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Review

Basement and alluvial aquifers of Malawi: An overview of groundwater quality and policies

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This paper highlights the quality of groundwater in basement and alluvial aquifers of Malawi through literature assessment. Groundwater in these aquifers serves about 60% of Malawian population. Alluvial aquifers yield high groundwater in excess of 10 L/s and more mineralized than basement aquifers. The values from literature are presented as ranges. The geochemical quality of both aquifer types are classified as good. However, in some cases values higher than maximum permissible limits (MPL) are worrisomely apparent. Significant levels for some elements have been demonstrated. Although groundwater policies and instruments are available, more groundwater research, monitoring, data archiving is needed.

Key words: Alluvial aquifer, basement complex, groundwater quality, borehole water, shallow wells, Malawi.

INTRODUCTION

Potable water is a core to sustainable development. Most of the surface water in use for domestic and industrial purposes is highly contaminated, thus requiring a great deal of treatment before reaching the end user. In some regions, even this surface water is scarce owing to the great distances covered just to get to the nearest water point. Besides, a great deal of treatment required to make surface water fit for use makes it a difficult task for communities, especially in developing countries. The alternative is groundwater, which is probably the cheapest and safest potable water source (Foster, 1986). Groundwater is perceived to be cleaner in terms of contaminants. However, depending on various factors, groundwater may be contaminated as well. Its physic-chemical characteristics may exceed recommended quality standards. This may arise from either geogenic control or anthropogenic interference. Various quality parameters in groundwater have been assessed (Adekunle et al., 2007; Rowland et al., 2008; Muneer et al., 2010). In some instances, dangerous high quantities of health threatening elements have been documented (Smedley and Kinniburgh, 2002; Xie et al., 2013; Wen et al., 2013) Correlations and impacts of groundwater contaminants on human health have been

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highlighted (Lyman et al., 1985; Hall et al., 2002). To safeguard human health, policies and standards regarding the use of groundwater for domestic and commercial purposes have been formulated in various countries. Most countries use the WHO standards (WHO, 2008) or have modified them to suit local conditions.

Most Malawians in rural areas depend on groundwater for domestic purposes (Government of Malawi (GOM), 2011). Open shallow wells have been in use since time immemorial. Recently, a lot of boreholes have been sunk through government initiatives, non-governmental organizations and international agencies (Stoupy and Sugden, 2003; Grimason et al., 2013). Borehole wells offer contamination freer water and guarantee safety to the drawer. Open wells on the other hand are prone to deliberate contamination and present physical dangers of falling in. Urban areas in Malawi depend much on surface water for potable water use, however this water flow originate from base flow in hills and mountains (Ngongondo, 2006). As such, variations in aquifer water quantity and quality has a significant contribution to variations in river water volume and quality.

Various policy documents have been formulated in Malawi as regards water resources use and degradation (GOM, 2011). The scientific community has been keen on quantity and quality of groundwater in Malawi as well as the SADC region. However, research work is still fragmented and data is not easy to come-by. This paper seeks to identify literature on Malawi's groundwater and use the same to summarize physico-chemical and biological values and related policies. At the same time, it will highlight various strides undertaken in Malawi as regards groundwater research and present areas where most study results have been published. The goal is to bring together values in one paper that will act as a starting point when identifying references about groundwater literature in Malawi.

SOURCES OF INFORMATION

A desk review approach was employed in this study. Google scholar, PubMed and Elsevier Scorpus were used to search for journal articles. General information about Malawi and policy documents were sourced from various government websites and published materials related to groundwater. Besides, some information came from theses available on university websites. The use rights were considered.

GEOLOGY OF MALAWI

Geography, general relief and climate

Malawi is a sub-Saharan African country south of the equator situated between latitudes 9° 22´ and 17° 7´ south and between longitudes 32° 40´ and 35° 55´ east. It is bordered by Mozambique to the south east and south west, Zambia to the west and north-west and Tanzania to the north east and north (Figure 1A). It has a geographical area of 118480 km^2. According to 2012 world bank records, Malawi has a population of 15.91 million (World Bank, http://data.worldbank.org/indicator/SP.POP.TOTL).

Mkandawire (2004) explained the geologic and climate characteristics of Malawi as follows. Malawi has an array of relief that strongly influences climate, hydrology and groundwater occurrence. The topography consists of (1) Plateaus that are gently undulating surfaces with broad valleys and large level areas on the interfluves generally located at 900-1,300 m above mean sea level (msl). They are extensively covered by a thick weathered material; (2) Mountainous areas that rises abruptly from the plateau, located 2,000–3,000 m above msl covered by a more erosion resistant underlying strata; (3) Escarpment that fall steeply from the plateau areas underlain by poor and fractured aquifer where erosion significantly strips away the weathering products; and, (4) The Rift valley floor (hosting the alluvial plain) located below 600 m above msl, is gently sloping and of very low relief (Figure 1B). There is considerable potential for groundwater in these areas. Based on topography, the country is divided into Water Resource units (Figure 2).

In terms of climate, Malawi's seasons are influenced by the migration of the Inter-Tropical Convergence Zone (ITCZ). However, climatic conditions are complex due to the wide topographic variation and the influence of Lake Malawi. Much higher rainfall is experienced in uplands as compared to low lands. The mean annual temperature is 22–23°C with less latitudinal effect.

Rainfall variability has a significant impact on variations in both water availability and total potential discharge in a particular catchment (McCarthy et al., 2001; Bloomfield, 2002; Ngongondo, 2006). However, processes other than rainfall play a significant role in the hydrologic processes of any catchment (Ngongondo, 2006). The numerous rivers, lakes, dams, lagoons and marshes existing in Malawi (GOM, 2011) connect with groundwater in either recharge zones or mainly in discharge zones.

