Hydrogeology and Groundwater Quality Atlas of Malawi

Bulletin

Ministry of Water and Sanitation

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

Kalin, R.M., Mleta, P., Addison, M.J.; Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedeza, A., Hinton, R. (2022) *Hydrogeology and Groundwater Quality Atlas of Malawi, Bulletin, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-00-0 151pp*

ISBN 978-1-915509-00-0

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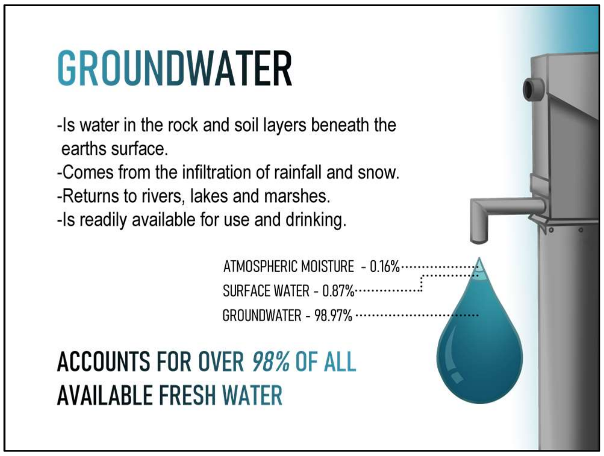
Developed with the support of UNICEF (Malawi), BAWI (Malawi), SWS (Scotland) and The University of Strathclyde (Scotland)

1st Digital Edition (22nd March 2022)

Foreword



The focus of World Water Day 2022 is Groundwater, Making the Invisible – Visible. To meet this challenge, the Ministry of Water and Sanitation has undertaken to update the previous 2018 Hydrogeological and Water Quality Atlas of Malawi, making it a living document that is periodically revised with new data and understanding so this precious resource can be managed effectively. Groundwater is the main available resource for nearly 85% of the rural population in Malawi. Groundwater supports the base flow in rivers across Malawi, and irrigation and agriculture are therefore dependant on the resource. Conjunctive use of Surface Water and Groundwater is required to meet growing water demands of Urban Populations, and town and market centres. Increasing Population, climate change and enhanced climate variability, deforestation, land use change and contamination from human wastes and agricultural activity are threats to the groundwater resources in Malawi. This document supports the Government to properly understand the quantities and quality of groundwater in Malawi so that it can be managed sustainably as required by the Water Resources Act 2013.

The challenges of climate change will bring about more dependence on groundwater for adaptation and resilience. Accordingly, there is a need to continually update groundwater knowledge in Malawi so that systematic and detailed information about groundwater occurrences can be incorporated into local, regional and national planning. The atlas provides an interpretive entry point for data held by the Ministry, and the hydrogeological and water quality maps produced under this programme covers the whole country with the same level of detail at local scale. Maps are detailed at Water Resource Area and Water Resources Unit as Integrated Water Resources Management in Malawi is devolved to these geographic areas, to aid understanding of the hydrogeological and groundwater occurrences in Malawi.

The maps represent a synthesis of the data available within the Ministry of Water and Sanitation and we call on the sector to share all information and knowledge with the Ministry. This 2022 updated Hydrogeology and Groundwater Quality Atlas will benefit from further investigations and data, and the Ministry urges all those engaged in Integrated Water Resources Management (Irrigation, Agriculture, Water Supply, Water Resources [Groundwater, Surface Water, Water Quality and Isotope Hydrology], Sanitation, Forestry, and Health) to document accordingly for the effective implementation of water resources programmes and projects in the country.

Honourable Abida Sidik Mia, MP
Minister of Water and Sanitation

Preface

Malawi's water scarcity index is climbing and contrary to popular belief, Malawi is not a water rich nation. Given Lake Malawi holds 7,750 km^3 of water, it dominates water resource management perceptions, however Lake level variation is ultimately limited between 471.5 and 477masl, and in 2022 ranged from 474 to 475.25masl, resulting in an annual renewable freshwater input of 35.9 km^3. The estimates of annual recharge to Groundwater (<100m depth) in Malawi are conservatively estimated to range between 1.0 km^3 and 7.7 km^3 with a total Groundwater volume of between 96.7 km^3 and 1,108 km^3, with an average age of between 95 and 140 years. Groundwater is thus the largest distributed available freshwater resource in Malawi, but as with Lake Malawi, one that is dependent on annual recharge. Groundwater is also vital for sustained river flow in Malawi, it is the key water resource that has potential to provide adaptation and resilience to development challenges and climate change if managed properly.

The Government of Malawi is committed to "provide adequate, reliable, and sustainable water and sanitation services to the people of Malawi to meet the ever-increasing demand for safe water for domestic, institutional, commercial, and agricultural use, with emphasis on the poor and rural communities". Although groundwater is a reliable resource when properly managed, the lack of professional oversight and limited information reaching planners, decision-makers and users commonly results in it being used as a second option to more expensive surface water schemes. Limited capacity results in a lack of proper and professional hydrogeological interventions, which has led to a 39.4% failure rate (16% non-functional, 23.4% partially functional) for rural single point groundwater water supplies. The Ministry is the National Water Policy holder, and has in place detailed guidance and standard operating procedures for the development, use and monitoring of Malawi's groundwater resources. There is a push to expand groundwater abstraction using 'solar' or 'reticulated' groundwater sources, and these investments must be implemented by professional hydrogeologists who gather and use site specific data to determine sustainable groundwater yields, limiting risks of wide-spread failure and over-abstraction of limited groundwater resources. Accordingly, all groundwater abstraction points must be vetted by the National Water Resources Authority (NWRA) and, were required, assigned abstraction permits that maintain groundwater resources for the environment (rivers/wetlands), industry, and agricultural uses.

The objective of this programme was to build on previous work including the 2018 Hydrogeological and Water Quality Atlas of Malawi, making this a living document that provides existing groundwater and water quality data as maps at local scale, while summarising the characteristics of aquifers and water quality parameters. This mapping initiative pulled together the available information (with geospatial data) within the Ministry of Water and Sanitation concerning groundwater and water quality characteristics. The National Borehole Database provided historical groundwater potential based on yield frequency distribution of boreholes, and the Water Quality Database provided historical geospatial groundwater quality data.

Joseph Magwira, Secretary for Water and Sanitation
Ministry of Water and Sanitation

Acknowledgements

The development of this atlas was supported through generous funding by UNICEF. The Ministry of Water and Sanitation, together with the authors and reviewers of this Atlas would like to acknowledge the support of staff from the Ministry in particular Zione Butao, Prince Mleta, Macpherson Nkhata, Gift Wanangwa, Owen Lin Phiri, Patrick Mlomba, Stellah Kaso, Vitumbiko Mwausegha, Ambrose Phiri, Kondwani Mponda, and Arnold Savison. This report specifically builds on the previous Malawi Hydrogeological and Water Quality Atlas (2018), and recognises the efforts by Donors, NGOs, CSOs, Academics and Consultants who support the Ministry to meet its objective of Water for All, Always. Special appreciation also to the consultants and academics involved in the production of this 2022 Edition of the Hydrogeology and Groundwater Quality Atlas of Malawi, and to the illustrator Arielle Kalin for bespoke conceptual hydrogeology drawings. They are especially thanked for the time and efforts made to translate the interpretation of groundwater resources data at not only the Water Resource Area scale, but also at Water Resources Unit where the Ministry of Water and Sanitation holds Water Resource Policy and the National Water Resources Authority (NWRA) enforces regulation, both seeking to implement Integrated Water Resources Management (IWRM) in Malawi.

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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

Executive Summary

Water is essential for life and occurs as surface or ground water. Most of the rural communities in Malawi depend largely on groundwater for their day-to-day water usage. Understanding the context of its storage, and the complexity and processes that control quantity and quality is essential to ensure that the finite resource is sustainably managed. The conservation and management of groundwater resources becomes even more critical as Malawi aspires towards achievement of SDG 6 goals by 2030 and the Malawi Vision 2063. Groundwater management is also responsible to regional and international protocols and statutes that Malawi is a signatory to.

The need for understanding of groundwater resources for strategic planning and investments led the then Ministry of Agriculture and Water Development, now the Ministry of Water and Sanitation to initiate the process of the development of the first groundwater Atlas in 2018. The Preparation of the Hydrogeological and Water Quality Mapping (2018) was completed by the Council of Geoscience of South Africa. The resulting Hydrogeological and Water Quality Atlas improved the understanding of the groundwater quantity and quality in Malawi. Here, this revised 2022 Hydrogeology and Groundwater Quality Atlas is an attempt to set up a living document that can be updated regularly as new, quality, data becomes available while taking into consideration the changing environment as impacted by climate change.

The stress on water resources is increasing in Malawi, this calls for increased information and understanding of groundwater occurrence, available safe yields, and water quality. Data is vital to predict how groundwater behaves in response to climate patterns, ever-increasing abstraction scenarios using hand pumps, electric submersible pumps from well fields, and changes in land use (such as deforestation, irrigation, dams and urbanisation). Therefore, the scope of this desk-based assignment focused on assessment of groundwater resources in the country at local scale while updating of hydrogeological mapping.

The Ministry of Water and Sanitation recognises the Atlas needs to be a living document to be updated regularly as new and reliable data becomes available, in particular for water quality and groundwater level maps. This update of the Atlas has been undertaken by Bawi Consultants Malawi in close partnership with the lead Hydrogeologist at Sustainble Water Solutions Ltd Scotland (SWS), calling on the expertise of various consultants and academics in response to the Terms of Reference issued by UNICEF Malawi entitled: Hydrological Water Quality Mapping - Revision of Atlas Document.

This Atlas is a successor document to the 2018 version, the Council for Geoscience field reconnaissance, drilling, testing and analysis has not been re-interpreted and stands in their document, however several desk-based refinements have been made that include the following:

a) The descriptions of Hydrogeology and Groundwater Quality for each Water Resources Area (WRA) have been expanded to be of consistent quality and quantity of analysis for planning, and new analysis at Water Resource Unit (WRU) level has been added.
b) The revised atlas includes definition and description of the shallow aquifers in Malawi as a system clarifying nomenclature to recognise the Malawi specific complexity for storage and transmission of Groundwater.
c) The diversity of formations within the groups has also been isolated according to geologic and mineral properties to facilitate enhanced interpretation of geogenic water-rock reactions that control groundwater quality (e.g. Fluoride). In some cases, aquifer groups have been separated

into specific types and units to conform with the general lay out of international geologic nomenclature.

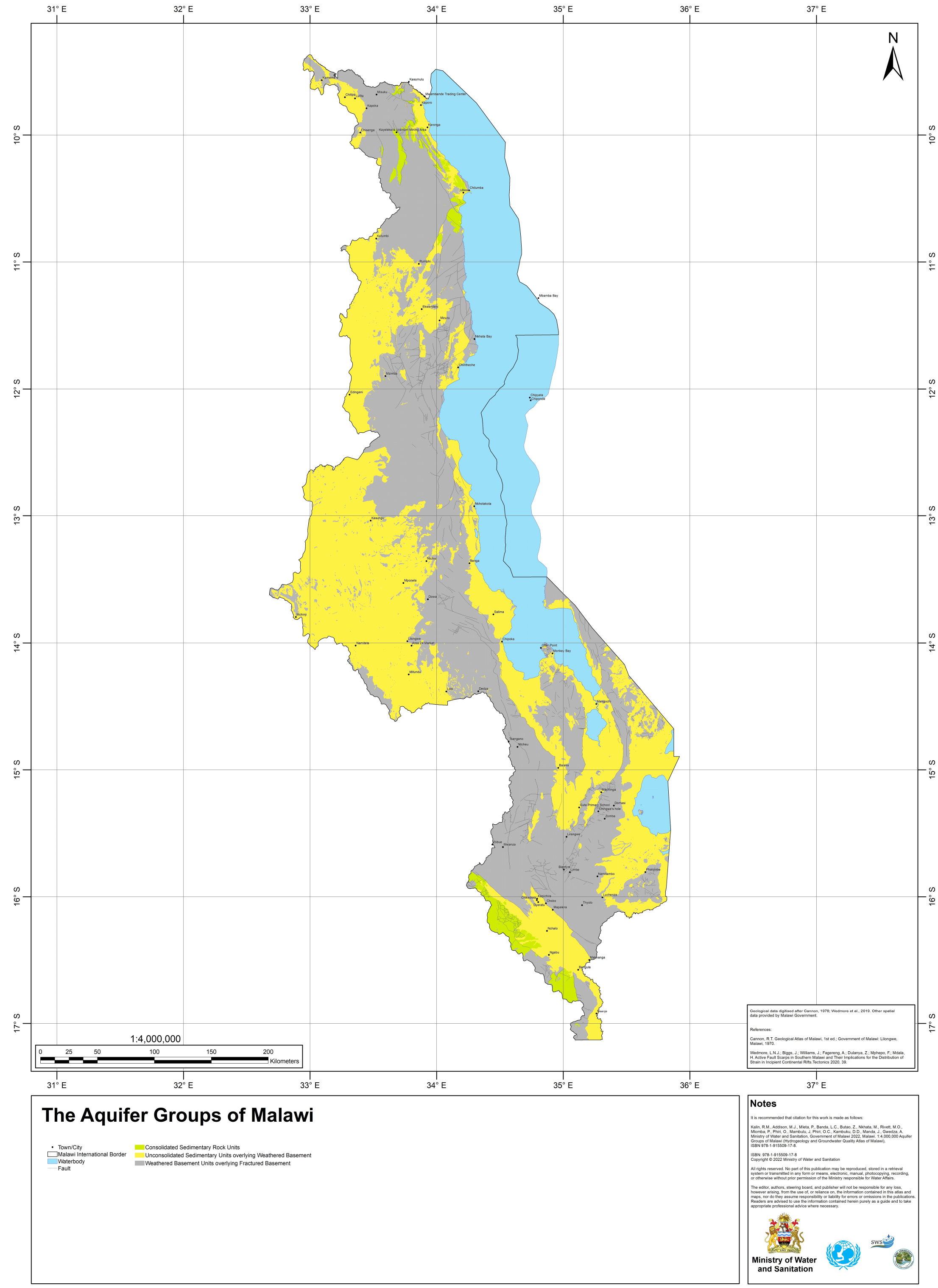
d) Current water strike data and well depths suffer from a lack of accurate site-specific surface elevation data, therefore water table maps from 1987 were digitized and transferred into the current assignment with indicative flow directions. Given the topographical control on groundwater flow in Malawi, this previous data is largely still valid with a need for collection of a revised national data set.
e) New information on water quantity and quality including calculations of groundwater recharge and storage for each WRU has been calculated, including the number of groundwater abstraction points, the mean (bulk) age of water; Fluoride and Arsenic risk maps; calculated Base flow Index [BFI] values presented on various National, WRA and WRU scale maps.
f) With this Atlas update, the Ministry can plan for future data and information gathering activities led by available data for each WRA and WRU for physiology, hydrogeological units, borehole yield and chemistry distribution.
g) Due to its size, WRA 1 has been sub divided to provide more detailed than generalized information.

The 2022 version of the Hydrogeology and Groundwater Quality Atlas does not present an in-depth account of each potential hydrostratigraphic / geogenic unit and linked aquifer systems, geological formation, or conditions and processes influencing groundwater quality in various WRAs and WRUs due to the limited availability of quality data in space and time. Despite the additions and modifications to the previous Atlas, there is need for routine updating of the Atlas as more monitoring and stratigraphic / hydrogeologic data becomes available. There is need also to address the sector data gaps through capacity building and enforcement of the standard procedures in the siting, drilling and testing of aquifers prior to borehole installations, in particular as larger yield / solar boreholes are designed and implemented (with required NWRA permits).

The revised Atlas presents, in simple and understandable terms, the form maps, drawings, and tables to support evidence-based planning and decision making in line for the achievement of the of the SDG 6 by 2030 and for the realizing of the goals of the Malawi 2063 (MW2063). The need for profound understanding of the whole processes and complexity of the various aquifer systems is fundamental to managing the water resource sustainably.

The Atlas makes data and information accessible in format that is easy, succinct, and visually attractive. It contributes to the advancing of the Government of Malawi mission and reform areas of encouraging data-based deliberations, planning, and decision-making processes among policy makers, academicians, researchers, stakeholders, citizens, civil societies, private sector and many others for the future of water availability and quality in Malawi at large. This will guide the sector in terms of investment packages that are required in the WRAs and WRUs.

It is hoped that the revised Atlas will serve key functions such as: readily available readable and useful source of information; convenient reference material for meaningful planning and decision making as a to guide investments in the country, and as a resource for the NWRA to implement groundwater resource and abstraction management and IWRM from Local to Trans-Boundary Scale in Malawi.



Geological data digitised after Cannon, 1978; Wedmore et al., 2019. Other spatial data provided by Malawi Government.

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Notes

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ISBN: 978-1-915509-17-8

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Figure 1. Map of the general aquifer groups of Malawi [Available as Map at A0 size]

Introduction to the Hydrogeology and Groundwater Quality Atlas

General

The stress on water resources is increasing in Malawi, this calls for increased information and understanding of all water resources including groundwater occurrence (**Figure 1**), available safe resource yields, and groundwater quality. Data that is vital to predict how groundwater behaves in response to climate patterns, ever-increasing abstraction scenarios using hand pumps, electric submersible pumps from well fields and changes in land use (such as deforestation, irrigation, dams and urbanisation). Therefore, a desk-based assessment of groundwater resources in the country was undertaken to update hydrogeological and water quality mapping at a detailed local level for a deeper understanding of the resource.

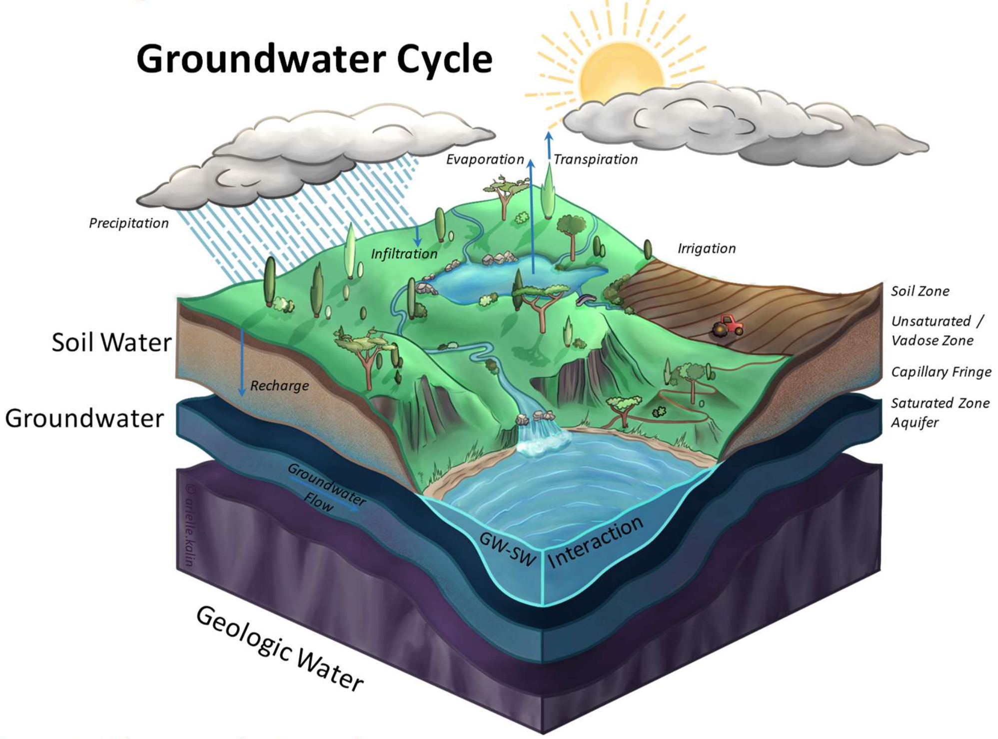


Figure 2a. The Groundwater Cycle

Understanding groundwater resources can be challenging, therefore World Water Day March 22, 2022 was dedicated to Groundwater, making the invisible visible. However, this natural resource is often poorly understood (**Figure 2a**), and consequently undervalued, mismanaged and even abused. In Malawi groundwater is central in the fight against poverty, to food and water security, to socio-economic development, and to the resilience to climate change. Reliance on groundwater is increasing in Malawi due to growing water demands combined with variation in rainfall patterns. Unlocking the full potential of groundwater in Malawi will require a concerted effort to manage and use it sustainably within the legislative framework of the Water Resources Act (2013) Malawi, overseen by the National Water Resources Authority (NWRA), and it starts by making the invisible visible. Of particular note is the focus on local-scale interpretation of the data held by the Ministry of Water and Sanitation as under the Water Resources Act (2013), Integrated Water Resources

Management (IWRM) should be focused at the Local Water Resource Unit (WRU) scale. This required re-evaluation of data at this scale and importantly production of maps at a high resolution for this purpose, and presentation of the output in digital form accessible to all.

A desk-based review was undertaken of data held by the Ministry of Water and Sanitation as the basis for the production of the maps and atlas. The aquifer mapping was based on the geological map of Malawi (1:100,000) prepared by the Geological Survey Department of Malawi. Each geologic formation in Malawi was reviewed for geographic extent and their relationships with depth. The majority of groundwater in Malawi exists in hydrostratigraphic units that are unconfined (**Figure 2b**) where precipitation infiltrates and directly recharges the groundwater, but there is anecdotal evidence (no data) on the extent of confined groundwater (**Figure 2b**), this is a major knowledge gap.

Groundwater potential and water quality data were held in databases under the custodian of the Ministry of Water and Sanitation of Malawi, together with information in the literature. The maps produced indicate a distribution of aquifer types, the groundwater potential, and the water quality in light of Malawi's drinking water standard for borehole and shallow well water quality (MS733:2005). The production of hydrogeological map was strongly influenced by the quality of the databases, particularly the fact that not all records in the databases were used owing to the inadequacies of the records, or that raw data from the previous published Atlas or from the wider stakeholders was not available. It is thus advised that the Ministry of Water and Sanitation should continuously improve and update their databases (and this atlas). This will help to improve the quality of the hydrogeological interpretation and groundwater management in Malawi. The hydrogeological and water quality maps of Malawi produced through this UNICEF funded programme should be used to assist in local scale to regional to international groundwater planning and development. It should serve as a reference document to inform water sector policy-makers and decision-makers on groundwater potential and development in the country. Furthermore, the maps are a good starting point to promote research development particularly on issues related to groundwater quality and occurrence and to map groundwater at detailed scales for areas of concern.

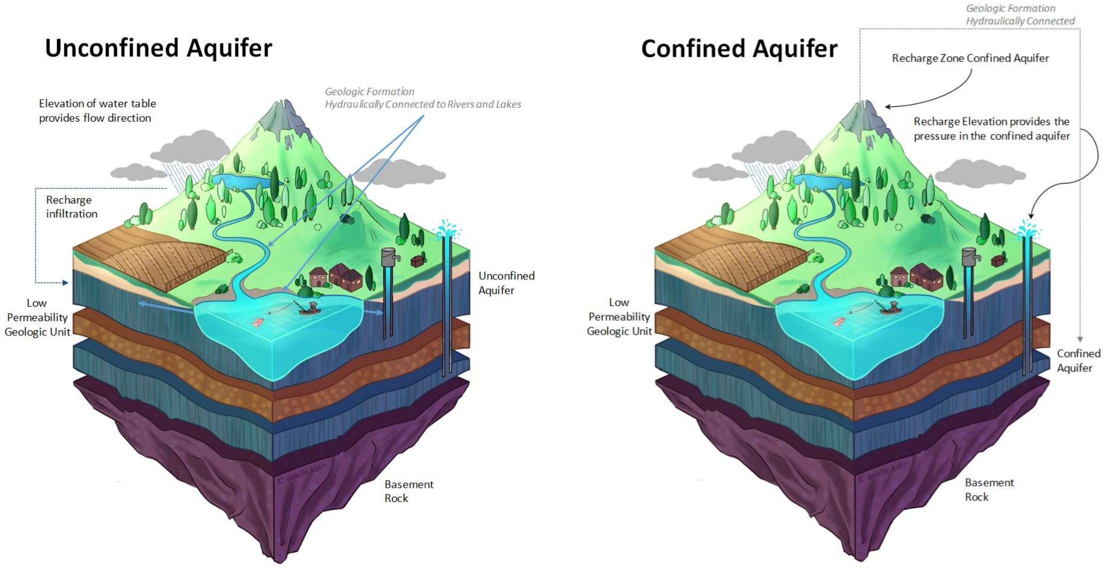


Figure 2b. Conceptual representation of Unconfined (left and Confined (right) groundwater resources.

Physiography of Malawi

Topographically, Malawi lies within the Lower / Eastern Great Rift Valley system. Lake Malawi lies within the rift graben and is a body of water with a surface area of about 29,600 square kilometres and a surface elevation of about 460 m above sea level (masl). As the country's most prominent physical feature it is socially and culturally significant. About 75% of the Malawi land surface consists of uplifted plateaus with elevations between 750 masl and 1,350 masl above sea level. Upland elevations rise to over 2,440 masl in the Nyika Plateau in the north and 3,000 masl at Mt Mulanje-Sapitwa in the south (**Figure 3**). The lowest point in Malawi is in the south where the Shire River leaves the country and enters Mozambique at 37 masl above sea level.

Malawi's main physiographic features are described in detail by Pike and Rimmington (1965) and are characterised by extremely diverse physical features. The nature of these features influences the local climate, hydrology and groundwater occurrences in the country. It is typically divided into four major physiographic zones:

- Plateau areas
- Upland areas
- Rift valley escarpment
- Rift valley plains

The plateaus are generally pene-plains with several wide valleys topographically separated from one another and generally draining Eastwards to the rift valley. The altitudes of the plateaus vary between 900 and 1,300 masl. The plateau areas are largely dominated by a thick mantle of unconsolidated sediments as colluvium and fluvial alluvium overlying saprolite derived from prolonged in-situ weathering of the underlying strata; this forms an extensive and important regionally distributed but locally discontinuous system of aquifers stretching from the south to the north of the country. Unconsolidated sediments, including lacustrine deposits are the geotype for approximately 64.9% of rural groundwater abstraction points for water supply are located in this geologic type.

The uplands comprise isolated intrusive mountains rising abruptly; the most prominent are Mulanje and Zomba in the south, Viphya and Nyika in the north and Dedza in the centre; these mountain plateaus reach altitudes of 2,000 to 3,000 masl and they consist mainly of granitic and syenitic intrusions. The comprehensive geology of these areas is found in Carter and Bennet (1973). High relief physiographic features also form at the rift valley escarpments. The Malawi Rift extends almost the full length of the country. Large scale block rotation decreases progressively to the west and forms a classic half graben. The key geological units of southern Malawi include the Karoo Supergroup (consolidated sedimentary units), the Upper Karoo Stormberg Volcanics, and the Jurassic-Cretaceous Chilwa Alkaline Province. High-grade metamorphic rocks of the granulite facies underlay these units and can be observed at the surface across areas of the south-central part of the country. The key hydrogeological units correlate with geological units. Broadly speaking, the porosity and primary permeability of the basement is low. Weathering and tectonic fracturing forms secondary permeability that is the controlling factor on groundwater storage and transmission in these units. About 33.8% of groundwater abstraction points are found in solely weathered and fractured basement, and only 1.3% in consolidated sedimentary geologic units.

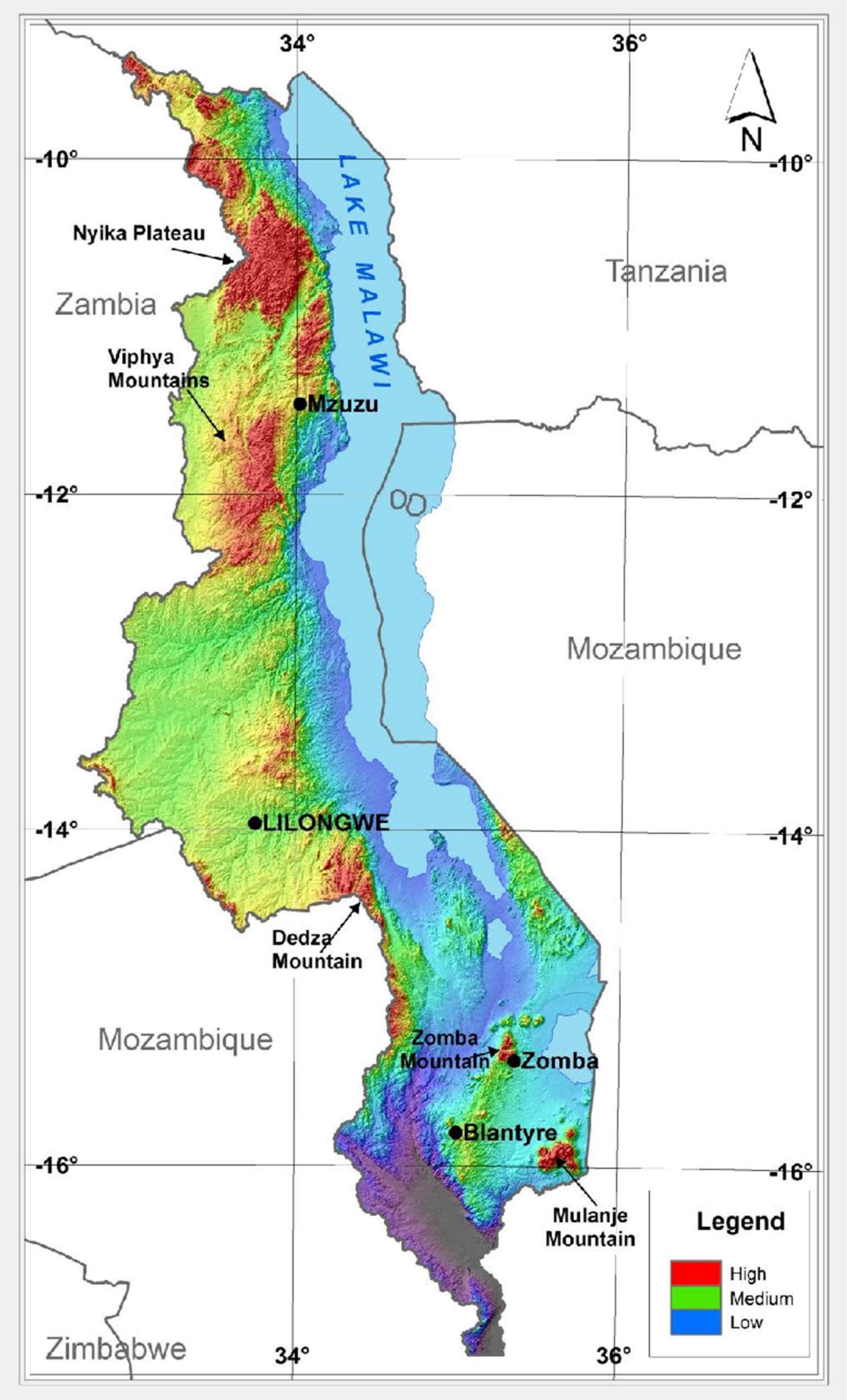


Figure 3. Topography of Malawi (after 2018 Council for Geoscience, National Hydrogeological and Water Quality Atlas)

The rift valley plains extend along the lakeshores of Lake Malawi, the Upper Shire and Lower Shire Valleys and along the lakeshores of Chilwa and Chiuta in the south. The approach to surface water bodies has gentle relief with wide areas of groundwater – surface water connection near Dambos (wetlands). The groundwater potential is very high, but with low groundwater velocities water quality issues such as increased salinity; groundwater abstraction schemes in unconsolidated sediments are found in Songwe, Dwangwa, Nkhotakota, Salima, Chikwawa, Ngabu and Nsanje.

Climate of Malawi

Malawi anecdotally is noted as a water rich nation, however this is due to the dominance of Lake Malawi as a major feature of the country. In fact, Malawi has a sub-tropical wet-dry climate that is strongly seasonal. There are three distinct seasons: the rainy season (wet) from November to April during which 90% of the annual precipitation takes place, the cool dry season from April through July, and the hot dry season from August to October (Pike and Rimmington, 1965).

Rainfall

There are two moisture sources for precipitation in Malawi, the Inter-Tropical Convergence Zone (ITCZ), and tropical depressions that form in the western Indian ocean and track across Madagascar, through the Mozambique Channel making landfall impacting mid to southern Malawi. A summary of bearing systems affecting Malawi is as follows:

- The ITCZ as a broad zone in the equatorial low-pressure, towards which the north-Easterly and south-Easterly trade winds converge.
- Tropical cyclones, which are essentially intense low-pressure cells that originate in the Indian Ocean and move from East to west, bringing widespread heavy rainfall mostly in southern Malawi, which can cause serious flooding.
- The Convergence Ahead of Pressure Surges (CAPS) system, which develops as high-pressure cells, that continues to move over the southern tip of the sub-continent. This leads to convergence ahead of the pressure surges causing isolated but locally heavy rains that normally precede the onset of the rainy season.
- The Easterly waves system is mostly active towards the end of the rainy season (March/April). The existence of Easterly waves in the atmosphere causes isolated but locally heavy rains in some parts of the country.

The annual rainfall in Malawi ranges from 700 to 2,400 mm (**Figure 4**) with a mean annual rainfall of 1,095 mm (Ngongondo *et al*., 2011). It can be seen in **Figure 4** that the distribution of rainfall is mostly influenced by the topography and the proximity to Lake Malawi. The highest rainfall occurs around the area north of Karonga Boma, with intensities higher than 2,054 mm, as well as around Nkhata Bay, Zomba and the south-Eastern corner of the country in the vicinity of Thyolo and Mulanje. A steep southerly gradient of rainfall intensity is evident from Mwangulukulu which rises again approaching the Nyika Plateau. The lowest rainfall is observed in the low-lying areas of the Lower Shire Valley and to the west of the central region of the country.

Temperature

Temperatures are influenced by the topography and decrease with increasing altitude. The mean maximum and minimum temperatures are 28°C and 10°C respectively in the plateau areas, and 32°C and 14°C respectively in the rift valley plains (**Figure 4**). The highest temperatures occur in October/November while the lowest temperatures are experienced in June/July.

A cool, dry winter season is evident from May to August with mean temperatures varying between 17 and 27 °C and falling to between 4 and 10 °C. In addition, frost may occur in isolated areas in June and July. The hot, dry season lasts from September to October with average temperatures varying between 25°C and 37°C. Humidity varies from 50% to 87% for the drier months of September/October and wetter months of January/February respectively.

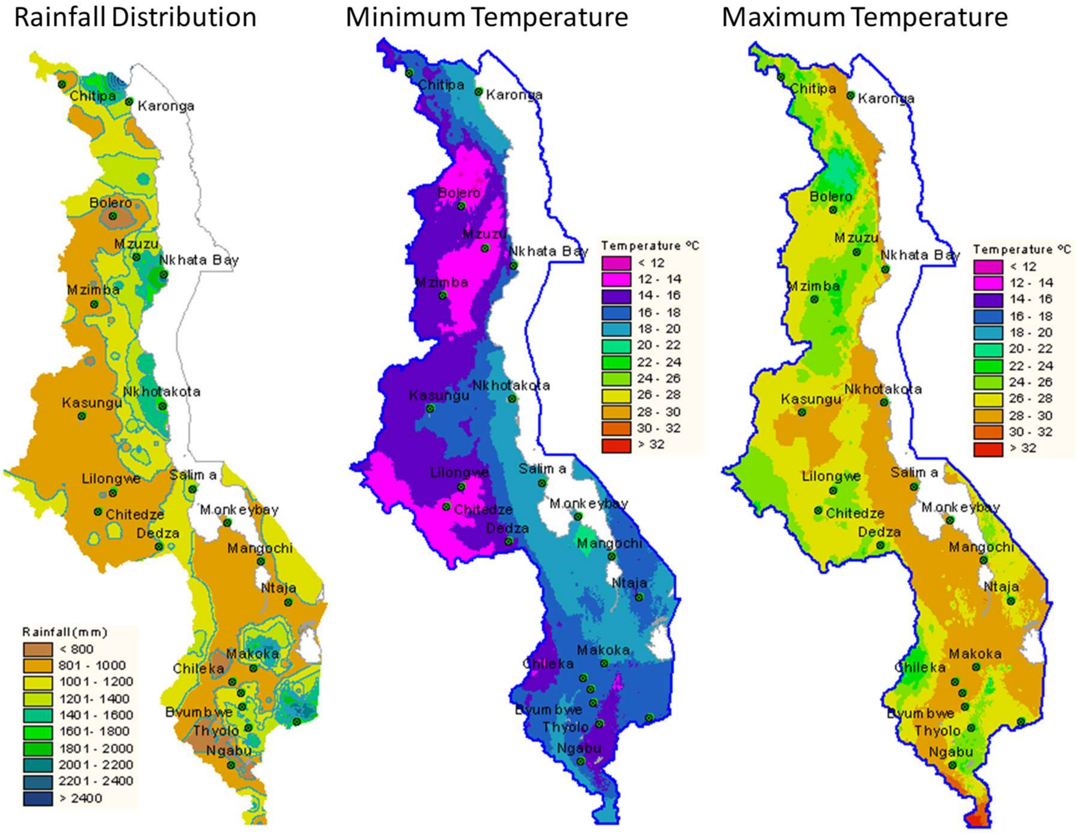

Rainfall Distribution Minimum Temperature Maximum Temperature

Figure 4. Annual rainfall distribution, minimum temperatures and maximum temperatures across Malawi [after Malawi Meteorological Office data and published distribution maps of Malawi https://www.metmalawi.gov.mw/dccms_climate.php]

National Water Budgets

Malawi is generally considered to be relatively rich in water resources in the form of lakes, rivers and aquifers, but in fact it is a water stressed nation, precipitated by rapid population growth. There are 17 Major Surface Water Catchments assigned as Water Resource Areas (WRA) for Integrated Water Resource Management (IWRM) (**Table 1, Figure 5**) and two major drainage systems:

- The Lake Malawi system is the most prominent hydrological feature in Malawi. It is between 560 km and 580 km long with a width varying from 15 to 80 km (Pike, 1964), and it is bounded by the countries of Malawi, Tanzania and Mozambique. The lake has a surface area of 28,750 km^2 and a volume of ca. 7,725 km^3 (Drayton, 1980; 1984). The system lies at the southern end of the East African Rift Valley system and its only outlet is the Shire River (**Figure 5**) with an average flow of 400 m^3/s. The upper course of the Shire River is an alluvial plain which passes to the lower course through a series of gorges, rapids and cascades. The Ruo and Mwanza are two of the main tributaries of the Shire River.

