Spatial model of groundwater contamination risks from pit-latrines under multiple sanitation scenarios in a low-income country

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Spatial model of groundwater contamination risks from pit-latrines under multiple sanitation scenarios in a low-income country

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Abstract

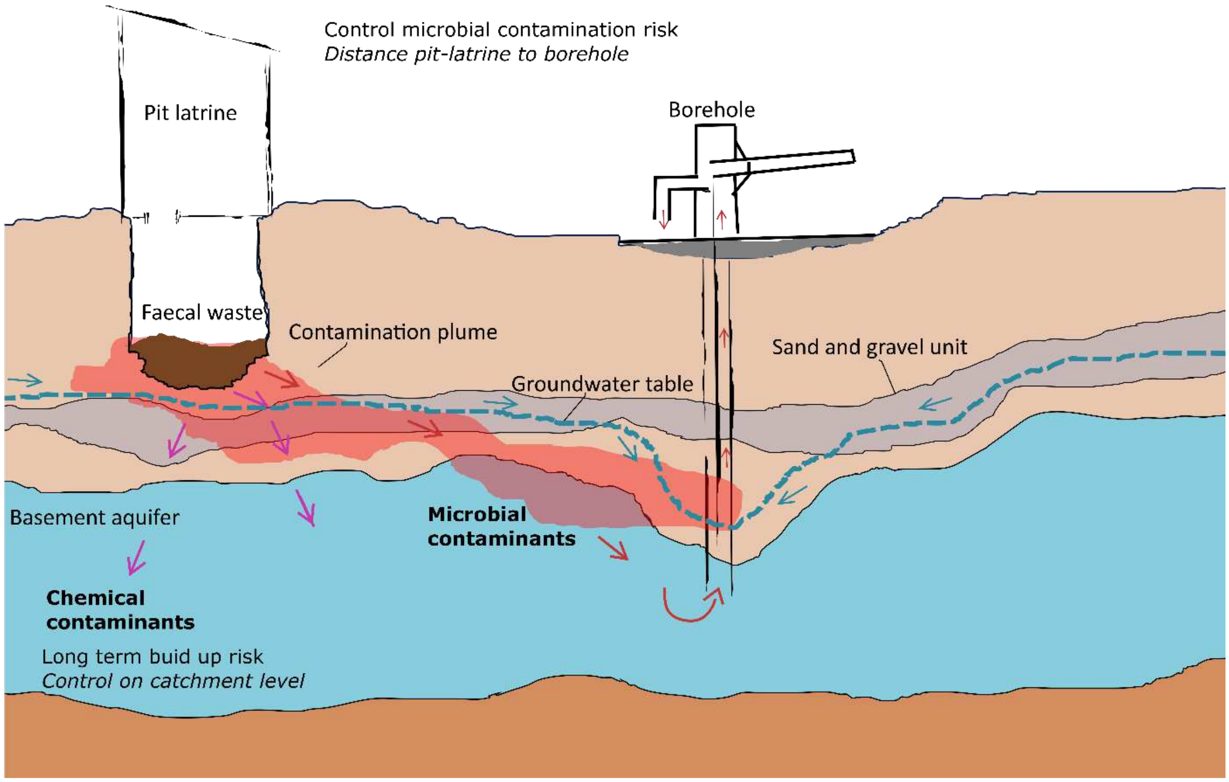
Pit-latrines are central to achieving UN Sustainable Development Goal 6 (SDG6) of ensuring "clean water and sanitation for all". Unless safely managed, pit-latrines result in groundwater contamination, which increases morbidity and mortality. Despite this, there have been no long-term spatial projections of future pit-latrine contamination risks. National survey data of over 100,000 water-points and 260,000 pit-latrines in Malawi was used to generate a novel, high-resolution model of pit-latrines from 2020-2070 under five population and three stakeholder informed sanitation policy scenarios.

The 'business as usual' model predicts a three-fold increase in the number of current water-points at risk of microbial pit-latrine contamination between 2020-2070, with a seven-fold increase in number at the highest risk of contamination. Current nitrogen loading into pit-latrines is comparable to national fertiliser application. The model predicts 8.2 mega-tonnes of faecal nitrogen will be disposed of into subsequently abandoned pit-latrines between 2020-2070. Guided intervention is necessary to prevent SDG6's push for sanitation undermining its goal of clean water.

Highlights

- Novel method to project groundwater contamination
- 5 population and 3 stakeholder informed sanitation policy scenarios for Malawi
- Business as usual model predicts a 3x increase in microbial borehole contamination
- Current nitrogen in pit-latrines comparable to national fertiliser in Malawi

Graphical abstract



Key Words

Groundwater, water quality, contamination, pit latrines, sustainable development

1 Introduction

The United Nations (UN) established the Sustainable Development Goal (SDG) 6 "clean water and sanitation for all" in 2015 (UN General Assembly, 2015). However, 3.5 billion people globally still lack safely managed sanitation (UNICEF & WHO, 2020). Improved sanitation is particularly important for reducing diarrhoeal disease, which causes 20% deaths of children under-five in Eastern and Southern Africa Amouzou et al., 2016 . Pit-latrines provide low-cost, basic excretion management (Graham & Polizzotto, 2013; Hinton et al., 2023; Nakagiri et al., 2016) and are used by over 1.8 billion people (Gwenzi et al., 2023). They are critical for reducing Open Defecation (OD)(Gwenzi et al., 2023; Hinton et al., 2023) , still practised by 419 million people globally (UNICEF & WHO, 2020). Pit-latrine usage is likely to increase as we near the 2030 deadline for the SDG6.2 goal of 'sanitation for all'. (Gwenzi et al., 2023).

Despite the importance of pit-latrines to meet SDG6.2, the associated pathogen and chemical groundwater contamination may undermine efforts to meet SDG6.1(UN Water, 2023) on clean drinking water (Bhallamudi et al., 2019; Diaw et al., 2020; Graham & Polizzotto, 2013; Gwenzi et al., 2023; Mkandawire, 2008; Pritchard et al., n.d.; Rivett et al., 2022). Increased pit-latrine usage and continual construction to replace filled pit-latrines will result in growing numbers of abandoned latrines, and pose significant environmental and public health concerns (Gwenzi et al., 2023; Hinton et al., 2023). Malawi has a particularly high risk of drinking water contamination from pit-latrines due to the large proportion (85%) of the population using groundwater for drinking co-located with pit-latrines for sanitation (90%)(Graham and Polizzotto, 2013; Hinton et al., 2023). Globally, only Burundi has a similarly large proportion of the population reliant on groundwater for drinking and pit-latrine sanitation (Graham and Polizzotto, 2013). It is estimated that 60.2% of Malawi's population have *E.coli* in their source drinking water (NSO, 2021) indicating faecal water contamination, and 64.6% of the population have no water treatment (WHO, 2019). Where water treatment is available, the most common method is bleach chlorination used by 25.2% of the population (WHO, 2019), which has low efficiency for pathogen removal and is generally not recommended by the WHO(Nielsen et al., 2022; WHO, 2019). The implications for unsafe drinking water on public health was underscored in Malawi's deadliest cholera outbreak which occurred in 2022-2023, and was partially attributed to high levels of drinking water contamination (Sokemawu Freeman et al., 2024) .The high burden of pit-latrine contamination of drinking water makes Malawi a pertinent case-study to model contamination risk.

To manage the risk of microbial groundwater contamination from pit latrines, water-points should not be in close proximity to pit-latrines (Diaw et al., 2020; Dzwairo et al.,2006; Graham and Polizzotto, 2013; Reed, 2014; Sclar et al., 2016; Tillett, 2013; Verheyen et al., 2009). But there are discrepancies between guidelines for pit-latrine distance from water-points, ranging from 10m to 75m (Water Aid, 2013; Banerjee, 2011.; Blantyre Water Board, 2005; Chidavaenzi et al., 2000; Franceys, 1992; Sphere Association, 2018; Reed, 2014). Controlling the distances between water-points and pit-latrines provides an approximation of risk-management for water-point microbial contamination.

Nitrogen (as NO_3, NO_2 and NH_4) is also a contaminant of concern in groundwater (Ahmed et al., 2001.; Diaw et al., 2020; Puckett et al., 2011; Rahman et al., 2021). Nitrate can arise in groundwater from the oxidation of ammonia, a principal component of human excreta. High nitrate in water is an environmental and public health hazard(Ahmed et al., 2001; Puckett et al., 2011; Rahman et al., 2021), with nitrite being linked to methemoglobinemia in infants and stomach cancer in adults(Rahman et al., n.d.). Nitrate is relatively stable in aerobic conditions, presenting a risk of large distance transportation and long-term build-up of nitrate contaminants (Canter, 1996). Prevention of nitrate in groundwater is consequently critical to maintain water quality, even when sources of contamination are removed(Ahmed et al., 2001.; Rahman et al., 2021). Sources of nitrate contamination, such as pit latrines, pose a long-term risk to groundwater quality (Ahmed et al., 2001; Gwenzi et al., 2023; Puckett et al., 2011), and high nitrate concentrations in groundwater have been recorded in some regions of Malawi (Mapoma et al., 2016; Missi and Atekwana, 2020; Pritchard et al., 2007, 2008). To manage nitrate contamination of groundwater from pit-latrines, nitrogen from human faeces must be prevented from entering groundwater, either by pit latrine emptying or creating physical barriers (lining) to the leaching of nitrogen(Ahmed et al., 2001). Management of risk requires monitoring of population density, type, and numbers of sanitation systems (Martínez-Santos et al., 2017; Ahmed et al., 2001; Diaw et al., 2020; Ndoziya et al., 2019.; Wright et al., 2013). Due to the potential long-distance transport of nitrates, contamination must be considered over larger scales, e.g., at catchment level (Canter, 1996).

Using high resolution population projections, we created a model of pit-latrine usage to predict groundwater contamination risk to 2070. The 5 Shared Socio-Economic Pathways (SSPs)(Riahi et al., 2017.) provided population growth predictions, accounting for demographics including age, sex, and education(KC and Lutz, n.d.). Combining SSP population projections with spatial population distribution models allowed spatially explicit population forecasts for various socioeconomic projections. Boke-Olen et al. (2017)(Boke-Olén et al., 2017.) combined SSP population projections with spatial distribution models to allow spatially explicit population forecasts for various socio-economic projections. They applied this model at a 30 arc-second resolution (approximately 1km at the equator) for an African population projection from 2000-2100. However, their results were not deemed to be at a sufficiently high resolution for analysis of the risks from pit-latrine usage as the previously discussed pit-latrine proximity is considered within 10-100m range. We apply a similar modelling approach at a greater 3 arc-second second resolution (approximately 100m at the equator)(Linard et al., 2012; Stevens et al., 2014; Worldpop, 2023) to produce higher-resolution and country-specific spatial population projections. We coupled the higher resolution population projections for Malawi with national survey data of over 100,000 water-points and 260,000 pit-latrines, to model pit-latrine use from 2020-2070, focusing on risks to groundwater in 2030 (end of the SDGs) (UN General Assembly, 2015.) and 2070 (end of Malawi's development plan 2063)(NPC, 2021).