Aquifer geology and characteristics

The geological setting of Malawi is mainly characterized by crystalline metamorphic and igneous rocks of Precambrian to lower Palaeozoic age (Carter and Bennett, 1973; Chilton and Smith-Carington, 1984). This is referred to as the basement complex that covers approximately 70% of Malawi's landscape and supplying water to about 60% of the population (National Statistics Office, 2002). The major lithological units of the basement aquifer complex are syenitic granites, charconoctic and ultra-basic

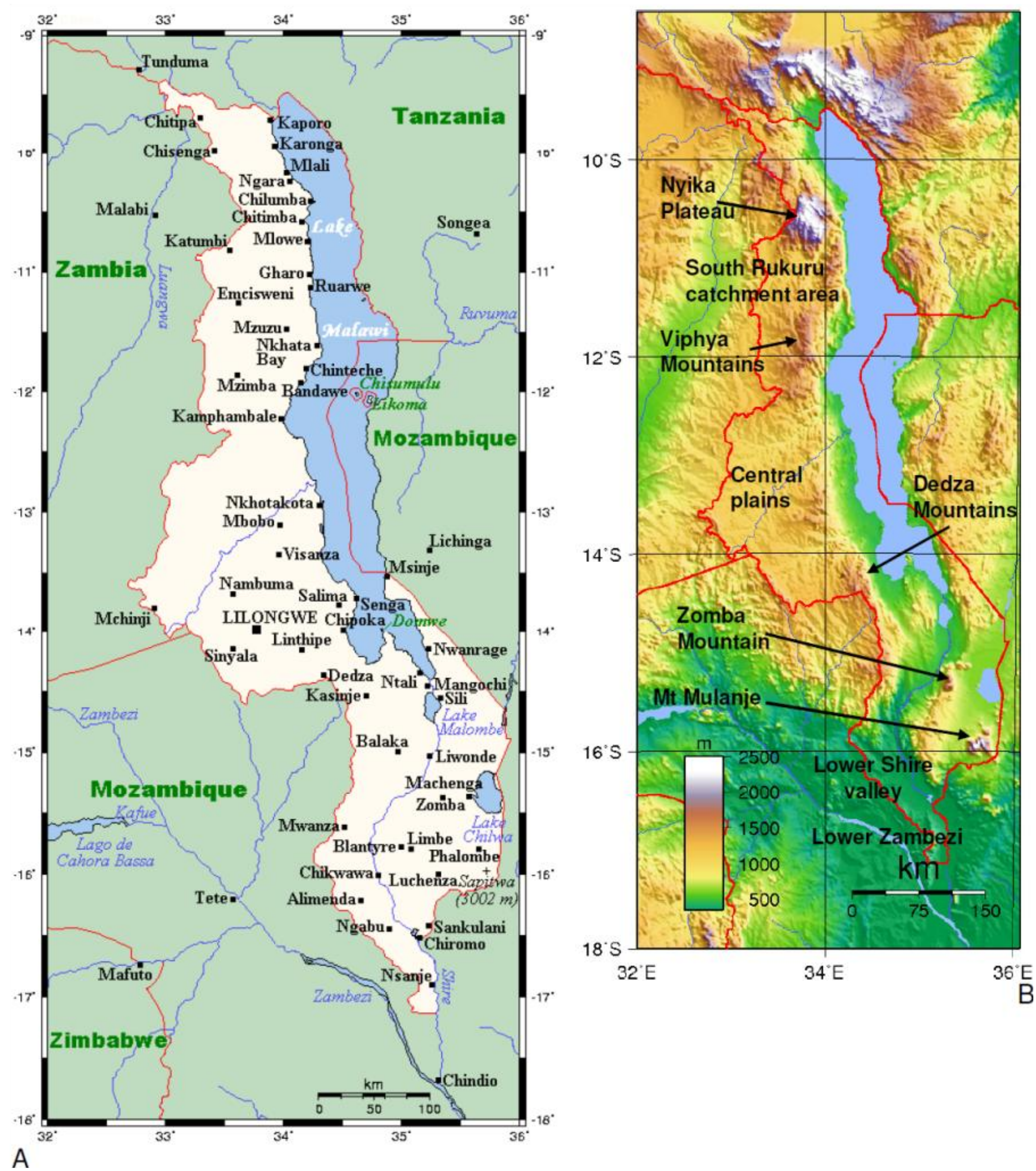

Figure 1. Map of Malawi illustrating (A) the political and administrative regions and (B) topographic zones.

gneisses, schistis, granulalite and quartzites (Mkandawire, 2004; Monjerezi and Ngongondo, 2012). Large inselberg of these rocks rises above the plateau as a result of epeirogenic events (Chilton and Smith-Carington, 1984). The lift valley has modified and interrupted this landscape. Groundwater is of variable qualities and quanti-