- The main water courses flowing into Lake Malawi are the Songwe, Linthipe, Bua, Dwangwa, North Rukuru and the South Rukuru. Most of these water courses emerge from plateaus and create inflows of approximately 360 m^3/s (Jury and Gwazantini, 2002). The main water courses have deep, steeply sided valleys, the slope flattens as they reach the Rift Valley and sediments are deposited in the annually flooded areas. The total catchment area of the lake is 97,740 km^2 with an annual flow of 918 m^3/s (Kainja *et al*., 2012). **Table 2** gives the inland runoff contribution to the lake from the three riparian countries, Malawi, Tanzania and Mozambique.

Most of Malawi's surface water resources and much of its groundwater resources are trans-boundary shared water resources. It is therefore important to recognize international water sharing agreements when planning and implementing IWRM. Lake Malawi and its catchment clearly shows the magnitude of these shared water resources (Table 2) and importantly the discharge from Lake Malawi through the Shire River is a major tributary to the Zambezi River that is managed through the multi-national Zambezi Commission (ZAMCOM).

While not of the same scale and magnitude of Lake Malawi, Lake Chilwa system is also shared with Mozambique. Lake Chilwa is an endorheic basin draining rivers originating from the Eastern slopes of the Shire Highlands, the Zomba Plateau and the northern slopes of the Mulanje Massif. In the area, evaporation dissipates the input such that the lake is saline and can dry up when evaporation rates exceed rainfall for two consecutive years (Jamu *et al*., 2012, Rivett et al. 2020). These authors also indicate that in the past the lake used to dry naturally over a 15 to 20-year period and paleo-hydrology in the past 1,000 years may have left remnant water quality signatures, however, the frequency increased in the 80s to mid-90s because it has not completely dried out in the last 20 years.

Table 1. Water Resource Areas delineated for Integrated Water Resources Management

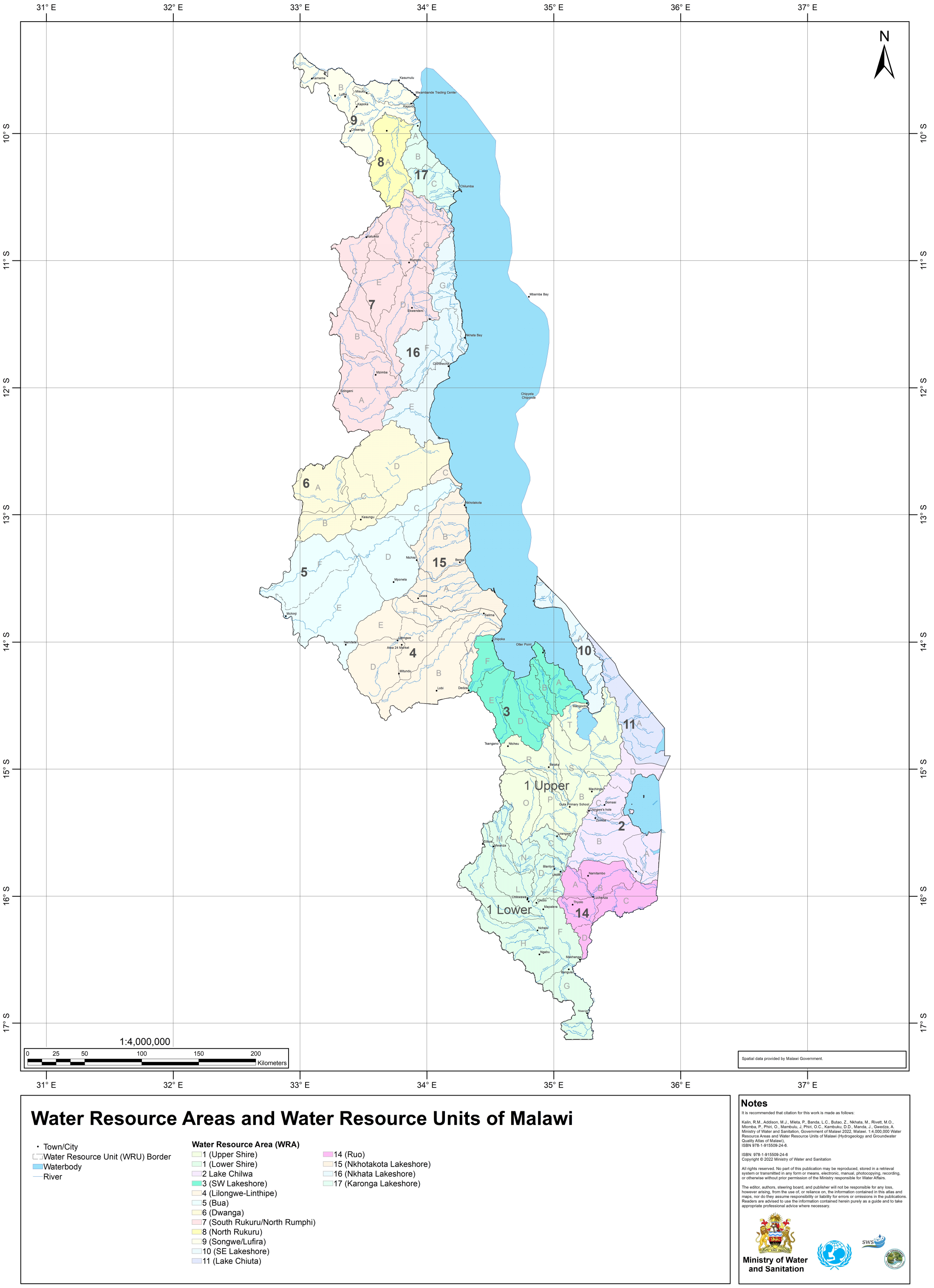
Water Resource Area (WRA)	Region	Area (Km^2)	Number of Water Resources Units (WRU)
1. Shire	**Southern & Central**	**18,911**	**16**
2. Lake Chilwa	**Southern**	**4,567**	**4**
3. South West Lakeshore	**Southern & Central**	**4,998**	**6**
4. Linthipe	**Central**	**8,885**	**6**
5. Bua	**Central**	**10,658**	**4**
6. Dwangwa	**Northern and Central**	**7,751**	**4**
7. South Rukuru, North Rumphi	**Northern**	**12,719**	**7**
8. North Rukuru	**Northern**	**2,088**	**1**
9. Songwe, Lufira	**Northern**	**3,730**	**2**
10. South East Lakeshore	**Southern**	**1,659**	**1**
11. Lake Chuita	**Southern**	**2,443**	**1**
12. Lakoma Island	**Northern**	**17**	**1**
13. Chizumulu Island	**Northern**	**3**	**1**
14. Ruo	**Southern**	**3,519**	**4**
15. Nkhotakota Lakeshore	**Central**	**4,819**	**3**
16. Nkhata Bay Lakeshore	**Northern and Central**	**5,533**	**3**
17. Karonga Lakeshore	**Northern**	**1,945**	**3**

Table 2. International contributions of runoff water to Lake Malawi.

	Malawi	Tanzania	Mozambique	Total
Catchment area of the lake (km^2)	64,372	26,600	6,768	97,740
Flow (m^3/s)	391	486	41	918
Percentage area (%)	65.9	27.2	6.9	100
Percentage flow (%)	42.6	52.9	4.5	100

Source: Ministry of Agriculture, Irrigation and Water Development, 2016.

The drainage system of Malawi has been divided into 17 Water Resources Areas (WRAs) and each WRA represents one hydrological basin. These WRAs are subdivided into 78 Water Resources Units (**Table 1**) that are local sub-catchments at which the Water Resources Act (2013) Malawi requires Integrated Water Resources Management planning and implementation, the area of each of these sub-units (Water Resource Units (WRU)) are shown in **Table 3**.



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ISBN 978-1-915509-24-6.

ISBN: 978-1-915509-24-6

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Figure 5. Location of main rivers and delineation of Water Resource Areas and Water Resource Units of Malawi [Available as Map at A0 size]

Table 3. Area of each Water Resource Unit at which local-scale IWRM should be planned and implemented

Water Resource Unit	Area Km^2	Water Resource Unit	Area Km^2
1A	1,546	*5D*	2,733
1B	1,984	*5E*	3,935
1C	735	*5F*	2,552
1E	335	*6A*	1,670
1F	1,185	*6B*	1,075
1G	1,467	*6C*	1,321
1H	2,118	*6D*	3,684
1K	1,844	*7A*	2,944
1L	851	*7B*	1,247
1M	880	*7C*	1,647
1N	573	*7D*	2,269
1O	1,484	*7E*	1,464
1P	657	*7F*	1,483
1R	1,502	*7G*	957
1S	1,178	*7H*	709
1T	571	*8A*	2,088
2A	943	*9A*	1,746
2B	2,083	*9B*	1,984
2C	683	*10A*	1,659
2D	859	*11A*	2,443
3A	910	*14A*	507
3B	386	*14B*	1,722
3C	784	*14C*	1,045
3D	1,176	*14D*	245
3E	993	*15A*	2,152
3F	749	*15B*	2,459
4A	577	*15C*	208
4B	3,274	*16E*	1,839
4C	1,615	*16F*	2,374
4D	1,849	*16G*	1,320
4E	953	*17A*	183
4F	616	*17B*	542
5C	1,439	*17C*	1,221

General Geology of Malawi

More than 80% of Malawi's land surface is dominated by Precambrian to lower Palaeozoic metamorphic and igneous rocks, referred to as the 'Basement Complex'. Lithologies include syenites, granites, charnockitic and ultra-basic gneisses, schists, granulites, and quartzites. Other lithologies include Karoo sedimentary rocks, the Chilwa Alkaline Province of intrusive igneous rocks, and Cretaceous to Pleistocene (mostly lacustrine) sediments. Quaternary unconsolidated sediments occur along the shores of Lake Malawi, Lake Malombe, and Lake Chilwa, as well as the upper and lower extents of the Shire River Valley and the Bwanje Valley. Geological sequences and lithological descriptions are presented in **Table 4, Figure 5 and Figure 6**.

Basement complex

The Proterozoic Basement Complex are mostly comprised of medium to high grade gneisses and granulites which have been subject to multiple deformation phases. Detailed geology was evaluated for the purpose of this Atlas. The most common geological facies are described below:

- Orthogneisses and meta-igneous rocks of various types and ages. Occur throughout the basement complex.
- Gneisses and granulites known locally as Pre-Mafingi. A wide range of lithologies which were regionally metamorphosed under amphibolite and granulite facies.
- The common rock type varies from felsic to mafic containing hyperstene, pyroxene, hornblende, biotite, quartz and plagioclase. K-feldspar, cordierite and sillimanite are also found.
- Biotite-hornblende gneiss with garnet sillimanite and diopside.
- Biotite gneisses are leucocratic to mesocratic and have sillimanite and hornblende; gneisses can contain graphite and sulphide minerals such as pyrite. Biotite gneisses grade into quartzo-feldspathic gneisses to dark biotite rich or biotite hornblende gneisses.
- Quartzo-feldspathic gneisses and granulites. Nationally extensive lithologies which exhibit characteristic gneissic bands and lenses (Morel, 1958). Compositions include quartz, oligoclase, andesine, orthoclase, K-feldspar. and biotite.
- Quartzite can be found in Mchinji, however is less common than quartzo-feldspathic gneiss and granulite (Thatcher and Wildspin, 1968).
- Pelitic schists and gneisses. Outcrop around Songwe where pelites are graphitic with muscovite and kyanite (Wilderspin, 1968); in Mchinji they are interbedded with quartzites.
- Quartzitic arenaceous and argillaceous rocks. Found west of the Nyika plateau underlying granite gneiss (Fitchers, 1971).
- Psammitic and pelitic rocks of Mchinji. Quartzites, quartz-schists, biotite gneisses, and migmatites.
- Cataclastic rocks. Outcrop in northern Malawi and comprise micaceous phyllonites and associated quartzites (Fitchers, 1971).
- Orthogneisses and intrusive rocks. Represented by amphibolites, pyroxinite, metapyroxenite, meta-anorthosite, and metagabbros (Bloomfield and Garson, 1965).
- Nephyline syenite. Outcrop at Chitipa within the Rumpi igneous complex (Kemp, 1970).

Table 4. Geological Successions of Malawi (compiled from Carter and Bennet, 1973).

Age		**Formation/Group**	**Dominant Lithology**
Cenozoic (66 MY to Recent)	Recent- Pleistocene	Alluvium	Clays, silts, sands and occasional gravels
	Pleistocene – Miocene	Sungwa, Chiwondo, Chitimwe and Timbiri beds	Lake sediments
Mesozoic (251-66) MY **Upper Palaeozoic**	Cretaceous	Lupata series and Dinosaur beds	Continental and Lake sediments
	Lower Cretaceous-Upper Jurassic	Chilwa Alkaline Province	Carbonatites, granulites and syenites
	Lower Jurassic	Karoo Supergroup: Stormberg	Basalts
	Permic-Triassic	Karoo Supergroup	Sandstones, shales, marls and conglomerates
Lower Palaeozoic (541-251) MY **Proterozoic** (1.0 BY–541) MY (1.6 -1.0) BY	Early Palaeozoic–Neoproterozoic	Granites of the lake Malawi Province	Granite plutons
	Neoproterozoic	Perthitic and Nephelinic syenites Phyllonites	Syenite
	Mesoproterozoic	Mafingi Group Mchinji Group Nyika and Dzalanyama granites	Metasediments Granites
Archean (1.8-1.6) BY		Basement Complex	Schists, quartzites, marbles, ultra-basics, gneisses, granulites Charnockitic gneisses and granulites

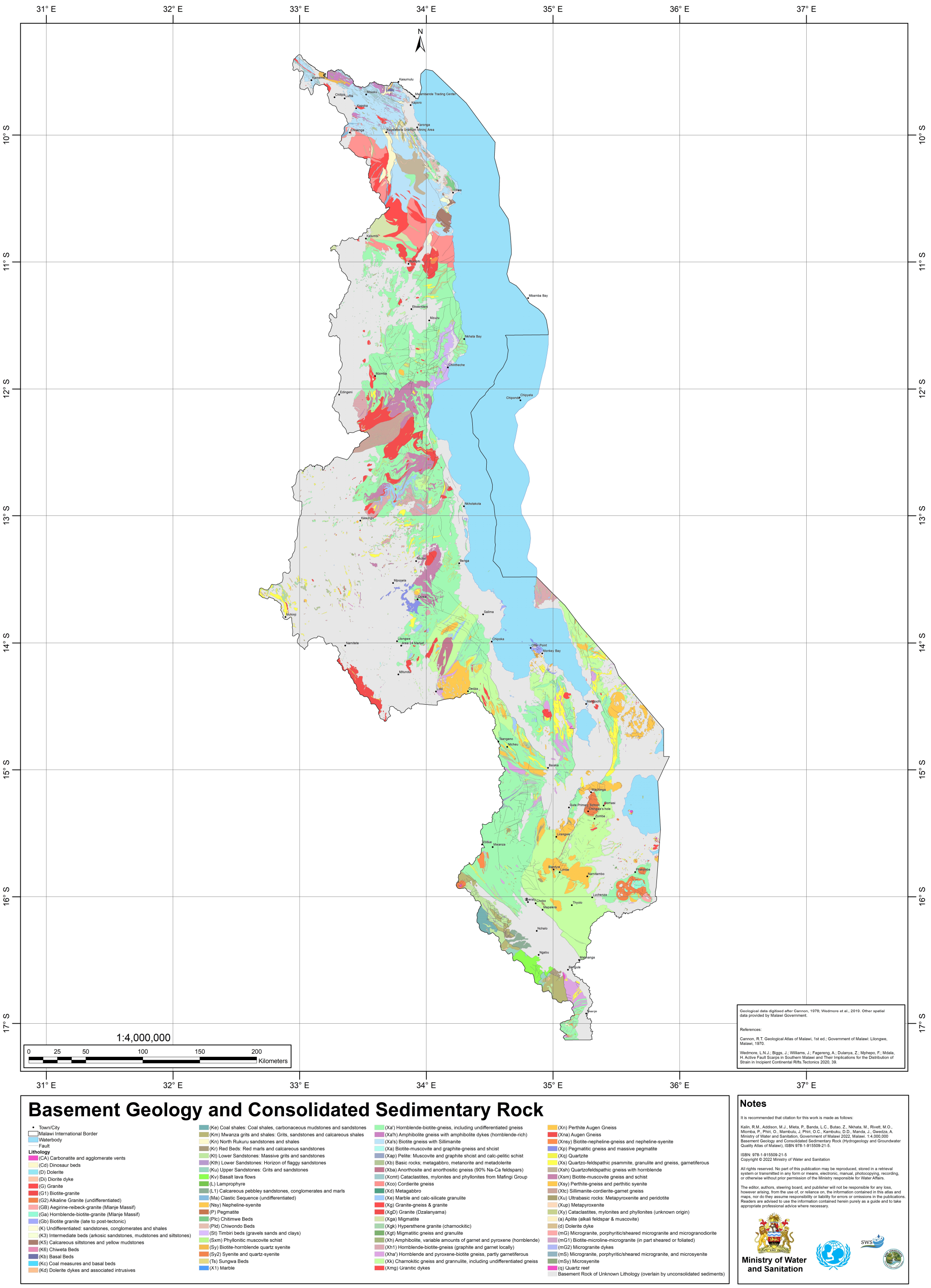
- Dzalanyama granite. Outcrops southwest of Lilongwe and Lake Malawi. Porphyritic microline granite with epidote.
- Anatectic perthitic syenites. Perthite augen-gneisses, perthitic syenite monzonites and minor granite. Perthitic complexes are found at Dedza and East of Lake Malombe.
- Granite and granite gneiss intrusions consist of Nyika granite and migmatites.
- Calco-silicate granulites and gneisses. Associated with marbles of both calcitic and dolomitic composition. Found in the central and southern parts of the country.
- Calco-alkaline granites. Pre-Karoo intrusive igneous rocks comprised of massive biotitic granite, known locally as the Lake Malawi Province (Bloomfield, 1968). Outcrops occur at the southern tip of Lake Malawi at Cape Maclear.
- The Chilwa Alkaline Province (CAP). Syeno-granite and nepheline syenite plutons, carbonatite vents, agglomerates, feldspathic breccia, and alkaline dykes (Bloomfield, 1961).
- Volcanic rocks. Early Jurassic emplacement, post Karoo sedimentation. Comprised of basaltic lava flows, dolerite dykes and sills.

Sedimentary rocks

Sedimentary rocks are uncommon in Malawi and comprise Karoo sediments and Cretaceous to Pleistocene lacustrine sediments occur in north-south trending basins (**Table 4** and **Figure 7**). The units contain conglomerates, sandstones, coal, carbonaceous shales, arkosic sandstones, mudstones, marls, and grits, and an outcrop of tectonically tilted sandstone in Chiweta. Lacustrine sedimentary rocks group contains the Sungwa, Chiwondo, Dinosaur, Chitimwe and Timbiri beds in northern part of the country, and the Lupata Series in the southern part of the country. They consist of a succession of pebbly conglomerates, coarse sandstones, sandy shales, and marls, and are underlain by the Karoo supergroup. All lacustrine sedimentary rocks are calcareous, characterised by distinct pink to brick-red color (Dixey, 1928).

Unconsolidated Sediments

Fluvial, alluvial and lacustrine sediments are widespread and common in Malawi and occur along river channels, escarpments and parallel to Lake Malawi from south to north. Quaternary unconsolidated sediments (**Table 4** and **Figure 7**) occur around other lakeshores of Lake Chilwa, Lake Chiuta, and Lake Malombe, and the Shire River valley too. These Quaternary deposits include colluvium, alluvium, fluvium, and lacustrine sediments which represent reworked material transported from surrounding highlands on either side of the rift valley (**Figure 7**). Significant accumulation of eroded sediments is observed in major river catchments, e.g., South Rukuru and Shire river valleys. Unconsolidated sediments comprise sand, gravel, clay, and silt.



Geological data digitised after Cannon, 1978; Wedmore et al., 2019. Other spatial data provided by Malawi Government.

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ISBN: 978-1-915509-21-5

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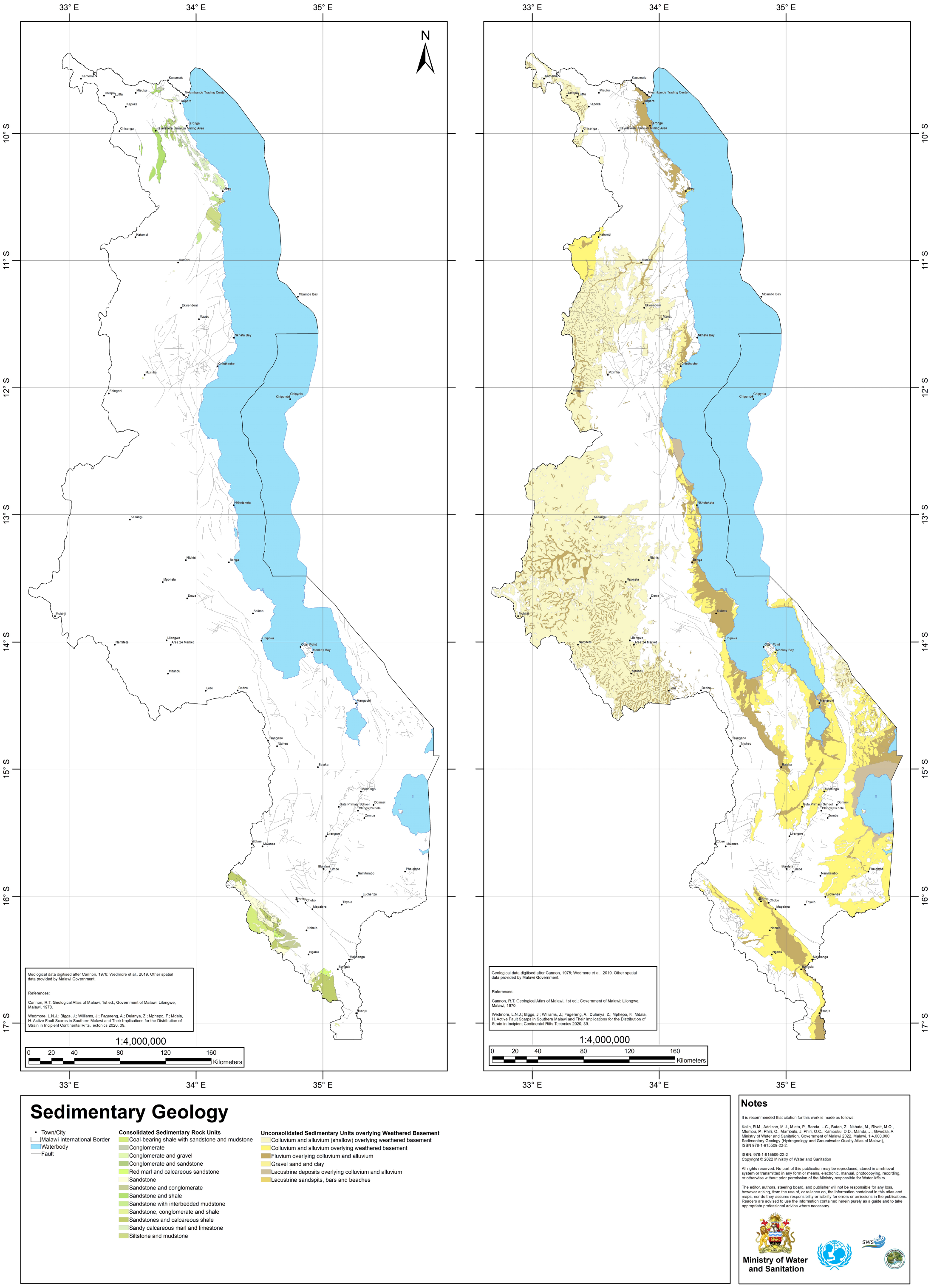
Figure 6. Basement geology of Malawi (after Cannon 1978 and Wedmore et al. 2019) [Available as Map at A0 size]



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ISBN: 978-1-915509-22-2

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Figure 7. Consolidated sedimentary rocks and unconsolidated sediments in Malawi (after Cannon 1978 and Wedmore et al. 2019) [Available as Map at A0 size]

Aquifer Mapping

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 5**). Consolidated sedimentary rocks of the Karoo Supergroup (Permian – Triassic) comprise the Consolidated Sedimentary Aquifers in Malawi (**Figure 8a**). 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 8b**). Colluvium has been deposited across much of Malawi on top of weathered basement slopes, escarpments and plains (**Figure 8b**). 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 5. Redefined Aquifer groups in Malawi with short descriptions.

Aquifer Group	Description
Consolidated Sedimentary Units (**Figure 8a**)	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 8b**)	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 8c**)	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 8c**). 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.

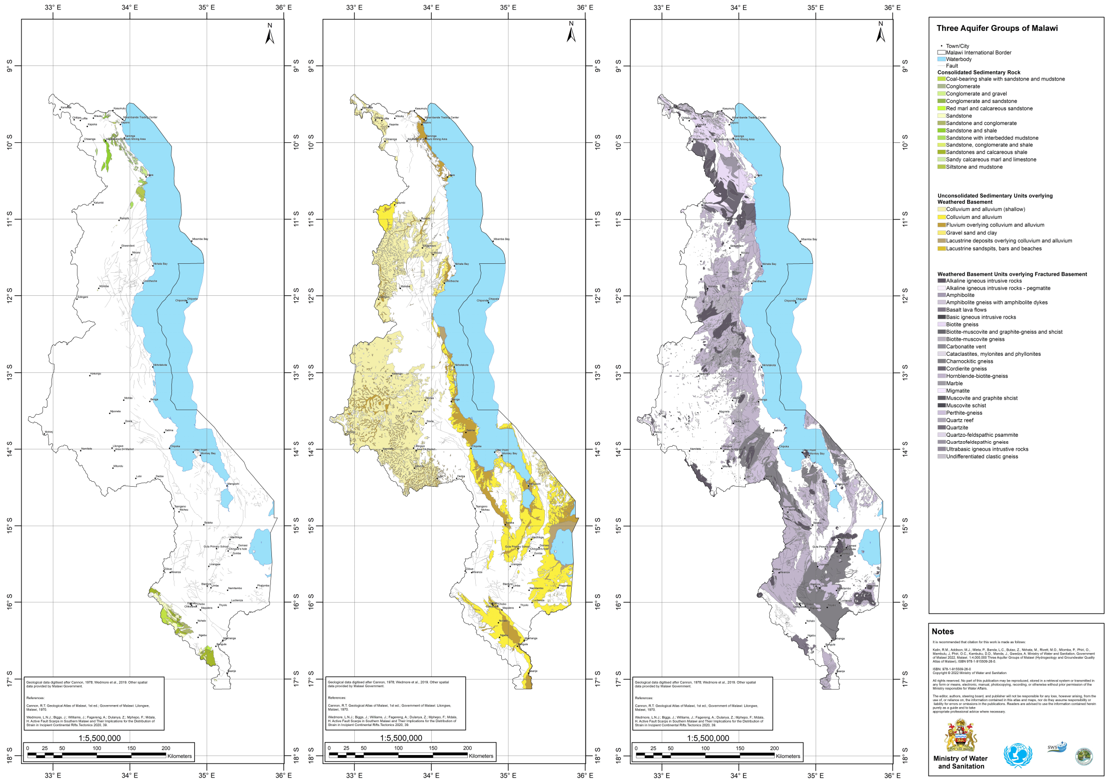


Figure 8a, b, c. Aquifer types of Malawi described together with geologic framework (a) the left most figure provides details of consolidated sedimentary units, (b) the centre figure shows unconsolidated fluvial, aeolian and lacustrine water bearing units overlying weathered basement, and (c) right most figure shows weathered basement (including saprolite) units overlying fractured basement that are highly variable as water bearing units. [Available as Map at A0 size]

The unconsolidated sedimentary units can be further subdivided into lacustrine sediments (**Figure 8e**), fluvial sediments (**Figure 8f**) and colluvium and alluvium (**Figure 8g**). These units may or may not be stratigraphically contiguous and hydrostratigraphically act as a single unit. Site specific data is required to confirm the hydrogeologic relationship of the units, the main storage capacity, and the sustainable yield of the combined hydrostratigraphy.

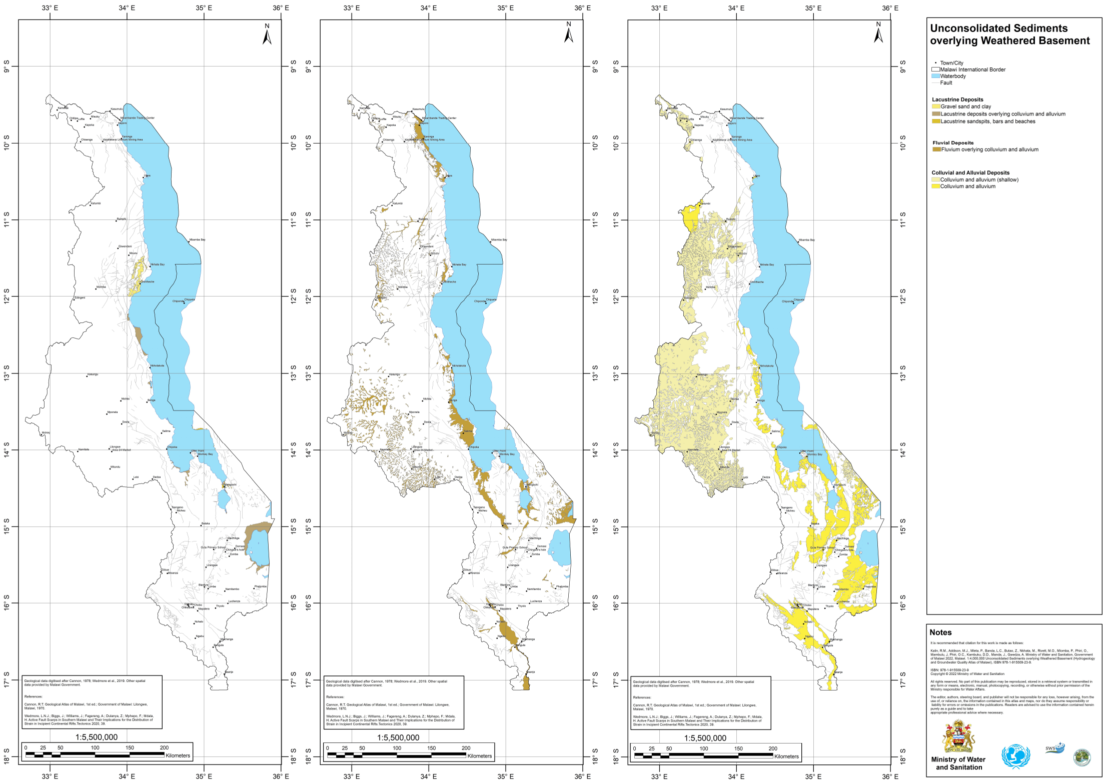


Figure 8e, f, g. Unconsolidated Sedimentary Units overlying Weathered Basement of Malawi described together with geologic framework (a) the left most figure provides details of unconsolidated lacustrine sedimentary units, (b) the centre figure shows unconsolidated fluvial units overlying either colluvium/alluvium or weathered basement, and (c) right most figure shows colluvium and alluvium overlying weathered basement. [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 and will occur at variable depths. The areal distribution of these units will be topographically and geographically controlled, with defined "aquifers" being localised and non-contiguous. Groundwater is stored and transmitted via intergranular pore spaces in the weathered (most probable areas of high groundwater storage in the saprolitic / saprock) zone, and also transmitted via fractures, fissures and joints in the fractured zone (most probable areas of highest hydraulic conductivity, K). The units may have limited storage, and the volume of groundwater available will be strongly dependant on the recharge catchment and interactions with surface water and rainfall-runoff at higher elevations. Therefore, detailed pump test analysis (sustainable yield determination) must be carried out for any large-scale abstractions combined with continuous monitoring of water levels and water quality (given possible geogenic sources and fast transport of groundwater contaminates e.g. e-coli from pit latrines).

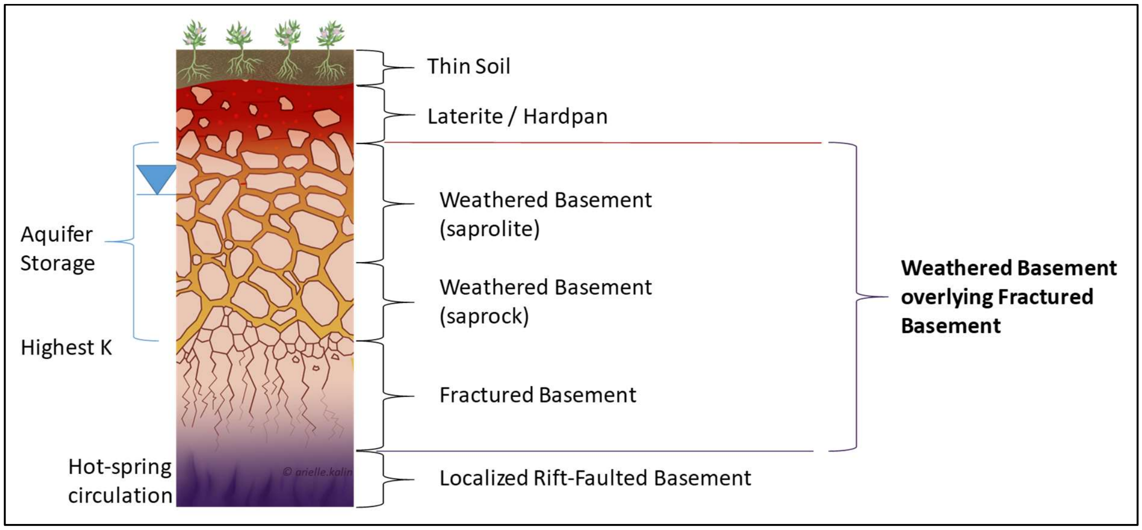


Figure 9a. Conceptualised stratigraphy of Weathered Basement overlying Fractured Basement aquifer group (not to scale).

Unconsolidated Colluvial and Alluvial Sedimentary Units overlying Weathered Basement

This sub-group of Unconsolidated Sedimentary Units overlying Weathered Basement 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.

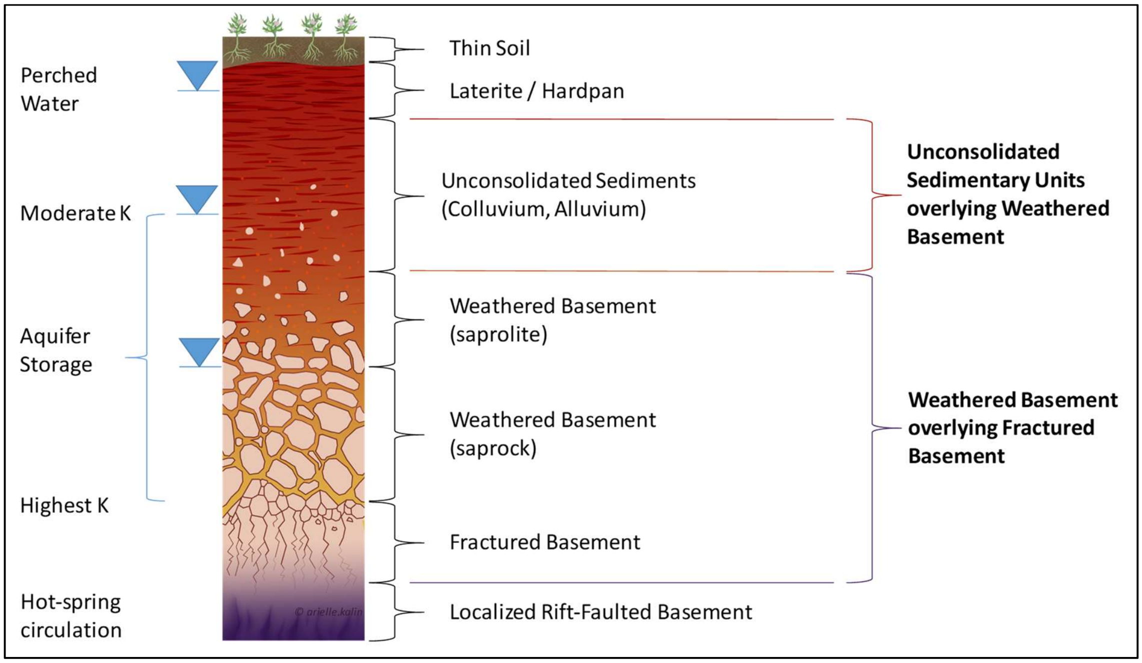


Figure 9b. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Colluvium and Alluvium) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

Unconsolidated Fluvial Sedimentary Units overlying Weathered Basement

This sub-group of Unconsolidated Sedimentary Units overlying Weathered Basement contains unconsolidated sediments including water deposited silts, sands, gravels, lacustrine sediments, and fluvial sediments (**Figure 9c**). Surface water is strongly linked with groundwater in Malawi, and much of groundwater flow is controlled by surface topography. Given the long dry season in Malawi, the water resources of Dambo (wet lands) and rivers depend on groundwater discharge during dry months to provide any flow or potential agricultural activity. The storage of groundwater in the upper unconsolidated sediments may or may not be in hydraulic connection with underlying weathered basement, and the storage potential will be dependent on the available porosity of the unconsolidated sediments and saprolitic zones. The underlying fractured basement may have higher hydraulic transmissivity, but will depend on the overlying storage. To date there is little or no available information on vertical flow directions and recharge as there are no dedicated groundwater monitoring infrastructure installed to evaluate these more complex systems, and as before it is highly recommended that site specific detailed hydrogeologic evaluation, pumping tests and water quality monitoring precedes any 'Solar' or 'Submersible' pumping system and that a robust monitoring programme is implemented with such investments.