We applied spatial variation in pit-latrine usage across administrative districts alongside estimates of the number of users sharing pit-latrines to predict pit-latrine users and density at 3 arc-second resolution (approximately 90m for Malawi). Together with policy makers, we co-developed 3 sanitation development scenarios with varying pit-latrine adoption (continued usage, increasing usage, and decreasing usage). Combining pit-latrine projections with contamination risk and faecal waste composition estimates from literature, enabled a novel time-series estimation of the risk for groundwater contamination. We present here the results for 'a business as usual' scenario of population demographics and pit-latrine adoption. Further scenarios are provided in the Supplementary materials.

This research presents a novel method for national identification and future prediction of vulnerable water-points at <100m resolution, enabling risk-basement investment of sanitation and water infrastructure. Though the case study is Malawi, the model can be applied to other countries and regions at similar risk of drinking water contamination. Model output will enable the Ministry of Water and Sanitation in Malawi to enact policy / management decisions for areas at the greatest risk of groundwater contamination from pit-latrines.

2 Methods

2.1 Study location

Malawi is a country in south-eastern Africa, Figure 1. Its population of over 20 million is mostly (84%) rural (NSO, 2021) . It is undergoing rapid demographic change with annual population growth of 2.6% (World Bank, 2023a) and urbanisation resulting in an expected 60% of the population classed as urban by 2060 (Commission and Malawi, n.d.). Malawi is one of the poorest countries in the world with a largely agro-based economy (employing over 80% of the population), making Malawi's economy particularly vulnerable to climatic shocks (World Bank, n.d.). Tropical cyclones and droughts have become more severe and frequent, causing substantial loss of life, economic impact, and environmental damage including to groundwater supplies (Rivett et al., 2022).

Groundwater provides the main source of drinking water for 85% of Malawi's population (Graham and Polizzotto, 2013), mainly accessed from boreholes/tube(NSO, 2021). Currently only 4.9% meet the requirement of SDG6.1.1, 'having improved drinking water source located on premises, free of E. coli and available when needed' (NSO, 2021; UN Water, 2023). Over 90% of the population use pit-latrines as their primary source of sanitation (Hinton et al., 2023; NSO, 2019; NSO, 2021; NSO & ICF, 2017).

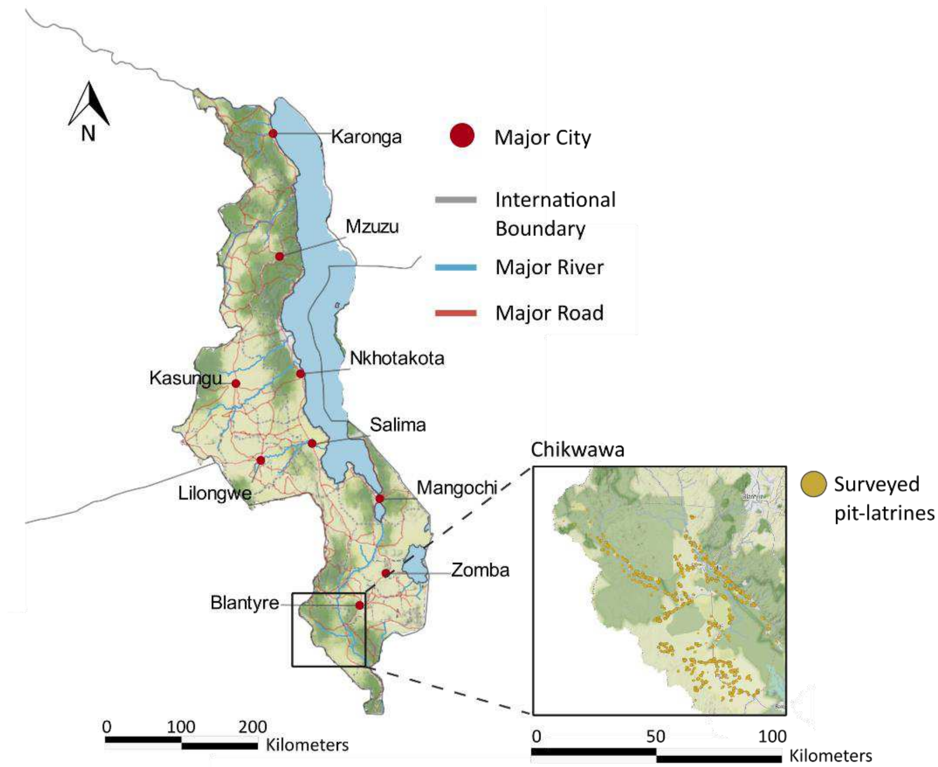


Figure 1: Map of case-study area (Malawi) showing major cities, rivers, and roads. The region of Chikwawa, where sanitation infrastructure is most comprehensively mapped, is highlighted with the locations of surveyed pit-latrines from the CJFWFP sanitation survey. Image made with QGIS using Stamen Terrain background.

2.2 Spatially explicit population estimation

Using a similar methodology to that outlined in Boke-Olen et al. (2017) and summarised in Figure 2, we generated a high resolution 3 arc-second resolution (approx. 90m in Malawi) spatially explicit gridded population projection from 2000 to 2070. The WorldPop 2000 unconstrained, 100m resolution population count for Malawi provided the initial spatial population distribution for the year 2000 at 3 arc-second resolution(Linard et al., 2012; Stevens et al., 2015; WorldPop., 2023). Locations of major roads in Malawi were accessed from the open-source Malawi Spatial Data Platform (MASDAP)(NSDC, 2023). Raster files of the distance to population centres and distance to roads in Malawi was calculated using the COGravity and distance functions respectively under the SDMTools packages(SDMTools, 2023) in R(R Core Team, 2023.). A unique spatial population grid was generated by combining the spatial population distribution, distance to roads, and the distance to population centres raster files, providing a population distribution weighted towards areas surrounding roads and population centres. The modified spatial population distribution was assigned into urban and rural areas based on the fraction of the cell classed as urban in 0.25-degree cells (approximately 39 km in Malawi) from Hurtt et al. (2011), Figure 2. Hurtt et al. (2011) provided urban fractions based on both socioeconomic and emissions scenarios. We assumed all scenarios follow a medium stabilisation emissions scenario, Representative Concentration Pathway (RCP) 6.0 (Fujino et al., 2006; Hijioka et al., 2008). In areas with a small proportion of cells classed as urban, there is a potential overconcentration of the population into urban cells. The urban population was distributed over a greater area by dividing the urban fraction outlined in Hurtt et al. (2011) by an 'Urban Fraction Smoothing Factor' (UFSF), ranging from 0-1.

Multiple socioeconomic scenarios of population growth and urbanisation were considered using the 5 shared socioeconomic pathway (SSP) scenarios that project population and urbanisation levels under hypothetical socioeconomic scenarios (Riahi et al., 2017). The SSP pathways were chosen due to their well-established scenario building and diverse representation of both population and economic change, representing not only population growth but also urbanisation. SSP1 and SSP5 are low population growth scenarios with high urbanisation. SSP3 and SSP4 are high population growth scenarios with low and high urbanisation respectively, and SSP2 represents a 'middle of the road' scenario with moderate population growth and urbanisation (Riahi et al., 2017).

The projected urban/rural population for a given SSP scenario was distributed between respective urban and rural cells based on weighted population value of the cells. This was repeated iteratively for subsequent years to produce population projections. The approach is summarised in Figure 2.

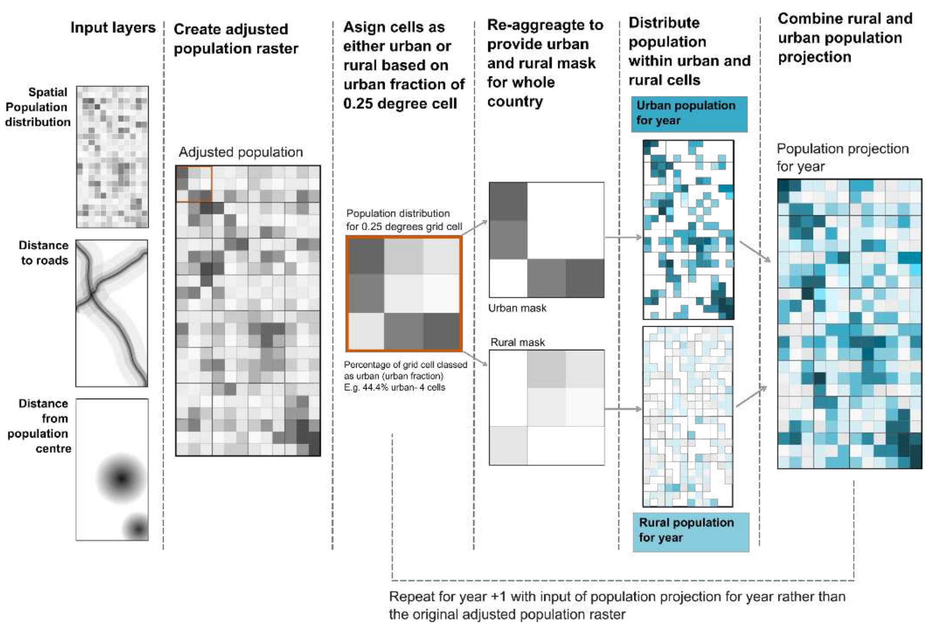


Figure 2: Diagrammatic overview of population projection methods. Methodology for population projections based on Boke-Olen et al., (2017). Input layers are the initial 100m Worldpop spatial population distribution for the year 2000(Linard et al., 2012; WorldPop., 2023) alongside raster files of the distance to roads and distance to population centres generated using the R SDMTools package(R Core Team, 2023; SDMTools, 2023). These are combined to create a weighted population raster for the year 2000. The weighted population raster is used to produce urban and rural masks into which the urban and rural population is distributed based on the adjusted Hurtt et al., (2011) urban fraction. The process is repeated iteratively with the previous year spatial population distribution used as input rather than the adjusted, weighted population raster.

2.3 Validation of population estimates

To validate our population estimates, the projected population distribution for the year 2020 (20 years of modelled distribution) was compared to the WorldPop 2020 population distribution for 3 arc-second and 30 arc-second resolution(Linard et al., 2012.; WorldPop, 2023). The results of different Urban Fraction Smoothing Factors (UFSF) were compared to WorldPop 2020 spatial population distributions at 100m and 1km resolution. UN-adjusted and non-adjusted were used as reference population distributions (Linard et al., 2012; WorldPop, 2023). Results are summarised in Supplementary materials Table 1 and 2. The Root Mean Squared Error (RMSE)(Chen et al., 2020; Yin et al., 2021) of the difference between the projected population raster and reference population raster was calculated using equation (1).

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(P_n - R_n)^2} \quad (1)$$

Where N is the number of cells within the raster file, n is the given cell investigated, P is the projected raster and R is the reference raster.

As the RMSE value can be strongly influenced by individual outliers (Yin et al., 2021.), we calculated the percentage of cells in which the projected population differed from the reference WorldPop raster (Linard et al., 2012.; WorldPop, 2023.) by more than 1, 10 or 100 people for 3 and 30 arc-second resolutions. For comparison, the RMSE value for Boke-Olen et al., (2017)(year 2020, scenario SSP2 RCP6) 30-arc second resolution was compared to WorldPop 2020 (UN-adjusted 1km resolution) population(Linard et al., 2012; WorldPop, 2023).

