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Spatial model of groundwater contamination risks from pit-latrines in a low-income country

Rebekah G.K. Hinton [a,b,*], Robert M. Kalin [a], Modesta B. Kanjaye [c], Prince Mleta [d], Christopher J.A. Macleod [b], Mads Troldborg [b]

[a] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK
[b] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK
[c] Director of Sanitation and Hygiene, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi
[d] Director of Water Supply, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi

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ABSTRACT

Pit-latrines are central to achieving UN Sustainable Development Goal 6 (SDG 6) 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 to 2070 under five population scenarios.

The results here are presented as a ‘business as usual’ scenario of population growth and pit-latrine usage, predicting a three-fold increase in the number of current water-points at risk of short-distance microbial pit-latrine contamination between 2020 and 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 and 2070. Change is necessary to prevent SDG6’s push for sanitation undermining its goal of clean water.

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 and 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 and 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, therefore, critical for reducing Open Defecation (OD)(Gwenzi et al., 2023; Hinton et al., 2023) which is still practiced by 419 million people globally (UNICEF and WHO, 2020). As such, pit-latrine usage is likely to increase as we near the 2030 deadline for the SDG 6.2 goal of ‘sanitation for all’ and a greater emphasis is placed on eliminating OD (Gwenzi et al., 2023).

Despite the importance of pit-latrines to meet SDG 6.2, pathogen and chemical groundwater contamination stemming from pit latrines may undermine efforts to meet SDG 6.1 (UN Water, 2023) relating to clean drinking water (Bhallamudi et al., 2019; Diaw et al., 2020; Graham and Polizzotto, 2013; Gwenzi et al., 2023; Mkandawire, 2008; Pritchard et al., 2008.; Rivett et al., 2022). Increased pit-latrine usage, and continual construction to replace filled pit-latrines, result in growing numbers of 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 combined with similarly large proportions using 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

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* Corresponding author.
E-mail address: Rebekah.hinton@strath.ac.uk (R.G.K. Hinton).

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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 the 2022–2023 cholera outbreak, Malawi's deadliest yet, which 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.

Ensuring pit-latrines are not built in close proximity to water-points is a key method in minimising the microbial contamination risk (Diaw et al., 2020; Dzwairo et al.,2006; Graham and Polizzotto, 2013; Reed, 2014; Sclar et al., 2016; Tillett, 2013; Verheyen et al., 2009; Mbae et al., 2024). But there are discrepancies between different guidelines for pit-latrine distance from water-points, ranging from 10 m to 75 m (Water Aid, 2013; Banerjee, 2011.; Blantyre Water Board, 2005; Chidavaenzi et al., 2000; Franceys, 1992; Sphere Association, 2018; Reed, 2014). Beyond microbial contamination, nitrogenous compounds (as NO_3, NO_2 and NH_4) are also contaminants of concern in groundwater (Ahmed et al., 2001; Diaw et al., 2020; Puckett et al., 2011; Rahman et al., 2021). Nitrate is a particular contaminant of concern, arising 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., 2021). Nitrate is relatively stable in aerobic conditions, presenting a risk of large distance transportation and long-term build-up of nitrate contaminants in groundwater (Canter, 1996). Prevention of nitrate in groundwater is consequently critical to maintaining 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); high nitrate concentrations in groundwater have been recorded in several 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 extent of sanitation systems (Martínez-Santos et al., 2017; Diaw et al., 2020; Ndoziya et al., 2019.; Wright et al., 2013).

Using high resolution population projections, we present a model of pit-latrine usage to predict groundwater contamination risk from 2020 to 2070. The 5 Shared Socio-Economic Pathways (SSPs)(Riahi et al., 2017.) provide population growth predictions, accounting for demographics including age, sex, and education (KC and Lutz, 2017). Boke-Olen et al. (2017) combined SSP population projections with spatial distribution models to allow spatially explicit population forecasts for various socio-economic projections (Boke-Olén et al., 2017). They applied this model at a 30 arc-second resolution (approximately 1 km at the equator) for an African population projection from 2000 to 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 the 10–100 m range. We apply a similar modelling approach at a greater 3 arc- second resolution (approximately 100 m at the equator)(Linard et al., 2012; Stevens et al., 2015; Worldpop, 2023) to produce higher-resolution and country-specific spatial population projections under multiple socio-economic scenarios. We couple 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 to 2070. Particular focus is given to risks to groundwater in 2030, as the date linked to the Sustainable Development Goals (UN General Assembly, 2015), and 2070, the end of the decade encapsulating the conclusion of Malawi's development plan, Malawi 2063(NPC, 2021).

We apply 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 90 m for Malawi). We present here the results for a 'business as usual' scenario of population change. Further population scenarios are provided in the Supplementary Materials.