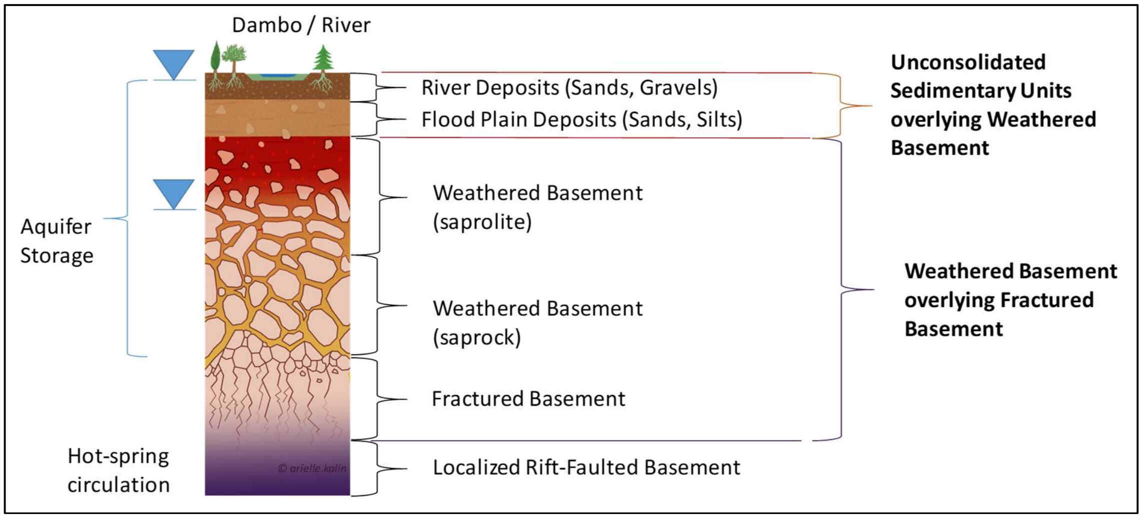


Figure 9c. Conceptualised stratigraphy of Unconsolidated Sedimentary Units (Fluvial deposits) overlying Weathered Basement, showing the potential for vertical heterogeneity and distinct aquifer units (not to scale).

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.

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 9d**).

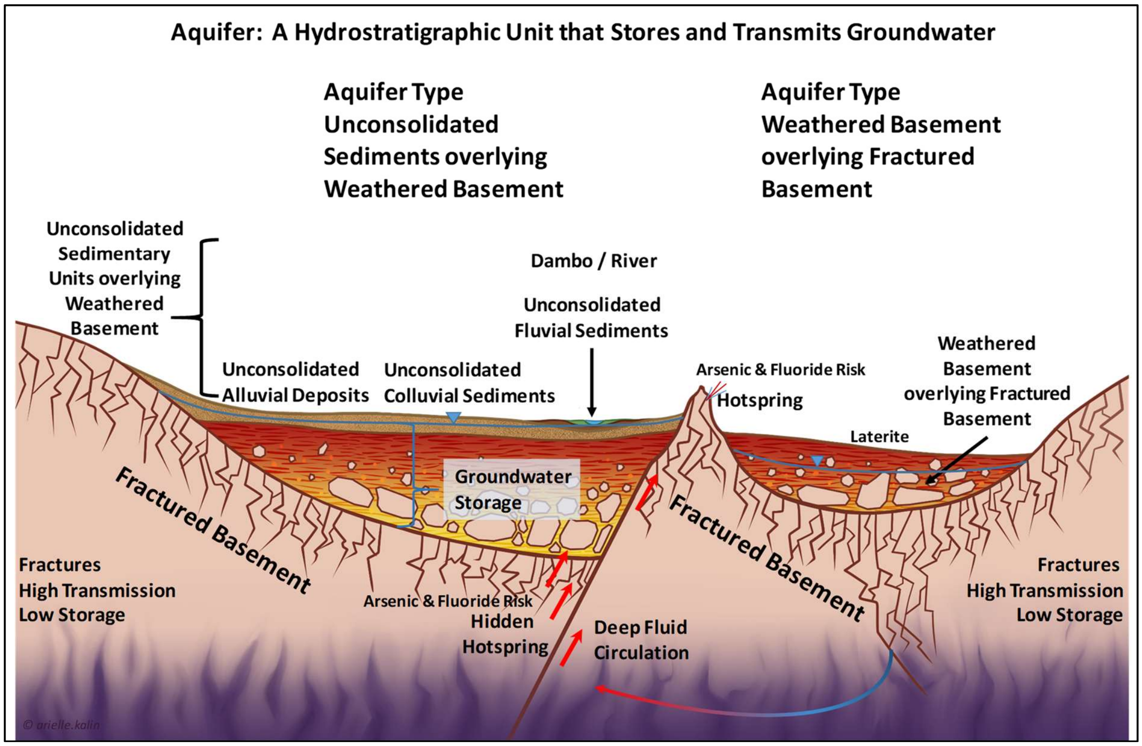


Figure 9d. An idealised cross-section of an Unconsolidated Sedimentary Units overlying Weather and Fractured Basement (left) acting as one hydrostratographic unit (Aquifer), and in the same geographic region but hydraulically separated, groundwater in Weathered basement overlying Fractured basement.

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.

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.

Groundwater flow regime: recent water table data and commentary

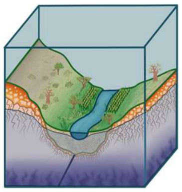
A very reasonable first presumption is that the modern-day groundwater flow regime (especially regional directions of flow as opposed to absolute water levels) may be expected to be similar to the circa 1987 benchmark water table (note: weathered basement overlying fractured basement is likely localised with respect to groundwater flow). Natural groundwater flow follows local topography and regional basin and sub-basin catchment drainage. Groundwater and surface-water flow divides appear concurrent with groundwater drainage toward base flow discharge to surface-waters, including rivers, lakes and wetland areas. These characteristics are expected to apply. Exception to the above benchmark modern validity may possibly be where (i) sizeable groundwater abstraction has induced regional flow regime changes with semi-local to regional cones of depression (lowered water tables) induced, where (ii) significant changes in recharge have occurred over extensive areas from land use changes such as deforestation increasing runoff and reducing recharge, (iii) where climate change / flooding intensity is affecting recharge, and (iv) where direct abstraction or impounding of surface waters (for supplies irrigation) impact localised to regional surface water – groundwater interaction.

Confined groundwater and ‘artesian borehole’ occurrence

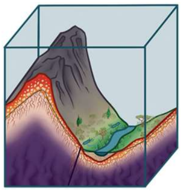
The presence of confined groundwater with sufficient head pressure to cause groundwater overflow at surface (without pumping) results when a borehole is screened in the confined aquifer unit (**Figure 2b**). Only a handful of ‘artesian well/borehole’ are noted in the Ministry of Water and Sanitation database and it does not hold geospatial coordinates for any boreholes that has artesian pressure. Less obvious confined or semi-confined (transient confined) groundwater conditions that may not lead to ‘artesian’ groundwater overflow at ground surface may also be present, but perhaps not recognised. Water level data most likely lack as well as sufficient geological log data to reliably identify confining aquitard units such as clay, silt and silt/mudstone horizons. The potential for semi-confined or confined groundwater conditions can exist down hydraulic gradient from upland recharge areas within lowland or plateau area containing increased low permeability clays/silts/fine-sand/mudstone deposited under low energy, lacustrine environments, and there is a critical need to map and evaluated all potential artesian groundwater conditions in Malawi.

Groundwater – surface-water interactions

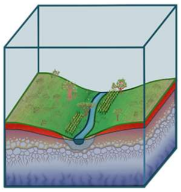
A variety of groundwater – surface-water interactions are found across Malawi. These include the following types with some examples of occurrence indicated.



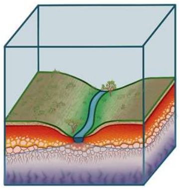
Dambo - Upland dambo at highland - plateau interfaces are supported by groundwater draining from the surrounding fractured basement and potentially perennial, base flow to the dambo from adjoining weathered basement and colluvium. Dambo may provide temporary reservoir storage, buffering precipitation inputs and delaying groundwater base flow expression and hence may maintain river flows (longer) during the dry season. Geological control is often evident with dambo and water courses downstream aligning with faulted or jointed areas of structural weakness that may serve as preferential conduits of groundwater flow.



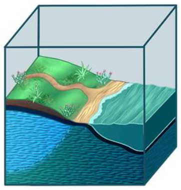
Upland spring flows and stream base flow - Springs and stream base flow in the uplands may be served by discharges from deep, well-drained sandy soils produced from the weathering of basement rocks, permeable colluvium deposits and hydraulically connected fractured basement.



Groundwater base flow to intermediate and lowland river reach – The groundwater flow regime is commonly observed to follow topography and WRA basin and WRU component catchment drainage with drainage toward and base flow discharge to intermediate and lowland rivers and streams common. Base flow indexes are generally high, for instance



Influent river/stream reach leakage to groundwater – Streams/river reaches may be permanently, or transiently 'losing' under low water table conditions and exhibit influent leakage and recharge of groundwater below. This is most probable in lowland, wider river valley or wide lakeshore plains where permeable streambed deposits are present and water tables below river levels.



Groundwater base flow to lowland lakes, wetland/dambo – Groundwater may discharge as base flow seepages to lowland lakes, small or large, and wetland/dambo areas. Recognising too groundwater may often discharge to near-lake river reaches indirectly to surface water.

Aquifer potential

The aquifer groups can be further classified with integration of borehole yield extracted from the Ministry of Water and Sanitation database (**Figure 10a**). This is important when considering hydrogeological mapping for groundwater management at WRA and WRU levels. The integration of borehole yield data in the hydrogeological mapping allows one to compare and delineate areas within the same aquifer where aspects of groundwater occurrence differ.

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 10a** provides the national spatial distribution of data together with the dominant geologic units. The distribution of the data held by the Ministry of Water and Sanitation as shown in **Figure 10b** indicates the data is clearly 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 rather professionally managed work to drill and test each groundwater well to determine the exact aquifer properties at each location. However, there appears to be a trend to borehole yields between 0.5 and 2.0l/s, with a very limited number of production boreholes reporting yields of ca. 5 to 50 l/s (these require confirmation, validation and confirmation analysis of sustainable aquifer yields under IWRM).

It is important this data is not used to specifically site 'solar' or 'mechanical' pumped boreholes as the data does not allow proper evaluation of aquifer properties over space and depth. It is highly recommended that at each site where planned 'solar boreholes' are considered, that a detailed hydrogeological study, including test boreholes and extended pumping tests (with multiple monitoring sites), followed by continual water quality and water level measurements at the cost of the donor or local WUA are undertaken to allow a complete Theis evaluation of the aquifer properties.

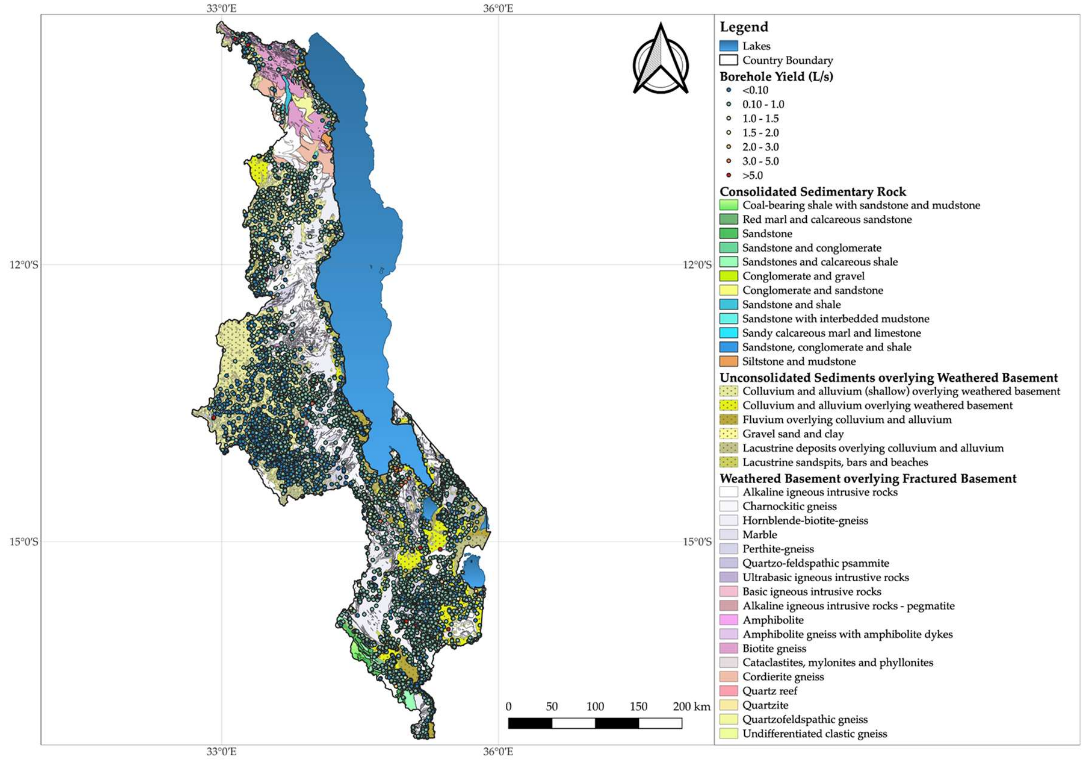


Figure 10a. Spatial Distribution of Aquifer Yield data held by the Ministry of Water and Sanitation

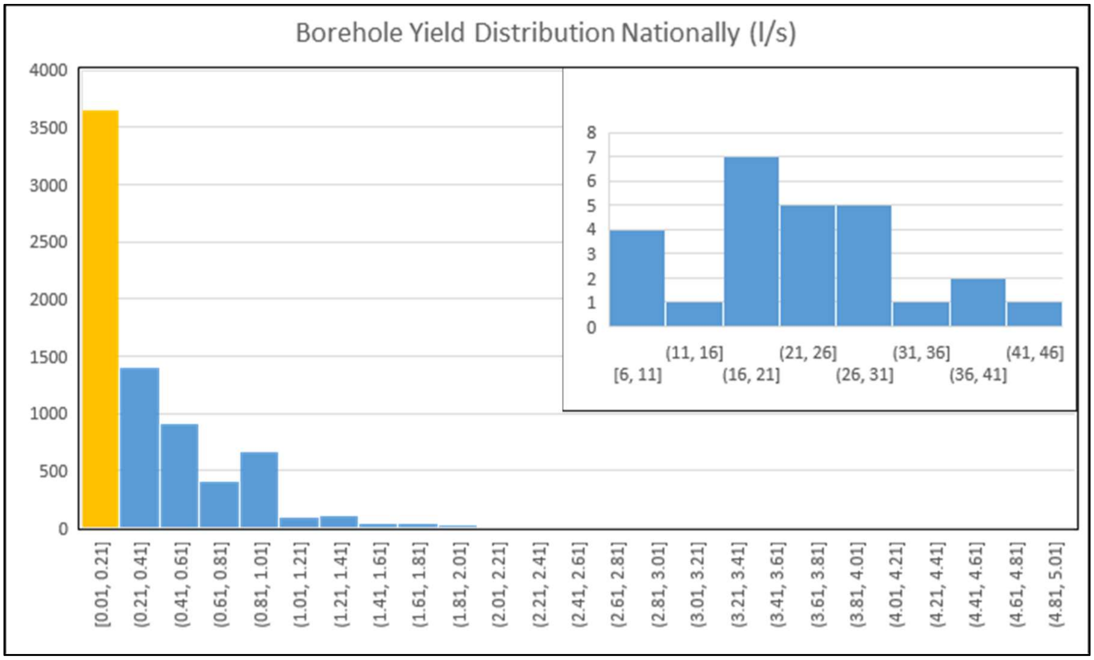


Figure 10b. Distribution (y axis n observations) of Aquifer Yield data, Ministry of Water and Sanitation

Consolidated Sedimentary Rock Aquifer Units

Consolidated sedimentary aquifers includes the Karoo Super group (Permian – Triassic). Karoo sedimentary rocks possess double porosities (primary and secondary porosities) although cementation has significantly reduced primary porosity in those units (Bradford, 1973). Semi-consolidated sedimentary rocks of Cenozoic age (lacustrine deposits) were combined with Dinosaur beds (Cretaceous sedimentation) and grouped together with the consolidated sedimentary rocks.

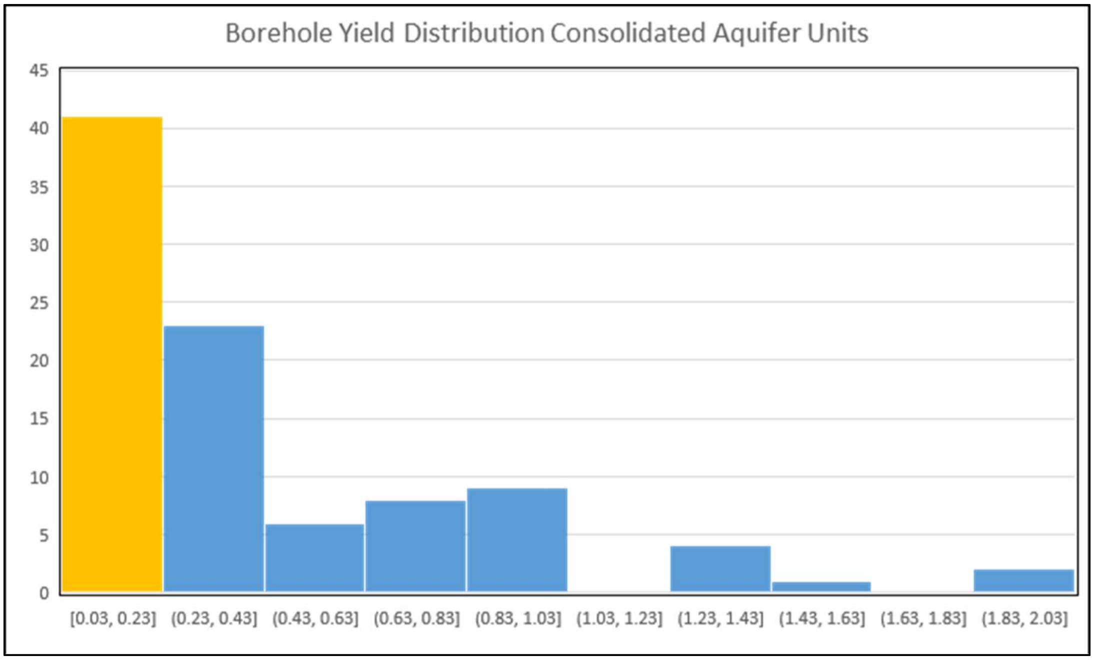


Figure 11. Distribution of Aquifer Yield (y axis n observations) for boreholes in the Consolidated Aquifer Units of Malawi

The distribution of aquifer yield for all boreholes in the Consolidated Aquifers of Malawi are shown in **Figure 11**. The data is skewed to values below 0.25 l/s, but there is a range between 0.25 and 2 l/s indicating some potential for higher yields for professionally (Hydrogeologist) designed and implemented boreholes. Given the potential for interbedded evaporates and calcic cementing, the water quality of any borehole drilled in a consolidated sedimentary aquifer should be tested during drilling, development and routine monitoring. There is no evidence of any calculated sustainable yield (water balance) for these aquifer units in Malawi and therefore site specific and regional monitoring of any high-yielding installations must be a requirement for any permitting.

Unconsolidated Sedimentary Units overlying Weathered Basement

The unconsolidated sediments overlying weathered and fractured basement aquifer type represent all sedimentary deposits of Quaternary age deposited via fluvial, colluvial, and lacustrine processes. Most sediments were either deposited in rift valley or off-rift valley basins, along lakeshores or in main river channels. These generally unconfined sedimentary aquifers are impacted by evapo-transpirated enrichment in dissolved solids and, where hydraulically connected to underlain fault zones, potentially impacted by deeper circulation. The water quality of any borehole drilled in unconsolidated sedimentary aquifers should be tested during drilling, development and routine monitoring

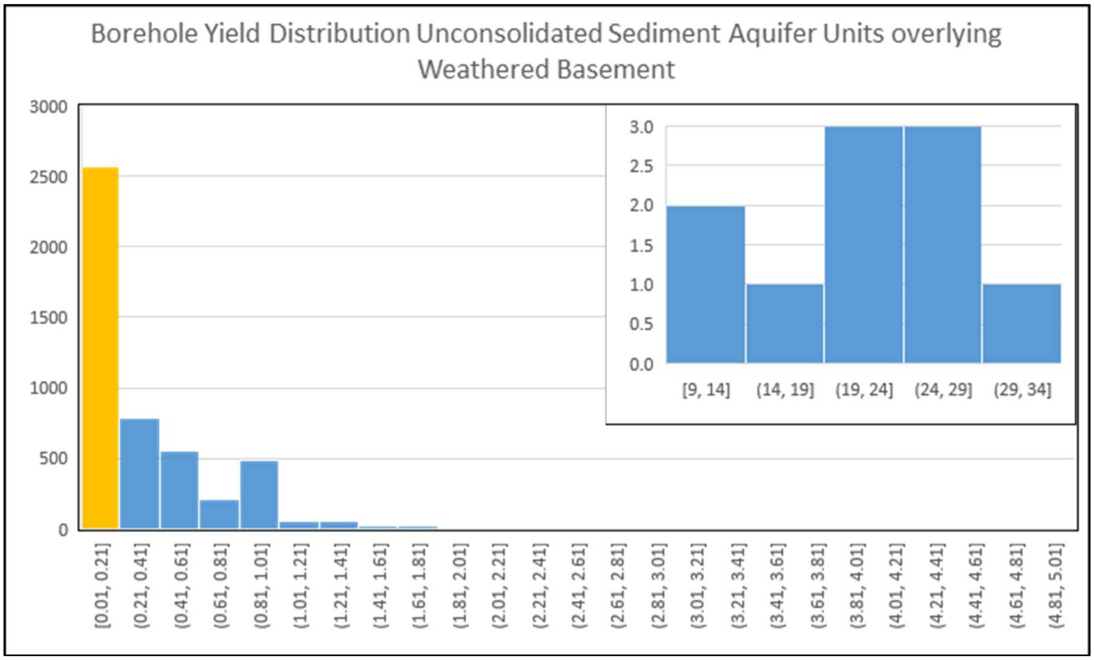


Figure 12. Distribution of Aquifer Yield (y axis n observations) for boreholes in Unconsolidated Sediment Units overlying Weathered Basement Aquifer type.

The distribution of aquifer yield for all boreholes in Unconsolidated Sediment Units overlying Weathered Basement are shown in **Figure 12**. The data is skewed to values below 0.25 l/s, and the number of values in this range is highly suspect, likely representing substandard well construction for boreholes to meet a minimum borehole yield rather professionally managed work to drill and test each groundwater well to determine the exact aquifer properties at each location. These values should be ignored when planning groundwater investments, and importantly site specific hydrogeologic testing is critical to the success of enhanced groundwater abstraction given there are yields between 0.25 and 1.5 l/s for this aquifer type with a limited number of high yield boreholes between 10 and 35 l/s. There is no evidence of any calculated sustainable yield (water balance) for these aquifer units in Malawi and therefore site specific and regional monitoring of any high-yielding installations must be a requirement for any permitting.

Weathered Basement overlying Fractured Basement

The weathered basement units overlying fractured basement aquifer type represents metamorphic and igneous rocks regardless of age were grouped together to represent basement aquifers. Fractured basement aquifers are overlain by a weathered zone of saprolite which mainly behave as one hydrostratigraphic unit, except where basement rock forms steep topographical highs (mountains/plutons/rift escarpments). Groundwater flow regimes are highly variable in fractured basement aquifers as secondary porosity is dominant. Weathered basement aquifers behave similar to unconsolidated sediments hydrogeologically, however, possess lower hydraulic conductivity and storage, and weathered basement aquifers are generally hydraulically connected to the underlying fractured zones.

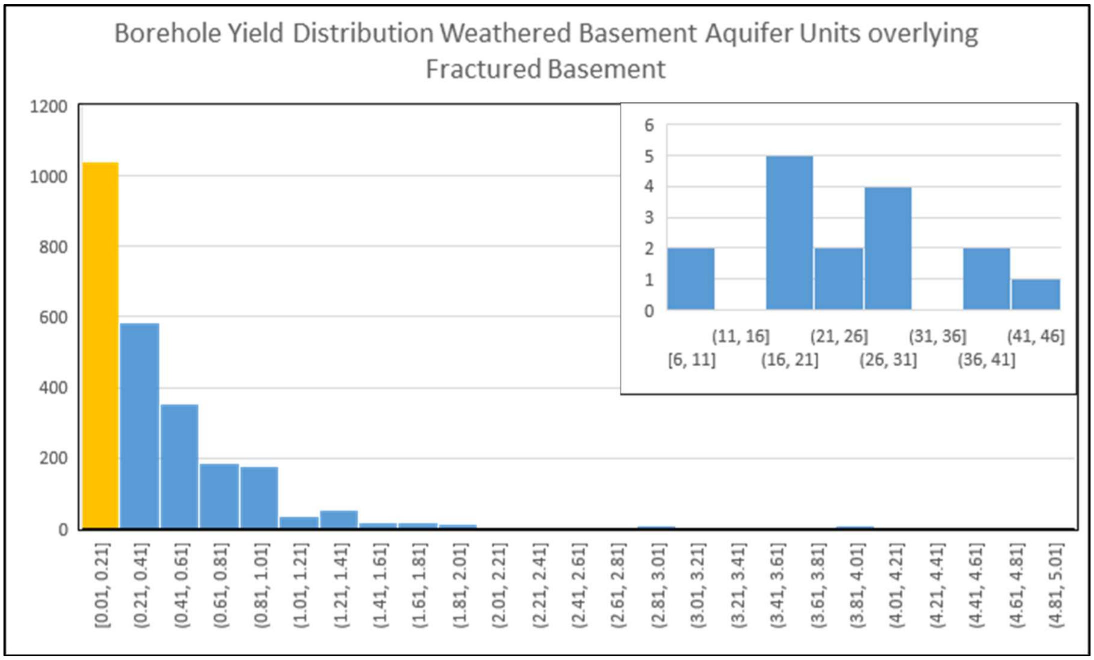


Figure 13. Distribution of Aquifer Yield (y axis n observations) for boreholes in Weathered Basement overlying Fractured Basement aquifer units.

The distribution of aquifer yield for all boreholes in Weathered Basement overlying Fractured Basement aquifer units are shown in **Figure 13**. As with the previous aquifer type, the data is skewed to values below 0.25 l/s, and the number of values in this range is highly suspect, likely representing substandard well construction for boreholes to meet a minimum borehole yield rather professionally managed work to drill and test each groundwater well to determine the exact aquifer properties at each location. These values should be ignored when planning groundwater investments, and importantly site specific hydrogeologic testing is critical to the success of enhanced groundwater abstraction given there are yields between 0.25 and 1.5 l/s for this aquifer type with a limited number of high yield boreholes between 5 and 50 l/s. Given the potential for fractured fluid flow at depth and geochemical water-rock reactions, the water quality of any borehole drilled in a consolidated sedimentary aquifer should be tested during drilling, development and routine monitoring. Importantly, the storage of weathered and fractured aquifers and the capture zone is important to evaluate as storage is generally lower in these aquifer types and as a result fluid velocity can be considerable acting as rapid pathways for contaminants (e.g. Pit Latrine loads). There is no evidence of any calculated sustainable yield (water balance) for these aquifer units in Malawi and therefore site specific and regional monitoring of any high-yielding installations must be a requirement for any permitting.

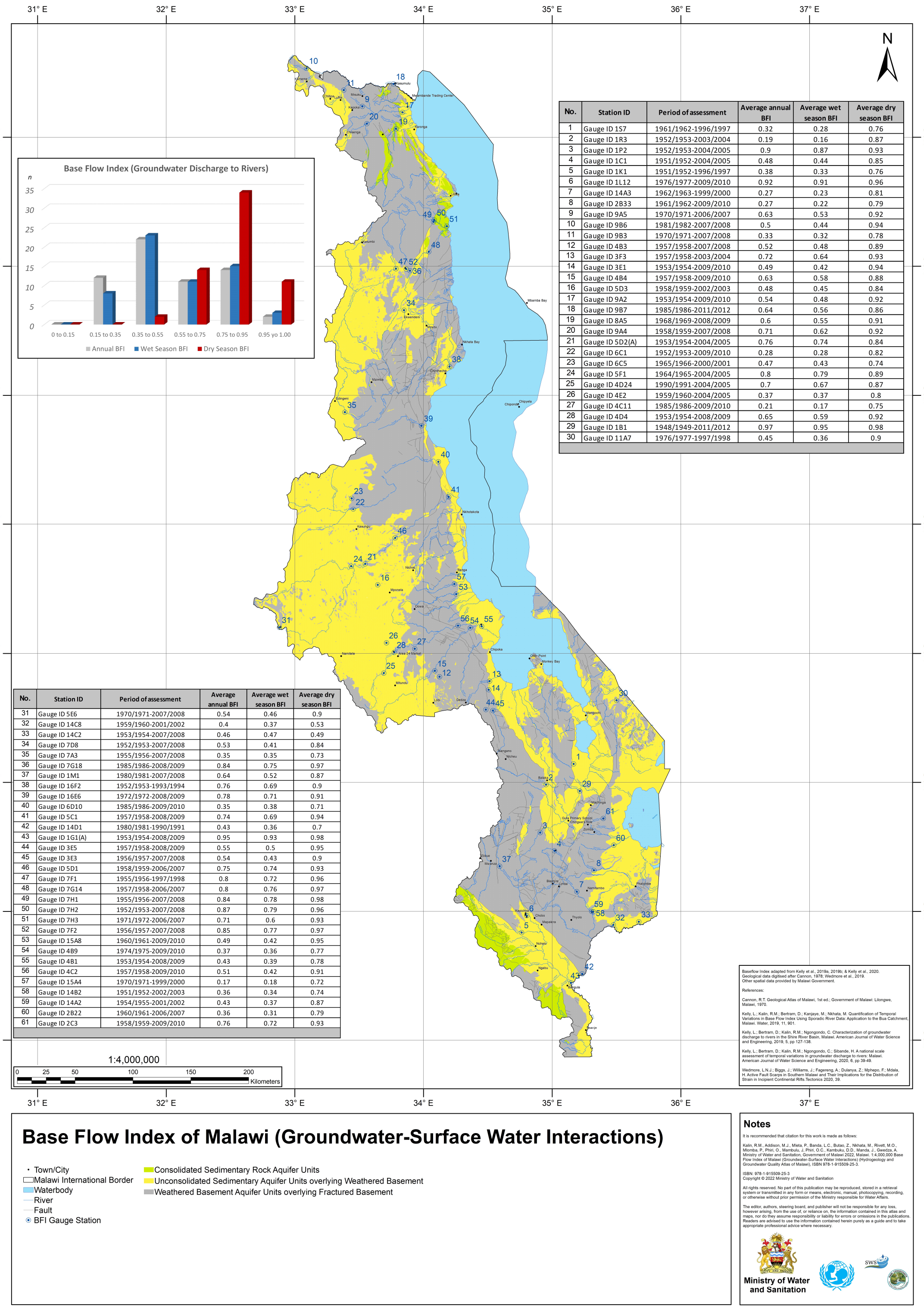
Base Flow Index: Groundwater Contribution to Surface Water Rivers

Base flow is the component of river flow derived from groundwater and other stored sources including slow-moving interflow, and hydraulically connected wetlands and lakes. The Base Flow Index of 61 rivers in Malawi was reported by Kelly et a. (2020), the location of these gauging stations is provided in **Figure 14**. Hydrograph analysis of long-term river discharge data is frequently used to determine base flow by separating the total river flow in a hydrograph into its fast-moving component (surface runoff) and its slow-moving component (base flow) (**Figure 15a**). Base flow can conceptually be considered as a flow from groundwater into the river (**Figure 15b**). Base flow is commonly expressed as the Base Flow Index (BFI) (**Table 6)**, a unit less parameter, ranging from near 0.0 [indicating a river with a relatively low proportion of groundwater discharge to the river as base flow], to close to 1.0; [indicating the flow in the river is mainly groundwater discharge]. Therefore, the base flow Index (BFI) is used as a proxy indicator of groundwater discharge.

The determination of base flow, and in particular its temporal and spatial variations, is needed to underpin Integrated Water Resources Management, Trans-Boundary water agreements and importantly planning of surface water storage for agriculture and energy security. Specifically, base flow and BFI data are used in low flow studies, environmental flow calculations, hydropower generation and as a groundwater availability indicator [expressed need for managed aquifer recharge]. Although the provision of base flow data is pertinent to all countries, it is especially crucial for countries such as Malawi which experience long dry seasons with limited rainfall and where rivers depend on groundwater to sustain flows as a result of the minimal surface runoff.

The long-term average annual and seasonal (wet and dry) BFI values for the 61 gauging stations across Malawi are shown in **Figure 14** and **Table 6**. The results indicate base flow varies spatially and temporally across Malawi. For example, the results found an average annual BFI for Malawi of 0.57, an average wet season BFI of 0.52 and an average dry season BFI of 0.97. This indicates that on average, 57%, 52% and 97% of the total river flow across Malawi is derived from groundwater as base flow for the annual, wet and dry season respectively (**Figure 16**). The distribution of individual results shown in **Figure 16** clearly indicates that all rivers in Malawi are highly dependent on groundwater base flow during the dry season for flow. Therefore, groundwater is a critical resource to keep rivers flowing across Malawi, and BFI follows a distinct seasonal pattern characterized by minimal difference between the annual and wet season base flow, but with a significant increase in the dry season.

This seasonal BFI results must be considered in the country's current National Irrigation Plan where design calculations appear to have focused on annual BFI values that are only valid for 4 to 5 months of the year. Identification and understanding of detailed changes in surface water – groundwater interaction is needed (e.g. joint river gauging and groundwater level monitoring across Malawi) are fundamental to ensure further degradation of the rivers does not occur, and IWRM planning can provide protection for rivers and wetlands. There is a need to evaluate trends which influence base flow behaviour, for example, rainfall, over-abstraction of groundwater and deforestation. Further research should aim to quantify the magnitude of these trends and evaluate these influencing factors.



No.	Station ID	Period of assessment	Average annual BFI	Average wet season BFI	Average dry season BFI
1	Gauge ID 1S7	1961/1962-1996/1997	0.32	0.28	0.76
2	Gauge ID 1R3	1952/1953-2003/2004	0.19	0.16	0.87
3	Gauge ID 1P2	1952/1953-2004/2005	0.9	0.87	0.93
4	Gauge ID 1C1	1951/1952-2004/2005	0.48	0.44	0.85
5	Gauge ID 1K1	1951/1952-1996/1997	0.38	0.33	0.76
6	Gauge ID 1L12	1976/1977-2009/2010	0.92	0.91	0.96
7	Gauge ID 14A3	1962/1963-1999/2000	0.27	0.23	0.81
8	Gauge ID 2B33	1961/1962-2009/2010	0.27	0.22	0.79
9	Gauge ID 9A5	1970/1971-2006/2007	0.63	0.53	0.92
10	Gauge ID 9B6	1981/1982-2007/2008	0.5	0.44	0.94
11	Gauge ID 9B3	1970/1971-2007/2008	0.33	0.32	0.78
12	Gauge ID 4B3	1957/1958-2007/2008	0.52	0.48	0.89
13	Gauge ID 3F3	1957/1958-2003/2004	0.72	0.64	0.93
14	Gauge ID 3E1	1953/1954-2009/2010	0.49	0.42	0.94
15	Gauge ID 4B4	1957/1958-2009/2010	0.63	0.58	0.88
16	Gauge ID 5D3	1958/1959-2002/2003	0.48	0.45	0.84
17	Gauge ID 9A2	1953/1954-2009/2010	0.54	0.48	0.92
18	Gauge ID 9B7	1985/1986-2011/2012	0.64	0.56	0.86
19	Gauge ID 8A5	1968/1969-2008/2009	0.6	0.55	0.91
20	Gauge ID 9A4	1958/1959-2007/2008	0.71	0.62	0.92
21	Gauge ID 5D2(A)	1953/1954-2004/2005	0.76	0.74	0.84
22	Gauge ID 6C1	1952/1953-2009/2010	0.28	0.28	0.82
23	Gauge ID 6C5	1965/1966-2000/2001	0.47	0.43	0.74
24	Gauge ID 5F1	1964/1965-2004/2005	0.8	0.79	0.89
25	Gauge ID 4D24	1990/1991-2004/2005	0.7	0.67	0.87
26	Gauge ID 4E2	1959/1960-2004/2005	0.37	0.37	0.8
27	Gauge ID 4C11	1985/1986-2009/2010	0.21	0.17	0.75
28	Gauge ID 4D4	1953/1954-2008/2009	0.65	0.59	0.92
29	Gauge ID 1B1	1948/1949-2011/2012	0.97	0.95	0.98
30	Gauge ID 11A7	1976/1977-1997/1998	0.45	0.36	0.9

No.	Station ID	Period of assessment	Average annual BFI	Average wet season BFI	Average dry season BFI
31	Gauge ID 5E6	1970/1971-2007/2008	0.54	0.46	0.9
32	Gauge ID 14C8	1959/1960-2001/2002	0.4	0.37	0.53
33	Gauge ID 14C2	1953/1954-2007/2008	0.46	0.47	0.49
34	Gauge ID 7D8	1952/1953-2007/2008	0.53	0.41	0.84
35	Gauge ID 7A3	1955/1956-2007/2008	0.35	0.35	0.73
36	Gauge ID 7G18	1985/1986-2008/2009	0.84	0.75	0.97
37	Gauge ID 1M1	1980/1981-2007/2008	0.64	0.52	0.87
38	Gauge ID 16F2	1952/1953-1993/1994	0.76	0.69	0.9
39	Gauge ID 16E6	1972/1972-2008/2009	0.78	0.71	0.91
40	Gauge ID 6D10	1985/1986-2009/2010	0.35	0.38	0.71
41	Gauge ID 5C1	1957/1958-2008/2009	0.74	0.69	0.94
42	Gauge ID 14D1	1980/1981-1990/1991	0.43	0.36	0.7
43	Gauge ID 1G1(A)	1953/1954-2008/2009	0.95	0.93	0.98
44	Gauge ID 3E5	1957/1958-2008/2009	0.55	0.5	0.95
45	Gauge ID 3E3	1956/1957-2007/2008	0.54	0.43	0.9
46	Gauge ID 5D1	1958/1959-2006/2007	0.75	0.74	0.93
47	Gauge ID 7F1	1955/1956-1997/1998	0.8	0.72	0.96
48	Gauge ID 7G14	1957/1958-2006/2007	0.8	0.76	0.97
49	Gauge ID 7H1	1955/1956-2007/2008	0.84	0.78	0.98
50	Gauge ID 7H2	1952/1953-2007/2008	0.87	0.79	0.96
51	Gauge ID 7H3	1971/1972-2006/2007	0.71	0.6	0.93
52	Gauge ID 7F2	1956/1957-2007/2008	0.85	0.77	0.97
53	Gauge ID 15A8	1960/1961-2009/2010	0.49	0.42	0.95
54	Gauge ID 4B9	1974/1975-2009/2010	0.37	0.36	0.77
55	Gauge ID 4B1	1953/1954-2008/2009	0.43	0.39	0.78
56	Gauge ID 4C2	1957/1958-2009/2010	0.51	0.42	0.91
57	Gauge ID 15A4	1970/1971-1999/2000	0.17	0.18	0.72
58	Gauge ID 14B2	1951/1952-2002/2003	0.36	0.34	0.74
59	Gauge ID 14A2	1954/1955-2001/2002	0.43	0.37	0.87
60	Gauge ID 2B22	1960/1961-2006/2007	0.36	0.31	0.79
61	Gauge ID 2C3	1958/1959-2009/2010	0.76	0.72	0.93

Baseflow Index adapted from Kelly et al., 2019a, 2019b; & Kelly et al., 2020.
Geological data digitised after Cannon, 1978; Wedmore et al., 2019.
Other spatial data provided by Malawi Government.