To compare available gridded population databases for Malawi, the total population count for 2020 was calculated for WorldPop datasets (UN-adjusted and non-adjusted and at 100m and 1km resolution)(Linard et al., 2012; WorldPop, 2023), Landscan(ORNL, 2023), Boke-Olen et al., (2017) projected populations (SSP2 RCP6)(Boke-Olén et al., 2017), and the model presented here. The percentage error from the World Bank Malawi 2020 population estimation was calculated (World Bank, 2023b).

2.4 Sanitation policy scenarios

The rural and urban population distributions were divided into administrative districts, boundaries available from MASDAP(NSDC, 2023). The Demographic Health Survey (DHS) 2015-2016 data was used to indicate the level of pit-latrine adoption for rural and urban populations each in district (NSO & ICF, 2017). The DHS 2015-2016 being the most recent survey providing a breakdown of the sanitation facility usage in urban and rural contexts, alongside district level data of 'improved' and 'unimproved' sanitation access (NSO & ICF, 2017). For each district, the ratio of improved/ unimproved sanitation use, for both urban and rural contexts, was used to scale the national percentage of the population utilising each type of sanitary facility. The percentage of the population in each district (rural and urban) using pit-latrines was multiplied by the spatial population distribution to estimate the distribution of pit-latrine users, see Figure 3.

Three stakeholder informed sanitation policy scenarios were proposed to account for high uncertainty in future sanitation infrastructure development. Scenario A assumed that from 2020-2070, the percentage of the population using pit-latrines remains the same as in 2015 using the pit-latrine usage data from the DHS 2015-16 survey (NSO & ICF, 2017). This is most similar to the current status of sanitation and is consistent with the Government of Malawi's current sanitation development plans in which there are no plans to deviate from pit-latrines as the main sanitation provision (NPC, 2021).

Scenario B assumed that the percentage of the urban and rural population using pit-latrines follows a linear model from the 2015-16 district pit-latrine usage (NSO & ICF, 2017.) to a 2070 forecast. The 2070 forecast was estimated by modelling the percentage of the population that will be using flush toilets (to septic tanks or sewerage systems) in 2070, applying a simple linear regression model using the lm() function in the Stats package in R(R Core Team, 2023.) and assuming the remaining population will be using pit-latrines. The model assumed that Malawi would achieve its target of ending OD, largely through pit-latrine promotion. This model is consistent with modelled projections of increasing the rate of pit-latrine to enable Malawi to end OD by 2070 (Hinton et al., 2023). Whilst each district has a different pattern of change in the number of pit-latrine users, this scenario had a national increase in pit-latrine use.

Scenario C assumed an increase in the provision of flush toilets to septic tanks and sewers from 2015 to 2070, modelled on the change in the percentage of the population using flush toilets observed in Botswana from 2001 to 2011(Statistics Botswana, 2015; Statistics Office, 2005). Botswana was chosen as a case-study of another Southern African Development Community (SADC) member state that achieved an ambitious shift from pit latrine promotion-focused sanitation to central provision of piped sewerage systems, following the declaration of the International Drinking Water and Sanitation Decade from 1981 (Bolaane and Ikgopoleng, 2011). Botswana's sanitation transition is considered an ambitious but achievable sanitation policy, providing a realistic scenario of a deliberate shift away from pit-latrine dependency. From 1981 to 2011, the percentage of Botswanan population using their own flush toilet increased from 8.6% to 25.2% (Statistics Botswana, 2015; Statistics Office, 2005). The linear trend of flush latrine adoption in Botswana was applied to the Malawi case study by adjusting the intercepts to the percentage of flush latrine usage in Malawi according to the DHS 2015-16 survey (NSO & ICF, 2017) for rural and urban contexts. The remaining population in 2070 was assumed to use pit-latrines. The model assumes an overall reduction in the percentage of the population using pit-latrines through promotion of flush toilets. The model assumes Malawi ends OD by 2070.

For Scenarios B and C, annual estimates of pit-latrine use are made for each district from a linear model (lm() function, R Stats package (R Core Team, 2023.)) of the district pit-latrine in 2015/16 levels (NSO & ICF, 2017) to 2070 projections. Scenarios B and C are summarised in Supplementary materials Figure 2.

2.5 Cumulative faecal loading

Spatial estimates of pit-latrine users for different years, SSP and sanitation policy scenarios were calculated as the product of the spatially explicit population and pit-latrine usage estimations. To evaluate spatial differences in latrine user density, the estimated number of latrine users was subdivided into river sub catchments, water resource units (WRUs) (Kalin et al., 2022). Nitrate contamination is considered on a catchment scale to account for long-distance nitrate transportation which is common in groundwater (Canter, 2019).

The quantity of excreta loaded into each WRU was calculated to identify WRUs at risk of groundwater contamination, with a focus on nitrogenous contamination. To calculate the volume of faecal waste the number of latrine users was multiplied by the estimated volume of faecal matter per capita per year using literature estimates. The cumulative loading of faecal waste was calculated by summing the volume of excreta per year produced by users from 2020 to 2070 for each WRU. Ranges in excreta volume and composition were used to account for uncertainty. For the volume of excreta produced, an average volume of extra per individual was used as 270 L/year, based on an extensive study of pit-latrine loading in Kampala, Uganda (Strande et al., 2018). To calculate the range of annual excreta values an upper estimate of 1000L per capita and a lower estimate of 100L per capita were applied (Strande et al., 2014, 2018, UNEP, 2023).

The number of latrine users was also multiplied by the estimated chemical composition of faecal waste to calculate the total volume of chemicals in the waste. The average, upper, and lower estimates of the chemical composition of faecal waste per capita per day were taken from literature (Strauss et al., 2003; Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000; Hansen and Tjell, 1979; Schouw et al., 2002; West et al., 2009). An average estimate of 12.5g/ppd Nitrogen content was taken from estimates used in compositing and EcoSan toilet designs (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000.). The upper estimate of 19g N/ppd was taken based on a study of adult excreta in Denmark, averaged 16g/ppd (range 12-19g)(Hansen and Tjell, 1979). The lower estimate of 7.6g/ ppd was taken based on a study of adults and children in Thailand, averaged 7.75g/ppd (range 7.6-7.9g)(Schouw et al., 2002). The average phosphorus content of waste was taken as 2g/ppd (Strauss et al., 2003). A lower estimate of 1.5g/ppd was taken from latrine design literature (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000)). An upper estimate of 3.7g/ppd was based on adult excreta in Denmark (range 1.8g-3.7g)(Hansen and Tjell, 1979). For potassium, an average estimate of 3g/ppd was applied (Strauss et al., 2003). A lower estimate of 1.8g/ppd was taken from a study of adult and child excreta, Thailand (range 1.8-2.7g)(Schouw et al., 2002). An upper estimate of 3.5g/ppd was taken (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000.). For carbon content, an average carbon estimate was taken as 17.9g/ppd in human excreta (West et al., 2009). A lower estimate of 14g was applied based a study of adult and child excreta in Thailand (range 14-26g)(Schouw et al., 2002). An upper estimate of 30g/ppd was from literature on latrine design and compositing (Strauss et al., 2003; Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000). The cumulative faecal load was divided by the area of the WRU to estimate the spatial density of faecal waste loading, Figure 3.

2.6 Latrine density

An extensive survey of pit-latrines, waste sites and water points in Malawi was conducted by the Government of Malawi through the Climate Justice Fund Water Futures Programme (CJFWFP) from 2012 to 2020, using semi-structured interviews of stakeholders at each facility. Trained staff delivered interviews in both Chichewa and English and provided the location of each site with a photograph of the facility. Responses were hosted on the data-platform mWater (mWater, 2023). Quality control was provided by the University of Strathclyde and all data collected was in line with the Government of Malawi ethics and was agreed with each participant . Data cleaning involved the removal of incomplete and duplicate responses resulting in 264,514 points for analysis.

The most comprehensively mapped district of Malawi was Chikwawa (Figure 1), with most surveys conducted in 2017. Case studies from the district of Chikwawa were used to approximate population per pit-latrine. The district of Chikwawa was divided into rural and urban based on the 2017 population; 3 urban and 3 rural regions were selected and the number of surveyed pit-latrines within case-study area was summed. The number of pit-latrines was divided by the estimated population using pit-latrines for each area calculated from the WorldPop 100m population estimate for the year 2017 (Linard et al., 2012; WorldPop, 2023). The urban and rural case studies were averaged to estimate the number of latrine users per latrine in urban and rural contexts. To estimate the number of pit-latrines, the number of pit-latrine users was divided by the number of users per pit-latrine for urban and rural cases.

To identify water-point contamination risk from pit-latrines, cells were classified according to the number of pit-latrines in each 3 arc-second grid. The equivalent distance a pit-latrine would be from a water-point in a 3 arc-second cell for given latrine density was estimated to provide estimate the associated risk. The number of latrines likely to be within a given radius of a waterpoint was estimated from the density of latrines using equation (2):

$$N \leq \frac{log(0.05)}{log(1-(\frac{\pi r^2}{l^2}))} \qquad (2)$$

Where N is the number of pit-latrines within a grid cell of length, l, necessary to have a 95% probability that at least one latrine will be within a radius r of a centrally located water-point.

Estimating the radius from a central water-point enabled comparison of latrine density estimates to the wider body of literature relating the water-point contamination risk to the distance to a pit-latrine(Water Aid, 2013.; Banerjee, 2011.; Blantyre Water Board, 2005.; Chidavaenzi et al., 2000.; Dzwairo et al., 2006.; Franceys, 1992; Graham and Polizzotto, 2013; Sphere Association, 2018.; Reed, 2014; Sclar et al., 2016.; Tillett, 2013; Verheyen et al., 2009.).

The CJFWFP water-point survey geolocated 126,994 improved and unimproved water points across Malawi, enabling identification of water-points at high risk of contamination (Kalin et al., 2019). 'Vulnerable water-points' were defined as boreholes, tube-wells or dug wells (both protected and unprotected) that were functional and in-use (but not primarily for agricultural, or livestock). Point locations of vulnerable water-points were aggregated into pixels, at 3 arc-second resolution, to generate a binary raster of vulnerable water-point presence/absence. Latrine density was considered in cells containing a 'vulnerable' water-point. Cells containing a vulnerable water-point in which the density of latrines exceeded a threshold density were identified, Figure 3.