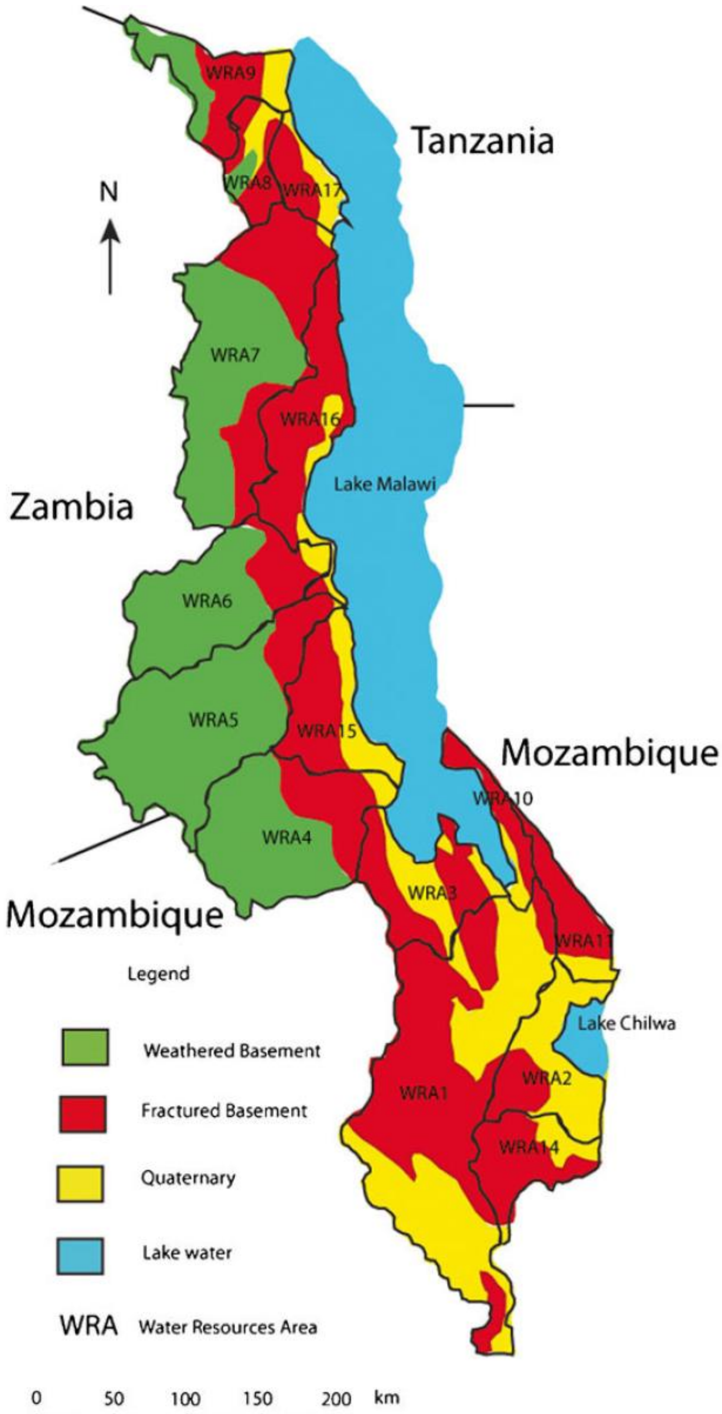

Figure 2. Outline of the geology of Malawi and Water Resource Areas (WRA) (Robins et al., 2013).

ties, unevenly distributed in time and space and is subjected to poor conservation and management (GOM, 2007). Aquifer recharges from broad interfluves and groundwater discharge in surface depressions. In terms of chemistry, the shallow component is less mineralized than the deeper component (McFarlane and Bowden, 1992). This basement is divided into weathered and fractured basement aquifers (Robins et al., 2013) (Figure 2). Besides basement complex, the quaternary alluvial aquifer exists in Malawi (Chimphamba et al., 2009; Robins et al., 2013) located mainly along the Lake Malawi shores and Lower Shire valley within the Great Lift Valley floor (Figure 2).

According to Makandawire (2004), transmissivity of the weathered basement aquifers are generally in the range of 5 to 35 m^2/day with estimated hydraulic conductivities ranging from 0.01 to 1 m/d. The storage coefficient, on the other hand, has been assumed to range from 0.01 to 0.001 (Mkandawire 2004). It is suggested that the groundwater is under unconfined to confined conditions. The water table is closer to the surface in the valley region and deeper in higher grounds (Mkandawire, 2004).

Borehole yields are generally highest where the saturated thickness of the weathered zone is greatest and the parent bedrock coarsest (Chilton and Smith-Carington, 1984). In general, however, the weathered basement aquifer produces low borehole yields (GOM, 2007; Chilton and Smith-Carington, 1984). Despite this, domestic water use (either shallow wells or hand-pump boreholes) can be sufficiently obtained (Chilton and Smith-Carington, 1984). On the other hand, alluvial aquifers are high yielding with recorded yields in excess of 10 L/s (Chimphamba et al., 2009; GOM, 2007). McFarlane et al. (1992) observed and concluded that very flat land at least one kilometer from the berg is generally likely to be high yielding than sites close to the berg in the plains of central region of Malawi. This was done through statistical analysis using data from about 1500 boreholes in this region.

Despite the relative expanse of the aquifer system, significant physical and chemical characteristics are observed on a local scale due to differences in mineralogy and structure (Chilton and Smith-Carington, 1984). The heterogeneity in terms of hydraulic characteristics and lithology is due to fractures, weathered zones and intrusions that control the occurrence of aquifers (Chimphamba et al., 2009; Pritchard et al., 2007).

GROUNDWATER QUALITY IN MALAWI

Introductory remarks

As mentioned earlier, spatial variation in chemical and physical quality is attributed to the heterogeneity of the aquifer system, groundwater flow regime and weathering processes (Chilton and Foster, 1995). Some shallow wells dry up in dry season forcing people to use surface water (e.g. rivers) which are grossly contaminated. Contamination of shallow wells is due to sanitation facilities being close to the wells (Dzwairo et al., 2006). The Water Resources Act of Malawi stipulates that water points be upstream of sanitation facilities. Fourie and van Ryneveld (1995) wrote that pollution from on-site is influenced by (1) varying subsurface conditions especially saturated versus unsaturated zones, (2) varying contaminant characteristics mainly mobility and persistence, and (3) varying mechanism of movement through materials.

Determination of quality of groundwater is very vital. For instance, determination of nitrates is considered significant as an indicator for water quality due to its association with blue baby syndrome effect, possible carcinogen and crude fecal pollution indication (Fourie and van Ryneveld, 1995). In general, determination of physical and chemical quality serves to provide a guide on the quality of groundwater for all purposes. In the case of poor quality, the results help in identifying and prescribing the water borne health implications in an area.

Aquifer quality characteristics

Various studies on groundwater quality have been carried out in several districts in Malawi. Table 1 summarizes the range of biological, physical and chemical quality parameters observed in various districts. The values in Table 1 are quoted from various papers published in refereed journals, conference proceedings and reports. However, due to limited papers found so far on Malawian groundwater, the values presented were all found from the search engines. The ranges are presented as they are found in the cited papers. Some large values where rounded off to remove decimal points. Some significantly higher range values are explained by the various authors themselves. However, this paper will try to highlight some of the issues already explained by the various authors on the values. The summarized results are for both boreholes and shallow wells. Shallow wells can be open unprotected or closed protected wells (Pritchard et al., 2007, 2008, 2009; Mkandawire, 2008). As such, high variations in range of values are expected if protected shallow wells are sampled together with unprotected open wells. Thus, the combined range of values will definitely result in a higher range. Most of the highest values for shallow wells are expected for open unprotected wells. Makandawire (2008) and Pritchard et al. (2008, 2009) observed higher values for fecal coliforms (FC) in unprotected open shallow wells both during dry and wet seasons. Similar observations were made for other parameters such as sulfates (SO_4), turbidity, pH and electric conductivity (EC). Some parameters improve during wet season while others worsen (Prichard et al., 2007, 2008, 2009). The difference in range values for the same district is an indication of the complexity of the aquifer. This depends on sampling location within the district even though the aquifer is either basement complex or alluvial. A synopsis of the results is summarized in Table 1a and b.