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Kelly, L.; Kalin, R.M.; Bertram, D.; Kanjaye, M.; Nkhata, M. Quantification of Temporal Variations in Base Flow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi. Water, 2019, 11, 901.

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Base Flow Index of Malawi (Groundwater-Surface Water Interactions)

- • Town/City
- ☐ Malawi International Border
- 🟦 Waterbody
- River
- Fault
- ⊙ BFI Gauge Station
- 🟩 Consolidated Sedimentary Rock Aquifer Units
- 🟨 Unconsolidated Sedimentary Aquifer Units overlying Weathered Basement
- ▨ Weathered Basement Aquifer Units overlying Fractured Basement

Notes

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

Kalin, R.M., Addison, M.J., Mleta, P., Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedza, A. Ministry of Water and Sanitation, Government of Malawi 2022, Malawi. 1:4,000,000 Base Flow Index of Malawi (Groundwater-Surface Water Interactions) (Hydrogeology and Groundwater Quality Atlas of Malawi), ISBN 978-1-915509-25-3.

ISBN: 978-1-915509-25-3

Ministry of Water and Sanitation

Figure 14. Location of surface water gauging stations where the Base Flow Index has been calculated (after Kelly et al. 2020) [Available as Map at A0 size]

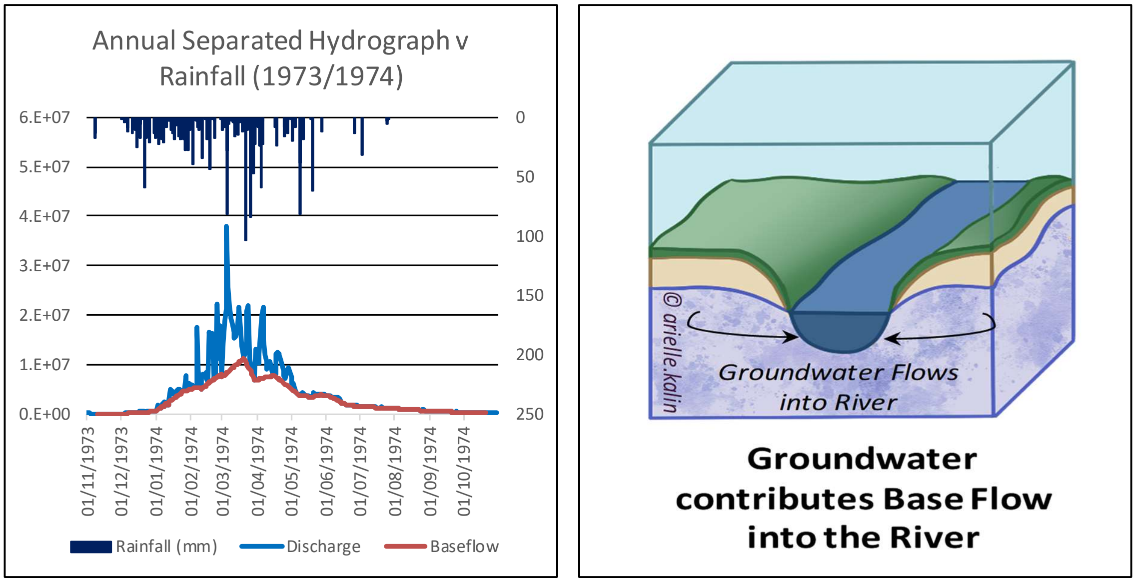


Figure 15a, b. Separation of Base Flow Component (a left) for the 1973 / 1974 wet season of the Bua River, Malawi (left y-axis l/s river flow, right y-axis precipitation mm) and (b right) idealised conceptual model of surface water – groundwater base flow interaction

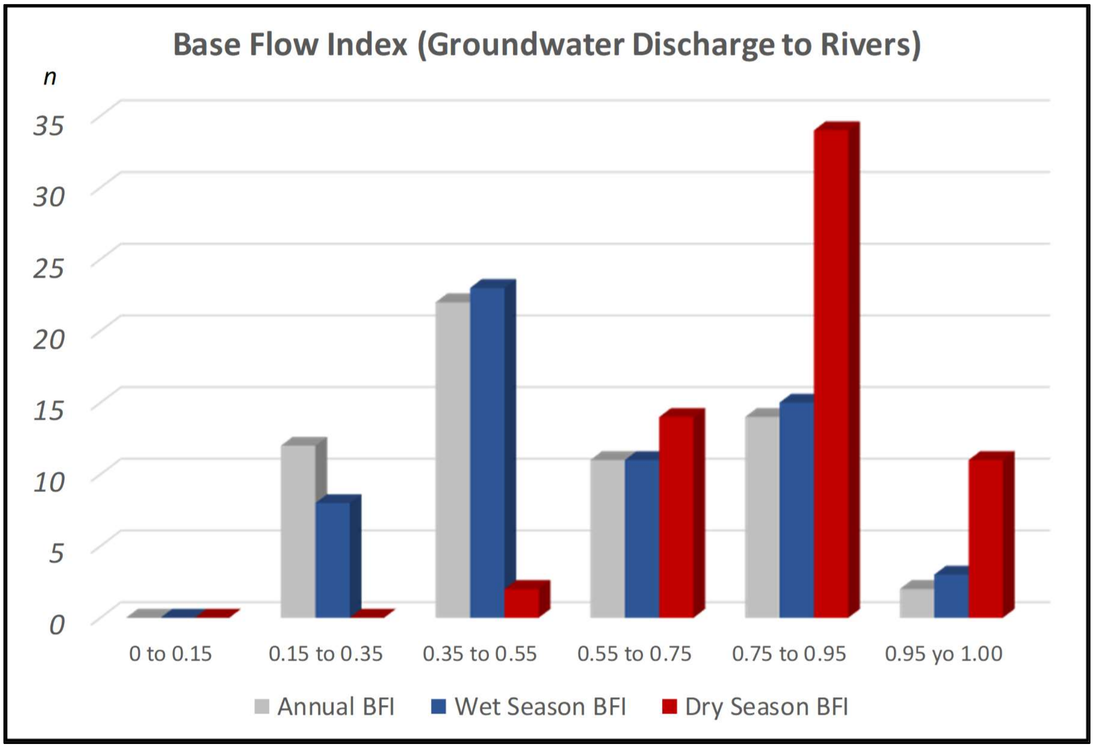


Figure 16. Distribution of all calculated Base Flow Indices for 61 rivers in Malawi, noting the extremely strong dependence of river flow on groundwater discharge during the dry season.

Table 6. Annual Base Flow Index of rivers across Malawi together with the seasonal (wet/dry) BFI (after Kelly et al 2020).

No.	Station ID	Period of assessment	Average annual BFI	Average wet season BFI	Average dry season BFI
1	Gauge ID 1S7	1961/1962-1996/1997	0.32	0.28	0.76
2	Gauge ID 1R3	1952/1953-2003/2004	0.19	0.16	0.87
3	Gauge ID 1P2	1952/1953-2004/2005	0.90	0.87	0.93
4	Gauge ID 1C1	1951/1952-2004/2005	0.48	0.44	0.85
5	Gauge ID 1K1	1951/1952-1996/1997	0.38	0.33	0.76
6	Gauge ID 1L12	1976/1977-2009/2010	0.92	0.91	0.96
7	Gauge ID 14A3	1962/1963-1999/2000	0.27	0.23	0.81
8	Gauge ID 2B33	1961/1962-2009/2010	0.27	0.22	0.79
9	Gauge ID 9A5	1970/1971-2006/2007	0.63	0.53	0.92
10	Gauge ID 9B6	1981/1982-2007/2008	0.50	0.44	0.94
11	Gauge ID 9B3	1970/1971-2007/2008	0.33	0.32	0.78
12	Gauge ID 4B3	1957/1958-2007/2008	0.52	0.48	0.89
13	Gauge ID 3F3	1957/1958-2003/2004	0.72	0.64	0.93
14	Gauge ID 3E1	1953/1954-2009/2010	0.49	0.42	0.94
15	Gauge ID 4B4	1957/1958-2009/2010	0.63	0.58	0.88
16	Gauge ID 5D3	1958/1959-2002/2003	0.48	0.45	0.84
17	Gauge ID 9A2	1953/1954-2009/2010	0.54	0.48	0.92
18	Gauge ID 9B7	1985/1986-2011/2012	0.64	0.56	0.86
19	Gauge ID 8A5	1968/1969-2008/2009	0.60	0.55	0.91
20	Gauge ID 9A4	1958/1959-2007/2008	0.71	0.62	0.92
21	Gauge ID 5D2(A)	1953/1954-2004/2005	0.76	0.74	0.84
22	Gauge ID 6C1	1952/1953-2009/2010	0.28	0.28	0.82
23	Gauge ID 6C5	1965/1966-2000/2001	0.47	0.43	0.74
24	Gauge ID 5F1	1964/1965-2004/2005	0.80	0.79	0.89
25	Gauge ID 4D24	1990/1991-2004/2005	0.70	0.67	0.87
26	Gauge ID 4E2	1959/1960-2004/2005	0.37	0.37	0.80
27	Gauge ID 4C11	1985/1986-2009/2010	0.21	0.17	0.75
28	Gauge ID 4D4	1953/1954-2008/2009	0.65	0.59	0.92
29	Gauge ID 1B1	1948/1949-2011/2012	0.97	0.95	0.98
30	Gauge ID 11A7	1976/1977-1997/1998	0.45	0.36	0.90
31	Gauge ID 5E6	1970/1971-2007/2008	0.54	0.46	0.90
32	Gauge ID 14C8	1959/1960-2001/2002	0.40	0.37	0.53
33	Gauge ID 14C2	1953/1954-2007/2008	0.46	0.47	0.49
34	Gauge ID 7D8	1952/1953-2007/2008	0.53	0.41	0.84
35	Gauge ID 7A3	1955/1956-2007/2008	0.35	0.35	0.73
36	Gauge ID 7G18	1985/1986-2008/2009	0.84	0.75	0.97
37	Gauge ID 1M1	1980/1981-2007/2008	0.64	0.52	0.87
38	Gauge ID 16F2	1952/1953-1993/1994	0.76	0.69	0.90
39	Gauge ID 16E6	1972/1972-2008/2009	0.78	0.71	0.91
40	Gauge ID 6D10	1985/1986-2009/2010	0.35	0.38	0.71
41	Gauge ID 5C1	1957/1958-2008/2009	0.74	0.69	0.94
42	Gauge ID 14D1	1980/1981-1990/1991	0.43	0.36	0.70
43	Gauge ID 1G1(A)	1953/1954-2008/2009	0.95	0.93	0.98
44	Gauge ID 3E5	1957/1958-2008/2009	0.55	0.50	0.95
45	Gauge ID 3E3	1956/1957-2007/2008	0.54	0.43	0.90
46	Gauge ID 5D1	1958/1959-2006/2007	0.75	0.74	0.93
47	Gauge ID 7F1	1955/1956-1997/1998	0.80	0.72	0.96
48	Gauge ID 7G14	1957/1958-2006/2007	0.80	0.76	0.97
49	Gauge ID 7H1	1955/1956-2007/2008	0.84	0.78	0.98
50	Gauge ID 7H2	1952/1953-2007/2008	0.87	0.79	0.96
51	Gauge ID 7H3	1971/1972-2006/2007	0.71	0.60	0.93
52	Gauge ID 7F2	1956/1957-2007/2008	0.85	0.77	0.97
53	Gauge ID 15A8	1960/1961-2009/2010	0.49	0.42	0.95
54	Gauge ID 4B9	1974/1975-2009/2010	0.37	0.36	0.77
55	Gauge ID 4B1	1953/1954-2008/2009	0.43	0.39	0.78
56	Gauge ID 4C2	1957/1958-2009/2010	0.51	0.42	0.91
57	Gauge ID 15A4	1970/1971-1999/2000	0.17	0.18	0.72
58	Gauge ID 14B2	1951/1952-2002/2003	0.36	0.34	0.74
59	Gauge ID 14A2	1954/1955-2001/2002	0.43	0.37	0.87
60	Gauge ID 2B22	1960/1961-2006/2007	0.36	0.31	0.79
61	Gauge ID 2C3	1958/1959-2009/2010	0.76	0.72	0.93

Groundwater Volume and Recharge

Due to uncertainties in the current recharge models for Malawi, the spatial distribution of recharge and a range of values were estimated based on aquifer type, areal extent and the estimated saturated thickness of each unit. Complex models of groundwater recharge are published, but given the heretofore simplified distribution of aquifer parameters, the results of these previous attempts have been ignored with a need for more research. The redefined geospatial extent of each aquifer type (**Table 7**) was determined at National, Water Resource Area, and Water Resource Unit (WRU) level so that local water balance equations can be developed to guide IWRM implementation planning.

Table 7. National area extent of each aquifer type in Malawi

No.	Aquifer Type Name	Combined Area (Km^2)
1	Consolidated Sedimentary Rock	2,517
2	Fluvial Units	7,644
3	Lacustrine units	1,506
4	Colluvium	33,529
6	W&F Basement	48,945

The conservative estimated volume of groundwater in the upper aquifer units across Malawi is calculated here (**Table 8**) as being between 96,656 and 1,108,340 Million Cubic Meters (MCM) which is between 96.7 to 1,108 km^3. The total recharge into all aquifer units' ranges between 1,031 and 7,731 MCM per year, and using these calculated volumes, the mean groundwater age in the upper aquifer units is calculated between 94 and 148 years. Given the importance of groundwater as a base flow component to surface water flows and the need to balance annual renewable groundwater with abstraction licenses (agricultural, consumptive) and environmental needs, the data in **Table 8** did not include the total (as yet unknown) saturated thickness of each aquifer unit in Malawi.

Table 8. Calculated range of groundwater volume of in Malawi, range of renewable annual recharge across Malawi, and the mean residence time (total/renewable) of groundwater across Malawi.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness High Est (km)	*MCM Groundwater Low Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	2,516.7	3%	15%	0.02	0.10	1,510	37,750	
Fluvial Units	7,644.0	10%	35%	0.02	0.10	15,288	267,541	
Lacustrine units	1,505.5	10%	35%	0.02	0.10	3,011	52,694	
Colluvum/Alluvium Units	33,528.9	10%	30%	0.02	0.06	67,058	603,520	
W Basement overlying F Basement	48,944.6	1%	10%	0.02	0.03	9,789	146,834	
	Area (km^2)	National Data		Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*96,656*	*1,108,340*	*Total Volume Groundwater*
	94,139.8	1,095	Average Rainfall	10.95	82.125	1,031	7,731	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 11 - 80 mm per year)						94	143	Calculated Average Residence Time of Groundwater (years)
* Million Cubic Meters						Low Est	High Est	

The details of the estimates used in these calculations are as follows. The estimate of porosity was from McDonald et al (2019) where "*Weathered basement and fractured volcanic rocks were assigned a mean ϕ of 5% (1–10%), which is representative of moderately decomposed crystalline basement*

(Taylor and Eggleton 2001, Petford 2003, Howard and Griffith 2009). Fractured sedimentary rocks were assigned a mean ϕ of 8% (3–15%) based on studies in the Karoo basin (Van der Voort 2001); the Voltaian Sediments (Pelig-Ba 2009), and the Benue Trough (Lott 1998). Mixed intergranular and fractured rocks were assigned a mean ϕ of 15% (10–30%) based on a studies in Nigeria (Samaila and Singh 2010), Botswana (Jones 2010), surrogates in the UK (Allen et al 1997) and global oil industry studies of porosity in cemented siliciclastic reservoirs (Morse 1994). Intergranular aquifers were assigned a mean ϕ of 25% (20–35%), a conservative value based on the studies in the Continental Terminale (Adelana and MacDonald 2008), the Chad Basin (Nwankwo et al 2009) and the Nubian Sandstone (Beavan et al 1991)."

The estimated saturated thickness of each aquifer type was assumed to be the difference between the depth of the borehole and the water strike, and was limited to the upper 100m. These were agreed with the Water Department based on data from the Ministry of Water and Sanitation dataset, and are limited to the range of boreholes currently installed in Malawi (most under 50 meters' depth with an average water column of between 10 and 30 meters. Future atlas editions should be updated with more confident estimates. Recharge data and its spatial distribution is complicated by many variables, some that are time dependent. These include precipitation amounts and intensity, climate conditions (temperature, wind speed, etc.), topography and runoff, soil type, underlying geology, vegetative cover, land use generally, and specifically, for instance, agriculture crop type. For this reason, the calculation of total groundwater volume, range of renewable groundwater recharge, and the mean groundwater age were undertaken for each Water Resource Unit in Malawi. Ultimately, IWRM implementation as legislated in the Water Resources Act (2013) Malawi, requires a water balance calculation and IWRM planning at WRU level.

Table 9. Mean annual rainfall (measured / GIS modelled) for each WRA between 1999 and 2019

WRA	Mean Annual Rainfall-Station Data	Mean Annual Rainfall-Interpolated (Modelled) Data	Maximum Modelled Data	Minimum-Modelled Data	Standard Deviation IDW Data
1	924	950	1,139	671	59
2	1,016	1,057	1,418	876	65
3	915	944	1,023	821	31
4	879	912	1,137	819	49
5	892	898	1,228	770	63
6	776	908	1,066	746	65
7	822	853	1,118	623	75
8	No Station	921	952	881	11
9	952	944	965	925	8
10	855	927	1,010	824	36
11	1,011	986	1,012	924	16
14	1,514	1,250	2,068	866	226
15	1,089	1,000	1,384	808	115
16	1,621	1,096	1,654	793	179
17	1,010	990	1,177	844	94

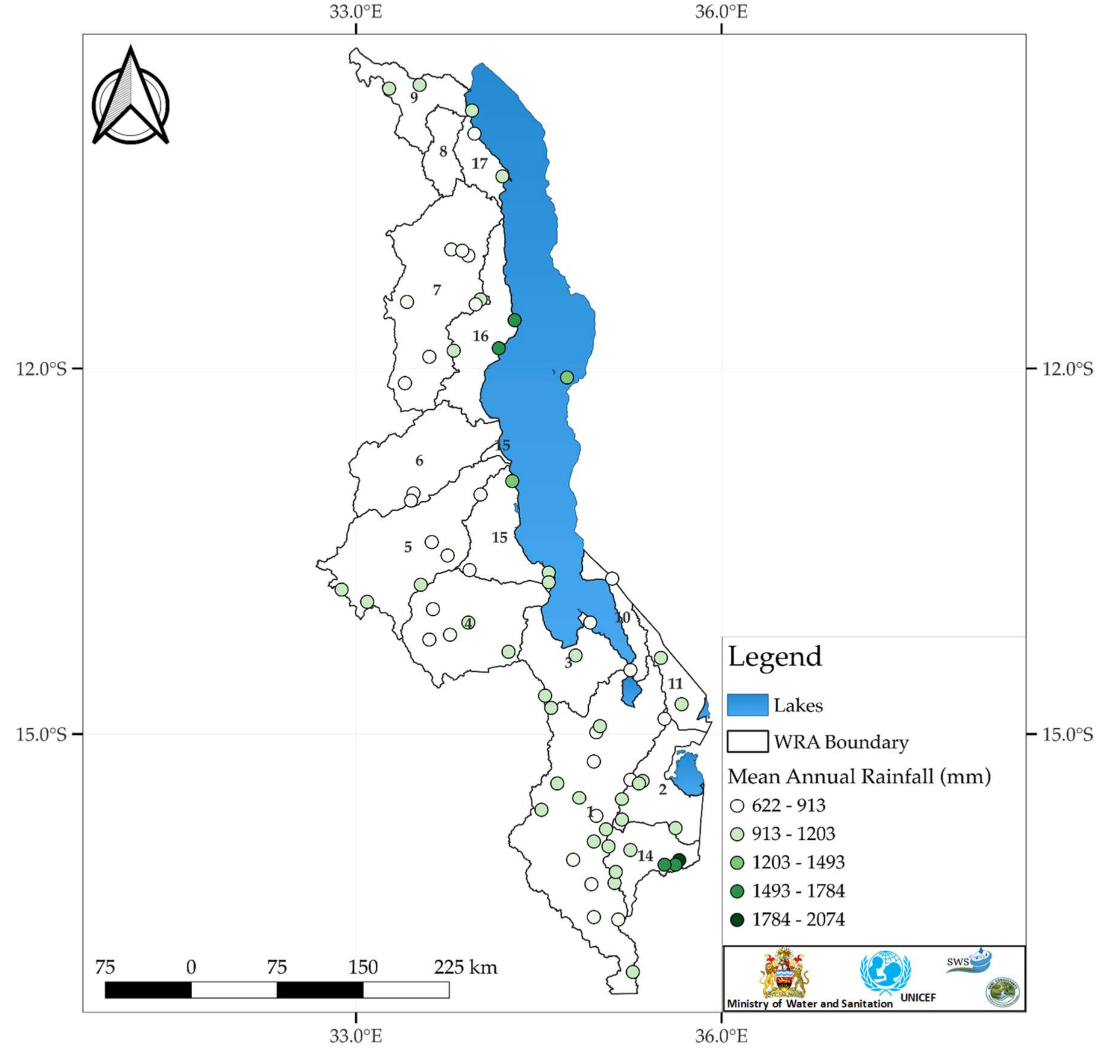


Figure 17. Location of Rainfall data stations used to model average rainfall for each WRU.

Calculation of recharge volumes at WRU level first requires the average rainfall in each WRU to be modelled via GIS. **Figure 17** shows the location of those rainfall stations that have continuous records from 1999 to 2019. Using this data provided by the Malawi Meteorological Office, the average inverse distance weighted (IDW) mean precipitation was modelled in GIS. **Table 9** provides the comparison of measured 20 year averaged rainfall against GIS IDW modelled averaged rainfall at Water Resource Area level. There is a high correlation between the measured and the modelled average rainfall of each WRA. The GIS IDW model was then used to calculate the mean annual rainfall for each Water Resource Unit (WRU) in Malawi (**Table 10**).

The range of calculated annual renewable recharge for all Water Resource Units ranges between 1.6 MCM per year and 265 MCM per year. The wide range of groundwater recharge volumes at WRU level indicates the need and local-scale importance of IWRM planning and implementation. Further GIS – Remote Sensing modelling should be undertaken to refine the calculations provided for each WRU within this update of the Hydrogeology and Water Quality Atlas of Malawi.

Table 10. Mean annual rainfall (measured / GIS modelled) for each WRU between 1999 and 2019

WRA	WRU	Station Names	Mean Rainfall-Station Data	Mean Rainfall-Interpolated Data (IDW)
1	A	- No Station -	-	955
	B	Chingale	873	980
	C	Chileka	842	965
	D	Chichiri/Mpemba	1,070	988
	E	Bvumbwe	1138	1,037
	F	Makhanga/Masambanjati	903	928
	G	Nsanje	981	947
	H	Nchalo/Ngabu	730	881
	K	Mwanza	979	956
	L	Chikwawa	751	907
	M	Neno	1,139	1,023
	N	- No Station -	-	1,026
	O	- No Station -	-	989
	P	Phalula/Walkers Ferry	914	920
	R	Balaka/Toleza	889	943
	S	- No Station -	-	951
	T	- No Station -	-	924
2	A	- No Station -	-	1,142
	B	Chanco/Makoka/Mombeza/Ntaja/Zomba	1,016	1,052
	C	- No Station -	-	1,054
	D	- No Station -	-	984
3	A	Mangochi/Monkey Bay	828	901
	B	- No Station -	-	924
	C	Nankumba	917	933
	D	- No Station -	-	958
	E	Ntcheu/Mlangeni	1,002	966
	F	- No Station -	-	964
4	A	- No Station -	-	922
	B	Dedza	922	940
	C	Nathenje	930	832
	D	Dzalanyama/Bunda	855	876
	E	Chitedze	865	874
	F	- No Station -	-	865
5	C	- No Station -	-	971
	D	Madisi/Mponela	779	833
	E	Kasiya/Tembwe/Mchinji	967	833
	F	- No Station -	-	833
6	A	- No Station -	-	883
	B	- No Station -	-	849
	C	Kasungu/Mwimba	776	842
	D	- No Station -	-	960

Note: Where no station is present in the WRU there is a need for investment for IWRM

Table 10 continued. Mean annual rainfall (measured / GIS modelled using inverse distance weighted IDW) for each WRU between 1999 and 2019

WRA	WRU	Station Names	Mean Rainfall-Station Data	Mean Rainfall-Interpolated Data (IDW)
7	A	Mbawa/Mzimba	809	881
	B	Euthini	768	853
	C	- No Station -	-	833
	D	Zombwe/Mzuzu/Bwengu	879	905
	E	Bolero	622	795
	F	Rumphi	714	783
	G	- No Station -	-	810
	H	- No Station -	-	939
8	A	- No Station -	-	921
9	A	- No Station -	-	942
	B	Chitipa/Misuku	952	947
10	A	Makanjira	855	927
11	A	Chikweo/Namwera	1,011	986
14	A	Thuchila	1,089	1,088
	B	Thyolo	1,200	1,146
	C	Mulanje/Mimosa/Lujeri	1,761	1,549
	D	- No Station -	-	1,035
15	A	Salima/Lifuwu/Dowa	1,050	968
	B	Ntchisi/Nkhotakota	1,149	1,021
	C	- No Station -		1,077
16	E	Chintheche	1,655	1,103
	F	- No Station -	-	1,147
	G	Nkhata Bay	1,587	990
17	A	- No Station -	-	886
	B	Lupembe	843	898
	C	Vinthukutu	1,177	1,046

Note: Where no station is present in the WRU there is a need for investment for IWRM

Groundwater Table Variability

The Government through the then Ministry of Agriculture Irrigation and Water Development established the groundwater monitoring network in 2008 under a Government funded Project in which 35 monitoring wells were drilled from 2009 to 2010 (6 of them now vandalised). These monitoring wells were equipped with data loggers in 2013 for automatic data collection. Additionally, under the National Water Development Program, the Government drilled 36 exploratory boreholes in the country [apart from the Shire River Basin] during the Hydrogeological and Water Quality Mapping Project (2014- 2015) funded by the World Bank. Due to their strategic locations, all the exploratory boreholes were established as monitoring wells and were equipped with data loggers in 2017 with funding from the Japanese International Cooperation Agency. However, two of these are vandalized. From 2016 to 2018, under a Project funded by AfDB, ten (10) additional monitoring wells were drilled in Five (5) districts of Rumphi, Nkhotakota, Mangochi, Ntcheu and Phalombe, and equipped with data loggers but one was vandalised before installation of logger and one after installation hence 8 are currently functional. In 2017-2018, a Hydrogeological and Water Quality Mapping Project took place in the Shire Basin and under this Project 30 exploratory boreholes were drilled in the Basin. Many of the exploratory boreholes are relatively deep wells. Government has also intended to equip the ones in the Shire River Basin with data loggers so that they become monitoring wells but unavailability of funding has made implementation not possible.

The network does not include multi-level installations into each hydro stratigraphic (aquifer) unit, does not substantially cover areas of high pollution potential for groundwater, and does not cover some aquifer units for instance the Karoo. The most important limitation is inadequate coverage of vertical scale of groundwater flow in aquifers (depth), and insufficient regional spatial distribution. Furthermore, only a few of the monitoring wells are used to assess the impact of motorized borehole abstractions and critically none for solar borehole systems (which must be mandated with a separate drilled monitoring well and automated water level monitoring). Monitoring wells for abstraction impacts are also few. Increasing the coverage and data sharing with the Water Boards and all Donors who install solar boreholes is essential. The network does not have automatically transmitting data loggers and data collection is undertaken in the field.

Malawi currently has 71 functioning monitoring wells. In terms of distribution in aquifers, the majority of these are in the colluvium overlying weathered basement, 51%, 33% are in the unconsolidated sediments overlying weathered and fractured basement, and 16% in the weathered basement overlying fractured basement. Location and results from the monitoring wells are provided for each WRA in the respective annexes. The monitoring of groundwater levels is responsibility of the Groundwater Division at the Department of Water Resources (DWR) under the Ministry of Water and Sanitation. The National Water Resources Authority (NWRA), established by the Water Resources Act (2013), will ultimately take over this responsibility when it is operationalised. The Water Quality Division is responsible for monitoring groundwater quality. Some parameters are measured in-situ (in the field), and some samples are taken to the Ministry's Water Quality Laboratories for analysis. Water quality data collection is largely adhoc and due to funding constraints often with limited quality sampling and chain of custody protocols. Many times only one parameter or a limited number of parameters are analysed. A full field and laboratory analysis must become standard so that appropriate QA/QC checks can be undertaken (such as ion balances where less than 10% of the ~80,000 water quality results reviewed at this time passed QA and were included in the atlas).

Groundwater level data collection from the monitoring stations is conducted most often manually using electric water level dippers by the Water Monitoring Assistants (WMA) in the districts. Data is collected on a weekly interval. There are also automatic data collection loggers installed in some monitoring borehole and the data is supposed to be downloaded to computers bi-annually, but sometimes a year passes without downloading. Many of the loggers are, however malfunctioning in recent years, and do not allow data download. The data is stored in excel worksheets.

Routine planned and implemented monitoring of groundwater levels and groundwater quality is critical to the meeting the legislative requirements for IWRM under the Water Resources Act (2013), and they should be two of the highest priorities for funding.

The importance of distributed and continuous groundwater level monitoring cannot be understated. **Figure 18** provides data from the Ngabu Water Office from 2009 to 2021 showing a clear annual trend of groundwater level declines and recharge over a long-term trend of declining groundwater levels most likely due to heavy agricultural abstraction punctuated by large recharge events during the floods of 2015 and 2019. All though the loss of crops, damage to infrastructure and the tragedy of loss of life is heavy during large flood events in WRA 1 Lower Shire, it is clear from the data in Figure 18 that without these periodic large flood events, the prognosis for groundwater resources in the Lower Shire is dire. Flood water management and large-scale irrigation planning must therefore include large-scale and well funded managed aquifer recharge (MAR) infrastructure.

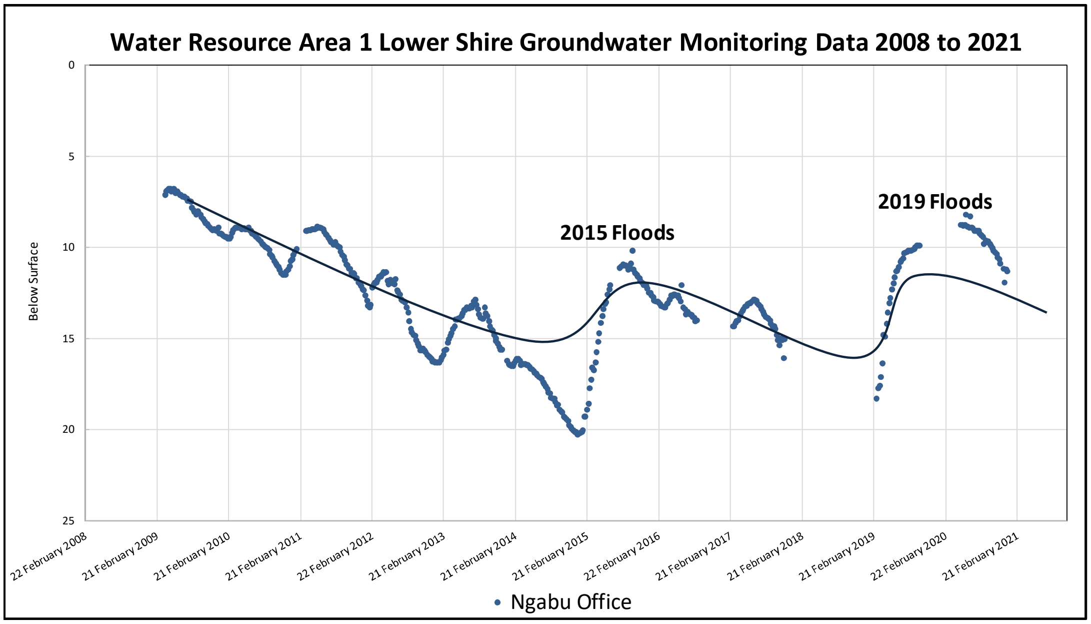


Figure 18a. Groundwater table variation at the Ngabu Water office 2009 to 2021 showing the relationship of groundwater storage with increasing abstraction and periodic major recharge events due to flooding in 2015 and 2019.

The importance of groundwater – surface water interaction in Malawi is clear from the analysis of base flow in rivers. However, along Lake Malawi there is a strong hydraulic connection between groundwater supplies and the Lake (Banda et al 2019). **Figure 19** shows the groundwater monitoring data for the Monkey Bay School (ca. 1.5 km from Lake Malawi) and the Mangochi Water Office (ca. 1km from Shire between Lake Malawi and Lake Malombe; together with the elevation of the Lake Malawi surface from 2008 to 2016. The water table at both of these groundwater monitoring stations are strongly influenced by the annual lake level variations (**Figure 19**), but because there is no continuous record of groundwater levels at these locations, it is not possible to determine what the effects from increasing urbanisation, groundwater abstraction and changes to the Barrage and Hydroelectric plants on the Shire River have had on groundwater flow. The contentious construction of a new abstraction and treatment facility in Monkey Bay (at a UNESCO World Heritage site) and the impacts on groundwater quality and abstraction in the Mangochi conurban area fail to benefit from an understanding of temporal and spatial changes in groundwater resources. These two case studies can be extrapolated to a range of groundwater – surface water interaction challenges across Malawi resulting from deforestation / land use change, irrigation and hydroelectric infrastructure, enhanced groundwater abstraction through 'solar pumped' boreholes, population growth and climate change.

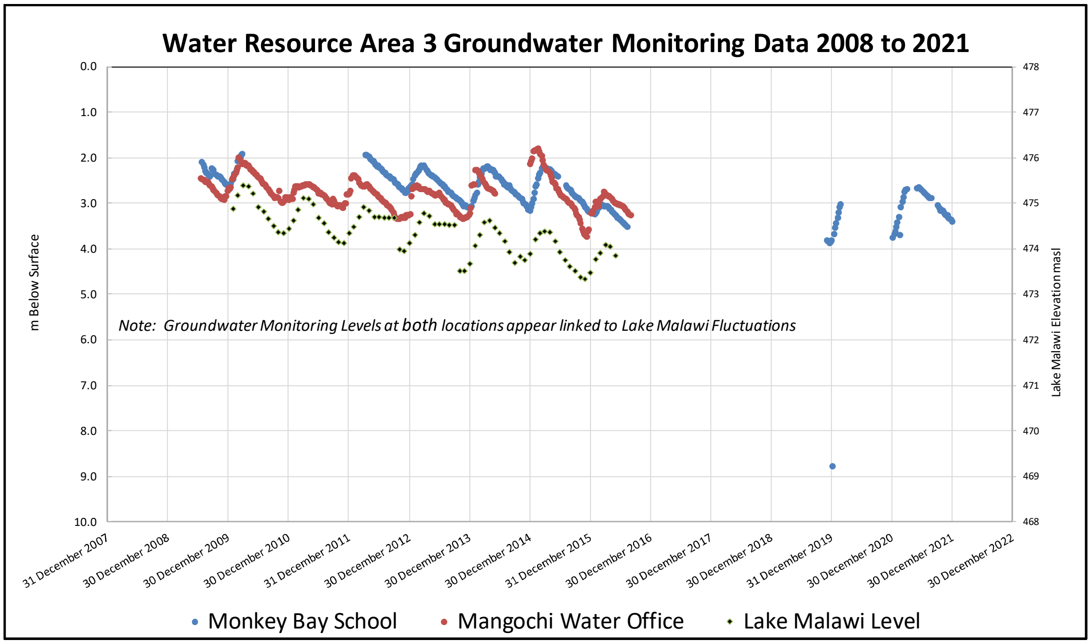


Figure 18b. Groundwater table variation at the Mangochi Water Office and the Monkey Bay School 2009 to 2021 showing the relationship of groundwater storage related to annual changes in Lake Malawi levels.

The interaction of surface water in lakes (Lake Malawi / Lake Malomba / Lake Chilwa) with groundwater must be considered for any groundwater abstraction less than 5 km from major water bodies. The natural water table and lake level variations will result in groundwater flow reversal and mixing of surface water and groundwater in the aquifer (**Figure 20a**). Small single abstractions may not influence this natural behaviour, however a large number of community abstraction points, or high yield 'Solar' or 'Submersible pumps will greatly affect the flow dynamics (**Figure 20b**).

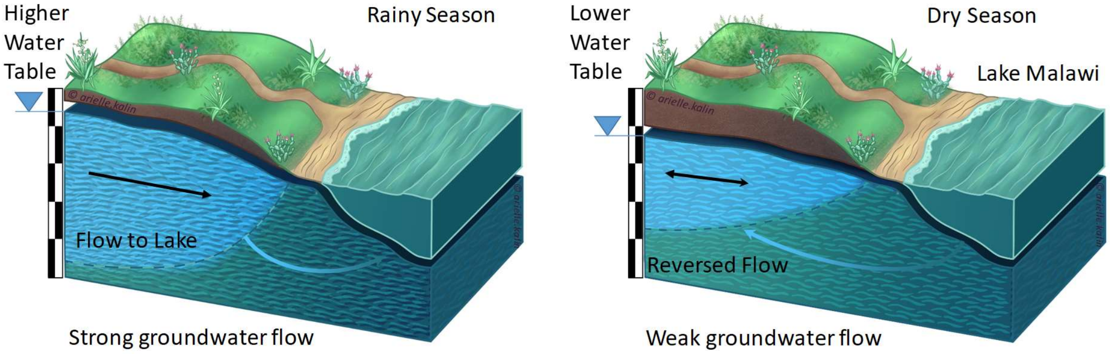


Figure 19a. Conceptual model of natural surface-water groundwater interaction along Lake Malawi. During the wet / rainy season higher groundwater levels result in groundwater flow to Lake Malawi (left) and during the dry season or at times when Lake Malawi levels are above groundwater levels, lake water flows inland in the aquifer.

Large scale domestic or commercial pumping of groundwater within 5 km of Lake Malawi (or other large lakes in Malawi) have a very high likelihood of inducing flow reversal and mixing of groundwater. This will result in high groundwater flow velocities with increased risk of contamination from for example pit latrines and septic tanks, agricultural activity, evaporated / saline water intrusion. Therefore, abstraction licensing by the NWRA should be implemented near the major surface water bodies in Malawi, and is critically needed. Any 'Solar' or 'Submersible' groundwater abstraction (planned or existing) should be evaluated for impact on the groundwater quality and quantity (with required on site and regular monitoring of water levels and water chemistry).