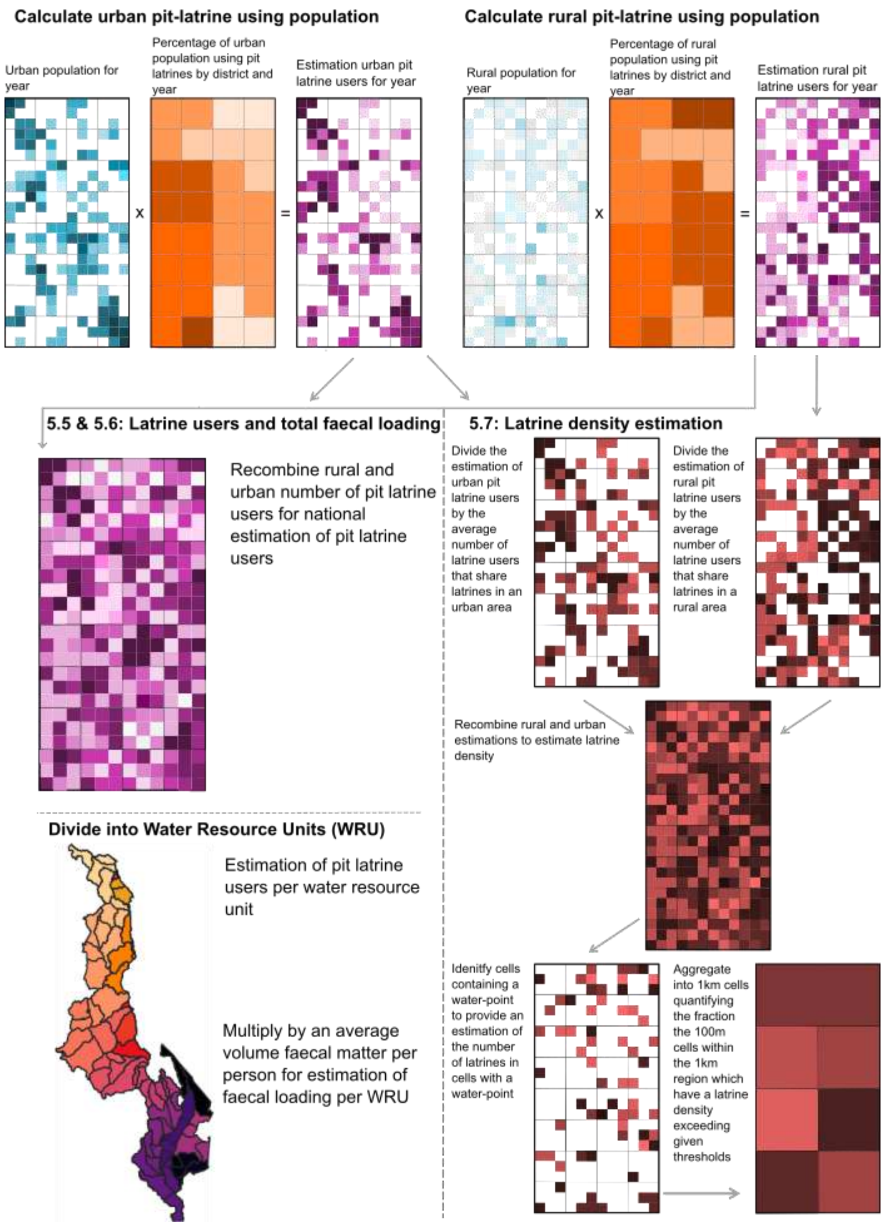


Figure 3: Diagrammatic overview of methods used in estimation of pit-latrine users and density. Blue grid cells represent population density, orange represents the percentage of people in a given district that use pit-latrines, purple grid cells represent latrine users and red cells represent latrine density. Darker colours relate to higher densities of population, latrine users and pit-latrines.

To account for spatial variation and uncertainty in population distribution and the locations of sanitation and water facilities, 3 arc-second grids were aggregated. The percentage of 3 arc-second cells within a 30 arc-second grid containing a vulnerable water-point with latrine densities exceeding the latrine thresholds was summarised under multiple scenarios.

CJFWFP water-point data (Kalin et al., 2019) identified whether water-points were within 100m of a latrine (Government of Malawi recommended spacing (Blantyre Water Board, 2005)), and was used for model validation. The percentage of vulnerable water-points within 100m of a latrine was calculated. Equation (3) enabled comparison of the percentage of cases in which a water-point was within 100m of a latrine with the percentage of cases in which a water-point was found within the same 3 arc-second grid cell as a latrine:

$$P_g = \frac{P_r l^2}{\pi r^2} \qquad (3)$$

Where P_g is the percentage of water-points with a pit-latrine within the same grid cell of length l, and P_r is the percentage of water-points with a pit-latrine within a radius, r (here, r=100 m). This assumes an even distribution of latrines within the cell and a centrally located water-point.

Further verification was achieved through visual inspection comparing the locations of pit-latrines from the CJFWFP sanitation survey to the modelled predicted latrine density for 2020, an example is shown in Supplementary materials Figure 5.

3 Results

3.1 Latrine density

A dataset of 126,994 water-points, surveyed from 2012-2020 by the Government of Malawi Ministry of Water and Sanitation staff under the Climate Justice Fund Water Futures Programme (CJFWFP)(Kalin et al., 2019), identified 49,000 'vulnerable water-points' (functional and in-use boreholes, tube-wells, or dug wells not used primarily for livestock or agriculture). Boreholes or tube wells were the most common vulnerable water-points (41,000), followed by protected dug wells (7,700) and unprotected dug wells (310). Of the vulnerable water-points, 23,100 reported a pit-latrine within 100m (58.6% of the 39,500 water-points for which a response was listed). This is equivalent to 15.1% of vulnerable water-points having a pit-latrine within the same 3 arc-second grid cell, calculated from equation (3).

The associated risk to water-points of given pit-latrine densities, calculated using equation (2), is summarised in Table 1. The number of cells surpassing thresholds of pit-latrine density is shown in Figure 4 with data summarised in Supplementary materials Tables 4 and 5. We estimate that in 2020, 11.5% of vulnerable water-points had at least one pit-latrine within the same 3 arc-second grid cell. This increases to 18.0% by 2030 and 33.6% by 2070.

Figure 5 shows a spatial representation of at-risk cells. Areas at highest risk of faecal water contamination are concentrated generally around urban centres. There is an increase in both the number of water-points at risk of faecal water contamination and the severity of risk to water-points. There is a 720% increase in the number of vulnerable current water-points within a 3-arc second cell containing 30 or more pit-latrines from 2020-2070.

Number of pit-latrines in 3 arc-second grid cell	Equivalent latrine radius estimate (>95% Confidence)	Risk level	Guideline exceeded
1 latrine	At least 1 latrine within 50m	Low risk	WaterAid **50m** distance(Aid, n.d.)
3 latrines	At least 1 latrine within 40m	Low- moderate risk	WEDC Loughborough University **40m** distance(Reed; Bob, 2014)
10 latrines	At least 1 latrine within 26m	Moderate risk	Sphere Project **30m** distance(Project, n.d.)
30 latrines	At least 1 latrine within 16m	Moderate-high risk	Chidavaenzi et al., (2000)(Chidavaenzi et al., n.d.)
50 latrines	At least 1 latrine within 12m	High risk	WHO **15m** distance(Franceys, 1992)
100 latrines	At least 1 latrine within 9m	Very high risk	Banerjee (2011) **10m** distance(Banerjee, n.d.)

Table 1: Conceptualised water-point contamination risk at given pit-latrine densities. Density of pit-latrines within a 3 arc-second grid cells (ca 90m in Malawi) and associated estimated distance of pit-latrines to a centrally located water-points, calculated by equation (2). The associated risk of a pit-latrine being located at the given proximity to the water-point is conceptualised.

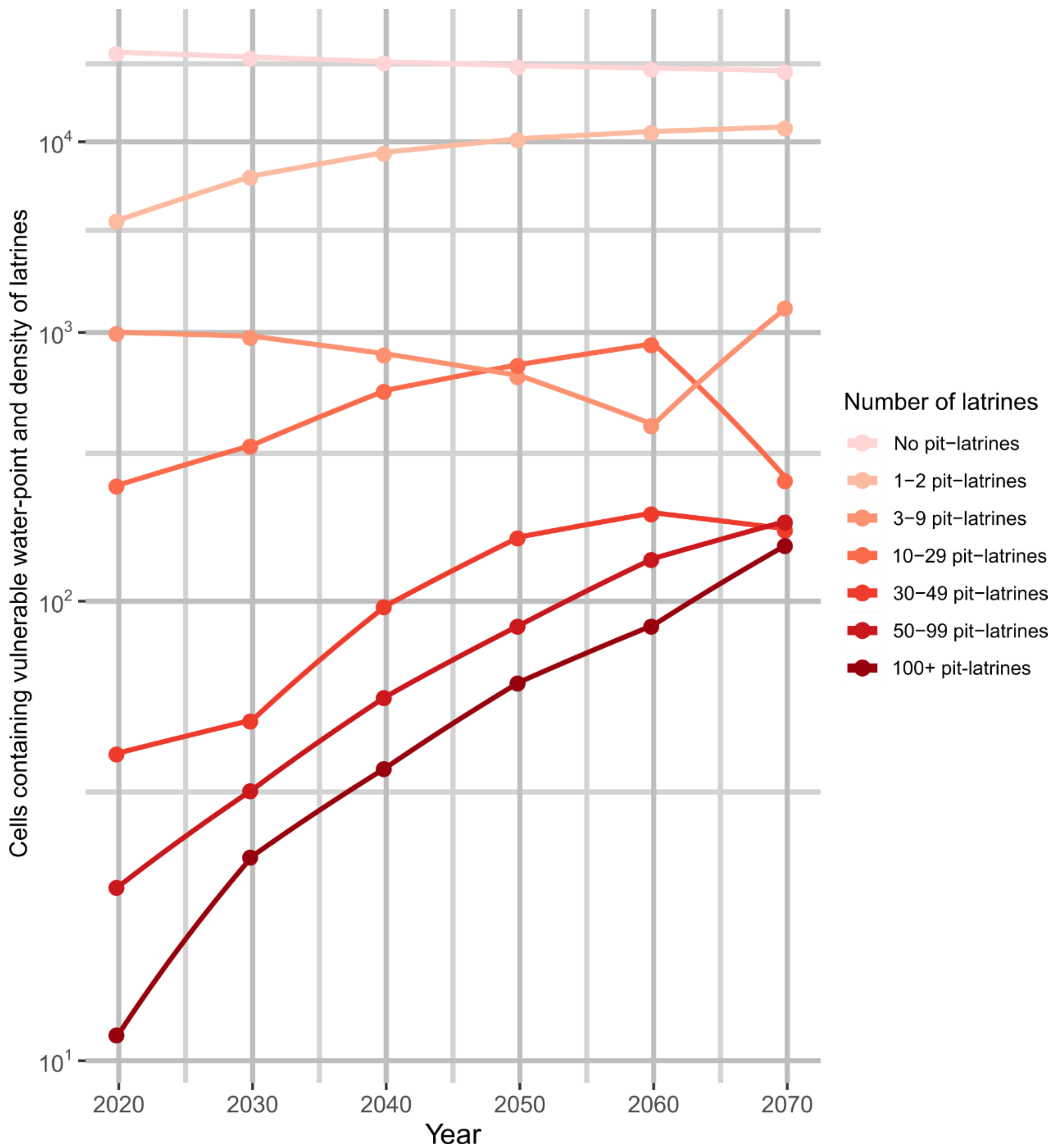


Figure 4: Change in number of vulnerable water-points at risk of contamination from 2020-2070. Number of 3 arc- second grid cells containing a vulnerable water-point and given densities of pit-latrines between 2020 and 2070 under SSP scenario 2, sanitation policy scenario A.

