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Acute health risks to community hand-pumped groundwater supplies following Cyclone Idai flooding

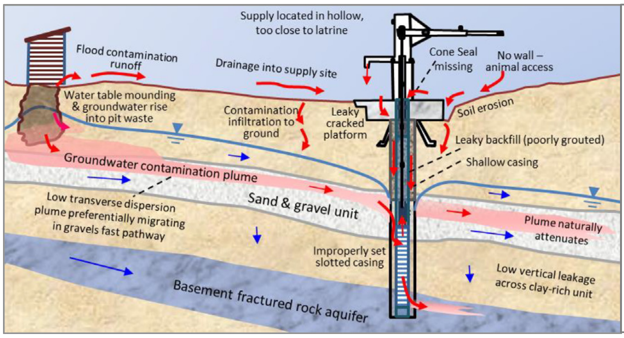
Michael O. Rivett [a,*,1], Laurent-Charles Tremblay-Levesque [b,2], Ruth Carter [a,3], Rudi C.H. Thetard [c], Morris Tengatenga [c], Ann Phoya [c], Emma Mbalame [d], Edwin Mchilikizo [e], Steven Kumwenda [f], Prince Mleta [d], Marc J. Addison [a], Robert M. Kalin [a]

[a] *Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK*
[b] *CARE International in Malawi, P/Bag A89, Lilongwe, Malawi*
[c] *USAID ONSE Health Activity, Health Programs Group Management Sciences for Health MSH, Lilongwe, Malawi*
[d] *The Ministry of Forestry and Natural Resources, Lilongwe Headquarters, Private Bag 390, Lilongwe, Malawi*
[e] *Mulanje District Water Office, Mulanje BOMA, Malawi*
[f] *BASEFlow, Galaxy House, Chichiri, Blantyre, PO Box 30467, Malawi*

HIGHLIGHTS

- *E. coli* contamination of 279 handpumped boreholes assessed post Cyclone Idai floods.
- Key concern: a year after Idai 40% of supplies showed *E. coli*, 20% classed 'unsafe'.
- Rebound at treated boreholes signifies a systemic problem from persistent sources.
- Pit latrines: credible source of the hit-&-miss, wet season, rebound contamination
- Concerted WASH sector investment in identified research and policy is advocated.

GRAPHICAL ABSTRACT



Multiple pit latrines
- Unlined pits
- Flood inundated
- High water table
- Leached pit waste *rendering*

Hand-pump boreholes
- Poorly located
- Poorly constructed
- Poorly maintained

UNSAFE

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ABSTRACT

This longitudinal flood-relief study assessed the impact of the March 2019 Cyclone Idai flood event on *E. coli* contamination of hand-pumped boreholes in Mulanje District, Malawi. It established the microbiological water-quality safety of 279 community supplies over three phases, each comprising water-quality survey, rehabilitation and treatment verification monitoring. Phase 1 contamination three months after Idai was moderate, but likely underestimated. Increased contamination in Phase 2 at 9 months and even greater in Phase 3, a year after Idai was surprising and concerning, with 40% of supplies then registering *E. coli* contamination and 20% of supplies deemed 'unsafe'. Without donor support for follow-up interventions, this would have been missed by a typical single-phase flood-relief activity. Contamination rebound at boreholes successfully treated months earlier signifies a systemic problem from persistent sources intensified by groundwater levels likely at a decade high. Problem extent in normal, or drier years is unknown due to absence of routine monitoring of water point *E. coli* in Malawi. Statistical analysis was not conclusive, but was indicative of damaged borehole infrastructure

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[*] Corresponding author at: GroundH2O Plus Ltd., Quinton, Birmingham B32 1DY, UK.
E-mail address: rivett@groundh2oplus.co.uk (M.O. Rivett).
[1] Now at: GroundH2O Plus Ltd., Quinton, Birmingham, B32 1DY, UK.
[2] Now at: Global Water Partnership, PO Box 24177, SE-104 51, Stockholm, Sweden.
[3] Now at: AECOM, Midpoint Alencon Link, Basingstoke, RG21 7PP, UK.

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Groundwater contamination
Hand-pumped boreholes
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WASH (Water, Sanitation and Hygiene)

and increased near-borehole pit-latrine numbers being influential. Spatial analysis including groundwater flow-field definition (an overlooked sector opportunity) revealed 'hit-and-miss' contamination of safe and unsafe boreholes in proximity. Hydrogeological control was shown by increased contamination near flood-affected area and in more recent recharge groundwater otherwise of good quality. Pit latrines are presented as credible e-coli sources in a conceptual model accounting for heterogeneous borehole contamination, wet season influence and rebound behavior. Critical to establish are groundwater level - flow direction, hand-pump plume draw, multiple footprint latrine sources - 'skinny' plumes, borehole short-circuiting and fast natural pathway (e.g. fracture flow) and other source influences. Concerted WASH (Water, Sanitation and Hygiene) sector investment in research and policy driving national water point based *E. coli* monitoring programs are advocated.

1. Introduction

Flood-related groundwater contamination by waterborne pathogens from human or animal waste fecal sources presents a human health risk that remains poorly constrained globally (Bain et al., 2014; Fennell et al., 2021; Gowrisankar et al., 2017; Sorensen et al., 2015). The review by Andrade et al. (2018) of the sparse developing country literature concludes this climate-related exposure to environmental bacterial or viral infection is understudied and, worryingly, human gastrointestinal health burden of flood-related groundwater contamination cannot be estimated at any scale.

Risks are greatest in low and middle income countries where research under emergency flood relief conditions is difficult. Published studies such as those in Chennai, India by Gowrisankar et al. (2017) and in Jakarta by Phanuwan et al. (2006) are rare. Still, symptomatic studies increase, including wet-season microbiological contamination of groundwater supplies correlating with rainfall, in Sub-Saharan Africa (Elisante and Muzuka, 2016; Lapworth et al., 2020; Parker et al., 2010; Ward et al., 2020a), Bangladesh (Dey et al., 2017) and Nepal (Shrestha et al., 2014). The sheer numbers of community water supplies heighten risks. The rural water supply technology of choice, hand-pumped boreholes exceed a million in Sub-Saharan Africa (MacArthur, 2015), and a recent audit in Malawi confirmed the existence of 84,782 boreholes and protected dug wells that are each a community lifeline to several hundred (Supplementary materials, Fig. S1). Although safer than surface water or hand-dug wells, flood submergence renders even boreholes unsafe (Andrade et al., 2018; Elisante and Muzuka, 2016). A susceptibility not appreciated by communities, educated away from unsafe surface water who then perceive groundwater as inherently safe. Hand-pumped boreholes and protected dug well supplies (collectively termed herein HPBs) are often used untreated and without routine monitoring following (supposed) bacteriological screening at commissioning (Ward et al., 2020a).

Concerns for short circuiting of wellhead contamination into HPB abstracted groundwater from poor drilling practices and lack of technical supervision of borehole installation are increasing (Banks et al., 2021; Fisher et al., 2015; Foster, 2013; Kalin et al., 2019); culprits include inadequate head-works sanitary sealing and borehole casings lacking or inadequately sealed (Ferrer et al., 2020). Flood-inundated boreholes are susceptible. Indeed, short circuiting of recent recharge water is muted to explain frequent occurrence of detectable *E. coli* in African HPBs at *c*. 50% of sites in recent surveys (incl. Malawi at 47%) (Banks et al., 2021; Lapworth et al., 2017, 2020; Sorensen et al., 2015). Mixing of short circuited water with other groundwater flows into HPBs is necessary to explain *E. coli* with observed mean residence times of HPB abstracted groundwater of years to low decades (Banks et al., 2021). Recognizing, an estimated *E. coli* half-life of 3 to 4 months in most groundwaters (Edberg et al., 2000; John and Rose, 2005) and attendant expectation of non-occurrence in groundwater over a year old (Banks et al., 2021).

Acknowledging other pathogen sources to groundwater, especially agricultural livestock manure, we focus upon pit latrine sources in Malawi where of the 268,161 sanitation points audited near water supplies, 201,624 were unlined pit latrines (Fig. S2). Although more environmentally sensitive latrine sanitation systems exist, basic pit latrines comprising an unlined pit up to *c*. 3 m deep, *c*. 1 m diameter hole with basic cover-housing have been implemented globally under WASH (Water and Sanitation Hygiene) programs allowing communities to be open defecation free (ODF) (Graham and Polizzotto, 2013). Groundwater resources are vulnerable to contamination from flood-induced release of sludge/waste water from a proliferation of latrines infiltrating to ground and their leaching via soil lateral interflows or rising, shallow water tables (Templeton et al., 2015). HPBs may be put at risk in some WASH programs where parallel implementation of HPBs and pit latrines can occur without sufficient stand-off distances between to safeguard water supplies. Uncertainties over latrine risks posed to groundwater are apparent from the poor international consensus on safe stand-off distances between latrines and water points and guidelines variously followed (Back et al., 2018; Graham and Polizzotto, 2013). Safe attenuation distances vary considerably with hydrogeological circumstance and pathogen (Diaw et al., 2020; Foppen and Schijven, 2005; Ishii and Sadowsky, 2008; Kanyerere et al., 2012; Taylor et al., 2004). Uncertainties are compounded by vulnerabilities to climate change and increased drought and flood extremes (Arnell and Gosling, 2016; Cuthbert et al., 2019).

Groundwater supply protection is a primary response to major flood events typically incorporated within international community emergency flood relief. Tropical Cyclone Idai March 2019 was one of the worst to hit Southern Africa, severely impacting Mozambique, Zimbabwe and Southern Malawi. Following flood subsidence in Malawi, local WASH partner NGOs mobilized borehole surveillance, assessment, repair and rehabilitation programs involving shock chlorination of affected supplies to address pathogen risks. Sector monitoring of emergency response intervention effectiveness is conventionally undertaken as a single round (*c*. 1–3 months) of assessment, HPB repair and rehabilitation and post-intervention assessment. Hence, it is unknown if flood rehabilitation remains long-term effective and HPB supplies uncontaminated. Particularly with regard to acute pathogen health risks as routine bacteriological monitoring is rare.

Our novel, longitudinal-in-time study supported by USAID and ONSE Health, implemented by CARE International in Malawi (CARE), breaks the conventional approach and implements monitoring of emergency flood relief activity by undertaking three, rather than one phase of borehole assessment, intervention and post-intervention assessment over the year following the Cyclone Idai 2019 flooding. Implemented under their emergency response 'Borehole Repair and Rehabilitation Project' (B2RP) (Tremblay-Levesque, 2019), the NGO's practical-research goal was to assess the effectiveness of their flood relief intervention and sustainability of community groundwater supply achieved. Within this emergency activity goal, our aims are:

- To assess via longitudinal study, the impact of Cyclone Idai flooding on acute pathogen *E. coli* contamination of HPBs and safety of water supplies achieved by rehabilitation over the three phases of emergency relief activity, extending to the following wet season a year after Idai;

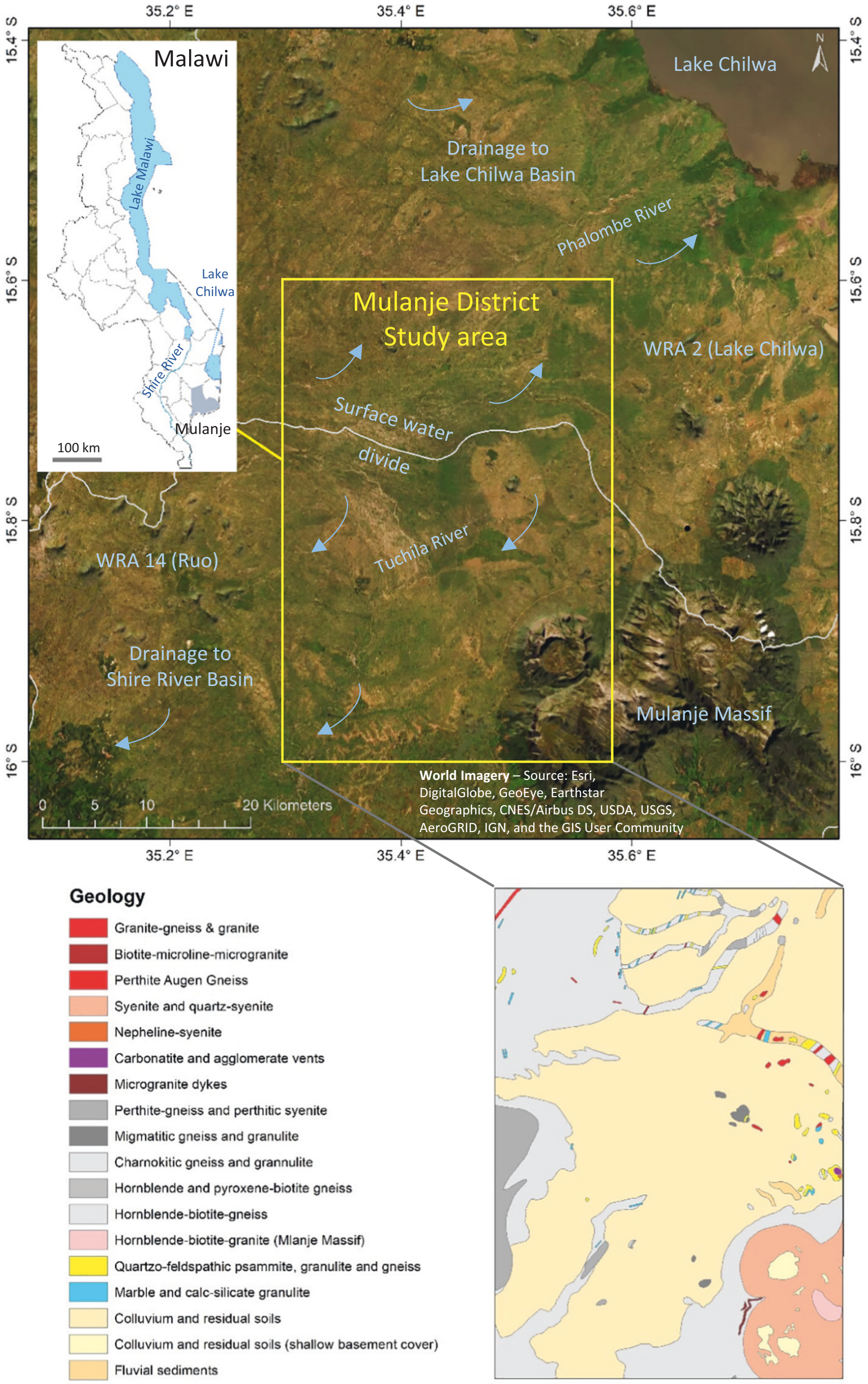
- To assess processes controlling pathogenic contamination of HPBs observed and the potential for pit latrines to be a key source of this contamination;
- To propose a process based conceptual model of contamination migration from pit latrines to HPB underpinning practice and policy development and outlining of WASH sector research needs;
- To make policy recommendations, especially on monitoring.