Table 1a. Range of expected Physical, Chemical and Biological quality of groundwater in Balaka, Blantyre, Chikhwawa, Chiradzulu, Karonga and areas in Central plains of Malawi.

Parameter	Balaka[a]	Blantyre	Chikhwawa	Chiradzulu	Dedza[k]	Karonga[l]	Central Plains[m]
pH	6.7 – 8.1	6.38 – 7.85[b] 6.42 –10.3[c] 6.56 – 8.81[d]	6.6 - 8.00[f] 5.0 – 9.0[h] 6.9 – 7.7[j]	6.14 – 7.91[c] 6.25 – 7.47[e]	6.4 – 7.7	6.3 – 8.1	6.4 – 7.0
TDS, mg/L	152 - 686	176 – 342[d;e] 172 – 338[c]	713- 2250[a] 16 – 26539[g]	74 – 179[c] 71 – 162[e]	99 – 2120	50 – 950	N/A
Turbidity, NTU	0.0 - 5.1	1.3 – 114[b] 0.0 – 62[e] 0.0 – 86[c]	0 – 209[i] 0 - 5.6[j]	0.0 – 812[c] 1.9 – 30.3[e]	1.5 - 12.5	N/A	N/A
EC, µS/cm	254 – 1428	180 – 383[b] 287 – 577[c] 294 – 570[e]	1450 – 2800[f] 254 – 15540[g] 221 – 6574[j]	174 – 299[c] 106 – 290[e]	195 – 4156	120 - 1735	N/A
Chloride, mg/L	N/A	13.6 – 35[b] 0 - 0.22[c] 0 - 0.14[e]	3.8 –11767[i] 8.1 –426[j]	0.0 – 0.18[c] 0.0 – 0.09[e]	8.5 – 248	4.7 – 990	2 – 19
Fluoride, mg/L	0.4 - 10.0	0.37 - 0.87[b]	0.59 - 1.93[f] 0.1 – 4.8[j]		0.2 - 1.1	N/A	0.5 – 7.02[n]
NO_3, (mg/L	N/A	0 - 3.2[c] 0 - 0.61[d] 0 - 1.92[e]	0.0 –178[j]	0.0 – 4.8[c] 0.0 – 0.03[e]	0.0 - 4.7	0.0 – 12.3	N/A
SO_4 , mg/L	0.0 - 33	0 – 83[c] 0 – 79[d] 0 - 18.5[e]	1.6 – 985[h] 1.1 – 2600[i]	0.0 – 113[c] 0.0 – 11.0[e]	5.1 – 887	0.0 – 505	114 – 2490
HCO_3, mg/L	N/A	N/A	143 –1314[h] 65 – 3110[i]	N/A	96 – 728	7.9 – 666	N/A
CO_3, mg/L	N/A	N/A	0.0 – 569[g]	N/A	0.0 – 49	0.0 - 72	N/A
Sodium, mg/L	N/A	15.3 – 24.3[b]	15.0 – 1178[j] 20.2 – 2050[h] 10 – 8320[i]	N/A	11.5 – 314	2.4 – 166	28 – 163
Potassium, mg/L	N/A	N/A	0.5 – 24.3[j] 0.4 – 13.8[h]	N/A	0.3 – 21.9	1.2 – 11.6	0.8 – 1.4
Calcium, mg/L	N/A	N/A	9.9 – 309.8[h] 6 – 876[i] 20.3 – 121[j]	N/A	15.8 – 351	3.6 – 412	62 – 555
Magnesium, mg/L	N/A	N/A	5.9 – 410.4[h] 1.0 – 1302[i] 12.8 – 54.3[j]	N/A	7.7 – 50.1	1.2 – 117	16 – 343
Iron , mg/L	N/A	0.1 – 0.8[b]	0.0 – 0.6[j]	N/A	0.0 – 1.1	N/A	0.02 – 0.23
Hardness, mg $CaCO_3$/L	108 - 1080	47 – 325[c] 47 – 210[d] 56 – 220[e]	6.0 – 1370[i]	3 – 165[c] 5.0 – 120[e]	71 – 1036	N/A	N/A
Fecal coliforms, cfu/100 mL	0 - 4230	0 – 11000[b] 0 - 28450[c] 0 – 17175[d]	0 – 9250[i]	0 – 29600[c] 13 – 4550[e]	N/A	N/A	N/A

Superscript denotes the main source of data for the district except where noted within the table: [a]Pritchard et al., 2008; [b]Palamuleni, 2002; [c]Pritchard et al., 2007; [d]Mkandawire, 2008; [e]Pritchard et al., 2009; [f]Sajidu et al., 2008; [g]Monjerezi et al., 2012a; [h]Monjerezi et al., 2012b; [i]Monjerezi and Ngongondo, 2012; [j]Grimason et al., 2013; [k]Kushe, 2009; [l]Wanda et al., 2013; [m]McFarlane and Bowden, 1992; [n]Msonda, 2003.

Table 1b. Range of expected Physical, Chemical and Biological quality of groundwater in Machinga, Mchinji, Mulanje, Mzimba, Nkhatabay, Rumphi and Zomba-Phalombe plains of Malawi.