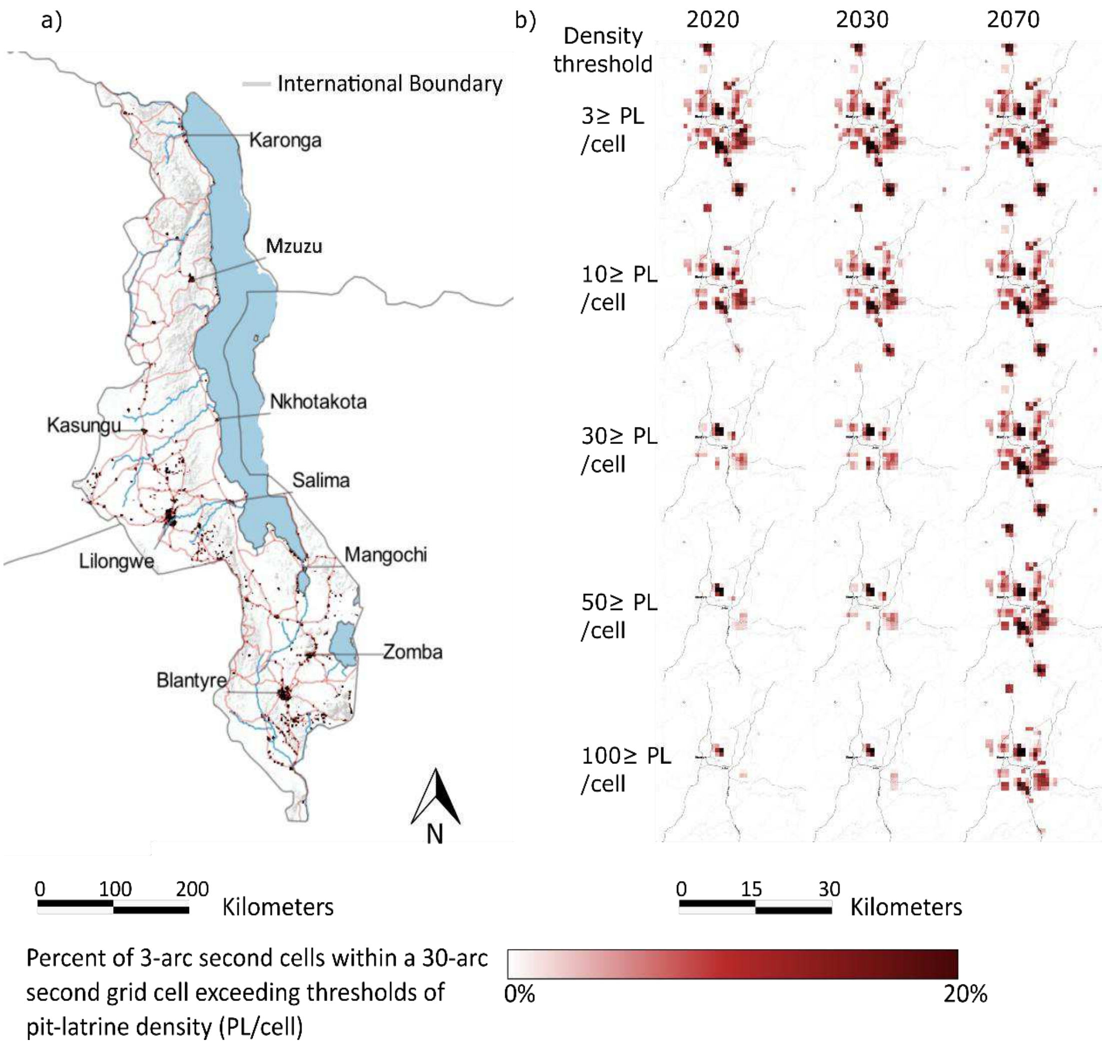


Figure 5: Spatial distribution of areas at greatest risk of faecal water contamination.

a) The fraction of 3 arc-second grid cells (approximately 90m) within 30 arc-second grid cells (approximately 9km) containing a vulnerable water-point and 3 or more predicted pit-latrines for the year 2070 under SSP2, sanitation policy scenario A. Darker cells indicate a higher fraction of cells within 30 arc-second grid cells containing both a vulnerable water-point and 3 or more pit-latrines. Image made with QGIS using Esri Terrain background.

b) Proportion of 3 arc-second grid cells within 30 arc-second grid cells containing vulnerable waterpoints and pit-latrine densities over given thresholds in Blantyre City Malawi for the years 2020, 2030, and 2070 under SSP2 scenario A. Image made with QGIS using Stamen Toner Light background.

3.2 Cumulative faecal loading

The cumulative national loading of faecal sludge components is summarised in Table 2. Upper and lower estimates are given based on upper and lower estimates of faecal loading and faecal waste composition. Under business-as-usual projections, 8.2 mega-tonnes of nitrogen in faecal waste will be loaded into pit-latrines from 2020-2070 in Malawi. Current annual volumes of nitrogen loading are comparable to the nitrogen in current national fertiliser application(Ritchie, 2020). Figure 6 shows the cumulative quantity of faecal sludge, per sub-catchment Water Resource Unit (WRU) from 2020-2070. Comparison of the faecal loading for WRUs by 2070 under the 5 SSP and 3 sanitation policy scenarios are summarised in Supplementary materials Figure 4.

	2020-2030	2020-2040	2020-2050	2060	2070
Cumulative volume faecal loading / giga-litres	51 (19-190)	130 (48-480)	230 (85-850)	340 (130-1300)	480 (180-1800)
Cumulative mass of Nitrogen / mega-tonnes	0.87 (0.53-1.3)	2.2 (1.3-3.3)	3.8 (2.3-5.8)	5.7 (3.5-8.7)	8.2 (5.0-12)
Cumulative mass of Phosphorous / mega-tonnes	0.13 (0.10-0.25)	0.44 (0.33-0.81)	0.73 (0.55-1.4)	1.0 (0.77-1.9)	1.3 (1.0-2.5)
Cumulative mass of Potassium / mega-tonnes	0.21 (0.12-0.24)	0.53 (0.32 -0.62)	0.94 (0.6-1.1)	1.37 (0.82-1.6)	2.0 (1.8-2.3)
Cumulative mass of Organic Carbon / mega-tonnes	1.3 (0.98-2.1)	3.2 (2.5-5.3)	5.5 (4.3-9.2)	8.4 (6.5-14)	12 (9.3-20)

Table 2: Cumulative faecal waste across Malawi (giga-litres) and constituent chemicals (mega-tonnes). Loading from 2020 to 2070 under SSP scenario 2, sanitation policy scenario A (no change). Cumulative quantity of faecal waste is estimated from projected number of pit-latrine users and estimates of faecal make up[58–60].

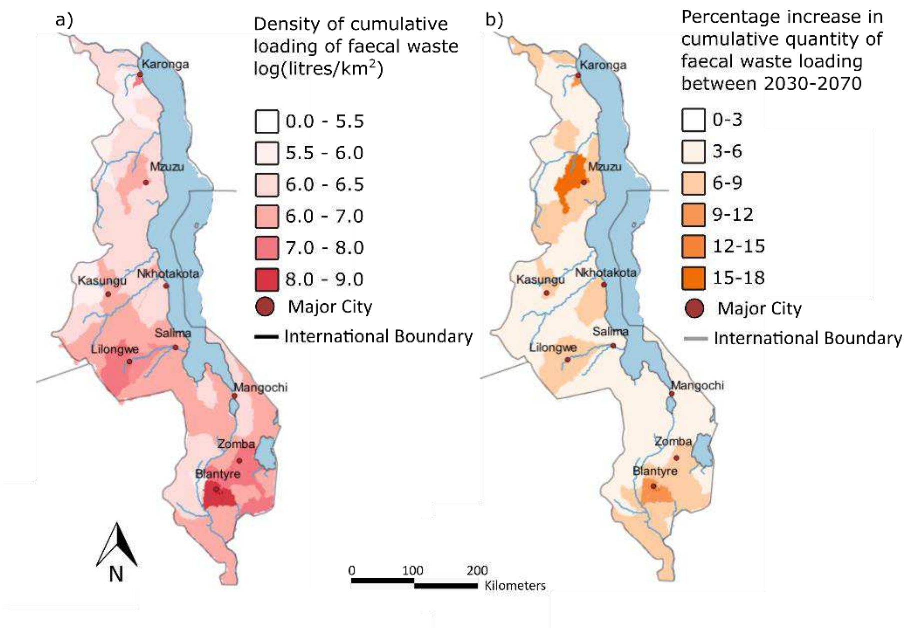


Figure 6: Spatial distribution of areas at greatest risk of chemical water-contamination from cumulative faecal waste loading. A) Density of cumulative loading of faecal sludge from 2020 to 2070 per km^2 in each WRU across Malawi. WRUs surrounding cities Blantyre, Lilongwe and Karonga have the greatest faecal sludge loading. B) Percentage increase of cumulative loading of faecal sludge (litres/ km^2), logarithmic scale, between 2030 and 2070. The WRUs around Blantyre, Lilongwe and Karonga have a significant increase in faecal loading density between 2030-2070, but WRU 7D around Mzuzu has a particularly high projected increase in faecal sludge density. Image made with QGIS.

3.3 Model verification and assumptions

Population projections (with model run from 2000-2020) were compared to gridded population datasets for 2020. Boke-Olen's et al.'s (2017)(Boke-Olen et al., 2017) spatially explicit population estimation for 2020 SSP2-RCP6 had a Root Mean Square Error (RMSE) of 933 when compared to WorldPop 2020 UN adjusted data at 1km resolution(Linard et al., 2012; WorldPop, 2023). Our model has a RMSE of 4.5 when compared to WorldPop 2020 UN adjusted data at 1km resolution. We applied an urban smoothing factor of 0.4 to the Hurtt et al. (2011)(Hurtt, et al., 2011) estimation to prevent overconcentration of the urban population. Our modelled population projections at 30 arc-second resolution for the year 2020 are highly accurate and show a difference from WorldPop 2020 1km spatial population distribution of 3.4% of cells differing by 1 person or more, 0.2% by 10 people or more, and 0.01% by 100 people or more (Supplementary materials Table S1). Our model therefore has a -1.64% total population estimate error compared to World Bank Malawi 2020 population (World Bank, 2023a). This is lower than Landscan (ORNL, 2023.), and Boke-Olen et al. (2017) total Malawi population predictions for 2020 (1km resolution) which have +49.6%, and +8.32% errors respectively (Supplementary materials Table S2).

We propose three sanitation policy scenarios, focused on pit-latrine usage, summarised in Supplementary materials Figures S1 and S2. Scenario A assumes the percent of the population using pit-latrines remains the same as the 2015/16 Demographic and Health Survey (DHS) estimate; 85.3% of the urban and 92.8% of the rural population(Zomba and Malawi, n.d.). Sanitation policy Scenario B assumes that, if the current rate of flush toilet acquisition continues and the remaining population use pit-latrines, 84.7% of the urban and 97.1% in rural population would use pit-latrines by 2070. Scenario C assumes that if Malawi follows the trend of flush-latrine adoption in Botswana(Statistics Botswana, 2015; Statistics Office, 2005.), 54.4% of the urban and 68.4% of the rural population would use pit-latrines in 2070. Spatial variation in pit-latrine use is summarised in Supplementary materials Figure S3.

Following data cleaning, we analysed 265,000 sanitation facilities (from the CJFWFP national sanitation survey completed in 2020). The number of users per latrine for urban and rural case-studies was calculated from the sanitation data. We estimated 9.4 and 12.7 people per latrine in urban and rural cases respectively, Supplementary materials Table 3.

4 Discussion

4.1 The burden of pit-latrines on safe drinking water

Open defecation (OD) in Malawi has fallen from 27.7% in 1992 to 5.9% in 2018 (NSO & Macro International, 1994; NSO &ICF, 2017) largely due to the promotion of pit-latrines. Given their short life (often filling in 2 to 3 years), continual pit-latrine construction is necessary not only to reduce the level of OD, but also to respond to population growth and to replace filled or unstable latrines (Hinton et al., 2023). Such unfettered growth in the number of pit-latrines is a potential crisis for groundwater quality.