2. Materials and methods

2.1. Study area and cyclone event setting

2.1.1. Study setting

The study area is located in the Mulanje District at Malawi's south east border with Mozambique (Fig. 1). Its topography and geology are controlled by its East African Rift Valley southern periphery location. Malawi is mostly covered by weathered and fractured Precambrian to the Lower Palaeozoic metamorphic basement rocks, overlain by valley



World Imagery – Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 1. Mulanje District study area showing hydrological and geological contexts.

Quaternary sediments around Lake Malawi and Shire River Basin to the south. Mulanje District mostly comprises amphibolite gneiss, fractured basement rock (Chimphamba et al., 2009), overlain in the north by Quaternary colluvium and residual soil deposits (Evans, 1965; Scheidegger et al., 2015). This unit tends to have higher yielding aquifers than the basement (Chimphamba et al., 2009), but both meet modest 0.25 L/s requirements for HPB community supply. Intrusions typically comprise granites and syenites and form the prominent Mount Mulanje (Mulanje Massif) range rising precipitously to over 3000 m asl (meters above sea level) in the study area immediate southeast with a network of rivers and streams draining from this high point (Kambwiri et al., 2014). Valley land is relatively flat and devoted largely to intensive agriculture and hosts many tea plantations as well as some animal farming with freely roaming livestock (Webb, 2011). Groundwater is mostly used to supply populations dispersed in small settlements (Kambwiri et al., 2014), or agriculture (Webb, 2011).

2.1.2. Tropical Cyclone Idai

The tropical climate in Malawi has pronounced seasons controlled by the inter-tropical convergence zone (ITCZ), partly influenced by the Mozambique Channel (Beard, 1997). The ITCZ extends over Malawi during the December–April wet season leading to monsoons, also occurring from disturbances in the Congo basin (Jury and Mwafulirwa, 2002). Very low rainfall in the May–November dry season leads to mid-to-late season drought (Jury and Mwafulirwa, 2002). The area is susceptible to extreme wet or dry weather events, including cyclones. Heavy rainfall 5–8 March 2019 severely affected Southern Malawi following a tropical disturbance over the Mozambique Channel that quickly developed into Cyclone Idai (Mutsaka et al., 2019; Tremblay-Levesque, 2019; World Meteorological Organisation, 2019). The Gov't of Malawi declared a State of Disaster on 8 March and its Dep't of Disaster Management Affairs (DoDMA) and the UN Resident Coordinator's Office reported as of 16 March that 840,330 people were affected, later revised to 975,000. Nearly 87,000 people were displaced into 173 IDP (Internally Displaced People) camps and 60 fatalities reported (Tremblay-Levesque, 2019).

2.1.3. Flood emergency situation

Preliminary DoDMA assessments and information from frontline partners such as CARE, MSF and the Malawi Red Cross Society revealed a pressing WASH situation. Access to safe drinking water in the IDP camps and wider flood affected areas of southern Malawi was a prime concern. The people-to-safe water point ratio was over 1000:1 in most camps, four times the Gov't standard. An impact evaluation by our Climate Justice Fund - Water Futures Programme (CJF) using the recently developed mWater Management Information System that holds data for all Malawi's rural water points (>120,000) (Kalin et al., 2019; Section 2.2) enabled rapid identification of some 3666 water points at risk of having been flooded. Many water points were suspected to be partially or fully submerged and no longer considered safe supplies. The risks to these water points were focused primarily on pit latrine sources, recognizing quite limited animal manure application to crops, or sewage contaminated river water infiltration more common in urban settings (Gowrisankar et al., 2017). Within a month of the flood, the above lead and other development organizations such as Oxfam, United Purpose, and GOAL distributing over 15,500 buckets for water collection and the equivalent in water treatment supplies to IDP camps in Southern Malawi. USAID/ONSE in collaboration with Feed the Children, Tiwalere II Project, supplied over 1 million sachets of powdered water guard to support drinking water treatment. Most though did not examine the condition of water points excepting the Scottish Gov't CJF Water Futures Programme through Strathclyde University that rehabilitated 360, MSF rehabilitated 43 boreholes, and United Purpose 60 boreholes (Tremblay-Levesque, 2019). There was hence an urgent need to assess, repair, and rehabilitate (e.g. shock chlorinate) boreholes in flood affected areas and ensure host communities resettling from camps are not left with problems of having to fix boreholes or replace worn-out infrastructure.

2.1.4. Borehole Repair and Rehabilitation Project (B2RP)

The B2RP initiative was a $200,000 flood response project funded by USAID through MSH's (Management Sciences for Health) Organized Network of Services for Everyone's (ONSE) Health Activity project. The B2RP was implemented by the University of Strathclyde in partnership with CARE International in Malawi (CARE) (Tremblay-Levesque, 2019). The B2RP target to repair and rehabilitate 200 boreholes in the catchment area of IDPs and wider flood affected areas of Mulanje District was surpassed reaching 218 boreholes helping over 180,000 people gain access to improved drinking water supplies. The field research reported herein was conducted in the course of the B2RP emergency response initiative and uses data collected during their three-step intervention process. The research was enabled by CJF's research activity in Malawi (Kalin et al., 2019; Truslove et al., 2019; Back et al., 2018; Rivett et al., 2019a, 2020) that developed with mWater.co a triaging system for disaster relief borehole rehabilitation.

2.2. B2RP three step intervention process enabling field data collection

B2RP followed in each of the three phases conducted a three-step intervention process implemented by a team of 21 field staff (5 Borehole Technicians, 9 WASH Field Officers, 5 Drivers, 1 Hydrogeologist, and 1 Project Manager). Research data herein are drawn from mWater mobile technology geo-tagged live information collected during each step (Tremblay-Levesque, 2019):

- *Water Point Needs Assessments (Pre-intervention survey)*: WASH Field Officer conducted assessments to assess civil works and pump problems that included functionality (leakage and discharge) and water quality tests to identify boreholes in most need of repair and rehabilitation actions required. Test results input to mWater automatically triaged water points based on functionality and contamination status into one of five problem categories.
- *Water Point Repair and Rehabilitation Works*: Borehole Technician teams received notification through mWater on boreholes to be visited and their problem category (non-functioning and highly contaminated boreholes - first priority; water quality issues and/or critical damage to water point infrastructure >300 users - second priority; etc.). Removal and disassembly of handpumps allowed a rated condition of all parts and headworks. Repair and rehabilitation works included temporary removal of surface and downhole pump infrastructure and replacement of all broken and worn-out parts. Access allowed borehole depth and standing water column measurements used herein to estimate water table elevations at rehabilitated boreholes. All repaired boreholes and others testing positive for Fecal (*E. coli*) contamination (i.e., showed detectable concentrations) were shock chlorinated using the Standard Operating Procedure set out in Supplementary materials Text Box S1.
- *Post Intervention Assessments (Post-intervention survey)*: Intervention effectiveness was assessed by functionality and water quality testing following rehabilitation completion.

The Phase 1 assessment was conducted in June–July 2019 during the early-to-mid dry season, as communities returned home 3 to 4 months after Cyclone Idai. Phase 2 was in November–December 2019 near the start of the following wet season, 9 months after Idai. Phase 3 was in February 2020 late-wet season approaching a year after Idai. Microbiological quality *E. coli* data were collected in the pre-intervention survey step of each phase referred to as Phase 1a, Phase 2a and Phase 3a herein and in the post-intervention survey step, Phase 1b, Phase 2b and Phase 3b herein to verify chlorination treatment effectiveness (Fig. S3). Water points evaluated and sampled in each phase varied somewhat due to relief work priority agenda and water point condition. Assessment in Phase 1a covered 260 water points with numbers slightly lower in later phases (as detailed in Section 3.1.1). Decreased sampling opportunity arose when water levels in some water points fell below the bottom of the borehole during the dry season. A few additions arose in response to relief needs being later met.

2.3. Waterpoint – borehole functionality assessment

Functionality testing was conducted before and after intervention works, comprising: a standard pumping test recording the time to handpump fill a 20 L bucket; a leakage test recording the number of strokes to yield water; and a physical examination of the HPB. The latter included visual inspection of the hand pump and civil works condition and may provide evidence of short circuiting of wellhead contamination (e.g., cracked or damaged aprons, missing fence, drainage channel cracked or damaged). Boreholes not meeting the Gov't standard of ≤80 s to fill a 20 L bucket (≥0.25 L/s) (MoAIWD, 2015) were deemed 'partly functional but need repair' as were boreholes that yielded water only after five strokes (the standard being 1–4 strokes) (MoAIWD, 2015). Boreholes with leakage problems were also classified 'partially functional'. Only boreholes yielding no water at all were classified as 'non-functional'. Boreholes upon arrival already fully or partly dismantled (e.g., head-works removed) were identified as 'abandoned or no longer existing'. Otherwise, HPBs passing these tests were classified as 'fully functional', not precluding the possible existence of management issues affecting water point sustainability.

2.4. Water quality surveys

Water quality surveys were conducted across all phases to assess fecal contamination, other key determinants of health concern and hydrochemical conditions, analyzing for 11 determinants in total (per Section 2.4.2). Temporal variation in health risks and effectiveness of water point intervention measures were hence established (Tremblay-Levesque, 2019; Carter, 2020). Data collection under emergency relief conditions meant the availability of temporal data varied between water points. A primary constraint was water points not being sufficiently functional to hand-pump samples, notably in Phase 1a. Of the 291 water points physically assessed in total (across all phases), 279 points were water quality sampled yielding a total of 907 water samples. Exclusive use of field probes or test kits enabling on-site wellhead analysis (excepting incubation of samples for fecal contamination assessment) enabled low-cost, real-time data critical to informing emergency relief decision making. Proven test kit methods were used although some are regarded as 'screening'.

2.4.1. Fecal contamination analysis

E. coli, a sub-group of the fecal coliform group, presence in water samples invariably indicates recent fecal contamination and acute health risks from pathogens. Fecal contamination risk was quantified using the Aquagenx® *E. coli* water quality test kits (Aquagenx, 2013). These rapid test kits are especially useful in low resource, emergency response settings (Brooks et al., 2017; Gronewold et al., 2017; Stauber et al., 2014). The Compartment Bag Tests used determine the Most Probable Number (MPN) concentrations of *E. coli* in 100 mL of water. Growth medium is dissolved in a 100 mL field sample that is added to each of the five compartments of the Aquagenx® Compartment Bag. Compartment Bags were then incubated at ambient temperature for 48 h. *E. coli* presence is confirmed by coloration changes in compartments and MPN concentrations quantified by matching the color sequence of the five compartments to one of the 32 rows of possible test result options given in the Aquagenx® Compartment Bag Test MPN Table (Aquagenx, 2013). The tabulation is based on the WHO (2017) drinking water risk categories for *E. coli*: 0/100 mL = Safe, 1–10/100 mL = Intermediate Risk, 11–100 mL^{-1} = High Risk, and > 100/100 mL = Very High Risk. This categorization hence recognizes the general consensus that drinking water should contain no *E. coli*, but *E. coli* numbers up to 10 to 20/100 mL may be tolerated in some countries as being of intermediate allowable risk (as is the case in rural Malawi). Risk categorization is translated into the following MPN concentrations within the Aquagenx® MPN table adopted: 0/100 mL = Safe; 1–3.7/100 mL = Probably Safe; 3.1–9.6/100 mL = Possibly Safe; 13.6–17.1 = Possibly Unsafe; 32.6–48.3/100 mL = Probably Unsafe; >100/100 mL = Unsafe (with minor MPN range overlap differentiated by color sequence allocated) (Aquagenx, 2013).

2.4.2. Supporting water quality chemical analysis

Supporting groundwater quality data collected included fluoride, nitrate and ammonium analysis via Trace2o™ Comparator Block and Wheels. Arsenic analysis used the 'Quick™ Arsenic for Water, Soil, and Wood' test strip kit. Field calibrated Trace2o™ pocket meter probes were used to measure well head parameters on hand-pumped, steady flow groundwater discharge collected in overflowing 20 L buckets. A Trace2o™ HL101 Pocket pH/°C/°F Meter was used to measure groundwater pH and temperature. A Trace2o™ HL102 Pocket Conductivity/TDS/Salinity Meter was used to measure electrical conductivity (EC) and total dissolved solids (TDS). Some data clean-up was undertaken prior to further data analysis on EC and TDS data pairs that failed to display an expected TDS (mg/L)/EC (μS/cm) ratio of *c.* 0.5 attributed to data recording or transcription errors. This reduced EC and TDS datasets from 224 to 207 samples used in subsequent data analysis for which a relationship of TDS (mg/L) = 0.5199 EC (μS/cm) - 24.147 (R^2 0.98) was observed. Turbidity testing was measured via a turbidity tube (5 to 1000 NTU). Free residual chlorine (FRC) determined post chlorination treatment used standard (swimming) pool testers (0 to 2.5 mg/L (ppm) range).

2.5. Data analysis

Temporal and spatial analysis of *E. coli* occurrence categorized to health risk at boreholes assessed changes in borehole safety with phase progression and influence of land (topographic) surface-water drainage and hydrogeological controls and land use (Carter, 2020). Spatial analysis and plots presented were produced used ArcGIS Desktop (v10.6), topography by creating layers using an open-source Digital Elevation Model (DEM) from USGS and geology drawn from Addison et al. (2020c) recent synthesis of old scanned maps (Cannon, 1970) and literature updates (Wedmore et al., 2020).