This research presents a novel method for national identification, and future prediction of, vulnerable water-points at <100 m resolution, enabling risk-basement investment into sanitation and water infrastructure. Though the case study is Malawi, the model could be applied to other countries and regions at similar risk of drinking water contamination. The output of this model will enable the Ministry of Water and Sanitation in Malawi to tailor their policy / management decisions in consideration of the 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, Fig. 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 (NPC, 2021)..

Groundwater provides the main source of drinking water for 85% of Malawi's population (Graham and Polizzotto, 2013), mainly accessed from boreholes/tubewells (NSO, 2021). Currently only 4.9% of boreholes/tubewells meet the requirement of SDG 6.1.1, '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, 2021; NSO and ICF, 2017).

2.2. Spatially explicit population estimation

Using a similar methodology to that outlined in Boke-Olen et al. (2017) and summarised in Fig. 2, we generated a high resolution 3 arc-second resolution (approx. 90 m in Malawi) spatially explicit gridded population projection from 2000 to 2070. The WorldPop 2000 unconstrained, 100 m 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), Fig. 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

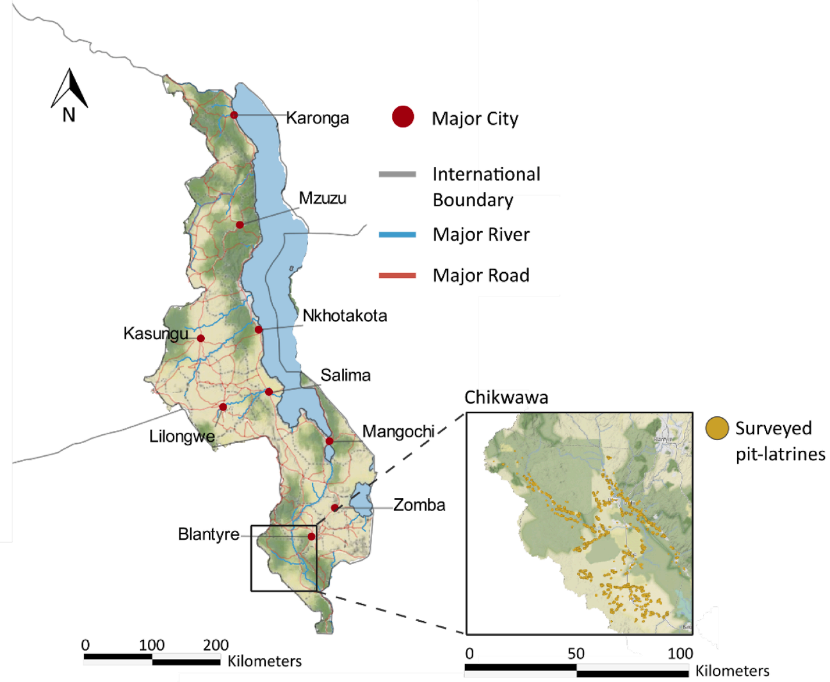

Fig. 1. Map of case-study area (Malawi) showing major cities, rivers, and roads. The region of Chikwawa, where sanitation infrastructure is most comprehensively mapped, is highlighted with the locations of surveyed pit-latrines from the CJFWFP sanitation survey. Image made with QGIS using Stamen Terrain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