Parameter	Machinga[o]	Mchinji[p]	Mulanje[c]	Mzimba[q]	Nkhatabay[r]	Rumphi[l]	Zomba-Phalombe
pH	6.70 – 9.37 7.05 – 9.50[f]	6.4 - 7.4	5.22 – 6.93	6.0 – 8.7	5.8 – 7.1	6.5 – 7.8	5.5 – 7.0[a] 6.30-7.15[f] 6.5 – 7.2[t]
TDS, mg/L	43 – 1772	39 - 215	27 – 161	29 - 1896	501 - 108	24 - 810	29 – 185[a]
Turbidity, NTU	Trace – 4.00	1 - 11	0.32 – 502	Bdl - 740	N/A	N/A	2.0 – 147[a]
EC, µS/cm	1050 - 31000 55 – 1676[f]	76 - 416	28.4 – 268	50 - 316	71 – 168	40 - 1630	129-805[f] 126 - 1806[t]
Chloride, mg/L	0.003 – 0.59	<0.01-17	0.0 – 0.96 0.01 - 0.17[e]	4.7 - 990	3.5 - 12.3	6.0 – 399	0.004-0.59[s] 0.0 – 40.5[t]
Fluoride, mg/L	0.35 – 10.3 0.24-7.51[f]	0.01-1.21	N/A	Bdl - 1.7	0.40 - 1.33	N/A	0.26-6.51[f] 0.0 – 4.5[t]
NO_3, mg/L	Trace – 58.3	0.01-0.39	0.0 – 2.0 0.0 – 0.01[e]	Bdl - 12.3	0 - 0.90	0.0 – 3.7	0.003 – 1.36[a] 0.0 – 48[t]
SO_4, mg/L	2.9 – 110	4.2-58.5	0.0 – 7 0.0 – 5.0[e]	Bdl - 505	0 - 0.91	0.0 – 53	2.9-110[s] 0.0 – 10[t]
HCO_3, mg/L	44.4 – 497	38.6-164	N/A	7.9 - 666	8.5 - 148	25 - 551	N/A
CO_3, mg/L	0.00 – 26.7	0	N/A	Bdl - 72.0	-	0.0 - 31	N/A
Sodium, mg/L	N/A	6 - 13	N/A	2.4 – 166	1.39 – 11.2	3.1 – 40	4 – 53[t]
Potassium, mg/L	N/A	0.7 - 6.8	N/A	1.0 – 11.6	0.84 – 6.16	1.0 – 12	N/A
Calcium, mg/L	N/A	9 - 45.4	N/A	3.6 – 412	6.94 – 43.9	7.4 – 142	4 – 47[t]
Magnesium, mg/L	N/A	2.7 - 12.6	N/A	0.97 – 117	1.23 – 4.32	1.0 – 45	N/A
Iron, mg/L	N/A	0.01 - 3.5	N/A	Bdl – 2.7	0.15 – 1.98	N/A	N/A
Hardness mg $CaCO_3$/L	3.49 – 199	25 - 161	0.0 – 325	14 - 1489	N/A	N/A	3.0 – 220[t]
Fecal Coliforms, cfu/100 mL	N/A	0 - 43	0 – 4020	N/A	0 – 0.5	N/A	0 – 6550[a]

Superscript denotes the main source of data for the district except where noted within the table: [a]Pritchard et al., 2008; [c]Pritchard et al., 2007; [e]Pritchard et al., 2009; [f]Sajidu et al., 2008; [l]Wanda et al., 2013; [o]Sajidu et al., 2007; [p]Mleta, 2010; [q]Wanda et al, 2011; [r]Kanyerere et al., 2012; [s]Chimphamba et al., 2009; [t]von Hellens, 2013.

Physical characteristics

Average values of pH in most cases indicate near-neutral groundwater compositions with a range of 6 - 8. The permissible levels of pH in groundwater for Malawi is 6 – 9 (Malawi Standards Board (MSB), 2005a). According to Table 1a and b, groundwater pH values lower than 6 for some places in Chikhwawa, Mulanje, Nkhatabay and Zomba can be encountered as well as those beyond pH 9 for some places in Machinga. Msilimba and Wanda (2013) reported a range of pH for groundwater in Mzuzu as 4.9 – 6.3 an indication of acidic waters in this area. Most of the groundwater recorded so far have pH range within the acceptable levels.

Total dissolved solids (TDS) were quoted as low, 24 mg/L with most of the higher values below the MPL value of 1000 mg/L (MSB, 2005a). However values higher than 1000 mg/L are reported in some areas such as those found in Chikhwawa, Dedza, Karonga, Machinga and Nkhatabay. These are same places where higher electrical conductivities were also observed. Chilton and Smith-Carington (1984) observed values of total dissolved solids up to around 2500 mg/L in Livulezi (central) and Dowa West (south-central). On the other hand, Bath (1980) concluded that total dissolved solids up to 2900 mg/L can be expected in Nkhotakota and surrounding lake shore areas in colluviums and weathered basement.

Higher turbidity range (Table 1) were observed for studies done in Blantyre (Palamuleni, 2002; Pritchard et al., 2007; Mkandawire, 2008; Pritchard et al., 2009), Chikhwawa (Monjerezi and Ngongondo 2012), Chiradzulu (Pritchard et al., 2007), Mulanje (Pritchard et al., 2007; Pritchard et al., 2009), Mzimba (Wanda et al., 2011) and Zomba-Phalombe plain (Pritchard et al., 2008). As mentioned earlier some of these observations were made for open unprotected wells (Pritchard et al., 2007, 2008, 2009; Mkandawire, 2008). The maximum permissible level for groundwater in Malawi is 25 NTU (MSB, 2005a) as such some places in the studied areas recorded in Table 1 had values higher than the MPL value. However, the average values indicated by authors themselves indicate that groundwater has values within acceptable levels in terms of turbidity.

The electrical conductivity (EC) values are in the range of 35 – 2800 µS/cm (Table 1). However, in some instances values higher than the maximum permissible level (MPL) of 3500 µS/cm (MSB, 2005a) can be expected for some places in Chikhwawa, Dedza and Machinga. Bath (1980) reported that electric conductivity as high as 7700 µS/cm can be observed in some areas in Malawi. Chilton and Smith-Carington (1984) also found mostly low-conductivity groundwater in basement aquifers from the Livulezi (central) and Dowa West (south-central) areas. In the Nkhotakota area on the western shores of Lake Malawi, Bath (1980) reported electrical conductivity values of 180–4600 µS/cm.

