Hydrogeology and Groundwater Quality Atlas of Malawi

Detailed Description, Maps and Tables

Water Resource Area 11

The Lake Chiuta 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

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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 11 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.

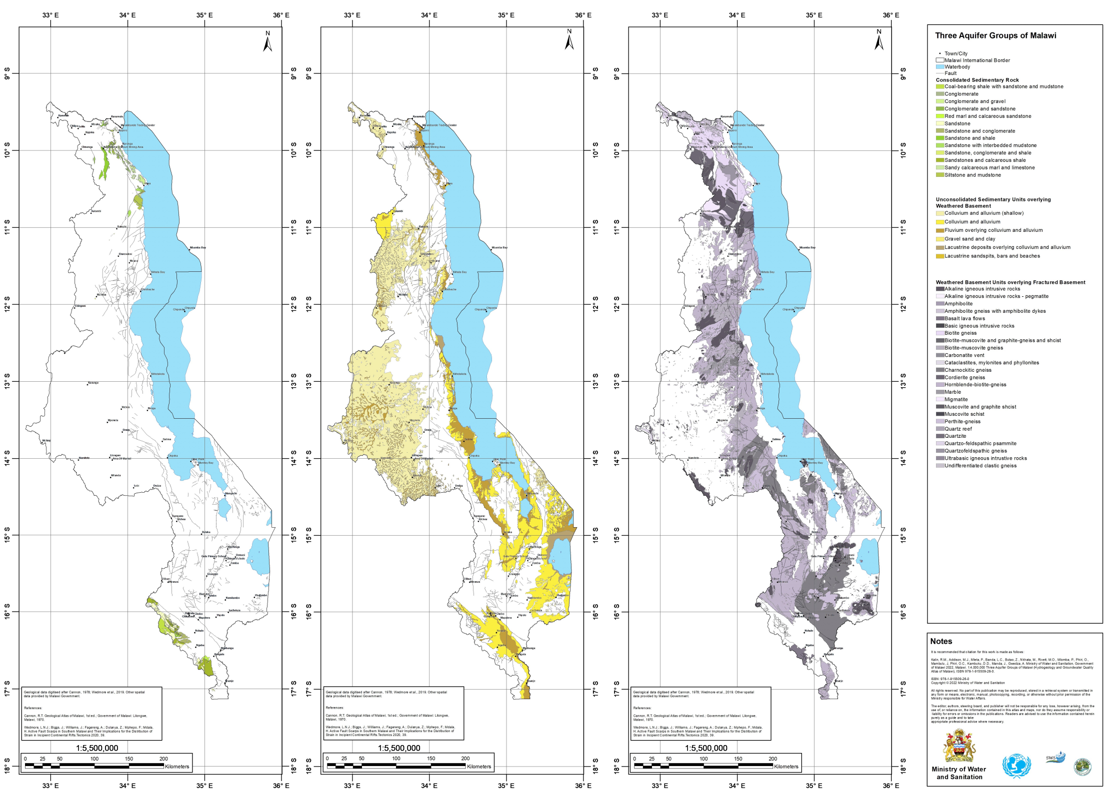


Figure 1a, b, c.   Aquifers of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most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

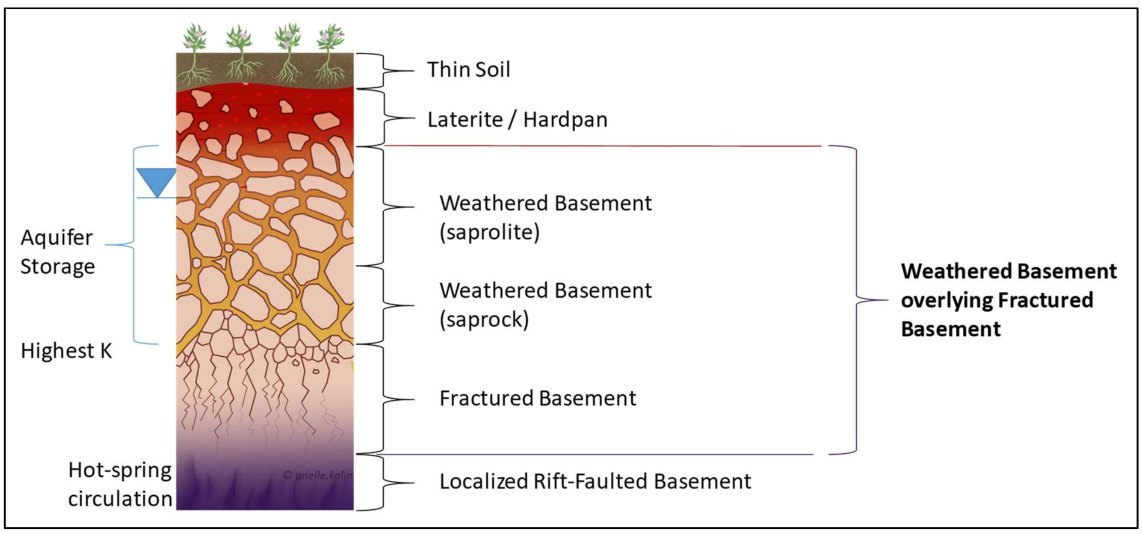


Figure 1d. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

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.

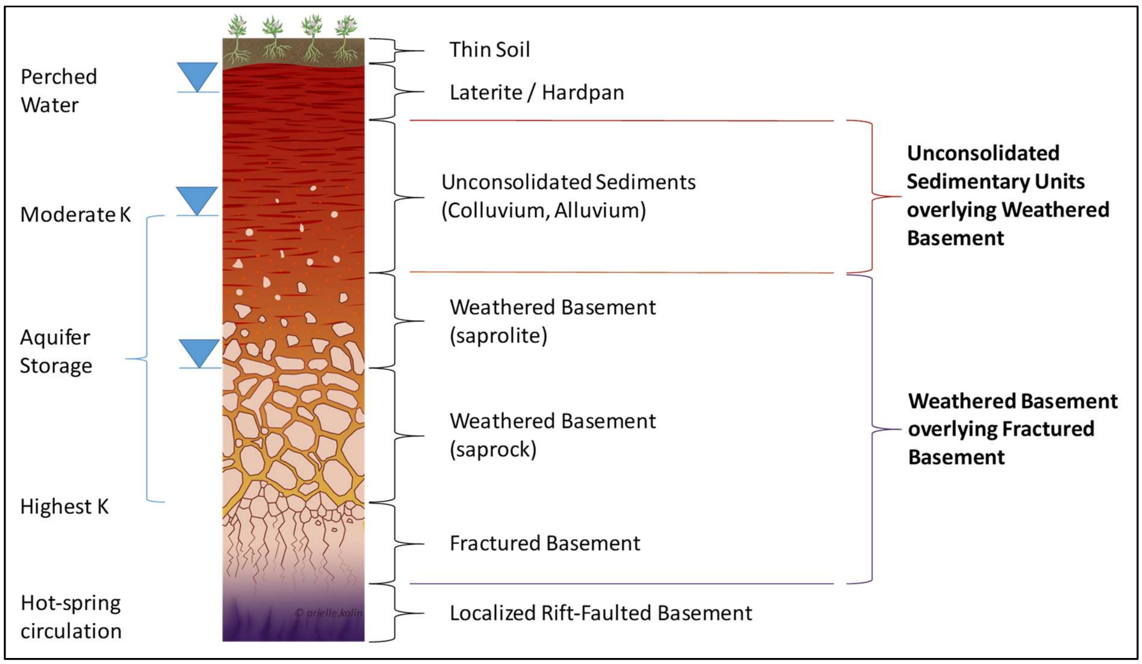


Figure 1e. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

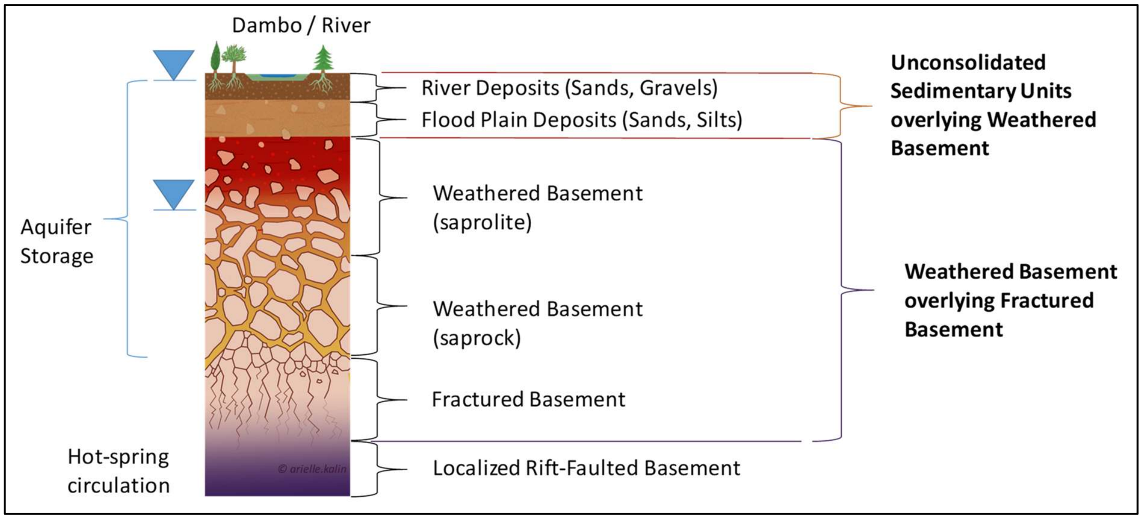


Figure 1f. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

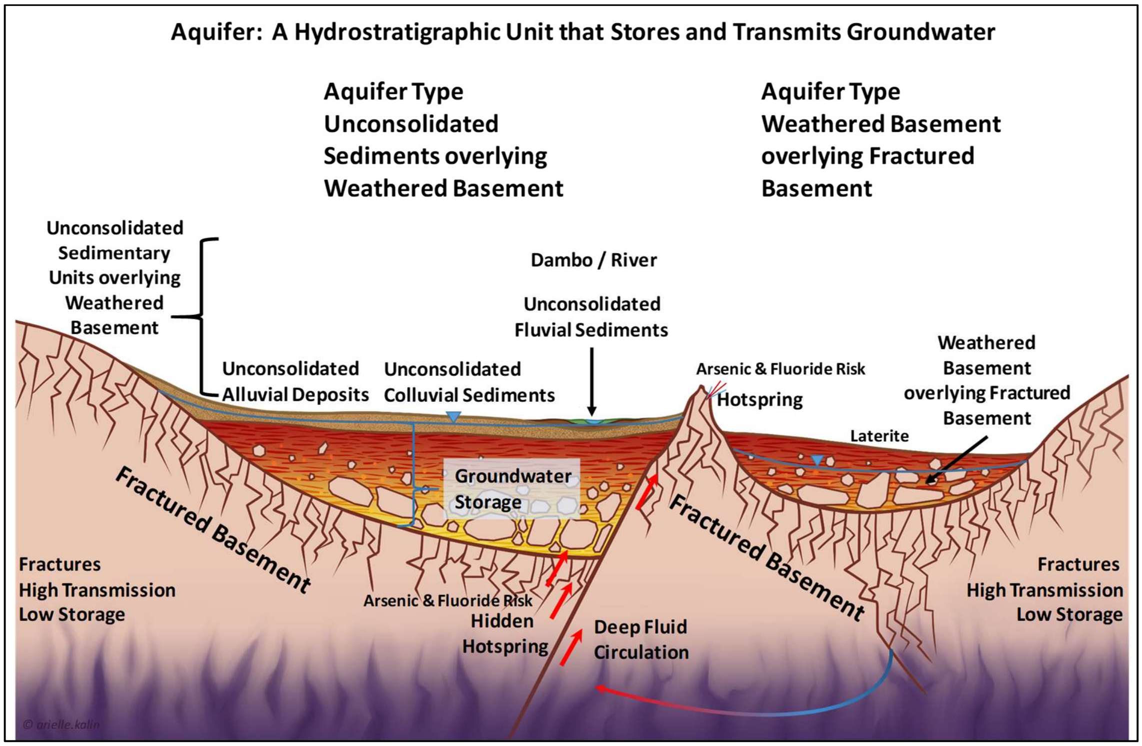


Figure 1g. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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 11 (WRA 11): The Lake Chiuta Catchment

The Water Resource Area (WRA) 11 in southern Malawi (**Figure 2a**) constitutes a single Water Resource Unit (WRU) (**Figure 2b**); WRU 11A, and occupies an area of 2,443 Km^2 along the Southeast of Lake Malawi where it forms an international borderline with Mozambique. Its riverine flows are dominated by Ngapani, Laurere, Luchima, Lusangusi, Nyenyesi, Chitundu, Sankhwi and Mpili Rivers with Lake Chiuta in the southeast side, hence the name Lake Chiuta Catchment. The catchment's topography is characterised mountain relief leading to plains around Lake Chiuta. Water Resources Area 11 is a Transboundary Unit for both surface and groundwater, therefore it is important that IWRM in WRA 11 is planned within an international water resources context.