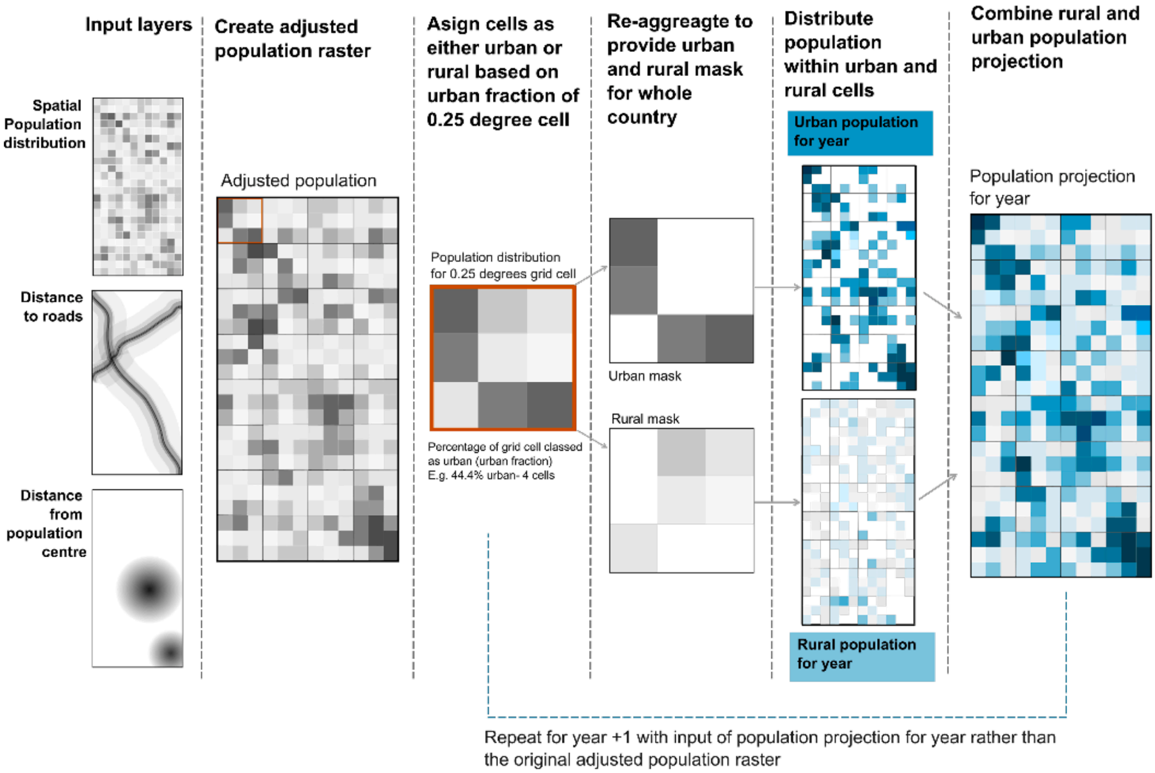

Fig. 2. Diagrammatic overview of population projection methods. Methodology for population projections based on Boke-Olen et al. (2017). Input layers are the initial 100 m Worldpop spatial population distribution for the year 2000(Linard et al., 2012; WorldPop., 2023) alongside raster files of the distance 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.

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 to 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 Fig. 2.

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 100 m and 1 km 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 Eq. (1).

Table 1

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

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 **50 m** distance (Water Aid, 2013)
3 latrines	At least 1 latrine within 40 m	Low-moderate risk	WEDC Loughborough University **40 m** distance (Reed,2014)
10 latrines	At least 1 latrine within 26m	Moderate risk	Sphere Project **30 m** distance (Sphere Association, 2018.)
30 latrines	At least 1 latrine within 16m	Moderate-high risk	Chidavaenzi et al. (2000) **20 m distance** (Chidavaenzi et al., 2000)
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) **10 m** distance(Banerjee, 2011)

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

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-′ond resolution was compared to WorldPop 2020 (UN-adjusted 1 km 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 100 m and 1 km 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. Pit latrine usage distribution

The rural and urban population distributions were divided into administrative districts, with 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 in each district (NSO and ICF, 2017). Based on stakeholder consultation, this model assumes a constant proportion of the population using pit-latrines from 2020 to 2070. 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).

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 and 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. Pit-latrine usage ranged from 75% in some urban areas to >95% in some rural areas, spatial distribution of pit-latrine usage is shown in Supplementary Information. 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 Fig. 3.

2.5. Cumulative faecal loading

Spatial estimates of pit-latrine users for different years, and SSP scenarios, were calculated as the product of the spatially explicit population and pit-latrine usage estimations. Loading of nitrate was considered over 10 km distances to account for long-distance nitrate transportation which is common in groundwater (Canter, 1996). An upper distance for groundwater lateral flow of 10 km was taken assuming a lateral velocity of up to 200m/year over 50 years (Gordineaux et al., 2013). To consider contaminant transportation, the quantity of excreta loaded into each 10 x 10 km grid cell was calculated to identify regions at risk of groundwater contamination, with a focus on nitrogenous contamination. There was assumed to be no lateral transfer between 10 x 10 km cells (Beusen et al., 2015). The volume of faecal waste was calculated by multiplying the number of latrine users by the estimated volume of faecal matter per capita per year using literature estimates. The cumulative loading of faecal waste was calculated by