Chemical quality

The chloride (Cl) MPL for borehole and shallow well drinking water in Malawi is 750 mg/L (MSB, 2005a). However, chloride concentrations up to 4000 mg/L have been recorded in Shire Valley and lower than 60 mg/L in Nkhotakota area (Bath, 1980). BGS (2004) observed concentrations of chlorides up to 2100 mg/L in groundwater from alluvial deposits close to the edge of the Karoo sediments. In South Rukuru catchment area, chloride concentrations of 4 – 2000 mg/L were reported by Bath (1980). Except for Chikhwawa (Monjerezi et al., 2012b; Monjerezi and Gongondo, 2012), Karonga (Wanda et al., 2013), Mzimba (Wanda et al., 2011), and Rumphi (Wanda et al., 2013), all the areas in Table 1 show values below the MPL of 750 mg/L. Nevertheless, the high values recorded in these areas are not rampant, an indication that the average majority of sampled groundwater had values less than 750 mg/L with very few exceptions. This is what is making the range to be so highly spread.

It is expected that areas located in Rift Valley floor will have high fluoride (F) levels (BGS, 2004). As such, Malawian groundwater in the alluvial plains, are likely to be most affected. Sporadically, some groundwater in the weathered basement may also have high concentrations greater than Malawi standards of 6 mg/L (MSB, 2005a). Groundwater fluoride levels less than 1 mg/L in areas of the basement complex in Malawi and concentrations between 2 mg/L and 10 mg/L from the alluvial regions have been reported by UN (1989). Bath (1980) reported a median concentration of fluoride <1 mg/L in basement aquifers of the Nkhotakota area. However, one of the samples recorded a value higher than 1 mg/L that resulted in an inflated range of <1 – 7 mg/L. Elsewhere, concentrations in the basement aquifer of South Rukuru are reported in the range <0.1–3.3 mg/L, nonetheless most of the results were below 0.6 mg/L (Bath, 1980). Much higher fluoride concentrations, up to 15 mg/L in some samples, have been reported by Bath (1980) in the lower Shire valley. At Ulongwe in Machinga District, fluoride levels of 8.6 mg/L have been shown to exist (Sibale et al., 1998). Carter and Bennett (1973) also reported existence of fluorides in Karonga (8.0 mg/L), Mwanza (3.4 mg/L), Mazengera in Lilongwe (7.0 mg/L), Nathenje in LiLongwe (7.0 mg/L), Nkhotakota (9.6 mg/L) and Nsanje (5.8 mg/L). Spatial and temporal analyses of fluorides levels in Nathenje in Lilongwe (part of central plains) indicate higher values for central part of the area and during dry season, respectively (Msonda et al., 2007). From Table 1, higher values of fluoride concentrations are expected in some places in Balaka, Central plains, Machinga, Nsanje and Zomba-Phalombe plains. There is evidence of fluorosis problem in these areas (Msonda et al., 2007, Sajidu et al., 2007). Values of fluorides higher than 6 mg/L are worrisome in Malawi. However the problem of fluoride is sporadic in the basement aquifer and not widely spread in the alluvial aquifer (UN, 1989).

The nitrates (NO_3) MPL for groundwater used for drinking in Malawi is 45 mg/L (MSB, 2005a). Bath (1980) summarized fluoride data showing fluoride concentrations much less than the MPL value in Nkhotakota, Bua, South Rukuru catchement area and Lower Shire valley. Sporadically high concentrations of nitrates in groundwater from the lower Shire valley (as high as 18.5 mg/L) have been observed (Bath, 1980). Nevertheless, the study concluded that nitrate concentrations were mostly less than 5 mg/L and many were below 0.7 mg/L. Also, UN (1989) reported groundwater nitrate values less than 1 mg/L from both the basement and alluvial aquifers in Malawi. Observations from Table 1 indicate that nitrates higher than 45 mg/L are expected in some places in Chikhwawa (Grimason et al., 2013), Machinga (Sajidu et al., 2007) and Zomba-Phalombe plain (von Hellens 2013).

In terms of sulfates, Chilton and Smith-Carington (1984) reported concentrations higher than 2000 mg/L in Dowa west of central plains of Malawi. Sulfate up to 2400 mg/L were recorded in groundwater from alluvial deposits close to the edge of the Karoo sediments (BGS, 2004). The MPL for sulfates in borehole and shallow wells drinking water for Malawi is 800 mg/L (MSB, 2005a). According to Table 1a, higher values were observed in some places in Chikhwawa (Monjerezi et al., 2012b; Monjerezi and Gongondo, 2012), Dedza (Kushe, 2009) and Central plains of Malawi (McFarlene and Bowden, 1992). In general, sulfate levels in weathered basement and alluvial aquifers are mainly below the MPL value.

Chimphamba et al. (2009) indicate that the expected bicarbonate (HCO_3) concentrations in weathered basement aquifer are 100 – 500 mg/L while for alluvial aquifers across the country it is expected that the values fall within 200 – 1000 mg/L. Most values for the districts recorded in this study are below 500 mg/L in the weathered basement except for some samples in Dedza (Kushe, 2009), Karonga (Wanda et al., 2011) and Mzimba (Wanda et al., 2013). In Chikhwawa (Lower Shire valley floor), the values in some places were above the expected maximum value of 1000 in alluvial aquifer. Carbonate (CO_3) concentrations were as high as 569 mg/L (Table 1) in places recorded in this review so far.

The nationwide expected value for sodium (Na) is in the range 5 - 70 mg/L in weathered basement and 20 - 1500 mg/L in alluvial aquifer. On the other hand, expected values for potassium (K) are in the range of 1 - 6 mg/L for weathered basement aquifer and alluvial aquifer (Chimphamba et al., 2009). The MPL for sodium in Malawian groundwater used for drinking is 500 mg/L (MSB, 2005a). However, that of potassium is not stipulated. Nevertheless, potassium MPL for drinking water (tap water) is stipulated as 50 mg/L (MSB, 2005b). Bath (1980) reported sodium concentrations for Nkhotakota (0.4 - 720 mg/L) and Lower Shire (14 - 3550 mg/L). From Table 1, sodium concentrations falling outside nationwide expected range are reported in various places within the recorded districts in both weathered basement and alluvial aquifers such as Chikhwawa (Alluvial aquifer mainly), Dedza, Karonga, Central plains and Mzimba. In terms of drinking water quality for sodium, some places in Chikhwawa (Lower Shire) and Nkhotakota area are expected to have sodium values higher than MPL value of 500 mg/L (Bath, 1980; Monjerezi et al., 2012b; Monjerezi and Gongondo, 2012; Grimason et al., 2013). Similarly, some places in Chikhwawa, Dedza, Karonga, Mzimba and Rumphi exhibit high concentrations of potassium (Table 1) than the nationwide expectation of 1 - 6 mg/L but below 50 mg/L MPL (MSB, 2005b) stipulated for tap water. This indicates that in most places in these areas, the values will be below the acceptable maximum normal drinking water standard for potassium.