Our model accounts for multiple population growth and urbanisation scenarios using the 5 shared socioeconomic pathways (SSPs)(KC and Lutz, 2017.; Riahi et al., 2017), hypothetical scenarios of global socioeconomic change. Each SSP population scenario is investigated alongside three sanitation policy scenarios (current sanitation policy, ending OD by pit-latrine promotion, or ending OD by expansion of piped sanitation). Whilst some sanitation policy scenarios are more probable under specific SSP scenarios, for example SSP1 'sustainability' is likely to be accompanied by more sustainable sanitation policy whilst SSP3 and 4 'fragmentation and inequality 'would likely have scenarios with higher pit-latrine dependency, all policy and SSP scenarios are considered to inform stakeholder decision making. All modelled scenarios, incorporating population and sanitation policy scenarios, predict increasing risks to groundwater posed by pit-latrines. The results here use SSP2, a 'middle of the road' model of socioeconomic growth and urbanisation(KC and Lutz, 2017; Riahi et al., 2017) and a sanitation policy scenario that assumes a constant proportion of the population using the sanitation systems as in 2015/16 (NSO &ICF, 2017) other SSP and sanitation policy scenarios are summarised in the Supplementary materials.

Microbial contamination is a significant problem in Malawi (Mkandawire, 2008; Pritchard et al., 2007, 2008; Rivett et al., 2022). Over 60% of the population's drinking water sources have measurable *E.coli* and 16.5% has over 100 faecal coliforms / 100ml (NSO, 2021), surpassing the Malawi's current rural water quality target of 50 Total Coliforms/100ml for untreated water (Mkandawire, 2008; Pritchard et al., 2008). The high-resolution model enables consideration of short-term movement of pathogens from pit-latrines to water-points (boreholes, tube-wells or dug-wells). Here, 3 arc-second grid cells containing both a vulnerable water-point and a pit-latrine are identified as presenting a risk of contamination. We predict that by 2030 (end of the SDG period) 18.0% of vulnerable water-points will have a pit-latrine within 50m (a cell containing a vulnerable water-points and 1 or more pit-latrines), exceeding both Government and NGO guidelines (Water Aid, 2013; Blantyre Water Board, 2005). This increases to 33.6% by 2070. Furthermore, we project an increase in the number of water-points at risk from contamination and the severity of risk. From 2020, there is a 720% increase in vulnerable-waterpoints considered at high contamination risk (within the same 3 arc-second grid cell 30 or more pit-latrines).

Literature and survey estimates of pit-latrine density support the results. Modelled water-point vulnerability was validated using results from the national 2012 to 2020 CJFWFP survey of over 100,000 water-points (Kalin et al., 2019). The number of surveyed water-points with a pit-latrine within a 3 arc-second grid cell was 15.1%. Our model is in good agreement, estimating that 11.5% of 3 arc-second grid cells contained both a pit-latrine and water-point in 2020. The difference is at least to some extent due to the model not accounting for grid cells containing multiple water-points. A case-study of Blantyre, Chiradzulu and Mulanje found that 25% of shallow wells were within 40m of pit-latrines or waste pits (Pritchard et al., 2007), resulting in a higher estimate than here; it should be noted this was not a country-wide analysis.

The cumulative faecal load in pit-latrines across Malawi from 2020 to 2070 projects a total of 482 giga-litres of faecal matter loaded into pit-latrines, containing approximately 8.2 mega-tonnes of nitrogen, 1.0 mega-tonnes of phosphorous, 2.3 mega-tonnes of potassium, and 19.6 mega-tonnes of organic carbon. From 2020 to 2030 alone there is an additional 51.2 giga-litres of faecal waste in the ground containing 0.9, 0.1 and 0.2 mega-tonnes of nitrogen, phosphorous, and potassium respectively. For reference, in 2019, 0.23 mega-tonnes of fertiliser containing 0.08 tonnes of nitrogen, 0.02 mega-tonnes of phosphorous and 0.02 mega-tonnes of potassium were applied in Malawi (Ritchie, 2020). The mass nutrients in faecal waste within pit-latrines is therefore comparable with that of fertiliser applied in Malawi. Whilst much of the waste will be broken down, absorbed, or microbially metabolised, it presents a risk of build-up within groundwater (Puckett et al., 2011; Zingoni et al., 2005), with significant public health, environmental, and policy implications.

The concentration of faecal sludge and associated risk of contamination for each Water Resource Unit (WRU) is the cumulative volume of faecal waste per WRU divided by the area of the WRU. WRUs surrounding key cities (WRU 1B, 1E2, 1C and 14A around Blantyre and WRU 4E and 4D surrounding Lilongwe) have the highest projected cumulative faecal sludge loading density from 2020 to 2070. WRU 17A (northern Malawi) has a low faecal loading of 2.9 giga-litres, however as it is concentrated within a small sub-catchment, the result is a high density of faecal waste. Policy and management interventions may require a change in sanitation infrastructure, focusing on waste removal, waste processing, or alternative water provision through piped water supplies and water source protection zones, to manage contamination risk (Zingoni et al., 2005).

4.2 Methodological Limitations

To evaluate microbial contamination risk, the distance of modelled pit-latrines to vulnerable water-points was estimated from pit-latrine density (Eq. 2). This assumes that water-points are centrally located within a cell known to contain a water-point; water-points could actually be located anywhere within the 3 arc-second cell. Only the density of latrines within the cell containing a water-point is considered for determining the risk of contamination, the dispersion of latrines within the cell is assumed to be random. This may result in the underestimation of the contamination risk in cases where the water-point is localised at the edge of a grid-cell and is at risk from pit-latrine contamination from neighbouring cells with. There may be overestimation in cases where the water-point is localised far away from the pit-latrines within the cell. This was mitigated by aggregating data from 3 arc-second to 30 arc-second resolution, identifying regions with high microbial contamination risk. The model also assumes radial groundwater flow i.e., preferential flow in the predominantly the weathered and fractured rock is not accounted for due to insufficient data on groundwater flow patterns within Malawi (Kalin et al., 2022). Assuming a radial approximation of risk of pit-latrine contamination of water-points is furthermore well established within literature (Chidavaenzi et al., 2000, Francey, 1992, Banerjee, 2011).

Only cells with a functional and in-use borehole, tube-well or dug-wells (vulnerable water-points) were used to estimate the contamination risk. From 2020 to 2070, these water-points may be abandoned, and new water-points constructed. It is also likely there will be more water-point containing cells in 2070 than assumed in the model due to increased water-point construction to meet the needs of the growing population(NPC, 2021). This study may underestimate the number of vulnerable boreholes if there is a significant growth in borehole numbers. It is expected that additional water-points will be constructed in areas with existing boreholes, due to the projected increase in population density and urbanisation, and thus will likely have the same risk of contamination as other boreholes within the modelled area. This is therefore considered to be an appropriate limitation as the study identified regions of high contamination risk. There was no differentiation of the risk between shallow and deep wells, water contamination risks may be higher where shallow wells are used, however as these were a minority of water-points (16.3%), the associated risks were not considered significant for a national level evaluation. Transition from vulnerable water-points to taps and piped water-supplies is also not accounted for (Rivett et al., 2019) as there is no information currently available on which to model these changes. Finally, water-point presence/ absence is a binary measure. If more than 1 vulnerable water-point is present within a cell, it may underestimate the contamination risk. These are assumed to be fitting limitations as the purpose of the study is the identification and prioritisation of areas for policy and management intervention which will still be identified in these cases.

There is uncertainty for population projections, particularly at high resolution over extended periods. Whilst high resolution population projections were utilised to identify vulnerable water-points (3-arc second resolution), results were aggregated to 30-arc second resolution to account for spatial variability and uncertainty in population estimates. The percentage of water-points within a 30-arc second resolution cell (approximately 1km at the equator), was used to identify areas at high risk of contamination providing estimations high risk at 30-arc second resolution, in accordance with high resolution literature population projections within this time frame (Chen et al., 2020; Boke-Olen et al., 2017). To further account for uncertainty in population projections, multiple scenarios of population growth were evaluated under the 5 SSP pathways (KC and Lutz, 2017.; Riahi et al., 2017) .

Latrines are assumed to be co-localised with the population, an assumption employed in the literature (Diaw et al., 2020). Some recommend that latrines should be no more than 50m from houses (Banks et al., 2007), therefore they were assumed to be within the same 90m grid cell as the modelled population. The model accounts for the number of users sharing a latrine by calculating the number of latrine users in the rural and urban areas of the Chikwawa case study from the CJFWFP survey (Kalin et al., 2019). In areas with very high population density, there may be more latrine users per latrine and therefore a lower latrine density than modelled. However, as it is recommended that no more than 20 latrine users share a latrine (Banks et al., 2007), these should still be identified as areas for intervention. Equally, the study may underestimate pit-latrines in very sparsely populated areas as fewer users may share a latrine in this context. Given the focus of this paper is on areas of high latrine density, this is not considered a significant limitation.

The cumulative quantity of faecal waste was used to estimate the mass of residual contaminants in the ground after pit-latrine abandonment (nitrogen, phosphorous, potassium and carbon). The model does not estimate the concentrations of contaminants in groundwater. While the model divides the cumulative loading of waste by the area of WRUs to give an indication of faecal waste density, data is not currently available on the pathways for contaminant mobility or the total volume of groundwater in each WRUs, therefore it was not possible to estimate the concentration within groundwater. Despite these limitations, the indication of areas with a high risk of chemical contaminants should guide further research and monitoring. We propose that there should be increased focus on national sampling efforts to assess chemical contamination of groundwater, accounting for contamination risks from pit-latrines.

Microbial and chemical contamination risks of water-points from pit-latrines assume that there are no barriers to groundwater contamination from faecal waste. Pit-latrines are assumed to be not being emptied, based on estimates that approximately 1% of pit-latrines are undergoing emptying in Malawi (Hinton et al., 2024). Similarly, pit-latrines were assumed to be unlined, around 10-15% of pit-latrines are estimated to be lined nationally (Chiposa et al., 2017, Hinton et al., 2024), where lining is used, interwoven logs and bamboo sticks are commonplace and can provide limited capacity to minimise contamination (Namwebe et al., n.d; Saxena and Den, 2022). Assumptions regarding lining and emptying of pit-latrines are therefore deemed to be justified.

4.3 Future directions

Further work incorporating aquifer volume, recharge, water-table depth, soil hydraulic conductivity and nitrate degradation, would enable better estimation of when groundwater resources may reach tipping points of nitrate levels (Templeton et al., 2015). Cumulative faecal waste and chemical loading estimates assume a constant value for faecal waste and chemical content using estimates for human faeces (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000; Strande et al., 2018). Further research could also incorporate spatial variation in faecal characteristics (Gwenzi et al., 2023; Kalulu et al., 2021). Microbial contamination prediction would be enhanced by further work on the variation in the groundwater table, pit latrine depth, soil type, biochemistry (Graham and Polizzotto, 2013; Islam et al., n.d.), hydraulics (Dzwairo et al., 2006), the direction of groundwater flow (Dzwairo et al., 2006; Back et al., 2018) as well as the type, age, and level of damage of the water-point (Escamilla et al., 2013). Temporal dynamics could also be considered; accounting for difference in contamination in the dry season and wet season (Mkandawire, n.d.; Pritchard et al., n.d., n.d.). Furthermore, an increased frequency of extreme weather events due to climate change could increase the frequency and severity of water-point contamination from pit-latrines (Rivett et al., 2022). We propose this methodology could be applied to other areas with a high risk of contamination from pit-latrines, particularly in Sub-Saharan Africa (Graham and Polizzotto, 2013; Nakagiri et al., 2016).