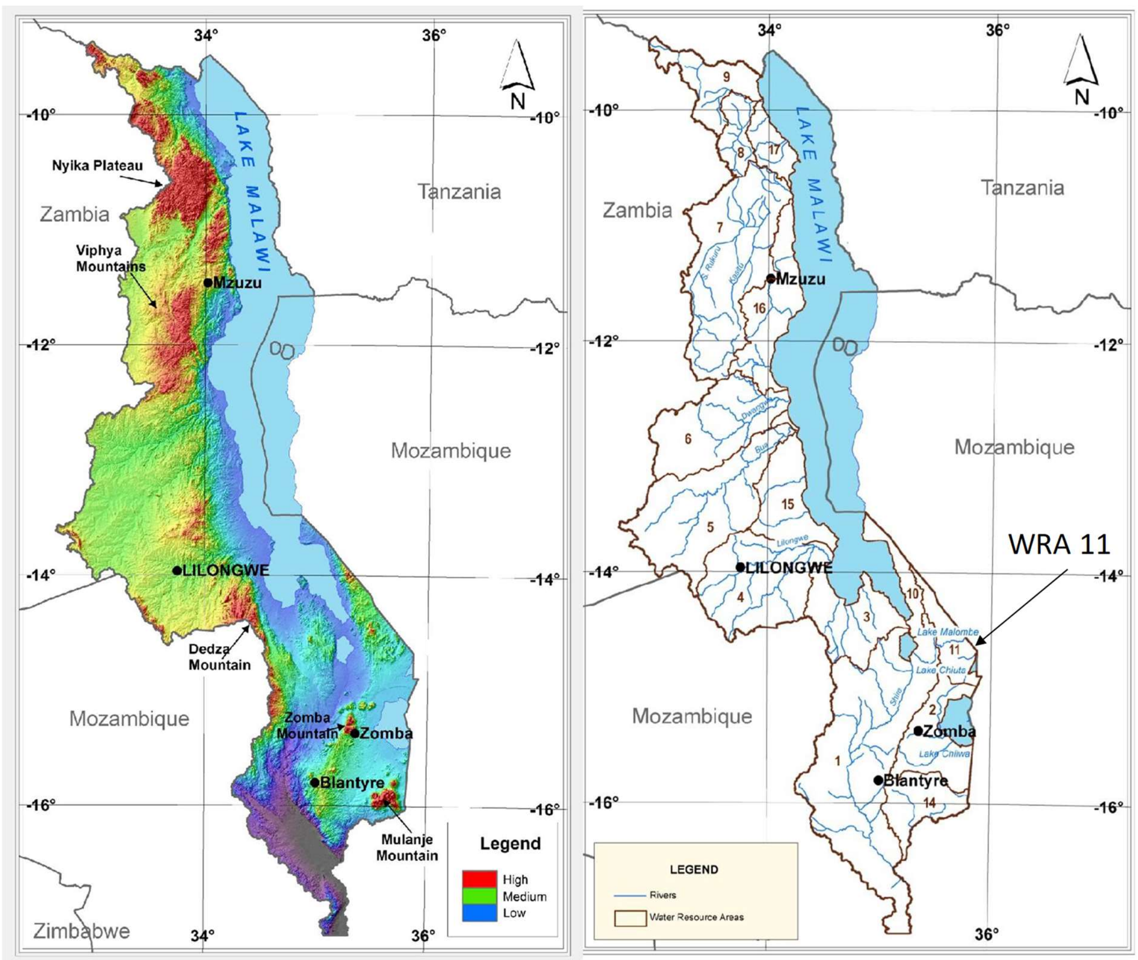


Figure 2. Location of WRA 11 with major rivers and topography shown.

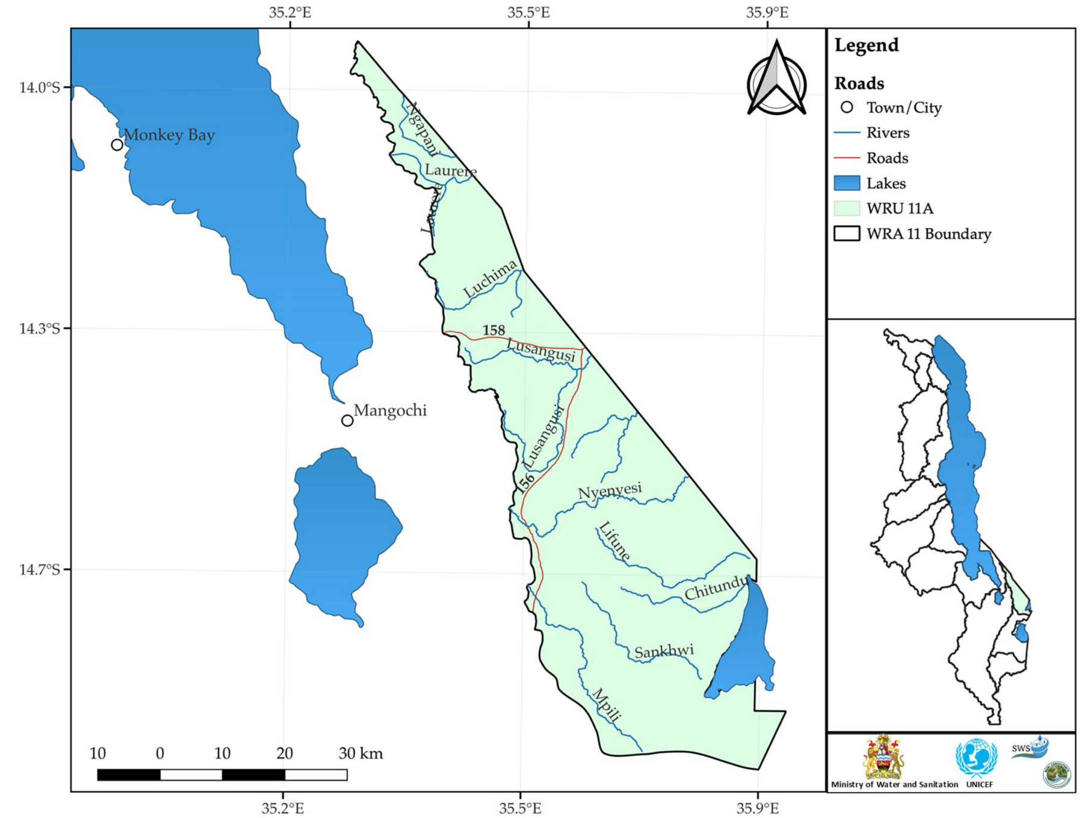


Figure 2b. Water Resource Area 11 and Water Resource Units

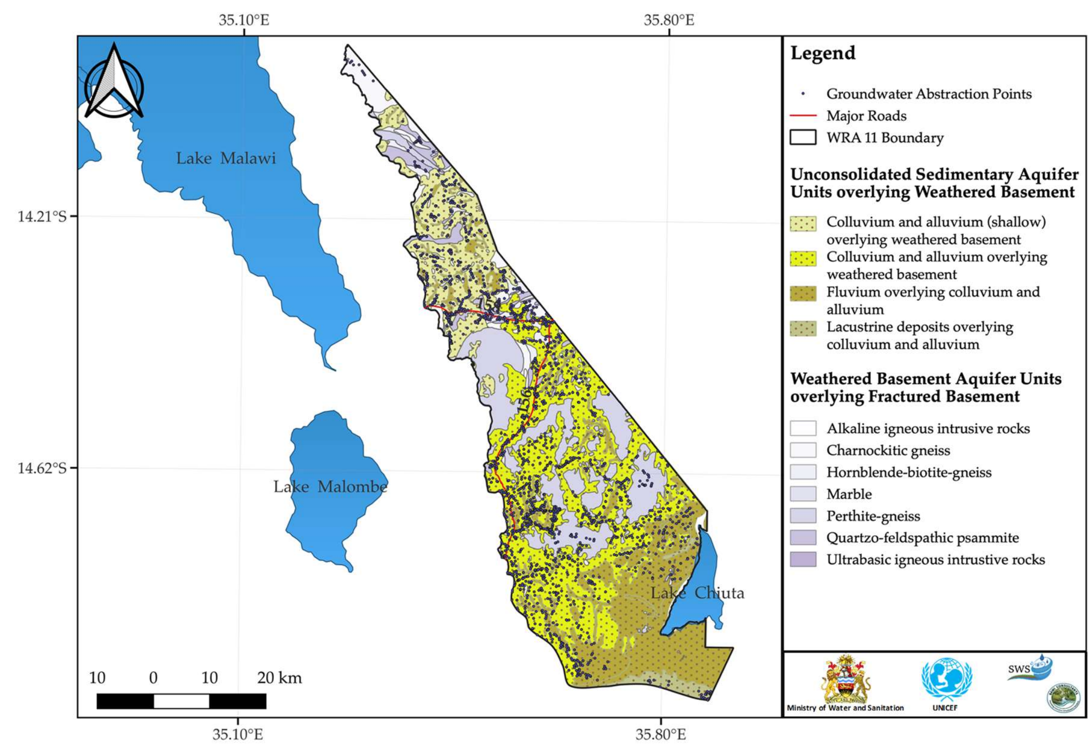
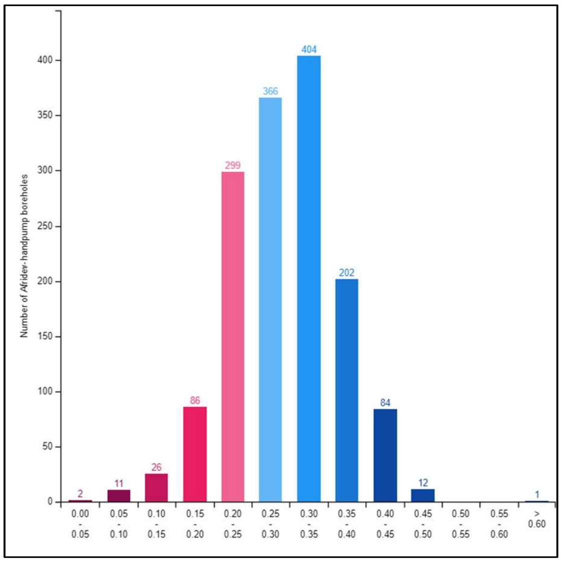


Figure 3. Distribution of groundwater abstraction points in WRA 11.

Groundwater Abstraction in WRA 11

Public abstraction points for groundwater are numerous in WRA 11 (**Figure 3, Table 2**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 3,478 known groundwater abstraction points, only 69.7% 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 11, only 65.9% are fully functional (defined as providing water at design specification).



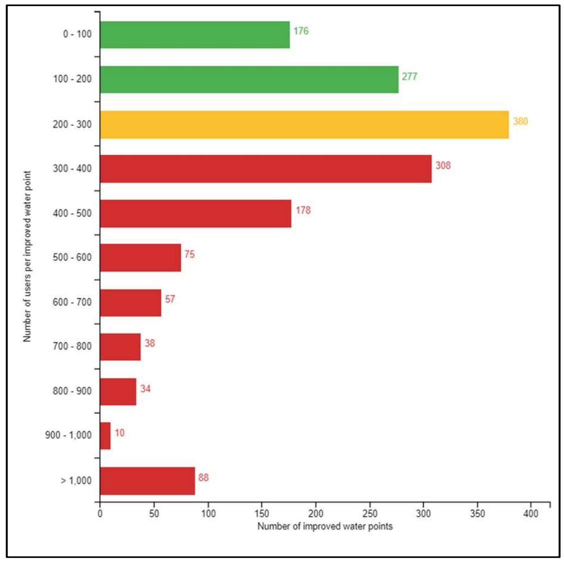


Figure 4a and 4b. Distribution of abstraction point yield (l/s) in WRA 11 (4a) and (4b) Distribution of the number of users per groundwater supply, green and yellow signify those abstraction points that fall within the Ministry of Water and Sanitation recommended population served by the abstraction 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 grossly exceeded and there is an investment need in WRA 11 from a population point of view. Many of the groundwater supply points provide water to more than 250 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, 6.9% of groundwater abstraction points do not provide sufficient water (September through November) most likely due to water table declines (**Figure 5a and 5b**). Shallow boreholes and dug wells (protected and unprotected) are the most heavily impacted, impacting the functionality of these water supplies. There is a strong correlation between the depth of the groundwater water supplies and the decline in seasonal water availability, and is assumed this is due to shallow dug well supplies or improperly installed boreholes that are more at risk to lowering water tables resulting in lower functionality during the dry season.

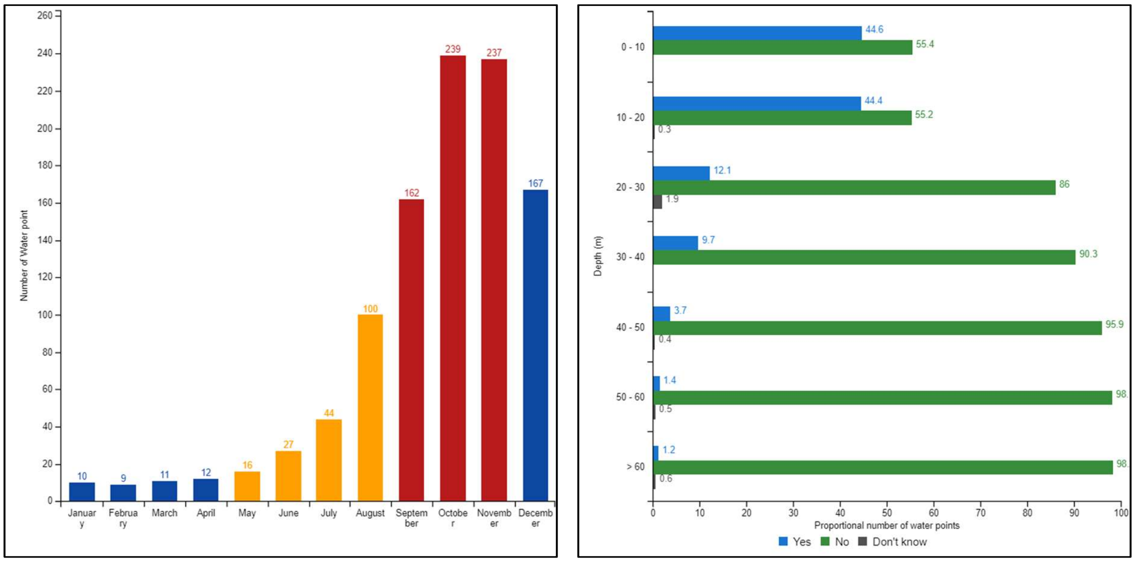


Figure 5a and 5b. Number of groundwater abstraction points in WRA 11 that do not provide adequate water (as a proxy for groundwater availability / water table or storage decline). (5b) Shows shallow groundwater abstraction points are most vulnerable to seasonal changes in groundwater (yes response indicated the water point goes dry) [Data from the 2020 National Water Point Survey].