Statistical analysis F- and *t*-tests (Kottegoda and Rosso, 2008; Kanyerere et al., 2012) were used to explore relationships between *E. coli* incidence and water point maintenance, civil work, and pump issues, i.e., commonly identified key potential environmental risk factors (Hynds et al., 2014; Ferrer et al., 2020) (Supplementary materials, Table S1). The calculations were completed using Data Analysis tools on Microsoft Excel based on the convention that $p \leq 0.05$ were considered statistically significant (Freedman et al., 1998). The null hypothesis tested was the variable causes no change in the level of *E. coli* contamination in a water point borehole supply; the alternative hypothesis was the variable does cause a change. The level of *E. coli* was defined by the concentration in MPN/100 mL. The civil work variables tested included: borehole functionality, pumping problems, cracked head-works platform, drainage channel cracked, fence/barrier missing, faulty drainage, pedestal broken, preventative maintenance adopted, age of the borehole and pumping rate of the borehole. In the absence of fully mapped pit latrines in the study area, proxy indicators were used of these sources: population density data (WorldPop, 2021) and numbers of household dwellings at radial distances from boreholes enumerated by QGIS (Quantum Geographic Information System) (Kuka and Bushati, 2014). This was implemented by assessing: 100 m radius the number of pit latrines (households) for clean and contaminated water points within a 100 m and similar for 50 m and 30 m radii, as well as

5 or less latrines in a 100 m radius versus 6 or more latrines and similar for 50 m and 30 m radius. Seasonal variables within the boreholes were also compared with the concentration of *E. coli* (MPN/100 mL). Such variables include borehole water level within contaminated vs. clean boreholes, whether the water point had been submerged (*E. coli* contamination within submerged vs. not submerged boreholes) and whether the detected water level within the borehole is seasonally present (*E. coli* contamination within seasonal vs. not seasonal boreholes).

Principle Component Analysis (PCA) (Lever et al., 2017) was undertaken on the Phase 3a data to identify relationships between variables, including preventative maintenance, damage with civil works, damage with pump, soil erosion, leakage head, likely submerged, *E. coli* contamination and presence of latrines within 100 m. PCA, a dimensionality-reduction method, is commonly used to analyze bacteriological and chemical water contamination due to its capacity to work across a range of bio-physical variables captured in different units (Ferrer et al., 2020; Liu et al., 2020; Olsen et al., 2012). PCA uses a standardization technique to transform the variables into comparable scales so that their variance is given equal value in the analysis. PCA relies on a covariance matrix computation to assess how variables vary in relation to each other based on their respective means. The result of the PCA identifies the percentage of the variance that can be accounted for by each variable. Principal components are ordered by their relative significance, i.e., PC no. 1 indicates the variable that carries that maximal amount of variance in the data set. A PCA bi-plot was developed using Analyse-it on Excel where variables which correlate strongest having their axis closer together on the plot (Lever et al., 2017; Analyse-it, 2020). The percentage relationship calculated by the PCA allows determination of the impacting variables and assigned risk factors to variables based on their relationship with *E. coli* occurrence (Moyo, 2013; Ferrer et al., 2020).

3. Results

3.1. E. coli contamination changes observed between phases

3.1.1. Phase coverage

Varying phase coverage of water quality by boreholes summarized in Table 1 influenced observed occurrence and assessment of temporal trends in *E. coli* contamination. The Phase 1a survey 3–4 months after the cyclone assessed the condition of 260 boreholes of which 173 were sampled. Boreholes not sampled were found to be abandoned, or not functional enough to provide water samples. Subsequent water point rehabilitation increased sampled boreholes to 218 in the post-rehabilitation Phase 1b survey. This followed the USAID/ONSE Health flood recovery intervention that including 46 newly sampled rehabilitated boreholes identified as non-functional or partially functional in Phase 1a.That intervention was 100% successful in bringing water points to functional and safe use. Increased numbers of sampled boreholes reaching 204 and 224 boreholes in Phases 2a and 3a respectively arising from greater hand-pumped sample availability with improved functionality following the initial rehabilitation. Numbers of sampled boreholes in Phases 2b and 3b were lower than in Phase 1b as fewer water points required physical repair works. Complete evaluation requires the water point to be out of use for 1 to 3 days and would leave the community without water, therefore those that were functional were only sampled to assess the effectiveness of chlorination on *E. coli* contamination found.

Data obtained provided good spatial coverage in each phase. However, due to acquisition and loss of water quality sampled boreholes across the phases, temporal trend assessment required determination of which water points had data during all phases. Of the eventual total 279 boreholes sampled, 154 boreholes straddled all three phases and afforded the main opportunity to assess temporal trends.

3.1.2. Observations across phases

Histogram plots of *E. coli* MPN contamination data expressed as health risk categories indicated a majority of 'safe' (0 MPN 100 mL^{-1}) boreholes in all phases (Fig. 2). Post-rehabilitation surveys could reach 100% safe boreholes, for instance Phase 1b, demonstrating chlorination was successful in lowering health risks in supplies post rehabilitation. Some occurrence of 'unsafe' boreholes in Phases 2b and 3b was due to chlorination not being undertaken for technical reasons or to respect community preferences. It did not signify chlorination ineffectiveness.

Surprisingly, increased *E. coli* contamination occurred between Phase 1a to Phase 2a, and further increased in Phase 3a (Fig. 2). 'Safe' water correspondingly declines across these phases from 94% to 78% to 63%. Percentage splits between safe (incl. probably and possibly) and unsafe categories drops from 95/5, to 84/16 to 74/26. Transition from 'probably safe' to 'probably unsafe' transcends few samples in Phases 1a and 2a reaching up to 19% of samples in Phase 3a. 'Unsafe' water (>100 MPN 100 mL^{-1}) is found in some 19% of Phase 3a boreholes sampled compared to 14% in Phase 2a and just 2% in Phase 1a. In fact, only 11 boreholes (6%) in Phase 1a registered any contamination (≥1 MPN 100 mL^{-1}) compared to 44 (22%) in Phase 2a and 84 (38%) in Phase 3a. Overall, 113 boreholes (41%) displayed some *E. coli* contamination at some point compared to 166 boreholes that never registering any contamination (the relative increase in the contaminated versus non-contaminated subset of boreholes sampled in phases is shown in Fig. S4). It should be acknowledged though Phase 1a results will be influenced by the decreased availability of boreholes for sampling due to non-functionality issues. A worst-case scenario (assuming all boreholes physically assessed but not sampled were contaminated) calculates a safe proportion of 62%. Essentially this is identical to Phase 3a at 63%.

To provide wider perspective, recent survey data in Malawi reported by Banks et al. (2021) found 47% of sites with ≥1 MPN 100 mL^{-1} that compares to our overall occurrence of 41%. However, most detections by Banks et al. were in the range 1–10 MPN 100 mL^{-1} with a median of only 2.6 MPN 100 mL^{-1} and no samples reaching 100 MPN 100 mL^{-1}. Hence, they did not observe gross *E. coli* contamination as found in this study. Their sampling was conducted between September and December 2017, the early to mid-wet season when groundwater levels are at their lowest.

Table 1

Numbers of water point boreholes surveyed and sampled during each phase and cumulative aggregate total of boreholes sampled and newly sampled boreholes in each phase.

	Phase 1		Phase 2		Phase 3	
	Cond.[a] survey	Post rehab.[b] survey	Cond. survey	Post rehab. survey	Cond. survey	Post rehab. survey
	1a	1b	2a	2b	3a	3b
Borehole condition surveyed	260	218	223	56	234	77
Boreholes sampled	173	218	204	54	224	77
Aggregate sampled boreholes	173	219	261	262	279	279
Newly sampled boreholes	173	46	42	1	17	0

[a] Cond. = Condition.

[b] Rehab. = Rehabilitation.

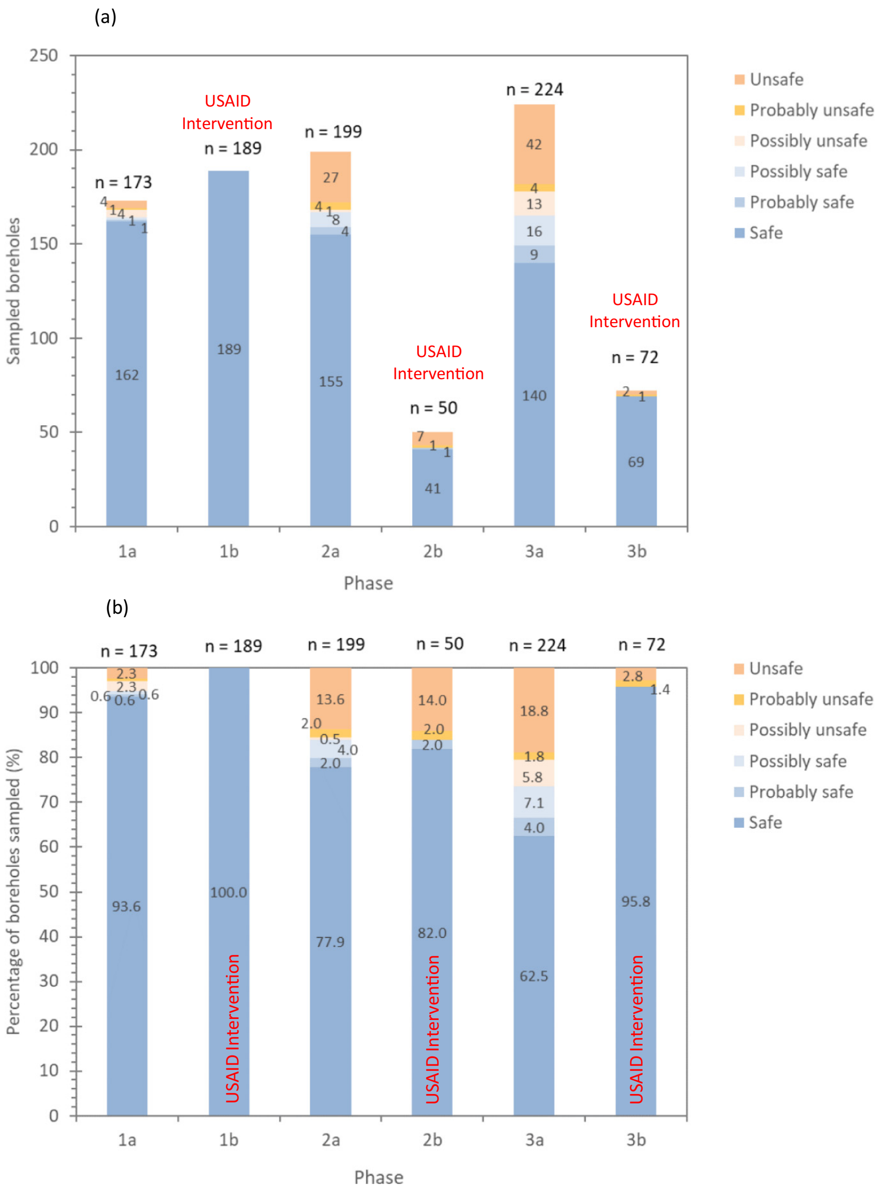


Fig. 2. Histogram plot of health risk category breakdown variation with phase shown as (a) numbers of boreholes sampled; and (b) percentage of boreholes sampled in each phase.

3.1.3. Contamination rebound

Phase 2a and 3a datasets allow some assessment of the long-term effectiveness of chlorination implemented for phase 1b that reduced *E. coli* to 0%. Health risk category histograms show evidence of pronounced contamination 'rebound' with for instance 32 boreholes in Phase 2a displaying contamination that had all previously undergone successful chlorination, i.e. returning 'safe' (MPN = 0) levels in Phase 1b (Fig. 3a). Some 23 of these boreholes had become 'unsafe' (MPN > 100). Rebound is even more pronounced and actually dominant in the Phase 3a contaminated subset of boreholes (Fig. 3b). Rebounded contamination following earlier phase successful chlorination occurs in some 60 boreholes with 44 in the three unsafe categories dominated by 33 boreholes classified as unsafe. The latter comprises 23 boreholes having undergone successful chlorination twice (treated in both Phase 1 and 2) and the remaining 10 boreholes chlorinated just once. Phase 2a displayed 31 boreholes in the contaminated subset that although uncontaminated at that time, but did become contaminated in Phase 3. More positively, some 115 boreholes tested in Phase 2a and 118 boreholes in Phase 3 always remain safe. Phase 3a exhibited contamination decreases in 24 boreholes of which 13 had previously been unsafe and were now mostly in the safe category. The overriding concern is the increased contamination in Phase 2a and even greater in Phase 3a that included rebound of contamination after successful chlorination.

Although contamination of Phase 1 boreholes was less certain due to non-functionality preventing sampling constraints, the fate of these boreholes and status at Phase 3a can be tracked. Comparison of Phase 1 and Phase 3a status confirms an overall change from safe conditions with 35 boreholes becoming unsafe (Fig. S5a). This change includes boreholes from both the 'Phase 1a not contaminated' (Fig. S5b) and 'Phase 1b repaired borehole' subsets (Fig. S5c). The previously contaminated subset of boreholes at Phase 1a ($n = 11$) exhibited a mix of migration to both safety and rebound to unsafe conditions (Fig. S5d).

