Threats to groundwater supplies from contamination in Sierra Leone, with special reference to Ebola care facilities

Groundwater Science Programme

Open Report OR/15/009

BRITISH GEOLOGICAL SURVEY

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Threats to groundwater supplies from contamination in Sierra Leone, with special reference to Ebola care facilities

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Keywords

Groundwater, Drinking water, Pathogens, Water Quality, Contaminant pathways, Contaminant sources, Ebola, Sierra Leone.

Front cover

A well close to the community care facility at Kumala Primary School, Sierra Leone. Used with permission from Enam Hoque (Oxfam).

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Executive Summary

The outbreak of Ebola virus disease in West Africa in 2014 is the worst single outbreak recorded, and has resulted in more fatalities than all previous outbreaks combined. This outbreak has resulted in a large humanitarian effort to build new health care facilities, with associated water supplies. Although Ebola is not a water-borne disease, care facilities for Ebola patients may become sources of outbreaks of other, water-borne, diseases spread through shallow groundwater from hazard sources such as open defecation, latrines, waste dumps and burial sites to water supplies.

The focus of this rapid desk study is to assess from existing literature the evidence for sub-surface transport of pathogens in the context of the hydrogeological and socio-economic environment of Sierra Leone. In particular, the outputs are to advise on the robustness of the evidence for an effective single minimum distance for lateral spacing between hazard sources and water supply, and provide recommendations for protecting water supplies for care facilities as well as other private and public water supplies in this region. Preliminary conclusions were:

- Considering the climate (heavy intense rainfall for 8 months), the hydrogeological conditions (prevalent shallow and rapidly fluctuating water tables, permeable tropical soils), the pervasive and widespread sources of hazards (very low improved sanitation coverage), and the widespread use of highly vulnerable water points there is little evidence that simply using an arbitrary lateral spacing between hazard sources and water point of 30 – 50 m would provide effective protection for groundwater points.
- An alternative framework that considers vertical as well as lateral separation and the integrity of the construction and casing of the deeper water points is recommended to protect water supplies from contamination by pathogens.
- The shallow aquifer, accessed by wells and springs, must be treated as highly vulnerable to pollution, both from diffuse sources and from localised sources.
- Diffuse pollution of groundwater from surface-deposited wastes including human excreta is likely to be at least as important as pollution from pit latrines and other point sources, given the low sanitation coverage in Sierra Leone.
- Even though conditions are not optimal for pathogen survival (e.g. temperatures of >25° C), given the very highly permeable shallow tropical soil zone, and the high potential surface and subsurface loading of pathogens, it is likely that shallow water sources are at risk from pathogen pollution, particularly during periods of intense rainfall and high water table conditions.
- Extending improved sanitation must be a high priority, in conjunction with improved vertical separation between hazard sources and water points, in order to reduce environmental contamination and provide a basis for improved public health.
- We recommend that risk assessments of water points are undertaken for health care facilities as soon as possible including: detailed sanitary inspections of water points within the 30 – 50 m radius suggested by the Ministry of Water Resource; assessments of the construction and integrity of the water points; a wider survey of contaminant load and rapid surface / sub surface transit routes within a wider 200 m radius of water points.
- Analysis of key water quality parameters and monitoring of water levels should be undertaken at each water point in parallel with the risk assessments.

The translation of policy on water, sanitation and hygiene into implementation needs complementary research to understand key hydrogeological processes as well as barriers and failings of current practice for reducing contamination in water points. A baseline assessment of water quality status and sanitary risks for e.g. wells vs boreholes, improved vs unimproved sources in Sierra Leone is needed. Understanding the role of the tropical soil zone in the rapid migration of pollutants in the shallow subsurface, i.e. tracing rapid pathways, and quantifying residence times of shallow and deep groundwater systems are key knowledge gaps.

1 Introduction

The outbreak of Ebola virus disease in West Africa has resulted in new care facilities being built, with associated water supplies, latrines, waste sites and burial sites. Although Ebola is not a water-borne disease, other diseases, such as cholera have been shown to spread through shallow groundwater from latrines and waste sites to water supplies. Often a pragmatic safe spacing of between 20 – 50 m is assumed, however, safe spacing is highly dependent on the hydrogeology of the shallow soil, the climate and the quality of the construction of both water points and latrines.

1.1 OBJECTIVES AND KEY QUESTIONS

The objective of this rapid desk study is to assess existing literature and evidence for sub surface transport of pathogens in relation to both the hydrogeological and socio-economic environment of Sierra Leone to provide: advice on the robustness of a single minimum figure for spacing between latrines (and other point sources of contamination) and water supply; recommendations for protecting water supplies for care facilities.

Key questions and work plan for the rapid desk study are:

1) What is known about the prevailing hydrogeological conditions within Sierra Leone?
2) What is known about available water quality data for Sierra Leone, or analogous urban areas in Africa?
3) What is known about pathogen survival and transport in the sub surface and shallow permeability in tropical soils?
4) Interpret the data from 1 – 3 within a source-pathway- receptor framework to provide recommendations on the robustness of a single minimum separation and appropriate designs to increase the protection of treatment centre water supplies.
5) Write up the results of 1-4 into an open report

This report starts by giving a brief overview of the public health and natural physical conditions of Sierra Leone. It then provides a review of the hydrogeology, water quality and pathogen survival conditions in Sierra Leone and analogous hydrogeological settings in Africa. The risks to groundwater supplies are then presented using a source-pathway-receptor framework. Finally recommendations for the protection of water supplies for care facilities and communities made and evidence gaps highlighted.

1.2 BACKGROUND AND PUBLIC HEALTH ISSUES IN SIERRA LEONE

Having only emerged from a ten-year civil war in 2002, during which most of the nation's public services and physical infrastructure were destroyed, Sierra Leone's public services are weak, and investment in new services has barely begun. As a consequence, water and sanitation coverage are extremely low. Table 1 sets out the most recent JMP data for Sierra Leone. The high rates of open defecation (especially in rural areas) and high dependence on surface water in rural areas present a particular public health hazard. In urban areas one-third of the population either practice open defecation and or use unimproved sanitation, and much of the access to "improved" water supply is by illegal and unsafe connections to public supply mains.

Table 1 Sanitation and water supply coverage, Sierra Leone, Source JMP 2014 update

(a) Sanitation coverage 2012 (%)

Urban				Rural				Total			
Improved	Shared	Other unimproved	Open defecation	Improved	Shared	Other unimproved	Open defecation	Improved	Shared	Other unimproved	Open defecation
22	42	26	10	7	19	35	39	13	28	31	28

(b) Water supply coverage 2012 (%)

Urban					Rural					Total				
Total improved	Piped on premises	Other improved	Other unimproved	Surface water	Total improved	Piped on premises	Other improved	Other unimproved	Surface water	Total improved	Piped on premises	Other improved	Other unimproved	Surface water
87	11	76	5	8	42	1	41	17	41	60	5	55	12	28

1.3 THE 2014 EBOLA OUTBREAK

The first cases of the current Ebola outbreak were reported in neighbouring Guinea and then later in Liberia: by 20 April 2014, 242 suspected cases had resulted in 147 deaths in Guinea and Liberia (Gatherer 2014). A recent study using genome sequencing by Gire et al (2014) suggest that this West African variant likely diverged from the central African lineages around 2004.

The Ebola crisis in Sierra Leone began with the first cases in the eastern districts of Kailahun and Kenema in early May 2014, close to the border with Guinea and Liberia. During the period June to November 2014 the infection spread westwards through Bo, Tonkolili, Bombali and Port Loko districts, reaching Western Area Rural and Western Area Urban (i.e. Freetown) from October onwards (Figures 1 and 2). By the end of January 2015 more than 10,340 cases (confirmed, probable and suspected) and 3145 deaths had been reported by WHO[1].

From December 2014 significant numbers of Ebola Care Facilities (and beds) were established. Prior to this, most victims recovered or died in their communities. Therefore, through most of 2014 it is probable that the contaminated body fluids, wastes and corpses were handled and managed in the community rather than at dedicated care facilities. The risk of contamination of the general environment (however short-lived because of the limited survival time of the virus) was consequently higher in 2014 than subsequently. From December 2014, an

[1] WHO (2015a) Global Alert and Response, Ebola Situation Report.
http://www.who.int/csr/disease/ebola/situation-reports/en/ last visited 4 March 2015

increasing number of victims were treated at Ebola Care Facilities, giving greater opportunity for safe handling and containment of contaminated wastes.

Nevertheless, in the latter part of 2014 and into 2015 disturbing (mainly anecdotal) evidence has emerged of poor practices, including:

- Health workers taking used personal protective equipment off-site into their homes;
- Ambulances being washed out in local watercourses;
- Solid wastes being dumped outside of care facilities; and
- Ebola care facilities being sited only metres away from pre-existing wells (see Figures 3 and 4).

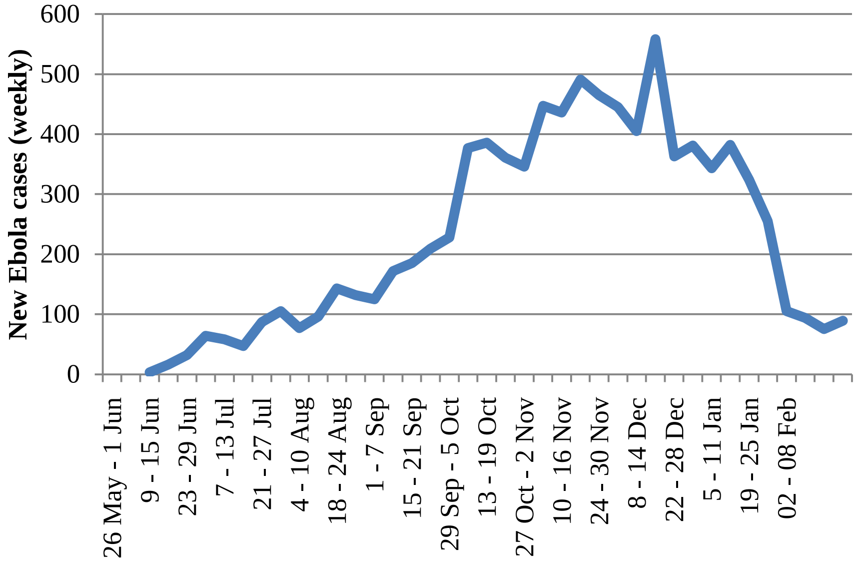


Figure 1 Ebola cases in Sierra Leone, weekly May 2014 to February 2015. Data source, Ministry of Health Sierra Leone. Weekly patient database statistics downloaded from WHO[1]

Water-borne epidemics are a recurring problem in Sierra Leone. There have been several cholera and Shigella outbreaks reported in different parts of Sierra Leone since the mid 1990's (e.g. Guerin et al. 2004; O Dyer 1995). A recent study by Nguyen et al. (2014) found that the consumption of unsafe water, and street vended water was a significant risk factor for *V. cholera* transmission during a 2012 cholera epidemic in Sierra Leone, despite recorded high levels of access to 'improved' water sources in urban areas as shown in table 1b above.

This was the largest reported outbreak in the country since 1995 with a total of 22,800 reported cases and 296 deaths. This study underlines the risks of such outbreaks occurring even where reported improved water source coverage is high, particularly in densely populated urban areas. Testing for residual chlorine in stored water and public supplies suggested that treatment was inadequate given the risks of transmission. The authors argue that the JMP classification of "improved" water sources is inadequate since it does not include water quality criteria. This is supported by a systematic review prepared for the JMP that indicated 1.8 billion people with access to improved water sources drink water that is faecally contaminated (Bain et al., 2014).

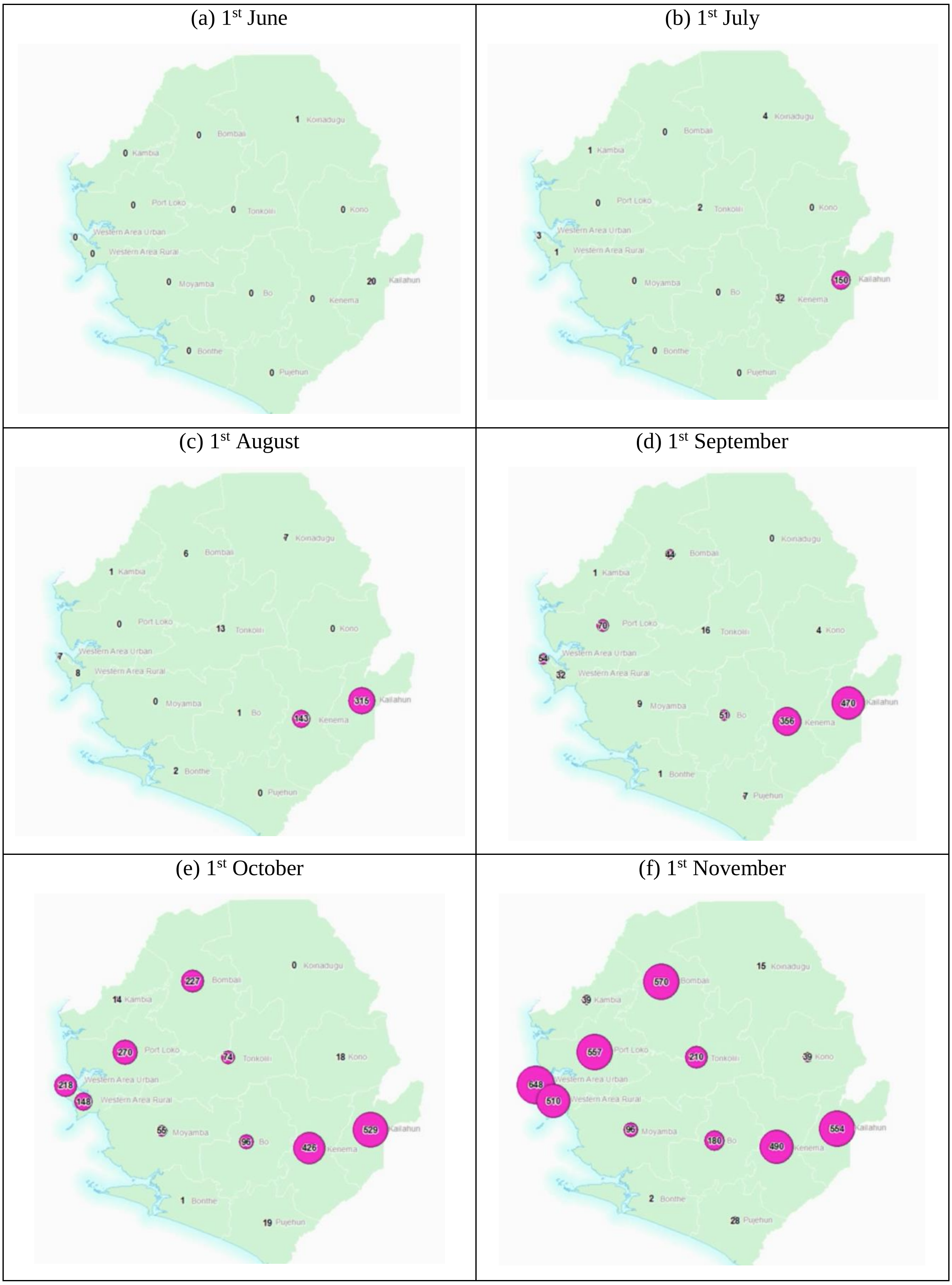


Figure 2 Spread of Ebola in Sierra Leone, June to November 2014, Source MapAction [**http://www.mapaction.org/?option=com_mapcat&view=diary&id=51**](http://www.mapaction.org/?option=com_mapcat&view=diary&id=51)**]**

Figure 3 A well close by the care facility at Magburaka Hospital. Used with permission from Ishmail Kamara (source: Ministry of Water Resources/ASI)

Figure 4 An Oxfam well close to the community care facility at Kumala Primary School. Used with permission from Enam Hoque (source: Oxfam)

1.4 CLIMATE, HYDROLOGY, GEOLOGY AND PHYSICAL RELIEF

1.4.1 Climate

Sierra Leone experiences a humid tropical climate in which mean annual rainfall is approximately twice the mean annual potential evapotranspiration. Rainfall is unimodal and highly seasonal, with a peak in August and dry season from December to March. Temperatures are relatively uniform throughout the year.

Rainfall over most of Sierra Leone commences in or around April, peaks in August, and reduces to near-zero in December (Figure 5). Inter-annual variation is generally limited as shown by the small interquartile ranges, however some extremes are possible as indicated by the large monthly ranges. Ambient air temperatures vary only within a narrow range 24 – 28 degrees C) over the year. The lowest temperatures occur in July, August and September, in the middle of the rainy season, and the highest in February and March in the latter part of the dry season.

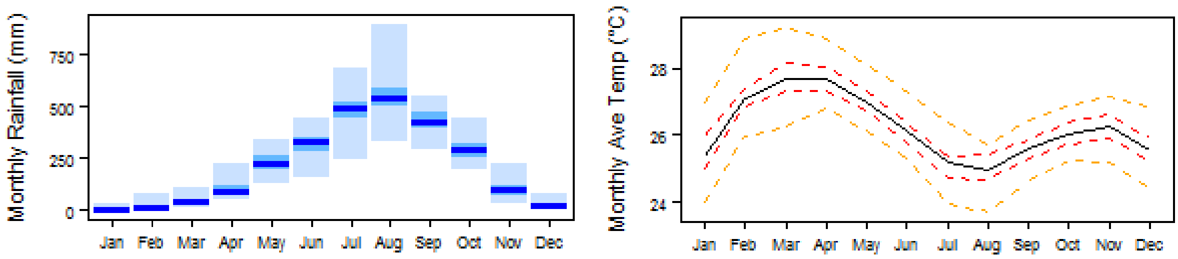


Figure 5 Monthly rainfall and temperature for Sierra Leone, source CRU data (Jones and Harris 2013) 1950 – 2012 median, interquartile range and max and min for each month

Mean monthly potential evapotranspiration (ET) has been estimated by FAO Climwat at six locations According to these estimates, mean annual potential ET ranges from 1,332 to 1,639mm across Sierra Leone.

The spatial distribution of mean annual rainfall is shown in Figure 6. Panels (a) and (b) show the patterns for two overlapping periods, from different sources. Panels (c) and (d) show as insets the rainfall pattern over the hilly Freetown peninsula. Mean annual rainfall ranges from around 1,750mm in the north-east to over 4,000mm in the Freetown peninsula.

There is some evidence of warming over recent decades (McSweeney et al, 2010) that mean annual temperature has increased by 0.8˚C since 1960, an average rate of 0.18˚C per decade and the frequency of hot nights has also increased. There is less convincing evidence for a long term trend in rainfall, and insufficient rainfall monitoring to determine changes in rainfall intensity.

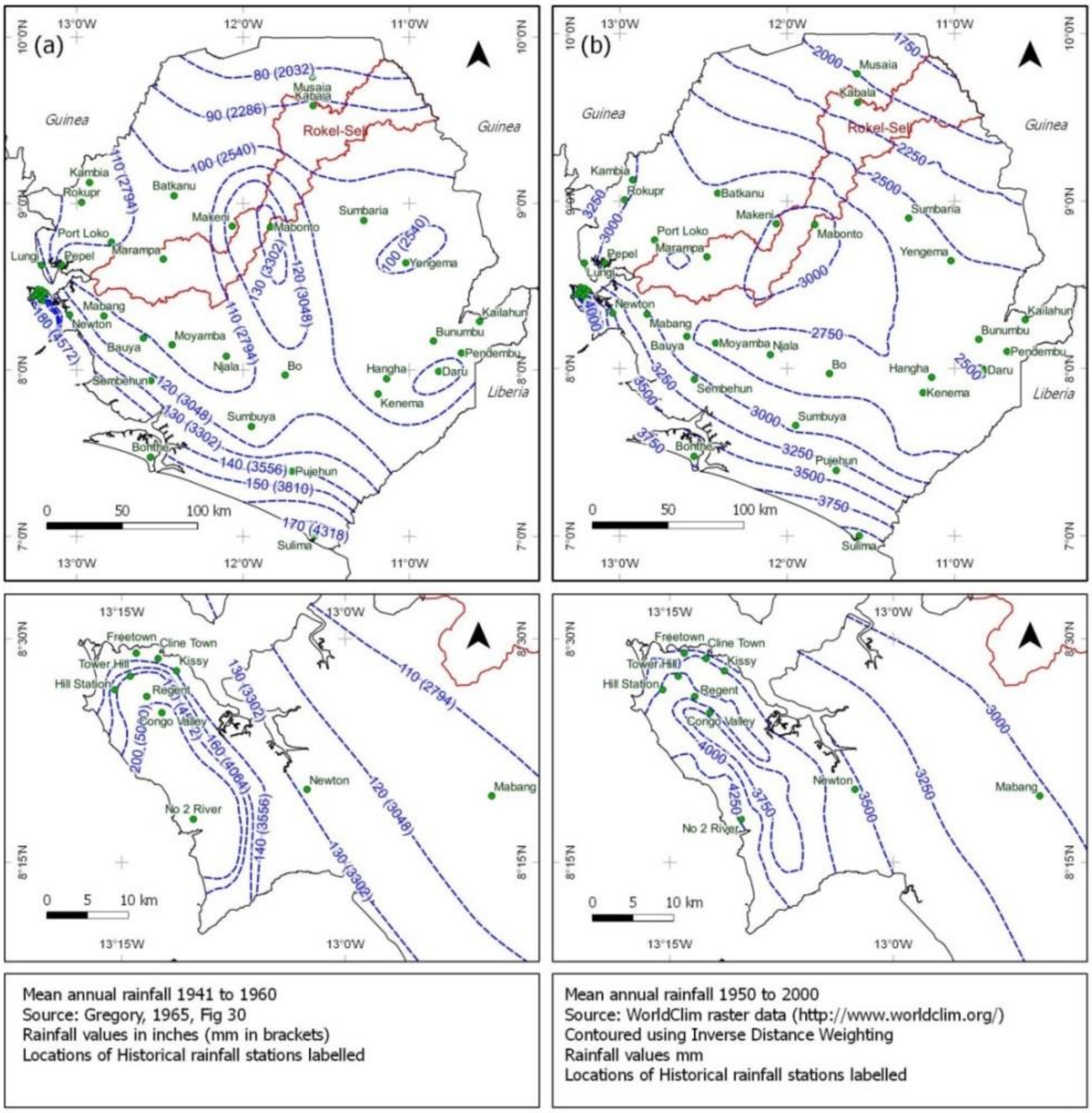
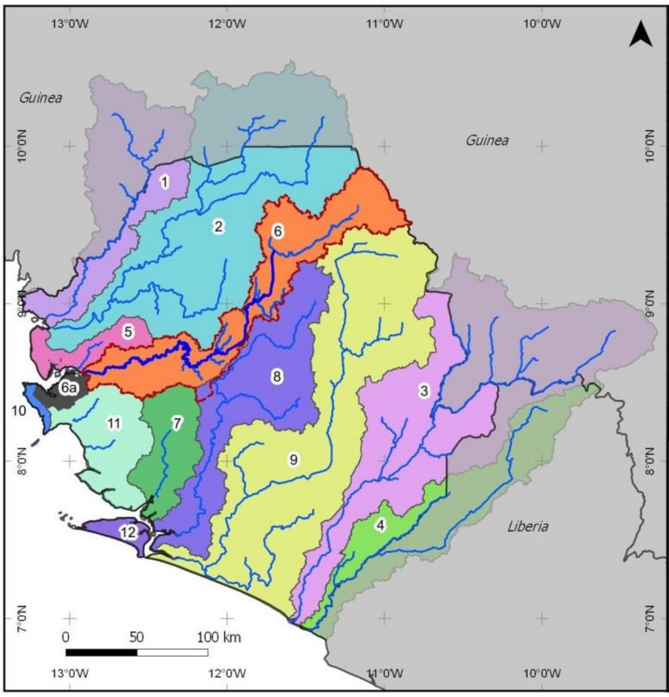


Figure 6 Rainfall over Sierra Leone. Sources of original data shown in Figure. This version is reproduced with permission from the Ministry of Water Resources/ASI

1.4.2 Hydrology

Five main rivers (Little Scarcies, Rokel, Jong, Sewa and Moa) flow from north-east to south-west, draining most of Sierra Leone's land surface. In addition six smaller basins and drainage areas (Great Scarcies, Lokko, Rokel Estuary, Western, Robbi/Thauka and Sherbro Water Resources Areas) complete the picture (Figure 7).

FAO (Aquastat) estimate Sierra Leone's total renewable water resources as 160km^3/year (out of 182.6km^3/year which is estimated as rain. This estimate of the nation's water resources – at 88% of mean annual rainfall - is certainly a gross over-estimate, as it fails to account adequately for evapotranspiration (Carter et al, 2015). A more realistic estimate is that given by Schuol et al (2008), of 59.3-98.4 km^3 per year, between 32% and 54% of mean annual rainfall.



Basin	Name	Country Area	Total Area
B 1	Great Scarcies Basin	2979	8303
B 2	Little Scarcies Basin	13383	18955
B 3	Moa Basin	9583	19835
B 4	Mano Basin	1959	7776
B 5	Lokko Basin	1565	1565
B 6	Rokel Basin	8236	8236
B 6a	Rokel Estuary (South)	579	579
B 7	Gbangbaia Basin	3121	3121
B 8	Jong Basin	8288	8288
B 9	Sewa Basin	19022	19022
B 10	Western WRA	223	223
B 11	Ribbi/Thauka WRA	3670	3670
B 12	Sherbro WRA	612	612
	Totals	**73220**	**100185**

Notes:
* Source HydroSHED catchment boundaries http://hydrosheds.cr.usgs.gov/index.php
* Rokel basin area has been modified after manually digitising the Rokel boundary (Red line)
* All areas are in square kilometres
* WRA - Water Resources Area
* "Country Area" is basin area inside Sierra Leone
* "Total Area" is total basin area
* Basin 6a is part of the Rokel River management area shown in GOSL documents. It is subdivided here for clarity

Figure 7 Sierra Leone's river basins and drainage areas. Source, reproduced with permission from the Ministry of Water Resources/ASI (2015)

Runoff is highly seasonal, reflecting the seasonal distribution of rainfall. Figure 8 shows the mean monthly flows for the Rokel river at Bumbuna (latitude 9.05N, longitude 11.73W), derived from what is probably the best river flow record in Sierra Leone. Discharge increases from May, peaking in September and decreasing to near-zero by March.