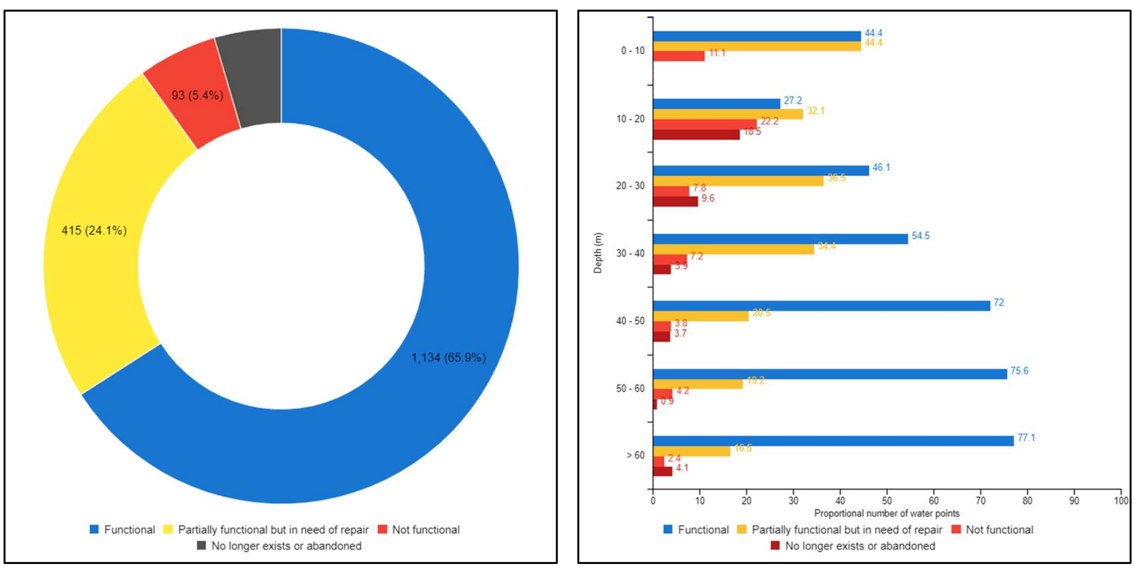


Figure 6a and 6b. Functionality (as percentage operational at design specifications) of groundwater abstraction points in WRA 11 [Data from the 2020 National Water Point Survey] and (6b) the functionality of groundwater abstractions points with depth of the installation. [Data from the 2020 National Water Point Survey]

The operational status of groundwater abstraction points is also linked to issues of infrastructure (e.g. pump / borehole) as well as aquifer stress. There are only 52.6% of groundwater abstraction supplies which are operation at design parameters, and 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 11 (after Kalin et al 2019).

Table 2. Number and Type of Groundwater Abstraction Sources in WRA 11 [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tubewell	2,322
Protected dug well	37
Protected spring	65
Unprotected dug well	769
Unprotected spring	285

Description of Water Resources WRA 11

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 Water Resource Area (WRA) 11 in southern Malawi constitutes one Water Resource Unit (WRU); WRU 11A.

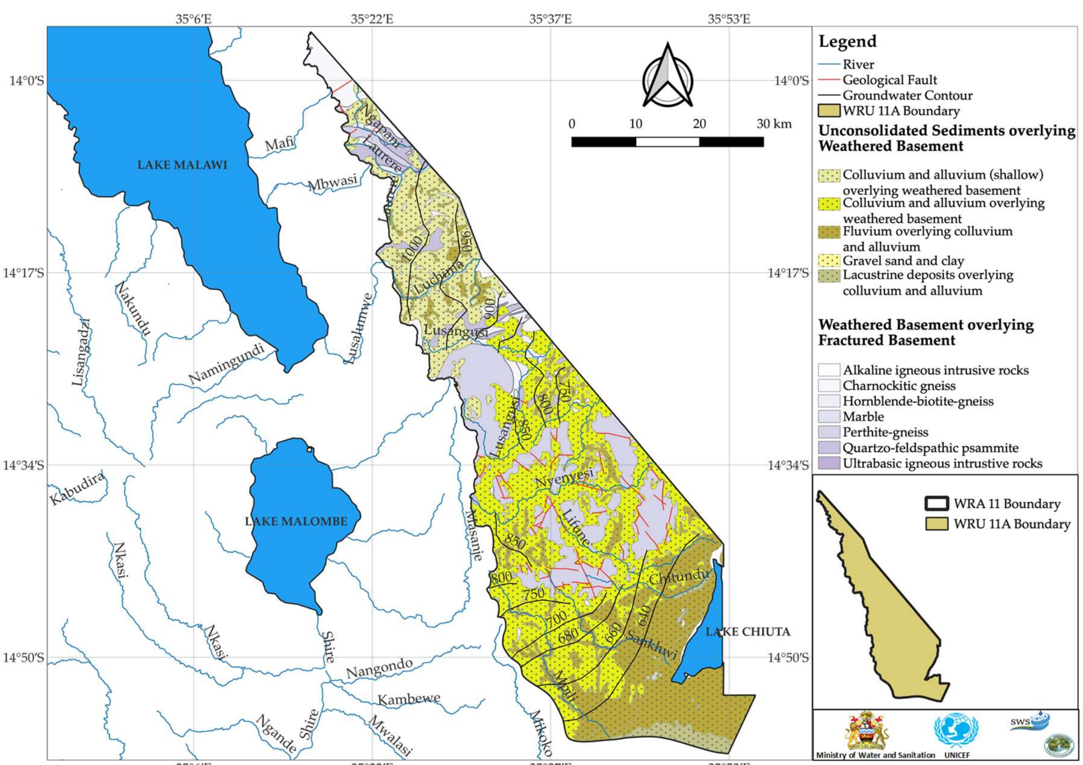


Figure 7a. Map showing the hydrogeologic units and water table for Water Resource Unit 11A wtihin Water Resource Area 11 (Lake Chiuta Catchment). [water table contour interval 20m]

Topography and Drainage

The catchment has diverse relief with upland terrain interspersed with river valleys and channels, and to the southern region plains leading to Lake Chiuta (**Figure 8**).

Key water resources management challenges are compounded by several dismal socio-economic factors dominated by high population growth, high rate of natural resource degradation and deforestation among others. Water resources availability remains a key challenge facing the rural communities in the catchment, with most of the households relying on boreholes, shallow wells and in the dry season they draw water directly from the wetland for their multiple uses.

The catchment offers limited opportunities of formal employment. Thus, the socio-economic development of the area largely depends on natural resources, such as land, water, fish, and wildlife. The area has poor, low-income households with no formal income. Most people, particularly in the rural areas are in the informal sectors. About 90 % of the population income stems from the farming, fishing, carpentry, bricklaying, water transportation and small business.

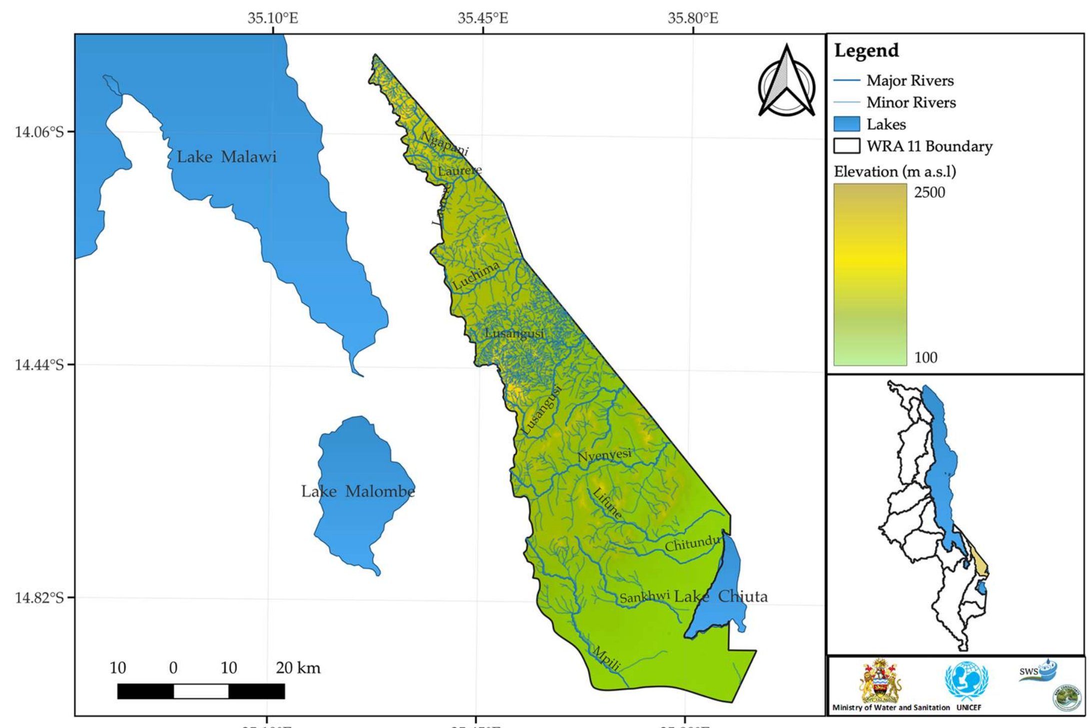


Figure 8. Drainage for the major rivers in Water Resources Area 11.

Geology – Solid

WRA 11 solid geology is mostly hidden beneath unconsolidated sediments and therefore unknown. It is assumed that a continuation of Precambrian to Lower Palaeozoic basement rocks composed of highly deformed sequences of charnockitic gneiss and granulite and biotite gneiss that extends to WRA

10. Similar outcrops of perthite gneiss grading into perthitic syenite occur throughout, exposed as Isolated topographic highs.

Geology – Unconsolidated deposits

Topography is uneven and where it is low, residual deposits and colluvium occur of unknown thickness. River alluvium, lacustrine deposits and dambo soils occur along the western shore of Lake Chiuta. Fluvial deposits within isolated dambos occur in the southeast where colluvial deposits are thickest.

Climate

A tropical climate occurs in the catchment with two distinctive seasons—a wet season and a dry season, with both cool dry and hot dry periods. The wet season starts in November ending in April. The first part of the dry season, cool-dry, starts in May ending in August and the last part, hot-dry, commences in September ending in October. Peak rainfall occurs between December and March. The lowlands of the area towards the Lake Chiuta experiences hot to very hot temperatures year-round, with average *minimum* temperatures 13.5ºC, experienced in June. The area receives a measured annual rainfall of 1,017 mm (**Figure 9**).

Table 3. Calculated mean rainfall in each Water Resource Unit within WRA 11. 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)
11	A	Chikweo/Namwera	1,011	986

Land use

WRA 11 is largely dominated by rain fed cultivation followed by open woodlands and open grasslands. There are also marshes and occurrence of small-scale wetland cultivation in the area.

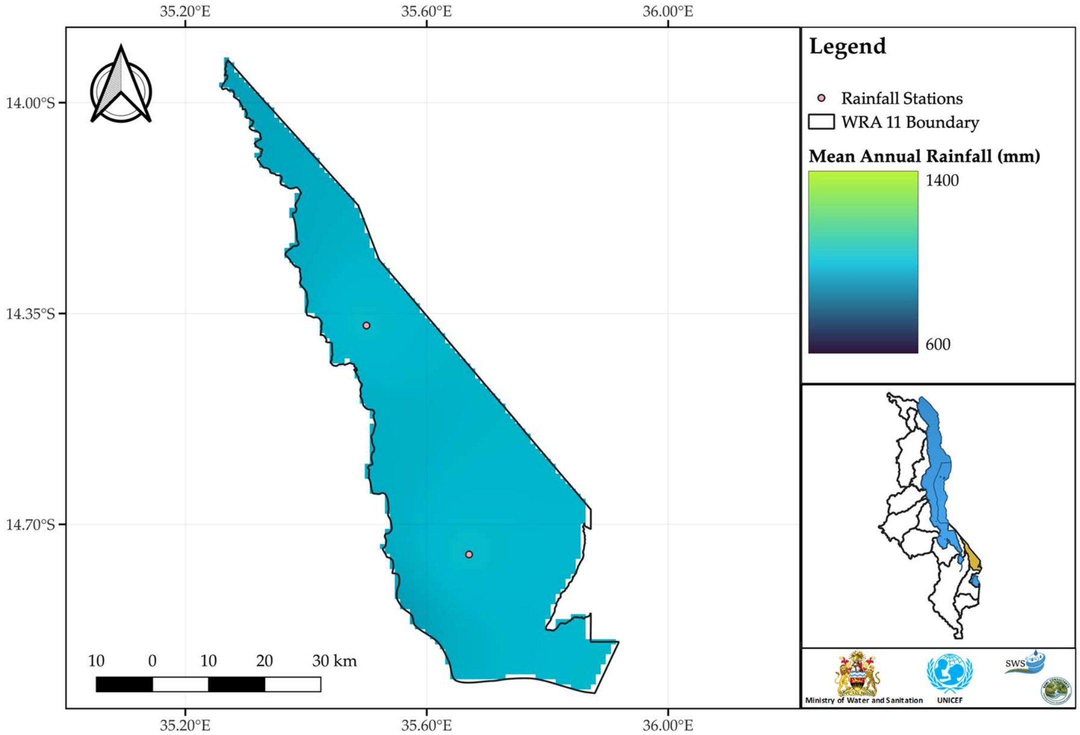


Figure 9. Rainfall distribution (GIS modelled using inverse distance weighted mean) across Water Resource Area 11 with the location of weather stations. Average rainfall measured is 1,017mm, average rainfall modelled is 986 +/- 16mm (range 924 to 1,012mm).