The change in safety of individual boreholes within the contaminated subset ($n = 113$) is illustrated in the stacked plot of MPN concentrations observed in each phase (Fig. 4). It is clear the USAID interventions had a substantial positive impact on the water quality of the water points after each intervention. Unfortunately, the plot provides some quantified indication of the greater rebound of contamination and *E. coli* load observed in Phase 3a of the 84 contaminated

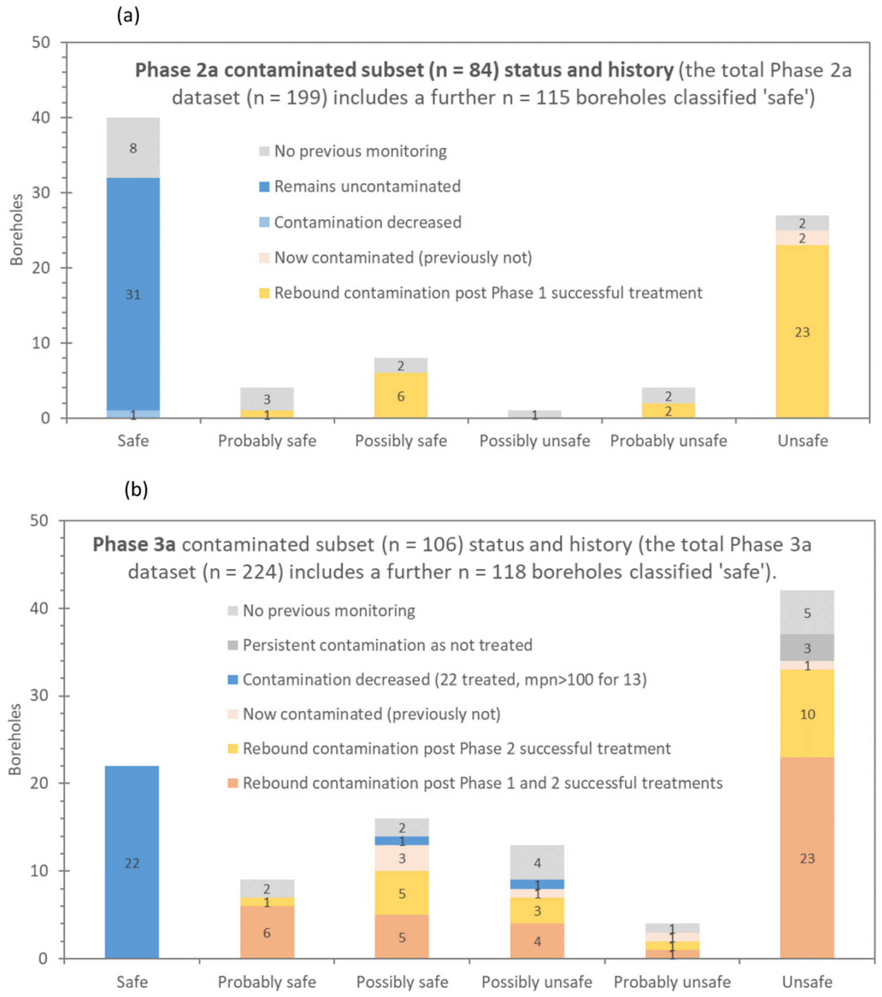


Fig. 3. Histogram plot of health risk category status and history for the contaminated subset of boreholes sampled at (a) Phase 2a, and (b) Phase 3a.

points compared to 44 points in Phase 2a (recognizing the low Phase 1a peak was partly attributed to not being able to sample non-functional boreholes). The success in Phase 1 chlorination is obvious with zero boreholes registering contamination in Phase 1b. The small numbers in Phase 2b and Phase 3b are mostly accounted for by a few boreholes not being chlorinated for various reasons as noted earlier.

3.2. Hydrological and hydrogeological controls

3.2.1. Precipitation

Whilst the cyclone itself represented an extreme event, intense precipitation input, the observed *E. coli* contamination requires understanding within the long-term precipitation record. Precipitation

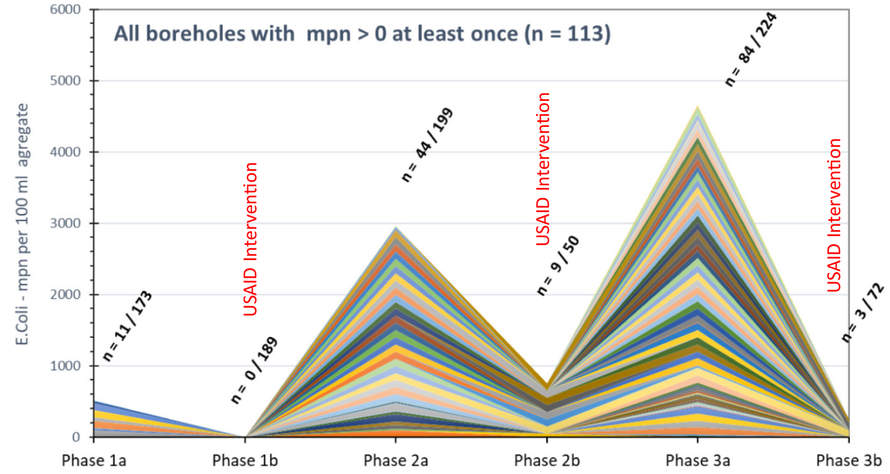


Fig. 4. Stacked plot of *E. coli* MPN estimates illustrating the change in safety of individual boreholes within the contaminated subset ($n = 113$) with time over the various phases. The stacked profiles aggregate the MPN per 100 mL concentrations of *E. coli* (limited to a maximum of 100 MPN per borehole (i.e. the thickest bands shown).

2010–20 data for Mulanje (Fig. 5; World Weather Online (2021)) plotted as monthly rainfall and a rolling average annual rainfall confirm the March 2019 cyclone provided the largest, nearly 400 mm, single monthly precipitation input for the entire decade previous. This input was exceeded though in the following 2020 wet season, reaching over 500 mm in January 2020 and approaching it at 350 mm in February 2020 – a period coinciding with Phase 3. The 12-month annual rolling average data confirm that the marked upturn in the rolling average evident in 2019 compared to the decade previous was sustained across 2020 as a consequence of the marked wet season following (Fig. 5b). Both 2019 and 2020 were very wet, their respective calendar year annual averages of 1450 mm and 1510 mm approaching double the mean annual average of 780 ± 140 mm for the 2010–18 period prior.

Low to average groundwater levels (water table) may be reasonably inferred from the rainfall record prior to the cyclone. The previous above average rainfall in 2017 was amid low to average rainfall since 2013 with some drought years. The closest national network observation borehole located in the Massif foothills at the south-east study area border (Fig. S6) is responsive to rainfall over the 2011–16 interval monitored; for instance, the marked 5 m water table increase in the January 2015 wet season (Fig. 5a inset). By extrapolation (recognizing spatial – hydrogeological variability of groundwater rise), groundwater levels will have significantly risen in the 2019 wet season, and with some intervening dry-season recession, yet further in the 2020 wet season. Both were wetter than 2015 and groundwater levels are expected to have been at their maximum during 2019–20 for the entire 2010–20 decade. The record suggests maximum groundwater levels with water tables closest to surface would have occurred around February 2020 rather than immediately after the cyclone.

Hence whilst pit latrines would have been most vulnerable to surface-water flooding around the time of cyclone, they would have greatest vulnerability to groundwater flooding and leaching in the following wet season when water tables were closest to surface. This conceptualization may very reasonably account for the maximum *E. coli* contamination of boreholes being encountered in Phase 3. Short circuiting of surface water - well head contamination into the borehole would have remained possible during high intensity rainfall events in the pronounced 2020 wet season (Fig. S6a, b), however, intervening rehabilitation works would have reduced this risk. The aforementioned lower *E. coli* incidence in Malawi groundwaters sampled by Banks et al. (2021) in late 2017 would accord with the lower water tables reasonably anticipated then from the lower (compared to 2019–20) precipitation that year that is proceeded by several drought years.

3.2.2. Observed groundwater flow field

Groundwater level data are surprisingly sparse in Malawi due to hand-pump infrastructure and sealing at ground surface inhibiting measurement access. Networks are also vandalized. Water level data collected during well rehabilitations when pumps were removed (to primarily estimate borehole standing water volumes for chlorination) represents a valuable opportunity and data were used to make water table and depth-to-water table plots (e.g. Figs. S7 and S8 and later manuscript figures as backdrops). Not obtaining, or not using such data regionally is perceived a widely overlooked opportunity in emergency relief efforts. It is recognized such water level data are biased towards the subset of boreholes that are contaminated, i.e. these being the boreholes primarily rehabilitated. For instance, Fig. S9 confirms the proportion of 'safe' health risk boreholes used to define the water table is correspondingly low.

The maximum groundwater levels in Phase 3 anticipated from the rainfall record is evident in the spatial data. For instance, the migration up the main (south-west) study area valley of the 700 m (asl) groundwater level contour (Fig. S7). The primary value though of the dataset is regional groundwater flow field definition that may enable groundwater management and protection. Similarity of the Phase 3 water table (Fig. S7c), offering highest individual phase spatial coverage, with the water table plotted from data amalgamated from all phases (Fig. S7d) confirms the value of increased spatial density coverage of the 'All phases' composite maps using all data obtained over the 2019–20 period. The contour-based expected flow directions annotated in Fig. S7 confirms the regional water table is primarily controlled by groundwater flow draining towards the main river network broadly following valley topography. Depths to water table were low, mostly within 5 m of surface and often within 1.5 m in the south-western area main valley lowlands where 'previously flooded' categorized boreholes were most common (Fig. S8).

The groundwater flow field comprises a 'southern catchment' a central groundwater flow divide area and a 'northern catchment' (Fig. S7d). Southern catchment groundwater flow generally follows the topography and Tuchila River catchment drainage from the Shire Highlands -

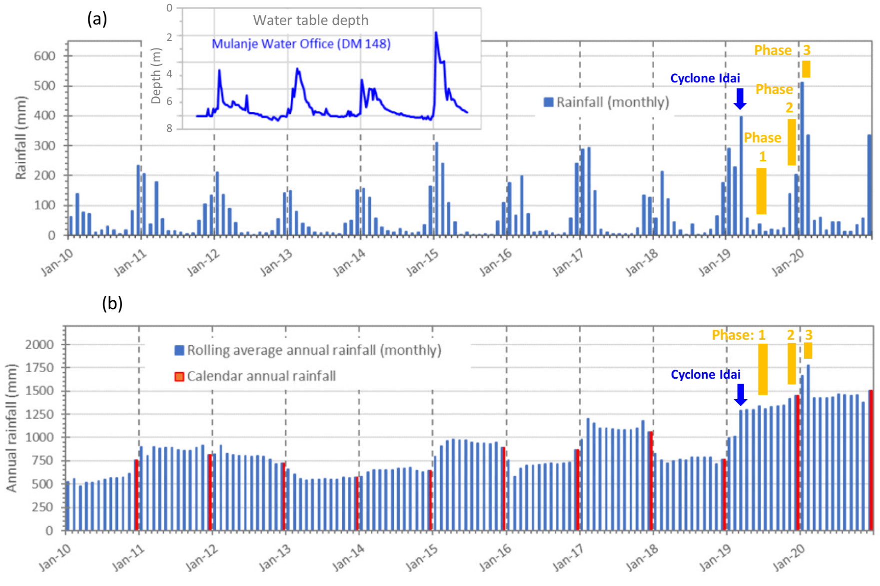


Fig. 5. Precipitation record 2010–20 for Mulanje as: (a) monthly rainfall; and (b) rolling average annual rainfall calculated from monthly data (data source: World Weather Online (2021)). These data are expressed as rainfall intensity in Fig. S6. The inset graph in (a) shows depth to water table observed in the Mulanje District Water Office Observation borehole (DM 148) over the 2011–2016 period monitored (time axes are aligned); its location is shown in Fig. S6 (with graphed data).

Mulanje range. The southern valley area is narrower and steeper than further north and accounts for the moderately steep and consistent hydraulic gradients from the upland recharge areas to the lowland rivers. Hydraulic gradients are fairly typical for alluvial valley aquifer settings; a groundwater head contour decline of *c.* 20 m occurring over *c.* 4 km in some near-river area giving a gradient of *c.* 0.005 (0.5%). Steeper gradients are expected and observed around the basement outcrop - Mulanje range foothills driving more rapid groundwater flows. Particularly where permeable sand-gravel lenses occur in the colluvium deposits or perhaps where effective porosities are low in the basement rock, especially where rock fracturing/jointing is laterally connective. Data contouring is sufficient to resolve groundwater flow divides that correlate with the surface water drainage to the different river systems. For instance, the local flow regime in the catchment head to the immediate south-west of the Mulanje range is resolved (Fig. S7d). Steep hydraulic gradients locally reflect the foothill topography.

The central study area to the north of the Mulanje range is characterized by a wider and flatter valley topography also reflected in shallow hydraulic gradients. The area forms a north-south groundwater divide mirroring the surface-water divide (compare Figs. 1 and S7d). Groundwater flows in the northern study area drain north eastwards towards the Phalombe River – Lake Chilwa basin, beyond the Rift Valley. The flow regime is consistent with the water table determined in our adjoining Lake Chilwa basin study shown to drain to the lake (Fig. S10; Rivett et al. (2020)). Groundwater flows to the south remain within the Rift Valley, draining into the Tuchila River catchment and ultimately draining westwards into the Lower Shire River Basin. The exact position of the main groundwater divide is challenging to define due to the shallowness of the gradients, limited boreholes and hence limited level data alongside probable transients of the divide.

3.3. Spatial assessment of *E. coli* health risks

3.3.1. Spatial observations

The spatial distribution of *E. coli* health risk categories (Fig. 6) confirms the increased contamination evident in Phase 2 and especially Phase 3 compared to post-cyclone Phase 1. Most sampled Phase 1 boreholes displayed contamination-free, safe water quality with occasional sporadic occurrences of contamination in the southern catchment, mostly in the south-west valley lowlands (Fig. 6a). These occurrences although in proximity to lowland flooded boreholes, also occur with contamination free, safe boreholes suggesting post cyclone a locally heterogeneous occurrence of *E. coli* contamination. Recognizing Phase 1 contamination may have been significantly under-estimated (inability to pump samples from non-functional boreholes) and that some 35 boreholes assessed in Phase 1 ultimately became unsafe by Phase 3a (Fig. S5a). Significantly, Phase 1 data suggest safe water from an *E. coli* perspective could be obtained from most of the study area a few months following the cyclone. Reduced human activities resulting from the displacement of communities who did not return for some months after the flooding may have contributed to this occurrence, especially if anthropogenic influenced wellhead contamination pathways are important.

The Phase 2 distribution (Fig. 6b) indicates a safe water status is predominantly retained in the northern catchment with isolated exceptions. Predominant emergence of boreholes that became categorized as unsafe (27 boreholes) and probably unsafe (4 boreholes) (per Fig. 2) were in the southern catchment. These occurrences again remain within proximity of safe supplies with spatially heterogeneous local problem manifestation apparent. Occurrences of unsafe supplies can be approximately zoned per the letter-labelled area in Fig. 6b. Some unsafe supplies occur along the foothills of the Mulanje Massif (label A and A′, Fig. 6b) where despite the early wet season timing, groundwater elevations appear notably higher in Phase 2 compared to Phase 1 bringing groundwater closer to surface, of higher gradients, more rapidly migrating. Unsafe supplies also occur across the mid-valley floor where flows drive westwards from the foothills where some mounding of the water table is evident (label area B). Closer to the river, unsafe supplies occur in area C on a trajectory down gradient of area B (and area A), and in area D further north. Areas B, C and D are all in lowland area where groundwater is near surface (Fig. S11) and some boreholes were known to have been previously flooded (Fig. S8).