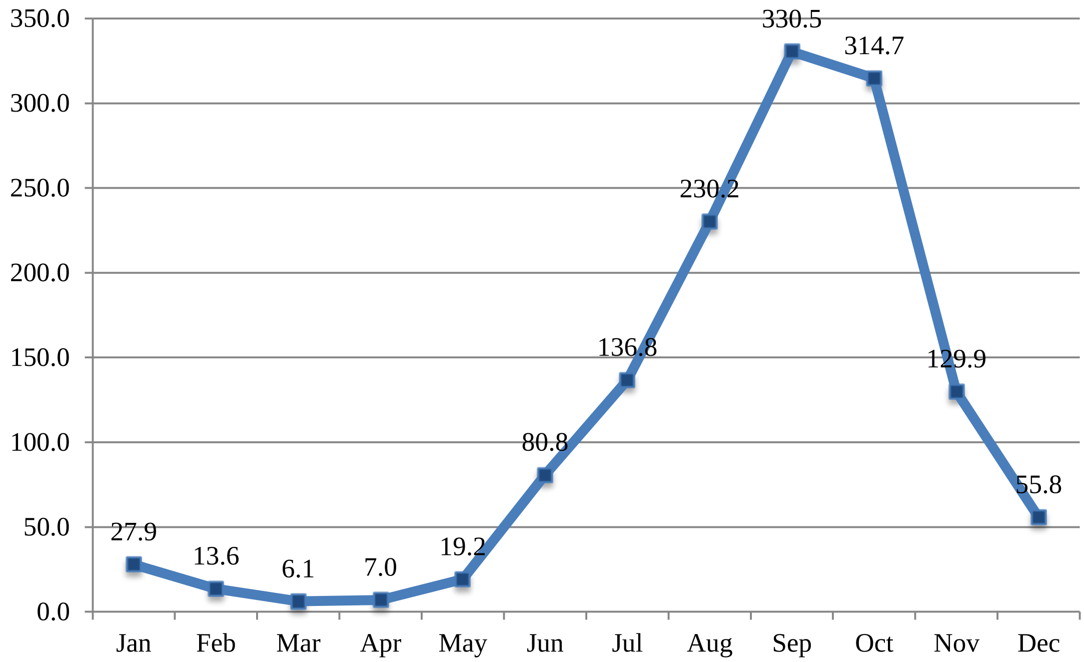


Figure 8 Mean monthly flows, Rokel river at Bumbuna, 1970-1978, m^3/s. Source, Nippon Koei UK (2005)

A number of studies (including Akiwumi, 1994; Nippon Koei, 2005; Carter et al 2015) have demonstrated that approximately 40% of the Rokel river flow (and by extension that of the other major rivers) consists of shallow seasonal baseflow – water which enters the shallow aquifers during the rainy season, and which discharges to the river within months in response to hydraulic gradients towards those rivers.

1.4.3 Geology

Figure 9 is a simplified geological map of Sierra Leone. Most of the country (with the exception of the Freetown Complex and the Bullom Group) is underlain by sedimentary, meta-sedimentary, igneous and metamorphic rocks of the Archaean Basement Complex and Lower Palaeozoic / Upper Proterozoic Consolidated Sedimentary formations. Table 2 sets out brief descriptions of the main geological units. These units are further described in section 2 in hydrogeological terms.

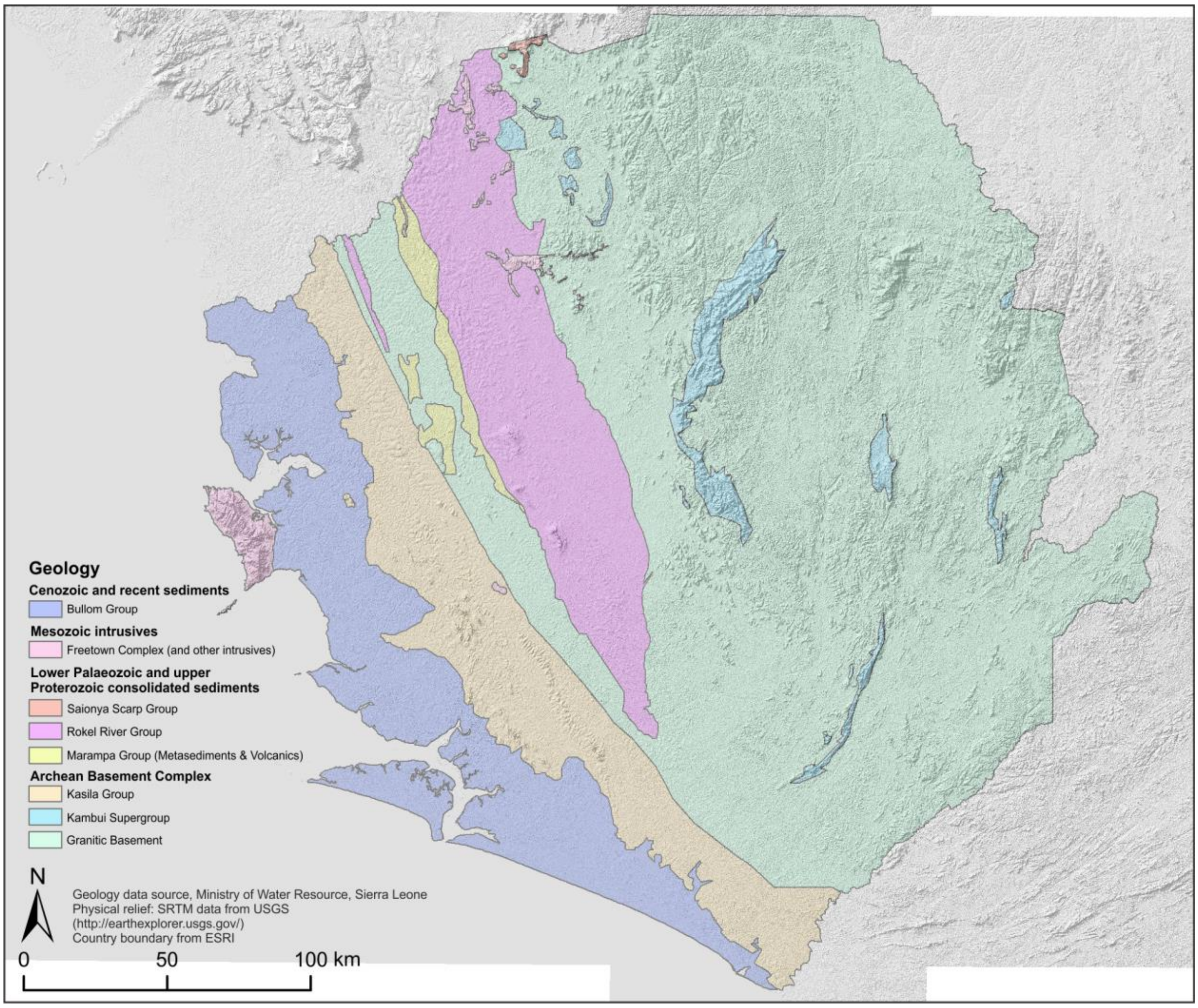


Figure 9 Simplified geological map of Sierra Leone. Source, Ministry of Water Resources/ASI (2015), relief from USGS SRTM data (accessed Feb 2015).

Table 2 Descriptions of the main geological units in Sierra Leone. Source, Ministry of Water Resources (2015)

Geological Unit	Age	Descriptions
Bullom Group: unconsolidated sedimentary rocks	Cenozoic (Tertiary and Quaternary to recent)	Poorly consolidated marine and estuarine sediments – sands, gravels and kaolinitic clays with some lignite
Ultrabasic Igneous Intrusives	Mesozoic (Jurassic and Triassic)	Freetown Peninsula Complex and other intrusive
Saionya Scarp and **Rokel River Group**: consolidated sedimentary rocks	Lower Palaeozoic (Cambrian) and Proterozoic	Variegated shales, siltstone, mudstone interbedded with volcanic and quartzite bands
Precambrian Basement Complex: ancient crystalline granitic gneiss with supracrustal volcanic and sedimentary belts	Neoarchean and Archean	**Marampa Group**: metasediments and volcanics **Kasila Group**: granulites basement granites, gneisses and migmatites. Volcanic greenstone, amphibolite and gneiss

1.4.4 Physical relief and soils

A coastal strip approximately 50km in width, covering about 15% of the country, gives way to inland plains and plateaus in the interior. The lower plains, covering 43% of the country rise from 40m in the west to 200m in the east. Swampy depressions in the west are known as bolilands. Figure 10 shows an elevation map of Sierra Leone (10a) and two insets which show detailed elevation models for two areas of Sierra Leone, the Freetown Peninsula (Figure 10b) and Lunsar (Figure 10c). Figures 10b and 10c illustrate the extensively weathered tropical soil terrain, including the distinctive duricrust development (see Bowden 1997) and the well-developed fracture network associated with the intrusive granites.

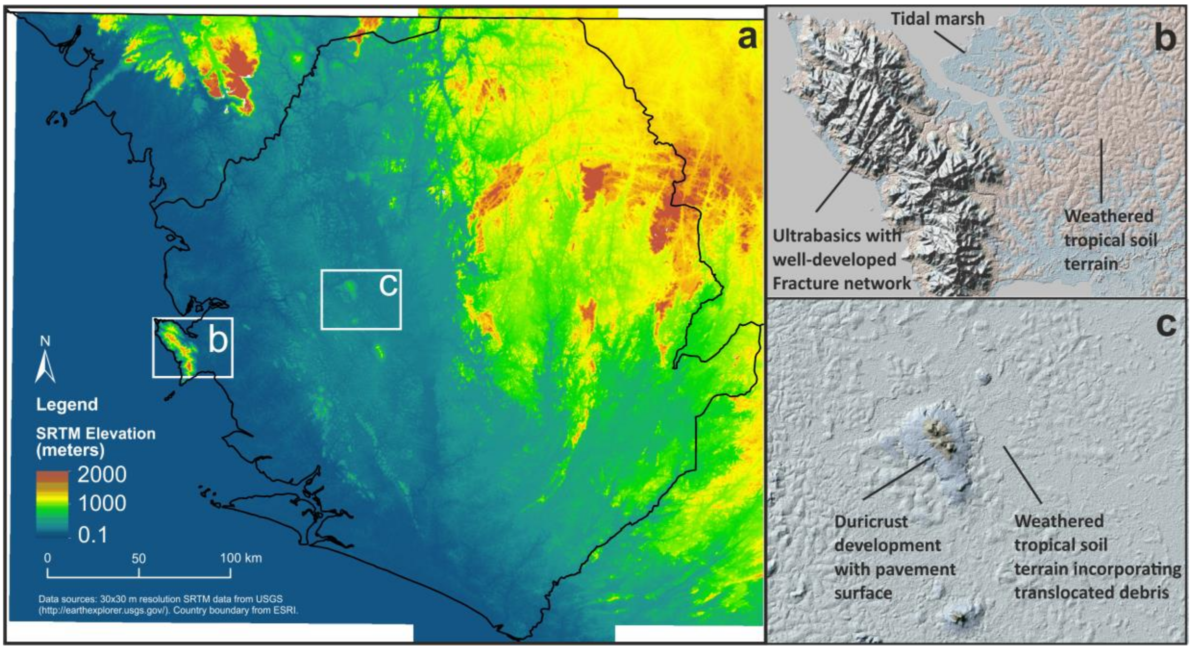


Figure 10 Physical relief of Sierra Leone a) Sierra Leone and surrounding region, b) Freetown peninsula, c) Lunsar. Data source, USGS SRTM data (accessed Feb 2015).

In the north-east and south-east, the plateaus range from 300m to 700m altitude, and cover 22% of the country. Hills and mountains in the east reach a maximum elevation of nearly 2,000m at Mount Bintumani in the Loma Mountains, while the hills formed by the Freetown Complex reach 800m around Sierra Leone's capital.

Figure 11 shows the distribution of soils in Sierra Leone. The lowland area in the western half of Sierra Leone is dominated by strongly weathered Ferrasols with low nutrient levels. The upland area to the east has a partial cover of Pisoplinthic Plinthosols[2], soils with accumulations of iron that hardens irreversibly when exposed to air and sunlight.

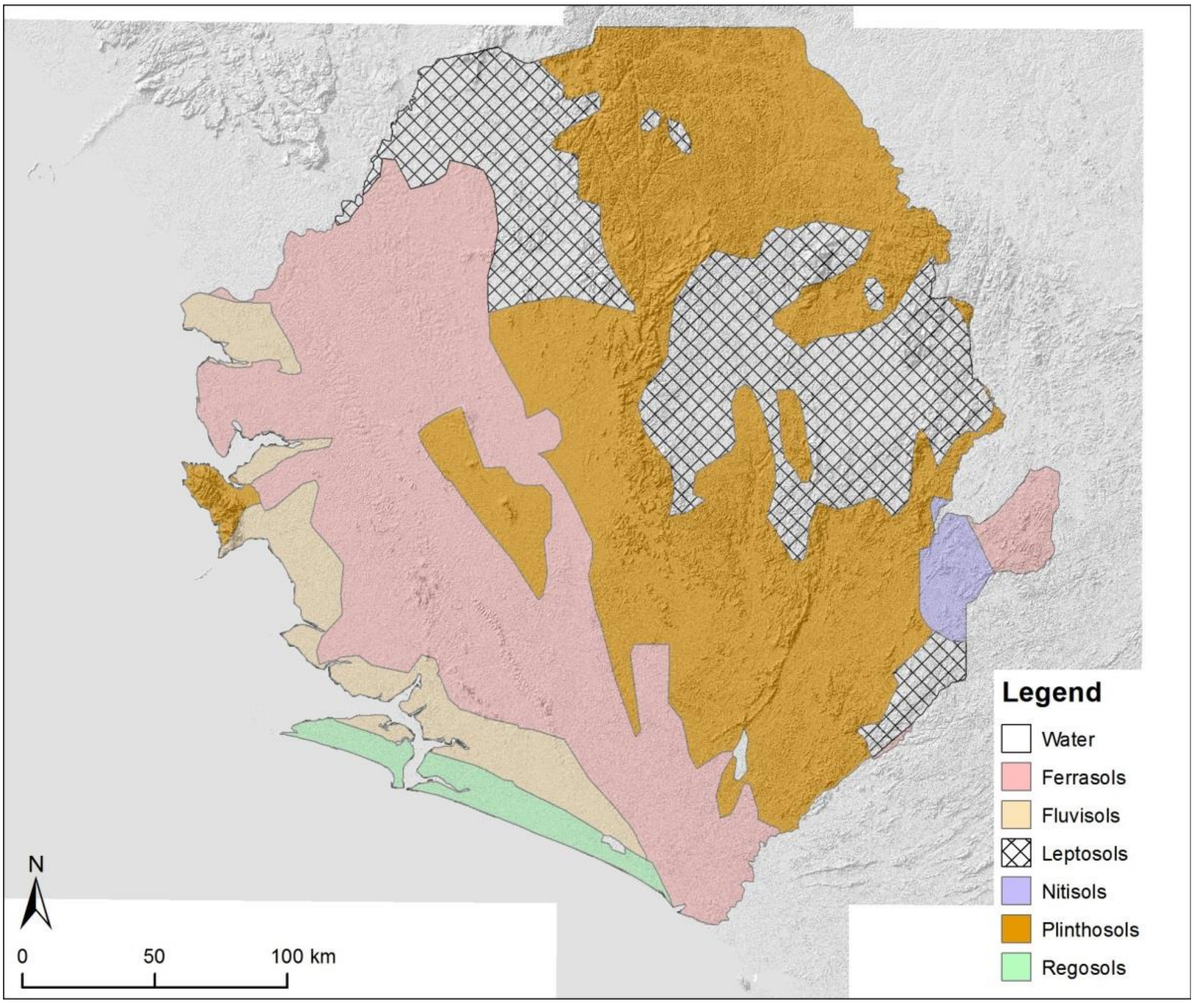


Figure 11 Soil map of Sierra Leone (soil data from Jones et al 2013, topography data (SRTM) from USGS, accessed in February 2015)

For simplicity these two iron rich soils are referred to as 'tropical soils' in the following sections of this report. Toward the coast these become yellow in colour. Elsewhere there are Lithic Leptosols, shallow soils over hard rock with bedrock close to the surface.

[2] Plinthosols are often referred to as 'iron stone' or 'Laterites' in the literature. This terminology has now been superseded by the use of term Plinthite. Red, iron-rich tropical soil profiles form by leaching of silicates and deposition of iron and aluminium oxides, and may take the form of clay-rich profiles, or they may present as hard consolidated layers, often several metres thick. In some cases they occur as gravelly deposits of iron and manganese oxides.

In many cases tropical soils contain openings and macropores which permit rapid movement of water. These also have non-linear increases in horizontal permeability as moisture content increases during the onset of the rainy season, and under high water table conditions.

Summary physical geography of Sierra Leone:

The physical context forming the background to this report is one in which poor sanitary conditions conspire with high and intense rainfall, rapidly responding hydrology, unfavourable geology and physical relief to pose significant threats to groundwater from human pathogens.

2 Review of existing studies relevant to Sierra Leone

This section summaries the current evidence base regarding: the existing hydrogeological understanding in humid tropics, particularly regarding rapid vertical and lateral pathways; water quality issues from different groundwater sources, issues of seasonality and impacts from sanitary sources; pathogen survival in humid tropical regions.

2.1 HYDROGEOLOGY

2.1.1 Overview of the hydrogeology of Sierra Leone

The main hydrogeological environments of Sierra Leone are summarised in Table 3. There will be a wide variation in the properties of the aquifers within each of the major hydrogeological units, however, the main distinction is between the relatively low permeabilities of the old, hard rocks of the Precambrian Basement Complex, Saionya Scarp/Rokel River Group and Ultrabasic intrusives on the one hand, and the higher permeability and storage of the Bullom Group sands. Within the Precambrian Basement, flow is through fractures giving rapid connections over 10s of metres.

The weathered basement rocks form the most widespread and important aquifer across Sierra Leone, The weathered zone is derived from the underlying parent rock formations, under intense rainfall and large seasonal groundwater table variations. The resulting thick tropical soils form an important part of both the unsaturated zone and shallow aquifers (Akiwumi, 1987; UN, 1988). Investigations of weathered basement aquifers elsewhere have highlighted the importance of flow paths at the base of the weathered zone where groundwater flows primarily through fractures associated with the stone line at the base of the collapse zone or the basal breccia (Wright and Burgess, 1992; Foster and Chilton 1993). At depth, below the weathered zone, open fractures can be found associated with fault zones or the regional stress field.

Above the fracture zone at the base of the weathered zone, the weathered rock can often be clay rich with a high percentage of kaolinite clay and in certain circumstances other clay minerals such as smectite (Fookes 1997). The upper section of the weathered zone, above the clay rich kaolinite often comprises red layers of material from which the clays have been leached, leaving oxides of iron, aluminium and manganese. These can often be on the form of indurated layers or gravelly layers, and both can rapidly transmit water horizontally. For example Bonsor et al. (2014) found permeability values of >300 m/d in these shallow layers (2 – 4 m depth), several orders of magnitude greater than the permeability of the deeper layers.

In weathered crystalline basement, most sustainable groundwater sources tend to exploit groundwater in fractures at the base of the weathered zone. This can be in fractures 15 – 40 m depth, depending on the thickness of the weathered zone. The mean residence of time of groundwater within this zone has been measured as 30 – 60 years by Lapworth et al (2013) in similar hydrogeological and climatic environments in southern Nigeria. Shallower sources which only exploit groundwater within the upper weathered material are generally much less reliable, and tend to dry up rapidly when the rains stop and this permeable soil layer drains (Boiurgois et al., 2013).

Table 3 Hydrogeology of Sierra Leone's main geological formations. Adapted from, Ministry of Water Resources (2015)

Hydrogeological Unit (Approx % of Land Area)	Sub-Units	Aquifer description	Well or Borehole depths (m)	Well yields (L/s)
Precambrian Basement Complex (78%)	Overlying valley fill deposits	Sands, gravels and clays overlying the basement rocks, can be high permeability, flow is intergranular	up to 15m	Nd likely to be 0.3 – 5 litres
	Weathered zone	Highly weathered rock often transformed to a thick tropical soil. Can have very high lateral permeability in shallow clay depleted layers	up to 20m (max 37m)	0.3 – 1.5
	Fractured crystalline bedrock	At the base of the weathered zone where the bedrock is extensively fractured but not clay rich, and also in deeper fracture zones associated with faults	35m (average) 60m (max)	0.3 – 1.5
Saionya Scarp / Rokel River Group (9%)	Weathered layer	Often clay	nd	nd
	Fractured sediments	Old sediments with little porosity, groundwater flows within fractures along old bedding plains	nd	nd
Bullom Group (12%)	Unconsolidated sands and clays (inland alluvial & coastal)	Groundwater flow is intergranular and storage can be high. Fracture flow is less common	10 to 20m	up to 3
	Interbedded sands and clays		30 – 80m	up to 6
Ultrabasic Igneous Intrusives (1%)	Fractured gabbros	Groundwater flow within fractures, often does not have a thick weathered zone developed.	nd	nd
	Weathered and fractured dolerites		nd	nd

Sub-vertical features allowing rapid transit of water from the ground surface to groundwater in the shallow permeable layers in the tropical soil, and sometimes deeper to the permeable fracture zones towards the base of the weathered zone. These sub-vertical features provide vertical pathways and *can include* geological features, such as quartz veins or faults, or biological features such as tree roots and old termite tunnels, and anthropogenic features such as abandoned wells, unlined pit latrines or poorly constructed wells (Wright and Burgess 1992, Hendricx and Flury 2001). The unsaturated zone in Sierra Leone, which is often a useful buffer for reducing contaminant loads from ground surface to aquifer can therefore be easily bypassed.

Early experiments using lithium bromide tracers in weathered basement geology in Botswana to model the movement of contaminants from the shallow subsurface to a borehole showed rapid transport times and good recovery, implying fracture flow with little diffusion (Lewis et al., 1980). Taylor et al. (2009) carried out a study in the weathered basement in Uganda using *E.coli* bacteriophage and forced gradient solute tracer experiments. The tracer was largely unrecovered, and rapid phage detection at the pumping well show that groundwater flow velocities exceed that of inert solutes and are consistent with statistically extreme flow pathways. This is consistent with size exclusion effects in colloid studies that show earlier arrival peaks for larger colloidal material compared to bulk solutes due to reduced matrix diffusion the and the development of preferential pathways (e.g. Sirivithayapakorn and Keller 2003; Lapworth et al., 2005).

Figure 12 shows some groundwater level data collected during the Sierra Leone water security project, which has included high-resolution monitoring of water levels in hand-dug wells and boreholes in the middle Rokel river basin. Lateral movement of groundwater is determined by the combination of hydraulic gradient and permeability. Hydraulic gradients become significant in the rainy season as water tables respond to rainfall-recharge, and gradients towards zones of low relief become established.

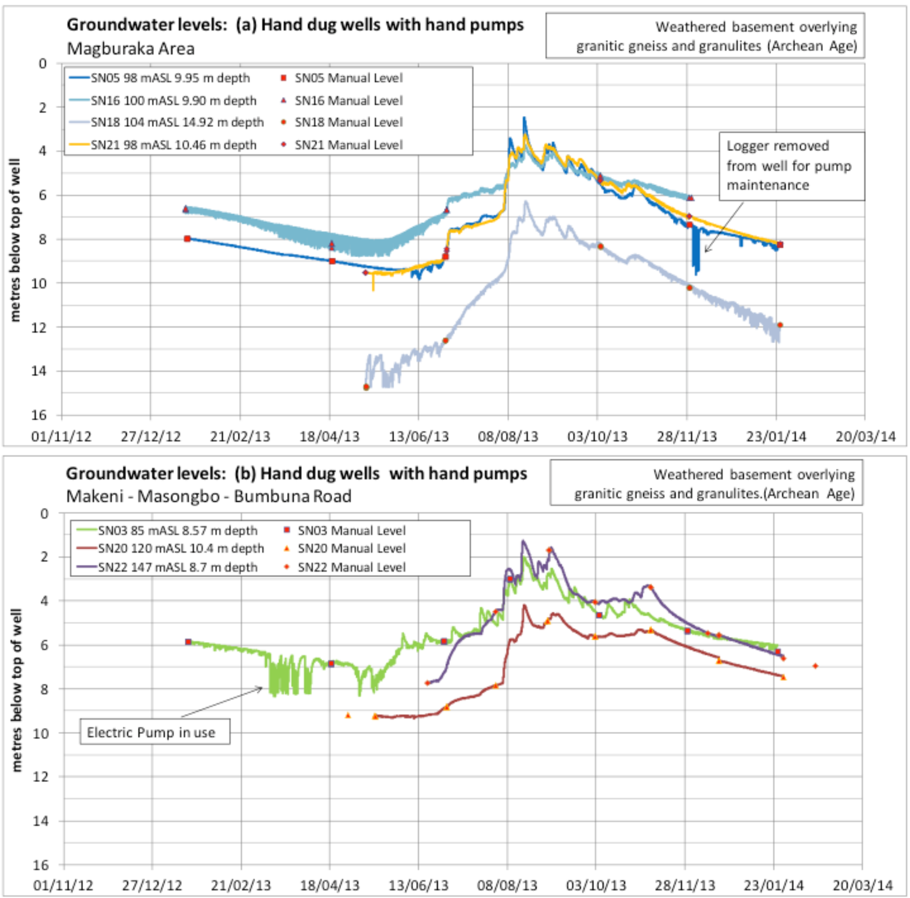


Figure 12 Groundwater levels for selected wells in Sierra Leone. Source, reproduced with permission from the Ministry of Water Resources (2015)

The graphs illustrates a number of key points:

- Water tables respond rapidly to the first rains in May;
- Water tables rise to a peak around mid- to end August, coinciding with the peak of the rains;
- Water tables recede rapidly after the peak rainfall month, despite the subsequent months having significant rainfall;
- Water tables continue to recede through the dry season, reaching their lowest levels in April.
- Average annual variation in 2013 recorded from 9 hand dug wells in the weathered basement was between 2.7-8 m, averaging 5.4 m

These observed data are consistent with the conceptual model of the hydrogeology of the weathered basement aquifer described above. Groundwater recharge is rapid during the rainy season often responding to individual rainfall events, which suggest the widespread existence of sub-vertical preferential flow pathways in the unsaturated zone. The high rate of discharge from the aquifer indicated by seasonal baseflow to the rivers, the drying up of many shallow wells and the relatively rapid decline of groundwater levels after rain can be explained by the existence of sub-horizontal preferential flow paths and zones of seasonally high permeability.