The MPL for calcium (Ca) and magnesium (Mg) in groundwater used for drinking in Malawi is 250 and 200 mg/L, respectively (MSB, 2005a). In Nkhotakota region, the groundwater is mainly of calcium-(magnesium)-bicarbonate type. In South Rukuru catchment area, concentrations of calcium up to 500 mg/L and magnesium up to 280 mg/L have been reported (Bath, 1980). According to Chimphamba et al. (2009), the nationwide expected value for calcium is in the range of 10 – 100 mg/L in weathered basement and 50 – 150 mg/L in alluvial aquifer. On the other hand, expected value for magnesium is in the range of 5 – 50 mg/L for weathered basement aquifer and 20 – 100 mg/L in alluvial aquifer (Chimpahmba et al., 2009). Based on the range indicated in Table 1, some places both in basement and alluvial aquifers had calcium values outside the expected nationwide range and in some instances higher than the recommended maximum permissible value of 250 mg/L, e.g. in some places found in Chikhwawa (Monjerezi et al., 2012b; Monjerezi and Gongondo, 2012), Dedza (Kushe, 2009), Karonga (Wanda et al., 2013), Central plains (McFarlene and Bowden, 1992), Mzimba (Wanda et al., 2011) and Rumphi (Wanda et al., 2013). Similarly, magnesium values in some places had values outside the expected nationwide range and in some instances higher than the recommended MPL of 200 mg/L such as in Chikhwawa and Central plains (Table 1).

The MPL for total iron (Fe) in groundwater for Malawian aquifers is 3 mg/L (MSB, 2005a). The nationwide expected range is 1 – 5 mg/L in both weathered basement and alluvial aquifers (Chimphamba et al., 2009). According to UN (1989), the range for total iron in weathered basement rocks and alluvial sediments is 1 – 5 mg/L. In Lower Shire Valley, a range of <0.1 – 84 mg/L have been reported and 0.8 - 82 mg/L in the weathered basement aquifers of Nkhotakota area by Bath (1980). Also, Bath (1980) recorded a range of total iron of <0.1 – 59 mg/L in Bua area of Central Malawi and <0.2 – 65 mg/L in South Rukuru catchment area. From Table 1, the highest value is 3.53 mg/L for Mchinji which falls below the maximum permissible level and within the expected range of 1 – 5 mg/L. Chilton and Smith-Carington (1984) explains the high values observed by Bath (1980) as possibly emanating from sampling methodology employed at that time that might have included particulate iron in the sample and likelihood of contamination from the pump material.

The MPL of total hardness (TH) in groundwater used for drinking is 800 mg $CaCO_3$/l (MSB, 2005a). The results in Table 1 indicate most values less than the MPL. However in some places the values recorded by cited authors in Table 1 show values above 800 mg/L in some places like Balaka, Chikhwawa, Dedza and Mzimba. It is therefore expected that some places in these areas will produce groundwater exhibiting characteristics of high hardness and unsuitable for drinking.

Manganese (Mn) concentrations of 0.1 – 0.4 mg/L have been reported in Central plains (McFarlane and Bowden, 1992), <0.001 mg/L in Mchinji (Mleta, 2010), <0.4 mg/L in Mzimba (Wanda et al., 2011) and 0 – 0.29 mg/L in Nkhatabay (Kanyerere et al., 2012). The values are below the MPL of 1.5 mg/L (MSB, 2005a).

Trace elements such as copper, lead, strontium, cadmium, boron, barium, beryllium, chromium, mercury have been analyzed in Nkhatabay and Lower Shire (McFarlene and Bowden, 1992; Kanyerere et al., 2012; Monjerezi et al., 2012; Grimason et al., 2013). However, no significant values were identified in these areas.

Phosphates of 0.16 – 1.16 were recorded in Nkhatabay (Kanyerere et al., 2012) while Sajdu et al. (2007) indicated that phosphates are not an issue in Machinga. Ammonia (0.0 – 0.5 mg/L) and nitrite (0.0 – 0.06 mg/L) were examined in samples in Blantyre (Mkandawire,

Table 2. Standards for drinking water in arid regions adopted in Malawi (Government of Malawi-UNDP, 1986).

Parameter	Good	Fair	Moderate	Poor
EC, µS/cm	0-750	750-1500	1500-3000	3000-6000
Na, mg/L	0-115	115-230	230-460	460-920
Mg, mg/L	0-30	30-60	60-120	60-120
Hardness, mg $CaCO_3$/L	0-250	250-500	500-1000	1000-2000
Cl, mg/L	0-180	180-360	360-710	710-1150
SO_4, mg/L	0-145	145-290	290-580	580-1150

2008) and were found to be lower than the MPL set by WHO (2008) of 1.5 and 3 mg/L, respectively. Arsenic is not a problem currently based on spot checks carried out by the ministry as well as studies done by various researchers in Malawi (Pritchard et al., 2007, 2008; Mkandawire, 2008; Kanyerere, 2012). All the arsenic values reported are below the MPL of 0.5 mg/L (MSB, 2005a).

Generally, it has been observed that alluvial aquifers probably have high salinity values particularly in lower Shire valley, eastern Bwanje valley and around Lake Chilwa (Bath, 1980; Monjerezi et al., 2011). In contrast, low salinity values for groundwater from weathered basement in the Bua catchment of western Malawi are on record (Bath, 1980). Elsewhere, in colluviums and basement aquifer, a very variable salinity has been observed in South Rukuru catchment area and in some instances high salinity values were recorded around Emcisweni in Mzimba District (Bath, 1980).