The Phase 3 distribution (Fig. 6c) displays similar distribution characteristics to Phase 2, but with further contamination increase with 42 boreholes unsafe, 4 boreholes probably unsafe and 13 boreholes possibly unsafe (per Fig. 2). Increased intensity of contamination occurs in the Phase 2 labelled area as well as newly labelled area B′ in the valley plain and C′ on the western side of the river. Again, these occurrences remain within proximity of safe supplies with heterogeneous local problem manifestation apparent. Although availability of safe supplies in the southern catchment remains apparent, concentrated area of multiple safe supplies are much rarer, the main area being labelled S.

The composite ‘all phase’ data depicts the maximum health risk encountered at any time over the study, a ‘worst case map’ (Fig. 6d). *E. coli* contamination is extensive in the southern area west of the Mulanje range, albeit with safe water still heterogeneously present. In contrast, from a kilometer or two northwards of the Massif supplies appear predominantly unaffected by contamination with isolated exception. A ‘north-south divide’ in health risk is apparent. This worst case map is in stark contrast to the ‘best case map’ (compared to in Fig. S12) which depicts minimum health risks encountered at supplies over the study (incl. data from the post-rehabilitation surveys). The comparison is spatially illustrative of the rebound of contamination previously shown in Fig. 4 that can occur after apparently successful (in the short term) rehabilitation of supplies.

3.3.2. Depth-to-groundwater influence

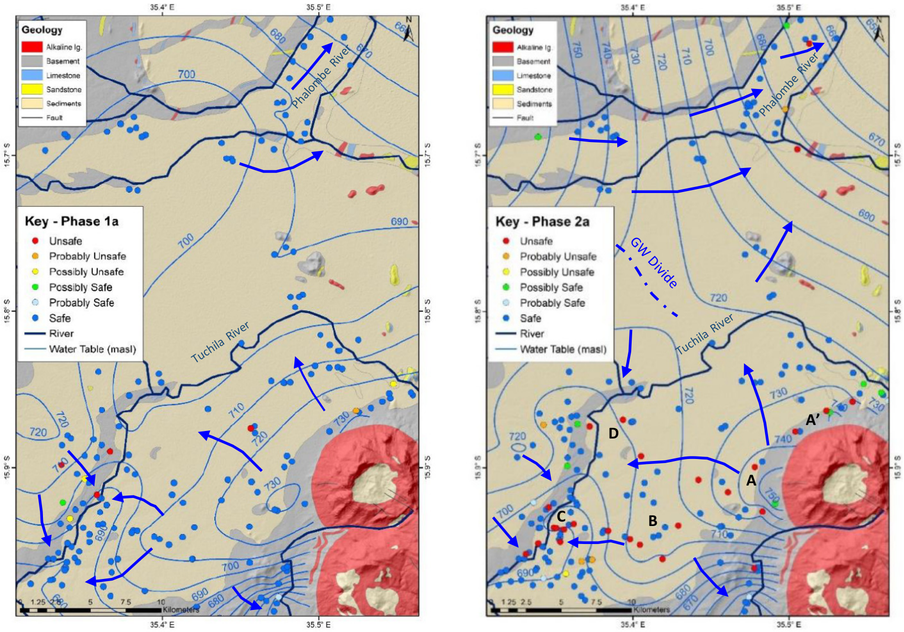
Control of depth-to-groundwater variation on contamination occurrence is evaluated in Figs. 7 and S11. Many boreholes in the southern and most in the northern catchment are in area with water tables within 5 m of ground surface and often closer with depth-to-groundwater variation modest (Fig. 7a). Whilst spatial maps show some concentrated occurrences of contamination in shallow water table area in the Southern catchment, the co-occurrence of contaminated unsafe and uncontaminated safe supplies in proximity generally does suggests that depth-to-groundwater control on contamination occurrence may not be that apparent. Both graphical plots confirm this is the case. Fig. 7c with the depth segregated data plotted as cumulative percentages of the various health risk categories indicates there is only marginally greater prospects of more contaminated, unsafe water being found in boreholes with less than 2 m depth to groundwater. And vice-versa, safe water is slightly increased in boreholes with greater depth to water table. The depth-to-water table variation influence upon observed contamination hence appears marginal at best. It should be recognized that low depths to groundwater typically encountered may still remain an important factor in causing water points, especially in the southern catchment, to be quite vulnerable to contamination. The general shallowness of the water table and associated vulnerability of groundwater to contamination requires diligent drilling and installation of borehole infrastructure to ensure wellhead protection.

3.4. Attribution of contamination to pit-latrine sources

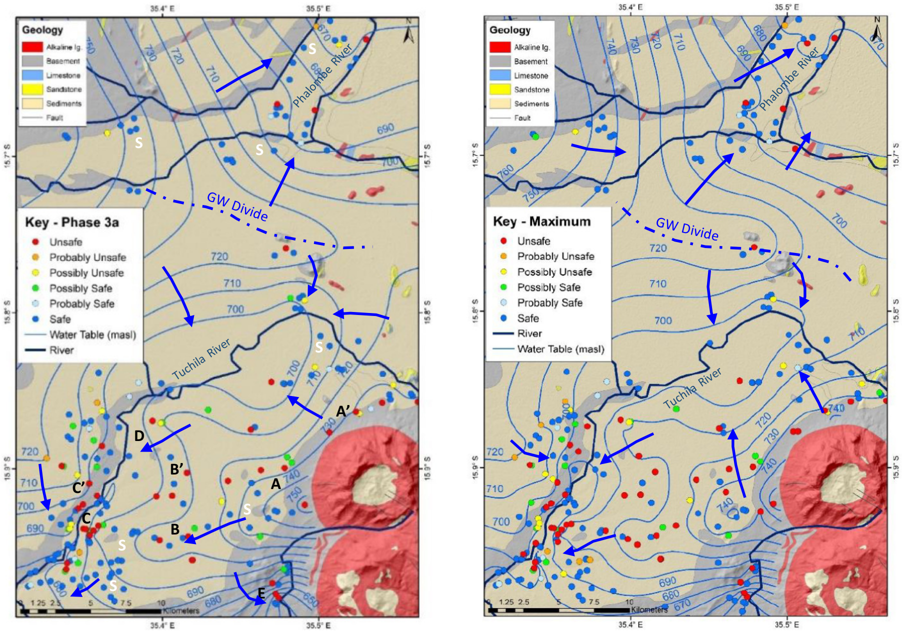
Several ‘first pass’ approaches were used to indicate whether observed *E. coli* contamination related to pit latrine sources. Proxy indicators of latrines, population density and households present radially, were necessarily used as latrine mapping was partial across the study area. Some example evaluation using the latter available mapping is, however, presented.

3.4.1. Spatial population density proxy indicator

Spatial population density may serve as a proxy indicator of latrine numbers surrounding water points as these may be expected to


(a) Phase 1 (June 2019)

(b) Phase 2 (Nov. 2019)


(c) Phase 3 (Feb. 2020)

(d) All phases – Worst case (maximum)

Fig. 6. Spatial distribution of *E. coli* health risk of sampled water points shown over phase contoured and composite (for (d)) water table and geological map for (a) Phase 1, (b) Phase 2, (c) Phase 3; and, (d) all phases maximum (worst case).

increase with population (Fig. S13). Maximum health risk data observed at sampled boreholes is shown relative to 2017 population density plotted at 100 m × 100 m pixel resolution (WorldPop, 2021). Population densities are highest in the southern catchment with the central groundwater divide area sparsely populated and northern catchment population moderate. Increased health risk broadly follows these population trends with more frequent and higher contamination present in the more populated southern catchment.

Increased population densities nestle around the entire western foothill fringe of the Mulanje range where contamination of supplies is evident (Fig. S13). Population across the southern valley floor ranges from very low to moderate with sporadic localized increase. Most contamination is found in these latter two areas, albeit recognizing the more limited borehole coverage of less populated area. Closer to the river, some higher population densities are locally found which variously coincide with safe and unsafe supplies. The most prominent concentration of unsafe supplies (in the south west, to the east of the river) appears close to only moderate, rather than high population densities. The northern catchment is characterized by generally low to moderate population densities, increased along the valley axis. Higher health risk boreholes do occur in areas of somewhat increased populations, mostly in the eastern, more down gradient part of the catchment.

3.4.2. Dwelling numbers with radial distance from water points

Dwelling numbers within fixed radial distances from water points provides a proxy indicator of pit latrine source incidence of greater

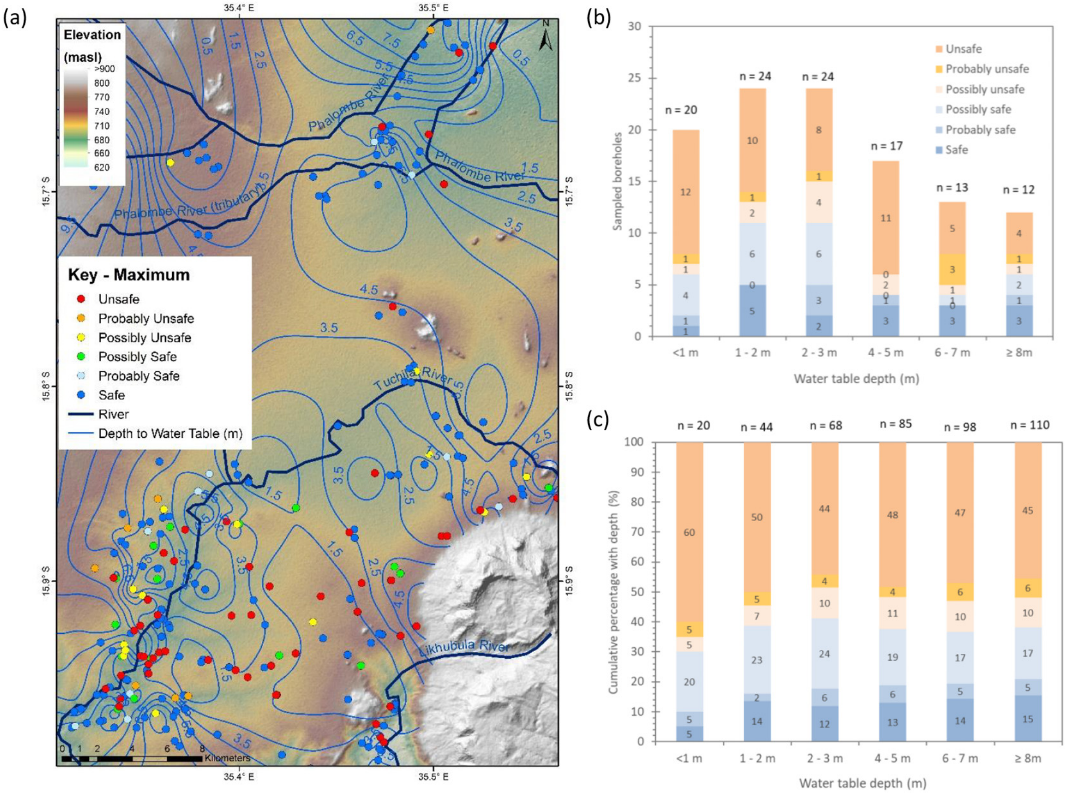


Fig. 7. Assessment of depth-to-water table control on contamination and increased health risk: (a) spatial distribution of maximum health risk for all phases data shown relative to contoured depth to water table; (b) and (c) graphical plots of depth-to-water table segregated health risk status.

granularity than the population density. Fig. 8 segregates datasets to *E. coli* contaminated boreholes and non-contaminated boreholes and shows the latter have marginally higher average number of pit latrines for all phases and all radii assessed. Although this difference is more apparent in Phase 1, it should be recalled that the subset of contaminated boreholes is by far the smallest in this initial phase (Fig. 2) and accounts for its greater standard deviation. The Phase 2 and especially Phase 3 data with greatest number of contaminated points is thought more representative and reveals negligible difference between contaminated and non-contaminated points. Each show *c.* 1 dwelling (and inferred pit latrine) within a 30 m radius of a water point, *c.* 3 dwellings within 50 m and *c.* 10 dwellings within 100 m.

The above renders a somewhat inconclusive result. It is reasonably argued that the radial approach is too simplistic and potentially masks pit latrines being the primary source (Back et al., 2018). This is because flow is not necessarily radially symmetric to a borehole, especially from distance and for groundwater flow in fractured rock systems. This proposition is further examined below.

3.4.3. Mapped pit latrines and groundwater flow influence at contaminated boreholes

The degree to which flow is approximately radially symmetric to an abstracting borehole depends on the interplay of hydrogeological conditions, abstraction and recharge rates and potential for directional

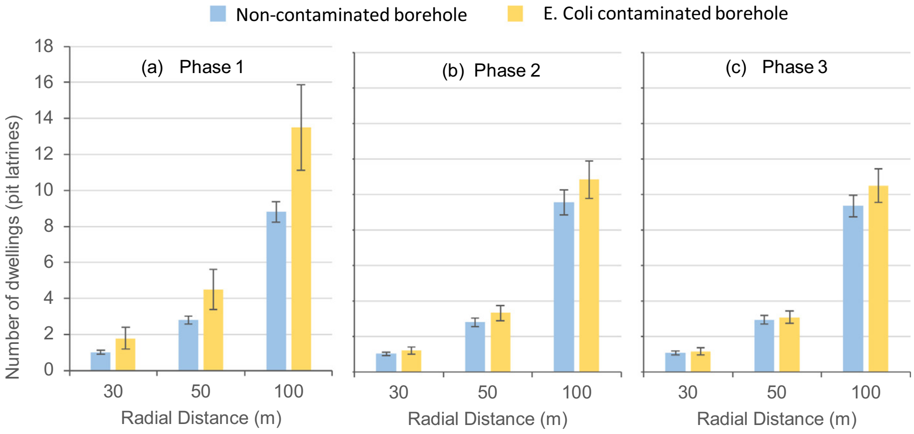


Fig. 8. Histograms of the average number and standard deviations of dwellings (and inferred pit latrines) within a 30 m, 50 m and 100 m radius of water points in the various phases sampled segregated to non-contaminated and *E. coli* contaminated boreholes (see Fig. 2 for individual phase sample number breakdown).

flow controls such as oriented fracture dominated flows. A significant proportion of abstracted flow could though arise from groundwater predominantly drawn from up gradient of the borehole. This directional bias is probable in higher velocity groundwater systems. For instance, permeable sand-gravel alluvial deposits or fractured zones possessing pronounced directional orientation. Such units also pose the greatest pathogen transport risks due to their greater rock pore apertures and decreased potential for attenuation. Low hand pump abstraction rates of 5–10 m^3/d typically found in Malawi (Rivett et al., 2018) (and elsewhere) may possess only modest ability to radially draw groundwater from cross and down gradient at distance. Radial draw would be greatest in settings with abstraction from less transmissive, finer grained units such as those of lacustrine origin and, or where hydraulic gradients and recharge rates are low.