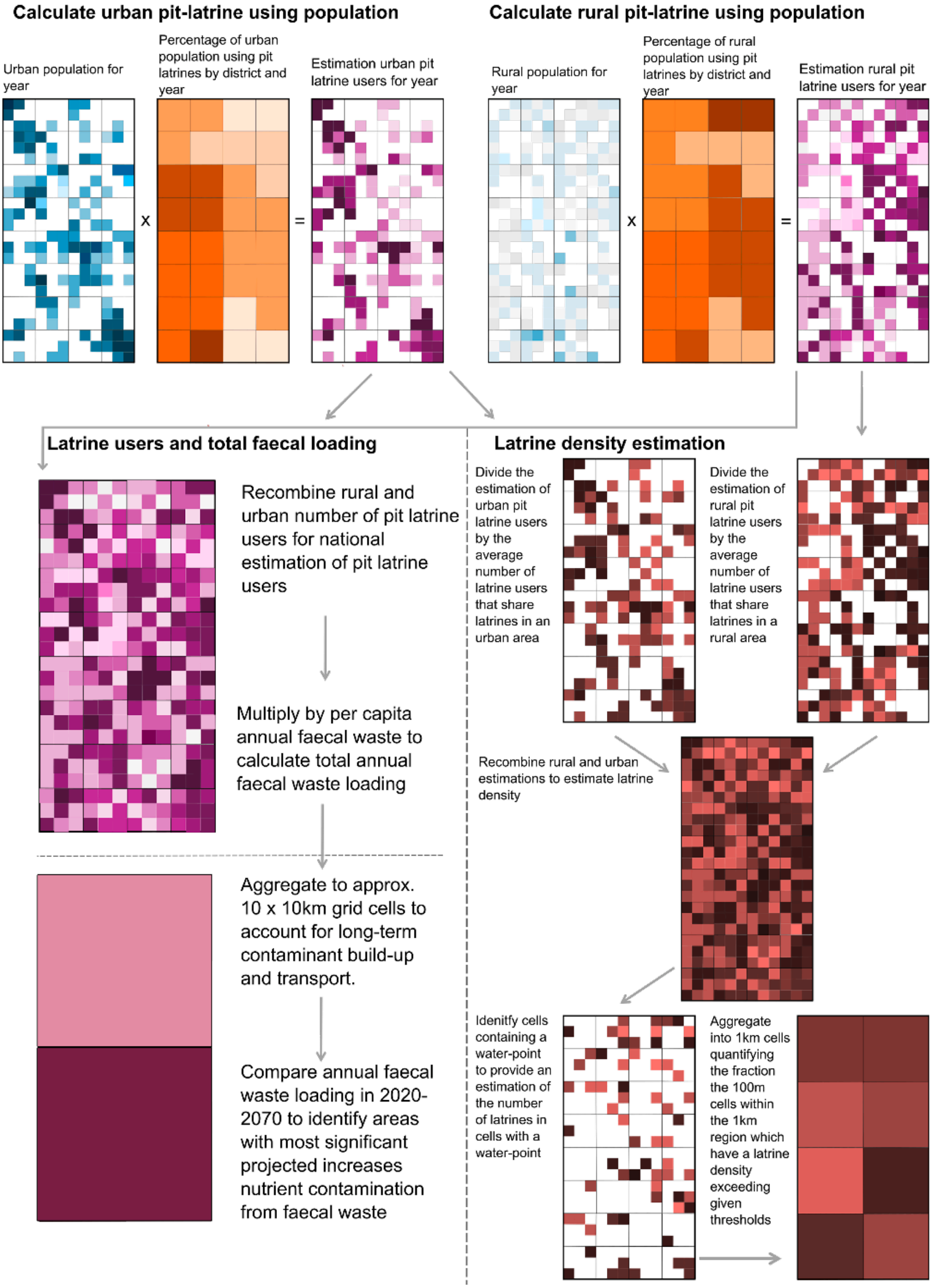

Fig. 3. Diagrammatic overview of methods used in estimation of pit-latrine users and density. Blue grid cells represent population density, orange represents the percentage of people in a given district that use pit-latrines, purple grid cells represent latrine users and red cells represent latrine density.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

summing the volume of excreta per year produced by users from 2020 to 2070. Ranges in excreta volume and composition were used to account for uncertainty. For the volume of excreta produced, an average volume of excreta 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 1000 L per capita and a lower estimate of 100 L 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 and Steinfeld, 1999; G.T.Z. Ecosan, 2000; Hansen and Tjell, 1979; Schouw et al., 2002; West et al., 2009). An average estimate of 12.5 g/ppd Nitrogen content was taken from literature estimates used in compositing and EcoSan toilet designs (Del Porto and Steinfeld, 1999; G.T.Z. Ecosan, 2000.). The upper estimate of 19 g N/ppd was taken based on a study of adult excreta in Denmark, averaged 16 g/ppd (range 12–19 g)(Hansen and Tjell, 1979). The lower estimate of 7.6 g/ ppd was taken based on a study of adults and children in Thailand, averaged 7.75 g/ppd (range 7.6–7.9 g) (Schouw et al., 2002). The average phosphorus content of waste was taken as 2 g/ppd (Strauss et al., 2003). A lower estimate of 1.5 g/ppd was taken from latrine design literature (Del Porto and Steinfeld, 1999; G.T.Z. Ecosan, 2000)). An upper estimate of 3.7 g/ppd was based on adult excreta in Denmark (range 1.8 g-3.7 g)(Hansen and Tjell, 1979). For potassium, an average estimate of 3 g/ppd was applied (Strauss et al., 2003). A lower estimate of 1.8 g/ppd was taken from a study of adult and child excreta, Thailand (range 1.8–2.7 g)(Schouw et al., 2002). An upper estimate of 3.5 g/ppd was taken (Del Porto and Steinfeld, 1999; G.T.Z. Ecosan, 2000.). For carbon content, an average carbon estimate was taken as 17.9 g/ppd in human excreta (West et al., 2009). A lower estimate of 14 g was applied based a study of adult and child excreta in Thailand (range 14–26 g)(Schouw et al., 2002). An upper estimate of 30 g/ppd was from literature on latrine design and compositing (Strauss et al., 2003; Del Porto and Steinfeld, 1999; G.T.Z. Ecosan, 2000).