Hydrogeology summary:

Infiltration from the ground surface to the sub-surface is likely to be relatively rapid, occurring within hours in some circumstances.

Sub-horizontal flow is likely to be rapid, as a consequence of the existence of preferential flow paths and low-permeability layers.

Groundwater in fractures below the weathered zone (typically 15 – 40 m thick) is likely to be less vulnerable to contamination due to the presence of the clay-rich layer. However, some fractures can rapidly transmit water rapidly through the hard rock.

The groundwater system can be conceptualised as two zones;

- A shallow (regolith) groundwater zone, accessed by dug wells and which is vulnerable to both diffuse surface and subsurface sources of contamination due to limited attenuation potential in the subsurface as well as rapid horizontal and vertical pathways which are likely to be regularly activated given the climate and geology of Sierra Leone.
- A deeper (hard rock) groundwater system with longer flowpaths and greater potential for natural attenuation of hazards which is accessed by boreholes.

2.1.2 Protection zones for groundwater points close to health centres

The evidence summarised above give rise to a number of questions which explore the feasibility of protecting groundwater consumers in Sierra Leone from faecal and other contamination.

1) What role is there for water source protection zones?
2) Is there a preference between different groundwater source types?

3) Are there any specific design and construction considerations which could better protect water consumers?
4) How relevant are these general considerations in the context of Ebola?

The first of these questions is the subject of this section while the second and third are addressed in the following section. The specific case of Ebola is addressed in the report conclusions.

The use of source (water point) protection zones (SPZs) has become well-established in public water supply practice in the UK and other countries. Resources for the present study do not allow for a full review of the subject, but a limited summary of UK practice is presented here, mostly based on Environment Agency (2009). In current practice, three zones are defined:

- **SPZ1 – Inner Protection Zone** is defined as the 50 day travel time from any point below the water table to the water point. This zone has a minimum radius of 50 metres.
- **SPZ2 – Outer Protection Zone** is defined by a 400 day travel time from a point below the water table. This zone has a minimum radius of 250 or 500 metres around the water point, depending on the size of the abstraction, except if the actual contaminant source has been verified.
- **SPZ3 – Catchment Protection Zone** is defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source. In confined aquifers, the source catchment may be displaced some distance from the source. For heavily exploited aquifers, the final Source Catchment Protection Zone can be defined as the whole aquifer recharge area where the ratio of groundwater abstraction to aquifer recharge (average recharge multiplied by outcrop area) is >0.75. There is still the need to define individual source protection areas to assist operators in catchment management.

The determination of source protection zones is carried out through four steps:

1) Data collation and conceptualisation
2) Calculations, modelling and hydraulic capture zone production
3) Technical review of hydraulic capture zones with modification, where appropriate, of the zone boundaries to produce the final SPZs
4) Documentation and publication of final SPZs

The entire procedure is based on a number of key assumptions, which, while are realistic for high-income countries such as the UK, do not apply in countries such as Sierra Leone currently. These include:

- A mandate within a designated public sector institution to pursue this approach to water resource protection – in Sierra Leone the legal framework is yet to be approved, and the water resources department of the Ministry is in its infancy;
- The availability of trained and experienced scientists with the physical and financial resources to undertake the necessary data collection, conceptualisation, calculation, modelling and decision-making – these are not yet available in Sierra Leone;
- The existence of centralised data management systems – in Sierra Leone even basic document filing is not adequate yet to contemplate this approach.

Nearly fifteen years ago DFID commissioned BGS to undertake a piece of work with parallels the present assignment. The ARGOSS (Assessing the Risks to Groundwater from On-site Sanitation) project resulted in a manual (BGS, 2001) containing guidance on determination of safe distances between pit latrines and groundwater wells or boreholes.

The ARGOSS guidance assumes that contamination at a groundwater source may come from either (a) seepage from pit latrines to the aquifer, then through the aquifer to the well, or (b) pollution because of poor design or construction of the well or borehole.

By way of numerous assumptions, approximations and modelling simplifications, the ARGOSS guidance provides a methodology for:

- Assessing the possible attenuation of contaminants in the unsaturated zone;
- Assessing attenuation with depth below the water table; and
- Assessing attenuation due to lateral movement of water in the aquifer.

The main drawbacks of the approach in relation to the present work are threefold:

- It did not consider multi-point source of pollution from widespread surface contamination (such as open defecation), which may well be the single most important pollutant source and pathway in Sierra Leone;
- It did not take sufficient account of preferential flowpaths and high permeability zones in the sub-surface. The model of permeability used in the approach is that there is a single ratio of horizontal to vertical permeability (ranging from 1 to 10);
- There is no allowance for seasonal fluctuation of water table in the approach – the rapidity with which pollutants can reach the water table is clearly much higher when that water table is very shallow; also the rate of movement in the aquifer will be determined largely by (relatively steep) wet season hydraulic gradients.

The final reason why neither the use of source protection zones nor the application of the ARGOSS methodology is appropriate for use in Sierra Leone is the burden of data collection which would be needed. The water point mapping exercise recently undertaken in Sierra Leone revealed the existence of 18,401 hand-dug wells and 1,952 boreholes. Despite the low sanitation coverage in Sierra Leone, there are probably at least five times this total number (say 100,000) of latrine pits. Undertaking assessments of even a fraction of these would be onerous in the extreme.

It is not simply the number of water points and latrines which would make such exercises impracticable, but also the heterogeneity and highly site-specific nature of the ground conditions at each site. In a very real and practical sense, the detailed hydrogeology of each site is not only unknown, but unknowable.

For these reasons the Ministry of Water Resources guidance document "Protection of water resources at and around Ebola care facilities" (Ministry of Water Resources, 2015b) adopted the simple notion of siting care facilities no closer than 30m from a hand-pumped well or borehole, and 50m in the case of a motor-pumped well or borehole.

Protection zone summary:

Given the nature of Sierra Leone's water supplies, the number of water sources involved, and the limited institutional capacity for undertaking site assessments, the implementation of a source protection zone strategy is unrealistic at the present time and remains a long-term option. Furthermore the capacity to regulate and enforce such an approach does not yet exist in Sierra Leone. Simpler approaches are needed.

2.1.3 Robustness of a single minimum separation between sources of pollution and groundwater abstraction points

A number of studies carried out in Africa relevant to this topic are reviewed in the following section, most studies have focussed on minimum separations between pit latrines and wells. As part of their recent literature review, Graham and Polizzotto (2013) included an assessment of the minimum separation distances between pit latrines and groundwater receptors recommended by studies in a range of typical hydrogeological settings. Separation distances of between 10-50m were commonly recommended. However, there was no detailed consideration of higher-risk settings such as those posed by tropical soils, which cover a considerable part of Africa, or karstic settings which require considerably greater separation distances. Furthermore, the fact that multi-point source contamination is widespread, such as from open defecation and animals, the framework of safe separation distances from point sources such as pit latrines breaks down.

Microorganisms have been assumed to not survive for very long after excretion but recent studies with viruses suggest that water quality may be impaired for a considerable length of time. Using a mixture of routine culture methods and genetic detection methods, Charles and co-workers detected viruses over 300 days after they were introduced in simulated groundwater systems (Charles et al., 2009). Using similar survival time for viruses in groundwater systems in the Netherlands, Schijven et al (2006) calculated that protection zones of between one and two years travel time would be required to ensure an infection risk of less than one in ten thousand per person per year. This is considerably longer than the 60 day travel time that is widely applied in Europe, or shorter in other parts of the world. Although a number of assumptions have been applied to the quantitative microbial risk assessments that were used to derive the travel time, it highlights the potential inadequacy of the current protection zones and the points to the need for water treatment to ensure that it is safe to drink.

A number of approaches have been used to define the quantities and transport distances of latrine-derived microbial contaminants. The majority of these have been culture-based studies of faecal bacteria; there has only been one study of viruses related to pit latrines (Verheyen et al., 2009).

Attenuation of microbes is likely to be dependent on the hydrological conditions both in terms of water levels and recharge rate and permeability of the aquifer, and is highly variable. Dzwairo et al. (2006) found faecal and total coliforms greatly reduced beyond 5 m from pit latrines in Zimbabwe, whereas Still and Nash (2002) found faecal coliforms to be attenuated to <10 cfu/100 mL after 1 metre in Maputaland, KwaZulu-Natal. In Abeokuta, Nigeria, Sangodoyin (1993) found coliform attenuation to be correlated both with distance from the source and with the depth of the groundwater well. In Epworth, Zimbabwe, groundwater contamination was higher in the dry season rather than in the wet, with coliforms detected up to 20 metres from the pit (Chidavaenzi et al., 1997). In Benin, Verheyen et al. (2009) found a positive association for detection of viruses in water sources with at least one latrine within a 50 m radius. They postulated that during the wet season viruses were transported in shallow groundwater whereas in the dry season contamination was likely to be from surface water.

In an informal settlement in Zimbabwe, Zingoni et al. (2005) found detectable total and faecal coliforms in over 2/3 of domestic boreholes and wells. In the area 75% of households used pit latrines and there were also informal trading areas. In Langas, Kenya, Kimani-Murage and Ngindu (2007) found that 50% of wells were within 30 m of a pit latrine and that all shallow wells were positive for total coliforms with 70% >1100 mpn/100 mL; however, in Kisumu, Kenya, Wright and co-workers failed to find a significant correlation between the levels of thermotolerant coliforms in water sampled from shallow wells and the density of pit latrines (Wright et al., 2013).

While clearly less important from a health perspective compared to microbiological contamination, chemical contaminants also pose a threat to water quality, and they are very useful tracers of microbiological contaminants, which are inherently more transient. Nutrients are also important in the fact that they are linked to the survival of pathogens in the environment. The chemical species of greatest concern from excreta disposed in on-site sanitation systems are regarded to be the macronutrients nitrate and phosphate. Pin-pointing specific sources is challenging as nitrate may be derived from numerous sources including plant debris, animal manure, solid waste and fertilisers. A common approach has been to compare areas that are similar but have different latrine densities. In an informal settlement in Zimbabwe, Zingoni et al. (2005) demonstrated that the highest nitrate concentrations were associated with the highest population and pit latrine density. Similar patterns have been observed in Senegal and Southern Africa (Tandia et al., 1999; Vinger et al., 2012). Studies in the peri-urban areas of Kisumu, Kenya have shown that the density of latrines within a 100m radius of the sources was significantly correlated with nitrate concentrations (Wright et al., 2013). In contrast, Sangodoyin (1993) found that nitrate concentrations were not related to distance from pit latrines in Abeokuta, Nigeria. In eastern Botswana the build-up of nitrogenous latrine effluent in soils and vertical leaching resulted in nitrate concentrations of above 500 mg/L (Lewis et al., 1980).

Direct measurements and well-designed studies are sparse and rarely consider rapid flowpaths or multi-point sources of contaminations. Graham and Polizzotto (2013) estimate lateral travel distances of 1-25 m for pit-latrine derived nitrate. Chloride is typically transported with minimal retention and frequently tracks nitrate (e.g. Lewis et al., 1980) unless subsurface conditions promote denitrification. Ammonia does not tend to accumulate in groundwater near latrines but can accumulate and persist in anaerobic conditions and when the water table intersects the base of the latrine pit (Dzwairo et al., 2006; Nyenye et al. 2013). Other contaminant tracers of waste water or faecal sources include potassium, sulphate and DOC and emerging organic contaminants (Sorensen et al., 2015a; 2015b).

Hazard source-water point separation summary:

A combination of the limited sanitation coverage, leading to an essentially diffuse (multi-point) surface hazard loading, vulnerable shallow geological terrain and climate in this region challenges the premise of safe lateral spacing between identified hazards, such as pit latrines, and drinking water supplies.

An alternative separation framework which is based on vertical separation, and minimises rapid bypass contamination pathways is a better approach in this setting for protecting groundwater supplies.

2.2 WATER QUALITY

This section initially assesses the available groundwater quality literature from Sierra Leone and then reviews a wider range of water quality studies across sub-Saharan Africa (SSA) in relevant hydrogeological settings. Given the varied geology of Sierra Leone, this includes studies carried out in basement, sedimentary and volcanic terrains, with an emphasis on weathered basement settings which cover the majority of the country. The literature search included areas with annual rainfall over ca.1000 mm and also includes some studies from karstic terrains, analogous to highly vulnerable settings found in lateritic terrains during the rainy season when water levels are high and lateral flow can exceed 300 m/d in some instances (e.g. Bonsor et al., 2014). This section provides a brief review of key water quality parameters, with a focus on microbiological contaminants which is the key water quality threat to water points, however it is recognised that other contaminants (such as NO_3, As and F) are also important from a water quality perspective in the long term.

An assessment of water quality variations in relation to hydrogeology, seasonality source type and specific high risk factors are made in this section. Table A2, in the appendix, summaries case studies from hydrogeologically relevant settings in Africa (n=51). Case studies (n=18) focused on the impact of sanitary sources, principally pit latrines, on groundwater quality across SSA are summarised in Table 5 (section 2.2.6). Studies covering aspects of non-sanitary sources of contamination such as industry, historical mining legacy and waste sites/landfills are not fully reviewed however, this and water quality from a wider literature search across SSA can be found in Lapworth et al (2015a). A handful of case studies include both specific assessments of impacts of pit latrines as well as broader environmental hygiene considerations in spring catchments and well capture zones and are included in both Table A1 and Table 5.

A large proportion of studies are drawn from urban and peri-urban settings where there are generally greater risks for groundwater contamination, but the review also includes studies undertaken within rural settlements. Urbanisation processes are the cause of extensive but essentially diffuse pollution of groundwater by nitrogen and sulphur compounds, salinity as well as pathogenic bacteria, protozoa and viruses (Morris et al., 2003). Household attitudes to hazards posed by drinking water can enhance quality problems with poor water treatment, types of drinking water vessels/storage, hand washing practices, perceptions of safe water quality using only visual parameters (normally clarity of the water), and knowledge on waste disposal practices (Kioko and Obiri 2012).

Overall, compared to other regions globally there have been relatively few studies carried out in Africa. The review draws mostly on research articles but also includes some reports and book chapters. It is recognised that these have been published for a range of purposes, with this in mind, the studies can be categorised into three broad groups and are identified by the notation ([1], [2] or [3]) in Tables A1 and Table 5:

1. Case-studies presenting data from a limited number of sites (n<20), limited temporal resolution as a single survey or use only basic chemical indicators and limited analysis of the results.

2. Case studies which either draw from larger data sets or include both chemical and microbiological indicators but have limited data analysis regarding sanitary risk factors.

3. Case studies with greater temporal resolution or are accompanied by a more thorough analysis of the data, for example using statistical techniques to understand the significance different risk factors on water quality observations.

Studies from group 3 provide the greatest insights regarding pollution sources, pathways and risk factors and can be considered as benchmark studies. It is clear from looking across the published literature that there has been a large number of groundwater quality related studies in southern Nigeria which account for some 30% of the published studies overall and most fall into either category 1 or 2 studies. Most of these studies are located near Lagos, Abeokuta and Ibadan in the south west, the Delta area in the south and Calabar. Other notable examples of locations that have a larger number of case studies include Lusaka in Zambia, Kampala in Uganda, Dakar in Senegal, and Addis Ababa in Ethiopia. These all have relevance to Sierra Leone given the varied hydrogeology, climate and socio-economic conditions found across Sierra Leone. Kampala (basement setting), Addis Ababa and Lusaka (basement and karstic settings) all have vulnerable hydrogeological settings analogous to those found in many parts of Sierra Leone. Dakar has comparable shallow coastal sedimentary aquifer systems. Studies in Southern Nigeria have both comparable hydrogeology and climate.

2.2.1 Baseline hydrochemistry and non-sanitary sources of contamination in Sierra Leone

While perhaps less important compared to microbiological contamination from a health perspective in the short term, in the long term a range of water quality issues need to be considered for Sierra Leone, these are briefly reviewed in the following section.

Wright (1982a) presents chemistry results from a seasonal study of the River Jong (also referred to as River Njala) in Sierra Leone. The waters are characterised as having very low SEC (range 13-30 μS/cm) but showed pronounced seasonal trends associated with changes in baseflow and throughflow contributions. Baseflow chemistry is characterised by higher pH (6-6.5) HCO_3, Si, Na, Ca, K and Mg, and lower Fe and turbidity.

A draft report by Mott MacDonald Int. (1991) states that fluoride concentrations were found to be >5 mg/L in around 20% of wells in the Bombali and Kambia area. Risks related to potentially elevated trace element concentrations in groundwater sources due to geogenic sources in mineralised zones (e.g. arsenopyrite mineralisation in the shallow weathered schist terrain for example) as well as heavy metal contamination (e.g. mercury) associated with mining waste processing activities are highlighted by Akiwumi (2008).

While there are very few published results for trace element analysis from groundwaters in these settings in Sierra Leone compared to other West African contries (e.g. Babut et al., 2003) data from soil, stream sediment and whole rock analysis suggest that groundwaters in the main gold bearing terrains (schist and granites of the Ankobra, Pra and Tano River basins) could have naturally elevated arsenic concentrations (Akiwumi 2008).

There is no As data available for groundwater in Sierra Leone, but there could be As related water quality concerns considering concentrations found in analogous settings in Ghana and Burkina Faso, where elevated As concentrations have been reported (up to 1640 μg/L) associated with geogenic sources and mining activities (Smedley 1996; Smedley et al., 2007). While certainly not considered as a major issue compared to faecal/sanitary sources of contamination in shallow wells in Africa, locally contamination from mine waste could lead to elevated trace element pollution in groundwater sources, as well as fish, particularly given the relatively low buffering capacity and low pH values found in these granitic terrains (Akiwumi 1987; Ouedraogo and Amyot 2013).

Table 4 Studies investigating groundwater contamination from pit latrines in analogous regions in SSA (n=19)

Region/Country (rural/urban)	Subsurface conditions	Sample sites (n)	Water quality parameters	Sampling time frame	Conclusion	Reference
[3]Kulanda town in Bo, Sierra Leone	Weathered Granitic Basement	Wells (33), lined and unlined	FC, SEC, NO_3, Turb, inorganic majors, pH	Wet season	No statistical significance found for pit latrine distance, lowest p value (0.06) for distance from field. Low pH concern for corrosion.	Jimmy et al. (2013)
[3]Kamangira, Zimbabwe (rural)	Sandy soils over fractured basement	Installed test wells (17)	NH_4, NO_3, turb, pH, Conductivity, TC, FC	Feb-May 2005	Low FC >5m from PL, N conc. usually below WHO standards	Dzwairo et al. (2006)
[3]Epworth, Zimbabwe (urban)	Fine sandy soils over fractured basement	New and existing wells (18) and boreholes (10)	Na, Zn, Cu, Fe, PO_4, NO_2, TC, FC	N/A	Elevated N and Coliforms in most of study area	Zingoni et al. (2005)
[3]Epworth, Zimbabwe (urban)	Fine sandy soils over fractured basement	Installed wells	N, SO_4, FC	2-8 week intervals 1998-1999	Rapid reduction in Coliforms, S and N 5-20 m from PL	Chidavaenzi et al. (2000)
[2]Lusaka, Zambia (urban)	Thin soils and karstic Dolomite	Existing wells (NA)	NO_3, Cl, FC	November 2003, March 2004, October 2004	Greatest FC loading from PL and other waste sources in wet season and dilution of N pollution	Nkhuwa (2006)
[3]Dakar, Senegal (urban)	Fine-course sands over sediments	Existing wells (47)	Broad hydrochemistry, FC	July and November 1989	Nitrate strongly linked to PL proximity	Tandia et al. (1999)
[2]NW Province, South Africa (rural)	N/A	Existing wells (9)	NH_4, NO_3, NO_2	June-July	High contamination <11 m from PL	Vinger et al. (2012)

Region/Country (rural/urban)	Subsurface conditions	Sample sites (n)	Water quality parameters	Sampling time frame	Conclusion	Reference
[3]Mbazwana, South Africa (urban)	Sands	Installed test wells (5)	FC and NO_3	Bimonthly 2000-2002	Low nitrate (<10 mg/L) and FC (<10/100mL) >1m from PL	Still and Nash (2002)
[2]Bostwana, Mochudi/Ramotswa (rural)	Well-poorly drained soils	Existing wells (>60)	P, N, stable isotopes and Cl	N/A	Variable N leaching from PL	Lagerstedt et al. (1994)
[2]Botswana (rural)	fractured basement	Existing well and observation well (2)	Broad Hydrochemistry, *E. coli*	October-February 1977	Contamination of wells near latrine with *E. coli* and nitrate	Lewis et al. (1980)
[3]Various, Benin (rural)	N/A	Existing wells (225)	Andenovirus, rotavirus	Wet/dry season 2003-2007	Viral contamination is linked to PL proximity	Verheyen et al. (2009)
[3]Langas, Kenya (urban)	N/A	Existing wells (35)	TC,FC	January-June 1999	97% wells positive for FC, 40% of wells >15m from PL	Kimani-Murage and Ngindu (2007)
[3]Kisumu, Kenya (urban)	Sedimentary	Existing wells (191)	FC, NO_3, Cl	1998 to 2004	Density of PL within a 100 m radius was significantly correlated with nitrate and Cl but not FC (*PC*)	Wright et al. (2013)
[3]South Lunzu, Blantyre, Malawi (urban)	Weathered basement	Borehole, springs and dug well (4)	SEC, Cl, Fe, FC,FS	Wet and dry season on two occasions	Groundwaters highly contaminated due to poor sanitation and domestic waste disposal. 58% of residence use traditional PL	Palamuleni (2002)
[3]Uganda, Kampala (urban)	Weathered basement	Piezometers (10)	NO_3, Cl, PO_4	March-August 2010 biweekly sampling	PL found to be a significant source of nutrients (N) compared to waste dump	Nyenje et al. (2013)
[3]Uganda, Kampala (urban)	Weathered basement	Installed wells and spring (17)	SEC, pH, P, NO_3, Cl, FC and FS	March-August 2003, weekly and monthly	Widespread well contamination linked to PL and other waste sources	Kulabako et al. (2007)

Region/Country (rural/urban)	Subsurface conditions	Sample sites (n)	Water quality parameters	Sampling time frame	Conclusion	Reference
[3]Uganda, Kampala (urban)	Weathered basement	Springs (4)	FC, FS, NO_3, NH_4	Wet and dry season for 5 consecutive weeks	Widespread contamination from PL and poor animal husbandry, both protected and unprotected sources unfit for drinking	Nsubuga et al. (2004)
[3]Uganda, Kampala (urban)	Weathered basement	Springs (25)	FC, FS	Monthly September 1998- March 1999	Spring contamination linked to local environmental hygiene and completion rather than on-site sanitation (*LR*)	Howard et al. (2003)
[3]Lichinga, Mozambique	Mudstone	Lichinga (25)	TTC, EF (Enterococi)	Monthly for 1 year	Higher risk at onset of the wet season and end of the dry season. Predominant source was from animal faeces rather than PL or septic tanks (*LR*)	Godfrey et al. (2006)

PL = Pit latrine, FC = Faecal coliform (values given as 0 are below detection limit of method), SEC= Specific electrical conductivity, TTC= Thermotolerant coliforms, TC = Total coliform, FS = Faecal strep, Turb=turbidity, *LR*=logistic regression, *PC*= Pearson's correlation. Concentrations in mg/L unless otherwise stated.

Jimmy et al (2013) and Ibemenuga and Avoaja (2014) present some hydrochemical data for urban and rural wells in Sierra Leone, but limited analysis and interpretation of results. Overall, both studies conclude that microbiological contamination is more of a health risk to users compared to inorganic contaminants. Both studies do show a significant proportion of sites with low (<6.5) pH values in groundwater sources. While this is perhaps not critical from a drinking water quality perspective it does have implications for microbiological survival and corrosion potential for infrastructure such as piped water sources and borehole casing. There is anecdotal evidence from the early 1990s in Sierra Leone that suggests this may have happened in boreholes drilled by JICA which failed within a few years of installation. High iron is also a widespread problem in wells and boreholes in Sierra Leone.[3]

2.2.2 Sanitary sources of contamination in Sierra Leone

There are four studies available that contain microbiological and chemical water quality data (nitrate) from wells and springs on the basement terrain of Sierra Leone related to sanitary sources of contamination, these are summarised in Table 5. Two early papers by Wright (1986 and 1982b) were seasonal studies carried out in rural settlements in South-Eastern Provinces in Sierra Leone. Both of these papers investigated a range of drinking water sources (wells, springs, streams and swamps), and the temporal changes in FC (faecal coliforms), FS (faecal streptococci) as well as *E. coli*, *S. faecalis*, *C. perfringens* and *Salmonella* spp. Both of these studies showed gross levels of microbiological contamination in unprotected springs and wells throughout the year (e.g. FC >30k cfu, mean 3k in Wright (1982b)), with higher levels of contamination for FC in groundwater towards the start of the wet season compared to larger rivers and comparable contamination to smaller surface water sources.

In groundwater sources, detailed seasonal studies point to increased risk of enhanced microbiological contamination from faecal coliforms and associated pathogens (e.g. *Salmonella* spp) during the onset of the dry season and the start of the wet season, and then a reduction in faecal coliform counts as the wet season progresses. The author suggest that this may be a dilution control, and the fact that shallow groundwater sources are the only reliable sources of drinking water in the dry season means there is a higher risk for users during this period. None of the settlements had sanitation facilities, and open defecation was cited as normal practice and none of the wells had any protection (unlined/covered), so surface sources and contamination from runoff would have likely been significant.