Mapped pit latrine data are incomplete for the study area, nevertheless mWater survey pit latrine data obtained for boreholes classified as 'unsafe' (>100 MPN/100 mL) are shown in Fig. 9 (23 boreholes) and Fig. S14 (10 boreholes with low numbers of pit latrines and possibly not fully mapped) (with omission of a further six unsafe boreholes having no pit latrine data). Radial zones of 50 m and 100 m radius are shown for each borehole together with an arrowed indication of the regional groundwater flow direction (longer arrow) from which any bias to up-gradient groundwater flows abstracted are predicted to occur based on our Fig. 6 local water table contouring data (noting all sites have been rotated in space to align groundwater flows from right to left horizontally to aid visual inspection). Many pit latrines can occur within a 100 m radius, up to *c*. 10 or more latrines per borehole. Latrines are often closer than 50 m and some less than 30 m with occasional latrines extremely close to boreholes. We do not attempt to correlate numbers of pit latrines with numbers of households, however, inspection of the plots shows increased latrine numbers around buildings or concentrations of buildings, but also buildings without latrines that may, or may not reflect shortfalls in mapping coverage.

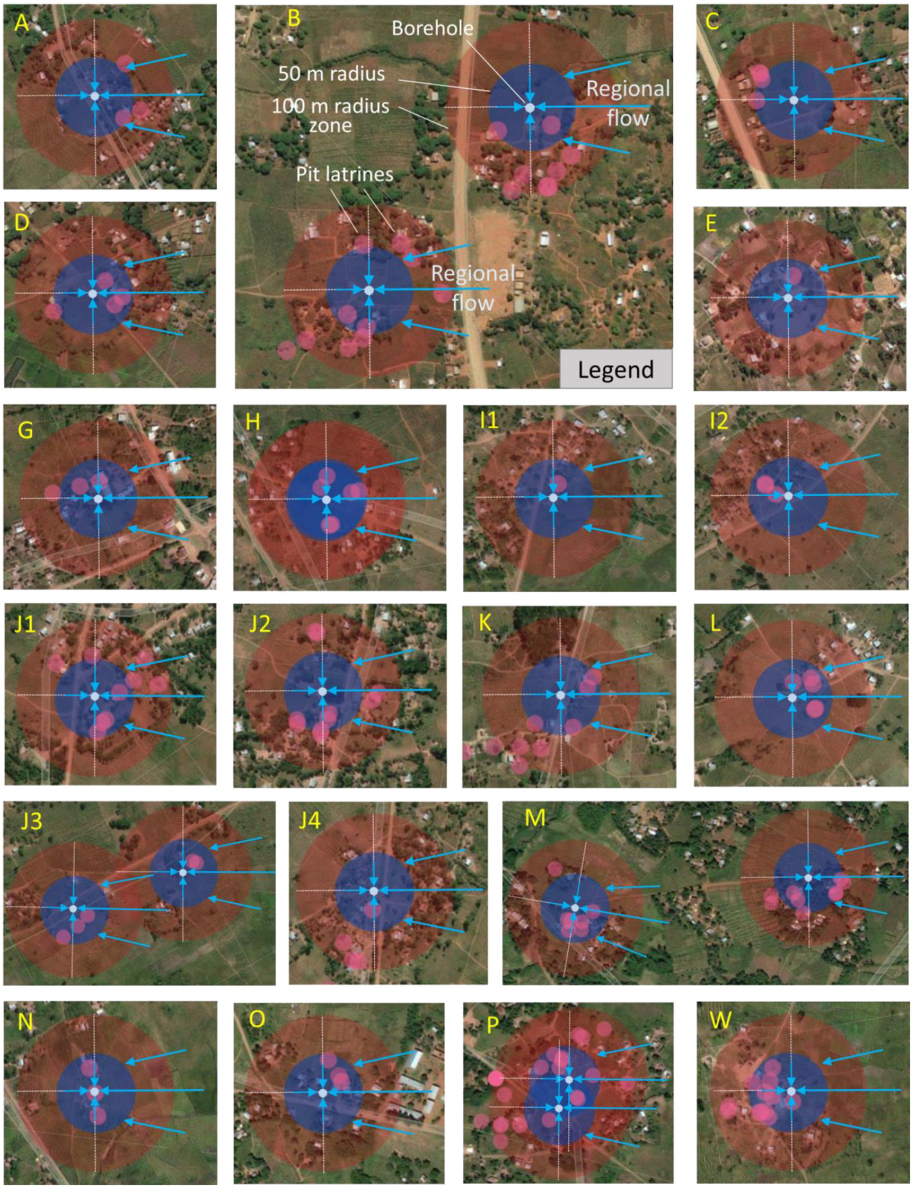
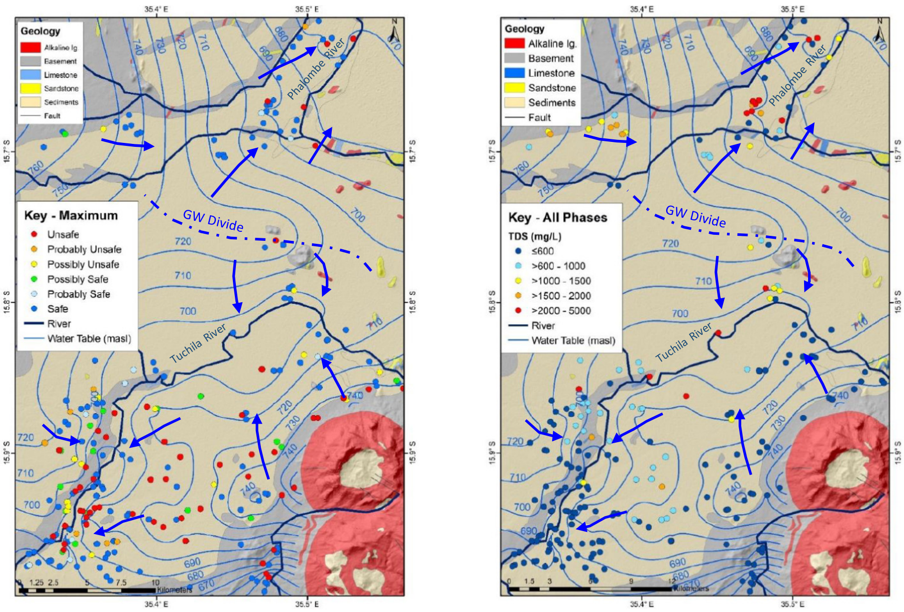


Fig. 9. Plots of local pit latrine (mWater) data obtained for boreholes classified as *E. coli* 'unsafe' (>100 MPN/100 mL) with 50 m and 100 m radial zones shown for each borehole together with regional groundwater flow directions (longer blue arrow) to indicate possible bias towards up-gradient groundwater flows abstracted (directions based on Fig. 6a local water table contouring, noting all sites have been rotated in space to align regional groundwater flows from right to left horizontally. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

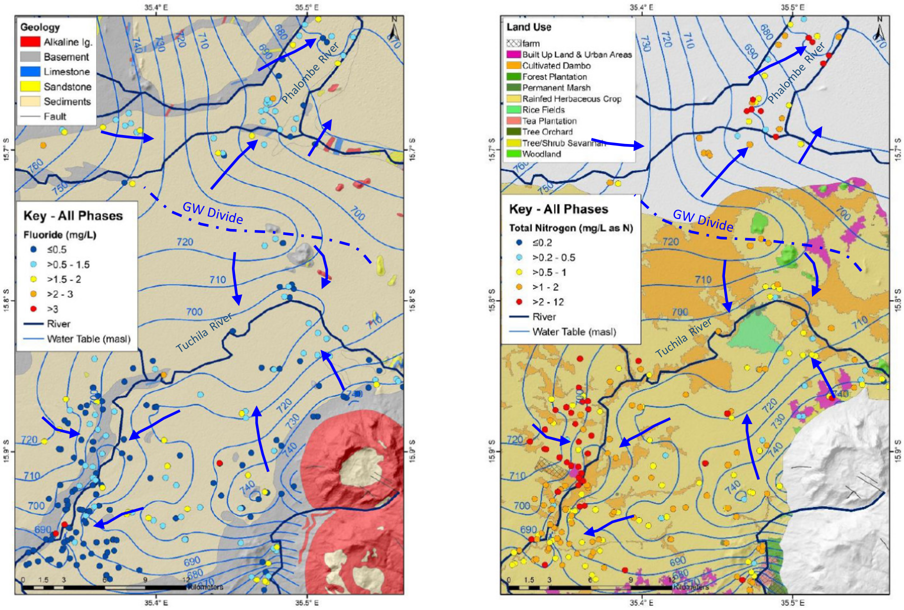
The contamination at the vast majority of borehole cases shown can potentially be explained by the existence of: latrines either being very close, within *c.* 30 m with increased prospects of radial draw in from any direction (signified by short blue arrows); loading from multiple latrine sources, and/or latrines located up groundwater gradient (within or close to the area of longer blue arrows) that have increased probability of contaminating boreholes if abstracted groundwater is biased from up gradient. For instance, up-gradient pit latrine sources appear to be the only, or primary (closest sources) in many of the cases (cases A, B (one of), D, E, H, I1, J1, K, L, J3, M (one of) and O in Fig. 9 and cases F, Q, X and Y in Fig. S14) and also contributing in other cases where both up-gradient and down-gradient sources exist. This compares to only single case C in Fig. 9 and cases U, V and Z in Fig. S14 where mapped latrines only occur down gradient. The potential significance of groundwater flow directions on borehole contamination risks posed is hence shown credible. The observations also underscore the need to map all existing and abandoned latrine distributions to accurately assess risks posed to supplies (Diaw et al., 2020).

3.5. Contamination insights and health relevance of other chemical determinants sampled

Health risk *E. coli* data are spatially compared in Fig. 10 with TDS, fluoride and total nitrogen (nitrate and ammonium) with summary box plot data shown in Fig. S15. The latter confirms that concentration variation between phases for these and other determinants is limited with the exception of groundwater temperature (Fig. S16 (see discussion in caption)). Hence aggregated data from all phases are appropriate


(a) Health risk E. coli

(b) TDS


(c) Fluoride

(d) Total Nitrogen and land use

Fig. 10. Spatial distribution of all phases maximum sampled borehole data for (a) *E. coli* health risk (worst case), (b) TDS and (c) fluoride plotted on all phases contoured water table – geological map; and, (d) total nitrogen (nitrate and ammonium) plotted on land use map.

to show in Fig. 10 spatial plots to increase data densities. Contamination insights from these chemical determinants, some informing *E. coli* contamination interpretation and their health relevance are outlined below.

3.5.1. Total dissolved solids (TDS)

The vast majority of boreholes supplies, around 70%, have a groundwater TDS below 600 mg/L recognized by WHO as having good palatability. A further 10% are below 1000 mg/L at which point WHO deems the water as increasingly unpalatable (Fig. S15). Of the remaining 20% above 1000 mg/L, almost 5% exceed the Malawi Maximum Permissible Limit of 2000 mg/L for groundwater supply. Most of the southern catchment with more widespread *E. coli* contamination exhibits good quality TDS, typically below 600 mg/L. This is especially in supplies towards the Mulanje foothills and in the southern valley, cyclone-flooded area. This occurrence would be consistent with these being recently recharged groundwater facilitated by faster flows in this somewhat steeper valley area with moderate to high hydraulic gradients. It may be inferred from the *E. coli* results though this fresh, low TDS recent recharge water is vulnerable to microbiological contamination. For instance, the flow-line in area B on Fig. 6 exhibits generally low TDS, but frequent 'unsafe' *E. coli* contamination levels.

Slightly further north, still within the southern catchment, gradually increasing 600–1000 mg/L TDS groundwater occurs across the mid valley plane and in some near-river area. This is ascribed to longer residence groundwater and is consistent with longer travel times from the upland recharge area in the widening valley. Groundwater variously show *E. coli* contamination. A little further north, mid study area, a 'line' of very high TDS groundwater trends southwest – north-east along the river valley. Although there are insufficient data (e.g. major ion) to conclude on salinity origins, the area is flat, of decreasing hydraulic gradient northwards towards the main groundwater divide and at distance from possible recharge areas, especially the north west uplands rather than the Mulanje range. The occurrences hence point to older, possibly (semi-)confined waters and is consistent with the absence of *E. coli* contamination observed in these geologically lower vulnerability supplies.

Similar observations apply to the other main area of high TDS, the prominent hotspot in the northern catchment. Here, *E. coli* contamination is, with a single exception, absent. The catchment displays salinity frequently over 1000 mg/L that increase eastwards and northwards consistent with the north-eastern flow direction and groundwater of increasing age. This is consistent with our recent findings from the adjoining Lake Chilwa basin (Fig. S17 plots TDS for both studies) into which groundwater migrates to the immediate north-east. That work confirms the importance of paleo-geohydrological control on the groundwater salinity observed and influence of paleo-lacustrine sediments (Rivett et al., 2020). The controls on salinity in our north-east study area are likely similar, albeit requiring confirmatory major ion data. Still, some supplies in the northern catchment do exhibit both safe levels of *E. coli* and low TDS and offer good supply prospects. These supplies are located close to the Phalombe River and could be abstracting influent leakage into groundwater of low TDS river water proposed by Rivett et al. (2020) a little further downstream nearing Lake Chilwa to account for the low TDS groundwater supplies also found there (see Fig. S17).