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. A comprehensive pilot survey was conducted in Chikwawa in 2017. 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 265,000 points for analysis. The national level survey was interrupted by Government restrictions surrounding coronavirus.

The most comprehensively mapped district of Malawi was Chikwawa (Fig. 1), with most surveys conducted in 2017. Case studies from the district of Chikwawa were used to approximate the population per pit-latrine value. 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 100 m 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 calculated to provide an estimate of 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 Eq. (2):

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

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 modelled latrine density 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.).

This study identified the risk of pit-latrine contamination to current water-points. The CJFWFP water-point survey geolocated 127,000 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 current 'vulnerable' water-point. Cells containing a vulnerable water-point in which the density of latrines exceeded a threshold density were identified, Fig. 3.

To account for 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 current 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 100 m of a latrine based on Government of Malawi recommended spacing (Blantyre Water Board, 2005), and was used for model validation. The percentage of vulnerable water-points within 100 m of a latrine was calculated. Eq. (3) enabled comparison of the percentage of cases in which a water-point was within 100 m 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:

$$P_g = \frac{P_r l^2}{\pi r^2} \tag{3}$$

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.

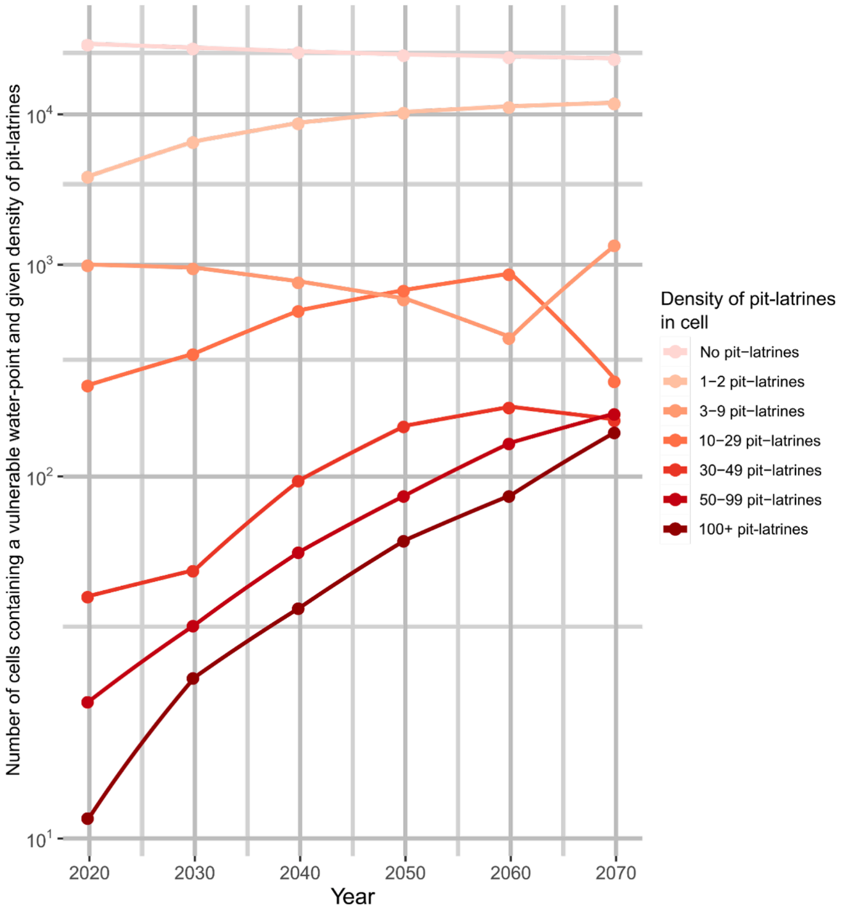

Fig. 4. Change in number of vulnerable water-points at risk of contamination from 2020 to 2070. Number of 3 arc- second grid cells containing at least one vulnerable water-point and given densities of pit-latrines between 2020 and 2070 under SSP scenario 2.

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 Fig. 3.

3. Results

3.1. Latrine density

A dataset of 127,000 water-points, surveyed from 2012 to 2020 by the Malawian 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 (7700) and unprotected dug wells (310). Of the vulnerable water-points, 23,100 reported a pit-latrine within 100 m (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 Eq. (3).

The associated risk to water-points of given pit-latrine densities, calculated using Eq. (2), is summarised in Table 1. The number of cells surpassing thresholds of pit-latrine density is shown in Fig. 4 with data summarised in Supplementary materials Tables 4 and 5. We estimate that in 2020, 11.5% of current 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.

Fig. 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 current 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-′ond cell containing 30 or more pit-latrines from 2020 to 2070.

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 to 2070 in Malawi. Current annual volumes of nitrogen loading are comparable to the nitrogen in current national fertiliser application (Ritchie et al., 2022). Fig. 6 shows the cumulative quantity of faecal sludge, by 10 x 10 km grid cells from 2020 to 2070. A summary of annual faecal waste loading for the year 2070 under multiple SSP scenarios is provided in the supplementary information.