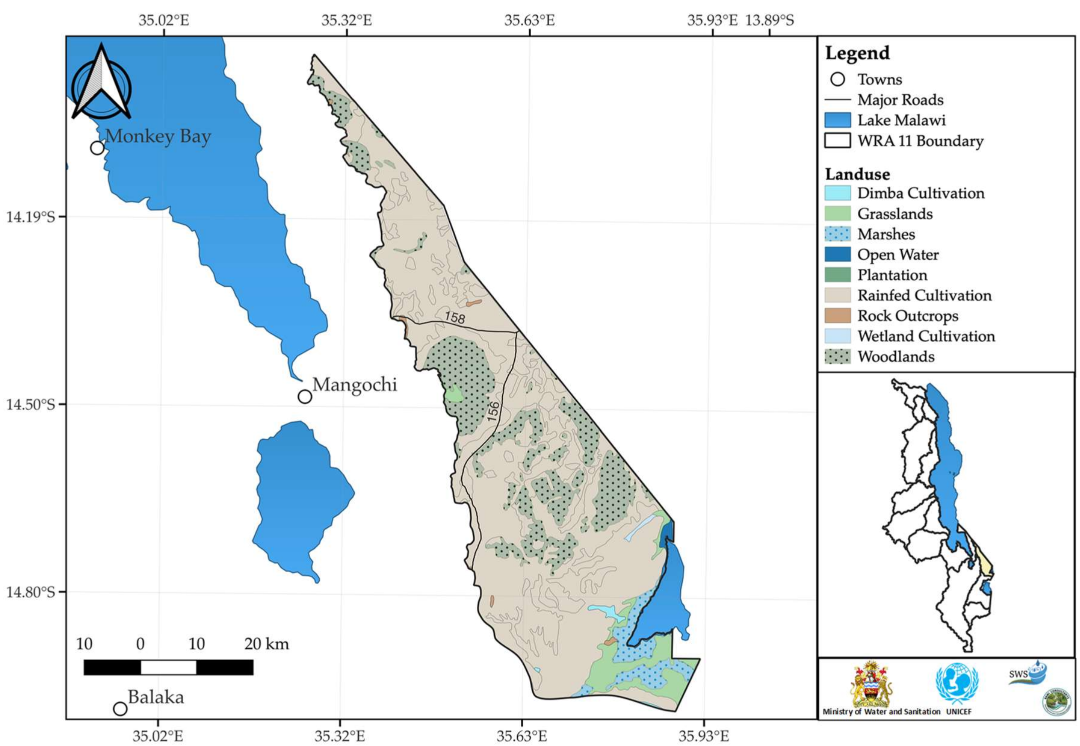


Figure 10. Land use in WRA 11 is dominated by rain fed cultivation.

Hydrogeology of WRA 11

Aquifer properties

WRA 11 is dominated by colluvium and fluvial deposits overlying weathered and fractured basement. The hydrogeological properties of these units have not been differentiated in the yield and borehole log data provided by the Ministry, therefore it is difficult to ascribe aquifer properties to the various units. There is a need to enhance drilling log records collected during drilling operations. The most productive aquifer units are most likely to be formed in fluvial valleys and where faulting and resulting weathered basement rocks are having a high storage coefficient. Fluvial and lacustrine sediments likely become finer grained approaching Lake Chiuta, likely interbedded with fine-clay flood deposits in and around dambos and the lake boundary (**Figure 11**).

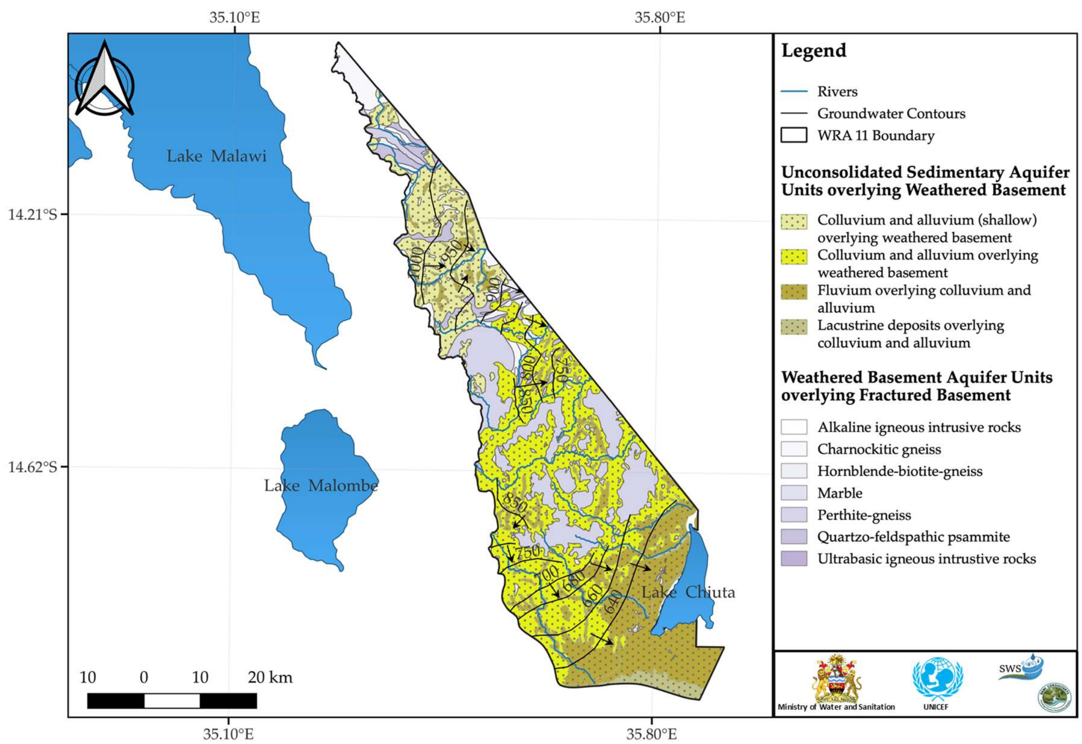


Figure 11. Groundwater level contours and flow direction in WRA 11 [1987 Hydrogeological Reconnaissance data]. [water level contour interval 20m]

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 11 is based on prior hydrogeological reconnaissance.

Groundwater level data for WRA 11 based on prior hydrogeological reconnaissance confirm groundwater flows follow topographic drainage (**Figure 11**). In the south unconsolidated sediments, groundwater generally drains south-eastwards towards the Lake Chiuta – wetland system. The groundwater divide follows the surface water divide between WRU 11A and 2D with groundwater flows respectively draining towards Lake Chiuta and Lake Chilwa. The latter is a large endorheic lake now separated from Chiuta by a sandbar. Hydraulic gradients towards Chiuta range from 0.004 to 0.008, equivalent to a groundwater velocity range of 7 – 14 m/yr for a nominal hydraulic conductivity of 1 m/d and effective porosity of 0.2. The shallower gradients arise from greater lakeshore extent between the Basement escarpment and shoreline. Groundwater flows further north in WRA 11 are obliquely towards and cross the national boundary entering Mozambique with gradients around 0.009 (0.9 %). Groundwater entering Mozambique probably discharges to the river – wetland system a little downstream from Lake Chiuta. The groundwater in WRA 11 should be considered a Trans-boundary water resources and it is recommended it should be evaluated within international water resource agreements.

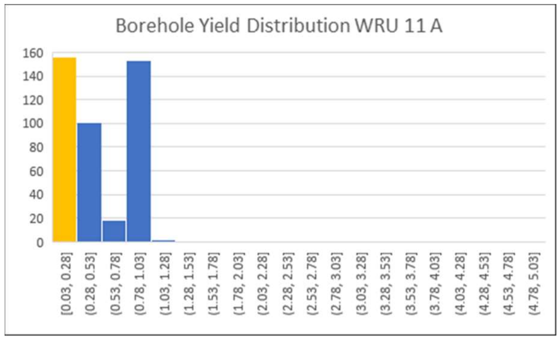


Figure 12. Distribution of Borehole Yield Data held by the Ministry of Water and Sanitation plotted for each Water Resource Unit within Water Resource Area 11 (y axis = *n* observations).

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. The number of values in this range 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 WRA11 there appears to be a trend to higher borehole yields related to alluvium aquifer units, with a number of production boreholes reporting yields of ca. 1l/s.

There are general trends which suggest the highest borehole yields are found in alluvial aquifers in the order of 1 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.

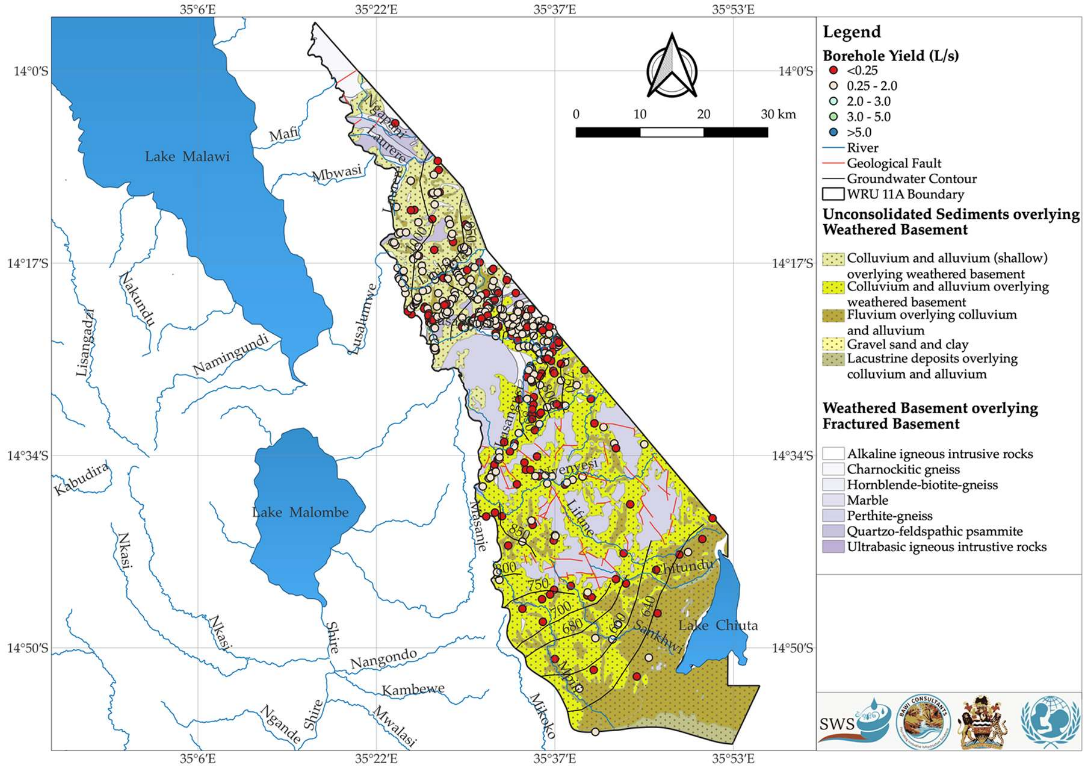


Figure 13a. Borehole Yield data held by the Ministry of Water and Sanitation for WRU 11A.

Groundwater Table Variations

There is only one operational groundwater monitoring stations within WRA 11 at the Namwera Well Field, the data is not complete but it does show near continuous (annual) readings and trends (**Figure 14a and 14b**). There is a low amplitude (ca 2m per 3 to 5-year period) variation in the water table that is overlain by short amplitude rises of up to 10 meters. This likely relates to both climate variable groundwater recharge and climate induced water pumping. Data from the 2020 National Survey suggested seasonal water table declines in shallow groundwater supplies and this is supported by the data in **Figure 14**. It is not possibly to determine any long-term trends that may relate to climate variability (rainfall and recharge relationships) unless data on aquifer pumping were included in an overall water balance. The magnitude of the seasonal variation suggests the monitoring point is unconfined and receives annual seasonal recharge. However, given here are no borehole logs or multi-level installations that separate different hydro-stratigraphic units and the data from each site is not complete, it is recommended that multi-level installations are placed into each hydrostratigraphic unit is an area for future investment, and a complete water balance is undertaken.

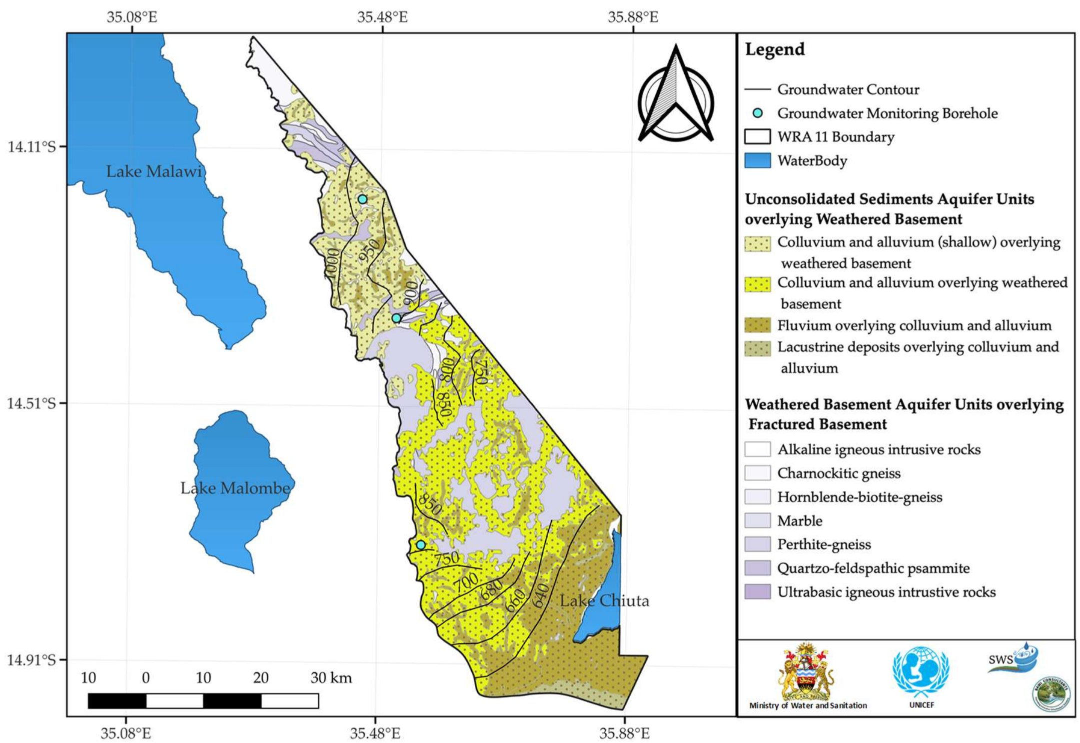


Figure 14a. Location of groundwater monitoring points in WRA 11.

