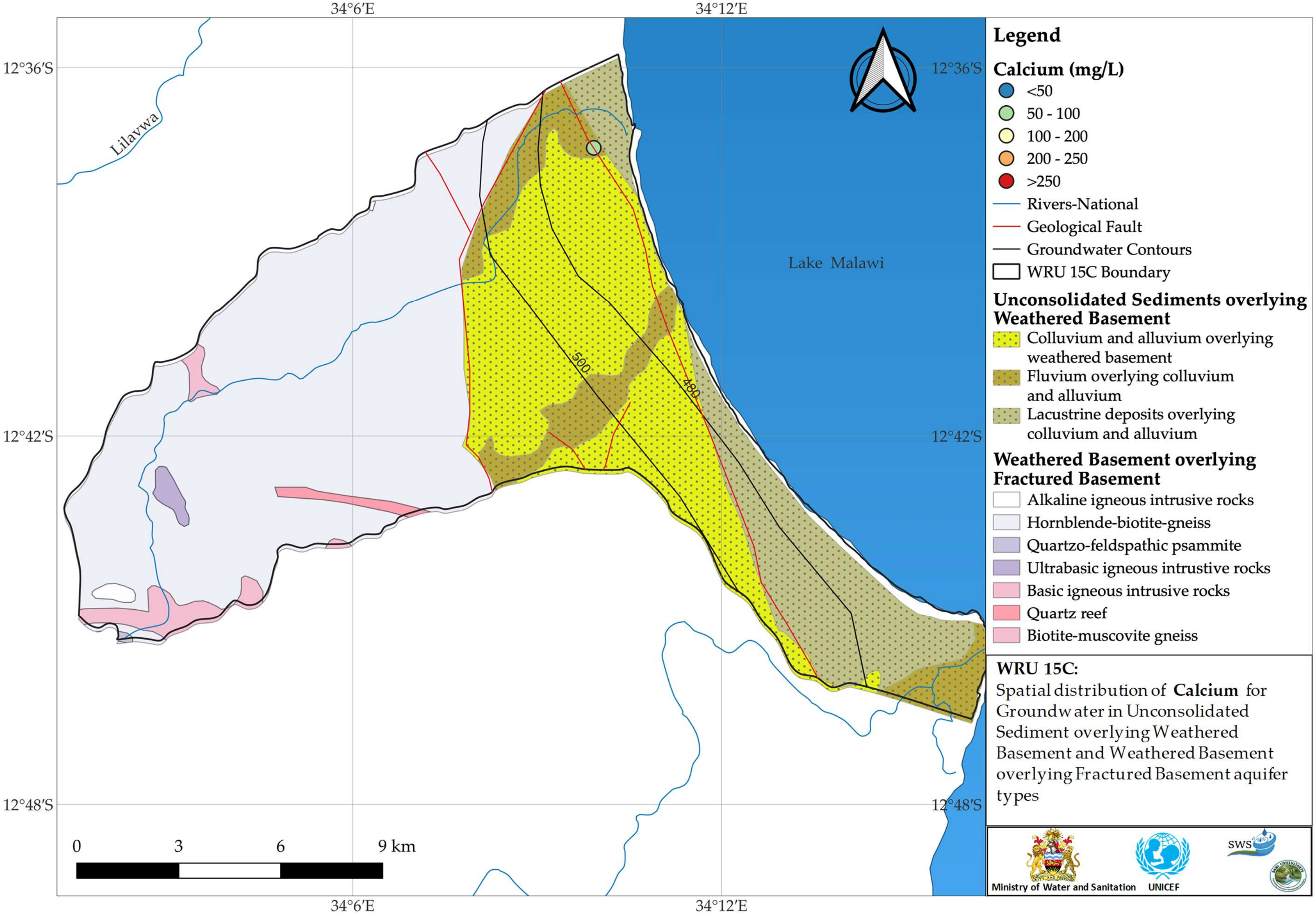


Figure WRU 15C.8 Groundwater Chemistry Distribution Calcium



WRU 15C:
Spatial distribution of **Calcium** for Groundwater in Unconsolidated Sediment overlying Weathered Basement and Weathered Basement overlying Fractured Basement aquifer types