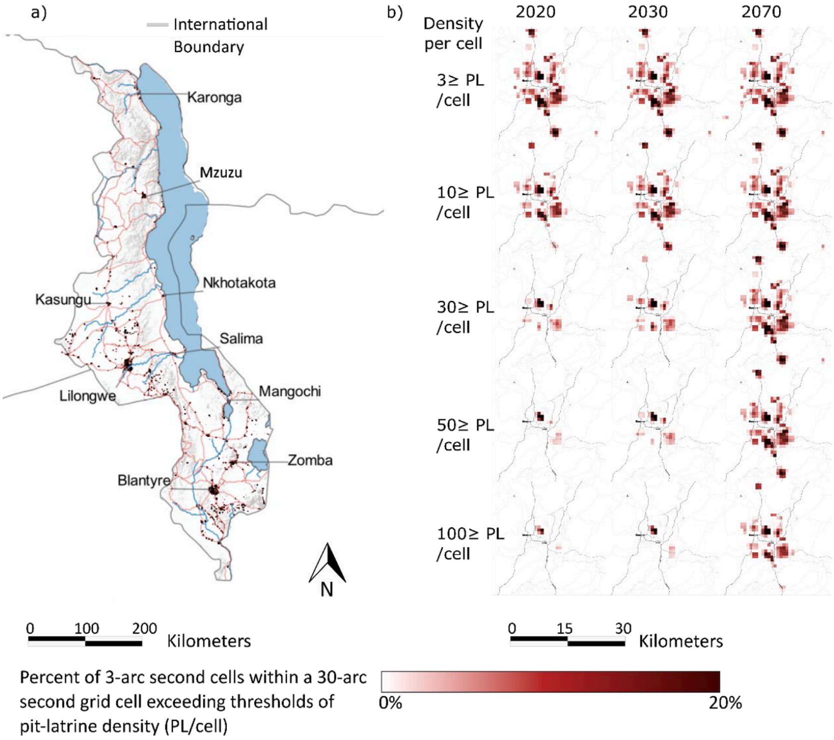

Fig. 5. Spatial distribution of areas at greatest risk of faecal water contamination. a) The fraction of 3 arc-second grid cells (approximately 90 m) within 30 arc-second grid cells (approximately 9 km) containing a vulnerable current water-point and 3 or more predicted pit-latrines for the year 2070 under SSP2. 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 current waterpoints and pit-latrine densities over given thresholds in Blantyre City Malawi for the years 2020, 2030, and 2070 under SSP2.Image made with QGIS using Stamen Toner Light background.

Table 2

Estimate of current and projected total loading of faecal waste across Malawi (giga-litres) and constituent chemicals (mega-tonnes). Loading from 2020 to 2070 under SSP scenario 2. Total quantity of faecal waste is the total amount of faecal waste loaded into pit-latrines in a time period, estimates from projected number of pit-latrine users and estimates of faecal make up. Mean values are given with ranges in brackets.

Total annual loading	2020-2030	2020-2040	2020-2050	2020–2060	2020–2070
Volume of faecal waste / giga-litres	51 (19–190)	130 (48–480)	230 (85–850)	340 (130–1300)	480 (180–1800)
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)
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)
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)
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)

3.3. Model verification and assumptions

Population projections (with model run from 2000 to 2020) were compared to gridded population datasets for 2020. Boke-Olen's et al.'s (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 1 km resolution(Linard et al., 2012; WorldPop, 2023). Our model has a RMSE of 4.5 when compared to WorldPop 2020 UN adjusted data at 1 km 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 1 km 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).

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 9.3 and 12.6 people per latrine in urban and rural cases respectively, Supplementary materials Table 3.

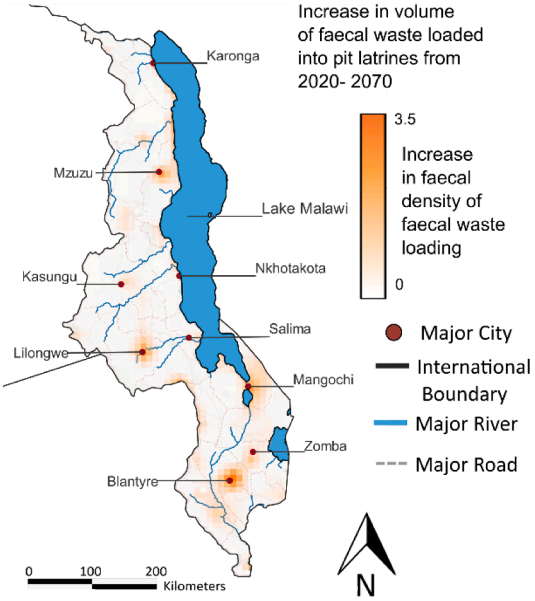

Fig. 6. Spatial distribution of areas at greatest risk of chemical water-contamination from faecal waste loading. Increase of annual faecal waste loading (megalitres/ km^2) from 2020 to 2070. Loading is calculated as annual faecal waste by pit latrine users over 10 x 10 km grid cells. Regions around Blantyre, Lilongwe and Mzuzu, and Mangochi have the most significant increase in annual faecal loading density from 2020 to 2070. Image made with QGIS.