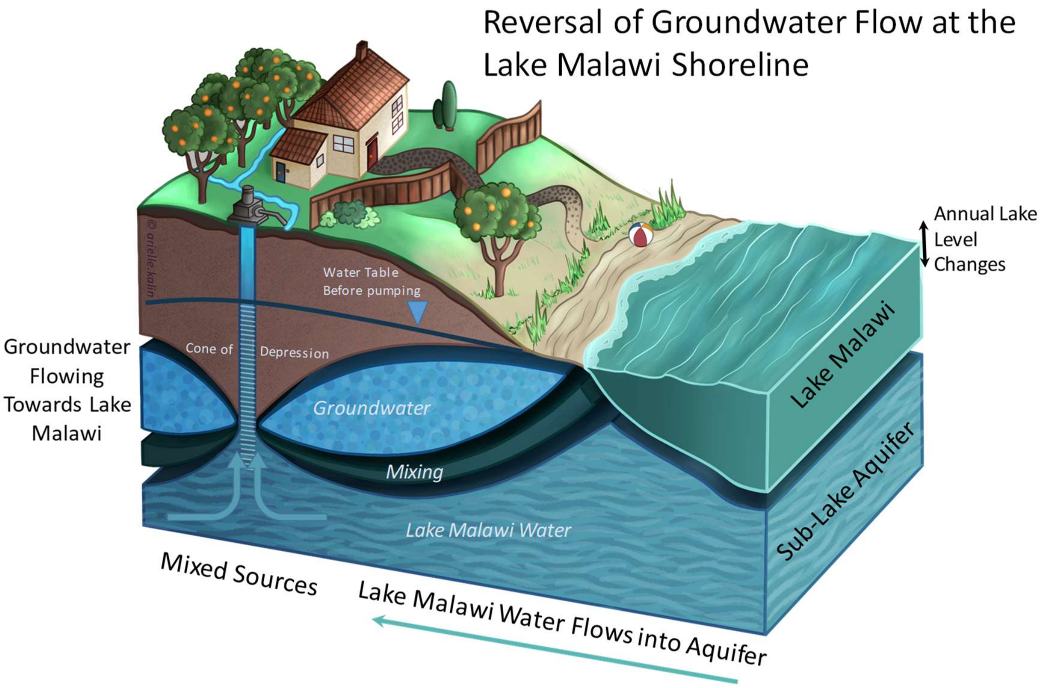


Figure 19b. Conceptual model of groundwater – surface water interactions that likely dominate the near shore groundwater table along the perimeter of Lake Malawi where large-scale groundwater abstraction is taking place.

Managed Aquifer Recharge

Managed Aquifer Recharge (MAR) is very topical as an engineered solution to capture flood water (or other sources) and allow the water to infiltrate naturally or through pumping, with the goal to use excess water and deliberately enhance groundwater storage for subsequent use or environmental benefits. The challenges around MAR relate to both the engineering infrastructure costs (e.g. reservoirs or injection wells), the operational and maintenance costs (e.g. removing silt or cleaning of borehole gravel packs), water quality concerns, loss of down-stream water for use, and the shear volumes of water in even small scale aquifers. **Figure 20a** shows a hypothetical 1km x 1km x 5m deep reservoir for MAR in Malawi that potentially could collect and infiltrate up to 5 MCM each year. However, when compared to a modest small scale recharge need for a local aquifer volume of 200MCM (based on water table fluctuations in **Figure 18a**), the cost benefit of MAR investment must be carefully considered, especially as the available water for recharge is highly seasonal in Malawi (**Figure 20b**).

Cost Benefit Ratio of Managed Aquifer Recharge

Aquifer Recharge Needed
100 km^2 x 10 meters water table x 0.20 =
200 million cubic meters (MCM)

Managed Aquifer Recharge (MAR)
1 km^2 x 5 meters deep =
5 million cubic meters (MCM)

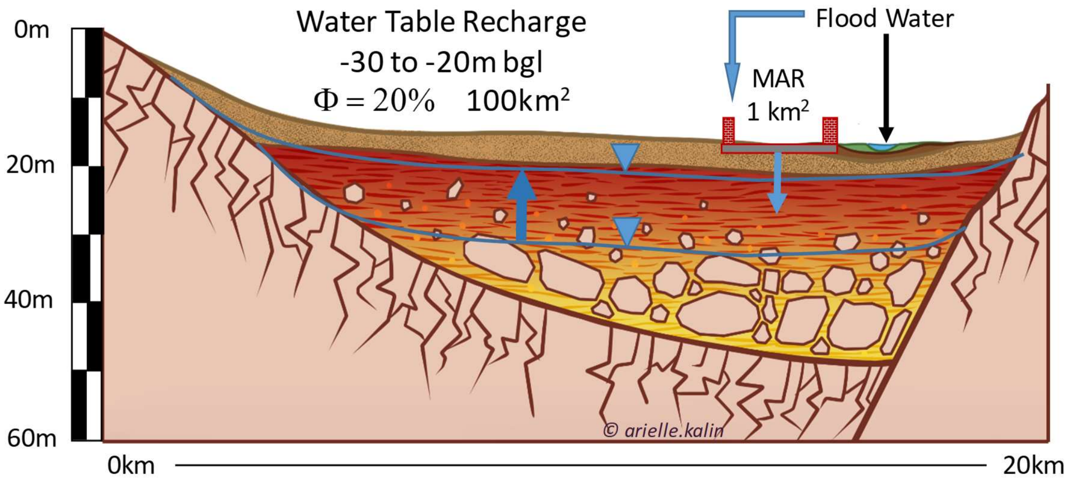


Figure 20a. Conceptual cross section showing the scale difference in water availability through MAR, and the potential annual water deficit of a small aquifer system in Malawi.

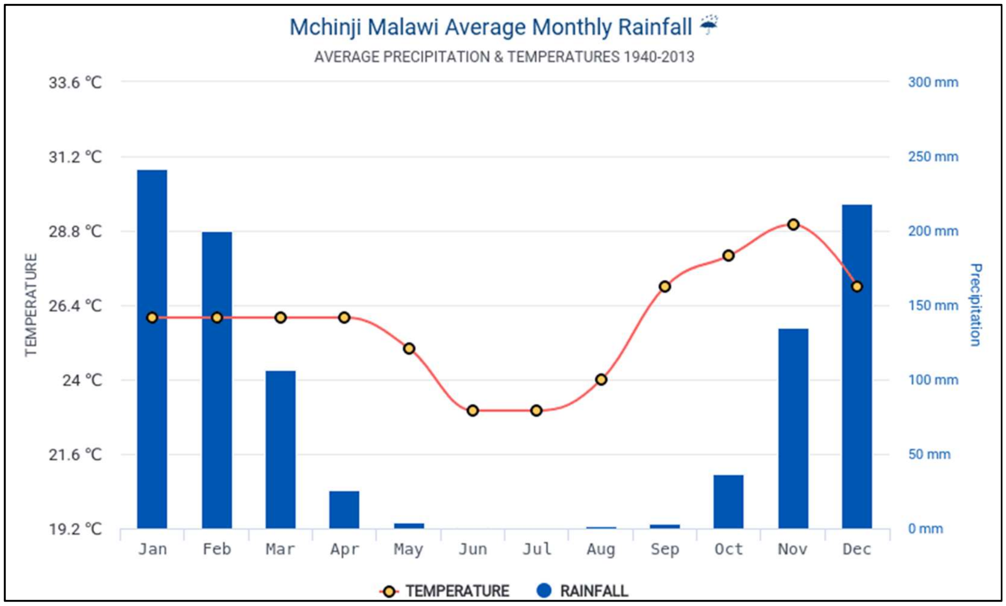


Figure 20b. Managed Aquifer Recharge will be dependent on available excess surface water runoff during rainfall events. The rainfall in Malawi is focused into a limited number of months reducing the temporal applicability of MAR.

Groundwater Quality of Aquifer Groups

Dominant Groundwater Quality Processes

Groundwater quality in Malawi is dominated by a relatively few controlling factors, however due to a lack of regular, national scale monitoring, it is not possible to develop a detailed understanding of the importance and control each of these processes have on local-scale water quality.

- Water-rock geochemical reactions (incongruent weathering and saprolite formation) specifically noting mineralogy that increases risk of geogenic species such as Fluoride, Iron, Manganese, Selenium, Arsenic and other trace elements.
- Ion exchange, in particular related to secondary clay minerals formed during weathering
- Evaporative enrichment (hot dry conditions enhance evapotranspiration and phreatic evaporation increasing groundwater salinity; in particular, where perched or shallow groundwater occurs)
- Deep fluid movement / hot spring (higher temperature geochemical reactions enhance the risk of geogenic species and/or transport water in contact with deeper geologic units)
- Paleohydrology (past lake levels, and evaporative enrichment or evaporate deposits that may be tectonically controlled or result from climate change / variability).
- Human-induced groundwater pollution (pit latrines, agrichemicals, industrial and municipal discharges)

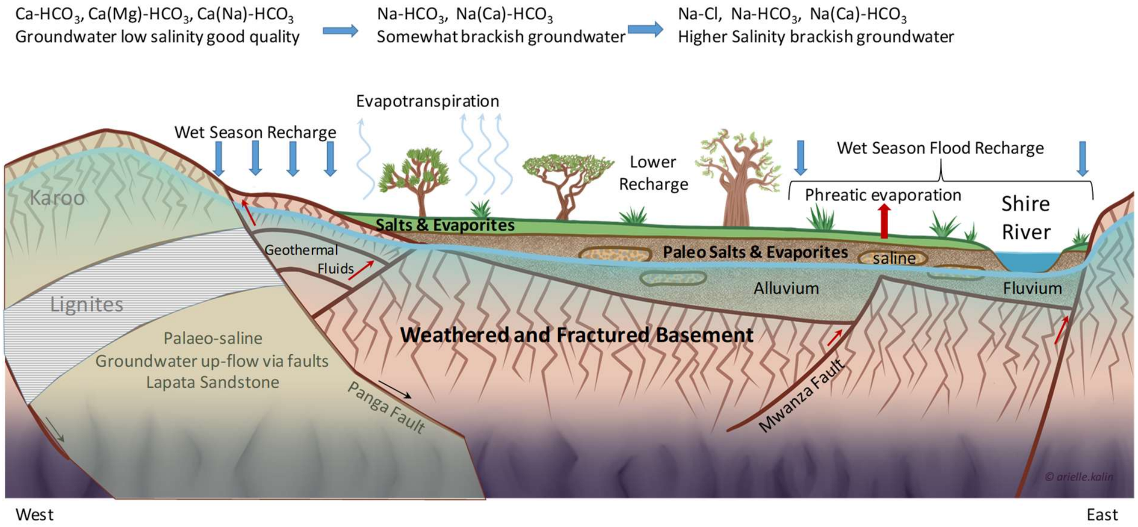


Figure 21a. Conceptual cross section of the Lower Shire WRA 1 where water-rock interactions, deep fluid movement / hot springs, shallow fluid movement from sedimentary rocks, flood – recharge events and high evapotranspiration and phreatic evaporation all have location dependant contribution to high groundwater salinity

The interpretation of Water Quality data in the Hydrogeology and Groundwater Quality atlas therefore is descriptive in nature, and the user of the data should undertake local and site specific water quality testing (together with hydrogeologic testing), using the results to determine the controls on groundwater quality and the risks from various sources of contamination.

Groundwater Salinity

The challenges of groundwater salinity occur throughout Malawi, in part due to the bi-modal weather patterns with a long stretch of dry hot months that result in evaporative enrichment of shallow / perched groundwater, and due to mineral dissolution (mainly consolidated sedimentary rocks and lenses of evaporate minerals). Shortly after gazetting of the Water Resources Act (2013), Polmanteer and Kalin (2014) together with the Ministry re-evaluated borehole siting and drilling practices as part of a review required for the operationalisation of the legislated National Water Resources Authority (as stipulated by the WRA 2013). This report led to a revision of various standard operating procedures, began the development of Borehole Forensics (developed between 2014 and 2016 by Kalin and others at Strathclyde Univ) to evaluate the root causes of borehole failures, and called for a National Drillers Association, and certification of all Drillers in professional hydrogeology and drilling practices.

One of the recommendations was, during drilling, to gather drill cuttings at regular depths for both geologic analysis and WQ analysis. Cuttings would have a known volume of distilled water added to it and measured for EC. This may not give fully accurate measure of the groundwater quality, but it can give a relative measure of quality between stratigraphic units and provide a vertical profile of predicted TDS for the borehole. The results of this practice can be seen in two boreholes drilled 1.5km apart in the Mwanza Valley, Water Resource Area 1, Water Resource Unit 1K (**Figure 21b**). The results should be used to place grout seals during well design isolating those geologic units that appears to have higher EC values, and care should be taken that no slotted casing nor gravel pack is installed.

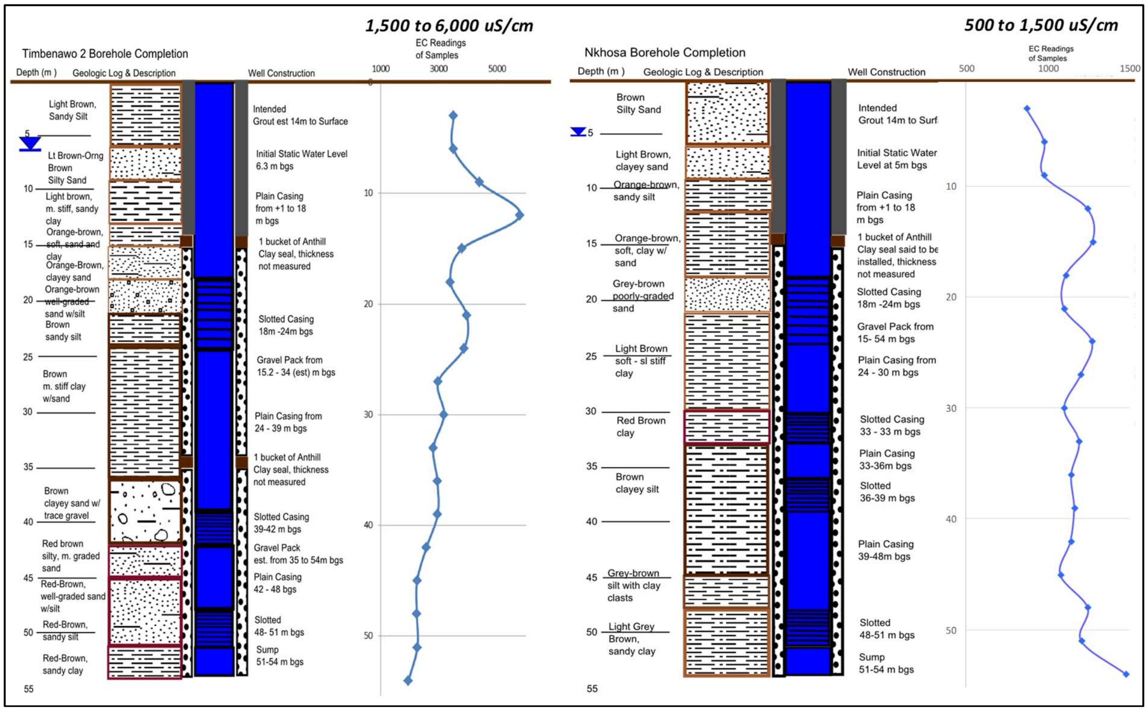


Figure 21b. Salinity profiles of drill cuttings from two wells drilled 1.5km apart in WRU 1K, Mwanza Valley, Chikwawa in 2014 showing localised salinity variation with depth. [after Polmanteer and Kalin 2014]

Groundwater Chemistry of Unconsolidated Colluvium and Alluvium Units

Unconsolidated Sediments (Colluvium and Alluvium) overlying Weathered and Fractured Basement arise from erosion and mass wasting of rift escarpment basement rock (**Figure 8b**). Thickness varies due to the tilted, block-faulted nature of underlying sequences, and may be up to 150 m or more where sediments have accumulated against large normal faults on the rift valley's flank. As drilling for water-supply boreholes is frequently less than 50m depth, maximum the thickness of unconsolidated deposits is not proven. Due to contrasting high and low energy depositional environments, deposits are heterogeneous, spatially and with depth.

In general, groundwater quality is good in colluvium, but in some areas the alluvium contains brackish water, particularly in the areas with high evaporation and slow moving groundwater such as Mangochi, Salima, around Lakes Chilwa and Malombe; and in the Lower Shire. In these areas groundwater can exceed 9,000 µs/cm (**Figure 22a**). Local scale maps showing the distributions of dissolved for each Water Resource Unit (WRU) are found in the annex for each WRA. Fluoride is generally less than 1.5mg/l with some exceptions. Measureable Nitrate is common generally below 5mg/l but with some measurements in excess of 25mg/l indicating a wide-spread source of N (most likely pit latrines). The relationship between Na and Cl (Figure 22a) shows Sodium is often in excess indicating that ion exchange (divalent for monovalent ions) is a geochemical process during incongruent weathering of the primary silicate minerals that make up the colluvium.

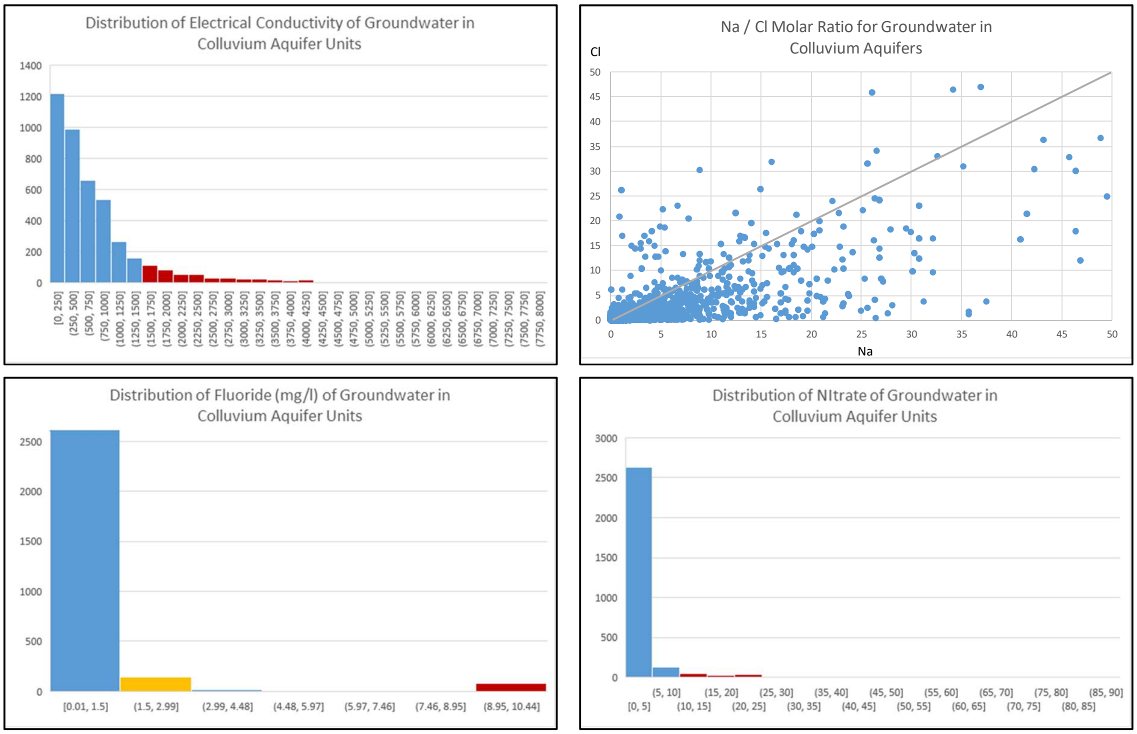


Figure 22a. Groundwater quality parameters (Electrical Conductivity µs/cm, Na/Cl Molar Ratio, Nitrate mg/l, and Fluoride mg/l) for groundwater from Unconsolidated Sedimentary (Colluvium) units overlying weathered basement in Malawi. [y axis is n number of observations]

Groundwater Chemistry in Unconsolidated Sedimentary Fluvial and Lacustrine Units overlying weathered basement

Coarse to fine grained, poorly sorted fluvial deposits are topographically deposited along rivers and dambos. These are generally thinner than colluvium and alluvium and may or maynot be hydraulically connected to the underlying weathered basement. Thick lacustrine deposits with increased low fine-grained sands, silt and clay layers may be more common in the central basin areas (**Figure 8b**).

In general, groundwater potential is good in alluvium, but in some areas the alluvium contains brackish water, particularly in Mangochi, Salima and around Lakes Chilwa and Malombe; in the Lower Shire around Elephant marsh. In these areas groundwater can reach upwards of 12,000 µs/cm. The areas where brackish water occurs are also along contacts of alluvium and other aquifers types, typically alluvium surrounding Lakes Chilwa and Malombe, as well as alongside of elephant Marsh, etc. and the most likely mechanism is phreatic evaporation (evaporation from the shallow slow flowing groundwater table that is periodically ‘flushed’ or mixed with flood waters of lower salinity).

Fluoride is generally less than 1.5mg/l in these systems with notable exceptions where the sediments are thin and rest on fluoride-bearing weathered basement. Measureable Nitrate is common generally below 2mg/l but with some measurements approaching 10mg/l indicating a wide-spread source of N (most likely pit latrines). The relationship between Na and Cl (Figure 22a) shows Sodium is often in excess indicating that ion exchange (divalent for monovalent ions) is a geochemical process during incongruent weathering of the primary silicate minerals that make up the colluvium.

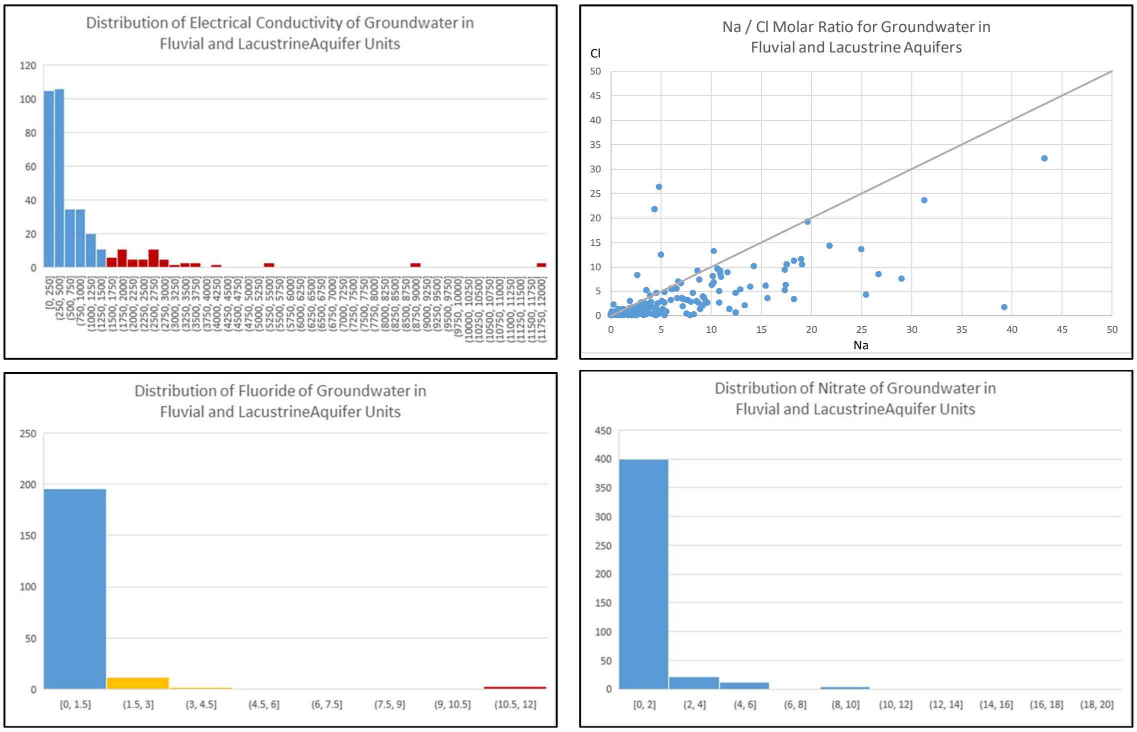


Figure 22b. Groundwater quality parameters (Electrical Conductivity µs/cm, Na/Cl Molar Ratio, Nitrate mg/l, and Fluoride mg/l) for groundwater from Unconsolidated Fluvial and Lacustrine Sedimentary units overlying weathered basement in Malawi. [y axis is n number of observations]

Groundwater Chemistry in Consolidated Sedimentary Rock Units

There are few groundwater abstraction points within Consolidated Sedimentary Rock units, and fewer that have detailed installation information and/or geospatial and temporal data. Therefore, the data available may not represent the full extent of groundwater quality in these units in Malawi (**Figure 8a**).

Groundwater quality in these sediments is occasionally good with mineralisation less than 1,000 µs/cm particularly boreholes completed at maximum depth of 50 m below ground surface, but deeper boreholes (60 m and more within the aquifer) can be as mineralised and saline up to 7,000 µs/cm. The increasing of salinity with depth can be explained by the scale of groundwater circulation tapped. Iron concentration is sometimes high in order of 10 mg/l.

Local scale maps showing the distributions of dissolved for each Water Resource Unit (WRU) are found in the annex for each WRA. Fluoride is mainly less than 1.5mg/l in these systems and is expected to be low given the lack of fluoride-bearing minerals (except where hot springs occur). Measureable Nitrate is common generally below 2mg/l but with some measurements approaching 15mg/l indicating a wide-spread source of N (most likely pit latrines). The relationship between Na and Cl (Figure 22a) shows a 1:1 relationship indicating evaporates (as NaCl) within the Sedimentary Rocks are a dominant source of salinity.

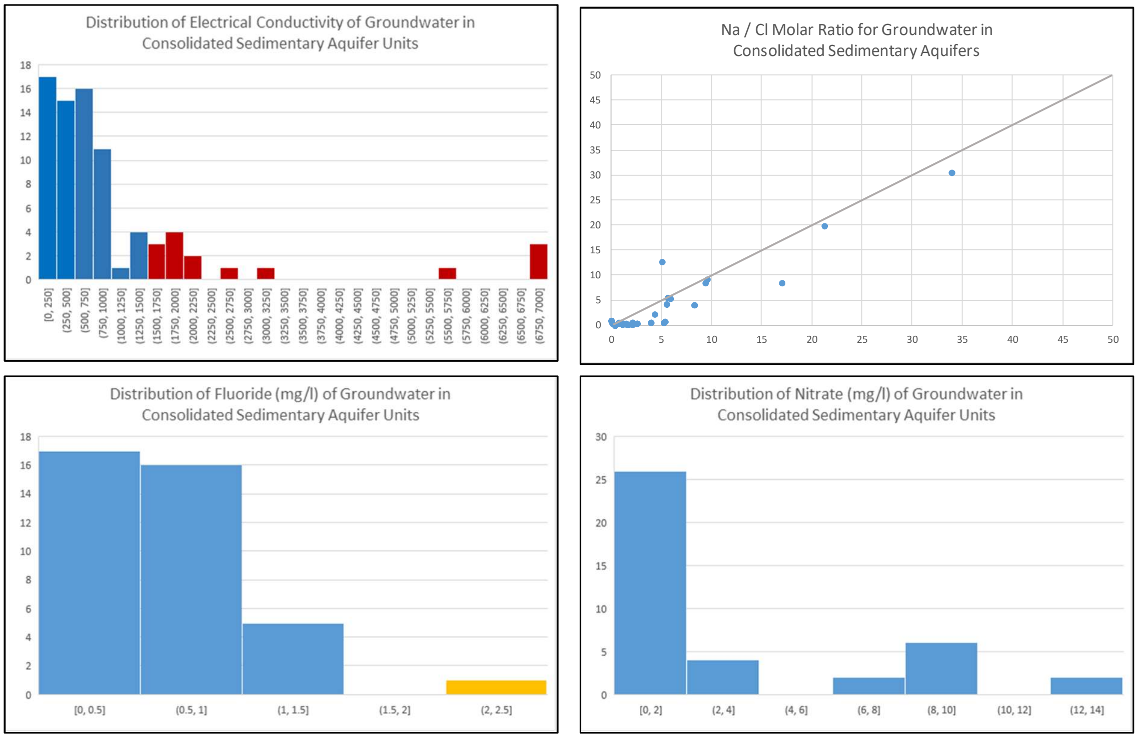


Figure 23. Groundwater quality parameters (Electrical Conductivity µs/cm, Na/Cl Molar Ratio, Nitrate mg/l, and Fluoride mg/l) for groundwater from Consolidated Sedimentary Aquifers in Malawi. [y axis is n number of observations]

Groundwater Chemistry in Weathered overlying Fractured Basement Units

Weathered basement (as saprolite and saprock) overlay Fractured Basement across most of Malawi, and is overlain by Unconsolidated Sediments in many areas (potentially hydraulically connected). The Groundwater Chemistry will be dominated by water-rock weathering reactions and the primary minerals in each location (highly variable as seen in **Figure 8c**).

Groundwater mineralisation in the weathered basement overlying fractured basement can be as low as 100 µs/cm and in generaly are less than 1,000µs/cm. However, areas of higher groundwater mineralisation of up to 7,500µs/cm were observed. Iron concentration is sometimes high in order of 10 mg/l. Fluoride is mainly less than 1.5mg/l but there are many measurements above 4mg/l and even above 6mg/l which place users at high risk of skeletal fluorosis (around 250,000 or more persons as identified by Addison et al 2020). It is therefore vital that all groundwater abstraction points are measured for Fluoride before commissioning, and importantly in areas containing Fluoride mineralisation, that routine (at minimum annual) Fluoride monitoring takes place. Elevated Nitrate is widespread generally up to 5mg/l but with some measurements approaching 50mg/l indicating a wide-spread source of N (most likely pit latrines) to high-transmissive fractures that support fast groundwater flow at distances over 100m. The relationship between Na and Cl (Figure 22a) shows Sodium is often in excess indicating that ion exchange (divalent for monovalent ions) is a geochemical process during incongruent weathering of the primary silicate minerals that make up the units.

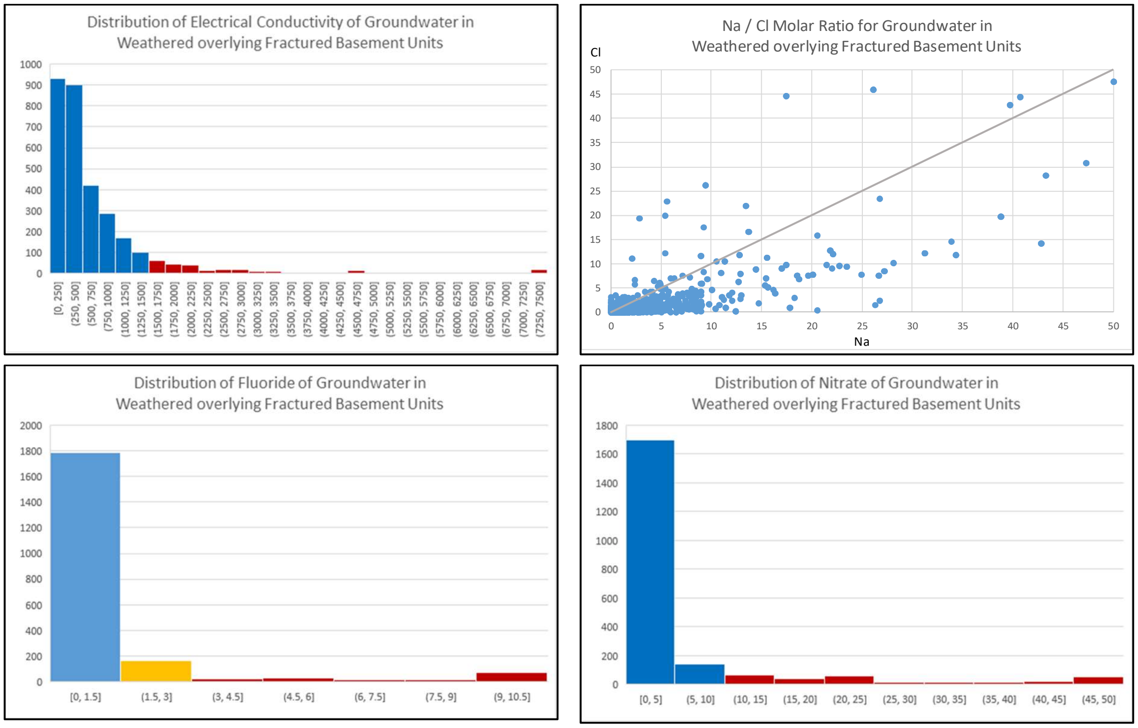


Figure 24. Groundwater quality parameters (Electrical Conductivity µs/cm, Na/Cl Molar Ratio, Nitrate mg/l, and Fluoride mg/l) for groundwater from Weathered overlying Fractured Aquifers in Malawi. [y axis is n number of observations]

National Water Quality Issues

Fluoride

Addison et al (2020) undertook a detailed risk assessment of Fluoride in Malawi Groundwater. In total, they compiled 1,126 groundwater fluoride concentrations from boreholes, shallow wells and natural springs were compiled, along with data for 28 hot springs (**Figure 25**). The separation of hot springs from other groundwater data allowed both groundwater fluoride source systems (shallow rock weathering vs. deep hydrothermal) to be analysed separately. The average fluoride concentration from the groundwater fluoride data set was 0.97 mg/L, with 87% of samples falling within the WHO standard for fluoride in drinking water of 1.5 mg/L. The remaining 13% had concentrations < 6 mg/L, with one outlier at 10.63 mg/L from a shallow well. Hot springs had significantly higher fluoride concentrations: all hot springs with corresponding fluoride concentration data (n = 28) exceeded the WHO standard, with an average of 6.38 mg/L.

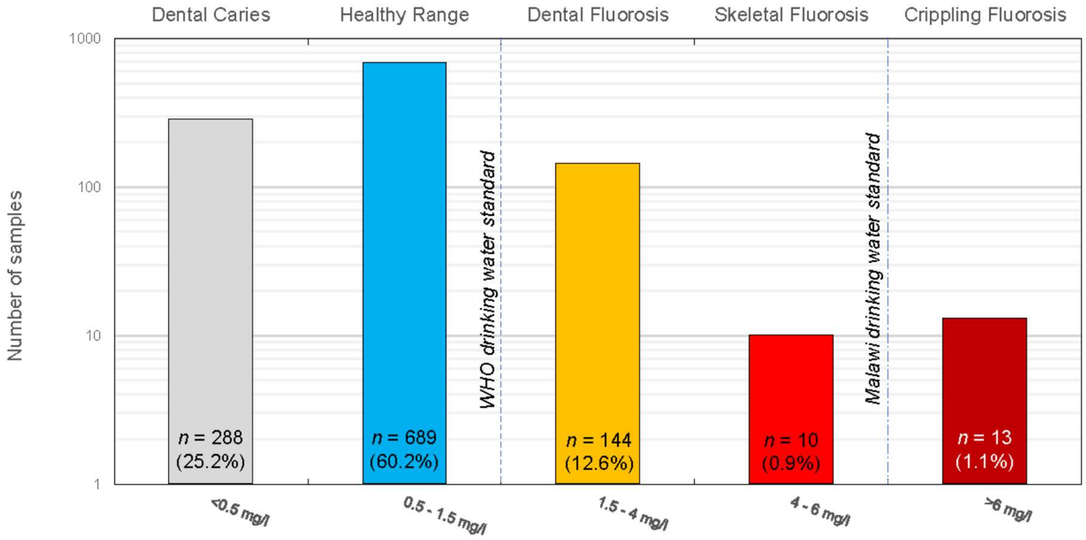


Figure 25a. Number and concentration range of measured Groundwater Fluoride in Malawi with geogenic Fluoride Health Risk, moderate and elevated geogenic risk is classification based on the WHO drinking water guideline of 1.5 mg/l and health impact (after Addison et al 2020).

The areas around fault fluid movement that are of highest fluoride risk are conceptualised in **Figure 26**. A map of groundwater vulnerability from geogenic fluoride developed by Addison et al (2020) (**Figure 27**) for Malawi based on the results from the statistical analysis and subsequent extrapolations. Sixty three site-specific 'Excessive Geogenic Fluoride' water points (hot springs) represent highly localised endemic fluorosis areas where local people use them for drinking. These water points pose the highest fluorosis risk in Malawi (**Figure 27**). The estimated number of people at risk from developing fluorosis from hot springs in Malawi is over 11,000. This is based on the average number of people per functioning water point, per local district (in the absence of users per water point data for hot springs).

'Elevated Risk geogenic Fluoride' zones account for 5.18% of Malawi's land surface and are presented as generic zones where there is a >60% risk of encountering groundwater with a concentration of over >1.5mg/L (**Figure 27**). These are predominantly weathered basement overlying fractured basement aquifer units and sub units of alkaline igneous lithologies. These are localised to plutons and intrusions associated with rifting and deformed meta-equivalents within basement rock. The number of people vulnerable from groundwater fluoride > 1.5 mg/L (thus dental fluorosis) in those zones is an estimated 250,000 (**Figure 27**), which constitutes about 1.4% of the population of Malawi. Water points within these zones total 1,168 which is about 2.3% of functioning and partly functioning direct groundwater abstraction points. Water points within this category plus all hot springs (n = 1,233) place at risk nearly 260,000 rural Malawians across the country.

Water points within 'Moderate-low Geogenic Fluoride' zones constitute 74.9% of water points (n = 37,279), potentially affecting 9.9 million people (**Figure 27**). This classification carries a relatively low statistical risk (10–17%) of encountering groundwater fluoride > 1.5mg/L. While the statistical likelihood is low, this still represents approximately 1–1.6 million people across these zones who may be drinking groundwater with fluoride concentrations elevated enough to cause dental fluorosis.

Subsurface fault fluid movement has been linked to localised endemic severe dental fluorosis (Addison et al 2021). These 'hidden hot springs' do not occur at the surface but rather are beneath the unconsolidated sediments of Malawi's rift basin discharging hydrothermal water from depth to shallow groundwater. The buried nature of hidden hot springs presented a key challenge to map risk (**Figure 26**). Basic geochemical proxy indicators (fluoride, sodium, calcium, magnesium) can be used identify possible locations where a detailed monitoring programme could be implemented.