Figure WRU 15C.9 Piper Diagram of water quality results with respect to the major aquifer type

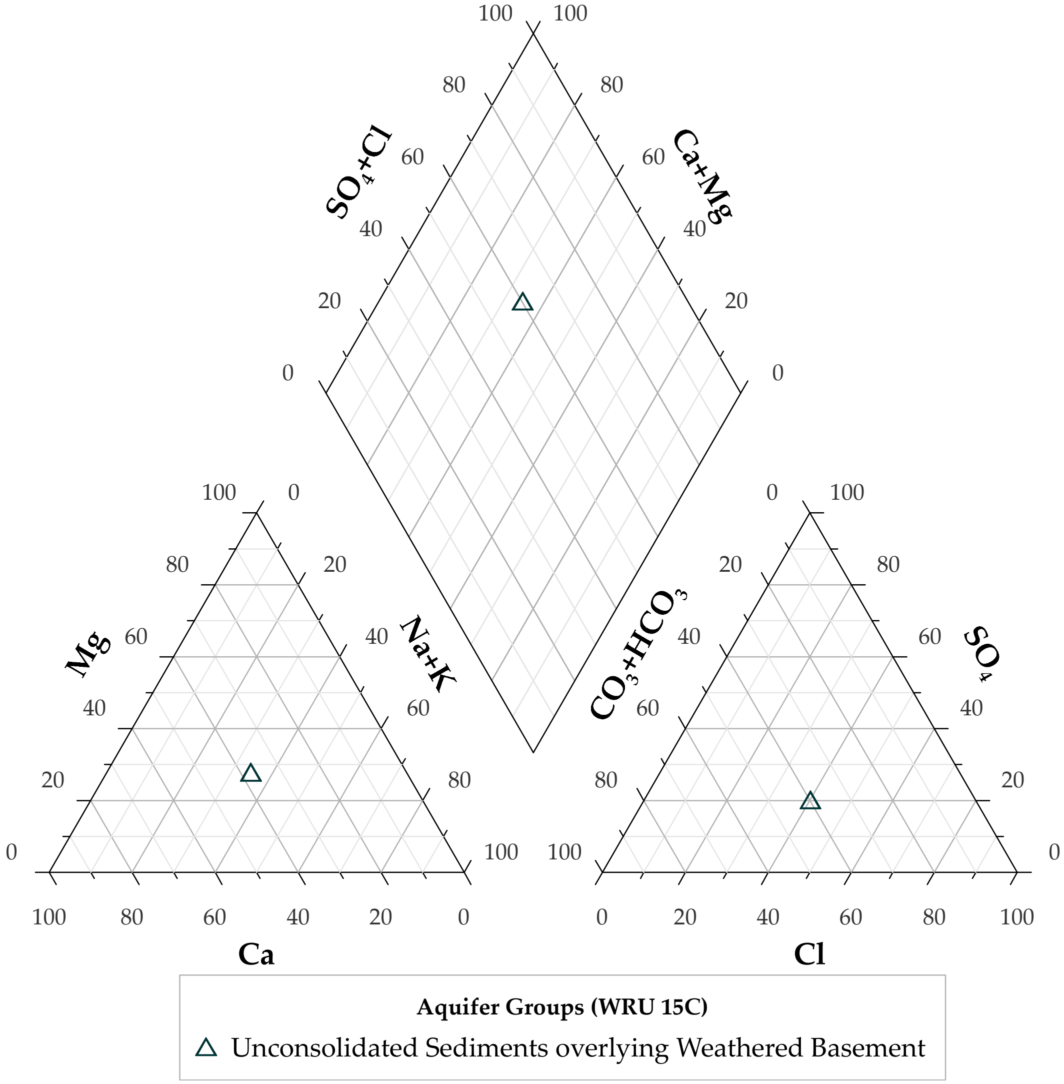
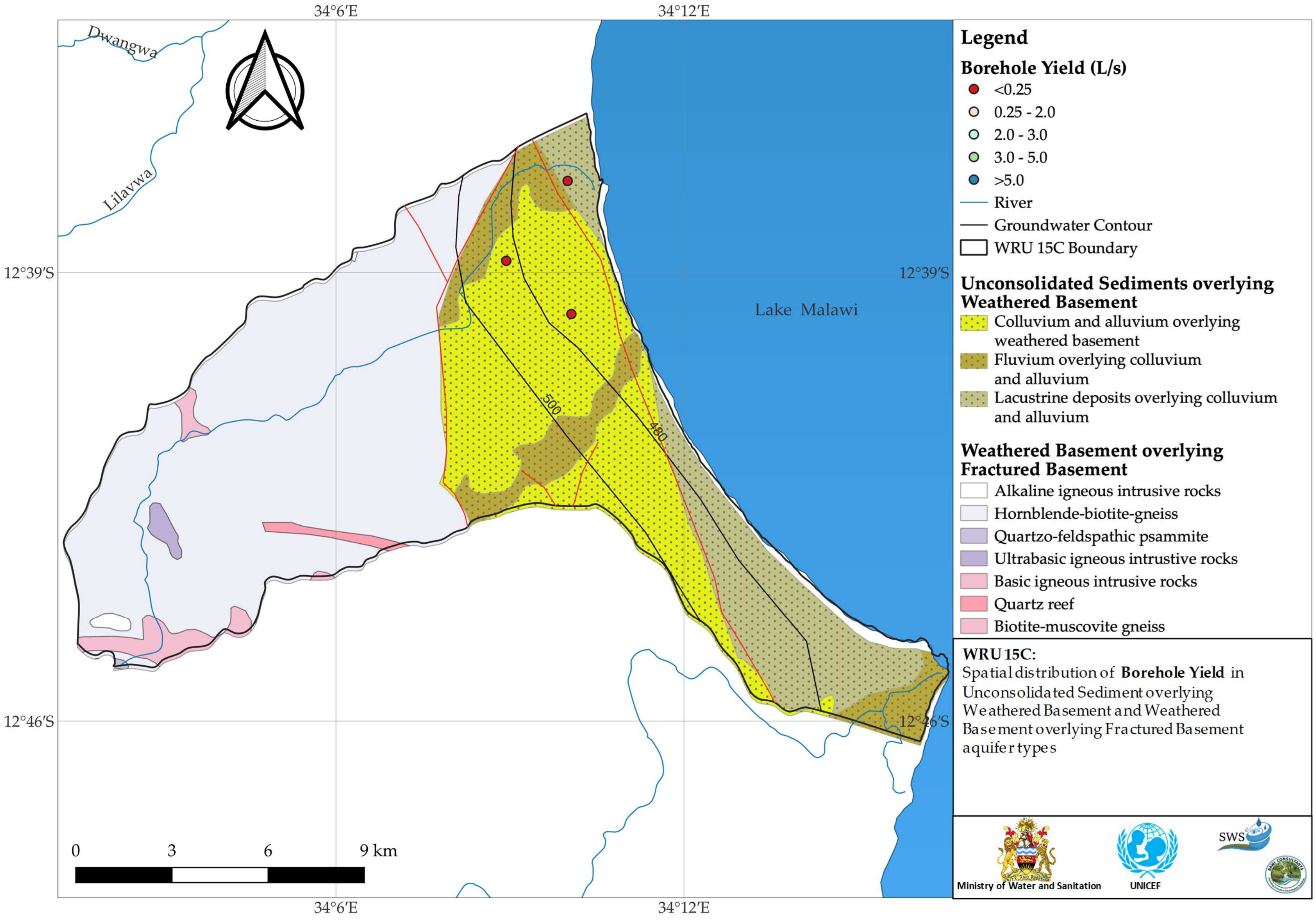


Figure WRU 15C.10 Borehole Yield Map for data held by the Ministry



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, Nkhotakota Lakeshore Catchment, Water Resource Area 15, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-14-7 69pp*