Two recent studies have carried out single campaign water quality surveys at the start of the wet season in wells in two different regions of Sierra Leone (Jimmy et al. (2013); Ibemenuga and Avoaja (2014)). Both papers conclude that microbiological contamination was the greatest health risk associated with drinking water (compared to major ion chemistry); however, neither study carried out trace element analysis for arsenic or heavy metals. Jimmy et al (2013) carried out a survey of lined and unlined wells (n=33) in the Kulanda township of Bo, and investigated the importance of different risk factors, including well depth, proximity to pit latrines, proximity to fields and well completion. Unlined wells were found to have poorer water quality compared to lined wells (Figure 13) and the shallow sources were more contaminated compared to deeper sources with regards to FC, nitrate and SEC (Figure 14). The relationship between NO_3 and FC and distance from nearest toilet shows generally lower concentrations where distances are >40m, but a high degree of variability for sites with toilets/pit latrines <40m, although this relationship is not statistically significant.

[3] Pers. coms., Peter Dumble, PDHydrogeology, February 2015

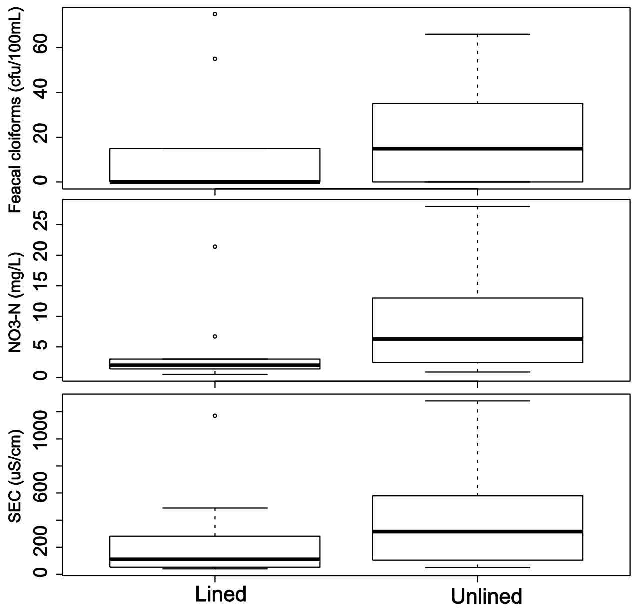


Figure 13 Box-plots of faecal coliform (FC), nitrate and SEC distributions in lined and unlined wells in Bo, Sierra Leone, data from Jimmy et al. (2013). Tukey box-plot used.

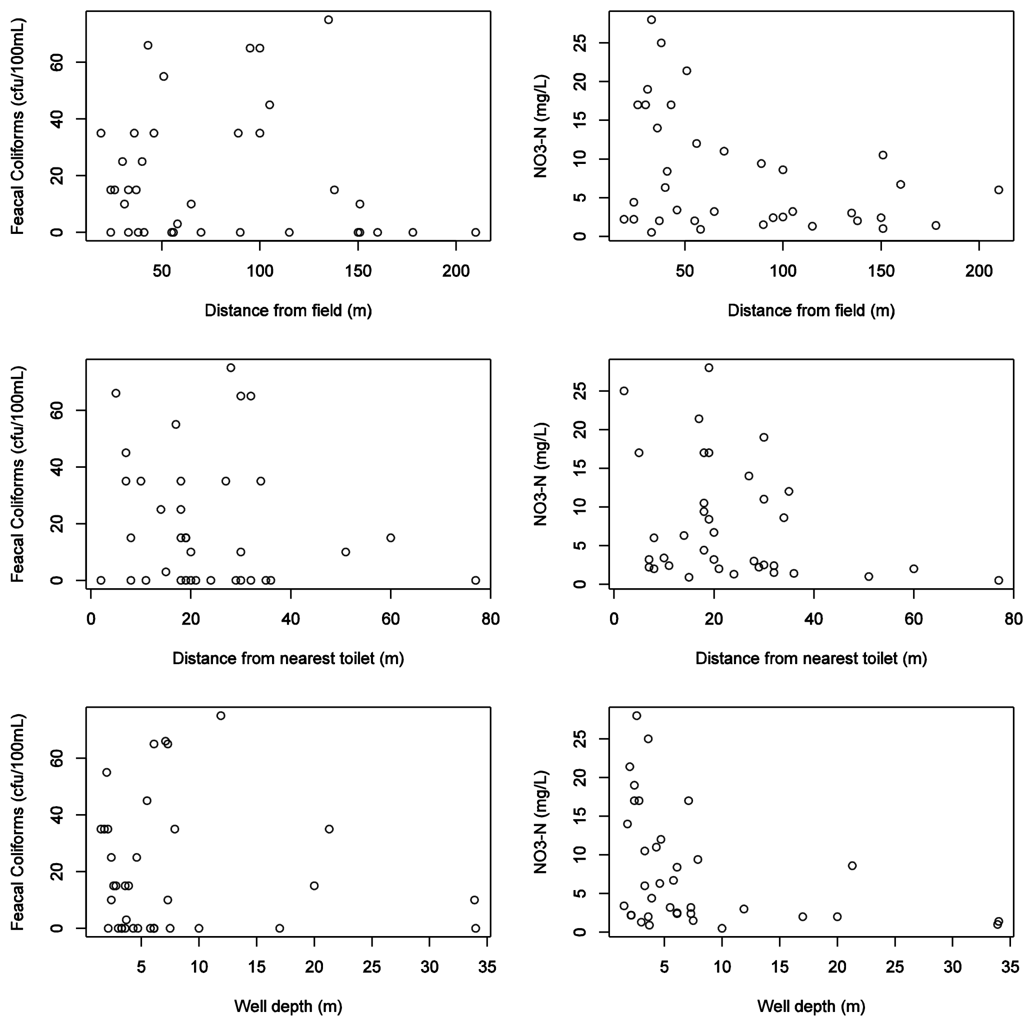


Figure 14 Relationship between water quality parameters and well depth, distance from nearest toilet and distance from field, data from Jimmy et al. (2013)

Using logistic regression, the distance from field boundaries were found to have the lowest p value (0.06) for predicting the presence of FC, with much larger p values for other predictors, such as distance from nearest toilet. The significance of this result should be treated with caution as the data set is small and the distance from the nearest toilet (e.g. rather than more conventional measures such as density within a particular search radius) may not be the best criteria to use for this type of analysis.

Ibemenuga and Avoaja (2014) present water quality results (FC, SEC and major ions, F, and some trace elements e.g. Fe and Cu) from a larger sample size (n=60) from rural settlements in the Bombali region of Sierra Leone. Overall, mean levels of FC were comparable (mean 16.6 cfu/100mL, range BDL-80 cfu) with those from Bo (mean 19.5 cfu/100mL, range BDL-75 cfu) (Jimmy et al (2013)). Median and mean nitrate and SEC values were comparable (Table 5, Figure 15) but Figure 15 does show that this study had a consistently smaller inter-quartile-range compared to the study carried out by Jimmy et al (2013). There is very little detail given in the paper regarding well construction and other risk factors in this study so it is difficult to draw any firm conclusions. The generally lower level of contamination could be due to the fact that these are from smaller settlements with lower levels of diffuse contamination in the subsurface. Both studies had ca. 60% of groundwater sources that were contaminated with detectable FCs and a similar overall FC distribution. Compared to the earlier studies by Wright (1986; 1982b), where sources had no protection, the level of faecal contamination found in the shallow wells in these two studies were two orders of magnitude lower on average, suggesting that well construction and protection is a highly significant factor controlling pollution pathways.

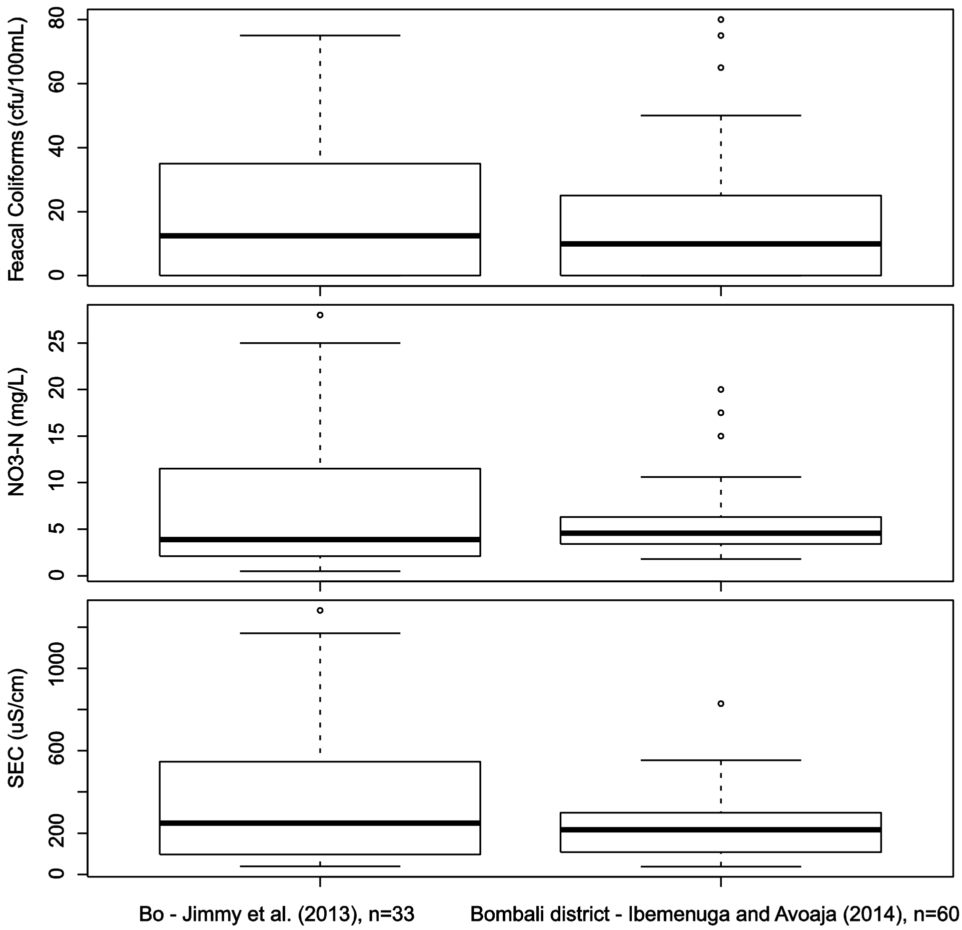


Figure 15 Comparison of water quality data from shallow wells from Bo and Bombali district, Sierra Leone. Data from Jimmy et al. (2013) and Ibemenuga and Avoaja (2014)

2.2.3 Chemical and physical indicators of groundwater quality degradation from comparable hydrogeological settings

Figure 16 shows the distribution of case studies used in this water quality review. Most are from West Africa, although there are also a number from East Africa including case studies in Uganda, Malawi and Kenya and Zimbabwe.

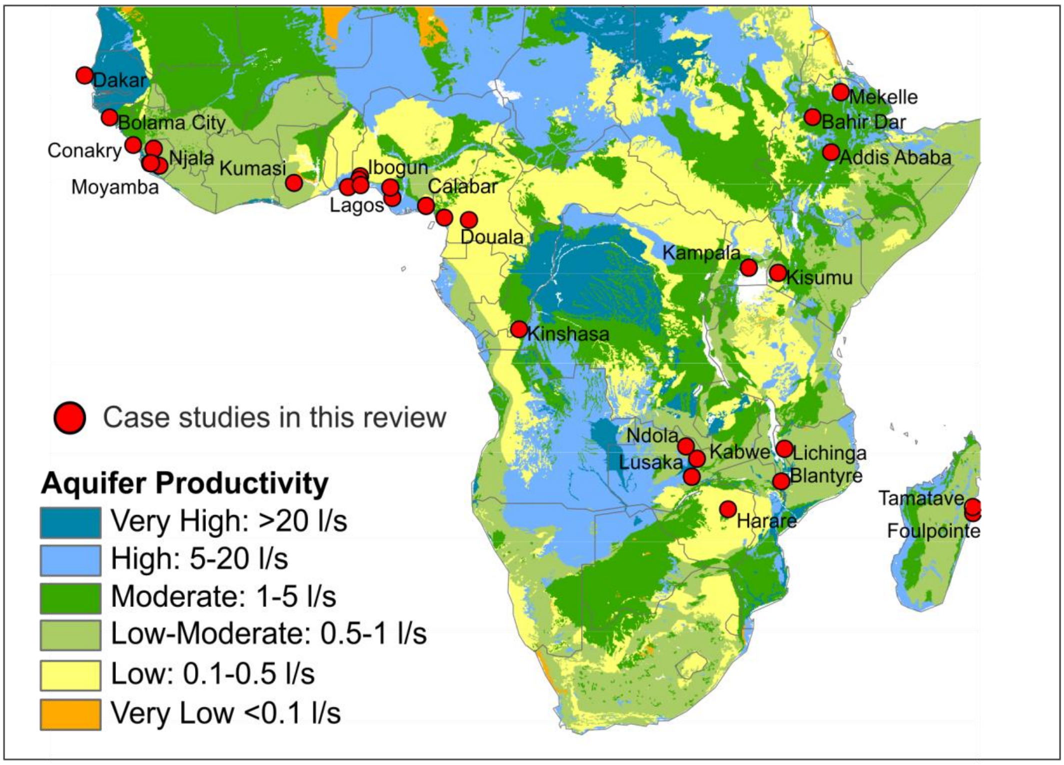


Figure 16 Location of case studies used in this review. Background map showing regional scale aquifer productivity from MacDonald et al. (2012)

PHYSICAL INDICATORS

Total dissolved solids (TDS) and specific electrical conductivity (SEC) are the most commonly applied physical water quality indicators in groundwater studies and are often used in combination with more specific indicators such as dissolved chemistry or microbiology (see Table A1). They have a major advantage of being field methods, which are relatively easy to deploy and versatile, enabling the user to carry out an initial assessment of water quality rapidly, and with minimal cost. The baseline quality of groundwater, with relatively low total dissolved solids (TDS) in most basement and alluvial settings, makes TDS a good indicator of contaminant loading (Figure 17).

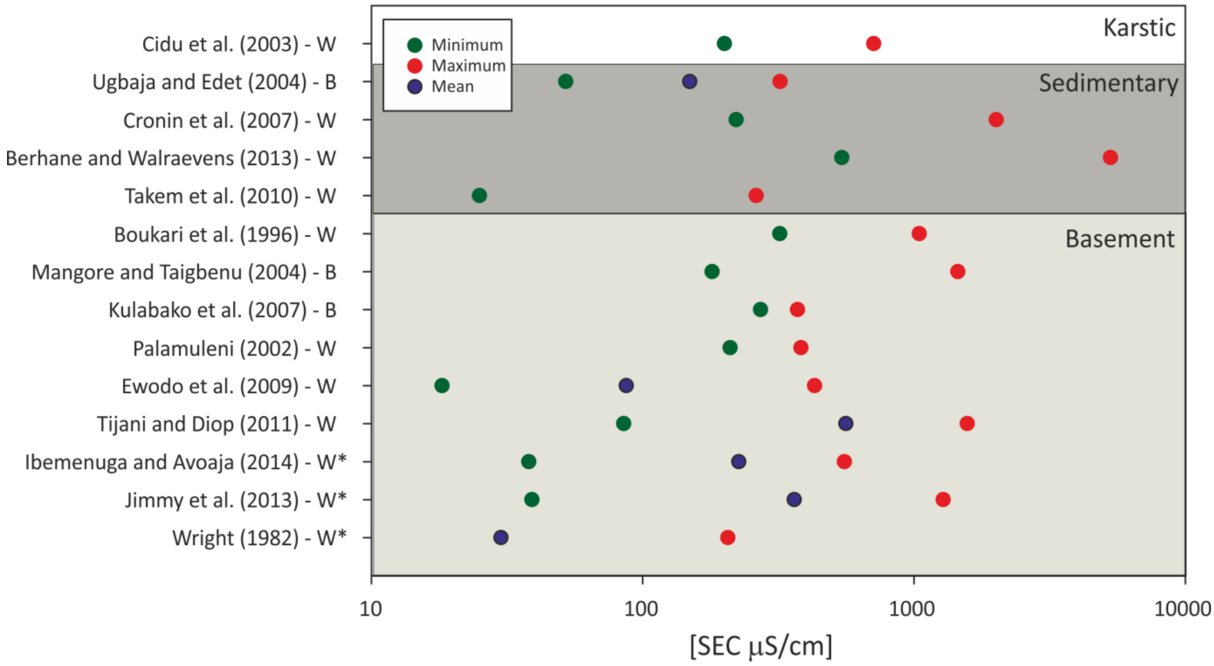


Figure 17 Summary water quality results for SEC from shallow groundwater studies carried out across hydrogeologically relevant terrains in SSA based on climate and geology. Data extracted from tables and figures in peer reviewed literature, some summary statistics (mean) are not available from the literature. W=wells, B=boreholes, *Data from Sierra Leone, note log scale on x-axis.

2.2.4 Nitrate and chloride

Nitrate and chloride are the most widely used chemical indicators of anthropogenic pollution. Nitrate data has been reported in over 80% of the groundwater studies summarised in Table A1. Summary statistics for a number of studies in basement and sedimentary settings in Africa is presented in Figure 18. The relatively simple sample preservation and analysis required makes these parameters attractive for initial water quality screening. Overall, nitrate concentrations ranged from Below Detection Level (BDL) to >500 mg/L (as NO_3), although typical maximum concentrations were generally below 150 mg/L (Figure 18). The WHO guideline value for nitrate is 50 mg/L as NO_3. The WHO has not published a health-based guideline for chloride, but suggests that concentrations over 250 mg/l can give rise to a detectable taste.

Both tracers have been used in a broad range of geologic and climate zones to investigate pollution from on-site sanitation, waste dumps, as well as urban agriculture (Table A1). Nitrate concentrations show a high degree of variability both within studies and between studies that have been reviewed. Two principle factors that affect nitrate occurrence are firstly the prevailing redox conditions in groundwater, and secondly the residence time and vulnerability of the groundwater body. There are several examples of low nitrate groundwater in Table 1 which show evidence of faecal contamination (Gelinas et al., 1996; Mwendera et al., 2003; Nkhuwa, 2003) which has implications for the potential for denitrification in shallow groundwaters. Nitrate has been used successfully to characterise urban loading to groundwater from a range of sources including pit latrines (Cissé Faye et al., 2004), landfills (Ugbaja and Edet, 2004; Vala et al., 2011) and applied to look at impacts on groundwater quality across different population densities (Goshu and Akoma, 2011; Goshu et al., 2010; Orebiyi et al., 2010). There are other sources of N loading to groundwater in growing urban areas including the impact of deforestations, and these can be delineated using N:Cl ratios and in one example by using $\delta^{15}N$ analysis (Faillat, 1990).

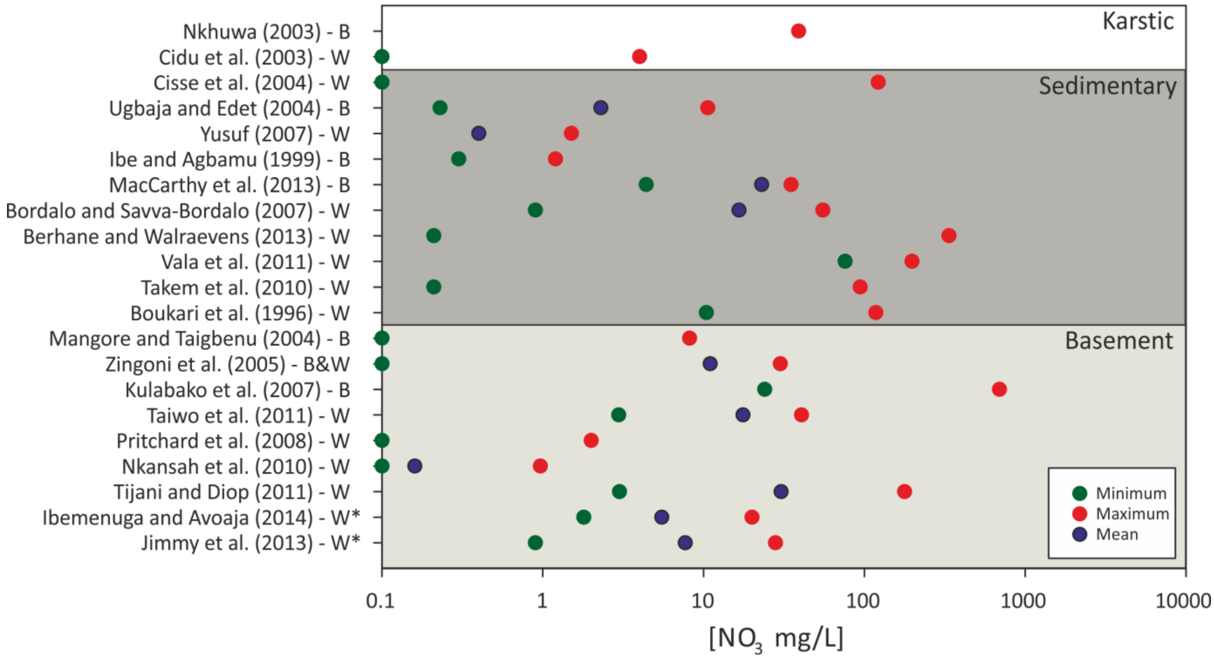


Figure 18 Summary water quality results for NO_3 from shallow groundwater studies carried out across hydrogeologically relevant terrains in SSA based on climate and geology. Data extracted from tables and figures in peer reviewed literature, some summary statistics (mean) are not available from the literature. W=wells, B=boreholes, *Data from Sierra Leone, note log scale on x-axis.

A series of geochemical transformations can occur in water with a high carbon concentrations and a progressive decline in redox potential, leading to the removal of nitrate by denitrification, the mobilisation of manganese and iron and the reduction of sulphate. Borehole mixing processes can cause dilution and overall lower nitrate concentrations while still having significant microbiological contamination. Lagerstedt et al. (1994) and Cronin et al. (2007) successfully used NO_3:Cl to fingerprint different sources of urban and peri-urban pollution in groundwaters in SSA. This has a certain appeal due to its simplicity; however, prevailing redox conditions and mixing processes need to be considered when using this approach. Many studies have effectively used nitrate in combination with other basic physical indicators such as SEC or TDS and turbidity to assess contamination and map areas of relatively high and low pollution.

2.2.5 Ammonium and phosphate

It is evident from the literature that only a minority of case studies (ca. 20%) contain data for NH_4 and close to 30% contain data for PO_4 (see Table A1). In part this is due to the more involved analytical procedures for NH_4, the high detection limits for PO_4 by ion chromatography and the fact that these parameters need to be analysed rapidly after sampling to ensure valid results. The WHO have not published health-based guidelines for ammonia and phosphate, but P is often the limiting nutrient in the aquatic environmental and therefore concentrations >20 µg/L are considered high in surface water bodies.

Both species are closely associated with contamination from pit latrines and leaking sewer systems. Examples of ammonia and phosphate contamination from the cities of Lusaka, Abeokuta and Calabar are shown in Table 1 (Berhane and Walraevens, 2013; Cidu et al., 2003;

Taiwo et al., 2011. Ammonium concentrations in groundwater range from BDL-60 mg/L, although most case studies had maximum concentrations below 10 mg/L. The highest concentrations were reported in Lusaka, Zambia where karstic limestone aquifer which underlies much of the city and very rapid transport times in the groundwater are implicated. Both indicators do not behave conservatively in soils and groundwater, for example NH_4 is positively charged and therefore has a strong affinity for negatively charged surfaces such as clays, for this reason, as well as microbiological processing, attenuation is particularly high in the soil zone.

Phosphate concentrations range from BLD-86 mg/L, although very few studies report values >20 mg/L. Phosphate has very limited mobility in the subsurface and has a strong affinity to iron oxy-hydroxides as well as carbonates, background concentrations are usually low, e.g. <0.2 mg/L, concentrations in urban groundwater are also usually low unless there is either a very high loading or very rapid groundwater flow for example in fractured basement or karstic limestone (Cidu et al., 2003; Nkansah et al., 2010; Zingoni et al., 2005).

2.2.6 Microbiological contaminants

Studies have shown that greater than 90% of thermotolerant coliforms (TTCs) are *E. coli* (Dufour, 1997 cited in Leclerc et al. (2001)) and as high as 99% in groundwater impacted by poor environmental sanitation in Africa (Howard et al. 2003). Despite this there have been some doubts about the reliability of TTCs to indicate faecal contamination in water. Although the TTC group includes the species *E.coli*, which is generally considered to be specific for faecal contamination, it also includes other genera such as *Klebsiella* and *Citrobacter* which are not necessarily of faecal origin and can emanate from alternative organic sources such as decaying plant materials and soils (WHO 2011).

Human faeces harbour a large number of microbes, including bacteria, archaea, microbial eukarya, viruses, protozoa, and helminths (Graham and Polizzotto, 2013). In the context of this review there have been no studies that have assessed protozoa or helminths, which exhibit little movement in groundwater due to their size (Lewis et al., 1982). The characteristics of microorganisms and the aquifer and soil environment that affect microbial transport and attenuation in groundwater are shown in Table 4.

Table 5 Factors affecting transport and attenuation of microorganisms in groundwater (from Pedley et al. (2006))

Characteristics of the microorganism	Aquifer/soil (environment) properties
Size	Groundwater flow velocity
Shape	Dispersion
Density	Pore/aperture size (intergranular or fracture)
Inactivation rate (die-off)	Kinematic/effective porosity
reversible adsorption	Organic carbon content
Physical filtration	Temperature
	Chemical properties of groundwater (pH etc.)
	Mineral composition of aquifer/soil material
	Predatory microflora
	Moisture content
	Pressure

In-situ sanitation, largely in the form of pit latrines, is often considered the dominant cause of microbiological contamination and a major cause of nutrient loading to water resources in SSA. This is a very well-studied area and a worldwide review has been published recently by Graham and Polizzotto (2013). The main findings from relevant studies carried out in SSA have been collated in Table 5 and are summarised below along with other studies specifically targeting contamination from sanitary sources. Given the low sanitation coverage, and the wet climate of Sierra Leone, surface sources such as open defecation are also significant, but it is noteworthy that there have been very few studies that have considered this a major source of contamination in this region.