'Low Geogenic Fluoride' carries a low statistical likelihood (<10%) of encountering elevated groundwater fluoride > 1.5 mg/L but still represents approximately 270,000 people who may be at risk. Water points within zones with insufficient data for a geogenic fluoride classification constitute 2% of water points (n = 979) and currently may affect an estimated 180,000 people. It is therefore imporant that a National Water Quality Monitoring programme is planned, funded and implemented that undertakes targeted geochemical sampling across Malawi and targeted sampling in areas prone to geogenic water quality risks.

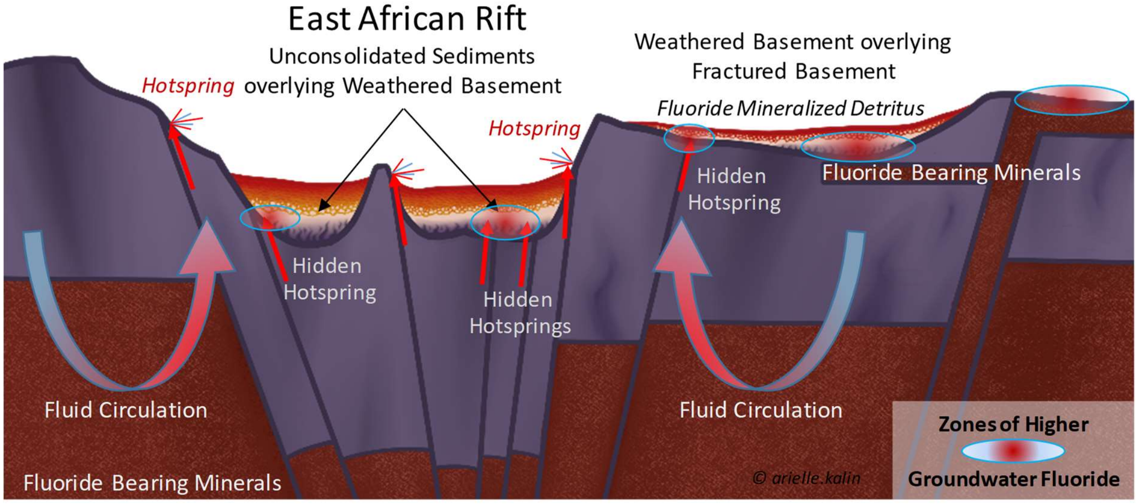


Figure 26. Conceptual model of subsurface fault fluids as a source of geogenic fluoride risk.

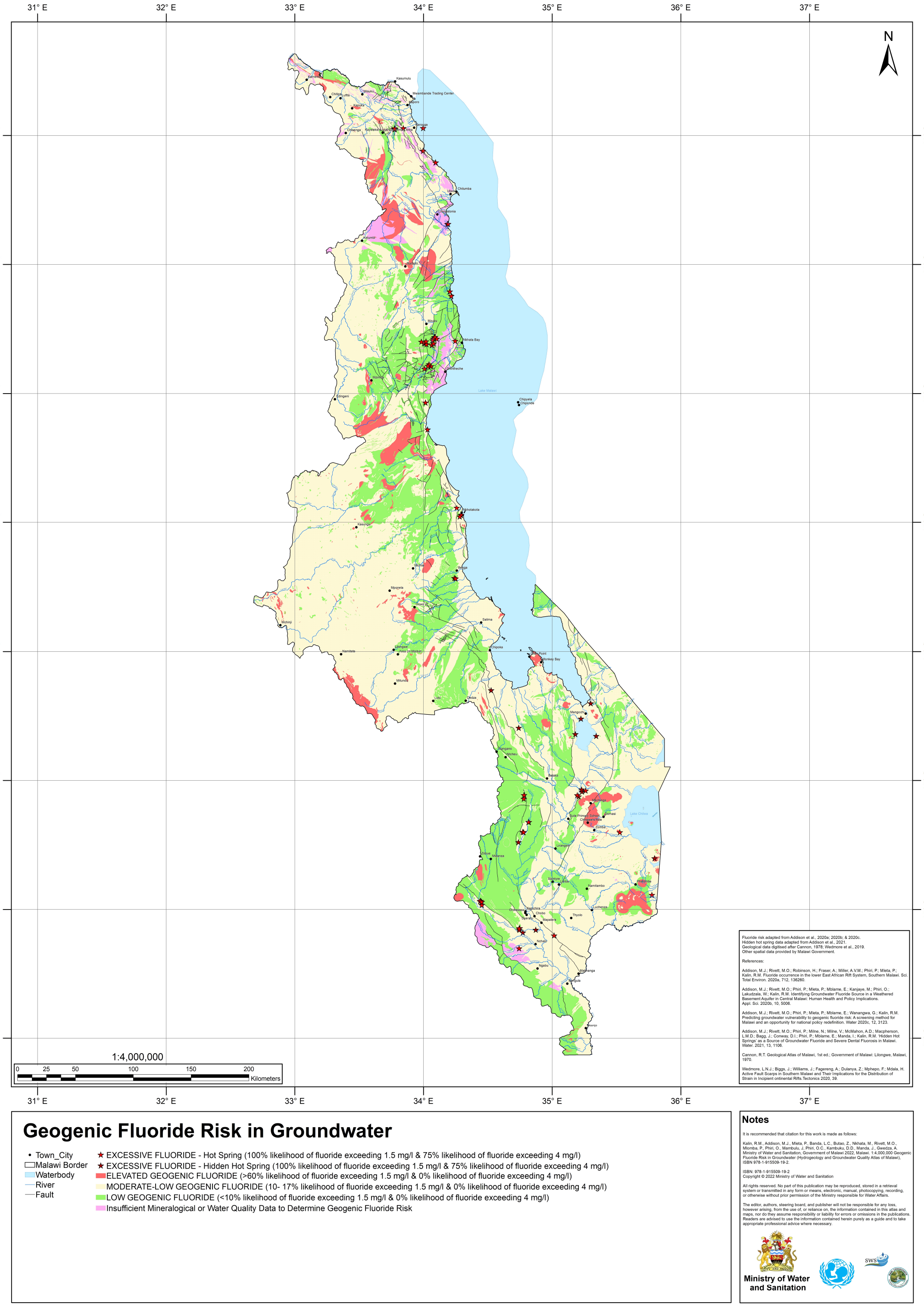


Figure 27. National Map of Geogenic Fluoride Risk in Groundwater based on statistical evaluation of geogenic risks (after Addison et al 2020). [Available as Map at A0 size]

E-coli

A recent longitudinal study of borehole chlorination following Cyclone Idai and subsequent e-coli analysis and re-chlorination (Rivett 2022) showed most groundwater abstraction points impacted by e-coli continue to rebound with systemic e-coli contamination. There is no systematic data on groundwater N-species, e-coli and other pathogenic or organic (including pesticides and herbicides) contaminants for groundwater abstraction points across Malawi. This recent study is the first to clearly provide Malawi specific hydrogeologic evidence of groundwater plumes from pit latrines as a likely source of wide-spread e-coli contamination of groundwater water (**Figure 28**). Malawi must begin to consider the cumulative effect of pit latrines as a loading function to soils and shallow groundwater as a significant long-term risk to water quality.

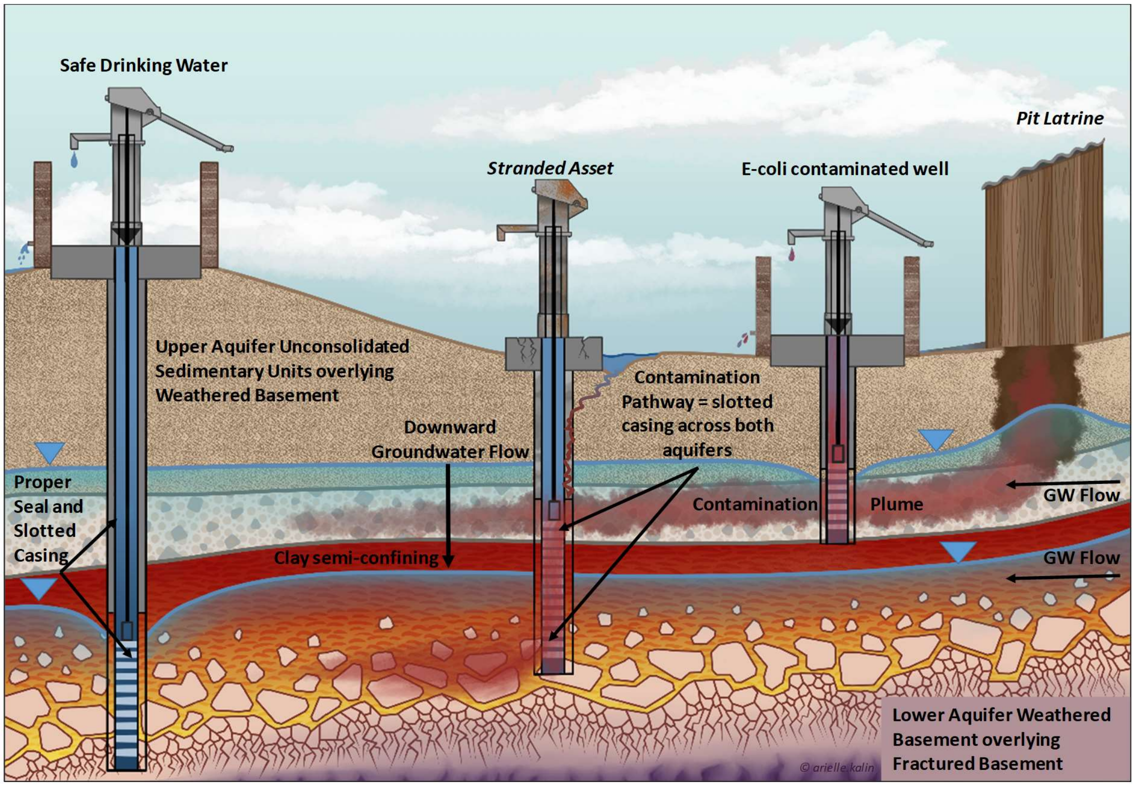


Figure 28. Conceptual risk model of the impact to groundwater from pit latrine fecal sludge loading in shallow aquifers in Malawi.

To model this potential risk, the spatial population distribution of Malawi 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 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 (**Figure 29**).

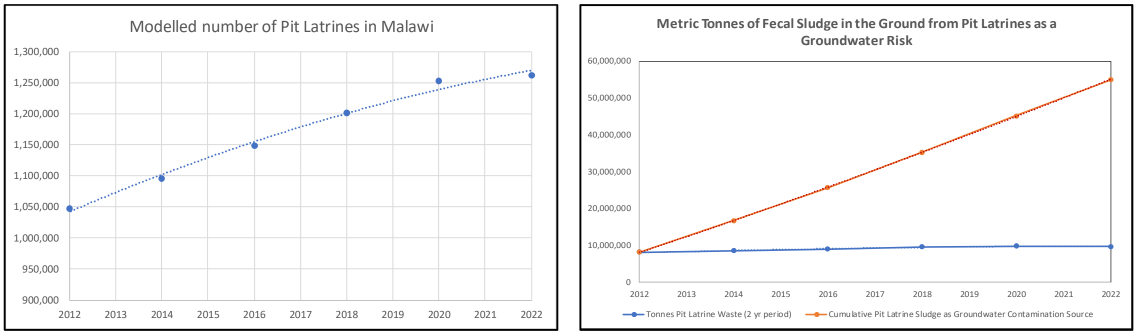


Figure 29. Modelled number of pit latrines (left) in Malawi 2012 to 2022 based on population and WASH statistics and the annual and cumulative metric tonnes of fecal sludge in pit latrines (right) as a source as a contamination risk to groundwater.

Table 11. Bi-annual and cumulative pit latrine sludge loading as potential source term of Groundwater contamination.

Year	Metric Tonnes after 2 year Pit Latrine Lifetime	Cumulative Pit Latrine Sludge (metric tonnes in the ground)
2011 - 2012	8,149,592	8,149,592
2013 - 2014	8,567,537	16,717,129
2015 - 2016	9,005,643	25,722,772
2017 - 2018	9,609,902	35,332,674
2019 - 2020	9,868,673	45,201,347
2021 - 2022	9,763,504	54,964,851

While these are modelled data and require validation and further study, a conservative estimate of 0.4 gms Nitrogen per Kg fecal sludge, it is possible that 22,000 metric tonnes of N-species are a source to groundwater. The analysis of Nitrogen in groundwater (this atlas) shows a wide-spread, low concentration (ca. <5g/l) of Nitrate across all aquifer types and WRA's / WRU's, with localised spikes in concentration up to 50mg/l. There is no systematic monitoring programme for groundwater, nor a monitoring programme in place to evaluate the environmental risks of pit latrine proliferation across Malawi. It is important this is included in any new National Groundwater Water Quality Monitoring Programme and any revision to the National Sanitation Policy.

Arsenic

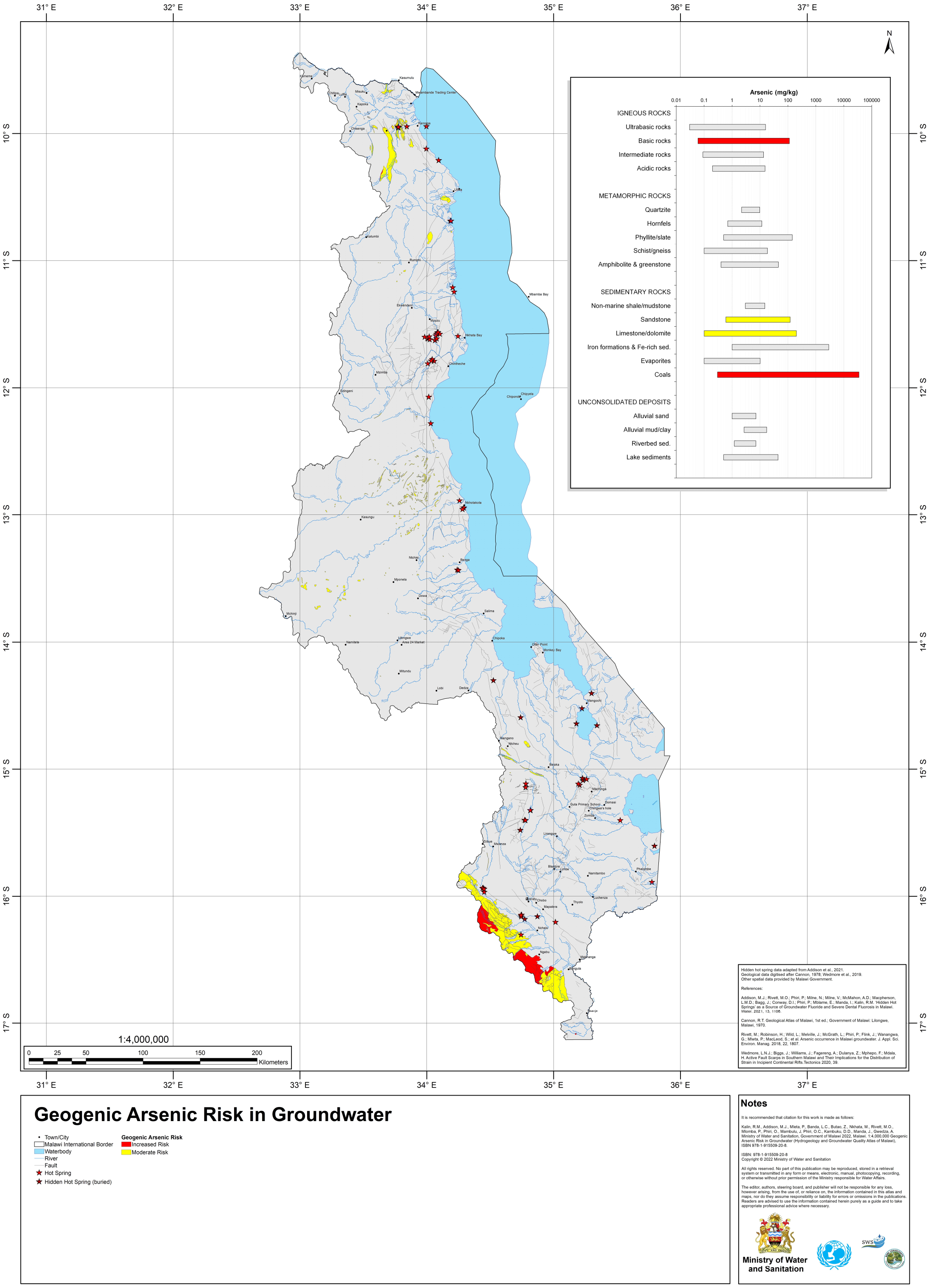
Arsenic in groundwater is a global concern due to its potential to impact human-health when Arsenic containing groundwater is used for drinking-water supply. The WHO drinking water guideline for Arsenic is 10 µg/l. Malawi has adopted the pre-1993 WHO drinking-water guideline of 50 µg/l, (MS733:2005) for waters delivered from boreholes and protected shallow wells.

Arsenic is geogenic (sourced from rocks and minerals that form groundwater aquifers). Rivett et al (2018) reviewed the anticipated rock arsenic content the results of which are summarised in **Figure 30**. A detailed national Water Quality survey for Arsenic has not been undertaken, but using **Figure 30** it is possible to estimate risk of arsenic containing groundwater. For example, biotite hornblende gneisses are unlikely to be greatly impacted by weathering with solid-phase arsenic expected to be low (<20 mg/kg). Coal shales in Lengwe National Park could pose high risk. Arsenic in groundwater may be connected with pyrite presence (data limited) and reduced conditions within igneous rocks such as basalt (up to 113 mg/kg). TA Ngabu is thus an area with higher arsenic risk in that weathering could be high in the Karoo basaltic bedrock. Alluvial deposits there are also partly derived from basalts may contain elevated iron-bearing magnetite and arsenic.

The groundwater at highest risk in Malawi is geothermal water (fault fluid movements). Rivett et al (2018) found Arsenic concentrations in geothermal groundwater are the highest measured during various surveys, but remain modest at <15 µg/l, and comparable to the archive Malawian literature survey maximum. Although there are sporadic concentrations of arsenic in groundwater that exceed the WHO 10 µg/l drinking-water guideline and can be considered troublesome, arsenic concentrations observed to date throughout Malawi still remain comfortably within the 50 µg/l limit applied for water delivered from boreholes and protected shallow wells.

The results published by Rivett et al (2018) suggest for the Malawian hydrogeological circumstance that arsenic concentrations in groundwater may be generally low. There is a need for further investigations of areas prone to geothermal groundwater contributions and / or reducing conditions, especially in alluvial aquifer systems with natural or anthropogenic sources of organic matter (rice cultivation, large number of Pit Latrines, etc.). In total only 1 % of Malawi groundwater (919 groundwater samples) has been tested for Arsenic. Hence there remains significant work to be done in the further assurance of water supply quality. Given that arsenic concentrations detected to date are mainly in the 1 – 20 µg/l range, there is a need for Malawi Ministry of Water and Sanitation to have the analytical capacity to routinely determine concentrations within this range and possible variation in population exposures to groundwater arsenic.

As Malawi pushes to enhance is use of groundwater through the drilling of deeper wells, and through the use of 'solar pump' boreholes that supply reticulated systems, the risk of encountering high arsenic containing groundwater increases. There are already known areas of high Iron across most WRAs in Malawi, and the Eh / pH relationship that allows Iron solubility also favours Arsenic mobility, and it is therefore important the Ministry of Water and Sanitation revised its Water Quality monitoring programmes to target and track Arsenic in groundwater in light of enhance groundwater exploration.



Hidden hot spring data adapted from Addison et al., 2021.
Geological data digitised after Cannon, 1978; Wedmore et al., 2019.
Other spatial data provided by Malawi Government.

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Notes

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

Kalin, R.M., Addison, M.J., Mleta, P., Banda, L.C., Butao, Z., Nkhata, M., Rivett, M.O., Mlomba, P., Phiri, O., Mambulu, J, Phiri, O.C., Kambuku, D.D., Manda, J., Gwedza, A. Ministry of Water and Sanitation, Government of Malawi 2022, Malawi. 1:4,000,000 Geogenic Arsenic Risk in Groundwater (Hydrogeology and Groundwater Quality Atlas of Malawi), ISBN 978-1-915509-20-8.

ISBN: 978-1-915509-20-8

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Figure 30. National Map of Geogenic Arsenic Risk in Groundwater based on evaluation of geogenic risks (after Rivett et al 2018). [Available as Map at A0 size]

Outline of Legislative and Policy Instruments for Groundwater Regulation

Legislation and Regulations

The Water Resources Act (2013) Malawi (WRA 2013) replaced the Water Resources Act of 1969. The WRA 2013 established the National Water Resources Authority (NWRA). Currently, there is on-going reorganization in government agencies on the management of water resources and operationalisation of the NWRA. A detailed assessment of Legislative and Policy Instruments for Groundwater Regulation was undertaken by the SADC and is found here (https://sadc-gmi.org/wp-content/uploads/2021/01/Malawi.pdf). The following summarises the SADC findings.

The WRA 2013, Water Works Act (1995), Water Resources Regulations (2018) [to operationalise the NWRA], National Water Policy (2005), National Sanitation Policy (2008) and Environmental Management Act (2017) (EMA) are in place that in part explicitly address the use, management, and protection of groundwater and provides the necessary tools for the state to regulate, manage, control, protect and develop groundwater resources in conjunction with surface water resources in Malawi. The human right to water is found in Sections 37 & 38 of the WRA (2013), and for groundwater prioritization of drinking water and basic human needs is focused on small-scale users. Hand pump wells are not thus subjected to EIA as a consideration for small scale domestic water uses.

Section 37 of the WRA (2013) requires regulation of abstraction and recharge, and the legal powers for reduction of use in times of water shortage, importantly including sustainable yield and the protection of groundwater discharge to wetlands / surface water. Permits are required for abstraction and EMA requires that EIA be undertaken. Section 86 of the WRA (2013) specifies the need for long term plans to ensure the sustainable use of groundwater, including drought management plans and cross-sectoral coordination.

The legislation categorises users as commercial and non-commercial. Permits to abstract water are issued to commercial users. The authorisation of groundwater use is not tied exclusively to land tenure as groundwater is considered a public asset and the NWRA is vested in government to manage the resource sustainably and restrict (in the public interest) the rights accruing from its use to prevent over-abstraction or inequitable access or use by landowners. Section 38 of the WRA (2013) guides groundwater use through rights, subject to a government-controlled, as permits for large scale users, with appropriate non-permit systems for addressing the needs of small-scale users.

The NWR 2013 Legislation requires regulation of borehole drillers, drilling and construction, information from drillers and maintenance of standards by the Ministry of Water and Sanitation for borehole drilling, construction, testing and maintenance. It also enables the regulation of groundwater exploration sets the Water Resources Unit (WRU) as the local area for IWRM to protect overused or vulnerable aquifers. It also allows designation of groundwater conservation areas.

WRA (2013) includes a mandate, competence and power of the relevant authorities in accordance with governance principles. All groundwater development activities are clearly required to be supervised and carried out by competent professional hydrogeologists, drilling companies or relevant bodies and professionals. However, there is a paucity of technical hydrogeological competence in Malawi, and a great need for capacity building.

The Ministry of Water and Sanitation is responsible for water affairs (surface and groundwater). Groundwater development and management is under the Department of Water Resources and Water Supply. Water Resources Department has three Divisions; Groundwater Division; Surface Water Division and Water Quality section. The Water Resources Board formed a fourth Division but this has been replaced with the NWRA, an autonomous government-sponsored body, according to the WRA 2013. The NWRA is responsible for the former Water Resources Board roles in addition to others.

NWRA responsibilities include the following;

- develop principles, guidelines and procedures for the allocation of water resources;
- monitor, and reassess, the National Water Policy and National Water Resources Master Plan;
- receive and determine applications for permits for water use;
- monitor and enforce conditions attached to permits for water use;
- regulate and protect water resources quality from adverse impacts;
- manage and protect water catchments;
- develop principles, guidelines and procedures for the allocation of water resources;
- within the guidelines of the National Water Policy, to determine charges to be imposed for the use of water from any water resource;
- gather and maintain information on water resources and from time to time to publish forecasts, projections and information on water resources;
- liaise with the relevant stakeholders for regulation and management of water resources;
- advise the Minister concerning any matter in connection with water resources;
- assist the Minister in the coordination of hydrological and hydrogeological investigations;
- coordinate the preparation, implementation and amendment of a water action plan and to recommend the water action plan to the Minister;
- at the request of the Minister, advise any other Minister on issues of policy relevant to the investigation, use, control, protection, management or administration of water; or any other issue that may be referred to it;
- review the law relating to water and advise the Minister on any amendments that may be required for the improvement or better administration of that law;
- advise the responsible Minister, as the case may require, on any dispute between agencies involved in water management that may be referred to it; and
- undertake any other functions conferred upon it under this Act or referred to it by the Minister from time to time.

The NWRA may, with the consent of the Director of Public Prosecutions given under the Criminal Procedure and Evidence Code, undertake the prosecution of offences arising under the WRA 2013 or in connection with the performance of its functions. The Authority may, for the purpose of performing its functions under this Act, establish committees and delegate to any such committee such of its functions as it considers necessary.

The Groundwater Division of the Ministry of Water and Sanitation is responsible for groundwater management. The Water Supply Division is responsible for operating and maintaining boreholes. The

Shire River Basin Agency (SRBA), created under a World Bank project, is a supporting organisation as a pilot Catchment Management Board under the NWRA, and ultimately, the aim is that the NWRA will oversee river basin/catchment management authorities or boards across the country, based on the major river basins (Water Resource Areas), ultimately devolved to local minor river basins (WRUs).

The 2008 National Sanitation Policy (NSP, 2008) outlines a broad framework enhance and support sanitation coverage in Malawi through formulation of sanitation strategies, plans and programs for improving the quality of life of the people of Malawi and the physical environment. The primary focus of the policy is safe disposal of excreta away from the dwelling units and work places, however it does not adequately address the potential risks to groundwater and is currently awaiting revision.

The Malawi National Water Policy (NWP), (2005) is in revision. It aims to provide guidance to manage water resources including protection groundwater by preventing pollution and overuse. The government's policy goal is to provide clean potable water to all people, reduce the incidence of water-borne diseases, and reduce the impact on women. It has general principles, objectives and strategies on water resources development, pollution and water supply including the roles of stakeholders in Integrated Water Resources Management (IWRM) and likewise of cross cutting issues. The WRA 2013 set out 17 WRAs and 78 WRUs as the geographical boundaries for IWRM. However, these are based on Surface Water catchments and groundwater recharge and discharge catchments have not yet been adequately evaluated or mapped.

Public access to hydrogeological data held by the state is promoted and facilitated through a guiding principle in the NWP 2005 that states: ‘Water regulation shall be based on reliable continuous data collection, management, and analysis to ensure accurate assessment of water resources and dissemination of information for effective planning of water resources development’. The policy advocates a strategy on establishment of a computerized networked database under Water Resources Management and Development for which the Ministry shall be responsible to manage and disseminate water resources and sanitation information.

The 2005 policy includes additional environmental principles needed to protect and sustain groundwater, including: the precautionary principle (including polluter-pays principle), the principle of subsidiarity, the principle of gender equity and social inclusion. The policy promotes mainstreaming of gender. Water pollution control for environmental sustainability advocates for EIAs (now within the EMA 2017) for projects. Principle 3.4.10 says “Water demand management approaches shall be adopted in all cases of water resources development and management, and water allocations shall consider ecosystem integrity and bio-diversity including aquatic and estuarine life”. Intergenerational equity is however not covered in the current policy.

Other key policy issues that are included in the policy include;

- For rural areas, technologies shall conform to the Village Level Operation and Maintenance (VLOM) concept;
- Water resources management shall be based on decentralization and local participation so that the unit of water resources management shall be the WRU catchment;
- Promotion of demand responsive/driven, beneficiary participation and empowerment;
- Creation of legal framework to guide implementation of the water policy; and
- Registration of all water facilities

Trans-boundary Groundwater Management

Most of the groundwater bodies in Malawi are Trans-boundary (**Figure 31a**) as described by IGRAC. To exemplify the need to review groundwater management within an international trans-boundary context, a case study (showing stable isotope results) is provided for a section of the Ruo Transboundary Aquifer System shared between Malawi and Mozambique identified as potentially problematic in terms of water quality and quantity (Fraser et al., 2020b).

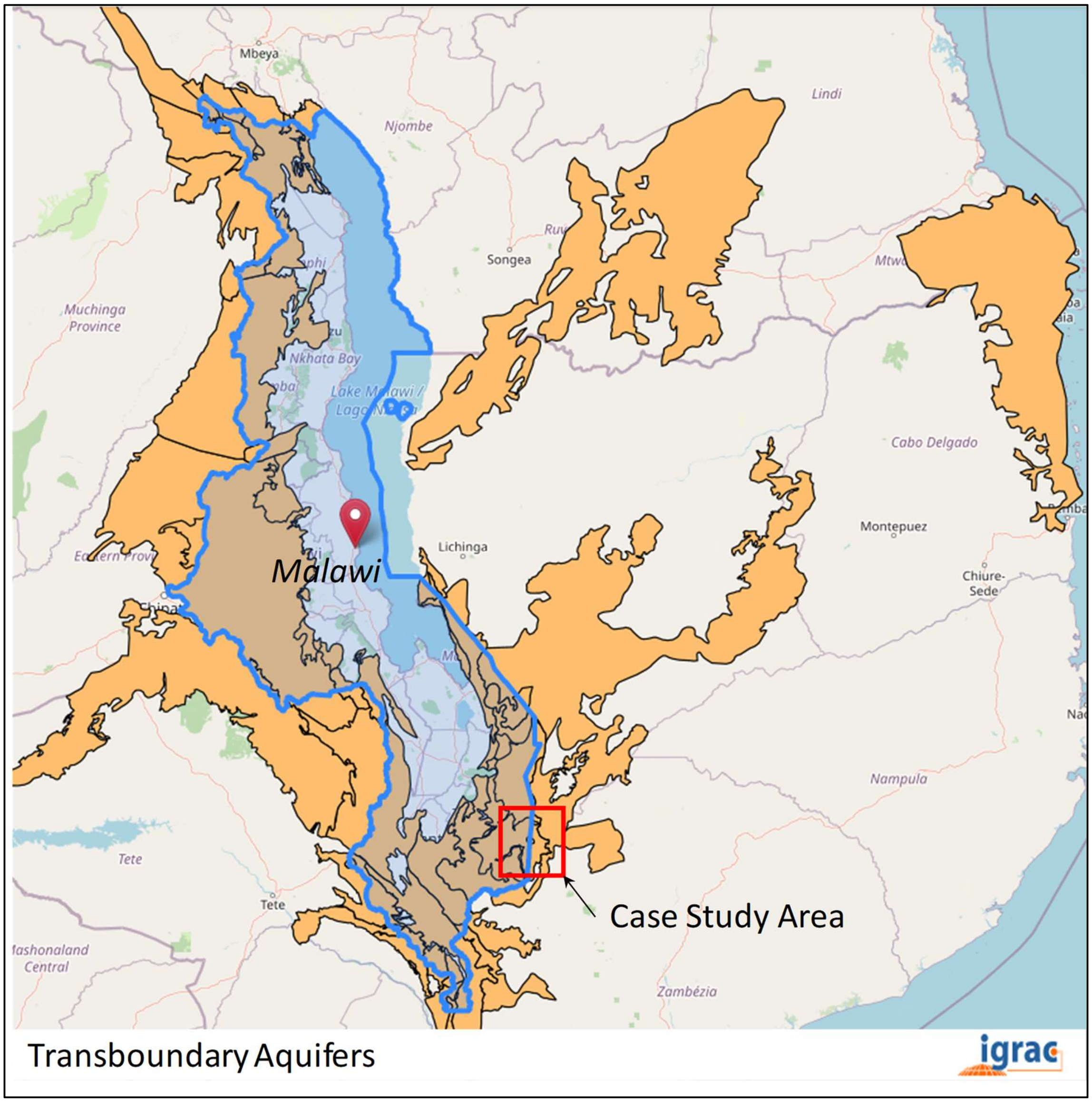


Figure 31a. Map of Transboundary Aquifers of Malawi. [After IGRAC 2021]

The Mulanje Massif, a mountainous area within Malawi to the north of the study area reaches an elevation of 3,002 meters is a granite igneous intrusion; and the valley plains and savannah leading away from the Mulanje Massif that are between 500 and 800 meters above sea level (**Figure 31**). The geology of the field area is dominated by Precambrian crystalline basement rocks are formed of gneiss and granulite. The basement complex is intruded by dykes and other igneous lithologies. Lying on top of the basement lithologies, colluvium dominates with superficial deposits of residual soils that are thin but quite extensive.

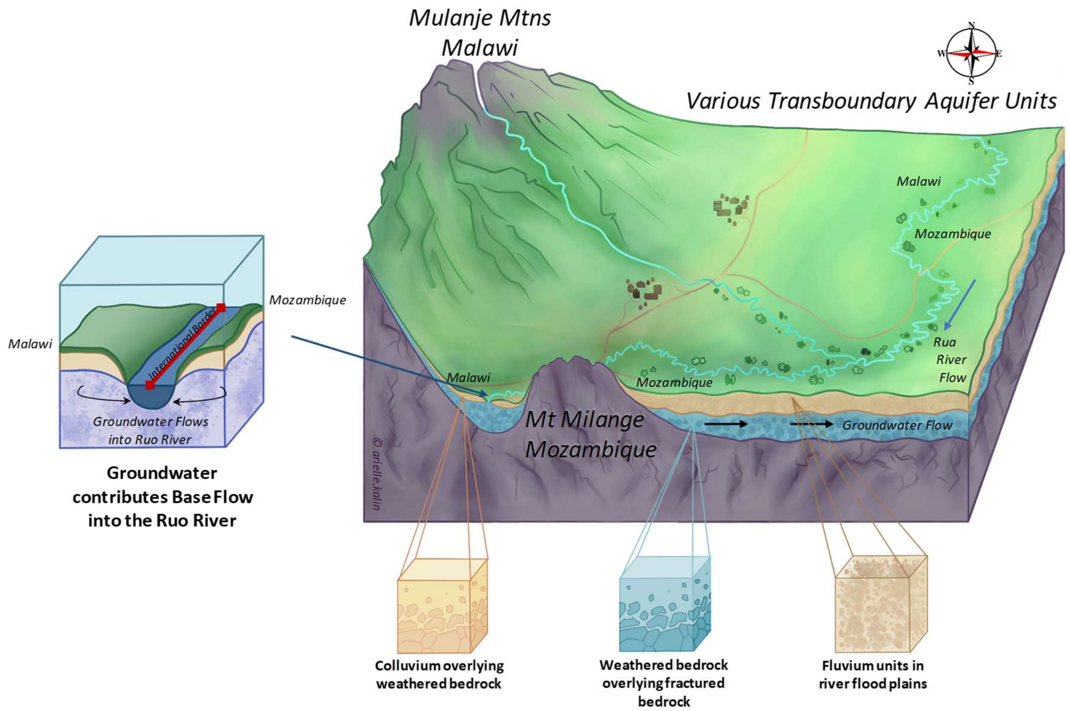


Figure 31b. Conceptual Model of the localised transboundary groundwater and surface water in WRA 14 (Mulanje / Malange) between Malawi and Mozambique.

The Ruo River forms the international border between Malawi and Mozambique (**Figure 31**). The river is the biggest tributary to the larger Shire River and forms part of the Shire River Basin. The Shire River Basin is part of the larger Zambezi River Basin. The Shire River catchment is 18,000 km^2 in area and its average outflow is 395 m^3 s^{-1}. The Ruo drains a catchment area of nearly 5,200km^2 including most of the watersheds of the Mulanje Massif and the Eastern slopes of the Shire Highlands south of Limbe, it enters the Shire from the East at Chiromo. On the Mulanje Massif the annual rainfall reaches up to 3.3 meters, and heavy rain on the mountain produces sudden runoff in the rivers that drain the mountains, which in turn play a major part in the flooding in the Lower Shire.

Much of the drinking water in this area is supplied by boreholes and hand-dug wells (Kalin et al. 2019). Two main aquifers exist from which groundwater is supplied: a weathered basement overlying fractured basement aquifer, and an unconsolidated colluvium aquifer overlying weathered basement (**Figure 32**). The lower unit is the weathered basement aquifer that stores and most likely transmits the transboundary movement of groundwater through secondary saprolitic porosity, formed by the hydrolysis of bedrock material by infiltration rainfall which causes mineral leaching, breaking down bedrock in a process known as saporilization (Fraser et al., 2020a). This aquifer unit has low borehole yields, a transmissivity of between 5-35 m^2/day and hydraulic conductivity of 0.5 - 1.5 m/d.

Groundwater is inferred to be flowing from Mozambique into Malawi in the northern extent, and from Malawi to Mozambique in the southern extent. The overlying superficial unconsolidated sedimentary aquifer unit (composed of mainly of colluvium and fluvial deposits) are likely hydraulically connected with the weathered and fractured basement. The superficial aquifer is highly productive, with a transmissivity of 50-300 m^2/day and hydraulic conductivity of 1-10m/d (Fraser et al., 2018). Within the field area, these aquifers cross the international border between Malawi and Mozambique.