An insightful picture hence emerges from the TDS data. Low TDS, fresher recharge waters become microbiologically contaminated predominantly in the southern catchment. This contrasts with low microbiologically contaminated groundwater in the northern catchment. Although less vulnerable to anthropogenic contamination, presumably due to increased low permeability, lacustrine origin, sediment protection, lower hydraulic gradients in the near-divide area, longer travel paths from recharge area and prolonged residence times, many of the supplies there are compromised by elevated salinities induced naturally by these same processes. This dichotomy is captured in the Fig. S18 plot of *E. coli* health risk category with TDS breakdown showing high TDS water predominantly associated with safe (*E. coli*) health risk water, and unsafe water without very high TDS. It should be recognized though of the $n = 381$ samples tested as *E. coli* 'safe', some 67% were <600 mg/L TDS and 85% of samples <1000 mg/L TDS. Hence the majority of groundwater abstracted does provide good quality drinking water from both microbiological and salinity perspectives.

3.5.2. Fluoride

Median fluoride concentration across all phases was 0.3 mg/L ($n = 610$ samples) (Fig. S15). The WHO drinking water standard of 1.5 mg/L (WHO, 2017) was exceeded by 7% of samples with just 1% exceeding 2 mg/L to a maximum of 3.3 mg/L; the current Malawi drinking water guideline value of 6 mg/L (former WHO guideline value) (Addison et al., 2020a) was hence not exceeded. Increased dental fluorosis is the primary risk of modest exceedance of the current WHO guideline (Addison et al., 2020b). Sporadic occurrence of fluoride over 1.5 mg/L is dispersed across both southern and northern catchments amongst lower concentrations with highest concentrations occur in the southern catchment (Fig. 10c). The area of most consistent low fluoride is in the extreme south-east study area where supplies were also found to have low *E. coli* health risk and TDS.

It is inferred from the dispersed distribution of low to moderate fluoride and absence of known significant faulting in the area that deep sources of fluoride are not responsible (Addison et al., 2020c). This is endorsed by the plots of fluoride versus temperature and TDS (Fig. S19). More likely explanation includes fluvial river sediments comprised of material eroded from Mulanje mountain, an alkaline igneous intrusion (Addison et al., 2020c). Alternatively, affected water points may be drilled into an alkaline rock hidden by sediments, recognizing river channels in the north-east of the study area expose small alkaline igneous rocks usually beneath sediments (Addison et al., 2020c).

3.5.3. Arsenic

Arsenic testing across all phases ($n = 430$ samples) indicated over 70% of samples were below the kit detection limit (<1 μg/L arsenic), with 28% registering 5 μg/L arsenic and just 1% (6 samples from six different boreholes) registering 10 μg/L, the WHO drinking-water guideline value. None were over the WHO guideline value. These boreholes were flagged to the district authorities for continued monitoring, but recognizing concentrations were well within the 50 μg/L arsenic limit adopted by Malawi (again based on the former WHO guideline). These results and advised response are consistent with the low occurrence of arsenic generally found in Malawi and general requirement to remain vigilant of risks (Rivett et al., 2019b).

3.5.4. Nitrogen (nitrate and ammonium)

Nitrate (and ammonium) concentrations in groundwater in Malawi are typically very low compared to many places globally, but rising due to increasing fertilizer application with intensification of agriculture. Pit latrine sources may also contribute nitrate or ammonium (depending on redox conditions) to groundwater (Missi and Atekwana, 2020). The nitrate and ammonium medians for the all phase datasets ($n = 610$ samples) were 0.45 mg/L and 0. 3 mg/L (as N) for nitrate and ammonium respectively (Fig. S15). Concentrations are hence generally low with 95th percentiles for each at 2 mg/L (as N) with maximum concentrations of 8 mg/L and 6. 4 mg/L (as N) for nitrate and ammonium respectively. All concentrations are hence within the Malawi drinking water standard of 10 mg/L (as N) nitrate (45 mg/L as nitrate). 'Total nitrogen' concentrations of ammonium and nitrate exhibited a maximum of 11.6 mg/L (as N); it is only this single maximum concentration sample that would exceed the nitrate standard numerically. A plot of nitrate versus ammonium (Fig. S20a) illustrates the vast majority of samples contain very low concentrations of each, <1 mg/L (as N). Whilst higher concentrations of ammonium occur with low concentrations of nitrate and vice versa as may be expected, there is some indication of moderate nitrate and ammonium co-occurrence in some samples suggesting potentially mixing of oxidized and reduced waters in some borehole samples obtained.

Spatial plots of nitrate and ammonium (Fig. S20) and total nitrogen (Fig. 10d) are quite similar. Concentrations are locally heterogeneous and increased in near-river, lowland valley areas in both northern and southern catchments. The central valley plain and especially the boreholes nearing the Mulanje range tend to contain lower nitrogen. Highest values notably occur towards the west of both northern and southern catchments, especially in the latter to the immediate west of the river. The distributions point to agricultural inputs, although pit latrine influence cannot be discounted. Mulanje is an agricultural intensive district with the land use map (Fig. 10d backdrop) indicating much of the area is covered by 'rainfed herbaceous crop' or 'cultivated dambo' wetland. The greatest concentration of nitrogen in the southern catchment occurs close to the only large 'farm' formally marked and near-river dambo close to the area of main borehole flooding. Comparison with *E. coli* health risk reveals 'safe' supplies have a fairly even distribution of nitrate and ammonium across the concentration range, with 'unsafe' supplies possibly lower in higher nitrogen concentrations. An obvious increase in nitrogen contamination correlating with increased *E. coli* contamination is hence not apparent.

3.6. Statistical analysis of factors influencing contamination

3.6.1. F-tests and t-tests

Results of the F-tests and *t*-tests are summarized in Table 2; the null hypothesis being a variable causes no change in water point *E. coli* contamination and, the alternative, the variable causes a change. The alternative hypothesis that poor functionality may lead to contamination was accepted for both F-test and the *t*-tests in Phase 1 but not for Phase 2 and Phase 3 where the null hypothesis and no relationship were found. The results are inconclusive and complicated by Phase 1 having a low number of contaminated water points (poor functionality meaning many could not be tested) and functionality being higher in Phase 2 and Phase 3. A lack of preventative maintenance and age of boreholes showed mixed results with no relationship of these factors to contamination exhibited by null hypothesis acceptance in the *t*-tests, but mostly alternative hypothesis acceptance in the F-tests suggesting increased age and lack of maintenance were influential. Regarding specific civil work factors most of which relate to increased potential of short circuiting of wellhead contamination, a damaged platform showed mostly a null, no relationship to contamination result. A fence barrier missing showed null results in the *t*-tests, but alternative hypothesis acceptance in the F-tests. Pumping rates and broken pedestals were predominantly null results. Drainage channel cracked and faulty drainage showed mixed results, but with only sufficient data available for Phase 1 testing. Taken together these factors do not provide strong evidence of short circuiting of surface water being significant overall, but neither can it be discounted. It should be recognized though the data analyzed do not provide opportunity to assess short circuiting problems that may arise from the subsurface elements of the borehole installation works, notably the integrity of the casing and sealing of the borehole annulus.

Testing of the influence of the average number of surrounding pit latrines (as households surrogate) in each radius likewise revealed a mixed result with some contrast between F-test and *t*-test results (Table 2). A null hypothesis result suggesting no relationship to radial latrine density metrics was apparent in all *t*-tests, however, some alternative hypothesis acceptance results with were observed in the F-tests, for instance in all the 100 m radial metric results. The latter would infer that contamination is more probable in areas within a 100 m of the water points that are more populated, albeit a result not ratified by the opposing *t*-test result. A similarly mixed result was found for the testing of seasonal – transient factors with a null hypothesis, no relationship result found for all *t*-tests again, but with mostly alternative hypothesis and influence of transient factors such as water level change and borehole flooding incidence observed in the F-tests. Overall, the mix of F-test and *t*-test results including contrasting F-test and *t*-test result for some individual variables are not particularly conclusive. There is hint, rather than a clear relationship, that some factors could be influential of *E. coli* contamination observed.

3.6.2. Principle Component Analysis (PCA)

The PCA analysis for eight variables related to HPB maintenance and quality performance reveal that preventive maintenance is PC no. 1 and the accounts for 19% of the variance in the data set. This is closely followed with the damages to civil works and to the pump each accounting for 15% of the total variance. This suggests the high impact which post drilling maintenance can have on the performance of the HBP and as one of the most critical factor preventing e-coli contamination of the water point. Secondary principal components include soil erosion and puddling (13% of variance) and leakage of the head or

Table 2
Results from the F-tests and *t*-tests showing the accepted null hypothesis that a variable causes no change in water point *E. coli* contamination, or the alternative (Alt.) that the variable causes a change.

Hypothesis	Phase 1		Phase 2		Phase 3	
	F-test	*t*-Test	F-test	*t*-Test	F-test	*t*-Test
Civil works variables						
Platform cracked or damaged vs. No civil work repairs required	Null	Null	Alt.	Null	Null	Null
Drainage channel cracked vs. No civil work repairs required	Alt.	Null				
Fence or barrier missing vs. No civil work repairs required	Alt.	Null			Alt.	Null
Faulty drainage vs. No civil work repairs required	Null	Alt.				
Pedestal broken vs. No civil work repairs required	Null	Null				
Pumping rate	Null	Null	Alt.	Null	Alt.	Null
Age of borehole	Alt.	Null	Alt.	Null	Alt.	Null
No preventative maintenance vs. Preventative maintenance	Alt.	Null	Null	Null	Alt.	Null
Clean partially functional vs. Contaminated fully functional	Alt.	Alt.	Null	Null	Null	Null
Pump problems vs. No pump problems	Null	Null				
Pit latrine density variables						
Number of Clean vs. Contaminated water points (within 100 m)	Alt.	Null	Alt.	Null	Alt.	Null
Number of Clean vs. Contaminated water points (within 50 m)	Alt.	Null	Null	Null	Alt.	Null
Number of Clean vs. Contaminated water points (within 30 m)	Null	Null	Alt.	Null	Null	Null
5 or less pit latrines vs. 6 or more pit latrines (within 100 m)	Alt.	Null	Alt.	Null	Alt.	Null
Seasonal – transient variables						
Meters of water in clean vs. in contaminated boreholes	Alt.	Null	Alt.	Null	Null	Null
E. coli contamination within seasonal vs. no seasonal variation	Null	Null	Alt.	Null	Alt.	Null
E. coli contamination in likely to have been submerged vs. Not likely boreholes	Null	Null	Alt.	Null	Alt.	Null

pedestal (12%). These factors and sensitivity to maintenance point to weak infrastructure provision during siting, drilling and installation note completed to acceptable hydrogeological practice or national standard operating procedures.

A PCA bi-plot matrix re-casted to highlight covariance using fecal contamination as feature vector was additionally conducted (Fig. S21). The vectors with the smallest angles have variances that are highly correlated to each other, whilst a 90-degree angle between axes shows no correlation in terms of covariance. The bi-plot clearly show that preventative maintenance variation correlates strongly with *E. coli* contamination, but their scales rise in opposing directions; i.e. this suggests less preventative maintenance, the more *E. coli* contamination. Therefore, it can be suggested that the more preventative maintenance work completed to keep the water point clean and safe helps specifically to reduce *E. coli* contamination levels. Given there were some communities that refused post-flood interventions, it is important these findings are communicated in the future to the local communities through Community Based Management so they can make informed decisions around implementation of preventative maintenance and its positive impact on health and well-being. The co-variance with location of pit latrines within 100 m and soil erosion are not as closely correlated but do vary in the same direction suggesting there is some influence from these factors on *E. coli* contamination.

4. Discussion

4.1. Conceptual model

Despite physical assessment and sampling of nearly 300 boreholes and successful rehabilitation of over 200 found to have issues, helping over 180,000 people gain access to improved drinking water supplies, it was surprising to find increased *E. coli* in many borehole supplies one year after Idai. Contamination rebound at boreholes successfully treated reveals a systemic contamination problem from persistent sources, exacerbated by a pronounced wet season. Ubiquitous pit latrines are credible sources to account for observed hit-and-miss HPB supply contamination and are presented as such within our conceptual model of pit latrine contamination of HPB supplies by pathogens and its exacerbation by flood event or wet season conditions (Fig. 11). The model provides an integrated framework for problem consideration. Pathways split to surface runoff with overland flow of contamination and subsurface groundwater contaminant migration. The former is more probable during flood events where water carrying contaminants from flooded pit latrines, rivers and animal waste may reach and inundate borehole, especially those located in depression features as illustrated. Groundwater contamination pathways may arise from groundwater mounding from waste water inputs to latrines, recharge and soil interflows through latrine wastes or increased regional groundwater levels rising into the pit and leaching latrine waste directly or else leaching the contaminated ground already present beneath a latrine.

Pit latrines are ‘small footprint’, *c.* 1 m in diameter, sources dotted heterogeneously around water points. Whilst some spreading of contamination footprint may occur from water table mounding from wastewater inputs, low transverse horizontal, and even weaker vertical dispersion of groundwater plumes (Gelhar et al., 1992; Klenk and Grathwohl, 2002; Robertson et al., 1991; Rivett et al., 2001; Rivett and Allen-King, 2003) leads to an expectation of discrete ‘skinny’ plumes emanating from latrine sources. Attenuation, especially in finer grained deposits, of colloid-sized (~1 μm) bacteria particles due to both filtration and adsorption (Robertson, 2021) may cause *E. coli* plumes to be yet further restricted, migrating preferentially through the more permeable, high velocity sands and gravel pathways (Bales et al., 1995), or following the principal axis of connected fracturing in Basement rock. Although plumes near a direct groundwater path-line may be intercepted by borehole supplies, plumes could very easily migrate close to, but past boreholes unnoticed. This ‘hit-and-miss’ problem nature likely contributes to the spatially heterogeneous contamination of supplies found with contaminated and uncontaminated supplies in close proximity. The problem is compounded by the low abstraction volume of HPBs (5–10 m^3/d observed in Malawi (Rivett et al., 2018)) that may often cause relatively minor radial influence and limited potential for lateral plume capture or plume ‘pull back’ from sources down gradient (with possible exception of abstraction from less permeable units). The overall corollary is groundwater flow understanding is crucial to assessing latrine risks to supplies.

Borehole design, installation and water point management can all make or break pathways (Elisante and Muzuka, 2016). Poorly designed and sealed boreholes permit short circuiting of contaminated water and so-called well head contamination that could arise from a variety of sources – local user activity, visiting animals and sink collection point for runoff (Fig. 11). The very presence of elevated *E. coli* in HPBs, including rebound a few months after what appeared successful treatment, coupled with expected *E. coli* attenuation - die-off within timeframes much shorter than abstracted groundwater mean residence times of years to low decades (found by Banks et al. (2021) and likely applicable here), signify the contribution of well head contamination short-circuit pathways contaminating HPB supplies and, or fast natural (permeable gravel etc.) aquifer pathways acting or a combination of each.