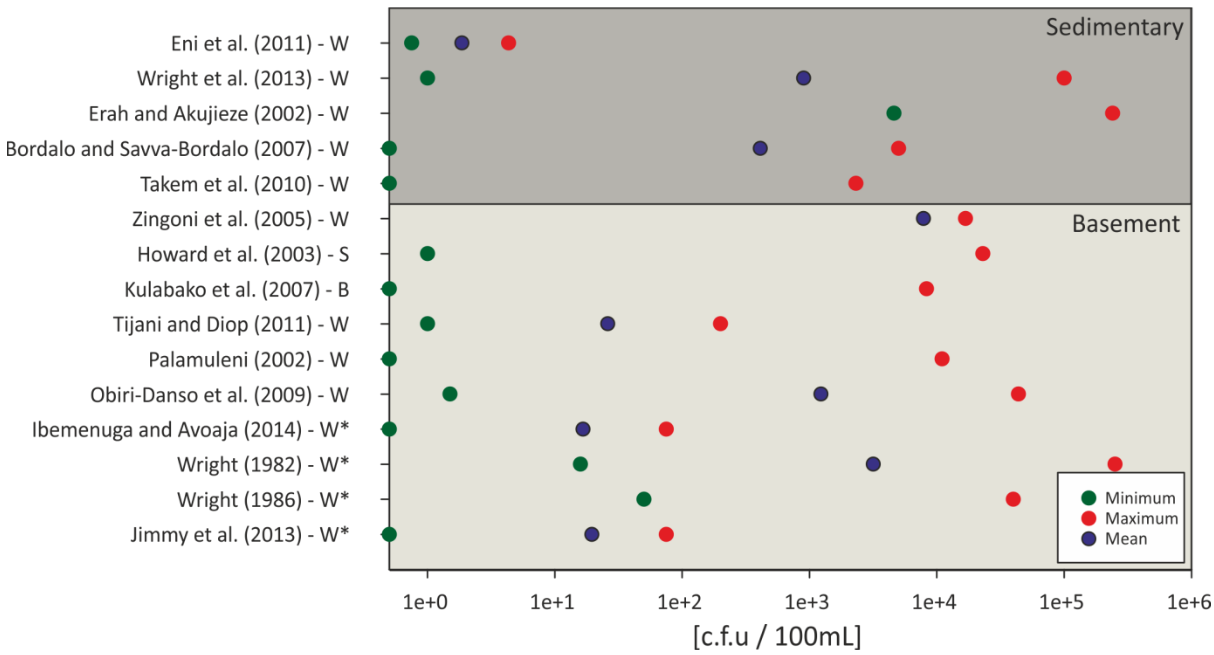


Figure 19 Summary water quality results for faecal coliforms from shallow groundwater studies carried out across hydrogeologically relevant terrains in SSA based on climate and geology. Data extracted from tables and figures in peer reviewed literature, some summary statistics (mean) are not available from the literature. W=wells, B=boreholes, S=springs, *Data from Sierra Leone.

Figure 19 shows summary statistics for FC contamination (cfu /100 mL) found in shallow groundwater sources from representative case studies across SSA, from both sedimentary and basement settings. There is evidence of widespread contamination in shallow groundwater sources with mean FC ranging from >10-10,000 (cfu/ 100mL). There is no significant difference between the level of contamination found in sedimentary and basement terrains from shallow wells (see Figure 19).

2.2.7 Seasonal trends in groundwater quality

A recent review by Kostyla et al (2015) found significant seasonal trends of greater faecal contamination in developing countries during the wet season irrespective of source type, climate and population. However, there are relatively few studies that have undertaken regular water quality monitoring over extended periods or have carried out detailed seasonal comparisons in Africa. An early study by Wright (1986) in Sierra Leone showed that wells and springs had a pronounced seasonality, with higher counts for FC and FS progressively during the dry season and reduced counts at the start of the wet season, dilution was implied as a controlling factor, which is likely given the strong seasonality in rainfall and the fact that sanitation was non-existent and open defecation was practised. A study by Howard et al. (2003) is one notable example where detailed seasonal monitoring of microbiological indicators was carried out over a twelve month period to characterise the risks factors for spring contamination in Kampala, Uganda. Significantly higher contamination was observed after rainfall events and there was strong evidence that rapid recharge of the shallow groundwater causes a rapid response in spring quality (Barrett et al., 2000). Godfrey et al (2006) collected data on TTC and enterococci monthly for a year, these results showed that microbiological contamination was enhanced in the rainy season and in the lead up to the rains, which could also be liked to well use and demand during this period as was suggested in the study by Wright (1986). A recent study by Nyenje et al (2013) showed that nitrate concentrations up-gradient and down-gradient of pit latrines over a four month period showed large seasonal changes, the data suggest that dilution from intense rainfall and recharge may be an important control.

Higher maximum FS (faecal streptococci) counts were found in the wet season compared to the dry season for studies in Uganda (Kulabako et al., 2007) and Malawi (Palamuleni, 2002). Higher maximum SEC were observed in all three case studies in the wet season, however median values are comparable. Changes in nitrate show a mixed picture with higher maximum concentrations in two studies from Uganda and DRC (Kulabako et al., 2007; Vala et al., 2011) during the wet season, while in the case study from Zimbabwe (Mangore and Taigbenu, 2004) lower maximum values were found (Table 1A). Median values for nitrate were lower in the wet season for both the Uganda and Zimbabwe case studies, which may indicate a dilution effect, while the higher maximum concentrations may be explained as a result of a pulse of contaminants at the start of the rainy season, evaporative effects concentrating N during the dry season or the rise in groundwater table picking up a plume of high N water in the unsaturated zone. Understanding seasonal trends in nitrate are complicated by the changes in redox conditions, particularly in low lying areas which are prone to flooding in the wet season which are not uncommon in SSA, e.g. Lusaka, Zambia. These may shift from an oxidising regime in during low water table conditions which retains NO_3 to a reducing regime where denitrification can take place during inundation (Sanchez-Perez and Tremolieres, 2003; Spalding and Exner, 1993).

Table 6 Comparison of microbiological water quality from multiple groundwater sources including boreholes, wells and springs

Town/city/area	Country	Geology/sites	Water Quality (cfu/100 mL)			Contamination	Reference
Oju area	Nigeria	Sedimentary n=30	Borehole: FC BDL-500 typically <200	Improved well: FC 50-500 typically >200	Trad. Well: FC>500	Borehole<<improved well<<traditional well	Bonsor et al. (2014)
Yaounde	Cameroon	Basement n=40	Spring: FC 2-72 FS 0	Well: FC 7-100 FS 0-100		Spring<Well	Ewodo et al. (2009)
Kumasi	Ghana	Basement n=9	Well: FC mean >30k, EC=0-1152	Borehole FC mean>20k EC 0-36		Borehole<Well	Obiri-Danso et al. (2009)
Blantyre	Malawi	Basement n=9	Borehole: FC 0-30 FS 0	Spring: FC 530-9500 FS 0-7000	Wells: FC 3500-11k FS 250-2650	Borehole<<Spring<Well	Palamuleni (2002)
Njala	Sierra Leone	Basement n=8	Spring: FC 50-30k FS 8-2500	Wells: FC 125-63k FS 5-2500		Spring<Well	Wright (1986)
Kampala	Uganda	Basement n=16	Spring: FC 29-10k FS 6-8.3k	Wells: FC 0-26^6 FS 0-26^8		Spring<<Wells	Kulabako et al. (2007)
Harare	Zimbabwe	Basement n=29	Borehole: FC 0-30k	Well: FC 0-30k		Borehole<Well for FC	Zingoni et al. (2005)
Douala	Cameroon	Sedimentary n=4	Spring: FC 1-950 FS 0-420	Borehole: FC 1-2.3k FS 0-1.4k		Spring<Borehole	Takem et al. (2010)
Kabwe	Zambia	Karstic n= 75	Borehole FC<2-630	Well: FC <2-28k		Borehole<Well	Lapworth et al (2015b)

FC= Feacal coliforms, FS=Feacal strep., EC=Entrococci, TC=Total coliforms

2.2.8 A comparison of results from wells, springs and boreholes

The vast majority of the studies that are included in this review contain data from shallow hand dug wells (ca. 60%), this is true of most published water quality studies in Africa, a further 22% include data from boreholes and 18% include results from springs. A small number of studies have compared a range of different groundwater sources, usually two different sources; boreholes vs wells (n=8) and wells vs springs (n=5) and boreholes vs springs (n=4). Table 6 summarises the results from comparative studies with two or more groundwater source types.

As you might expect, overall wells are generally the most contaminated groundwater source type compared to springs and boreholes. Open and unlined wells are consistently of poorer quality compared to lined or 'improved' wells (e.g. Godfrey et al 2006; Jimmy et al., 2013; Lapworth et al., 2015b). In some studies springs have been found to be better quality compared to boreholes (Takem et al. 2010) and others cases the trend is reversed (Palamuleni 2002) or both sources were found to have comparable levels of contamination by FC (e.g. Abiye 2008). It is important to note that many of these studies contained very few observations for each source type and generalisations should be treated with caution however, together they form a more compelling body of evidence. Overall there is no clear patterns that emerge regarding water quality in different hydrogeological settings, i.e. basement or sedimentary, comparable mean and maximum levels of contamination are found for FCs and nitrate. With perhaps the exception of highly karstic settings for microbiological and nitrate the following order of water source quality (best to worst) is found as follows: boreholes >> improved wells = springs > traditional wells. Improved wells do not generally exhibit the same level of gross contamination observed in traditional wells and springs. However, in the majority of studies, wells (both improved and unimproved), are found to have water with unacceptable levels of contamination with faecal coliforms by WHO standards (and typically > 100 cfu/ 100 mL) in at least some part of the year and often throughout the year.

There is some evidence that the water quality of wells may be affected by usage rates, i.e. with fewer groundwater sources being relied on towards the end of the dry season there is greater risk of contamination, e.g. from materials used for drawing water, especially for unimproved sources (Godfrey et al. 2006; Wright et al., 1986). For boreholes this contamination pathway is generally not a major risk factor and this supports the generally better quality found in these types of sources. The lower storage volume of shallow boreholes compared to wells may also be an important factor.

Water quality summary:

There is little convincing evidence that water quality is consistently better at distances >30 m from individual pit latrines – what evidence exists suggests a link with density of contaminant sources

The water quality of shallow groundwater accessed by shallow wells is often of very poor quality, based on faecal coliform and nitrate data, for at least some of the year in most settings, and all year in many cases.

Water quality from boreholes is generally of better quality compared to wells and springs probably because it accesses deeper groundwater and has better protection around the well head.

Wells are highly vulnerable to microbiological hazards, particularly surface material introduced by rope and buckets. There are significant seasonal changes in water quality in wells, with generally poorer water quality observed at the end of the dry season and during the onset of the wet season.

Seasonal pressures on particular water sources may increase the likelihood of water quality deterioration in wells (and spring collectors).

2.3 PATHOGEN SURVIVAL

2.3.1 Introduction

Pathogens contaminate the subsurface from many different sources: leaking sewers; septic tanks; surface application of faecal sludge in agriculture; surface waste; and pit latrines to name but a few. Once in the soil layer, or having reached the groundwater, pathogens are subject to a broad range of environmental factors that dictate the survival time of the pathogen and the distance that it can migrate from its source. In addition, the nature of the pathogen itself determines its interaction with the environment, and thus its survival and mobility in the subsurface. In the broadest sense, there are three main groups of pathogens that that are of concern in groundwater: viruses; bacteria and protozoa (Table 7). The characteristics of each group of pathogens are quite distinct, which contributes to their different behaviours in the environment.

Groundwater has been identified as the vehicle of pathogen transmission in numerous outbreaks of waterborne disease. In the USA and elsewhere, summaries of the sources of waterborne disease highlight the importance of groundwater. Statistics collected by the US water-borne Disease Outbreak Surveillance System between 1971 and 2008 show that 30% of the 818 outbreaks of disease were a result of supplying untreated drinking water from groundwater sources (Wallender et al. 2013; Craun et al. 2010). Over a similar time period in Norway 44% of water-borne disease outbreaks could be linked to groundwater sources (Kvitsand & Fiksdal 2010). There are fewer examples of outbreaks attributable to groundwater being reported in Sub-Saharan Africa (SSA), possibly due to the numerous confounding factors present in SSA that complicate the exposure-risk relationships (Payment & Hunter 2001), but the widespread and high levels of contamination in water from hand-dug wells and shallow boreholes in urban and rural areas means that inevitably they will be source of disease transmission (Kimani-Murage & Ngindu 2007). Given the extent to which these sources are used in SSA, the burden of disease attributable to the consumption of contaminated groundwater will be high.

The duration and extent of the recent outbreak of Ebola in Western Africa has raised questions about the possible importance of environmental sources of the virus and whether it might persist in body fluids long enough to present a risk of transmission by indirect routes, including the contamination of water. Furthermore, the sudden and necessary diversion of medical attention towards the control of Ebola in the affected countries has caused concern amongst some that the classical water-related diseases are being ignored, and that there might be a silent increase in their prevalence.

This section of the report summarises the current knowledge about the survival of pathogens in the sub-surface, and the factors that contribute to their dispersal through groundwater. Our review will draw upon two relatively recent published reviews of the fate and transport of pathogens in groundwater (Pedley et al. 2006; Tufenkji & Emelko 2011) to create the foundation of this report, and expand upon the reviews with more recent significant findings. Both of these reviews provide the reader with a link to the early, but still relevant literature.

For the purpose of this report we will concentrate our discussion upon the viral and bacterial pathogens – in particular those pathogens that may inform conclusions about the potential for Ebola virus and *Vibrio cholerae* to survive and migrate through groundwater – in the context of the environmental conditions that exist in Sierra Leone. This section will firstly cover a short summary of the physical and chemical characteristics of the cholera vibrio and the Ebola virus so that parallels can be drawn with alternative microorganisms that may be used as their surrogates in a risk assessment. This will be followed by a review of the factors that influence the length of time that bacteria and viruses survive in the subsurface and the characteristics of the pathogens and the environment that control the movement of the pathogens through groundwater. Taken together, the survival and transport data can be used to estimate the extent to which the pathogens may disperse in groundwater from a particular source.

Table 7 Characteristics of the major pathogen groups

Pathogen group	Characteristics
Bacteria	Bacteria are prokaryotic microorganisms, which means that they do not have a defined nuclear membrane (lack an identifiable nucleus) or other organised intracellular structures. Although their size varies considerably between species, individual cells range in width between 0.5µm and 5.0µm. Bacteria are ubiquitous, and can colonise the most extreme environments. The vast majority are harmless saprophytes. They can have a variety of shapes, and some species are motile. Apart from a few exceptions, the bacterial cell contains all the cellular components necessary for to metabolise nutrients to generate energy, and for it to replicate. This characteristic means that some pathogens may be able to maintain themselves in the environment when the conditions are favourable to their replication. Some species of bacteria produce spores that are highly resistant to environmental stress and may survive for years, even decades. Other bacteria may enter a dormant state when the environmental conditions are unfavourable. The significance to human health of this dormant state is being investigated.
Viruses	Viruses are obligate intracellular parasites, which means that they have an absolute requirement to infect a host cell in order to replicate. Outside the cell they are dormant. Hence, once a virus has been expelled from the host into the environment it cannot replicate itself. Viruses are orders of magnitude smaller that bacteria – between 20nm and 300nm – and have a much simpler structure. For some virus species, for example the enteroviruses, their simplicity makes them particularly resistant to environmental stress, and they can survive considerable amounts of time when the environmental conditions are favourable. Some pathogenic viruses capture a portion of the host cell membrane when they replicate (e.g. measles virus, mumps virus, influenza virus), but others remain uncoated (e.g adenovirus, norovirus, poliovirus). The surface of the latter group carries a charge derived from the relative levels of ionisation of the amino and carboxyl groups in the proteins that encase the nucleic acid. The nett charge on the surface is a function of the composition of these proteins and the pH and the ionic strength of the surrounding medium. Schijven et al (2006) consider viruses to be the most important pathogens in groundwater due to their persistence and small size. From their analysis of virus attenuation in groundwater, they have proposed protection zones of one to two years travel time for the Netherlands to achieve an infection risk of 10^{-4} per person per year.
Protozoa	Protozoa are single-celled, eukaryotic microorganisms. Unlike bacteria, the cell has a defined nucleus surrounded by a nuclear membrane, and the identifiable intracellular organelles. There are a number of pathogenic species, although Giardia, Cryptosporidium and Entamoeba are the most frequently referenced in relation to water-borne disease. However, recently there has been a growing interest in the waterborne transmission of *Toxoplasma gondii*. Protozoa are ubiquitous in water and soils. Most of the enteric protozoa produce cycts, or oocysts, as part of their life cycle. Cysts are a dormant form of the organism that play an important role in the transmission of the pathogen. Cysts (and oocysts) are highly resistant to environmental stress, remaining viable for several months at low temperatures, and can often survive the normal doses of chlorine used to disinfect drinking water. Cysts vary in size depending on the species of protozoa, but for Giardia, Cryptosporidium and Entamoeba they are in the range of 4µm to 20µm in diameter.

2.3.2 Characteristics of Ebola virus and *Vibrio cholera*.

EBOLA VIRUS

Ebola virus belongs to the family *Filoviridae*. The genome of the virus is a single strand of negative-sense RNA. The virus has a pleomorphic structure which folds to form the characteristic “U” or

“6” shapes that are seen in electron micrograph images. The virus capsid is surrounded by a lipid membrane that it derives from the infected host cell. The virion is approximately 80nm in diameter, but can vary considerably in length, occasionally reaching 14µm (Anon 2014).

Three characteristics are particularly important when looking for possible surrogates to help gauge the survival and transport potential of the virus: the presence of a modified lipid envelope; the capsid structure; and the RNA genome. The virus envelope plays a crucial role in the process of infection by attaching to the surface of the target cell and then fusing with the cell membrane to release the virus capsid and nucleic acid into the cell cytoplasm, where new copies of the virus will be generated. But membranes can be fragile, and the envelope surrounding the virus may be particularly vulnerable to environmental conditions.

Very few survival studies have been attempted with Ebolavirus, and the ambient conditions used for the experiments were not representative of the environmental conditions in SSA. Consequently, only limited conclusions can be drawn from these studies. In the dark and at 20^{o}C - 25^{o}C, Ebolavirus infectivity was reduced by 1 $\log_{10}$ in 35 hours and by 4 $\log_{10}$ in 6 days when incubated on a number of surfaces (Sagripanti et al. 2010). This inactivation rate is similar, although slightly longer, than the inactivation rate published by Smither et al (2011) who was studying survival in aerosols. Inactivation rates in the environment would be expected to be greater due to the sensitivity of the virus to UV irradiation (Sagripanti and Lytle, 2011). Given the difficulty of working with Ebolavirus, estimates of environmental survival times might be derived from studies of other virus groups with similar characteristics: single-stranded, negative sense RNA; pleomorphic capsid; and lipid envelope. Viruses of the family paramyxoviridae (for example, measles virus, mumps virus, Hendravirus and Nipahvirus) share these characteristics. Ecologically, Nipahvirus and Hendravirus have even greater similarities to Ebolavirus, being a recently emerged zoonotic disease with a natural reservoir in bats (Fogarty et al. 2008; Scanlan et al. 2014). Laboratory studies have shown that the survival of Hendravirus is inversely related to temperature. At 4^{o}C, 22^{o}C and 56^{o}C, the half-life of the virus was 308, 50.2 and 1.85 hours respectively (Scanlan et al. 2014). Hendravirus is also highly sensitive to desiccation, surviving for less than two hours under these conditions (Fogarty et al. 2008). Environments with a low relative humidity (between 20% and 30%) generally favour the survival of enveloped viruses (Tang 2009), suggesting that the Ebolavirus might be less stable in regions with high relative humidity.

No reports of the water-borne transmission of paramyxoviruses could be found; however, several reports have been made of the potential for avian influenza virus – another RNA enveloped virus - to be transmitted through water (Hinshaw et al. 1979; Achenbach & Bowen 2011; Brown et al. 2007). Avian strains of influenza maybe an anomaly among enveloped viruses because the host lives on or near water and the virus may have evolved to use water as a transmission route.

V.CHOLERAE

Cholera is a disease of antiquity that was first described over 2000 years ago, although the causative agent was not identified until the mid/late 19th Century. *V.cholerae* is a Gram-negative bacillus (Gram-negative is one of two outcomes of a diagnostic staining technique widely used in microbiology. Under the microscope Gram-negative cells are red whereas Gram-positive cells are dark blue/purple. Bacillus simply means rod-shaped) that has a very characteristic “comma” shape when viewed under the microscope. The bacterium is a facultative anaerobe, which means that it can grow in environments with and without oxygen (Valdespino & Garcia-Garcia 2011). *V.cholerae* has a single flagellum (a hair-like structure) at one end of the cell that is used to propel the cell through water. Consequently, *V.cholerae* is motile and can move itself within its immediate environment (Janda 1998). The relevance of this facility to the potential dispersal of the organism in groundwater is unknown, but it is very unlikely to make a significant contribution particularly in flowing water systems.

Members of the genus *Vibrio* are normal inhabitants of marine environments, and water bodies that are immediately in contact with marine environments such as estuaries. Unlike some other vibrio species *V.cholerae* does not have an absolute requirement for a saline environment, so this organism can also be isolated from freshwater where the saline conditions are replaced by warmth and organic nutrients (Janda 1998; Jutla et al. 2013; Rebaudet et al. 2013a). Several publications since the mid-1990s have developed the idea of cholera epidemiology being linked to coastal aquatic environments and the abundance indigenous phytoplankton (cited in Jutla et al. 2013). The apparent correlation with phytoplankton abundance has spurred a number of studies into the use of satellite imagery to monitor the phytoplankton and provide an early warning of cholera outbreaks (Jutla et al. 2013). Two recent reviews of the distribution of cholera outbreaks in Africa suggests that the coastal link may not be as strong as it is in other parts of the world (Rebaudet et al. 2013a; Rebaudet et al. 2013b): only a minority of total recorded cases could be attributed to coastal areas (Rebaudet et al. 2013b). Although the Great Lakes Region and the Lake Chad basin appear to have a particularly high number of cases, and that outbreaks seem to occur with the rainy season, *V.cholerae* has rarely been isolated from water samples (Rebaudet et al. 2013b). These authors report only one incidence of the vibrio being isolated from a well.

Certain species of bacteria can survive prolonged exposure to adverse environmental conditions by producing spores. These spores can survive for years, sometimes decades, and germinate under the right conditions. Gram-negative bacteria do not adopt this strategy, but appear to undergo a cellular transformation that puts them into a dormant state where they are metabolically viable but cannot be grown by standard laboratory culture methods. This state is known as Viable but Non-Culturable (VNC). *V.cholerae* has been show to enter a VNC state in water where it may play an important role in the initiation of epidemics (Alam et al. 2007). During outbreaks of cholera in crowded urban slums it is inevitable that the local environment will become contaminated with the pathogen, and it is highly likely that it will contaminate vulnerable shallow wells (Momba et al, 2006; Rebaudet et al. 2013b). *V.cholerae* can survive in freshwater, particularly when the water is contaminated with organic nutrients, as might be expected of many of the wells in urban slums. Its potential for long-term survival in these conditions is increased if the bacterium enters a VNC state, and the VNC state may present a risk to human health. The presence of biofilms on the walls of the well may also create an environment that allows the cholera vibrio to extend its survival time (Alam et al. 2007). However, this is speculative and there appears to be very little firm evidence to suggest that groundwater is an important vehicle for the transmission of cholera, and no evidence was found to indicate that *V.chloerae* is transported through groundwater.

2.3.3 Factors affecting the survival and mobility of bacteria and viruses in the subsurface

Studies of virus survival and mobility in the subsurface have been carried out using non-enveloped viruses. Ebola is an enveloped virus so it is difficult to say how relevant the findings from current literature will be. Groundwater is widely used as a source of water for drinking, agriculture and industry. Globally, it is estimated that two billion people rely on groundwater (Tufenkji & Emelko 2011). Groundwater has always been considered to be of a better quality than surface water due to the protection given by the soil layers that restrict the ingress of microbial pollutants. From this perspective, groundwater is often consumed untreated or is given a minimum amount of treatment, such as chlorination. But frequently this is insufficient to prevent outbreaks of disease. Techniques that help to reduce the likelihood of contamination at the point of abstraction, such as groundwater protection zones that are applied in many developed countries, depend on an understanding of the survival and mobility of pathogens in the groundwater systems that are being used. To this end there has been a substantial amount of work carried out in the laboratory and at field sites to build an understanding of the most important factors that contribute to pathogen survival and transport (Table 8). The data from these studies inform models that can then be used to predict the risks of contamination at different points away from the source.

Table 8 Factors that influence the survival and mobility of bacteria and viruses in the subsurface (adapted from Pedley et al. (2006)

Factor	**Viruses**		**Bacteria**	
	Influence on survival	**Influence on migration**	**Influence on survival**	**Influence on migration**
Temperature	Longer survival at low temperatures	Unknown	Longer survival at lower temperatures	Unknown
Microbial activity and diversity	Varies: Some viruses are inactivated more readily in the presence of certain microorganisms; some are protected; and for some there is no effect.	Retard migration via attachment to biofilms	The presence of indigenous microorganisms appears to increase the inactivation rate of enteric bacteria. Community diversity rather than microbial density is important and certain species may have a greater inhibitory effect. Several mechanisms will be involved. Biofilms may harbour pathogens and either extend or limit their survival.	Biofilms
Moisture content	Most viruses survive longer in moist soils and even longer under saturated conditions; unsaturated soil may inactivate viruses at the soil water interface.	Virus migration usually increases under saturated flow conditions.	Most bacteria survive longer in moist soils than in dry soils.	Bacterial migration usually increases under saturated flow conditions.
pH	Most enteric viruses are stable over pH range of 3 to 9; however, survival may be prolonged by near neutral pH values.	Low pH typically increases virus sorption to soils; high pH tends to cause desorption and facilitates greater migration.	Most enteric bacteria will survive longer at near neutral pH.	Low pH encourages adsorption to the soils and the aquifer matrix; the tendency of bacteria to bind to surfaces and form biofilms may reduce detachment at high pH.
Dissolved Oxygen	Possible decrease inactivation in anaerobic water	Unknown	Faster death rates at low DO levels.	Varies. Some bacteria are retained more strongly under low DO conditions, whereas others migrate farther.