We suggest that ongoing work is needed to maintain databases that underpin risk management of pit-latrines to groundwater under rapid population change. This work should also be used to target monitoring of groundwater quality in areas identified as at high risk of contamination. Finally, revisions to the sanitation policy must take groundwater contamination into account to limit effects that could undermine efforts to improve public health.

5 Conclusions

- Using a novel high resolution spatial model of pit-latrine usage, we project microbial and chemical pit-latrine contamination.
- Under all modelled scenarios of population change and sanitation policy, we project and increase in both microbial and chemical pit-latrine groundwater contamination.

- We predict a three-fold increase in the number of water-points at risk of microbial pit-latrine contamination from 2020-2070 under business-as-usual population growth and sanitation policy scenarios.
- Current annual national nitrogen loading in pit-latrines is comparable to nitrogen fertiliser application.
- Dynamic monitoring of sanitary infrastructure risks is needed to manage the growing risk of pit-latrine contamination on groundwater.

Author contributions

R.H, R.K, C.M and M.T designed the study. R.K was PI and managed the CJFWFP data collection. R.H. conducted the formal analysis. R.G.K.H wrote the original draft of the manuscript. R.K, C.M, M.T, M.K and P.M contributed to the writing and reviewing of the final version of the manuscript. R.K. supervised the study.

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.

Data availability

All data presented here as well as data for alternative population scenarios and sanitation policy scenarios is available to download on Github (https://github.com/Rebekah-Hinton/Predictive-pit-latrine-groundwater-model). Georeferenced CJFWFP sanitation and water-point data is available online on the mWater portal. Water Resource Units (WRU) and District boundaries were obtained from MASDAP (www.masdap.mw).

Ethics

Informed consent was obtained from all subjects involved in the study. All data collected were in line with the Government of Malawi ethics and was agreed with each participant.

Code availability

Code for the model is available on Github (https://github.com/Rebekah-Hinton/Predictive-pit-latrine-groundwater-model).

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6 Supplementary materials

6.1 Population projections

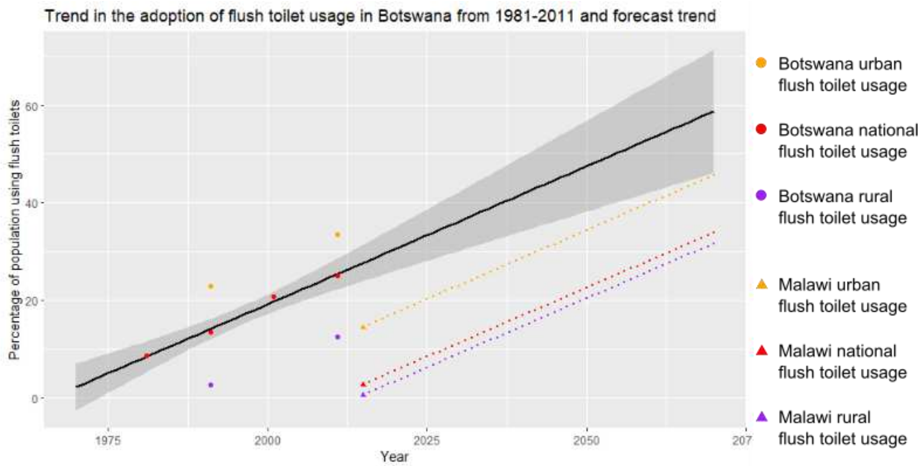
Urban Fraction Smoothing Factor	RMSE				Percentage cells where population difference exceeds					
	Non-adjusted		UN-adjusted		1 person/ cell		10 people/ cell		100 people/ cell	
	3 arc-second	30 arc-second	3 arc-second	30 arc-second	3 arc-second	30 arc-second	3 arc-second	30 arc-second	3 arc-second	30 arc-second
1.0	13.46	10.73	13.30	6.87	**6.02**	3.51	**0.25**	0.19	0.03	0.02
0.8	12.10	10.15	11.95	6.20	6.06	3.49	0.26	0.19	0.03	0.02
0.6	10.60	9.46	10.46	5.43	6.12	3.45	0.27	0.20	0.03	0.02
0.4	8.88	8.61	8.78	4.49	6.23	**3.43**	0.28	0.19	0.02	0.01
0.2	6.73	7.42	6.73	3.21	6.49	3.49	0.31	**0.16**	**0.01**	**0.00**

Supplementary materials Table 1: Supplementary materials Table 1: Comparison of model performance, applying urban smoothing factors, with Worldpop 2020. Comparison of modelled population projections, with varying urban smoothing factors applied, for 2020 compared to WorldPop 2020 population projections using root mean square error (RMSE) and the percentage of cells exceeding thresholds of difference at 3 arc-second (Worldpop 100m dataset) and 30 arc-second (Worldpop 1km dataset). For the RMSE calculations, modelled population is compared to both UN adjusted and non-adjusted WorldPop 2020 population distributions and resolutions. The percentage of cells at 3-arc and 30 arc-second resolutions in which the projected population in 2020 differed from the WorldPop 2020 population (non-adjusted) population distribution by more than 1 person, 10 people or 100 people is summarised. The Urban Fraction Smoothing Factor for which there was the smallest number of cases differed between the projected population and WorldPop is highlighted in bold.

Population dataset	Resolution at equator	Estimated Malawi population 2020/million	Percentage difference to World Bank 2020 population
WorldPop 2020	100m	17.94	-6.22
WorldPop UN-adjusted 2020	100m	19.90	+4.00
WorldPop 2020	1km	18.43	-3.68
WorldPop UN-adjusted 2020	1km	23.00	+20.18
Landscan 2020	1km	28.61	+49.55
Boke-Olen et al., ("High-resolution African population projections from radiative forcing and socio-economic models, 2000 to 2100," n.d.) population projection	1km	20.72	+8.32
Hinton et al., population projection	100m	19.06	-1.64

Supplementary materials Table 2: Population of Malawi as estimated from different available gridded population distributions for 2020. Predicted population compared to the WorldBank 2020 population to estimate the percentage error.

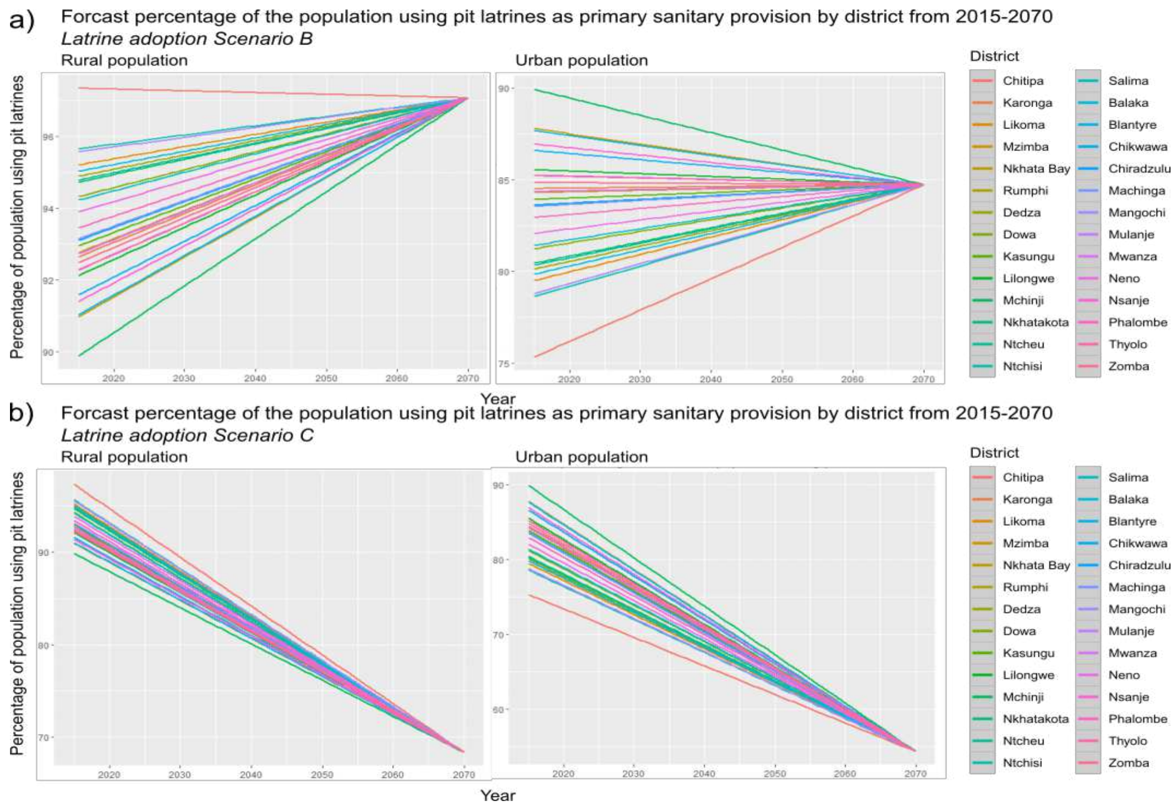
6.2 Latrine adoption scenarios



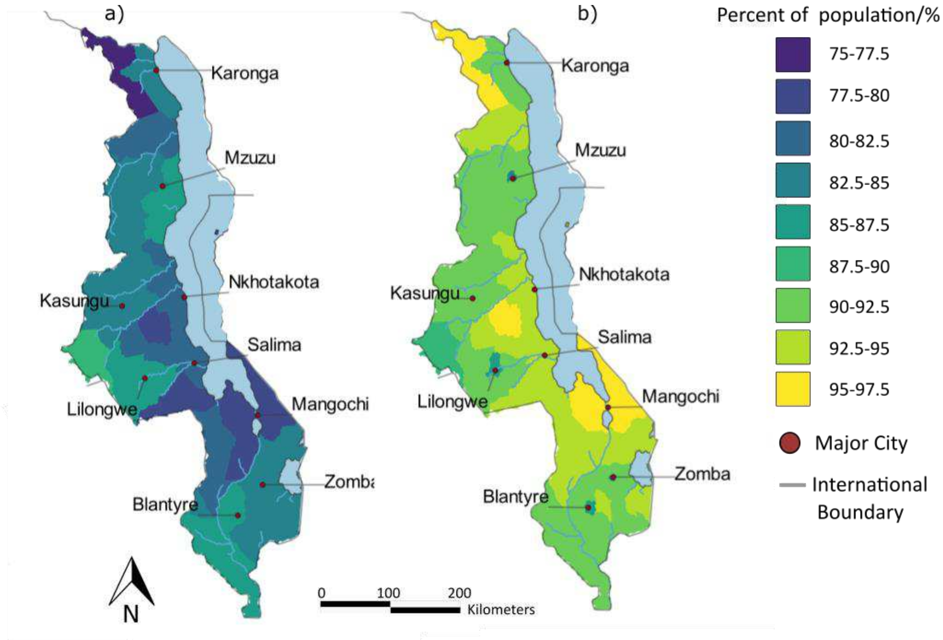
Supplementary materials Figure 1: Forecast percentage of the population using flush toilets for Malawi if Malawi follows the rate of flush toilet adoption seen in Botswana from 1981-2011. The trend in Botswana's flush toilet adoption is shown with data-points as circles. The 2015 DHS survey results for the level of flush latrine adoption in Malawi are represented by the triangles. Orange signifies flush toilet usage in urban areas, red is national and purple is in rural areas. The projected trend for Malawi's flush toilet usage is shown in dashed lines.