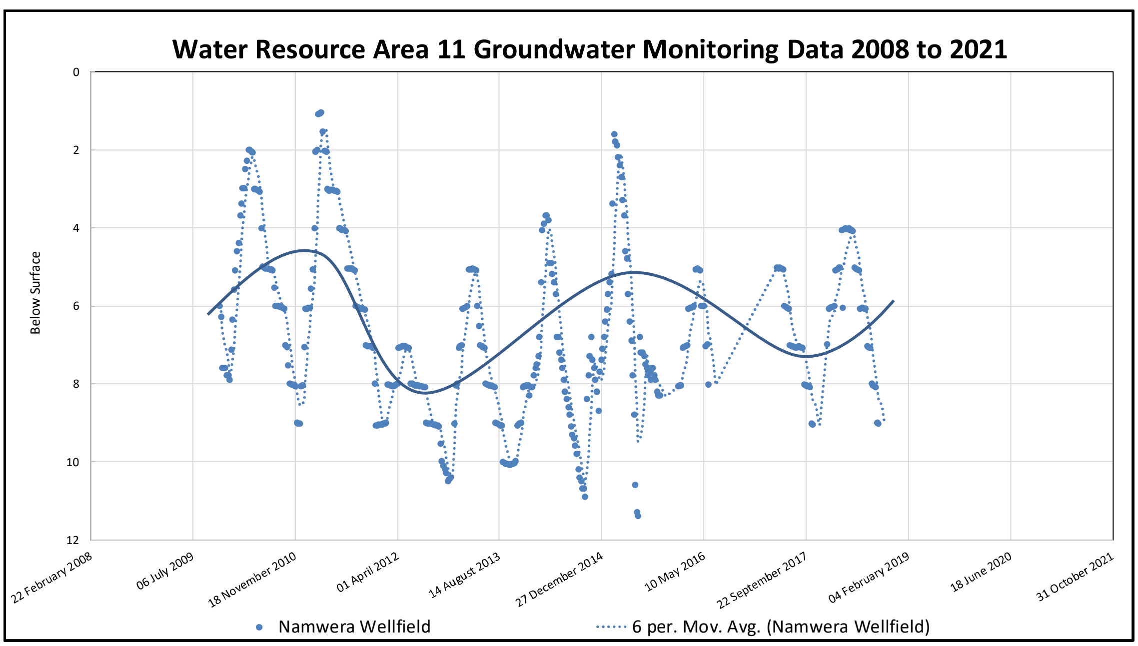


Figure 14b. Groundwater Level Monitoring Data held by the Ministry of Water and Sanitation for stations in Water Resources Area 11. (units assumed to be meters below ground level).

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).

Table 4. Groundwater volume per hydrogeologic unit and the estimated annual recharge for WRU 11A, 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	570.6	10%	35%	0.02	0.10	1,141.3	19,972.2	
Lacustrine units	40.0	10%	35%	0.02	0.03	80.1	420.3	
Colluvial etc.	1,168.9	10%	30%	0.02	0.06	2,337.7	21,039.4	
W & F Basement	640.3	1%	10%	0.02	0.03	128.1	1,921.0	
	Area of WRU (km^2)	11A	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*3,687.1*	*43,352.9*	*Total Volume Groundwater*
	2,419.9	986	Average Rainfall in WRU	9.86	73.95	23.9	178.9	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]						155	242	Calculated Average Residence Time of Groundwater (years)
						Low Est	High Est	

The calculated volume of groundwater recharge in WRA 11 ranges between 23.9 Million Cubic Meters (MCM) and 178.9 MCM per year, with a mean age of groundwater of 200 years across the Water Resource Area **(Table 4**). There is a need to better constrain water volume/balance aspects of the basin and to expand the use of Isotope Hydrology and properly modelled and measured groundwater age constraints.

Table 5. Distribution of dissolved species in groundwater WRA 11. 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 11	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	6.9	275	14.3	13.0	0.4	0.8	17.1	3.3	25.8	8.1	0.3
Std Dev	1.0	343	30	61	1.3	0.4	38	2.8	28.9	7.5	0.7
Median	6.9	180	10.1	3.9	0.1	0.8	9.0	2.8	17.1	5.8	0.1
Max	9.0	3,700	583	932	20	1.9	460	49	414	65	6.4
Min	4.0	22.0	0.6	0.1	0.0	0.0	0.7	0.1	0.9	0.1	0.0
n	981	934	941	964	613	823	944	944	944	895	336

Groundwater quality WRA 11

Groundwater major-ion water quality in WRA 11 has considerable data available within the Ministry of Water and Sanitation and is limited to those analyses which have geospatial information, data which was reported as 'zero' or below reported minimum detection limits were ignored (**Table 5**). In general, the water quality is good with localised areas of high TDS (presented as EC) likely due to evaporative enrichment of groundwater. Stable isotope studies of the Lake Chiuta – groundwater interaction would enhance the understanding of the surface water – groundwater interaction in this part of WRA 11.

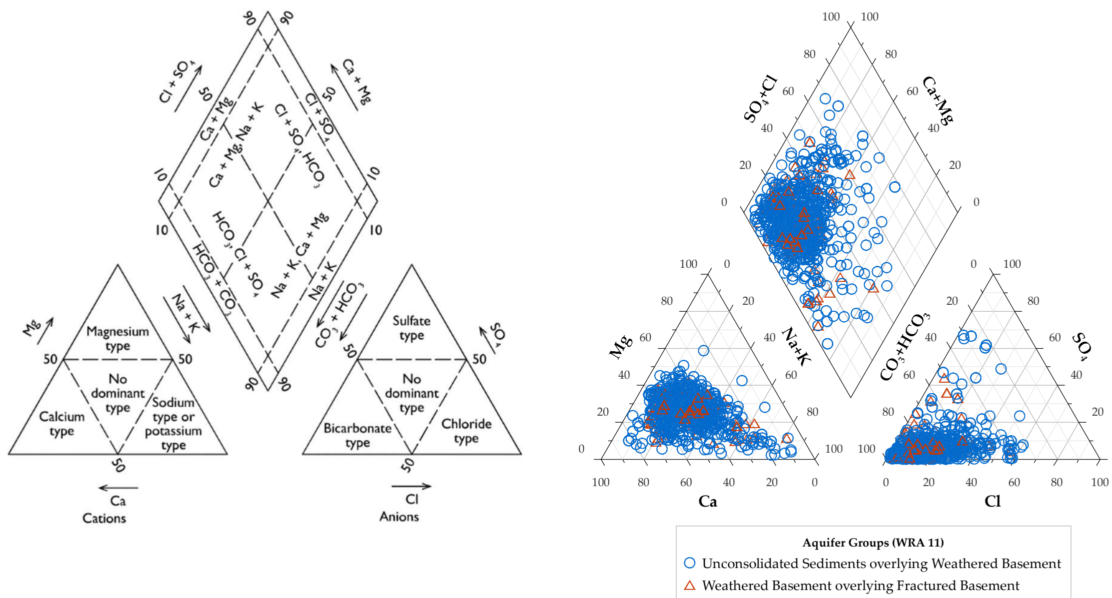


Figure 15a, 15b. Piper Diagramme of Groundwater Samples in WRA 11 and for each Aquifer Type in WRA 11.

Piper plots of the WRA 11 water quality data suggest most water has expected major geochemical changes from water-rock interactions dominated by Ca-Mg-HCO_3 type waters with a clear trend for increasing Na-Cl-SO_4 likely due to evaporative enrichment (**Figure 15a and 15b**). The average groundwater age 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, however in low-lying areas there are zones of high EC groundwater likely related to evaporative enrichment.

The distribution of key dissolved water quality species in groundwater of WRA 11 is provided in **Figure 16** however caution for over interpretation is advised given water quality results with geospatial coordinates though available, are not routine nor targeted on specific aquifer units in WRA 11, and there is a need to develop a systematic water quality monitoring approach in all WRAs to meet the Water Resources Act (2013) requirements.

Figure 16 Distribution of chemical species in groundwater within WRA 11 (y axis = *n* observations)

Groundwater quality - Health relevant / aesthetic criteria

Salinity

Generally, the TDS of groundwater in WRA 11 is low based on wide-spread water quality analyses held by the Ministry of Water and Sanitation (**Figure 16**). It is recommended that investment in routine monitoring of public water supplies is planned and implemented prior to enhanced groundwater resource utilisation.

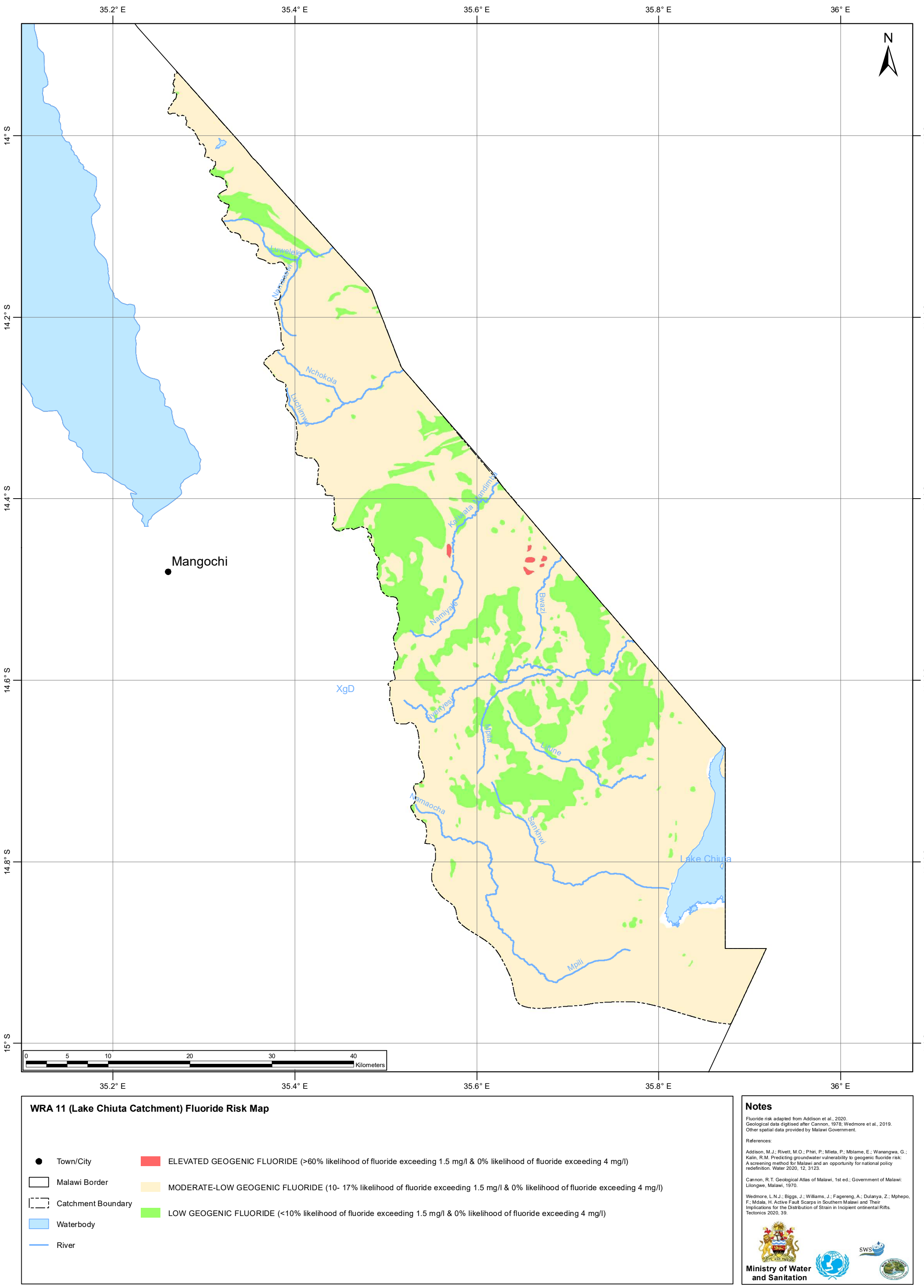


Figure 17. Groundwater Fluoride Risk Map WRA 11 (after Addison et. al. 2021).

Fluoride

There is little prevalence of hot springs in WRA 11, placing **Lower Risk** category for fluoride in groundwater. Groundwater data drawn from the recent national-scale assessments (**Figure 16 and Figure 17**) reveals only a handful of existing analyses are above 1.5mg/l, these areas should be targeted for re-analysis as given the co-location with major faults is unknown and those water points in proximity to faults may 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 Fluoride risk and it is recommended that a detailed and systematic survey of groundwater quality in WRA 11 is planned and implemented.

Arsenic

A recent national collation of arsenic groundwater survey data (Rivett et al 2018) found widespread low concentrations but with only a few above the WHO 10 μg/L guideline that were usually associated with hot spring/geothermal groundwater, often with elevated fluoride. There is no systematic analysis for Arsenic in WRA 11 and it is recommended that a detailed and systematic survey of groundwater quality in WRA 11 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 11.

	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**
11A	392,105	419,710	448,598	477,213	506,852	441,732	1,450,553,506	1,740,664
WRA 11	**392,105**	**419,710**	**448,598**	**477,213**	**506,852**	**441,732**	**1,450,553,506**	**1,740,664**

Water resource unit 11 (**Table 6**) has a modelled total of 1,740,664 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 49,627. WRA11 covers roughly 1.97% 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. 4,002 metric tonnes of fertiliser would be used in WRA1 per year. The model results indicate 43 times more faecal matter was added to this WRA than fertiliser over this 10-year period.