Factor	Viruses		Bacteria	
	Influence on survival	**Influence on migration**	**Influence on survival**	**Influence on migration**
Salt species and concentration	Certain cations may prolong survival depending upon the type of virus.	Increasing ionic strength of the surrounding medium generally increases sorption.	Generally unknown. Cholera vibrios have a preference for saline conditions, but are able to survive In freshwater. Saline groundwater may extend the survival of *V.cholerae.*	Increasing ionic strength of the surrounding medium generally increases sorption.
Association with soil/aquifer matrix	Association with soil generally increases survival, although attachment to certain mineral surfaces may cause inactivation.	Viruses interacting with soil particles are retained at the point of attachment.	Adsorption onto soil surfaces reduce inactivation rates. The number of bacteria on surfaces may be several orders of magnitude higher than the concentration in the aqueous phase.	Interaction with the soil inhibits migration.
Soil properties	Probably related to the degree of virus sorption.	Preferential flow pathways through soils (Artz et al. 2005). Small differences in the internal structure of soil cores can have a big effect on migration. Soils with charged surfaces, such as clays, adsorb viruses.	Probably related to the degree of bacterial adsorption.	Preferential flow pathways through soils (Artz et al. 2005). Small differences in the internal structure of soil cores can have a big effect on migration. Soils with charged surfaces, such as clays, adsorb bacteria.
Bacteria/virus type	Varies between different virus types. Possible that the process of inactivation is gradual and may be reversible under certain conditions (Alvarez et al. 2000).	Sorption to soils is related to physico-chemical differences in the secondary and tertiary capsid structure, the presence or absence or absence of a membrane envelope, and amino acid sequence.	Varies between different species. Some species are able to enter a dormant state (Viable Non-Culturable) that may extend their survival in the sub surface. Some indications that VNC cells may be of health significance.	Some species of bacteria are more capable of binding to surfaces; variation may also occur between strains of the same bacterial species. Some bacterial species are motile and may respond to physical or chemical stimulants. Motility unlikely to be significant in the dispersal of bacteria at scale.

Factor	Viruses		Bacteria	
	Influence on survival	**Influence on migration**	**Influence on survival**	**Influence on migration**
Organic matter	Organic matter may prolong survival by competitively binding at air-water interfaces where inactivation can occur.	Soluble organic matter competes with the viruses for adsorption on to sol particles which may result in increased virus migration.	The presence of organic matter may act as a nutrient source for bacteria, promoting growth and extending survival.	Organic matter may condition solid surfaces and promote bacterial adsorption.
Hydraulic conditions	Unknown	Virus migration generally increased at higher hydraulic loads and flow rates.	Unknown	Bacterial migration generally increased at higher hydraulic loads and flow rates.
Clay minerals and colloids	In combination with other factors, virus survival is affected by the type of clay mineral.	Clay minerals strongly adsorb viruses and will restrict the mobility of viruses. Attachment to colloids may further restrict mobility; however, there is evidence that colloids may increase the mobility of attached pathogens in groundwater	Unknown	Bacteria can adsorb to clay minerals, which may restrict their mobility on the subsurface. Attachment to colloids may further restrict mobility

Temperature

Temperature is probably the most important factor influencing the inactivation of bacteria and viruses in the environment (Pedley et al 2006). Inactivation rates at particular temperatures are different for bacteria and viruses and will vary considerably between different species of bacteria and viruses; however, the general trend is for a direct correlation between temperature and inactivation rate. With a few exceptions (for example, Vinten et al. 2002) bacteria and viruses tend to survive longer at lower temperatures. This trend is more apparent for some organisms than for others. Figure 20 and Figure 21 below show the link between water temperature and the inactivation rate coefficient for bacteriophage MS2 and Poliovirus 1. The data for these figures was taken from a table of compiled inactivation rate coefficients published in Pedley et al (2006). Poliovirus 1 and MS2 were the only two microorganisms, including bacteria, for which a reasonable number of studies had published the inactivation rates at different temperatures. The trend of higher inactivation rates at higher temperatures is clear for MS2 but much less so in the case of Poliovirus 1. The reason for this difference is not clear, but it may result from the biological differences between the two viruses (suggesting that Poliovirus survival in water is less dependent on temperature), or from differences between experiment designs when using the two viruses.

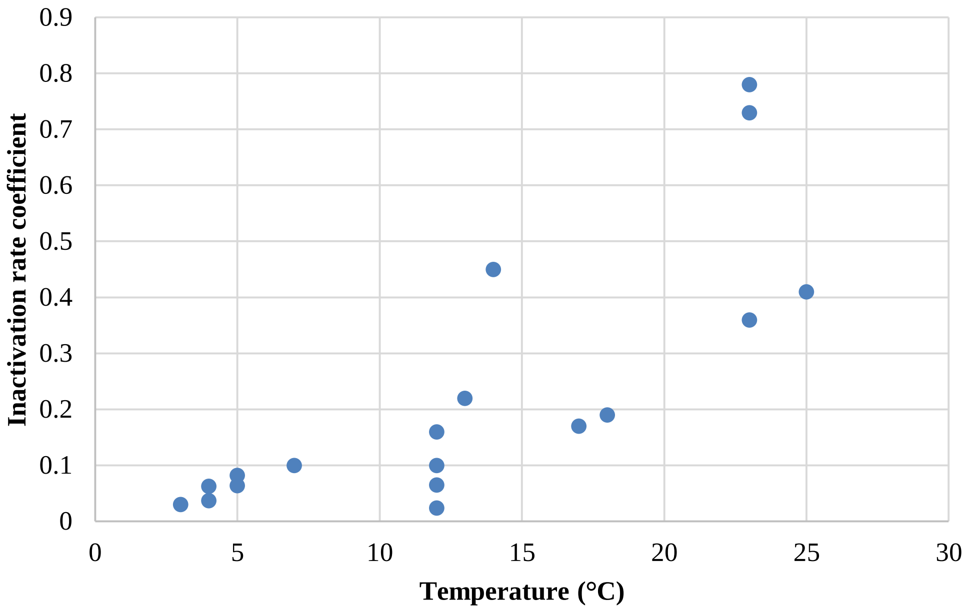


Figure 20 Effect of temperature on the inactivation rate of bacteriophage MS2 in water (reproduced from data in Pedley et al 2006)

The effect of temperature on the mobility of bacteria and viruses in the subsurface is not known, although there is a suggestion from the literature that the retention of bacteria may be greater at higher temperatures (Tufenkji & Emelko, 2011).

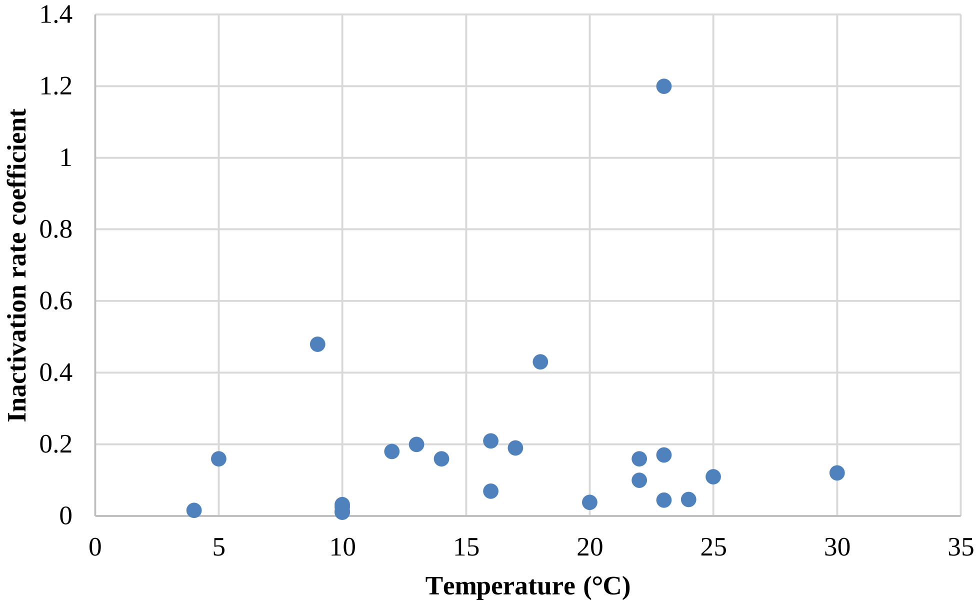


Figure 21 Effect of temperature on the inactivation rate of Poliovirus 1 in water (reproduced from data in Pedley et al 2006)

MICROBIAL ACTIVITY AND DIVERSITY

Soils are populated with a very complex and diverse range of microorganisms, with some estimates being as high as one million distinct genomes in pristine soils (Torsvik et al. 1990; Bunge et al. 2005). Such a diverse indigenous micro-flora represents a significant barrier for any introduced and non-native species to become established. van Elsas et al., (2012) studied the survival of *E.coli* O157 in soils that had been enriched with increasingly complex mixes of indigenous soil microorganisms and found an inverse relationship between the soil species diversity, although not density, and the survival time of the introduced species. But the relationship may not entirely be a result of community complexity, as there are indications from comparative studies of livestock bedding that certain microbial species may have a greater influence over the survival of *E.coli* O157 than others (Westphal et al. 2011).

Stated simply, indigenous microorganisms out-compete the pathogens (Toze 2003), but this disguises a multitude of different process that might occur in the soils. Competition for nutrients is very likely to be a factor mediated by the diversity of indigenous species being able to exploit all nutrient sources. However, the importance of particular species suggests other mechanisms of suppression, such as the presence of antibiotics (Ramette et al. 2003), and predation by protozoa might influence the survival time of pathogens.

The relationship between microbial activity and virus survival is not straight forward. Predation by prokaryotic and eukaryotic cells in soils and aquifers, and the harsh environments created by indigenous microbial species will reduce the number of viruses, but the magnitude of the effect may be dependent on the particular virus type (Hurst et al. 1980; Matthess et al. 1988), with some viruses being more susceptible than others.

Biofilms will develop naturally on any surface that is moist and is exposed to microorganisms. Biofilms can vary in size and complexity from a single layer of cells over the surface to a thick glutinous film that is easily visible to the naked eye. Thicker biofilms generate different environments as distance from the surface increases: the surface areas may be aerobic and relatively nutrient rich whereas the deeper biofilm will be anaerobic and nutrient poor. Biofilm growth on soil particles and the aquifer matrix may incorporate pathogens and potentially extend their survival time in the aquifer. Alam et al. (2007) were able to maintain VNC forms of *V.cholerae* in biofilms for 495 days and still recover viable cells following passage through animals. In contrast Banning et al. (2003) suggest that biofilms may limit the survival of pathogens in groundwater by effectively competing for nutrients.

Moisture content

In many settings, an increase in the soil moisture correlates with longer survival times of bacteria and viruses, but there are exceptions. In soils with a low moisture content, the inactivation rate of poliovirus decreased as the moisture content increased to 15%. As the soil moisture content was increased above 15% the inactivation rate of the virus started to increase (Hurst et al, 1980) Furthermore, greater migration has been observed under saturated conditions.

pH

Most bacteria and viruses tend to survive longer within the pH range 6 to 8. However, enteric microorganisms must be able to survive exposure to stomach acids before being carried into the intestine. Most enteric viruses are stable over a pH range of 3 to 9.

pH has a strong influence over the adsorption of bacteria and viruses to surfaces. In general, adsorption of bacteria and viruses to the aquifer matrix and soils increases as the pH decreases. Higher pH values can result in desorption and remobilisation of some viruses.

Dissolved oxygen

The role of dissolved oxygen in the survival of mobility of pathogens in the sub-surface has not been well characterised. There is some evidence to suggest that dissolved oxygen levels may be linked to the retention of bacteria on surfaces and their survival time; however, the evidence is contradictory and depends on the bacterial species (Tufenkji & Emelko 2011).

Ionic strength

The ionic strength of water has a significant impact on the survival and transport of bacteria and viruses in the sub-surface, but the magnitude and direction of the effect is influenced by the species of bacteria or virus, the nature of the aquifer matrix and the type of ions in the water. Certain cations have been shown to prolong the survival of some virus types. In contrast, some enteric bacterial species survive longer in freshwater than seawater, which shows that a high salt concentration can have disinfecting properties. Increasing ionic strength generally increases the adsorption of viruses and bacteria to the soil/aquifer matrix (Bellou et al, 2015; Knappett, et al, 2008; Walshe et al, 2010), although the opposite has been reported with the bacteriophage strains MS-2 and φX174 when passed through columns of Al-oxide coated sand (Zhaung and Jin, 2003). Studies have shown that viruses can desorb from surfaces as a result of sudden changes in the ionic strength of the suspending medium, for example following rainfall events (Hurst and Gerba 1980; Bales et al, 1993; Busalmen and Sanchez 2001; Krauss and Griebler, 2011). This may be significant in areas with high annual rainfall or where long dry spells that are interrupted by sudden and heavy downpours.

Soil properties

Most of the information regarding the effect of soil properties on the survival and mobility of pathogens has come from studies of *E.coli* O157 and various *Salmonella* species. The focus on these pathogens reflects the concerns about the contamination of groundwater from the surface spreading of manure on agricultural land. Vinten et al. (2002) found some variation in the survival times of *E.coli* and *E.coli* O157 in soils from different locations and between soils in laboratory and field conditions. Survival times were short (half-life between 1.8 and 2.9 days), but a small proportion of the population had a half-life in the soil of between 15 and 18 days (Vinten et al. 2002).

The migration of microorganisms through the soil is influenced by the soil structure. Using soil columns and *E.coli* O157 as the representative pathogen, Artz et al. (2005) showed that migration rates were substantially reduced in compacted soils, but were significantly increased in the presence of earthworm burrows. Similarly, root systems can provide pathways for the rapid migration of microorganisms through soils (Kemp et al. 1992), although conversely, these authors quote others who suggest that the production of polysaccharides by plant roots may retard the transport of microorganisms through the soil.

Clay minerals in soils are known to adsorb viruses, and can either increase or decrease their survival in the subsurface. The interaction between clay minerals and viruses is described in more detail in a later section. In a recent study soils collected in the South East of the UK, several factors in addition to clay mineral content were found to strongly influence the ability of soils to attach two strains of bacteriophage (Chi-Hiong 2013). Although the two virus types of bacteriophage showed some differences in their preference for soil properties, aluminium and soil pH were particularly important for the attachment of both virus types.

BACTERIA/VIRUS TYPE

The survival times of bacteria and viruses can vary considerably between the different groups of microorganisms, and within the groups between different species. In a summary of inactivation studies compiled by Pedley et al (2006) the inactivation rate coefficients in groundwater ranged between 0.0058 day^{-1} for the bacteriophage MS2 at 7^{o}C to 5.3 day^{-1} for *V.cholerae* at 9-13^{o}C. Although these are extreme values from single publications, they highlight the general observation that viruses have a slower inactivation rate than bacteria. Despite the wide variation in survival times, the sort of inactivation rates to expect are 0.03 $\log_{10}$ per day for enteric viruses and 0.09 $\log_{10}$ per day for enteric bacteria (Tufenkji & Emelko 2011).

Microorganisms vary considerably in size (Table 9) and are known to overlap with the pore sizes of rocks and some soil types (Figure 22).

Table 9 Approximate sizes of selected bacteria and viruses (adapted from Pedley et al. (2006))

Class	Microorganism	Size
Virus	Bacteriophage (common surrogates of enteric viruses)	20-200nm diameter
	Poliovirus	30nm diameter
	Adenovirus	80nm diameter
	Hepatitis A virus	27-32nm diameter
	Ebola virus	80nm diameter, but can be up to 14µm in length. Pleomorphic and enveloped.
Bacteria	Bacterial spores (*Bacillus* spp; *Clostridium* spp)	1µm
	E.coli	0.5µm x 1µm – 2µm
	Salmonella typhi	0.6µm x 0.7µm – 2.5µm
	Shigella spp.	0.4µm x 0.6µm – 2.5µm
	Vibrio cholerae	0.5µm x 1.4µm – 2.6µm

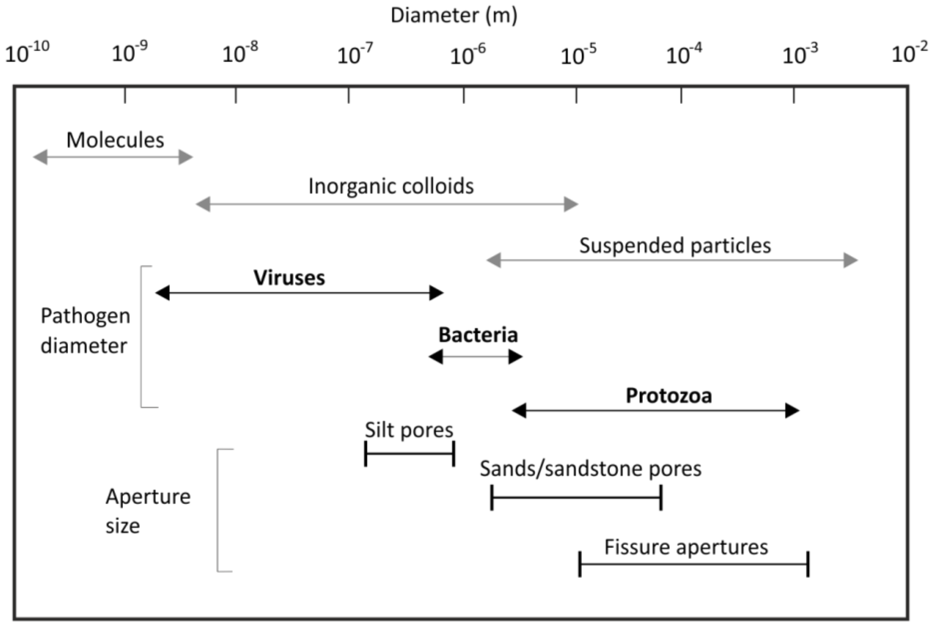


Figure 22 Examples of pathogen diameters compared to aquifer matrix apertures, colloids and suspended particles (adapted from Pedley et al. 2006 and Lapworth et al. 2005).

Where the size of the microorganism is larger than the pore spaces in the soils and aquifer matrix the mobility of the organism will be restricted by filtration or straining. This mechanism is particularly important for limiting the mobility of larger pathogens, such as the protozoa, but if the soil or aquifer system has particularly small pore sizes, bacteria and viruses may also be retained by filtration. However, where fissures of sufficient size exist enteric viruses and other and other faecal-derived microorganisms can penetrate aquifers to quite significant depths (Powell et al. 2003).

The method of replication is a key difference between bacteria and viruses that has implications for their survival in the subsurface. Viruses are obligate intracellular parasites, which means they must infect a host cell in order to be able to reproduce themselves: there is no exception to this rule. Outside the host, virus particles are inert and do not carry any of the cellular material that is necessary for the production of energy or the synthesis of the biomolecules that produce the daughter viruses: these services are provided by the host cell after infection. Human pathogenic viruses, therefore, cannot replicate in the environment. Once released from the host their numbers will decline at a rate determined by the particular virus type and the nature of the environment. In contrast bacteria are reproductively self-sufficient. Each cell has a complete set of metabolic systems that allow it to reproduce itself in a favourable environment. Hence, there is the potential for bacterial pathogens to increase in numbers – if only temporarily – when they are released into the environment, and their die-off rate will be determined by the balance between their rate of inactivation and replication. For most bacterial pathogens in the environment, the former greatly exceeds the latter.

Some species of bacteria, for example *V.cholerae* (Janda 1998), are motile. These cells can propel themselves through the suspending medium using hair-like surface structures called flagella: some species have a single flagellum at one end of the cell, whereas others have multiple flagella in different arrangements on the cell surface. Cells tend to swim in the direction of their long axis at about 35 diameters per second (Tufenkji & Emelko 2011). Under the microscope, the direction of movement of a single cell appears random, but many motile species of bacteria can orientate their movement in response to a particular stimulant, such as a chemical, light, or magnetic field. Viruses are not motile.

ORGANIC MATTER

Dissolved organic matter adsorbs to surfaces of grains and inhibits microbial attachment, thus lowering retention. Organic layer may prime surfaces for the development of biofilm (Wimpenny 1996) that may eventually restrict pore space and increase straining, also biofilm may increase the potential for pathogens to be eliminated by grazing by indigenous biofilm organisms (Banning et al. 2003; Tufenkji & Emelko 2011). Organic layers may provide hydrophobic binding sites for the adsorption of viruses with hydrophobic groups on their surface.

HYDRAULIC CONDITIONS

There is no evidence to suggest that the hydraulic conditions have a noticeable effect on the survival of bacteria or viruses, but at higher hydraulic loads and faster flow rates there is less retention of bacteria and viruses on solid surfaces and an increase in the dispersal of the pathogens (Pedley et al. 2006).

CLAY MINERALS AND COLLOIDS

This section will overlap to an extent with the soil section above, but the purpose here is to concentrate on particular clay minerals that are of relevance to Sierra Leone, and the colloids produced from these minerals. Studies have concentrated on a limited number of clay minerals, particularly kaolinite and different forms of smectite, especially montmorillonite (Chi-Hiong 2013). Virus attachment to clay minerals is complex, and there is evidence that different viruses may interact with the minerals in different ways (Chrysikopoulos & Syngouna 2012; Lipson & Stotzky 1985a; Lipson & Stotzky 1985b). Lipson & Stotzky (1985) found differences in the relative levels of attachment of Reovirus and coliphage T1 to kaolinite and montmorillonite, but did not observe competition for binding sites when the two viruses were added together, suggesting that variations in surface properties of the clay minerals is important for the specificity of virus attachment. Attachment to the clays was pH dependent, with a higher level of attachment of Reovirus at lower pH values (Lipson & Stotzky 1985a), but adsorption was not blocked when the positively charged sites on the minerals were chemically blocked.

Bacteria and viruses can attach to clay colloids in groundwater, through hydrophobic interactions (Chrysikopoulos & Syngouna 2012). In studies using glass beads to simulate the aquifer matrix, the flow of bacteria and viruses through the column was shown to be retarded when bound to clay colloids (Vasiliadou & Chrysikopoulos 2011; Syngouna & Chrysikopoulos 2013). The mechanism proposed by these authors to explain this observation is that the bacteria and viruses attach to the colloids, which then attach strongly to the glass beads. If these laboratory findings do mimic the interactions taking place in soil and aquifer systems, the presence of clay colloids derived from kaolinite and montmorillonite may limit the dispersal of pathogens.

2.3.4 Implications for Sierra Leone

Temperature has a strong influence on the survival times of bacteria and viruses in water. At the average temperature of the groundwater in Sierra Leone (ca. 26°C), the inactivation rates of pathogens are likely to be quite high, so the survival times will be short relative to colder environments. Nevertheless, the survival times will vary considerably between different pathogens and it is likely that virus pathogens will survive longer than bacterial pathogens and faecal indicator organisms.

The chemical and physical characteristics of soils and the aquifer matrix have an important role in the adsorption of pathogens onto these surfaces. Bacteria and viruses are adsorbed by the types of clay minerals found in Sierra Leone which will restrict the migration of the pathogens from the source. However, it is likely that the groundwater will contain colloidal material from the clay minerals, which may enhance the migration of pathogens through the aquifer.

Sierra Leone has witnessed a number of cholera outbreaks, and it seems feasible that *V.cholerae* will contaminate groundwater at these times. The literature is limited, but *V.cholerae* has been isolated from wells in SSA. *V.cholerae* is known to transform into a dormant state (VNC) in adverse environmental conditions, and there is some evidence to suggest that it remains a risk to human health when in this state. The significance of the VNC state for the survival and dispersal of *V.cholerae* in groundwater is unclear, but it may allow the bacterium to travel further than would be anticipated from the viable cell, and it will be very difficult to detect in groundwater samples using standard microbiological methods.

Potentially high levels of organic contamination in groundwater from latrines and surface wastes may counteract the capacity of the soils and the aquifer matrix to adsorb pathogens and allow them to migrate further than they would in a clean environment. However, it may also create conditions that help to reduce the survival times of pathogens.

Pathogen survival and transport in the subsurface has been studied and reported on for several decades. Most of the work has been done in developed countries with mainly temperate climates. The data shows that the fate of pathogens in the subsurface is determined by a complicated and poorly understood set of interactions between several known factors and possibly as many unknown ones. Consequently, it is extremely difficult to predict the behavior of a pathogen when it is released into the environment, even in regions where these studies have been done. There is significantly less information about the environmental survival of pathogens in SSA, which is a knowledge gap that does need to be filled before a reasonable attempt can be made to assess the risks from pathogens moving through groundwater.

Pathogen survival summary:

Based on average groundwater temperatures in Sierra Leone (26°C), inactivation rates for pathogens are likely to be high. Nevertheless, survival times will vary considerably between different pathogens and overall viruses are likely to survive longer than bacteria.

Physical and chemical processes within the soil attenuate pathogens and restrict migration. However, colloidal attachment may in some cases enhance migration due to size exclusion effects (i.e. reduced diffusion) along preferential flowpaths.

The dormant state that *V.cholerae* can exist in (VNC) suggests that its survival and dispersal in the subsurface could be greater than would be expected for viable cells, and necessitates the use of sequencing techniques for detection.

Fate and transport of pathogens are determined by interactions between multiple factors, e.g. initial pathogen levels, nutrient levels, temperature, completion for resource with other groundwater micro-macro fauna to name a few. There are very few studies that have considered pathogen survival in conditions relevant to Sierra Leone.

3 Risks to groundwater supplies: a source-pathway-receptor framework for Sierra Leone

To help identify the risks of pathogen contamination in groundwater supplies used for drinking it is helpful to frame the problem within a source, pathway receptor framework. This provides the basic framework for most groundwater risk assessments. The causes of groundwater quality degradation may be separated into those related to the source of the contaminants and those which govern their transport i.e. the pathways, into and through the water environment. The receptors in this particular study are taken to be the water supplies used for drinking – mainly groundwater sources, (such as wells boreholes and springs) but also small streams and swamp areas since they are also used in Sierra Leone. Key potential sources, pathways for groundwater receptors are summarised in Table 10.

For microorganisms in faecal and other waste materials, the main barrier to their movement into groundwater is the soil and unsaturated zone. As discussed earlier, once in the subsurface, a complex interaction of other physical, chemical and biological factors control the survival and mobility of the microorganisms (Pedley et al., 2006). Once the microorganisms has reached the groundwater the main factors that enable attenuation are dilution and the groundwater travel time to the various water supplies, which as described above can be rapid in Sierra Leone.