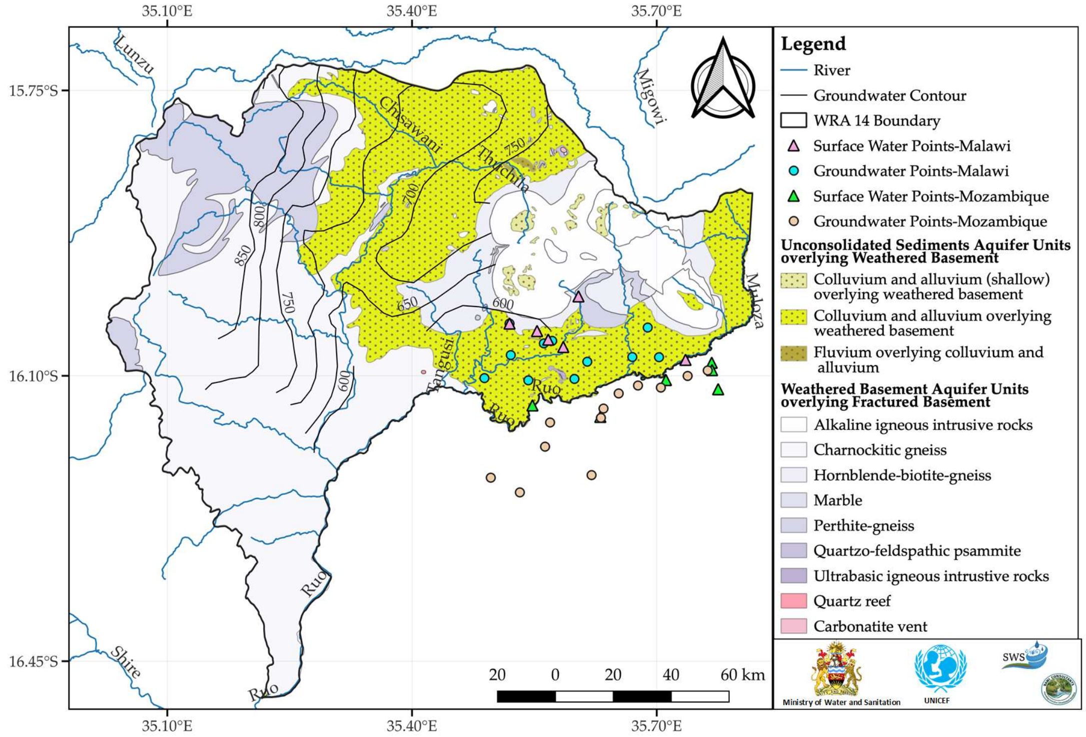


Figure 32. Hydrogeology Map WRA 14 and location of sample points for isotope measurements [water level contour 50m]

Recharge to the aquifers within the region is reported to occur primarily from direct rainfall infiltration and, where the aquifers are in hydraulic contact with rivers or lake water, by losses from surface water. However, the Base Flow Index, proxy for groundwater flow to rivers, in the study area show a BFI of 0.46 0.47 and 0.49 for the annual average, wet season and dry season respectively. These results suggest ca. 50% of surface water flow originates as groundwater discharge to the Ruo River. With this connection, the application of isotope and geochemical analysis can be used to confirm the conceptual understanding of transboundary interactions in the geologically complex setting.

Samples were collected by Fraser (2020) in Malawi and Mozambique (**Figure 32**.) and isotope results (**Figure 33**) showed the isotope results strongly overlap in distribution, confirming an overlap of transboundary groundwater source flow between Malawi and Mozambique. Flow in the Ruo, overlaps with the groundwater isotope results supporting the concept that groundwater maintains base flow in the Ruo River from transboundary groundwater (note: rainfall from high elevations of Mulanje are isotopically lighter in **Figure 3**, and do not impact the isotopes of the Ruo River in the study area. These transboundary interactions need to be taken into consideration within an on-going management strategy is it is highly likely both surface water and groundwater are transboundary.

For this transboundary aquifer, international (government to government) cooperation and management is generally required. This is usually done through an international transboundary agreement or an international institutional governance mechanism. International agreements over shared groundwater, however, are still in their infancy and are often difficult and time-consuming to develop. Furthermore, the legal mechanisms to facilitate these agreements are limited. As there is already evidence of local scale transboundary cooperation in within the field area, a case could be made to substitute a national level agreement for district-level management. The Malawi District of Mulanje, situated on the south-East border between Malawi and Mozambique is party to semi-regular meetings with the neighbouring Mozambique District, Milange. Representatives from the two districts meet and discuss shared issues such as trade, border control and management of their shared river, the Ruo, that runs along the border between the two districts (and forms the national boundary between Malawi and Mozambique). A strong case can be made for the addition of transboundary groundwater to be added to this working group's mandate. An informal local agreement over the use and management of transboundary aquifers in Malawi might include clauses for agreed monitoring strategies, regular exchange of data, joint monitoring of boreholes and rivers, the inclusion of local stakeholders such as communities and local businesses. It could also meet during times of flooding and drought to discuss mitigation and adaption strategies for water security.

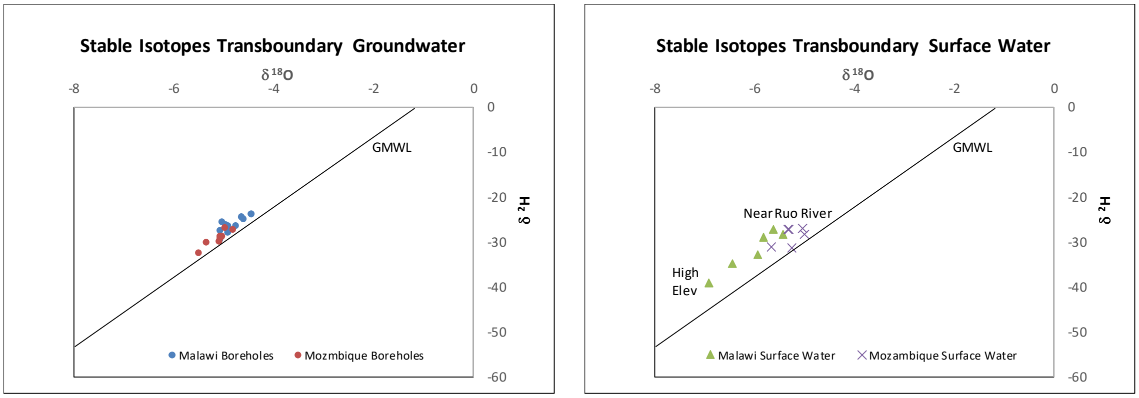


Figure 33 Results of $\delta^{18}O$ and $\delta^{2}H$ Isotopes of transboundary groundwater (left) and surface water (right) plotted on the global meteoric water line, most samples have the same stable isotope values and therefore are likely the same groundwater and surface water source with exception of precipitation derived at higher elevations.

Conceptual use of the Hydrogeology and Water Quality Atlas Data: Case Study

Topography and Drainage of Case Study Area

To facilitate the interpretation of hydrogeological properties using the data in this updated version of the Malawi Hydrogeology and Groundwater Quality Atlas, a case study area at the boundary between WRU 4B and WRU 4C was chosen. The case study is located on the Eastern edge of the Kasungu-Lilongwe Plain; a 6,000 Km^2 elevated plateau west of the Malawi Rift valley, dominated by Lower Palaeozoic–Precambrian basement rock and colluvium with elevations varying from 979 – 1,760 m above sea-level (masl) (**Figure 34**). Topography is flat undulating scrubland with Nkhoma and Chilenje hills forming local topographical highs in the North East (**Figure 35**). Drainage in the area generally occurs as seasonal (wet season) overland flows within ephemeral streams such as the Machete River northwest from the Nkhoma and Chilenje hills towards the Lilongwe River, and South East towards the Linthipe River (**Figure 35**). The area lies on a small ridge between the surface water catchments for the Lilongwe and Linthipe Rivers and the Nkhoma and Chilenje Hills represent the divide between those catchments. This area also acts as a groundwater divide between the Linthipe and Lilongwe sub catchments.

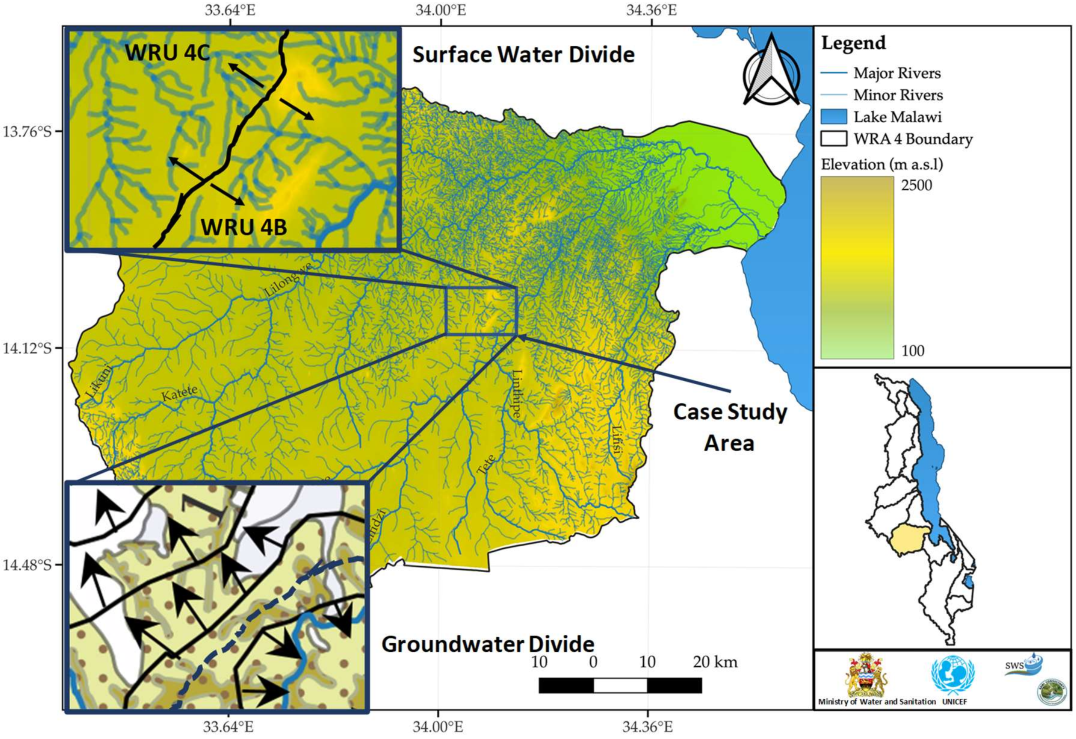


Figure 34. Study Area topography and drainage showing location of study area; inset top left showing surface water divide in study area; inset bottom left showing groundwater divide in study area.

Climate

Regional climate is sub-tropical/semi-arid with a distinct wet season (November–April) and dry season (May–October) (Banda et al., 2019). Local weather is characterised by mild winters (average temperature range: 10 - 22 °C) and hot summers (average temperature range: 19 - 29 °C). Most of the annual rainfall occurs during the summer months; monthly rainfall at the peak of the wet season (January) can reach an average of 222 mm, falling to <1 mm at the dry season peak (August). Mean annual precipitation averages between 922 and 930 mm (**Table 12** this Atlas).

Table 12. Measured and GIS modelled average annual precipitation WRU 4B and 4C (study area), data used in the calculation of groundwater volume and annual recharge volume in each WRU.

WRA	WRU	Station Names	Mean Rainfall-Station Data	Mean Rainfall-Interpolated Data (IDW)
4	B	Dedza	922	940
	C	Nathenje	930	832

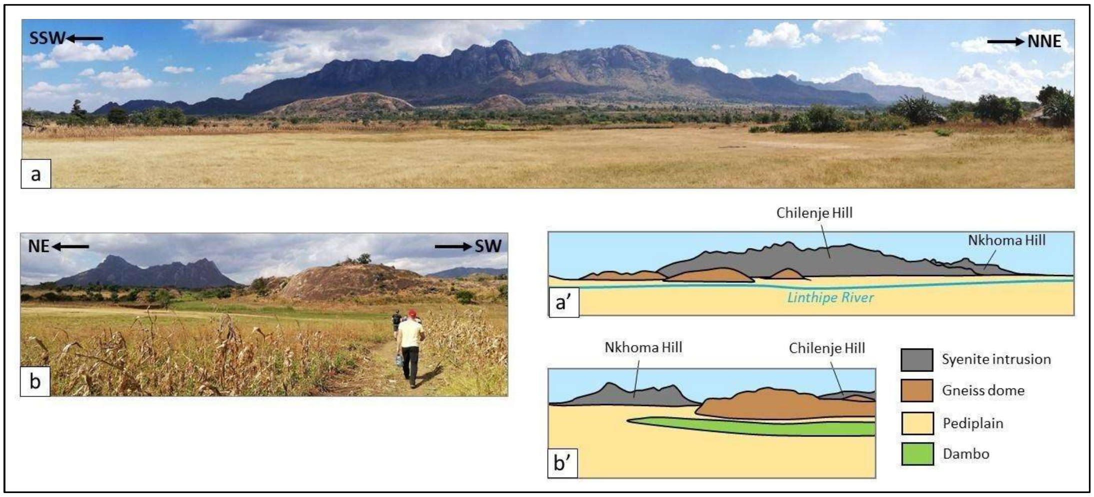


Figure 35. Topographical photographs of Nkhoma and Chilenje hills in the case study areas (after Leborgne, 2021).

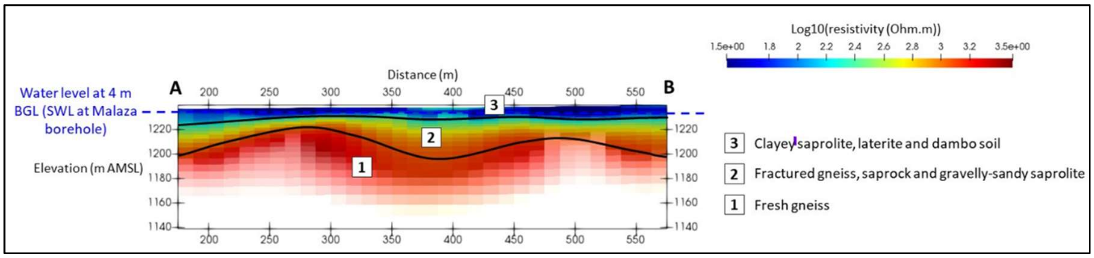
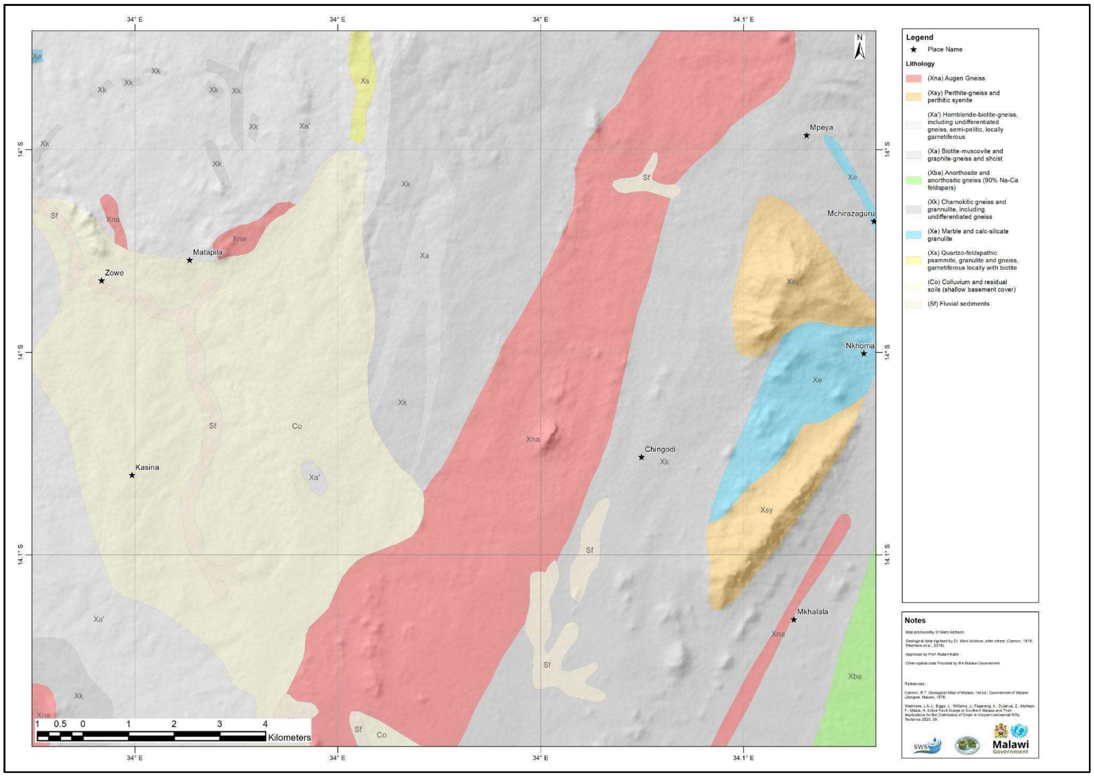


Figure 36. Geophysics of upper 50 meters of subsurface in the study area (after Leborgne, 2021)

Geology

Geophysics was used to evaluate the near-surface geology (**Figure 36**). Lithology in the case study area is dominated by a mix of basement (meta-igneous and meta-sedimentary) rocks: augen gneiss (meta-granite), perthitic syenites, charnockitic gneiss and granulite, hornblende-biotite gneiss, and calc-silicate marble (**Figure 37**). Gneissic foliations and lineation all strike southwest-northeast and dip 40–44° northwest. Hornblende-biotite gneiss occurs as a plunging syncline within charnockitic gneiss and granulite in the northwest. Nkhoma and Chilenje hills in the East are perthitic syenites which have been intruded into the host basement causing isolated uplift of marbles and locally steep topography. Small, isolated dambo wetlands composed of fluvial sediments occur in the south and west. The western section contains colluvium deposits which form part of the Eastern edge of the Kasungu-Lilongwe Plain: a shallow sedimentary basin not connected to the rift valley and drained by the Lilongwe and Linthipe Rivers (Addison et al., 2019; Thatcher, 1969).

The area is situated on a topographical plateau some distance from the main rift valley. No structural features (faults; jointing; dykes/sills) occur in the area, the nearest large fracture is 10 Km northeast, and the nearest rift fault is 30 Km in the same direction. It is inferred that rift valley processes may exert minimal influence in the case study area. Structural separation from the rift valley results in no hot spring activity within 70 Km (after Addison et al., 2020b). The main structural features present are northeast-southwest trending regional basement folding and paleo-syenitic intrusions at Nkhoma and Chilenje Hills (**Figure 37**).



Map producedby Dr.Marc Addison.

Geological data digitised by Dr. Marc Addison, after others (Cannon, 1978; Wedmore et al., 2019).

Approved by Prof. Robert Kalin

Other spatial data Provided by the Malawi Government

References:

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 37. Surface geology at the case study area showing areas where Fluoride containing minerals / geology are prevalent (the pink areas of augen gneiss rocks).

Hydrogeology

Groundwater data from 16 water points (8 boreholes, 4 natural springs and 4 hand dug shallow wells) together with 1987 recon data were used to conceptualise the water table (**Figure 33, Figure 34**). Nkhoma and Chilenje Hills represent a groundwater flow divide, separating aquifers on either side. Primary groundwater recharge occurs from streams flowing onto alluvial fans at the base of the hills, or as direct infiltration from rainfall during the wet season, either in stream beds, on alluvial fans, or where there is no confining laterite later overlying the weathered basement aquifer units. Shallow natural discharge occurs at ephemeral streams in the northwest and South East (**Figure 38, Figure 39)**. Temporal changes in water table elevation (limited by boreholes going dry) suggest seasonal swings may be large at up to 8 m and likely reflect low aquifer storage. Geophysical data (Leborgne, 2019) show that regolith aquifers (weathered basement) in the ca area ese study area exhibit uneven thickness, ranging from 0 – 60 m depth and are often semi-isolated due to uneven bedrock surfaces (caused by folding). Bedrock often breaches the surface as linear gneiss mounds which strike southwest-northeast, perpendicular to local groundwater flow (assumed from consistent decrease in groundwater elevation South East – North West from Chilenje Hill) (after Addison et al., 2019). Pumping test data from five sites within the area show hydraulic conductivity (K) is variable but low in those aquifers (K = 0.03–0.2 m/day) (Storey, 2019). A cross-sectional aquifer profile was developed, based on available geophysical and local groundwater data, and is presented in **Figure 39**.

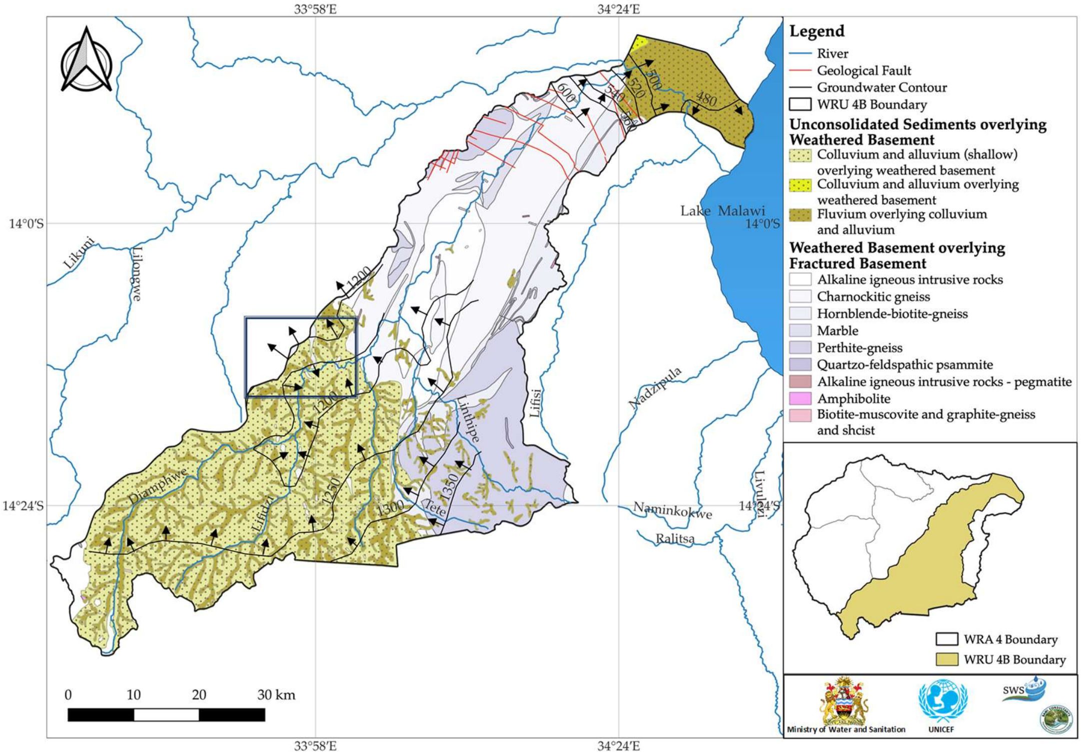


Figure 38 Aquifer units in WRU 4b showing the case study area with water table and groundwater flow directions [water level contour interval 50m]

Main Aquifer Types

Aquifers in Malawi were historically represented by a single aquifer type at a given location. A more detailed categorisation of aquifer types in 3D was developed for this atlas, designed to accurately reflect vertical complexity within the aquifers present. Of the three aquifer types described for Malawi, two are present in the case study area (**Figure 38, Figure 39**):

- Unconsolidated sediments overlying weathered basement.
- Weathered basement overlying fractured basement.

Unconsolidated Sediment Aquifer overlying Weathered Basement

Unconsolidated sediments occur overlying weathered basement aquifers in the case study area and often produce high yields where present. They usually occupy low-lying, flat areas and represent accumulations of weathered material from nearby hills and gneiss mounds, fluvial material transported by ephemeral streams after wet season rainfall events (or flooding), or alluvial fans at the base of the Nkhoma and Chilenje hills. The latter are often very transmissive and constitute a primary recharge source for underlying aquifers. Unconsolidated sediments are present throughout much of the case study area, becoming increasingly dominant toward the west. This is due to both a surface water divide and a groundwater divide at the south Eastern edge of the Lilongwe River basin - sediments are transported northwest from this basin edge (high elevation) location toward the Basin centre where sediment accumulations are thickest (outside the study area). Unconsolidated sediments are an important aquifer due to high hydraulic conductivity values and storage potential, compared to other aquifer types. One borehole in the southwest screened in unconsolidated colluvium displays a hydraulic conductivity an order of magnitude higher than other boreholes screened in weathered or fractured basement aquifers.

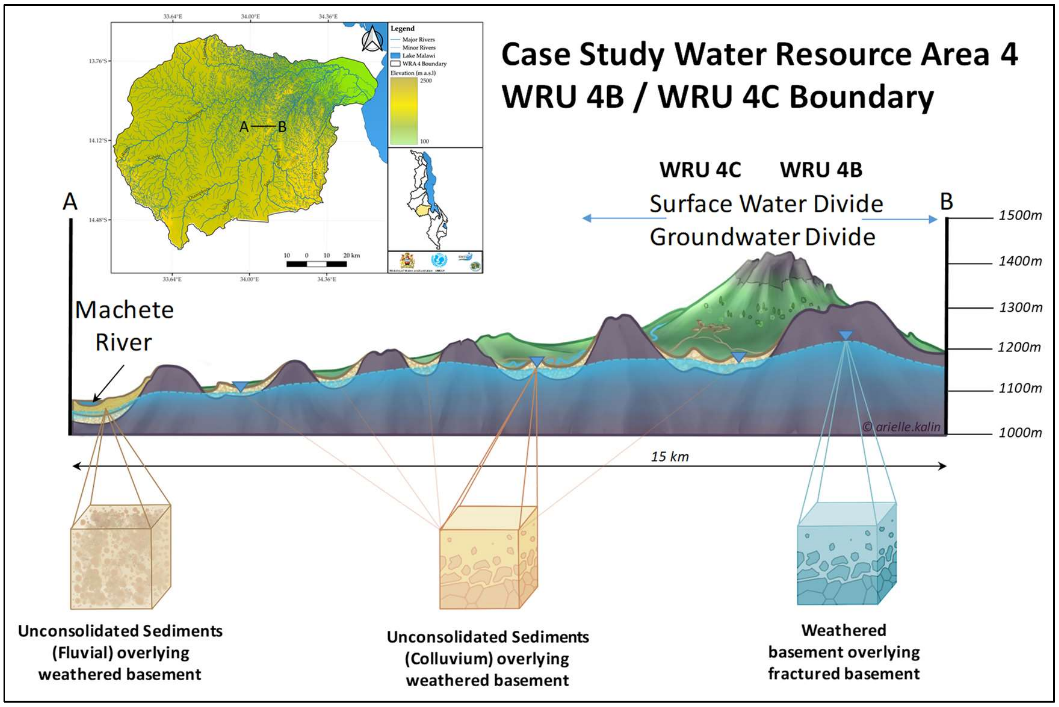
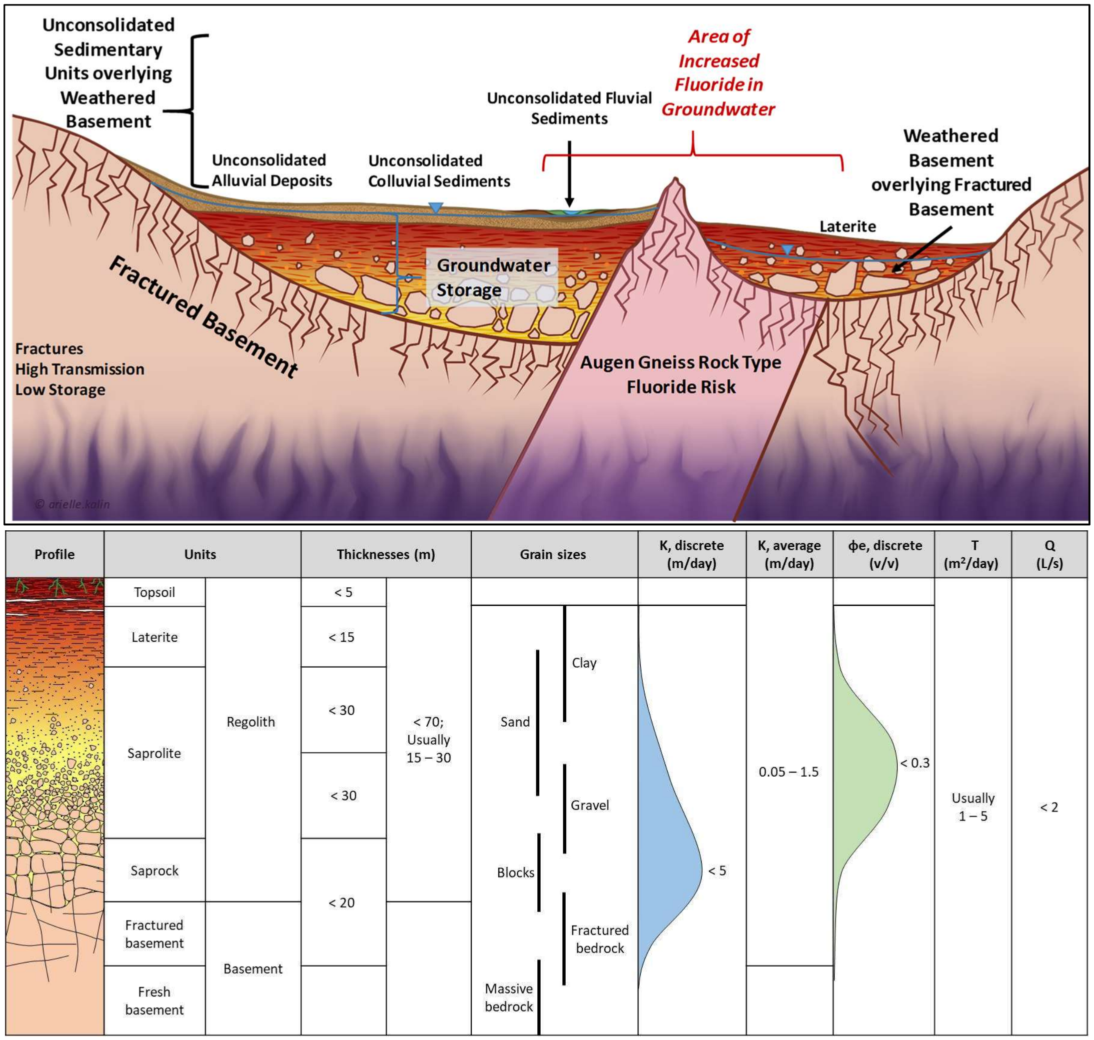


Figure 39 Cross-sectional aquifer profile for case study area.

Weathered Basement Aquifer overlying Fractured Basement

Weathered basement aquifers represent in-situ weathering of basement rock near the surface and range in thickness from 5 m to 30 m. The aquifer profile (**Figure 40**) illustrates key hydrogeological controls within the 'Weathered basement Units overlying fractured basement' aquifer type. A regolith aquifer containing saprock and saprolite layers of varying thickness is the main storage unit. Localised fracturing in underlying basement rock increases permeability and limited storage where present, however, the lateral extent of permeability remains unknown. Uneven bedrock surfaces have created isolated sub-aquifer units which may become increasingly isolated during the dry season when groundwater levels are low. The aquifers exist under semi-confined conditions due to discontinuous clay layers at the base of the laterite layer. Boreholes drilled where there is clay often have resting water levels above the original water strike (Chilton and Smith-Carington, 1984).



Profile	Units		Thicknesses (m)		Grain sizes	K, discrete (m/day)	K, average (m/day)	ϕe, discrete (v/v)	T (m²/day)	Q (L/s)
	Topsoil	Regolith	< 5	< 70; Usually 15 – 30			0.05 – 1.5		Usually 1 – 5	< 2
	Laterite		< 15		Clay					
	Saprolite		< 30 < 30		Sand Gravel			< 0.3		
	Saprock		< 20		Blocks	< 5				
	Fractured basement	Basement			Fractured bedrock					
	Fresh basement				Massive bedrock					

Figure 40 (Top) Aquifer profile for weathered basement overlying fractured basement aquifer type. (Bottom) Breakdown of constituent layers within aquifer profile showing main aquifer properties for each layer present (after Leborgne, 2021)).

Recharge occurs at the base of the Nkhoma and Chilenje Hills (**Figure 39)**, at alluvial fans, places where unaltered and fractured gneiss is exposed as gneiss mounds, and at areas where topsoil/laterite is absent exposing saprolite (Leborgne, 2019). Higher groundwater levels may facilitate increased sub-aquifer connectivity (flushing) during the wet season, down-hydraulic-gradient from the Nkhoma and Chilenje Hills in North West and South East directions, following decreasing altitude (Addison et al., 2019), however, influence to the groundwater system from this process is assumed to be minimal based on low hydraulic conductivities (Storey, 2019) and perpendicular flow barriers.

Hydrostratigraphic Units

Each aquifer type consists of individual hydrostratigraphic units (**Figure 41**). A hydrostratigraphic unit was defined as a geological unit which exhibits distinctly different hydrogeological properties (hydraulic conductivity; porosity; mineralogical composition; geochemistry) to a neighbouring unit, and were named accordingly. Two hydrostratigraphic units within the unconsolidated sediments aquifer group occur in the study area: ‘Colluvium and alluvium overlying weathered basement, and ‘Fluvium overlying colluvium and alluvium’.

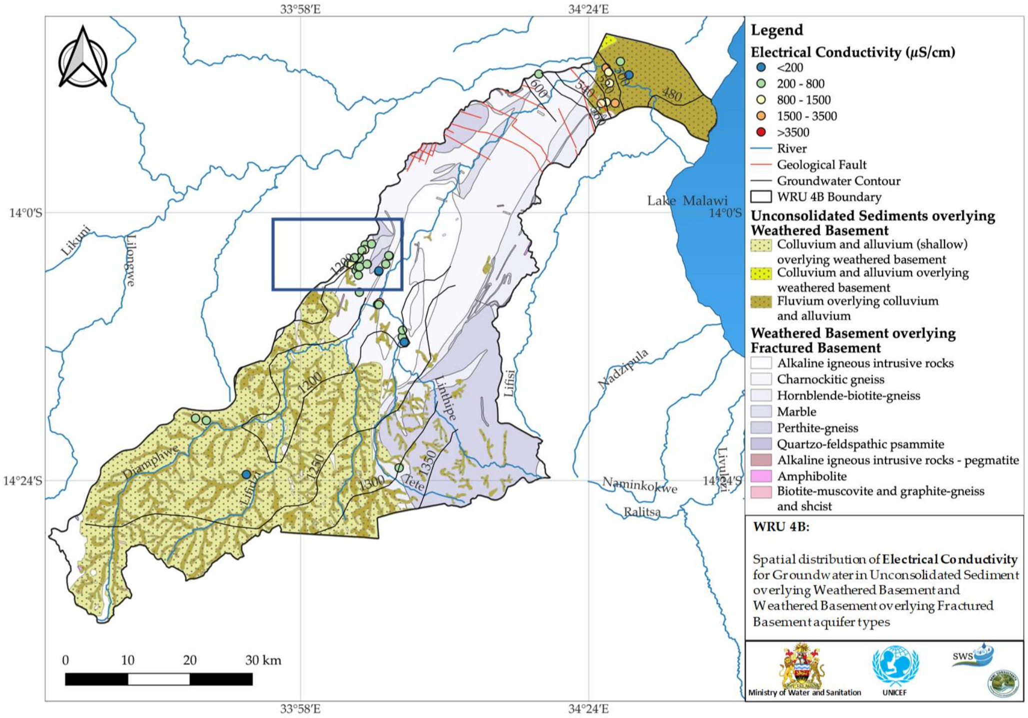


Figure 41a. Hydrostratigraphic units, water table, and electrical conductivity of groundwater in WRU 4B, with the boundary of the case study area. [water level contour interval 50m]

The colluvium and alluvium unit represents a relatively thin veneer of poorly-sorted sediments which accumulated in topographical lows. The fluvial unit represents more transmissive outwash sediments transported by ephemeral streams and occur as narrow units overlying the colluvium and alluvium unit, along stream beds. The weathered basement aquifer type contains seven individual hydrostratigraphic units in the study area, all of which belong to the Malawi Basement Complex - a diverse group of metamorphic gneisses, schists and meta-igneous rocks which have been extensively deformed during at least two deformation phases (Canon, 1970).

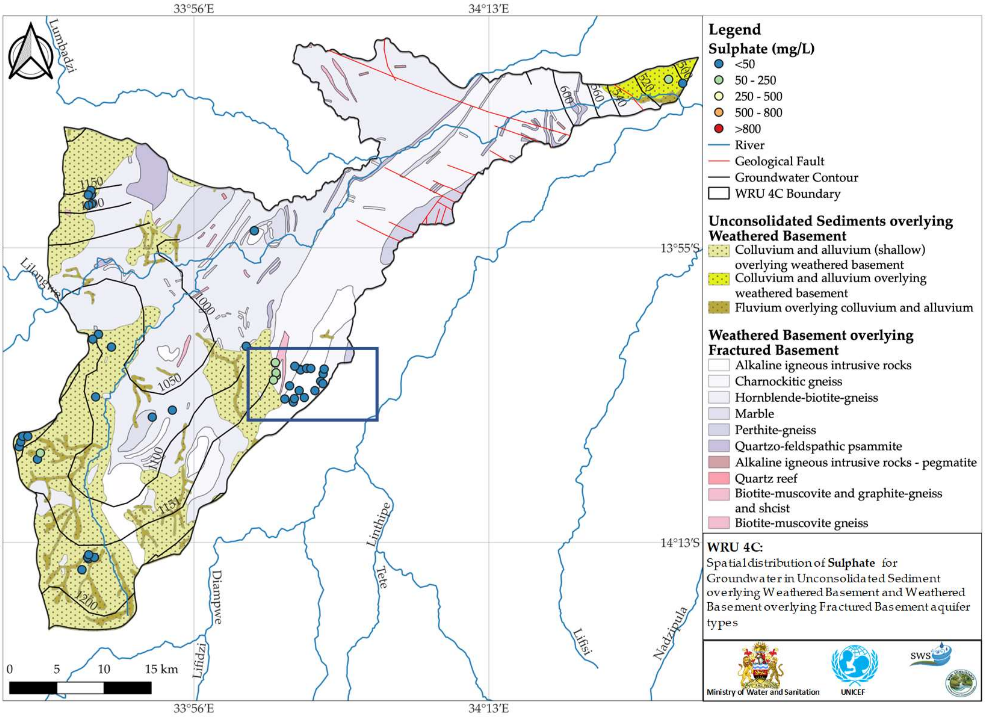


Figure 41b. Hydrostratigraphic units, water table, and electrical conductivity of groundwater in WRU 4C, with the boundary of the case study area. [water level contour interval 50m]

Groundwater Recharge in the Case Study Area

The volume of groundwater and the volume of annual renewable groundwater (recharge) was calculated for each Water Resource Unit in Malawi as part of this atlas. Using the results from WRU 4B and a study area of ca. 150 km^2, the volume of recharge in the case study area can be estimated (low to high) at between 1.4 MCM and 10.6 MCM per year. Local-scale IWRM requires groundwater abstraction volumes, estimated base flow discharge to wetlands and rivers, and irrigation/evapotranspiration for agricultural to set licensing limits on abstraction.

Table 13. Groundwater volumes WRU 4B and estimated renewable recharge.