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Water Resource Unit (WRA) 11 Figures

Figure WRA 11.0: Aquifer Units and Groundwater Level Contours Water Resources Area 11

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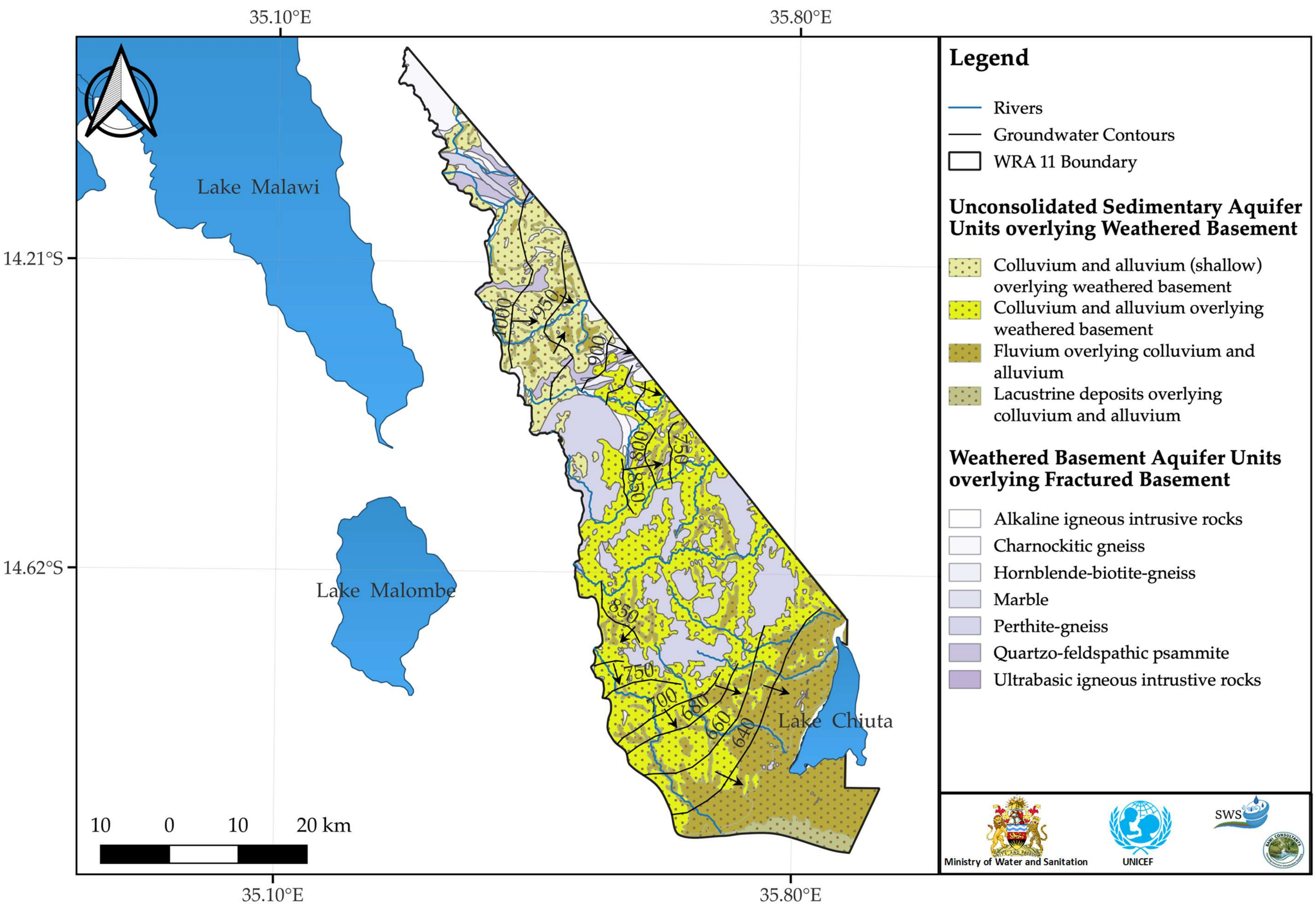