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 and Macro International, 1994; NSO andICF, 2017) largely due to the promotion of pit-latrines. But to maintain pace with the growing population, alongside continuing the mission to eradicate OD, an increasing number of pit latrines will be required (Hinton et al., 2023). Such continuous pit latrine construction presents a potential crisis for groundwater quality. Our model simulates multiple population growth and urbanisation scenarios using the 5 shared socioeconomic pathways (SSPs)(KC and Lutz, 2017.; Riahi et al., 2017), scenarios of global socioeconomic change, all 5 iterations 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), other SSP scenarios are summarised in the Supplementary materials and the Github Repository.

Contamination of water-points from pit-latrines has been identified as a significant concern in the provision of safe drinking water in Malawi (Mkandawire, 2008; Pritchard et al., 2007, 2008; Rivett et al., 2022; Hinton et al., 2024a). Due to the lifespan of pathogenic microorganisms, microbial contaminants are modelled over short distances from onsite sanitation systems to groundwater water-points (Mbae et al., 2024). The high-resolution model enables the necessary consideration of short-term movement of contaminants (including pathogens) from pit-latrines to water-points (boreholes, tube-wells or dug-wells). Here, 3 arc-second grid cells containing both a current vulnerable water-point and a pit-latrine are identified as presenting a risk of contamination. We predict that by 2030 (the end of the SDG period) 18.0% of current vulnerable water-points will have a pit-latrine within 50 m (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 is predicted to increase to 33.6% by 2070. Furthermore, we project an increase in the number of current water-points at risk from contamination as well as the severity of said risk. From 2020, there is a 720% increase in current vulnerable-waterpoints considered at high contamination risk (at least 1 latrine within 20 metres).

Literature and survey estimates of pit-latrine density support these results; the 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 with this, 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 40 m of pit-latrines or waste pits (Pritchard et al., 2007), resulting in a higher estimate than this model; 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 et al., 2022). The mass nutrients in faecal waste within pit-latrines is therefore comparable with that of fertiliser applied in Malawi; it should be noted that the implications for groundwater contamination for fertiliser and pit latrine derived contaminant loading are distinct. Fertiliser application is more diffuse and predominantly surface level whilst pit latrine loading is subterranean and more concentrated, furthermore the responses of the plant-soil-groundwater continuum differ. Whilst much of the waste will be broken down, absorbed, microbially metabolised, or enter into surface water (Goderniaux et al., 2013; Beusen et al., 2015), it presents a risk of build-up within groundwater (Puckett et al., 2011; Zingoni et al., 2005), therefore having significant public health, environmental, and policy implications.

The concentration of faecal sludge and associated risk of contamination is summarised for 10 x 10 km grid cells. The increase in faecal waste loading in 10 x 10 km cells is compared for the years 2020 and 2070. Cells surrounding the cities of Blantyre, Lilongwe, and Mzuzu had the highest densities of faecal waste loading as well as the highest projected increases in loading of faecal waste, areas surrounding these cities are projected to have 3 fold increases in the density of faecal waste loading, and the potential for long-term groundwater contamination build up, over the coming 50 years. This presents a cause for concern notably for groundwater nitrate contamination with over 5% of water-points in Malawi, largely in areas surrounding the cities of Blantyre and Mzuzu, already exceeding safe nitrate concentration levels (Hinton et al., 2024). Policy and management interventions may require a change in sanitation infrastructure and management, such as pit-latrine lining and emptying, in areas in which such contamination is a concern (Hinton et al., 2024b). Similarly, areas identified as vulnerable may require changes to water provision, whether by altering groundwater abstraction through deepening well points, better implementing water source protection zones, or by expanding piped water supplies (Zingoni et al., 2005).

4.2. Methodological limitations

To evaluate short-distance (such as microbial) contamination risk, the proximity 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. Equally, there may be an overestimation of risk 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 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 the literature (Chidavaenzi et al., 2000; Francey, 1992; Banerjee, 2011).