Aquifer Type	Area of Aquifer Type (km^2)	Porosity Low Est.	Porosity High Est.	Sat Thickness Low Est (km)	Sat Thickness Low Est (km)	*MCM Groundwater High Est	*MCM Groundwater High Est	
Consolidated Sedimentary Rock	0.0	3%	15%	0.02	0.10	0.0	0.0	
Fluvial Units	632.3	10%	35%	0.02	0.10	1,264.6	22,130.8	
Lacustrine units	0.0	10%	35%	0.02	0.03	0.0	0.0	
Colluvial etc.	964.3	10%	30%	0.02	0.06	1,928.6	17,357.7	
W & F Basement	1,675.7	1%	10%	0.02	0.03	335.1	5,027.2	
**Blantyre requires 0.140 Million Cubic Meters of Water each day equivilant to 50 MCM per year*	Area of WRU (km^2)	4B	WRU	Recharge Rate Low Est. (mm)	Recharge Rate High Estimate (mm)	*3,528.4*	*44,515.7*	*Total Volume Groundwater*
	3,272.4	940	Average Rainfall in WRU	9.4	70.5	30.8	230.7	Renewable Groundwater Recharge Volume
The average recharge is thought to be in the range 1% to 7.5% of annual rainfall, (typically 8-60 mm per year) [Chilton]						115	193	Calculated Average Residence Time of Groundwater (years)
* Million Cubic Meters						Low Est	High Est	

Groundwater Abstraction in the Case Study Area

Public abstraction points for groundwater are abundant in the study area (**Table 14**) and it should be noted there are likely some unaudited private groundwater abstraction points. Of the 165 known operational groundwater abstraction points, 80.0% are improved sources. The dataset contains public water supplies that use groundwater and does not include non-standard unprotected household sources using rope pumps. 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 61.4% of groundwater abstraction supplies which are operation at design parameters, and the distribution of functional, partly functional, non-functional and abandoned groundwater abstraction points is relatively constant with depth of abstraction point (**Figure 42**). 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 8 (after Kalin et al 2019).

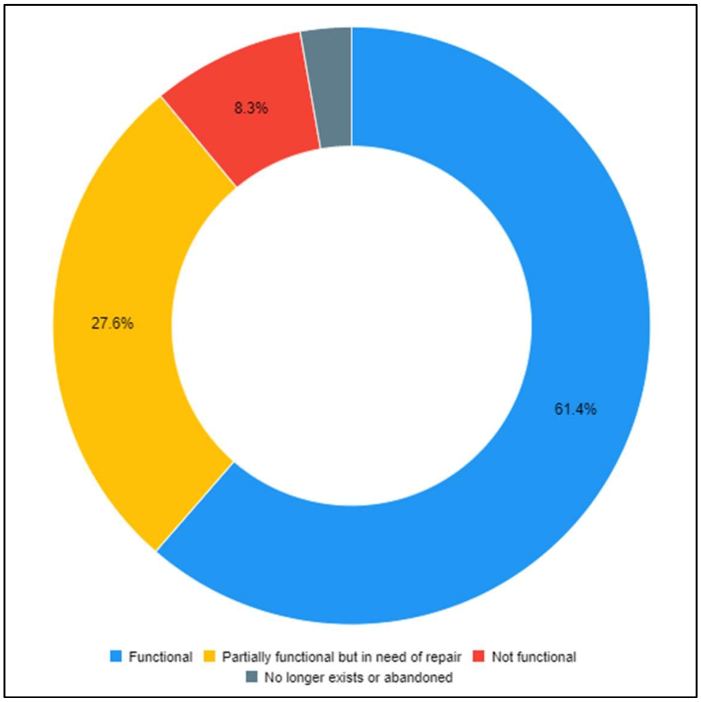


Figure 42. Functionality (as percentage operational at design specifications) of groundwater abstraction points in the study area [Data from the 2020 National Water Point Survey]

This data can be used to estimate the water resources impact of rural groundwater use given 250 Users per abstraction point x 40l / person / day x 165 groundwater abstraction points = 1.65megaliters per day, which is 0.6MCM per year. When compared to the calculated annual renewable recharge, groundwater abstraction using only hand pumps in the study area uses between 6% and 43% of the total groundwater recharge each year. Detailed information on groundwater abstraction by all sources is needed for IWRM, and must be required for licensing of any 'Solar' high yield abstraction.

Table 14. Number and Type of Groundwater Abstraction Sources in the 150km^2 area of the Case Study area [Data from the 2020 National Water Point Survey]

Type	Number of Groundwater Abstraction points
Borehole or tube well	109
Protected dug well	19
Protected spring	4
Unprotected dug well	33

Example Pumping Test and Borehole Yield Determination

The Chimkamda site (**Table 15**) is within the Hornblende Biotite Gneiss geology of the weathered basement overlying fractured basement aquifer in WRU 4B. At the site, the borehole was 100 metres from a large outcrop of basement rock and directly beside the borehole (5 metres) there is a smaller outcrop of basement rock. The testing of this borehole was chosen as it provided a clear hydrogeologic test of the weathered basement overlying fractured basement aquifer type. The site has a large section of soils exposed which provided a good understanding of the laterite layering above the aquifer unit The basement was extremely weathered (saprolitic) and fracturing was evident in the large basement outcrop. The main hydrogeological unit would be that of the weathered basement with a large saprolite layer supported by extensive fracturing allowing for movement of water to the weathered zones. Combined they account for the main storage of water, with the fractures likely less storage. The weathered basement outcrop bedside the borehole could suggest that the aquifer unit is near the surface and the aquifer is unconfined. The stream beside the borehole was extremely low flowing and any hydraulic connected to the aquifer system and any continual flow (not from recent rainfall) is likely a result of interflow of groundwater.

The Step Drawdown Test (SDT) as part of borehole forensic analysis of the aquifer properties and borehole construction (**Figure 43a**) was planned with 4 steps at 60 minutes each (**Table 16**), with the final step at 1l/s. From **Figure 43b** is can be observed that the first (0.25l/s) and second (0.5l/s) steps are relatively stable however the third (0.75l/s) and fourth (1l/s) steps are less stable with the final step drawing down 8.2 metres over 60 minutes.

Following the SDT, a constant rate pumping test (CRT) was undertaken using the critical pumping rate determined by the SDT. A Cooper-Jacob analysis produced a transmissivity of 2.85m^2/s, while the Neuman analysis using curve matching gave a transmissivity value of 2.15m^2/day. Recovery data was also interpreted following both the SDT and CRT. Using the Theis recovery on the CRT, a transmissivity of 7.13m^2/day was calculated. The recovery from the SDT obtained a T value of 3.56m^2/day. However, it was observed that the recovery drawdown data did not return to the original standing water level (original SWL), suggesting considerable aquifer depletion and low radial storage. This is typical of other results in this hydrogeologic unit where one finds reasonable high yields but poor storage, resulting in the water point only providing water when seasonal recharge is greatest. This case site shows the risk of 'solar pump installations' as seen in the study area where there was limited hydrogeologic testing that resulted in poor performance and stranded assets / abandoned infrastructure.

Borehole yield data from the Ministry of Water and Sanitation for the study area average less than 0.25 l/s with a few exceptions as high as 1 l/s. If it is assumed that groundwater is the main water supply, these community boreholes currently pump around 602,250 m^3 (0.6 MCM) of water per year (250 users per borehole, 40l/person/day, 365 days per year). This is between 6% and 43% of total local recharge per year (pro rata from **Table 13**). The implementation of 'solar pump' boreholes in a location such as this must be planned carefully so as to not deplete groundwater tables, forcing current hand pumps to go dry, and it is therefore strongly recommended that a local groundwater level monitoring site is established where any mechanical pump is installed.

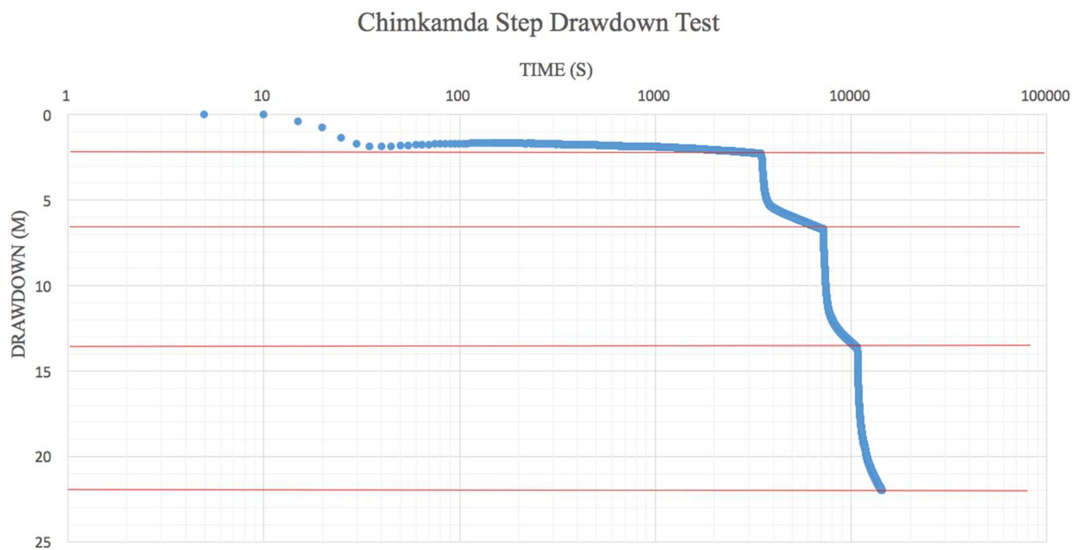
Table 15. Chimkamda Borehole Information

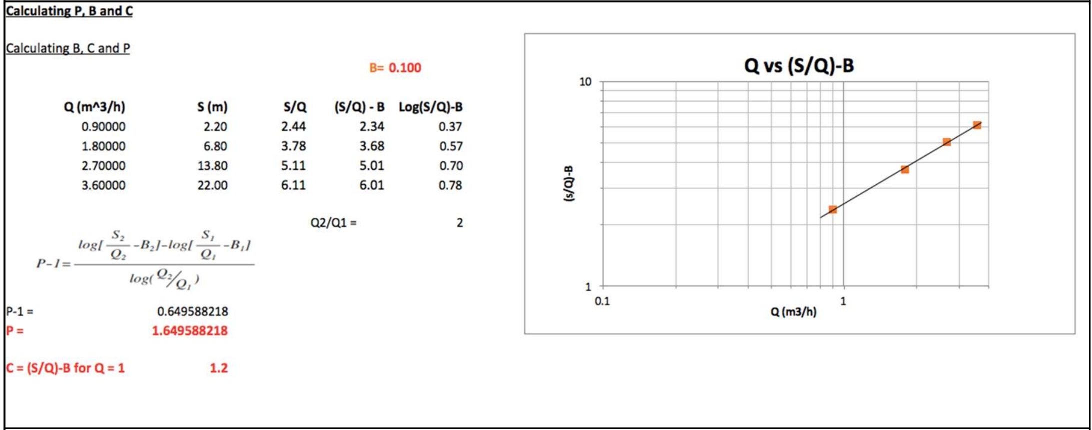
Site Name and mWater ID	Chimkamda - 19122593
GPS Location	-14.017027, 33.970902
Date of instillation	09/19/2002
Height to Pedestal (m)	0.54
Static water Level (m)	8.88
Camera Survey Depth (m)	66
First slotted casing depth observed (m)	58.1
Length of Slotted Casing observed(m)	6.3
Deviation Tool Depth (m)	62
Deviation Ratio	0.0175

Table 16. Step Drawdown flow rate and drawdown at each step:

Step	**Flow Rate (m^3/hr)**	**Drawdown (m)**
1	**0.9**	**2.2**
2	**1.8**	**6.8**
3	**2.7**	**13.8**
4	**3.6**	**22**

Figure 43a. Deploying the Envirotech EI-150 camera downhole as part of the borehole forensics analysis of Chimkamda Borehole





Calculating P, B and C

Calculating B, C and P

B= 0.100

Q (m^3/h)	S (m)	S/Q	(S/Q) - B	Log(S/Q)-B
0.90000	2.20	2.44	2.34	0.37
1.80000	6.80	3.78	3.68	0.57
2.70000	13.80	5.11	5.01	0.70
3.60000	22.00	6.11	6.01	0.78

Q2/Q1 = 2

$$P-1=\frac{log[\frac{S_2}{Q_2}-B_2]-log[\frac{S_1}{Q_1}-B_1]}{log(Q_2/Q_1)}$$

P-1 = 0.649588218

P = 1.649588218

C = (S/Q)-B for Q = 1 1.2

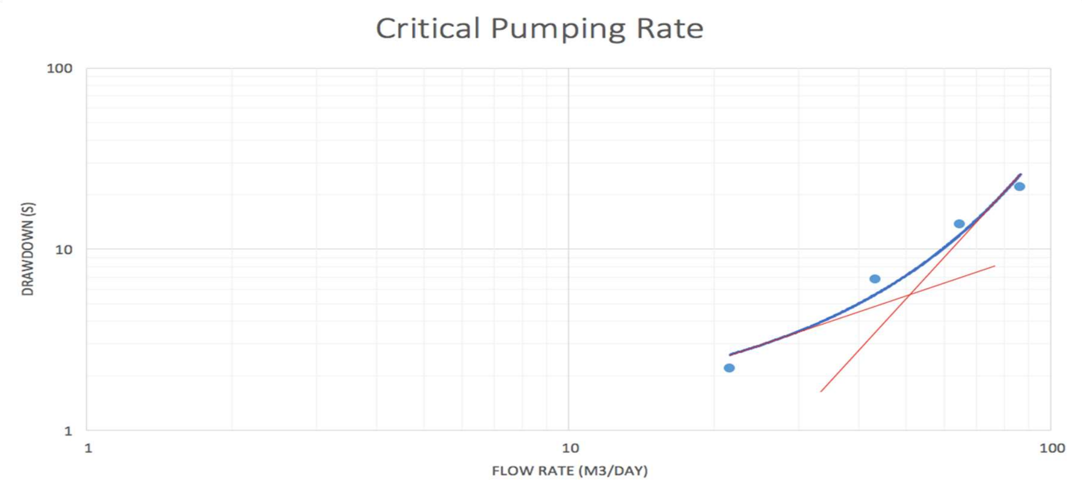


Figure 43b. Calculation of P, B and C coefficients (note: calculated in m^3/hr) and results of Step Drawdown test indicates the critical Pumping rate (maximum sustainable rate) = 52 m^3/day or 0.6 l/s

Recovering Pumping Efficiency for Iron Fouled Boreholes

The study area also had reported incidents of high iron content water, and therefore a Borehole Forensic study (**Figure 43a**) (after Kalin 2019) was carried out on a range groundwater abstraction points in the study area. Poor well design, water quality, and siltation can affect the long-term efficiency of pumped boreholes across Malawi (data provided in each WRA annex show iron is widely found in groundwater across Malawi). The Malawi Bureau of Standards (2005) maximum allowable iron content of drinking water is 3 ppm. Iron is common in groundwater in Malawi and likely poses no direct adverse health risks to humans, but rather manifests as other health risks for example, favouring surface water over the taste, smell, and appearance of iron-rich borehole water would increase the risk of waterborne illnesses which are more common in unprotected water points. These same criteria of water acceptance may ultimately lead to borehole abandonment.

Aqueous iron in waters of neutral pH is found in ferrous form, Fe^{2+}. Fe^{2+} is oxidised to Fe_2O_3 upon entering the aerobic waters of an actively pumped borehole (Stafford and Kalin 2019). This iron oxide precipitates on pump parts and borehole casing, reducing pumping efficiency. The occurrence of Fe^{2+} in groundwater is commonly associated with the biochemical reduction of iron oxyhydroxide, which is a weathering product of iron-bearing rocks and relies on the fermentation products of organic material and is a common constituent of many clays and soils. Beyond iron slimes limiting the functionality of a borehole, biofouling is also an indication of a downhole environment favourable to other bacteria such as E. coli, which can coexist with iron slimes. Of course, microbial production of nearly all concerning species is also increased in the presence of organic contaminants, such as decomposing plant polysaccharides or waste originating from pit latrines.

Chemical treatment of boreholes in Malawi has typically been limited to chlorine-based sterilisation, commonly in the form of sodium hypochlorite, as a defence against waterborne pathogens such as e-coli and cholera. While chlorine is an effective biocide, it does little to break down masses of material or remove hardened iron precipitates. For this, acids and acid blends are commonly used, most often in combination with physical treatment such as brushing, surging or jetting. The Chimkamda borehole had considerable iron biofouling and a Biological Activity Reduction Test (BART) kit identified the presence and approximate Colony Forming Units (CFU) per mL of iron-related bacteria. These tests yield positive results from the presence of both iron-oxidizing and reducing bacteria (collectively referred to as iron-related bacteria), including sheathed iron bacteria, Gallionella, pseudomonads and enteric bacteria.

The *Chimkanda* borehole iron concentrations measured at 1.86 ppm. It yielded a BART result suggesting moderately aggressive iron-related bacteria. When dismantling the Afridev, the were coated in orange slime which was soft, slippery, and made it difficult to hold onto the weight of the rods. While worn, and likely from the original installation, the other Afridev parts appeared normal.

Iron precipitation on the rising main progressed and worsened with depth, going from clean to black to orange. The top six metres were clean 56 mm white rising main. The next six metres showed black scale that was less than one mm thick and evenly coated the rising main, which cleaned to reveal the same 56 mm white pipe. The final, deepest 5.5 m section of rising main was evenly coated in two to three mm orange slime. Error! Reference source not found. shows the slime which was texturally like a soft mud and had adhered to the pipe but could be easily wiped off. When cleaned, the same white 56 mm pipe was seen with no residual hardened material, though appeared to have lightly stained the pipe. However, once treated there was a 3 to 5% increase in borehole pumping efficiency (**Table 17**).

Figure 44. Examples of the contamination observed at Chimkanda borehole showing a deepening progression of black precipitate to orange iron - bacteria slime on the rising main.

Table 17. The pumping efficiency improved from 50.8% to 54.3% at 0.25 L/s, improved from 34.1% to 37.3% at 0.5 L/s, and improved from 22.3% to 28.4% at 0.75 L/s.

	Step	Q (L/s)	Q (m3/d)	s_w (m)	s_w/Q (d/m^2)	BQ	CQ^2	Efficiency
Pre- rehab	1	0.25	21.6	2.31	0.107	1.158	1.120	50.8%
	2	0.50	43.2	6.73	0.156	2.316	4.479	34.1%
	3	0.75	64.8	13.70	0.211	3.473	10.078	25.6%
	4	0.90	77.8	22.00	0.283	4.168	14.512	22.3%
Post-rehab	1	0.25	21.6	2.32	0.107	1.277	1.073	54.3%
	2	0.50	43.2	6.92	0.160	2.553	4.292	37.3%
	3	0.75	64.8	13.37	0.206	3.830	9.658	28.4%

This case study shows the importance of routine testing and rehabilitation of groundwater abstraction points. There is no detailed step draw down pumping test data held in the Ministry of Water and Sanitation database, therefore it is not possible to define a baseline efficiency of the current plethora of boreholes across Malawi. A 5% decline in the efficiency of water transmission from the aquifer to the borehole will increase pumping water depths, and for 'solar' or 'electric' submersible pumps, increase the electricity demands / costs and potentially reduce the functional life of the system. The lack of detailed raw pumping test data, monitoring data and well construction information is a significant limitation for investment planning and abstraction of groundwater under IWRM. There is a need to have a team of fully qualified hydrogeologist work with the Ministry of Water and Sanitation to collect, collate, review and interpret all existing records held by the Ministry, other parts of Government and by the wider stakeholder (Donor, NGO, CSO) community.

Groundwater Quality in the Case Study area

The case study area has reported high concentrations of Fluoride in groundwater, and provides detailed insights to geogenic water quality risks (Addison et al., 2020). Groundwater quality is representative of the wider area where fresh recharge at topographical highs becomes increasingly mineralised down hydraulic gradient towards discharge points in ephemeral stream beds, as was shown with TDS in the area – lowest TDS values were observed in unprotected springs at the base of the Chilenje and Nkhoma hills, becoming increasingly higher towards the northwest where the deepest sediments occur **(Figure 45, Figure 46**). All groundwater is considered fresh, the highest TDS value observed was only 536 mg/L (**Table 1**). The presence of basement rocks of alkaline igneous composition (**Figure 40 and 47**) creates an increased risk of groundwater fluoride contamination of water supplies in the area.

Table 18. Summary statistics of groundwater quality data from groundwater in the case study area.

Geochemical element	Mean	Median	Max.	Min.	Std. Dev.
pH	7.22	7.23	7.54	6.77	0.21
EC (µS/cm)	561.33	520.00	1067.00	147.60	255.91
TDS (mg/L)	281.35	261.00	536.00	74.90	128.28
F (mg/L)	1.58	1.41	3.75	0.29	0.94
Cl (mg/L)	14.91	8.12	89.26	1.08	18.36
NO_2 (mg/L)	0.05	0.03	0.77	0.03	0.12
Br (mg/L)	0.04	0.03	0.18	0.03	0.03
NO_3 (mg/L)	42.98	21.62	276.77	0.13	62.14
PO_4 (mg/L)	0.06	0.05	0.27	0.03	0.05
SO_4 (mg/L)	22.68	11.29	137.12	0.69	31.97
Ca (mg/L)	54.84	54.67	98.98	14.69	22.27
Mg (mg/L)	27.57	27.04	59.68	7.12	13.87
Na (mg/L)	21.79	23.60	44.06	6.53	9.83
K (mg/L)	1.33	0.96	4.38	0.10	1.03
Total Alkalinity $CaCO_3$ (mg/L)	222.26	234.68	403.34	56.78	90.80
Total Alkalinity HCO_3 (mg/L)	271.16	286.31	492.07	69.27	110.78

Piper plots (**Figure 45 Figure 46**) largely fall within a mixed-type domain with a linear trend in composition from Ca (and Mg) water to Na (and K) attributed to increased cation exchange of Ca in recent recharge groundwater with sodium from clay-based and alkaline igneous lithologies progressively encountered along flow lines to discharging streams. Anions exhibit a predominant HCO_3 type water with a trend to increased Cl content. Data confirm anticipations of recent recharge waters associated with the basement rock–colluvium–superficial deposits and the influence of acidic conditions from soil CO_2 and rock mineralogy that promote dissolution of Ca (and Mg) carbonates leading to the predominant Ca-HCO_3 water type. Evaporitic enrichment (including mixing with evaporated water) is probable and promotes increased sodium and chloride and occurrence of Ca-Na-HCO_3-Cl, Na-HCO_3-Cl, and Ca-HCO_3-Cl-type waters.

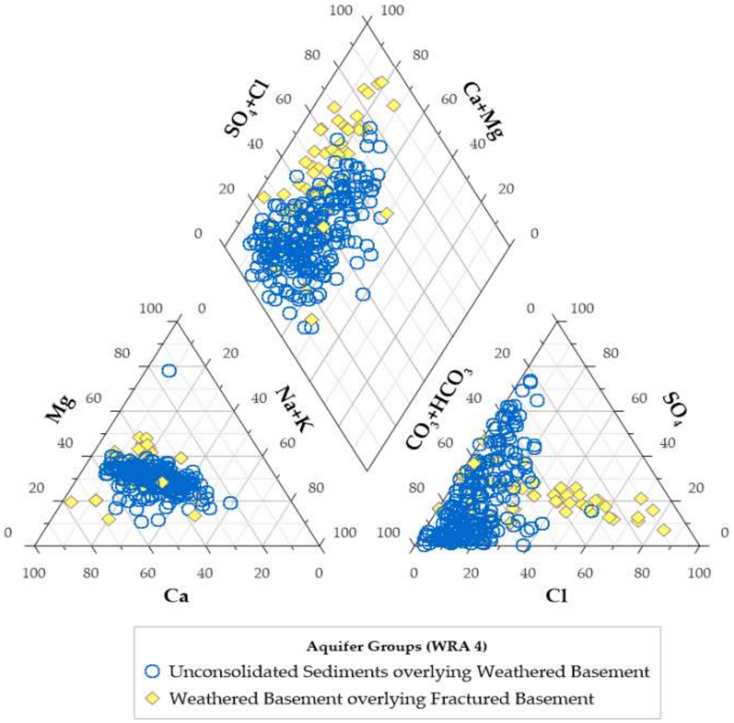


Figure 45. Water quality data for the wider WRA 4 which contains data for the case study area. Data were presented per aquifer group.

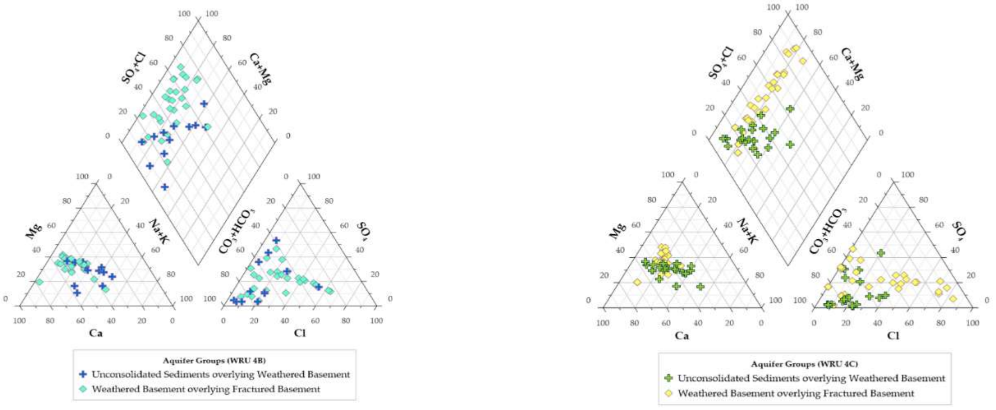


Figure 46. Water quality data for the wider WRU 4B (left) and the wider WRU 4C (right) both which contains data for the case study area.

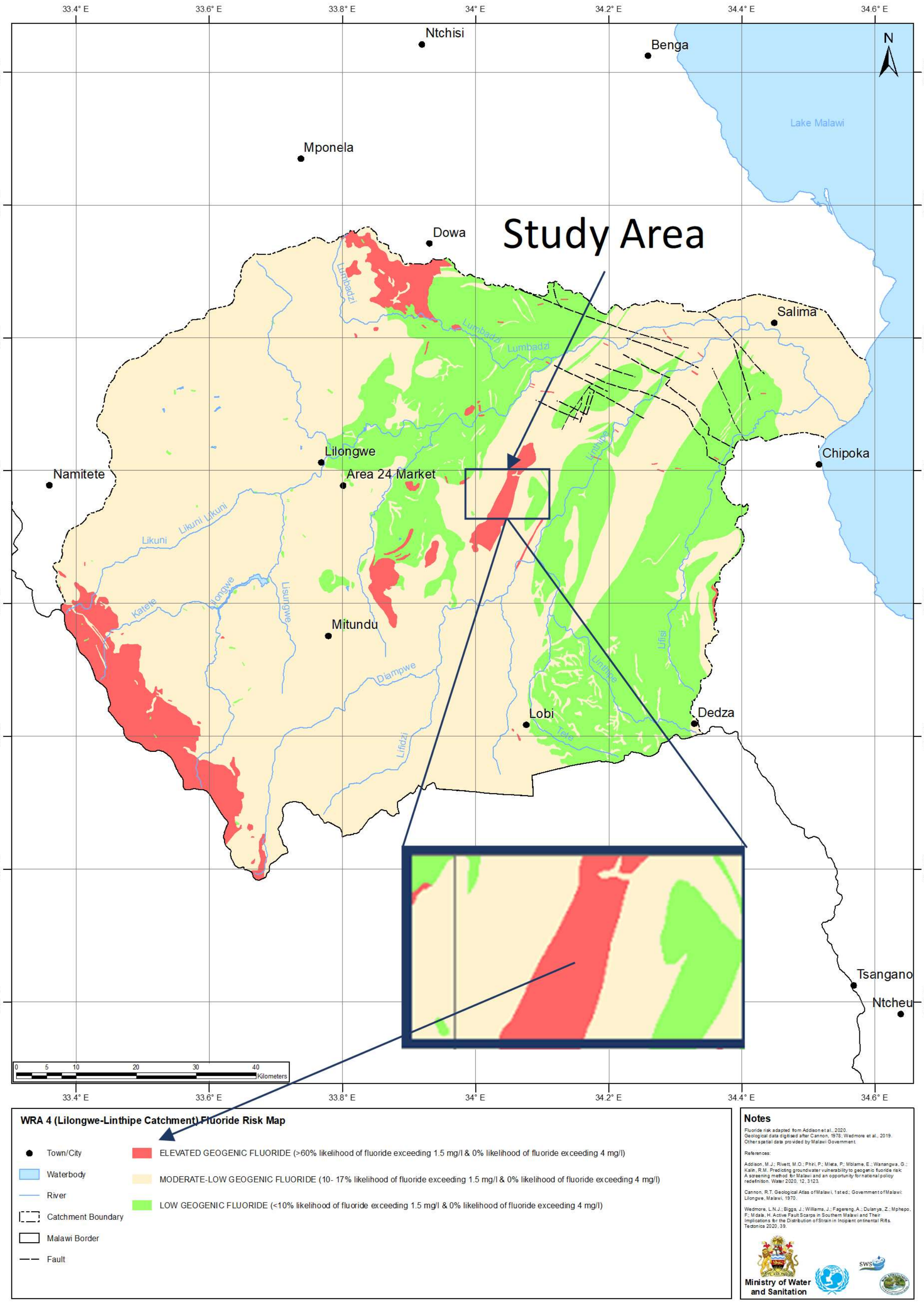


Figure 47. Geogenic groundwater fluoride zones present in the Case Study area. Individual lithologies are presented as zones of elevated groundwater fluoride risk (Addison et al., 2020).

Groundwater Quality - Health relevant / aesthetic criteria in the case study area

Fluoride

Groundwater fluoride in the case study area has been well characterised (Addison et al., 2020). Generic groundwater fluoride concentrations are controlled by lithological composition - lithologies containing higher fluoride-bearing minerals (e.g. alkaline igneous rocks) bear elevated fluoride concentrations in groundwater compared to other lithologies (**Figure 47**). Fluoride distribution is controlled by the weathered basement aquifer profile and are generally not transported far from source rocks due to low permeability and groundwater flow barriers (**Figure 39**).

The source of fluoride is Augen gneiss (**Figure 40 and 47**) within granitic rocks that occur as sub-linear South West – North East trending outcrops with regular surface expressions (linear gneiss mounds). Highest groundwater fluoride concentrations were found in boreholes drilled into this lithology. A fluoride risk map of the area of Water Resources Area 4 is provided in the WRA 4 annex (**Figure 47**) which displays zones of fluoride risk based on statistical relationships between individual lithologies and groundwater fluoride concentrations. There is >60% risk of encountering fluorosis-inducing fluoride concentrations in groundwater (>1.5 mg/L) from boreholes drilled into zones of elevated risk, compared to <17% risk in other zones (Addison et al., 2020). 1.5 mg/L is the upper limit for dissolved fluoride in drinking water set by the World Health Organisation (WHO) to mitigate fluorosis risks from drinking water supplies globally. Malawi’s limit for groundwater from boreholes and wells is higher at 6 mg/L but are under review with consideration to reduce to nearer the WHO level.

SDG 6.1.1 Water Supply Service Levels

The Sustainable Development Goal 6, to ensure access to water and sanitation for all (2015 – 2030), include a number of aspirational defined targets:

- 6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all
- 6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations
- 6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
- 6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity
- 6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate
- 6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes

and

- 6.A by 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies
- 6.B Support and strengthen the participation of local communities in improving water and sanitation management

SDG Indicator 6.1.1 tracks the proportion of population that is using an improved drinking water source, that is located on the premises, available when needed, and free of faecal and priority chemical contamination. Improved drinking water sources include piped water, boreholes or tube wells, protected dug wells, protected springs, rainwater, and packaged or delivered water. If it meets all of the criteria it is considered 'Safely Managed'.

Drinking water from an improved source that does not fulfil the above-mentioned criteria is categorized as "basic" services, provided that the collection time is not more than a 30-minute round trip, including queuing. If the improved drinking water source is located further away, the service is categorized as "limited", and if the drinking water sources is unimproved or surface water, it is categorised accordingly.

The vast majority of rural groundwater supplies will not meet SDG6.1.1 Safely Managed Service Level in the next decade. Review of the data held in the Ministry of Water and Sanitation indicates there is not sufficient groundwater quality data, laboratory capacity, and funding to assure that priority pollutants (Fluoride, Arsenic, E-coli and various POPs) are measured and risk assessed on a regular basis. Data from the 2020 National Assessment indicates:

- In Malawi there are 85,327 Groundwater Abstraction Points, of which 10,778 are unimproved
- Of these 4,073 have been abandoned and an additional 6,337 are non-functional
- Of the 74,917 functional or partially functional groundwater abstraction points, 9,098 (12%) suffer groundwater table declines during the dry season and no longer provide water.

In the Case Study Area (**Figure 48** as an example subset) it is obvious the target for availability of water when needed and within 30 minutes round trip is also not being met.

- Of the 6,989 households surveyed, (0) none were Safely Managed, 3,575 had Basic Service, 4,410 had Limited Service, 770 had Unimproved Service and 226 were using surface water.

This highlights the need for Donors, NGOs/CSOs, Water Managers and Professionals to acknowledge the complex hydrogeology of Malawi, to work with the Ministry of Water and Sanitation to review each water point as fit-for-purpose (Borehole Forensics), and to invest in site specific professional hydrogeology prior to implementation of new groundwater supplies. To date, little proper hydrogeologic study is carried out before the siting, drilling and commissioning of rural water supplies, this data is needed by the Ministry of Water and Sanitation to document and report on Sustainable Development Goal targets.

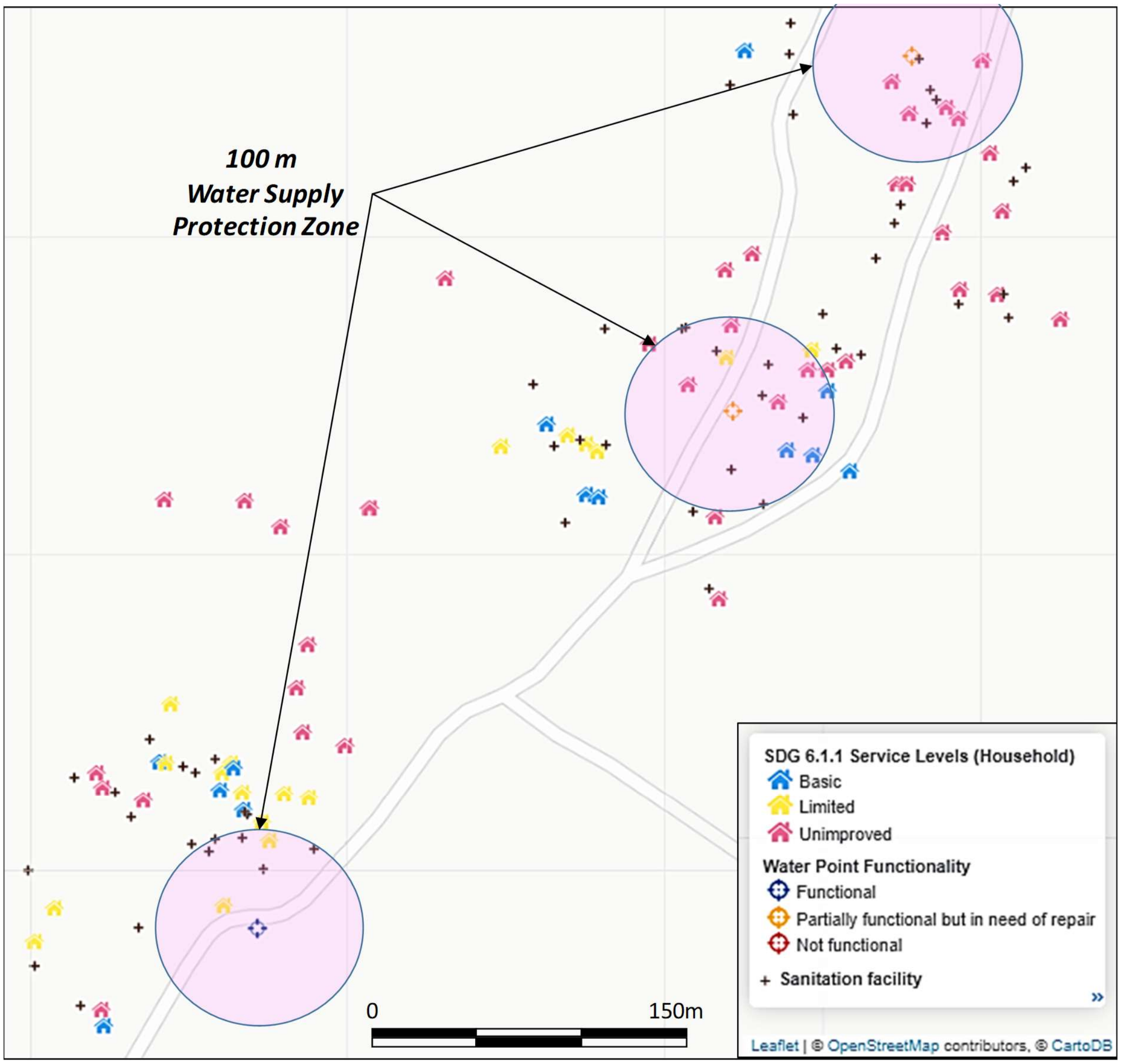


Figure 48. SDG 6.1.1 Water Supply Service Level in random location in the Case Study Area. Note the co-location of sanitation facilities and water points.

Summary

This case study provided insights to a site specific use of the generic data held by the Ministry of Water and Sanitation and presented in the various publications that make up this Hydrogeology and Groundwater Quality Atlas of Malawi.

It is important that all existing groundwater abstraction infrastructure is evaluated for its 'fit for use' to meet SDG6 and Malawi Vision 2063, and that all future groundwater investments, infrastructure development, and decommissioning of stranded assets take place within an Integrated Water Resource Management framework, and with an appreciation of the complex nature of the hydrogeology of Malawi.

Groundwater has the potential to be a major resource for climate change adaptation and resilience, but only if it is managed correctly and within a conjunctive surface water – groundwater strategy.

Hydrogeologic and Water Quality Bulletin, Annexes for each Water Resources Area and each Water Resource Unit, and Maps

This Hydrogeology and Water Quality Atlas is a series of connected publications including a main Bulletin, various Annexes that provide the details and localised maps of Hydrogeology and Groundwater Quality at WRA and WRU level, and a series of A0 National Maps. The full reference with ISBN for each of these publications is as follows.

Hydrogeology and Groundwater Quality Atlas Bulletin

1. 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, Bulletin, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-00-0 150pp

Hydrogeology and Groundwater Quality Atlas WRA Annexes

1. 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, Shire River Catchment, Water Resource Area 1 Upper Shire, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-01-7 167pp

2. 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, Shire River Catchment, Water Resource Area 1 Lower Shire, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-02-4 129pp

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Ministry of Water and Sanitation

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Bulletin 22nd March 2022

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, Bulletin, Ministry of Water and Sanitation, Government of Malawi, ISBN 978-1-915509-00-0 151pp*