	Urban area 1	Urban area 2	Urban area 3	Rural area 1	Rural area 2	Rural area 3
Population	6,787	1,200	2,998	51,207	107,404	87,706
Pit-Latrines	934	73	168	3,320	10,084	6,178

c Table 3: Summary of 3 urban and rural case-studies in Chikwawa used to estimate the population per pit-latrine. The population was estimated from the 2017 WorldPop population distribution for Chikwawa and summed within each of the areas. The number of pit-latrines within each area was summed from the CJFWFP pit-latrine survey (largely in 2017) in which Chikwawa was most comprehensively mapped.

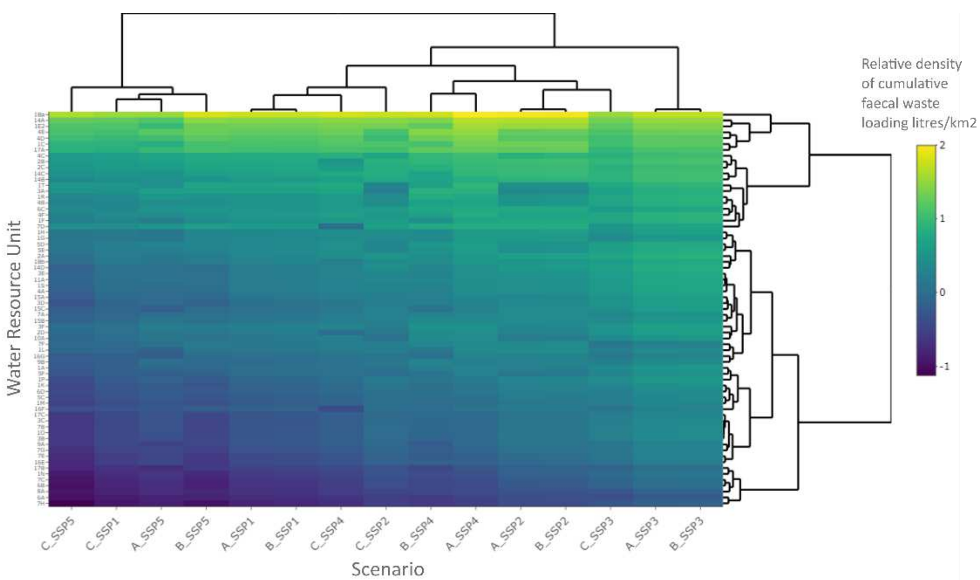


Supplementary materials Figure 2: Summary of pit-latrine using population in sanitation scenarios B and C. a) Forecast percentage of the population using pit-latrines as their primary source of sanitation for rural and urban contexts for different districts in Malawi under latrine adoption Scenario B (increasing pit-latrine usage). Districts have a level of pit-latrine usage in 2015 from the DHS 2015/16 survey. All districts are assumed to have the national average projected level of pit-latrine usage in 2070. b) Forecast percentage of the population using pit-latrines as primary source of sanitation for rural and urban contexts for different districts in Malawi under latrine adoption scenario C (decreasing pit-latrine usage). Districts have a level of pit-latrine usage in 2015 from the DHS 2015/16 survey. All districts are assumed to have the national average projected level of pit-latrine usage in 2070. The level of pit-latrine usage in 2070 is projected by modelling the adoption of flush toilets based on the observed trend in flush toilet usage in Botswana from 1981-2011.



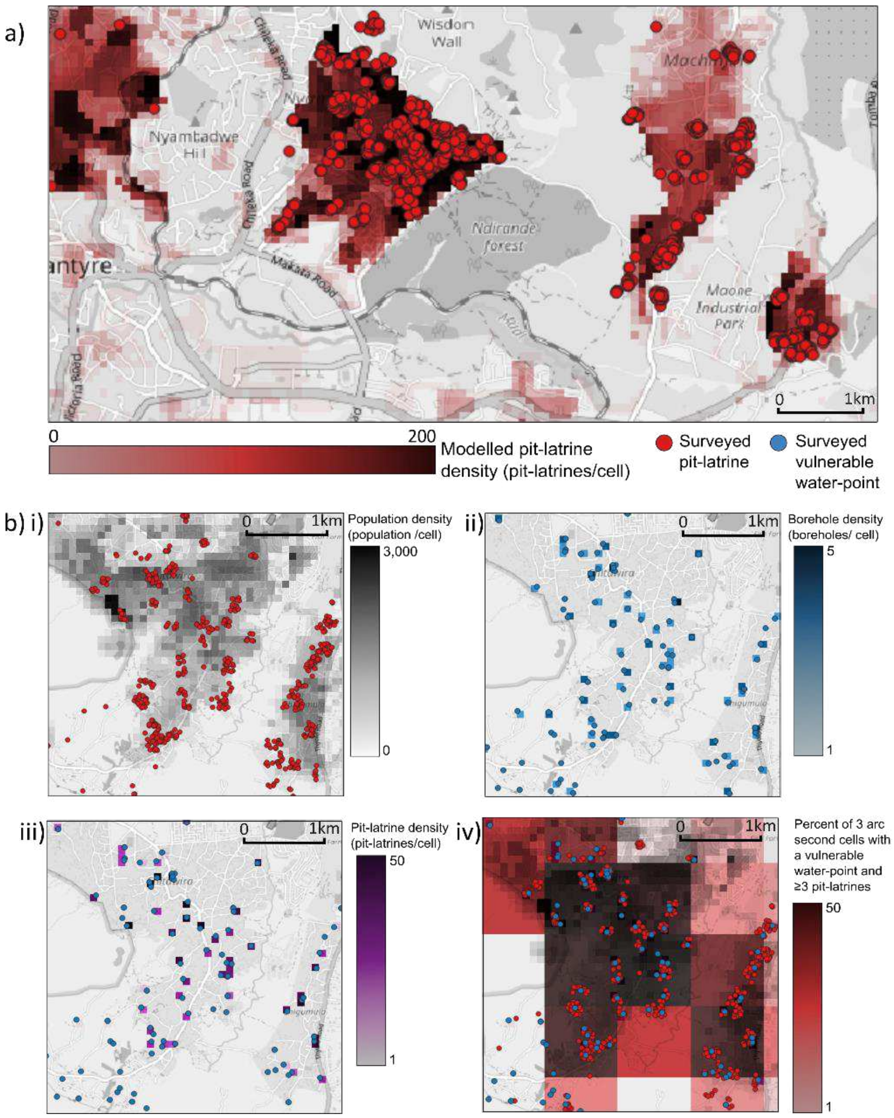
Supplementary materials Figure 3: Spatial variation of pit-latrine usage. Percentage of the 2015 population using pit-latrines as their primary form of sanitation in (a) urban contexts and (b) rural contexts, data from DHS 2015-16 survey.

6.3 Faecal loading



Supplementary materials Figure 4: Double dendrogram showing results of unsupervised hierarchical clustering analysis of faecal loading under multiple sanitation policy and socioeconomic scenarios. Water Resource Unit (WRU) clustering units are organised by row and pit-latrine/ socioeconomic scenarios are clustered by column (Sanitation policy scenario A, B and C and SSP scenarios 1-5). The scale bar is a logarithmic scale of the relative density of cumulative faecal waste loading for the year 2070 with the WRUs with the highest density of faecal waste loading with the highest value. Similarity between WRUs (shown in y-axis) and scenarios (x-axis) is represented by the height of the nodes in the plot with more similar scenarios having shorter nodes. Pit-latrine scenarios A and B show high similarity for all SSP scenarios; however, sanitation policy scenario C typically shows higher similarity to sanitation policy scenarios A and B of lower population growth and urbanisation SSP scenarios.

6.4 Latrine Density



Supplementary materials Figure 5: Example of methodology and results compared with CJFWFP survey data, 2017, for Blantyre. Images made with QGIS using Open Street Map background. a) Example region of North-East Blantyre. Estimation of pit-latrine density for Malawi, 2017 (darker areas have a higher estimated number of pit-latrines). The locations of mapped pit-latrines based on the 2012-2020 CJFWFP sanitation survey are shown as red points (majority of surveys in this region were conducted in 2017).

b) Example of steps in the methodology, applying an example of an area of Southern Blantyre. i) Population density is shown in grey with higher population densities as a darker colour. The locations of mapped pit-latrines are shown as red points. ii) The density of water-points is shown in blue with darker blue with higher densities of water-points within 3 arc-second grid cells. Locations of known waterpoints as blue points. iii) The density of pit-latrines projected as being within the same 3 arc-second grid cell as water-points in shown in purple. Locations of known water-points as blue points. iv) Aggregated data to 30 arc-second grid resolution, the percentage of water-points in a 30 arc-second resolution grid in which there are 3 latrines or more within the same 3 arc-second grid cell as the water-point. Locations of known water-points as blue points and locations of mapped pit-latrines are shown in red.

Number of latrines in 3 arc-second grid	2020	2030	2040	2050	2060	2070	Percentage change
No latrines	1,081,167	1,061,816	1,042,209	1,025,595	1,015,103	1,008,596	-6.7%
1-2 latrines	185,588	375748	564,178	724,138	827,361	908,633	+390%
3-9 latrines	37,418	36,647	33,094	28,034	19,046	11,765	-68.6%
10-29 latrines	10,557	13,013	20,421	27,002	33,362	15,242	+44.4%
30-49 latrines	1,671	2,333	4,332	6,401	7,511	9,125	+446%
50-99 latrines	613	1,388	2,681	4,171	6,131	9,445	+1,441%
100+ latrines	162	393	888	1,986	3,237	7,511	+4,536%

Supplementary materials Table 4: Number of cases with given densities of pit-latrines per 3 arc-second grid cell across the whole of Malawi for 2020-2070. For the years 2020-2070. SSP 2, Sanitation policy scenario A.

Number of latrines in 3 arc-second grid	2020	2030	2040	2050	2060	2070	Percentage change from 2020 to 2070
No latrines	37,889	35,092	32,574	30,670	29,523	28,394	-25.1%
1-2 latrines	3,590	6,297	8,667	10,449	11,557	12,332	+244%
3-9 latrines	1,002	962	803	647	408	1,312	+30.9%
10-29 latrines	242	340	562	723	891	253	+4.6%
30-49 latrines	39	47	97	160	193	170	+336%
50-99 latrines	20	32	54	85	136	181	+805%
Over 100 latrines	11	23	36	59	85	151	+1,273%

Supplementary materials Table 5: Risk to vulnerable water-points. Number of cases of pit-latrines within the same 3 arc-second grid cell in cells as a vulnerable water-point (domestically used borehole, tube well or dug-well) at given thresholds of pit-latrine density for the whole of Malawi. For the years 2020-2070. SSP 2, Sanitation policy scenario A.