3.1 GROUNDWATER VULNERABILITY

In recognition of the importance of protecting groundwater resources from contamination, techniques have been developed for predicting which areas are more likely than others to become contaminated as a result of human activities at the land surface. Once identified, areas prone to contamination can be subjected to certain use restrictions or targeted for greater attention. Groundwater vulnerability is a term that has been in use for more than 40 years. A general definition is given by the US Natural Research Council (1993): "Groundwater vulnerability: the tendency and likelihood for [contaminants] to reach [a specified position in the groundwater system] after introduction at [some location]." Most other definitions replace the phrases in brackets with specific terms. The most commonly used definition (e.g. U.K and most other European countries) is: "The tendency and likelihood for general contaminants to reach the water-table after introduction at the ground surface"

The vulnerability of groundwater to pollution depends upon:

- The time of travel of infiltrating water
- The contaminant attenuation capacity of the soil and geological materials through which the water and contaminants travel

If the contaminant source is at the ground surface and the source is the water-table then the main pathways to consider are the soil and the unsaturated zone. Since the soil is biologically active many pollutants can be attenuated. However, if the contaminant source is buried beneath the soil, then only the unsaturated zone should be considered where there may be less opportunities for attenuation. In general, fractured aquifers with shallow water tables are assessed to be extremely vulnerable (e.g. O Dochartigh et al. 2005).

If groundwater protection strategies are considering the water supply sources as the receptor rather than the groundwater, then the travel times and attenuation potential of the saturated aquifer should also be taken into account. In areas where fracture flow and rapid transit dominates (such as in shallow tropical soils with heavy rainfall), the travel time horizontally through the shallow sub-surface can be very short, this pathway may not have significant attenuation potential.

Table 10 Hazard sources and pathways for contamination of water points in Sierra Leone (adapted from Lapworth et al. 2015a)

Component	Category	Risk factors
Regional considerations		Population density Land use category Physical relief Rainfall amount and intensity
Sources	Municipal/ household including domestic livestock	***Surface sources:*** Open defecation from humans and animals Surface waste sites ***Sub-surface sources:*** Latrines Septic tanks Soak-aways Waste pits Cemetery or other burial sites (Open) sewers ***Other potential hazard sources:*** Market places, Abattoir waste, both liquid and solid
	Hospital or Treatment centre	Liquid waste discharge to soak-aways/surface channels Solid medical waste disposal Latrines/septic tanks on site
	Industry e.g. mining	Process plant effluent Solid waste disposal Storage tanks Site runoff
Pathways	Horizontal and vertical pathways in unsaturated and saturated zone	***Shallow sub horizontal pathways in tropical soil*:** Tropical soils, e.g. Plithosol/Ferrasol horizons present Shallow depth to water table Thin soils and low organic matter content Natural rapid bypass from tree roots and burrows ***Vertical and horizontal pathways in saturated zone:*** Thickness of low permeability zone above weathered basement Thickness and maturity of weathered basement zone Fracture size, length and density in the more competent bedrock below weathered basement
	Local/ headwork pathways	Lack of dugwell headwall and/or lining Lack of well cover Use of bucket and rope – soil/animal/human contact Gap between apron and well lining Damaged well apron Propensity for surface flooding Gap between borehole riser/apron Damaged borehole apron Eroded or de-vegetated spring backfill

Extreme vulnerabilities are associated with highly fractured aquifers which offer little chance for contaminant attenuation. The likely vulnerabilities of a range of broad categories of aquifer types relevant to Sierra Leone are shown in Table 11.

Table 11 Generalised pollution vulnerability for hydrogeological environments found in Sierra Leone (adapted from Lawrence et al., 2001)

Hydrogeological environment		**Travel time to saturated zone[b]**	**Attenuation potential**	**Pollution vulnerability**
Weathered basement	Permeable tropical soils[a]	Days-weeks	Low-High	High-Extreme
	Thick weathered layer (>20m)	Months-years	High	Low
	Thin weathered layer (<20m)	Weeks-months	Low-High	High
Thick sediments associated with rivers and coastal regions	Shallow layers	Weeks-months	Low-high	High
	Deep layers	Years-decades	High	Low
Minor sediments associated with rivers	Shallow layers	Days-weeks	Low-high	Extreme
	Deep layers	Months-years	High	Low

[a]e.g. Ferrasol or Plinthosol horizons present, [b]higher travel times may operate for short periods of time during high intensity rainfall and when water tables are high, equally longer travel time are also possible in some settings

3.2 CONCEPTUAL MODELS OF PATHWAYS FOR GROUNDWATER CONTAMINATION

This section focuses on summarising the main types of drinking water sources or 'receptors' used in Sierra Leone, the key sources of hazards, both surface and subsurface sources, and the major pathways for transmission of pollutants to groundwater receptors. These are summarised briefly in Table A2 (see appendix) and through the use of simplified schematic diagrams of key processes and accompanying text in the following section. These conceptual models show worst-case scenarios under high water table conditions in basement terrains, i.e. typical conditions found in August-September. Surface water sources are of generally poor quality, and are highly vulnerable to surface sources of contamination. Apart from the public supply to Freetown which is piped from the Guma Valley reservoir, most domestic water used in Sierra Leone are from hand dug wells, boreholes make up less than 10% of groundwater sources. The supply and treatment from public supplies are intermittent at best, and household treatment is essential[4] in Freetown and elsewhere. Household treatment of groundwater sources is also highly intermittent and is only likely to be more widespread during outbreaks of water-borne disease.

Figure 23 shows a schematic of the main drinking water sources for Sierra Leone which include wells, boreholes and surface water. Springs are also used in some locations, for the purpose of this report these can be considered analogous to unlined traditional wells as they essentially access the same shallow groundwater zone and are highly vulnerable to open defecation.

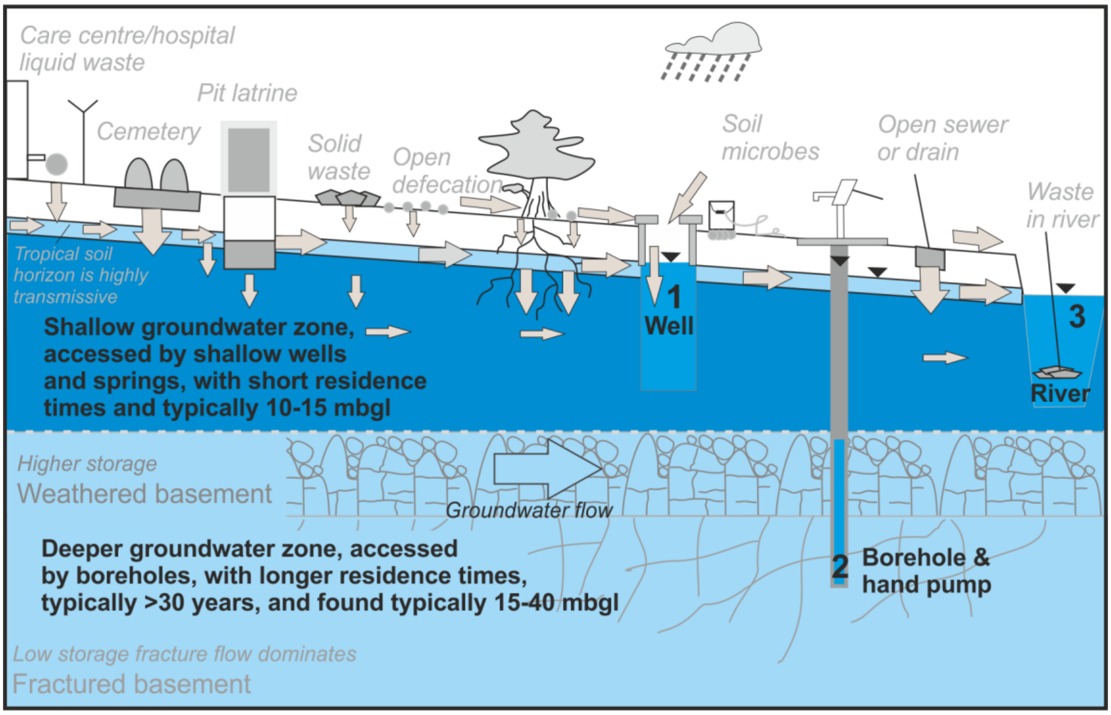


Figure 23 Groundwater receptors and key groundwater zones typically found in Sierra Leone and elsewhere in tropical basement terrains. Sources of contamination and key pathways have been greyed out for clarity. High groundwater level conditions with highest risks are presented.

As well as the three key sources of drinking water (labelled 1-3 in Figure 23) two key groundwater zones have also been highlighted: i) the 'shallow groundwater zone' (typically less than 20 metres below ground level - mbgl), which is typically accessed by wells and springs and has shorter residence times and is susceptible to rapid pathways in tropical soils; ii) the 'deeper groundwater

[4] Pers. Coms., February 2015. St John Day, Technical Advisor with Adam Smith International; Paul Lapworth, former resident in Freetown, Sierra Leone overseeing Tearfunds relief programme.

zone' which is accessed by boreholes, and in a few cases by deep wells, and has much longer average residence times, typically 20-30 years (Lapworth et el., 2013), and is greater than 20 mbgl within the higher storage weathered basement and fractured basement. A low permeability zone is located above the higher storage weathered basement zone which is low yielding and is therefore not suitable for groundwater abstraction. Surface water sources include streams, swamps and in the case of Freetown a purpose built reservoir.

The key sources of hazards relevant to groundwater and surface water supplies are highlighted in red in Figure 24. These include surface sources of contamination, open defecation by humans and livestock (1), solid waste (2), soil microbes (3) - some of which are opportunistic pathogens or more prevalent in the environment such as *V Cholera*, liquid waste from domestic and municipal sites applied to the surface (4). These sources, in most cases, will be largely attenuated in the biologically active soil zone through biological and physio-chemical processes and are therefore are conventionally viewed as less of a threat to groundwater quality. However, where these sources are widespread and essentially diffuse (such as the case in urban settings) and the climate is very wet, such as in Sierra Leone, these should be considered a significant source of hazard to groundwater and surface water supplies. This is a particularly important hazard source for wells where ropes and buckets are used which come in to regular contact with surface sources of hazards.

Subsurface sources include cemeteries (5), pit latrines (6) and open sewers and drains, and in the context of Ebola, burial and waste disposal pits (7). These sources, by their very nature, do not benefit from potential hazard attenuation in the soil zone and are closer to the groundwater table, and highly permeable tropical soil zone, and therefore pose a considerable risk to water sources. The sanitation coverage of Sierra Leone is low, and therefore overall the risks from pit latrines may be less compared to other countries in SSA.

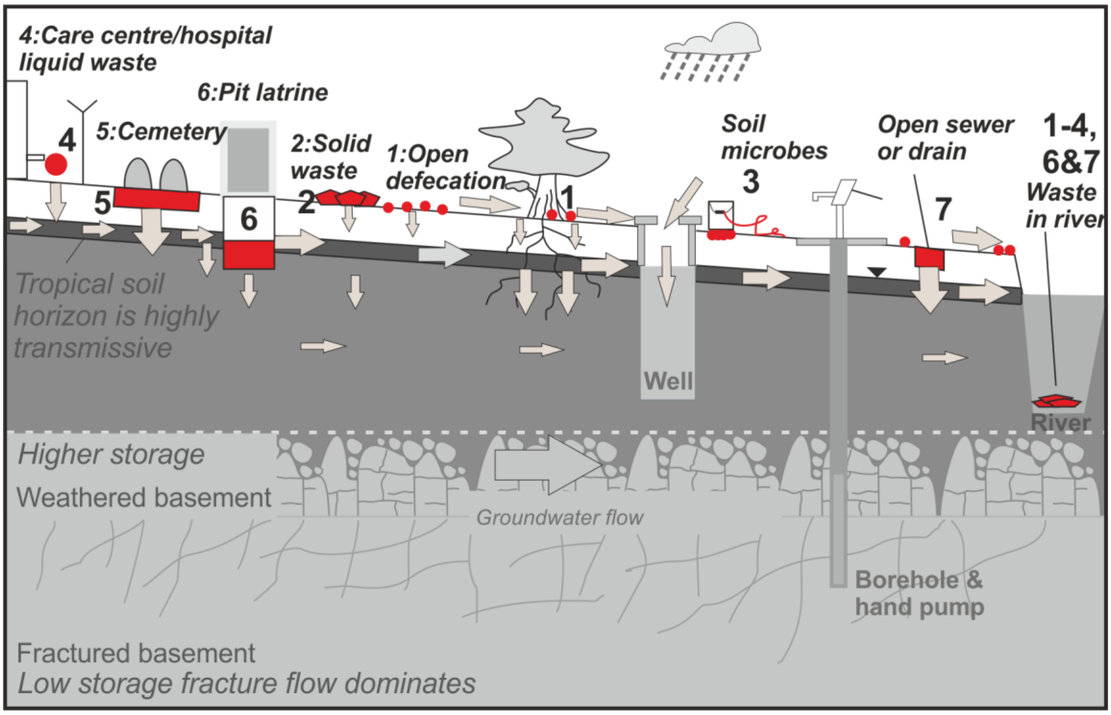


Figure 24 Schematic showing key sources of hazards relevant to groundwater and surface water supplies. Receptors and pathways have been greyed out for clarity. High groundwater level conditions with highest risks are presented.

Surface water sources are particularly affected by surface sources of contamination (1-4) as well as subsurface sources 6 and 7, see Figure 24. Pit latrines and open sewers may drain directly into surface water courses, and the contents from pit latrines are sometimes disposed of directly into surface water bodies, giving rise to considerable risks to downstream users. The current pit emptying practices, if/when they happen, are not well documented for Sierra Leone.

Figure 25 summarises the key pathways, highlighted in orange, including surface and subsurface pathways for migration of pollutants from sources to receptors. Surface pathways include surface runoff (1) which can contaminate surface waters and poorly constructed wells, bypass pathways for contamination of well and spring collectors by ropes, buckets used to draw water (2). Shallow sub-surface pathways include vertical soil flow from surface (3) and subsurface sources (4) where there is hydraulic continuity, e.g. from a liquid discharge or from a buried source such as a pit latrine, cemetery or buried waste.

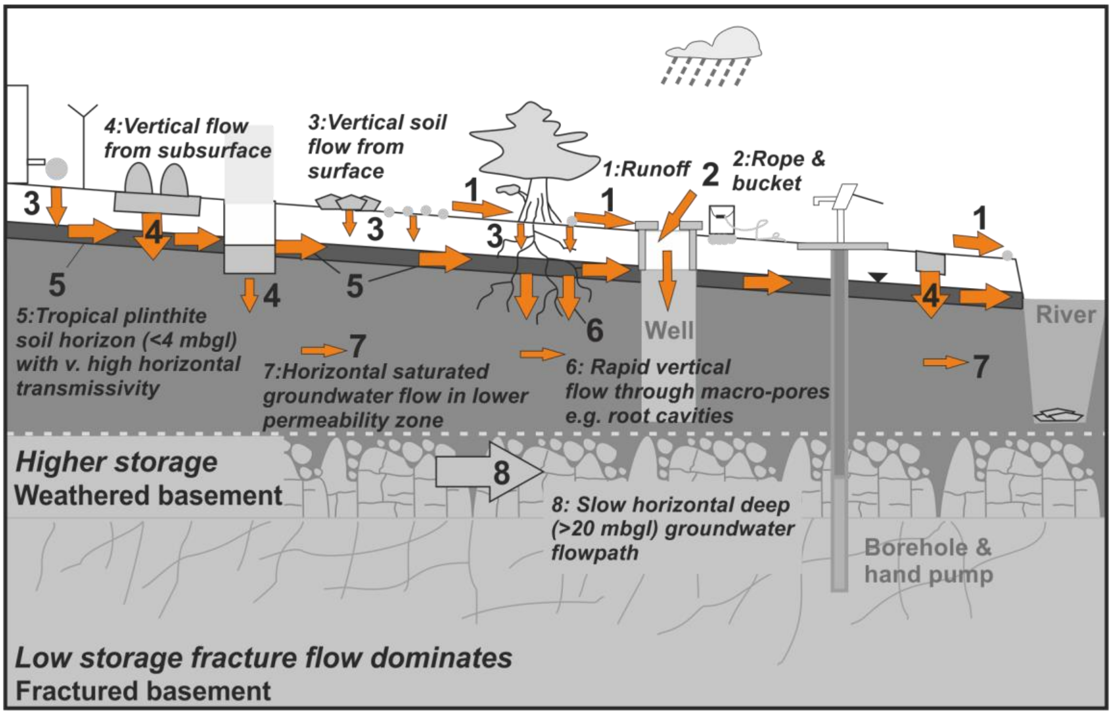


Figure 25 Schematic highlighting key pathways for hazard migration to groundwater sources. Pathways and receptors have been greyed out for clarity. High groundwater level conditions with highest risks are presented.

Very rapid horizontal pathways exist in the shallow tropical soil zone (5), which may be laterally extensive, providing transmisivities in excess of 300 m^2/day. Rapid vertical pathways also exist due to the presence of natural macro-pores e.g. from burrows and tree roots (6), which can reach significant depths in places. Combined, these more rapid pathways make shallow wells and spring sources particularly vulnerable to contamination and are increased during high water table conditions or when soil infiltration capacity is exceeded. Horizontal saturated groundwater flow, both in the lower permeability horizon above the weathered basement (7) and in the weather basement and fractured basement (8) is a pathway which can affect deeper groundwater sources such as boreholes. These pathways are slower and longer and provide the greatest attenuation potential for hazards.

In areas with red tropical soils groundwater flow exhibits extremely high permeability characteristics, i.e. very rapid transient pathways may operate for short periods of time and show sudden changes in permeability. The combination of high rainfall and the prevalence of these types of tropical soils suggest that a significant part of Sierra Leone, and neighbouring regions, may be susceptible to these types of extreme hydraulic flow conditions. This, combined with the fact that diffuse open defecation is widespread, cast doubt on the simplistic use of single minimum separation distances from particular hazard sources, and requires further investigation.

Key source-pathway-receptor considerations for water points in Sierra Leone:

Given the low sanitation coverage in Sierra Leone, surface sources of faecal contamination are likely to be as important as pit latrines and other buried sources.

Very rapid shallow lateral pathways in the tropical soil zone under high water tables and intense rainfall conditions, with limited potential for attenuation, are a major pathway for contaminant migration to shallow water points.

Pathways which bypass natural attenuation, either from buried sources or due to the use of ropes and buckets, are a particular risk for traditional and improved wells.

Surface waters and shallow groundwater receptors are most at risk from hazard sources; water points such as boreholes which access deeper groundwater have greatly reduced risk of contamination.

4 Recommendations

4.1 APPROPRIATE DESIGNS TO INCREASE THE PROTECTION OF EBOLA HEALTHCARE FACILITY WATER SUPPLIES

To protect groundwater sources from pathogenic pollution there are three broad design and construction responses possible:

- Define and protect “catchments” of springs, wells and boreholes from diffuse pollution (by way of protection zones);
- Contain and treat human wastes effectively on- or off-site (by appropriate sanitation technology choices);
- Address design, location and construction aspects of hand-dug wells and boreholes in order to reduce or eliminate the risk of localised pollution directly to the water point.

Comprehensive source protection of catchment zones is challenging and is not a realistic option for most water points in Sierra Leone, and therefore remains a long term option. Improved sanitation and improved water point construction are more attainable in the short-to medium term and this is where efforts should be focussed now.

4.1.1 Sanitation

In the absence of any realistic short- to medium-term possibility of developing sewerage and sewage treatment, only two options remain: septic tanks with drain fields or constructed wetlands; or conventional on-site sanitation using pit latrines. The first of these is a relatively high-cost option which demands significant space. It is only realistically possible in limited circumstances.

Given Sierra Leone’s extremely low levels of improved sanitation coverage (Table 1), an ambitious target would be to reduce the presence of human excreta in the environment by significantly improving access to improved latrines at the household level and shared latrines in dense settlements. From a purely technical viewpoint, ecological sanitation at household level in dense settlements would appear to be an attractive possibility, but its success would depend greatly on public perceptions and attitudes. A few organisations have implemented ecosan projects in Sierra Leone, and it would be important to review their outcomes and sustainability to inform any subsequent activities.

4.1.2 Water supply from groundwater

The most common water point type in Sierra Leone is the hand-dug well (64% of all improved water points), with or without a handpump. Design and construction guidance tailored for the Sierra Leone context was recently published (Ministry of Water Resources 2014a). Issues such as location relative to latrines (guide distance of 30m or more), timing of construction in relation to seasons, use of dewatering pumps, and construction of protective headworks are all addressed. Major issues regarding hand-dug wells in Sierra Leone are:

- The high proportion which are seasonal (approximately 50%). The implication is that consumers are driven to alternative (possibly inferior) sources, including surface water and swamps, in the dry season;
- The large proportion (45%) which are accessed by bucket-and-rope (without a winch), easily permitting pollution directly via the well shaft;
- The high breakdown rate of handpumps (the water-point mapping revealed 60% ‘snapshot’ functionality for handpumps), so adding even more to the number of wells which are accessed by bucket-and-rope.
- The high rates of pathogenic contamination found in hand dug wells in some studies

We do not know (and it would be difficult to ascertain) what proportion of hand-dug wells have adequate low-permeability annular backfill.

Boreholes make up 7% of the nearly 29,000 water points which were mapped by WSP (2012). Recent activity by Swiss consultancy Skat under the umbrella of RWSN and funded through DFID's WASH Facility has included the promotion of RWSN's Cost-effective Boreholes Code of Practice. A number of training activities have been carried out, and a guidance document published (Ministry of Water Resources, 2014b).

Issues related to Sierra Leone's water supply boreholes include:

- The challenges around handpump maintenance, as for hand-dug wells;
- The 34% of boreholes with handpumps which are reported as being seasonal. This may be partly an issue regarding siting, and partly due to the commissioning of low-yielding boreholes which should not have been put into service;
- The very likely poor construction standards, given the absence of adequate supervision, and an Africa-wide tendency to undervalue the importance of sanitary seals.

The design and construction details of spring boxes are well-known. Only 1% of water points surveyed in the 2012 water point mapping (WSP, 2012) fell into this category, although a further 26% of water points are described as 'standpipe or tapstand'. How many of these are spring-fed is not known.

A key recommendation of this report is for donors and Government to invest urgently in extending and improving sanitation through tried-and-tested technology options. Over time this would significantly reduce the pathogen load in the urban and rural environment, leading to the possibility of reduced faecal-oral disease.

Priority recommendations for groundwater supply in Sierra Leone are to focus on issues pertaining to siting, design, construction quality and maintenance of hand-dug wells and boreholes with and without handpumps. Extending safe, reliable and sustainable groundwater services will reduce the present high dependence on unsafe surface water sources.

High priority should be given to extending the coverage of improved water supply from well-sited, designed and constructed groundwater sources. At least as much effort will need to be expended on ensuring the effective utilisation, repair and maintenance of the services provided by such infrastructure. Operational research should focus on the institutional, governance, political, cultural, financial and socio-economic obstacles to achieving scale-up of truly sustainable services.

4.2 RISK ASSESSMENT OF WATER POINTS FOR EBOLA CARE FACILITIES AND COMMUNITY WATER POINTS DOWN GRADIENT OF HEALTHCARE FACILITES

A simple site assessment is currently being used to assess risks within close proximity to water points at and around Ebola care facilities (see Ministry of Water Resources 2015b). The proposals outlined below build on and extend this approach.

Based on the evidence from this desk study we recommend that local risk assessments are carried out for water points that supply care facilities and community water points down gradient or in close proximity (possibly up to 200 m) to the treatment facility. This larger radial search reflects the potentially rapid pathways in shallow horizons and the need to better quantify the density of hazard sources in the vicinity of water points. We suggest that an initial assessment is carried out as soon as possible, ideally within the next 3-6 months that includes a sanitary risk assessment and water quality assessment[5]. Longer term monitoring (6-24 months) for water quality should be

[5] Examples of sanitary risk assessment forms can be found on the WHO web site e.g.:

carried out during the wet and dry season for a minimum of two seasons to establish water quality from these water sources, seasonal water table fluctuations and an assessment of risks from rapid pathways should be also carried out.

A framework for the risk assessment to characterise the sources and pathways for contamination of water points in the short and longer term is outlined below:

In the short term (3-6 months):

- A full sanitary risk inspection (targeting sources within a 30 m radius of the water point) and pollution assessment should be made at each water point during both the wet and dry season. This should be undertaken by assessors after appropriate training
- An assessment of hazard sources within a 200 m radius of the water point, including point and multi-point sources such as open defecation, to identify the key contamination sources and their densities. This should be carried out in both the wet and dry season.
- An assessment of the design, construction and integrity of the water point, paying particular attention to protection against rapid surface and sub-surface transport routes. This could include examining drilling and construction reports or using downhole cameras to inspect casing integrity.
- Water quality analysis of key water quality parameters at each water point should be undertaken, including as a minimum: TTC, turbidity, specific electrical conductivity and pH, which then continues for a minimum of two dry and two wet season sampling rounds.

In the longer term (6-24 months):

- An assessment of the seasonal changes in depth to groundwater should be undertaken for a minimum of one full hydrological cycle, ideally using automatic water level loggers to capture rapid seasonal changes in response to rainfall as well as regular manual dips.
- An assessment of rapid shallow subsurface pathways within a 200 m radius. This includes an assessment of the geological and soil conditions paying particular attention to shallow permeable layers that can be activated during the wet season under intense rainfall and high water table conditions.
- Continued water quality analysis for at least two wet and dry seasons. A full inorganic chemical analysis should be carried out on at least one occasion.

In the short term, if water points are found to have faecal contamination then either treatment or the provision of an alternative safe source for drinking water is required. For community water points, household treatment is recommended, while for larger sources, such as boreholes for care facilities, treatment at source may be required. In the long term alternative water points such as deep boreholes that have less risk of contamination need to be considered.

http://www.who.int/water_sanitation_health/dwq/wsp170805AppC.pdf

4.3 EVIDENCE GAPS FOR UNDERSTANDING RISKS TO GROUNDWATER SOURCES

This desk study has highlighted the that there are few high quality combined hydrogeological and water quality studies that have been carried out in Africa, and there is limited evidence from local studies in Sierra Leone on hydrogeological conditions from which to draw strong conclusions. As a consequence, this report has relied heavily on evidence from analogous regions. Groundwater monitoring is now being undertaken in Sierra Leone as part of the DFID funded Water Security project and is beginning to generate some useful data on links between rainfall, groundwater levels and river flow.