WRU 11A Figures

Figure WRU 11A.1 Land Use and Major Roads

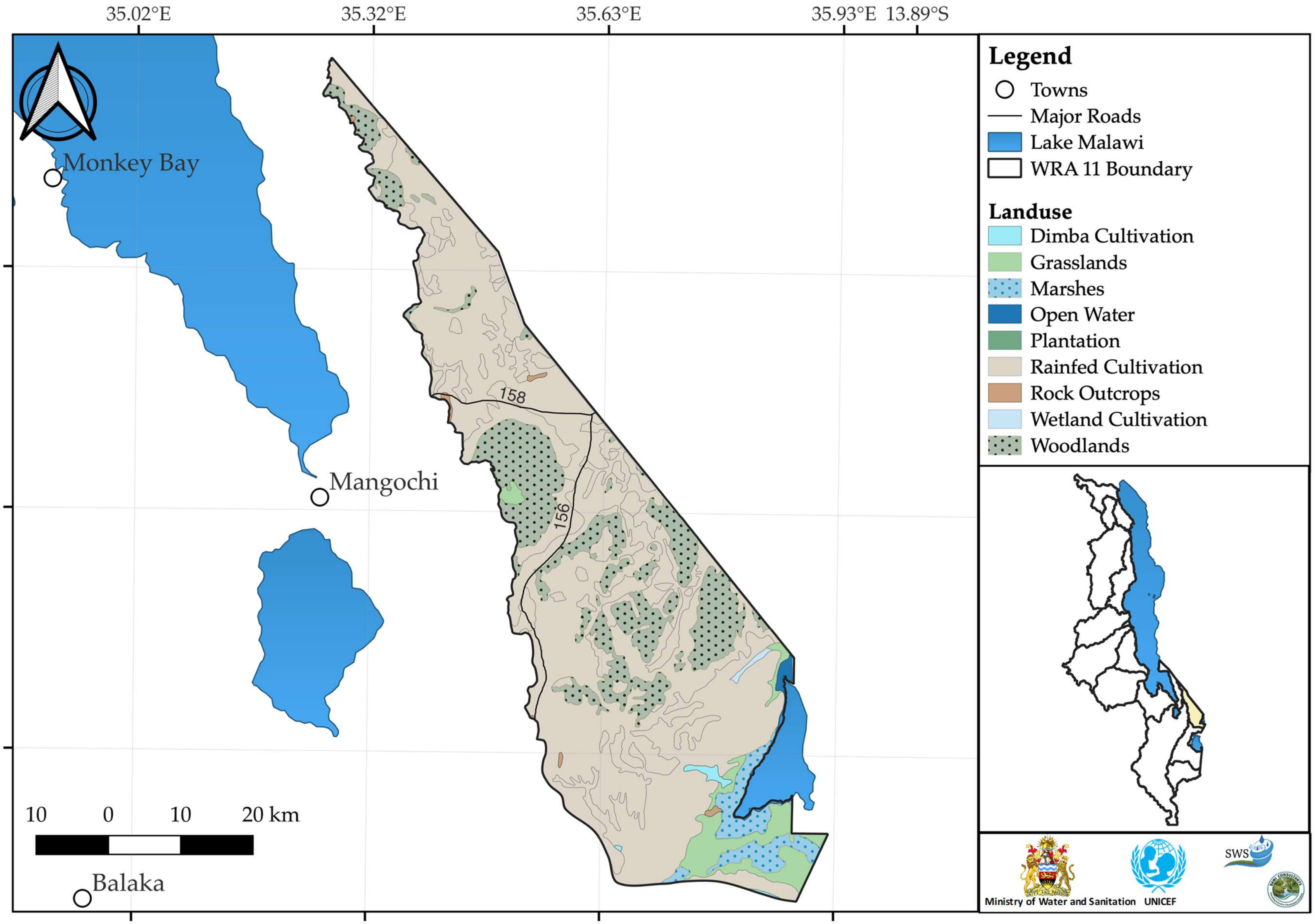


Figure WRU 11A.2 Rivers and Wetlands

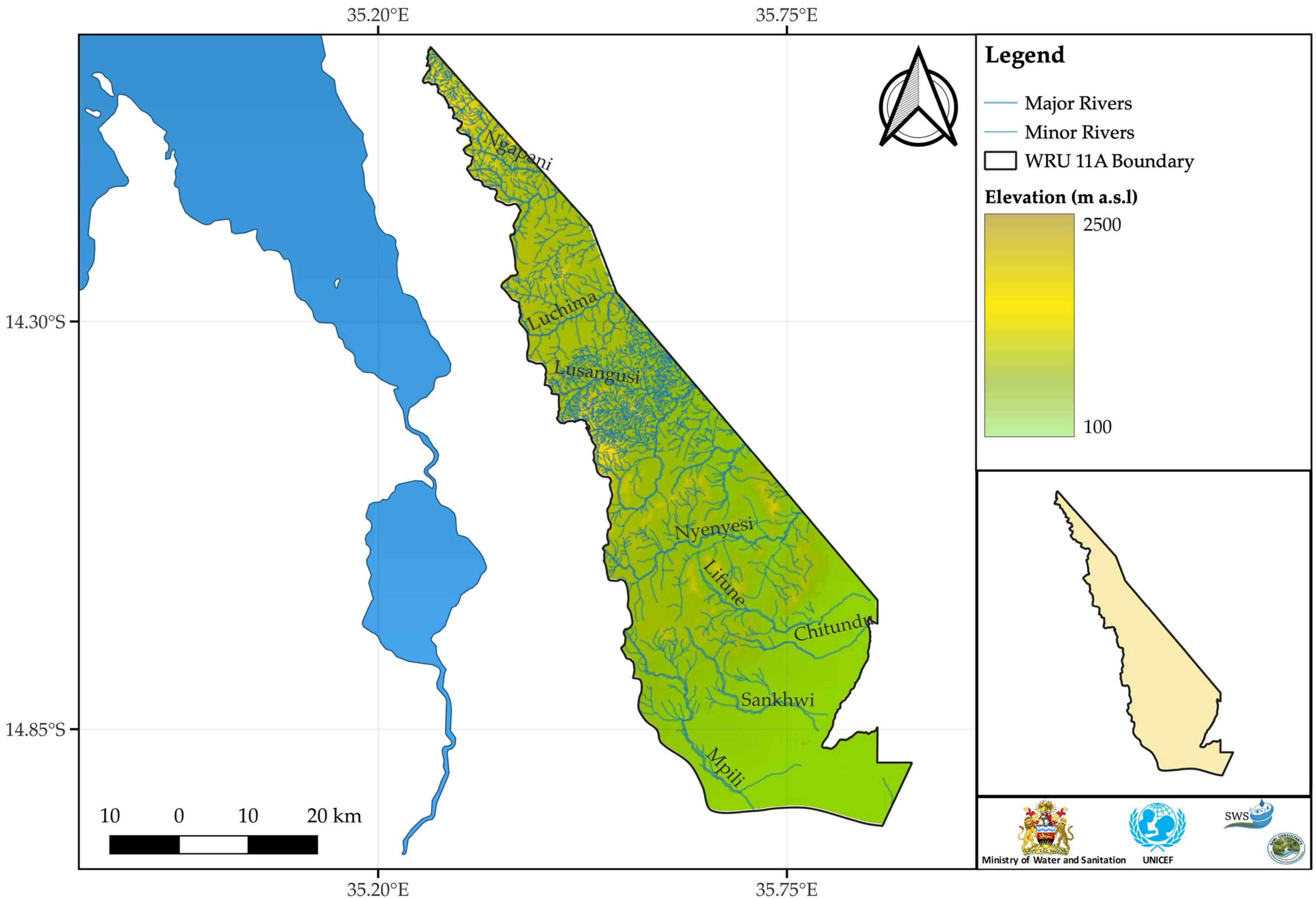


Figure WRU 11A.3 Hydrogeology Units and Water Table

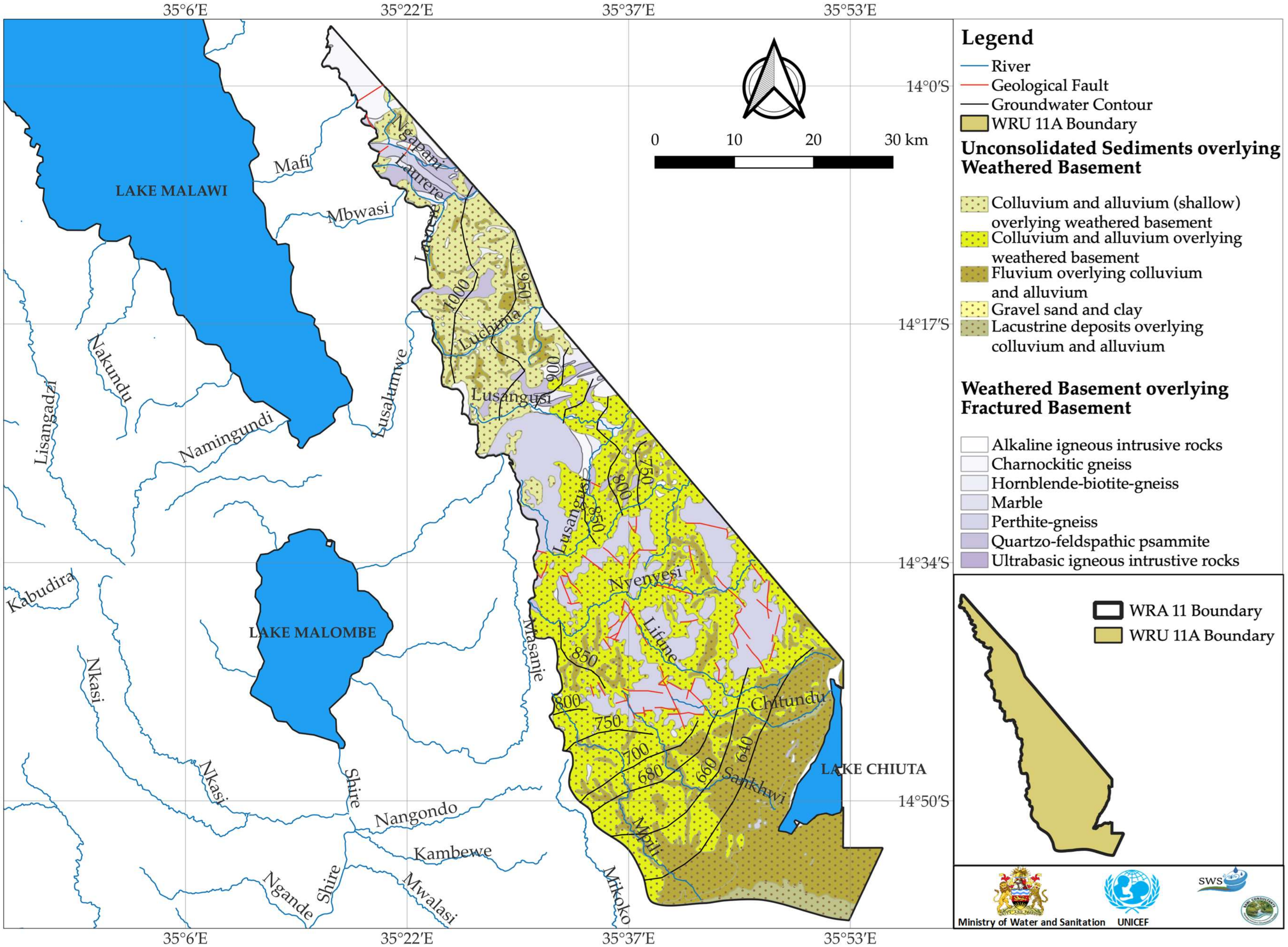


Figure WRU 11A.4 Groundwater Chemistry Distribution Electrical Conductivity

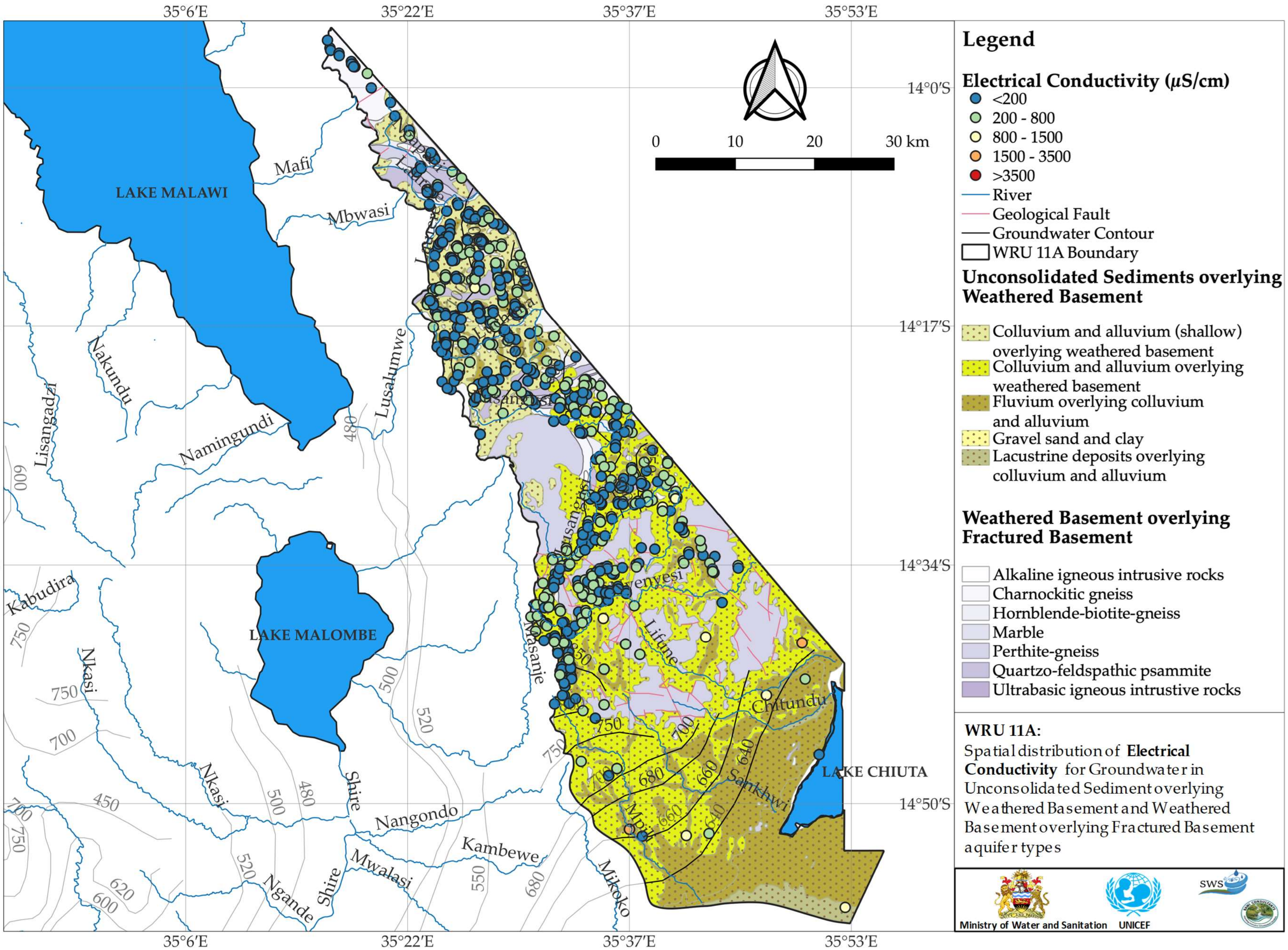


Figure WRU 11A.5 Groundwater Chemistry Distribution Sulphate

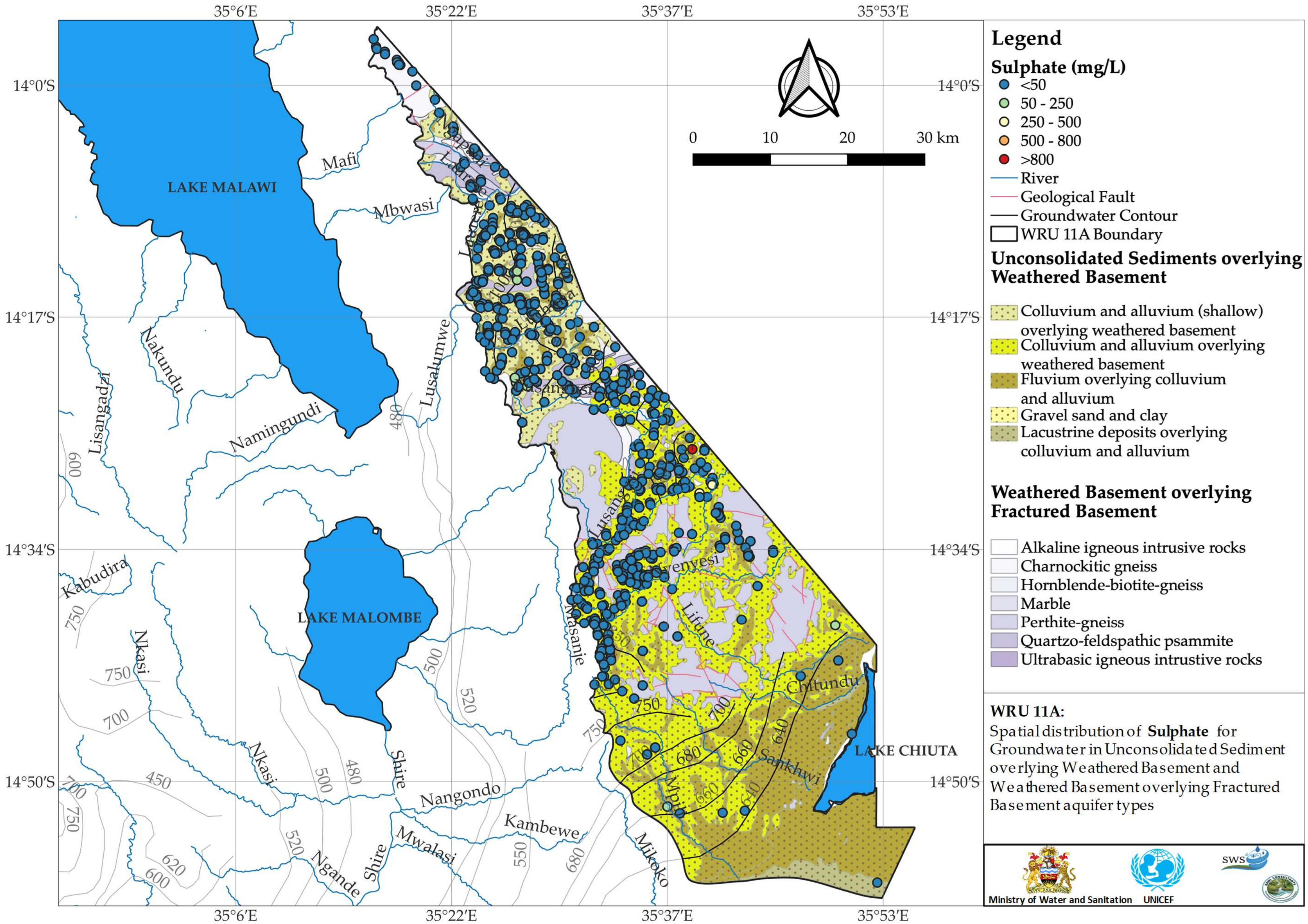


Figure WRU 11A.6 Groundwater Chemistry Distribution Chloride

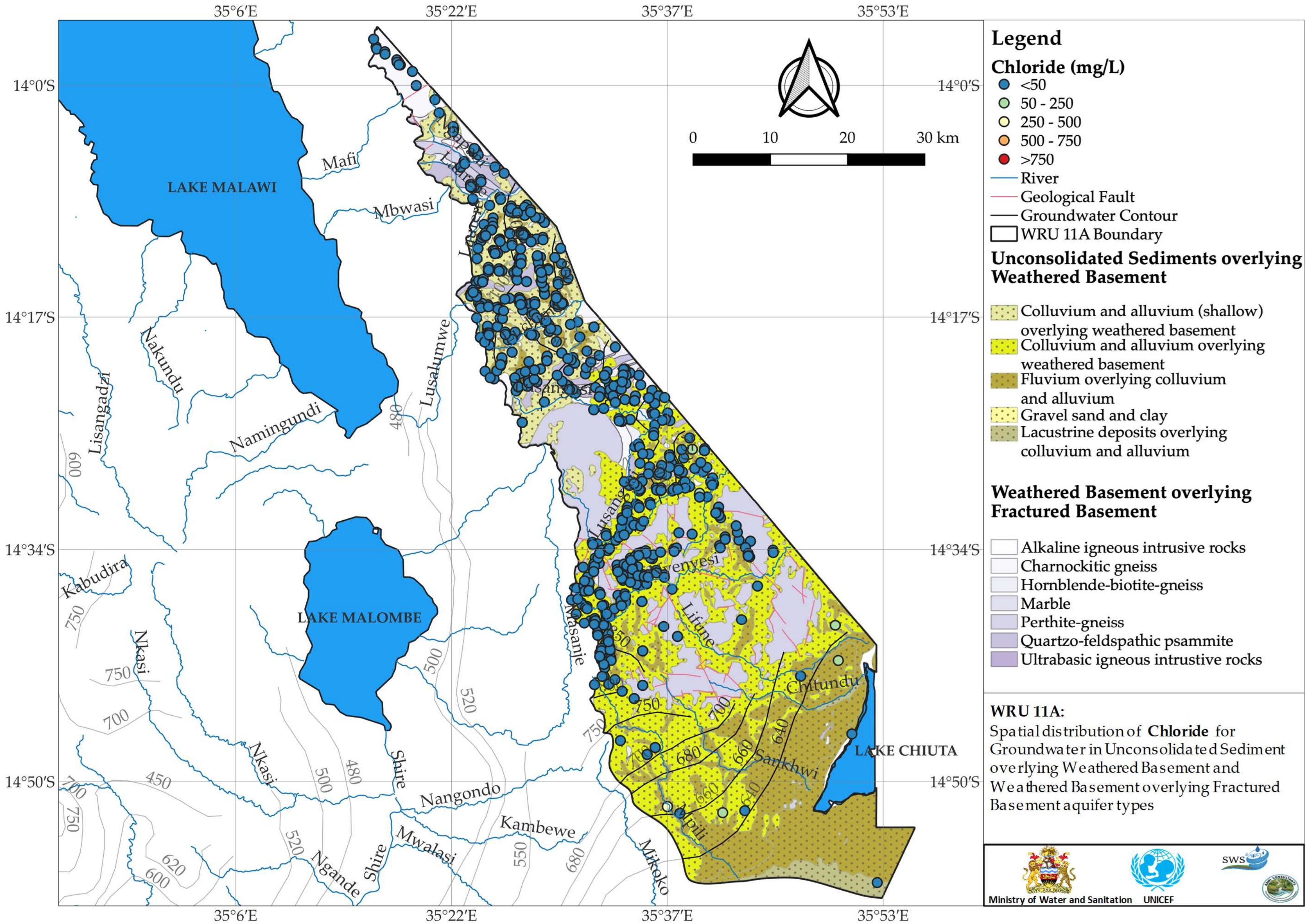