Fecal coliforms

Aquifer microbial contamination is from pit latrines, septic tanks, cesspool, leaky sewers and landfill leachate (Pedley and Howard, 1997). Major variations in fecal coliforms are observed between wet and dry seasons. Wet seasons are expected to produce shallow well waters with high fecal coliforms, especially if open and unprotected. However boreholes exhibit lower and below MPL for fecal coliform. Fecal coliform values of 129 – 920 colony forming units (cfu)/100 mL were observed in shallow wells in Mzuzu (Msilimba and Wanda, 2013). The authors concluded that the wells are contaminated since the values exceed the maximum recommended value of 50 cfu/100 ml (MSB, 2005a). Similar situations were observed by authors in Balaka, Blantyre, Chikhwawa, Chiradzulu, Mulanje and Zomba-Phalombe plain (Table 1).

Overall quality of groundwater

In general, high contents of cations, anions and total dissolved solids (TDS) are limiting factors to the use of groundwater (BGS, 2004; Kundell, 2008). However, based on Table 2, groundwater quality in both basement and alluvial aquifer in Malawi can be classified on average as good in terms of major cations, total hardness and sulfates. But, there are sporadic exceptions in few cases in some places within the studied districts where the groundwater quality in some parameters ranges from moderate to poor as can be observed from Table 1 when compared with Table 2.

POLICIES ON GROUNDWATER IN MALAWI

GOM (2008) identified challenges facing the water sector as (1) unharmonized policies and laws, (2) inadequate stakeholder coordination, (3) poor catchment management, (4) lack of capacity and (5) inadequate water supply and sanitation. Policies and legislation related to water resources, on the other hand, have been formulated such as the National Environmental Policy (NEP), National Strategy for Sustainable Development (NSSD), Environmental Management Act (EMA), National Environmental Action Plan (NEAP), District Environmental Action Plans (DEAPs), National Water Policy (NWP), Water Resources Act (WRA), Water Works Act (WWA) and other sectoral policies which also focus on the water resource such as the Agriculture Policy and the Forestry Policy (GOM, 2011). Standards on groundwater are available and the Malawi Standards Board is responsible for their formulation and updates. However, there are still coordination, enforcement and monitoring challenges that reduce the impact of these instruments (GOM, 2011).

Malawi is a member of the Southern Africa Development Community (SADC) that has a regional groundwater vulnerability initiative (Robins et al., 2007). The SADC established a water sector in 1996 (Molapo and Puyo, 2004). Besides, SADC has a regional strategic action plan for integrated water resource development and management that establishes rules and procedures to implement joint management of water resources between countries. There is also the Zambezi river basin commission within SADC for which Malawi is party to (Molapo and Puyo, 2004). The regional grouping established a subcommittee for hydrogeology that serves as supervisor or steering group for implementation of projects of regional magnitude (Molapo and Puyo, 2004). SADC protocol on shared watercourse systems of 1995 (and revised in 2000) places great emphasis on governance of shared water (Ramoeli, 2002; Pietersen 2005; Molapo and Puyo, 2004). It should be noted that the aquifers in Malawi are shared among adjacent states (Mkandawire, 2004; Turton et al., 2004). However, the geographic extent of the transboundary aquifers is not known which leads to management problems (Turton et al., 2004). Above all, Government of Malawi is trying its best to achieve the targets set in the millennium development goals (MDGs) and other policies. It is conclusively clear that Government of Malawi is striving at best in groundwater resources management despite the existence of various challenges.

SUMMARY OF INADEQUACIES AND POSITIVE STRIDES ON GROUNDWATER IN MALAWI

There have been some studies on groundwater in Malawi as shown in the preceding sections. Besides quality studies, some cited examples include (1) investigation of the weathered basement aquifers (Jones, 1985; Acworth, 1987; Chilton and Foster, 1995), (2) major village water supply programme featuring the introduction of village level operation and maintenance of hand pumps (Smith-Carington and Chilton, 1983), (3) Dambo research (McFarlane and Whitlow, 1990; McFarlane and Bowden, 1992) and (4) improving community based management of boreholes (DeGabriele, 2002).

However, no time series hydrologic data of any type are being collected and archived except for data collected during the drilling of boreholes (Robins et al., 2006). There is no regular groundwater monitoring done indicating a deficiency in sustainability interventions of the resource (Mleta, 2010; GOM, 2011). On a positive note, percentage of rural population with improved water source including boreholes, protected dug wells, is 82% as at 2011 as compared to 75% in 2008 (World Bank, http://data.worldbank.org/indicator/SH.H2O.SAFE.RU.Z). The responsibility of monitoring groundwater quality is vested in the hands of Department of Water through its regional and district offices.

Some significant studies on improvement of ground water quality in Malawi have been carried out such as defluoridation using clays (Msonda, 2003), gypsum (Masamba et al., 2005) and bauxite (Sajidu et al., 2008 and 2012). Pritchard et al. (2009) studied the potential of using indigenous methods of purifying water by utilizing plant extracts. These studies have yielded remarkable results. Various groundwater modeling application studies have been done in some areas (Monjerezi et al., 2012b; Wanda et al., 2013). Besides, a comprehensive groundwater resource assessment has not been examined for Malawi yet (Mkandawire, 2004).

CONCLUSIONS

Groundwater quality in Malawi can be classified as good except for some sporadic zones where some elements exceed recommended drinking water guideline values; Chimphamba et al. (2009) quoted standards adopted by Government of Malawi for drinking water in arid regions. Alluvial aquifers have high values of fluorides in some places, a situation that leads to fluorosis problems. Traces of similar incidences have been observed in weathered basement aquifers. High content of cations, anions and total dissolved solids have led to well abandonment. Saline groundwater conditions have been observed in some places like eastern Bwanje valley, Lake Chilwa and Lower Shire. However serious incidences of groundwater contamination are not imminent as indicated by fecal coliform, nitrate and sulfate observations, except in shallow wells. The amount of chemical elements found in these aquifers can be attributed mainly to the geological setting of the aquifer complex itself. The paper has shown that most of the studies are concentrated in southern region especially the Shire Valley. Thus, the conclusions are based on district level studies. More flow modeling and reactive groundwater modeling are needed to understand the hydrochemistry of the aquifer as well as mobilization and speciation of chemical species within. Transboundary groundwater data sharing, archiving and monitoring need to be in place for a better management of the shared aquifer. Multi-country research on the basement aquifer is necessary to promote sharing of knowledge between research establishments and water management institutions.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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