Given the important role rapid horizontal (and vertical) pathways in tropical soils have in the migration of contaminants in the subsurface, and their widespread occurrence in this region, and Africa more generally, this is a key topic that warrants further investigation.

Even by African standards, the failure rate of water sources is high in Sierra Leone. Research focused on understanding the factors controlling the high failure rates (hydrogeological or otherwise) of shallow groundwater sources in the dry season would be beneficial.

A baseline assessment of water quality status and sanitary risks in Sierra Leone using a robust survey approach is needed to address the limited local evidence currently available. For example, this could take the form of wet and dry season campaigns for wells vs boreholes, improved vs unimproved sources in contrasting high risk and low risk hydrogeological terrains in Sierra Leone.

Tracing and quantifying residence times and pathogen occurrence in the subsurface, including in shallow groundwater systems as well as deeper systems is key to making a robust assessment of the vertical separation required between sources of pollution and groundwater points.

New techniques such as molecular marker methods (e.g. Mattioli et al., 2012) for fingerprinting pathogens, fluorescence sensors for rapidly mapping microbiological contamination of water sources (e.g. Sorensen et al., 2015b), and attention on type/depth of water point may help resolve key sources and pathways for contamination of groundwater points in this region.

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Appendix

Table A1 Groundwater quality surveys in representative regions in Sub-Saharan Africa (n=51), adapted from Lapworth et al (2015)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*		Sampling time frame	Conclusion and sources of contamination	Reference
[2]Bombali, Sierra Leone	Granitic Basement	Wells (60)	FC 0-80, mean 16.6 SEC 38-554 NO_3 25-280 Turb, and other majors, pH <6.5		Single study during the wet season May-June 2010	Wells contaminated with FC, 60% above. Who standards. Low pH concern for corrosion.	Ibemenuga and Avoaja (2014)
[3]Njala, Sierra Leone	Granitic Basement	Springs and wells (8)	FC 50-39k, mean 3.2k FS 5-2k		Monthly Wet and dry season sampling	Increased contamination during the onset of dry season and at the start of rainy season	Wright (1986)
[3]Moyamba, Sierra Leone	Granitic Basement	Springs and shallow wells (13)	FC 15-251k FS 12-63k, mean 501 SEC 7.6-206, mean 30 Turb, pH 5-6.5		Transition from dry to wet season, multiple sampling occasions	Increase risk during onset of wet season sustained risk during dry season for wells. No sanitation, open defecation practiced.	Wright (1982)
[3]Bo, Sierra Leone	Granitic Basement	Wells (33) lined and unlined	FC 0-75, mean 19.6 NO_3 0.5-28, mean 7.7 PO_4 0.01-11.5, mean 1.7 SEC 39-1281, mean 362		Wet season	Distance from field significant predictor of FC, not distance from toilet/PL	Jimmy et al. (2013)
[3]Conakry, Guinea	Volcanic rocks, fissured	Wells (69)	**Mod.wells** FC 370-1x10^5 FS 90-9k NO_3 2-46 NH_4 0.06-7 Cl 17-130 F 0-0.16 Turb. 1-70	**Trad. wells** FC 50-2 x10^5 FS 150-2 x10^4 $NO_3$7-51 NH_4 0.01-8 Cl 8-284 F 0.0.38 Turb. 1-63	Dry season April-May 1994	Widespread contamination by nitrate and FC linked to poor sanitation and well construction	Gélinas et al. (1996)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*	Sampling time frame	Conclusion and sources of contamination	Reference
[2]Various. Ivory coast	Basement	Boreholes (230)	NO_3 mean 69	1981 and 1982	High nitrate (up to 200 mg/L) linked to domestic pollution and deforestation	Faillat (1990)
[2]Bolama City, Guinea Bissau,	Sandy soils and Cenozoic –Modern sediments	Wells (28)	SEC 27-326, mean 136 Turb. 1-26, mean 6.5 TC 0-23000, mean 2306 FC 0-5000, mean 410 Fecal Enterococci 0-850, mean 74 NO_3 0.9-55.3, mean 16.6 NH_4 0.01-1.37, mean 0.11 NO_2 0.03-0.13, mean 0.04 Cu, Fe, Cr, As,	July 2006	80% of wells contaminated with FC linked to widespread use of PL	Bordalo and Savva-Bordalo (2007)
[2]Cotonou, Benin	Quaternary to mid Pleistocene sandstone	Dug wells in upper aquifer in densely populated area (379)	SEC 320-1045 Mn 0.06-0.19 NO_3 10.4-118 PO_4 <0.05-21.6 SO_4 3.14-86.3	May 1991, August 1991 and April 1992	High P and K concentrations in upper aquifers linked to anthropogenic pollution	Boukari et al. (1996)
[1]Kumasi, Ghana	Precambrian Basement	Hand-dug wells (10)	TDS 6-230, mean 113 NO_3 0-0.968, mean 0.16 PO_4 0.67-15, mean 7.8 TH 8-103, mean 54 TC and EC <20	N/A	Water quality survey showed that water quality parameters were within WHO drinking water guideline values	Nkansah et al. (2010)
[3]Kumasi, Ghana	Precambrian Basement	Borehole and wells in peri-urban communities (9)	Fe 0.001-0.955 Mn 0.018-0.238 Pb 0.005-0.074 TC 3-16.8×10^6 FC 1.5-4.37×10^4 Enterococci 1.3-53.5	Monthly between Dec 2000 and Jan 2001	Poor quality overall, contamination linked to proximity to PL and refuse tips as well as livestock	Obiri-Danso et al. (2009)
[3]Ilesha, Nigeria	Basement	Wells (86)	Mean results: NO_3 35 Cl 34 SO_4 2.8	Single survey	Evidence of anthropogenic impact on water quality degradation using PCA	Malomo et al. (1990)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*	Sampling time frame	Conclusion and sources of contamination	Reference
[1]Benin City, Nigeria	Quaternary to mid Pleistocene sandstone	Boreholes and open wells (6)	Pb 0.03-0.25 Zn 0.98-7.19 Cr 0.02-1.1 Cd Nd-0.23 FC 4600-240000 FS 600-35000	Single survey	Elevated Pb, Cr, Cd and Zn attributed to indiscriminate waste disposal and FC occurrence linked to PL, soak-always and septic tanks	Erah and Akujieze (2002)
[2]Calabar, Nigeria	Tertiary to recent sands and gravels	Existing wells (20)	BOD 0.06-4.09, mean 1.72 N 0.09-3.5, mean 2.15 Cl 0.1-1, mean 0.45 FC 0.75-4.32, mean 1.86	N/A	FC, nitrate and Cl had a positive correlation with urbanisation	Eni et al. (2011)
[1]Ibadan, Nigeria	Basement, banded gneiss and schist	Existing wells (N/A)	TSS 159-186.6, mean 174 Cl 1.1-10, mean 5 TC 2300-9200, mean 5120	Dry season	Gross pollution of groundwater attributed to poor well construction, PL and waste management	Ochieng et al. (2011)
[2]Ibogun, Pakoto, Ifo, Ogun State, Nigeria	Cambrian basement geology and weathered regolith	Dug wells, communities of 5000-20,000 people (20)	TDS 100-2200 TH 6-246 NO_3 0.8-88 TC 0-0.6 (cfu x10^5) FC 0-0.2 (cfu x10^5) FS 0-0.7 (cfu x10^5)	July-August 2009	Water quality standards for nitrate, FC, FS not met for significant proportion of wells	Adelekan (2010)
[1]Lagos, Nigeria	Alluvium over sedimentary	Urban wells (18)	TDS 79-1343, mean 514 TH 24-289, mean 110 Na 8-274, mean 79 NO_3 0.05-1.51, mean 0.4 Pb 0-1.9, mean 1.6 Zn 0-4.2 mean 0.3	Survey August to October 2004	Sources of contamination included sanitation, textiles, pharmaceuticals, food, tanneries, motor industry	Yusuf (2007)
[1]Surulere, Lagos, Nigeria	Alluvium over sedimentary	Wells and boreholes in a middle class area (49)	Al 1-99 µg/L Cd 1-98 µg/L Pb 1-24 µg/L	July 2009	Pb and Cd above WHO drinking water standards in >30% of sites	Momodu and Anyakora (2010)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*	Sampling time frame	Conclusion and sources of contamination	Reference
[1]Abeokuta, Nigeria	Basement igneous and metamorphic	Shallow wells including sanitary survey (40)	All bacterial count>20 Maximum 800 EC+PA+SAL	December 2005	Shallow groundwater is highly contaminated with bacteria. Sources include pit latrines, livestock and solid waste	Olabisi et al. (2008)
[2]Abeokuta, Nigeria, urban & peri-urban	Basement igneous and metamorphic	Shallow wells (76)	**Urban** (mean) TDS 402 TH 30.3 NO_3 12.02 PO_4 0.21 Pb 0.25 Zn 0.12 TC 10500 **Peri-urban** (mean) TDS 263 TH 31.7 NO_3 10.7 PO_4 0.03 Pb 0.19 Zn 0.09 TC 10000	Dry season	Mean values for Pb, nitrate EC and TC > WHO standards. Trading, textiles, transport, cottage industries, pit latrines Generally higher in dry season	Orebiyi et al. (2010)
[1]Peri-urban area, Abeokuta, Nigeria	Basement igneous and metamorphic	Hand-dug wells (25)	TDS 50-270, mean 163 NO_3 2.97-40.7, mean 17.6 NH_4 0-0.59, mean 0.11 PO_4 12-86 µg/L , mean 46 TH 12-210 , mean 106	Rainy season 2008	Direct surface run off into wells is suggested as possible contamination source	Taiwo et al. (2011)
[1]Warri River plain, Delta, Nigeria	Alluvial Benin formation	Boreholes near WW treatment plant	TDS 16-81 COD 0.4-44.4 NO_3 0.3-1.2 Fe 0.05-0.15	2 year sampling campaign	River infiltration, municipal wastewater, agriculture, oil industry	Ibe and Agbamu (1999)
[1]Warri River plain, Delta, Nigeria	Quaternary and older sedimentary sequences	Dug wells	Fe 0.32-2.75 Pb 0.058-0.443 Ni 0.008-0.188 V 0-4 Cr 0-9 Cd 0.75-8.5 Zn 0-1.8	N/A	Pb, Ni exceed WHO standards. Sources include Warri River, settlement, refinery. Highest values in village 3 km from refinery	Aremu et al. (2002)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*	Sampling time frame	Conclusion and sources of contamination	Reference
[1]Masaka, Nigeria	Cretaceous sandstone and clay	Dug wells, high density (12)	TDS 528-935 NO3 44.5-92.5 Alk 67-179 Cl 41-118 Fe 0.085-0.199 Cr 0.005-0.0126 TC 25900-78400	Samples taken in wet season	WHO standards exceeded for a range of contaminants including nitrate, TDS, Cr, Cd and TC. High density settlement with shallow water table	Alhassan and Ujoh (2011)
[2]Yaounde, Cameroon	Basement	Springs and wells in high density area (> 40)	SEC 18.2-430, mean 87 FC 60% >100 FS 5%>100	One-off survey	Groundwater's in high density zones show significant degradation (chemical and microbiological), linked to PL	Ewodo et al. (2009)
[2]Douala, Cameroon	Alluvium over Pliocene sand and gravel	Springs , wells and boreholes (72)	SEC 25-362 NO_3 0.21-94.3 FC 0-2311	One-off survey	High levels of FS indicative of contamination from PL, related to age and density of settlement	Takem et al. (2010)
[2]Kinshasa, DR Congo	Alluvial and sedimentary sequences	Wells including sanitary survey	**Dry season** TDS 180-450 NO_3 76-118 PO_4 0.53-4.6 TH 110-149 Pb 0.04-0.09 Cd 0.13-0.20	**Wet season** TDS 200-710 NO_3 97-198 PO_4 3.6-14.6 TH 17-52.5	Latrines, metal works, solid waste dumps are main sources of contamination	Vala et al. (2011)
[2]Dakar, Senegal	Quaternary	Wells (56)	NO_3 0-122	July-October 1997	Nitrate contamination from point-source seepage in urban areas	Cissé Faye et al. (2004)
[2]Mekelle, Ethiopia	Mesozoic sediments	Wells, springs and boreholes (100)	SEC 542-5300 TDS 330-3454 NH_4 0.01-2.38 NO_3 0.21-336 Cl 5.76-298 F 0-1.27, PO_4 0.001-0.58	N/A	Highly variable water quality indicative of a range of redox zones and sources of contamination	Berhane and Walraevens (2013)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*		Sampling time frame	Conclusion and sources of contamination	Reference
[2]Bahir Dar, Ethiopia	Weathered and fractured Alkaline Basalt	Dug wells and protected pumps in inner, middle and outer zones (8)	**Middle and inner city** TDS 20-600 NO_3 0.18-57.2 NH_4 0-12 Cl 46-270 FC 93% of sites Mean 1.5 log cfu EC 80% sites mean 1.4 log cfu	**Outer city** TDS 20-70 NO_3 0.08-8.8 NH_4 0-12 Cl 0-40	Sampling over a 5 month period 2006/2007	Groundwater contamination linked to population density and urbanisation. All dug wells and boreholes had microbiological contamination in excess of WHO/EU standards. Dug wells had significantly higher FC.	Vala et al. (2011)
[1]Addis Ababa, Ethiopia	Volcanics	Boreholes and springs (9)	Alk 8-41 NO_3 0.72-35 NO_2 <0.01 COD 6.8-41 Cl 6.8-28 PO4 <0.03-0.1 Pb 4.6-25 SEC 300-1200 TC 0-34000		Various	The authors made a link between the surface water quality and groundwater quality. Major sources of contamination inferred were domestic waste, and industrial pollution from textile industry and petrol stations	Abiye (2008)
[1]Addis Ababa, Ethiopia	Volcanics	Springs and boreholes (10)	Zn 0.87-146 Ni 0.31-0.98 Cu 0.44-1.82 Pb 4.3-56.2 Cd <0.1-0.2 Co <0.1-0.12		2002	Geogenic sources of heavy metals is the likely sources of groundwater contamination in this setting due to high heavy metal concentrations in soils and rocks	Alemayehu (2006) Goshu and Akoma (2011) Goshu et al. (2010)
[1]Addis Ababa, Ethiopia	Volcanics	Springs and wells (63)	Ni 2-152 µg/L Pb <1 Co 0.5-165 As <3 Zn <20-2100 Cu 1.5-164 Cd 0.3-12.3 Cr 18.2-214		Februrary-March 2004, July to September 2005	Urban area, leaching from polluted soils.	Demlie and Wohnlich (2006)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*		Sampling time frame	Conclusion and sources of contamination	Reference
[3]Kisumu, Kenya (urban)	Sedimentary	Existing wells (191)	TTC 0->100k mean 894 NO_3 0.06-45 mean 15 Cl 0-225 mean 796 F 3-29.6 mean 6.2		1998 and 2004	Density of PL within a 100 m radius was significantly correlated with nitrate and Cl but not FC (*PC*)	Wright et al. (2013)
[2]Lichinga, Mozambique and Timbuktu, Mali	Quaternary/ Basement gneiss-granite complex	Hand dug wells: Timbuktu(31), Lichinga (159)	**Timbuktu** SEC 221-2010 NO_3-N 35 med Cl 500	**Lichinga** SEC 220 med NO_3 5.6 med Cl 13.5	Timbuktu September 2002 to May 2003 Lichinga, April 2002-August 2004	Contamination of groundwater sources from on site sanitation traced using N:Cl	Cronin et al. (2007)
[3]Lichinga, Mozambique	Mudstone	Lichinga (25)	TTC, EF (Enterococi)		Monthly for 1 year	Higher risk at onset of the wet season and end of the dry season. Predominant source was from animal faeces rather than PL or septic tanks. (*LR*)	Godfrey et al. (2006)
[2]Kampala, Uganda	Weathered Basement	Wells and springs	**High density** NO_3 mean 67 Cl mean 59 TC mean 14	**Low density** NO_3 mean 22 Cl mean 21 TC mean 544	Contrasting hydrological conditions	Significantly higher contamination in high density regions compared to low density	Barrett et al. (1998)
[3]Kampala, Uganda	Weathered Basement	Springs (25)	TtC (FC) FS BLD-23000		Monthly between September 1998-March 1999	Evidence of rapid recharge to springs following rainfall. Local environment hygiene and improved sanitary completion shown to be more important than on-site sanitation for spring protection (*LR*)	Howard et al. (2003)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*		Sampling time frame	Conclusion and sources of contamination	Reference
[3]Kampala, Uganda	Weathered Basement	Monitoring wells (16)	**Dry season** SEC 272-345 P BDL-0.11 N BDL-5.5 NO_3 24-144 Cl 31-50.5 TC 0-131 FC 0-35	**Wet Season** SEC 280-372 P BDL0.04 N BDL-263 NO_3 24-692 Cl 28-192 TC 29-10000 FC 6-8300	2003: weekly March-May and September in dry season, and June to August, wet season.	High population density with pit latrines and livestock sources identified. Microbiological water quality deterioration after heavy rainfall	Barrett et al. (1998)
[1]Kampala, Uganda	Weathered Basement	Boreholes and wells (28)	Limited inorganic and organic suit, no microbiology		September and October 2011	Nitrate concentrations suggest poor sanitation and diffuse contamination.	Nachiyunde, Kabunga et al. (2013)
[3]Uganda, Kampala (urban)	Weathered basement	Piezometers (10)	1.5 m down gradient of pit latrines NO_3 5-90 Cl 50-1100 $PO_4$0.1-2 NH_4 5-40		March-August 2010 biweekly sampling	PL found to be a significant source of nutrients (N) compared to waste dump. NH_4 removal by nitrification	Nyenje et al. (2013)
[1]Lusaka, Zambia	Dolomite	Wells and streams in intensely urbanised area (9)	SEC 200-710 NO_3 <0.1-43 NH_4 <0.25-3.5, Cl 4.6-36 PO_4 <0.1-4, B <1-10, As <0.2-0.49 Pb 0.14-0.67, Hg <0.4-13		July 2001	Values for nitrate and Hg were in excess of WHO standards on some occasions. Poor sanitation and solid waste disposal implicated.	Cidu et al. (2003)
[2]Lusaka, Zambia	Dolomite	Boreholes (7)	FC 0-45 TC 0-58 SEC 401-1060		Single survey	Evidence for contamination in health centre boreholes by FC, poor waste management implicated	Nkhuwa (2008)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*		Sampling time frame	Conclusion and sources of contamination	Reference
[3]Lusaka, Zambia	Dolomite	Private and public boreholes (N/A)	Alk 124-564, NO3 0.03-39, NO2 0.002-42, NH4 0.08-60 Cl 42-102, TC 1-TNTC FC 21-TNTC, BOD 2-69 COD 9-320		Various: 1995-2000	Hydrochem, microbiology and incidence of cholera outbreaks compiled to show the rapid deterioration of GW sources associated with poor sanitation	Nkhuwa (2003)
[2]Ndola, Zambia	Dolomite and basement lithologies	Wells (123) and boreholes (60) surface waters (41)	**Wells (median)** TC 7 Zn 11.4	**Boreholes (med)** TC 0 Zn 139	April-June 2013	Geological control on trace metal contamination. TC for wells>boreholes but no FC data collected.	Liddle et al (2015)
[3]Kabwe, Zambia	Dolomite and basement	Private (13) and public (12) boreholes, private wells (57)	**Dry season** *Wells* NO3 0.1-187 (18) FC 10-6800 (180) Boreholes NO3 0.1-38 (6) FC <2-28 (<2)	**Wet season** *Wells* NO3 0.15-174(22) FC 2-27600 (570) Boreholes NO3 0.1-41 (6) FC <2-760 (<2)	Dry and wet season 2013-2014	Widespread NO_3 and FC contamination in shallow wells in both wet and dry seasons, wet>>dry. Generally good quality in peri-urban boreholes but evidence of contamination in some urban boreholes	Lapworth et al (2015)
[3]South Lunzu, Blantyre, Malawi	Weathered basement	Borehole, springs and dug well (9)	**Dry season** SEC 210-330 Cl 21-35 Fe 0.1-0.8 FC 0-5200 FS 0-640	**Wet season** SEC 306-383 Cl 14-29 Fe 0.4-0.7 FC 0-11,000 FS 0-7000	Wet and dry season on two occasions	Groundwaters highly contaminated due to poor sanitation and domestic waste disposal. 58% of residence use traditional PL	Palamuleni (2002)

Area	Geology	Sample sites (n)	Results from selected water quality parameters*		Sampling time frame	Conclusion and sources of contamination	Reference
[3]Southern Malawi	Weathered basement	Shallow wells (26)	**Dry season** NO_3 0-2.6 NH_4 detectable most samples FC 0-9k TC 0-17k As, F also	**Wet season** NO_3 0-4.4 TC 0-77k FC 0-9k	Wet and dry season	Overall contamination levels higher during wet season for two districts and lower for one district and significantly higher in unprotected sources.	Pritchard et al. (2008)
[2]Tamatave and Foulpointe, Madagascar	Weathered basement and unconsolidated sediments	Boreholes (53)	FC 73%>0, 55% 0-10, 54%>10 NO_3 4.4-35, mean 23 Pb 1-215, mean ca. 5		One-off survey	Widespread drinking water contaminated with FC and concerns over Pb from pump materials	MacCarthy et al. (2013)
[3]Epworth and Harare, Zimbabwe	Granite	Wells and boreholes, transect of formal and informal zones (18)	NO_3 0-30, mean 11 PO_4 0-27.2, mean 3.03 FC 0-2, mean 0.75 (cfu x10^4)		Survey carried out with duplicate sampling	Pit latrines, faecal coliforms in older and informal trading areas, urban agriculture, home industries and commercial areas	Zingoni et al. (2005)

SEC-specific electrical conductivity, PCA=Principal component analysis, *LR*= logstic regression, TDS= total dissolved solids, TH=total hardness, , BOD-biological oxygen demand, COD=chemical oxygen demand, FC=faecal coliforms, EC= E. Coli, TC=total coliforms, FS=faecal streptococcus. Microbiological units as cfc/100 mL unless stated otherwise, TNCT=too numerous to count, BDL=below detection limit. Notation: [1]Case-studies presenting data from a limited number of sites (n<20), limited temporal resolution as a single survey or use only basic chemical indicators and limited analysis of the results; [2] Case studies which either draw from larger data sets or include both chemical and microbiological indicators but have limited data analysis regarding sanitary risk factors; [3] Case studies with greater temporal resolution or are accompanied by a more thorough analysis of the data, for example using statistical techniques to understand the significance different risk factors on water quality observations.

Table A2 Conceptual framework for hazard sources and pathways for groundwater and surface waters

	Surface water	**Traditional wells**[a]	**Springs**	**Improved wells**	**Boreholes**[b]
Major hazard sources	Surface sources: These include open defecation by humans and animals, surface soil amendments, sewers, shallow drains and surface application of waste water	Surface sources: Same as for surface waters, materials used to draw water from collector contaminated with soil microbes and sanitary sources from hands Subsurface sources: These include all buried sources of solid and liquid waste (e.g. pit latrine, soak away, waste dump, and cemetery).	Surface sources: Same as for surface waters, materials used to draw water from collector contaminated with soil microbes and sanitary sources from hands Subsurface sources: These include all buried sources of solid and liquid waste.	Surface sources: materials used to draw water from collector contaminated with soil microbes and sanitary sources from hands Subsurface sources: These include all buried sources of solid and liquid waste.	Subsurface hazards: These include buried sources of solid and liquid waste (e.g. pit latrine, soak away, waste dump, and cemetery).
Major hazard pathways	Surface runoff, open sewer systems	Surface runoff directly into well, bypass pathway from use of contaminated materials (e.g. rope or bucket). Vertical and horizontal soil flow from buried hazard sources.	Surface runoff directly into spring collector, bypass pathway from use of contaminated materials (e.g. bucket). Vertical and horizontal soil flow from buried shallow hazard sources.	Vertical and horizontal soil and groundwater flow to well. Crack in sanitary seal, well lining. Bypass pathway from use of contaminated materials to draw water.	Horizontal groundwater flow in saturated zone to borehole intake.
Hazard susceptibility under high groundwater table conditions	High at all times	Very high due to lack of barrier to horizontal soil and shallow groundwater flow to well.	High due to limited soil attenuation and potential activation of shallow rapid horizontal pathways to spring	Moderate due to some protection from shallow horizontal soil and groundwater flow by casing. Some attenuation in saturated zone	Low due to narrow diameter of casing and generally deeper casing, and high attenuation capacity in saturated zone
Hazard susceptibility to extreme rainfall conditions	High due to strong link to runoff sources of contamination and limited attenuation potential	Very high due to strong link to runoff sources of contamination.	High due to strong link to surface runoff sources of contamination, difficulty in protecting spring catchment from encroachment by animals	Moderate due to reduced lateral pathways in soil and shallow groundwater. Erosion or bypass of sanitary/annular seal possible, large diameter means this is more likely	Low due to limited rapid pathways from surface or buried sources of hazards
Possible interventions for safer supply	Not suitable for drinking without treatment at household level*.	May be best to stop using unless there is no alternative source of water. Install well casing, sanitary seal, cover and use of alternative water lifting device such as hand pump. Generally not suitable for drinking without household treatment*.	Improved citing of springs and ensure better spring protection in surface capture zone, very difficult to manage in rural areas, this is not realistic in urban/peri-urban areas. Generally not suitable for drinking without treatment*.	Improved citing of wells in relation to sources of hazards. Stop main pathway from surface through use of rope and bucket, e.g. cap and install hand-pump. Deepen casing and improve sanitary seals. Often not suitable for drinking without treatment*.	Improved citing of borehole in relation to sources of hazards. Maintenance: replace cracked casing, ensure adequate sanitary seals are maintained. Often suitable for drinking without treatment if well maintained/cited.

[a] Hand dug wells with no surface protection, [b] Assuming that the initial installation of a borehole is of a high standard, *Regular household treatment is not realistic in Sierra Leone or many other countries in SSA, if there is high turbidity (likely for surface waters) this may render treatment using chlorination only partially effective.

Appendix References

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