Figure WRU 11A.7 Groundwater Chemistry Distribution Sodium

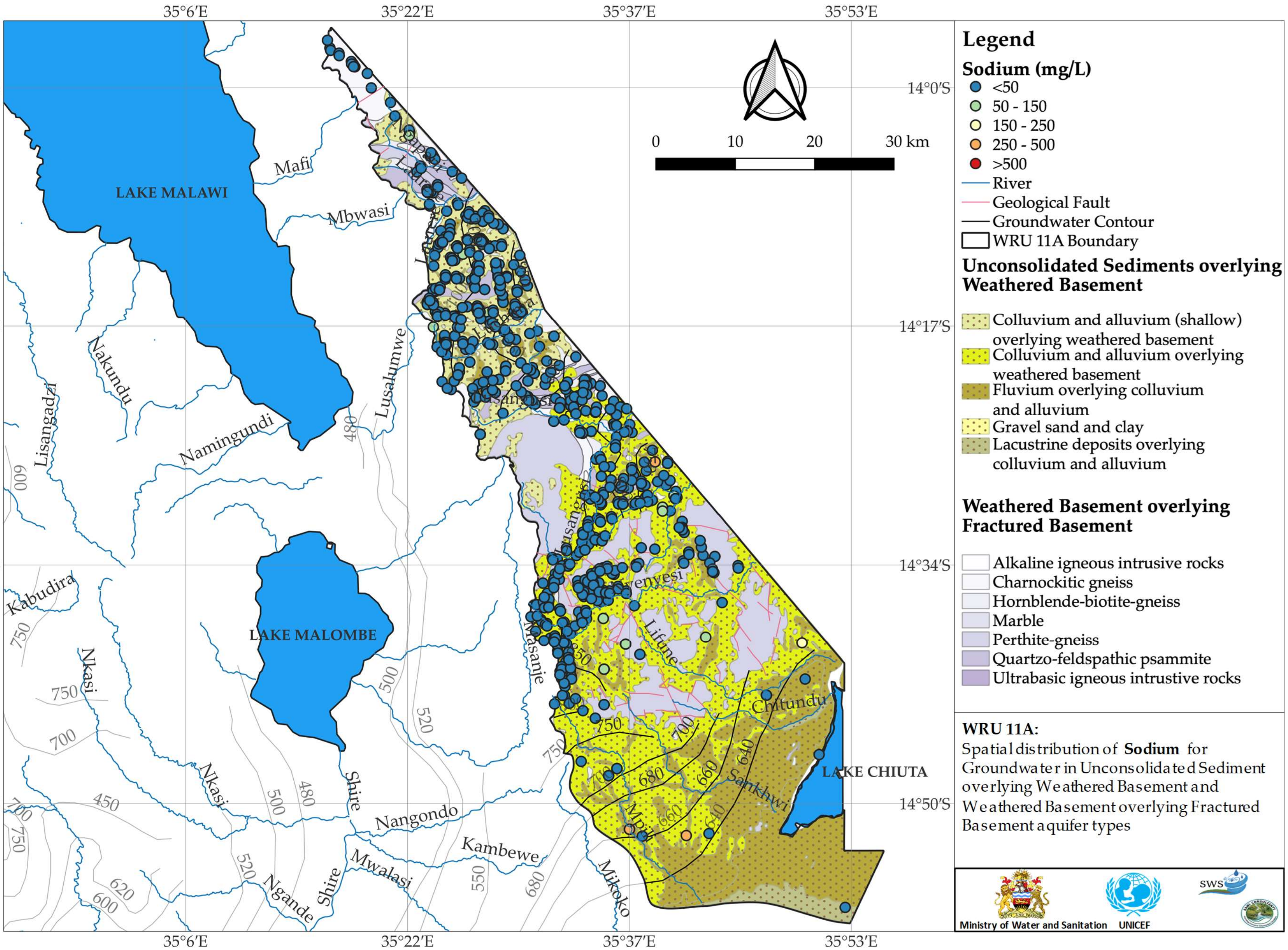


Figure WRU 11A.8 Groundwater Chemistry Distribution Calcium

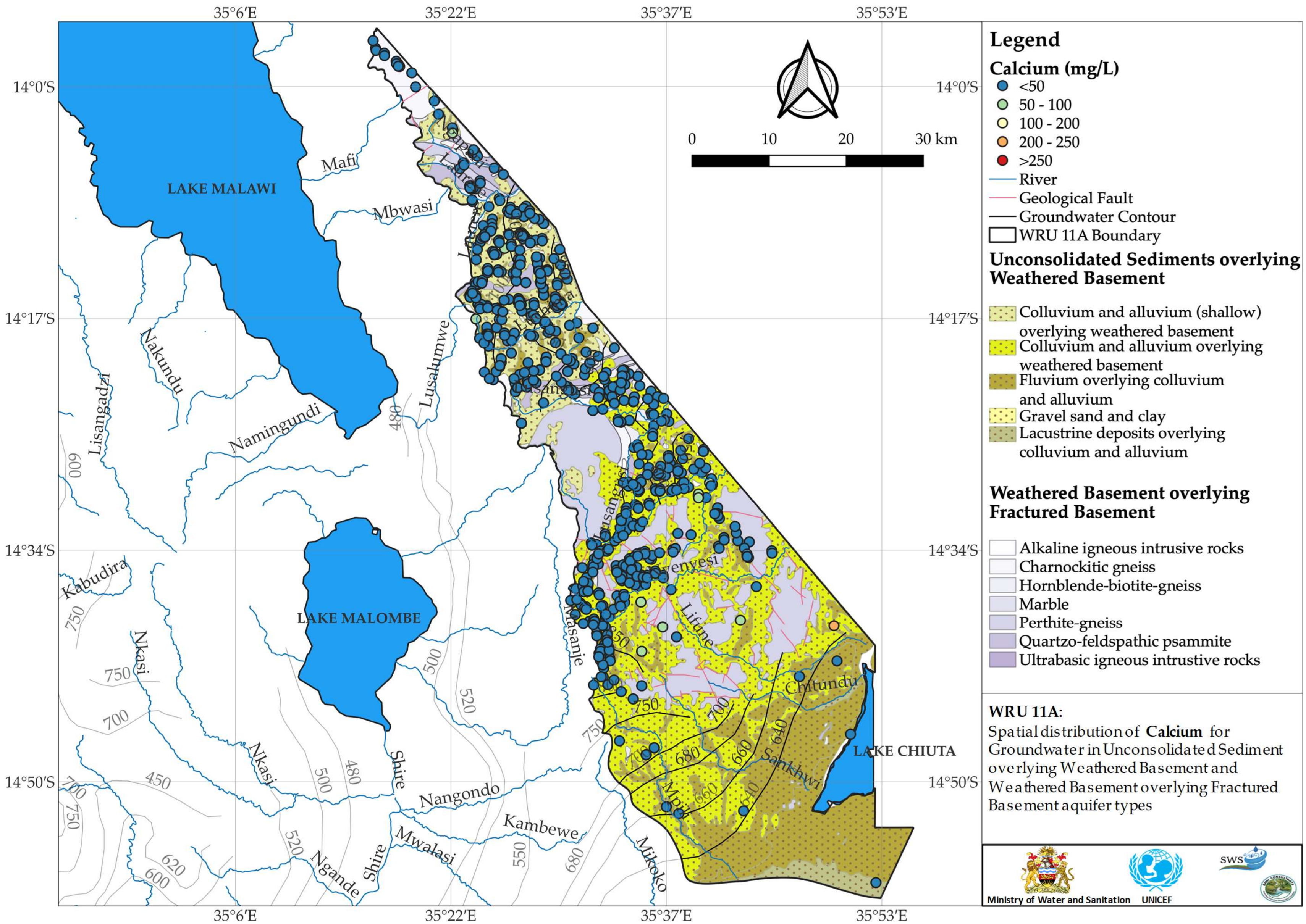


Figure WRU 11A.9 Piper Diagram of water quality results with respect to the major aquifer type

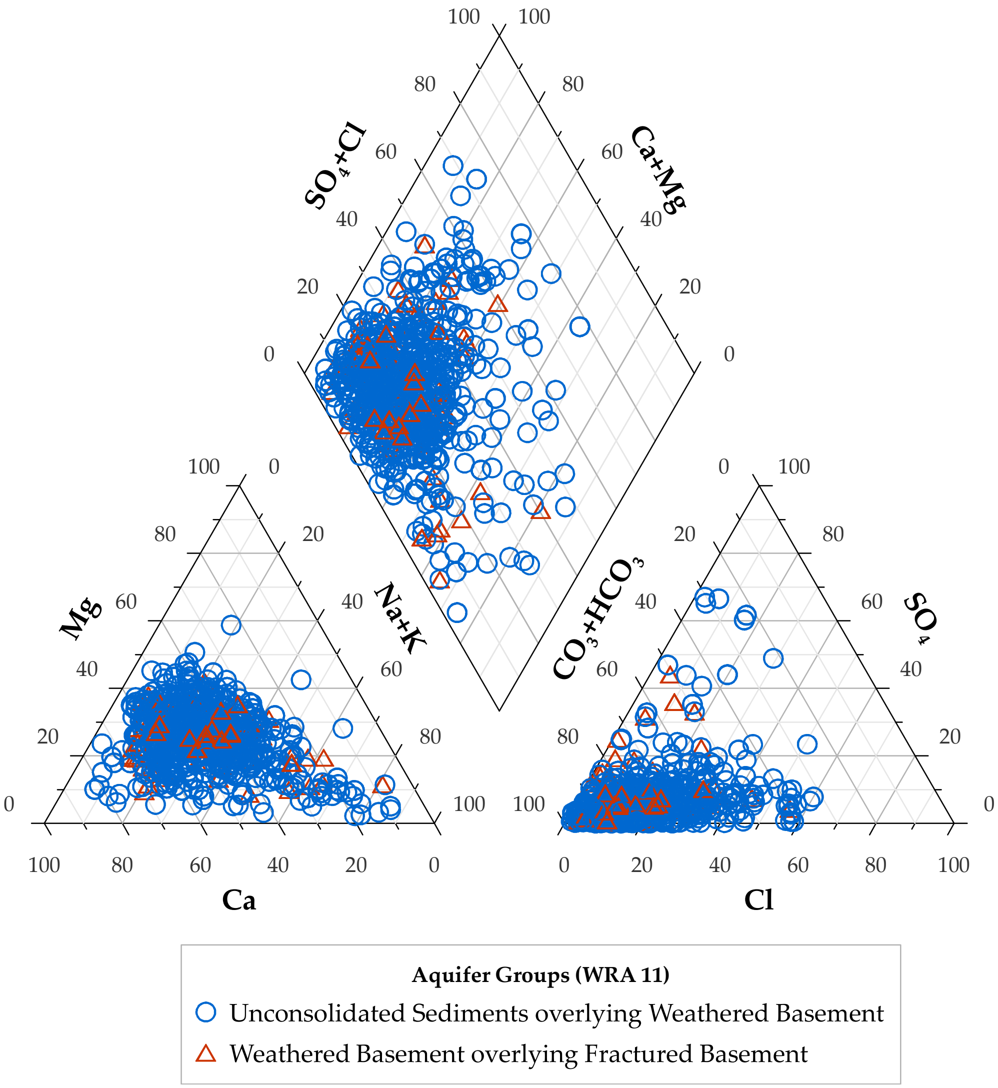
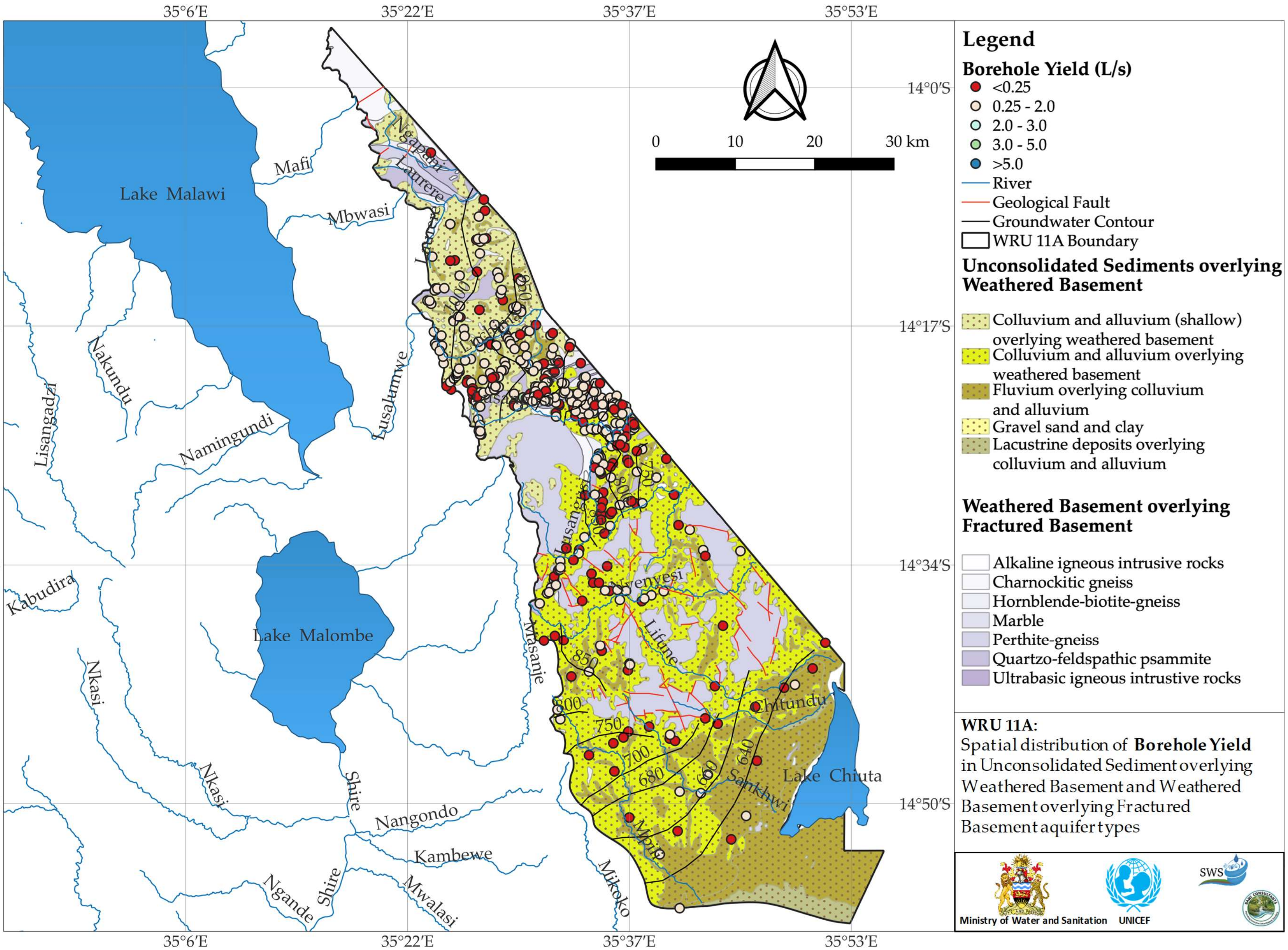


Figure WRU 11A.10 Borehole Yield Map for data held by the Ministry



Ministry of Water and Sanitation

Hydrogeology and Groundwater Quality Atlas of Malawi

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