A correctly installed and suitably located borehole may overcome most, if not all of the pit latrine and short circuiting contamination risks posed (compare the two example boreholes in Fig. 11). Significant risk may be mitigated by simply adopting good hydrogeological practice, generally not often followed in our experience. These include siting of boreholes away from houses, pit latrines, and other sources of contamination. Choosing locations supported by geological – geophysical investigation (Leborgne et al., 2021) and avoiding hollows or lower ground ensuring drainage is away in all directions with low borehole flood inundation and water spillage risk. Good practices to promote borehole sealing and avoid short-circuiting allowing protection of groundwater resource include: the use of a larger temporary casing in the upper 5 m to allow cement grouting of the main casing; drilling to sufficient depth (approaching 50–60 m for the Afridev hand-pump) to capture and slot-screen and clean gravel pack high quality groundwater aquifer units and avoid shallow vulnerable units; grouting of the annulus around the main borehole casing extending up to the larger temporary casing with cement grouting of the upper 5 m of main casing upon temporary casing removal and completion with a cement platform sealed headwork (Fig. 11).

Key questions are embodied by the conceptualization requiring concerted efforts of the research and practitioner WASH sector, including:

- Are significant borehole occurrences of *E. coli* driven by short-circuiting of surface water run-off and wellhead contamination entry into borehole, or is entry of contamination to HPBs primarily via groundwater pathways, or a combination of both?
- How significant are multiple, intense release pit latrine point sources of pathogens and associated discrete plumes versus other more diffuse sources such as agricultural livestock or manure application sources over a wider area with presumably more dilute inputs of pathogens and diffuse plumes?
- How important is short circuiting, poorly sealed borehole annulus entry of groundwater plumes into boreholes versus natural, deeper groundwater pathways into the well screen at depth?
- Are borehole depths and screens set deep enough? The study median depth borehole of 27 m with a typical 15 m well screen used in Malawi (Rivett et al., 2020) and study area water table depth of ca. 4 m below surface has only 8 m casing below the water table offering fair protection. However, the 10th percentile study borehole depths of just 14 m suggests a borehole subset at insufficient depths to be assured of protection from shallow groundwater plumes.
- Are the stand-off distances between pit latrines and HPBs (30 or 50 m in Malawi depending on guidance implemented (Back et al., 2018))

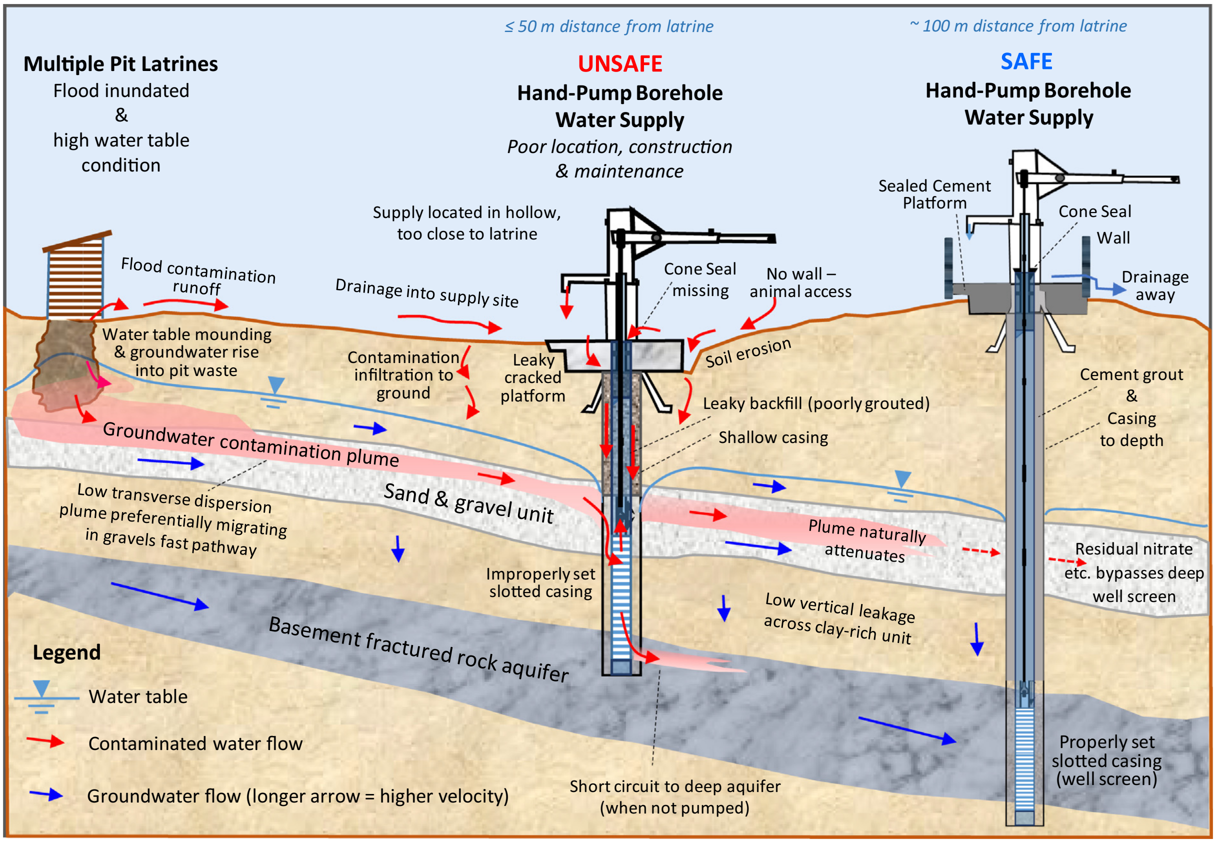


Fig. 11. Conceptual model showing processes controlling *E. coli* - pathogen contamination of hand-pump borehole supplies by pit latrines and increased risks posed by flood event - wet season conditions. An unsafe and safe supply are conceptualized.

sufficient to provide safeguard in higher velocity, permeable unit groundwater fast pathway settings (e.g. coarse sands – gravels, or well-connected fractured rock)? How common are these fast pathways and can they be identified and responded to in practice (through borehole siting and logging, geophysics, etc.)?

4.2. Policy recommendations

A range of policy recommendations arise from the study and our conceptualization that underpin attainment of improved human health protection in Malawi and elsewhere. These include:

- Increased routine (quarterly to semi-annual) *E. coli* (pathogen) monitoring of all community HPBs to better safeguard health of communities who typically use water untreated for drinking. This would overcome shortfalls in our study of having baseline data against which contamination risks following flooding events or pronounced wet seasons may be assessed. It would confirm if supplies are suffering from systemic contamination from persistent pathogen sources, or event driven, one-off exposures.
- Increased longitudinal confirmation monitoring of emergency flood relief borehole rehabilitation programs enabling later follow-up to establish rehabilitation treatment effectiveness and ensure sustainability of supplies and verification that contamination rebound does not later occur and go unnoticed.
- Within the above, increased monitoring of wet season contamination risks needs to be prioritized. Areas vulnerable to flooding, shallow water tables, or significantly changing water table elevations should be prioritized.
- Increased monitoring locations, measurement, and routine use of groundwater level data is required for temporal assessment of water table changes and spatial assessment of groundwater flow directions that underpin assessment and management of pit latrine (and other source) risks to water supply. Such datasets are not 'optional extras' to groundwater quality studies, but essential.
- Supporting the use of radial 'stand-off' distances separating pit latrines and water points to provide well head protection that is necessarily conservative (albeit recognizing the very poor international consensus on a safe distance (Back et al., 2018; Graham and Polizzotto, 2013)), priority assessment should nonetheless be given to existing or proposed latrine (or other) sources located up hydraulic gradient (often but not always land uphill – a possible proxy) that pose greatest risk, including sources beyond stand-off distances in high velocity systems (e.g. gravel or fractured units with high gradients in the foothills). Attention should be given to minimum vertical distance clearances of pit latrine bases above expected water table high elevations (presently not specified in Malawi guidelines) due to the attenuation potential of the unsaturated zone.
- Borehole installations, well head completions and maintenance regimes should be technically supervised (installation) or audited (borehole forensics) by professional hydrogeologists and validated as fit for purpose, employing measures that prevent short-circuiting of contaminated water into supply, e.g. casing and sealing off shallow units, raised and sealed borehole head-works.
- As found herein, recently recharged groundwater usually offers the best prospects of low TDS, good quality water supply, but is vulnerable to contamination. Land use development and management policy needs to safeguard this resource through increased use of groundwater vulnerability assessment, protection and monitoring programs that may underpin land use planning and decision making (including on deployment of pit latrine – sanitation services).

4.3. Research recommendations

Recommendations for research underpinning the assessment of public health risks posed by pit latrines to hand-pump supplies identified in this study and our review of the supporting literature include the following that are notably wide ranging and require concerted WASH sector effort:

- To undertake research level, highly instrumented field studies of pit latrine - groundwater plume generation in key hydrogeological settings to better understand plume transport, controls and help parameterize risk assessments elsewhere. Outputs should contribute to setting of stand-off distances and decisions on the use of basic pit latrines versus more advanced sanitation system designs.
- To undertake studies focused on the dynamics of pathogen releases from pit latrine sources, covering flood event and wet season conditions, and drier and more usual years.
- Increased validation that HPBs infrastructure itself is not contributing to short-circuiting of wellhead contaminated surface water and, or shallow groundwater entry into the well bore. The expectation is such problems should be easily remedied by the adoption and enforcement of standard practices (Banks et al., 2021). Recognizing though retrospective assessment of short circuiting problems arising from subsurface elements of the borehole installation works conducted years to decades previous is challenging and may require forensic downhole inspection approaches (Mannix et al., 2018; Kalin et al., 2019; MacAllister et al., 2020).
- Improved estimation of the capture zones of groundwater reaching low volume hand-pumped supplies in the typical range of hydrogeological settings (e.g. alluvial and basement rock aquifers) via modelling and field observational studies that examine and predict radial versus preferential up gradient draw of groundwater and contaminant to a water supply.
- Development of biogeochemical – isotopic etc. toolkit approaches that may be used to identify the provenance of *E. coli* and other pathogenic contamination observed in water supplies and correctly attribute contamination to sources responsible, pit latrines and others.
- Development of cost-effective, rapid and easy-to-use monitoring methods that allow more regular screening and testing of pathogens, including viruses, in community water supplies (Ward et al., 2020a,b).

5. Conclusions

To our knowledge this is the first longitudinal flood relief study to assess the impact of a major flood event, Cyclone Idai, on pathogenic contamination of community hand-pumped groundwater supplies. It establishes the microbiological safety of 279 community supplies over three phases, each phase comprising water-quality survey, rehabilitation and treatment verification monitoring. Phase 1 contamination three months after Idai was moderate, but likely underestimated with many un-sampled (due to non-functionality) boreholes later becoming contaminated (recognizing it is not possible to know if groundwater standing in these boreholes was contaminated or not in Phase 1). Increased Contamination in Phase 2, and even greater in Phase 3 a year after Idai with 40% of supplies registering *E. coli* contamination and 20% 'unsafe', is concerning and would have been missed by typical single-phase flood-relief projects. Contamination rebound at boreholes successfully treated months earlier signifies a systemic problem from persistent sources intensified by the pronounced wet season following Idai. Groundwater levels were likely a decade high around Phase 3 and hence soil-interflow and shallow groundwater leaching of pit latrine sources also at a maximum. Groundwater pathway contamination will exhibit a lagged arrival compared to run-off contributions and hence later phase contamination at boreholes may possibly include contamination initially released at the cyclone depending on the unknown persistency of *E. coli* or other pathogens under the field conditions. Problem persistency and extent in normal, or drier years is also unknown due to absence of routine monitoring to establish baselines; i.e. it is unclear if the health risk identified is a wet-year problem only.

Spatial analysis including flow-field delineation revealed 'hit-and-miss', heterogeneous contamination of safe and unsafe boreholes in proximity. Hydrogeological control was shown by increased contamination near flood-affected area and in more recent recharge groundwater otherwise of good quality and hence deserving of increased protection measures. Pit latrines are presented as credible sources, not proven in the scope of this research, within a conceptual model accounting for hit-and-miss borehole contamination. Pivotal to the model and critical to establish are groundwater level – semi-regional inter-granular and fracture flow direction, hand-pump limited plume draw, small yet ubiquitous footprints for latrine source - 'skinny' plumes, borehole short-circuiting and fast natural pathway influences. Statistical analysis of factors undertaken, although inconclusive, was variously indicative of damaged borehole civil works and increased pit-latrine numbers being influential. Mixed results are not inconsistent with the conceptual model, the recognition that enumeration of pit latrines posing risk needing to extend beyond simple radial metrics and individual borehole varying significance of other pathogen sources (agricultural, well-head activity) to be assessed alongside. Insights from our preliminary use of mapped pit latrine location data support the need for the gathering and use of such data in future work to accurately assess pit latrine influences (as endorsed by the recent work of Diaw et al., 2020).

Policies that drive increased monitoring of post-flood intervention effectiveness, routine monitoring of pathogens and appropriateness of borehole installation works are advocated to better protect human health. In the recognition that hand-pumped boreholes are deployed hand-in-hand with basic pit latrine sanitation in many WASH programs globally, concerted WASH sector investment in the range of research indicated is likewise warranted to inform emerging sanitation policy implementation and protection of water supply (AMCOW, 2021).

CRediT authorship contribution statement

Michael O. Rivett: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Laurent-Charles Tremblay-Levesque:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Ruth Carter:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Rudi C.H. Thetard:** Investigation, Resources, Writing – review & editing, Funding acquisition. **Morris Tengatenga:** Investigation, Writing – review & editing. **Ann Phoya:** Investigation, Writing – review & editing. **Emma Mbalame:** Writing – review & editing. **Edwin Mchilikizo:** Investigation, Writing – review & editing. **Steven Kumwenda:** Investigation, Writing – review & editing, Supervision, Project administration. **Prince Mleta:** Writing – review & editing. **Marc J. Addison:** Formal analysis, Writing – review & editing, Writing – review & editing, Visualization. **Robert M. Kalin:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150598.

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