Only cells with a currently functional and in-use borehole, tube-well, or dug-wells (vulnerable water-points) were used to estimate the contamination risk. The model assumes future contamination risks based on the locations of these current water-points. The life expectancy of boreholes and wells exceeds 25 years (Driscoll et al., 1986) and whilst handpump components may have a shorter life-span of 10–15 years, these may be replaced and repaired (Truslove et al., 2020). Whilst from 2020 to 2070, current water-points may be abandoned, and new water-points subsequently constructed, it is assumed that rehabilitation will be preferred to abandonment and replacement (May, 2024). Equally, where rehabilitation is not possible, replacement boreholes will be primarily constructed in the same location as current boreholes in order to serve the same population. It is 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). Predicting the locations of future water-points was deemed beyond the scope of this study as it is not only influenced by population growth but also heavily regulated by local government, with Governors able to ban the sinking of new boreholes in regions where there is depletion of groundwater resources (Mulwafu and Mwamsamali, 2017). In Blantyre, new borehole and dug-well construction is largely banned, although there are reports still of illegal water-point construction (Mwale, 2023). Where new boreholes are constructed, it assumed that, due to urbanisation, they will be in areas of high population and thus will likely have the same risk of contamination as other boreholes within the modelled area. 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. Furthermore, it is assumed that even in regions where piped water is available, or becomes more available, alternative water-points will still be used in combination with piped-water infrastructure as is commonly observed (Chidya et al., 2016; Alda-Vidal et al., 2018). These multiple reasons result in high uncertainty in future water-point construction and, as such, this study only considers locations of current water-points. This study may therefore underestimate the number of future vulnerable boreholes if there is a significant growth in borehole numbers. 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. In addition, water-point presence/ absence is a binary measure within this model, the limitation being that 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-′ond resolution), results were aggregated to 30-′ond resolution to account for spatial variability and uncertainty in population estimates. The percentage of water-points within a 30-′ond resolution cell (approximately 1 km at the equator), was used to identify areas at high risk of contamination providing estimations high risk at 30-′ond 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). It is recommended that latrines should be no more than 50 m from houses (Banks et al., 2007), therefore they were assumed to be within the same 90 m 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 rural and urban areas from the CJFWFP survey. As surveying was restricted by the COVID-19 pandemic, rural and urban user estimates were restricted to the most comprehensively mapped region of Malawi: Chikwawa. The rural and urban pit latrine sharing distinction is thus based on a relatively small sample size of 21,000 pit latrines and not in the more populous urban areas of Blantyre and Lilongwe, creating risk of systematic bias in estimating national pit-latrine numbers. This limitation is considered appropriate as estimates of rural and urban pit latrine sharing fall within literature estimates (Tumwine et al., 2003; Hinton et al., 2023; Gudda et al., 2019). Chikwawa is considered an appropriate study region from which to base estimates of sanitation usage as it is a well-established case-study region for both urban (Lwesya Sibale and Fischer, 2023; Kacheche, 1984) and rural case-studies (Masangwi et al., 2009; Joshua et al., 2021; Kumwenda et al., 2014). It has been used as a basis of groundwater studies (Rivett et al., 2018; Pritchard et al., 2008) as well as being representative for national water and sanitation (WaSH) characteristics (Kumwenda et al., 2017). Within the model, further distinction between rural and urban areas is provided by differentiating between the percentage of pit latrine usage in rural and urban areas on district levels enabling another way of differentiating between urban and rural characteristics. Whilst manual validation showed good model performance in key urban centres, areas with very high population density may have more latrine users per latrine and therefore a lower latrine density than modelled. As it is recommended that no more than 20 latrine users share a latrine (Banks et al., 2007), these areas still pose a concern regarding safe and effective sanitation provision and 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 as insufficient information is available for both contaminant degradation, which is strongly influenced by the subsurface environment (Jessen et al., 2017), and transportation which is influenced by groundwater flow. This is of particular note in the case of nitrogenous compounds in which an oxidising environment is required for nitrification of ammonia to nitrate. Anaerobic conditions surrounding pit-latrines and in areas of high leachate may result in higher levels of ammanox reactions of ammonia and denitrification of nitrate, preventing leaching of some nitrogenous compounds into groundwater (Robertson et al., 2021). 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., 2024b). 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., 2024b), where lining is used, interwoven logs and bamboo sticks are commonplace and can provide limited capacity to minimise contamination (Namwebe et al., 2008; 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 groundwater flow, recharge, water-table depth, soil hydraulic conductivity, and the biogeochemical context of groundwater, including notably the oxidation state (Jessen et al., 2017) , would enable better modelling of areas at high vulnerability of high macronutrient concentration. Microbial contamination prediction specifically would be enhanced by further work on the variation in the groundwater table, pit latrine depth and age (Mbae et al., 2024), soil type, biochemistry (Graham and Polizzotto, 2013; Islam et al., 2016), 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). Considerations of soil type and sanitation construction should also be greater explored for their implications for high attenuation of microbial contaminants (Graham et al., 2013; Back et al., 2018; Banerjee et al., 2011) as should the influence of pit latrine density as a driver of contamination aside from only influencing lateral proximity (Mbae et al., 2024). Temporal dynamics could also be considered, accounting for difference in contamination in the dry season and wet season (Mkandawire, 2008.; Pritchard et al., 2007;2008). Alternative contaminants are also not expressly explored within this paper, further work is needed to explore how pit-latrine density may influence contamination patterns of emerging contaminants of concern from pit-latrines such as microplastics, pharmaceuticals, and synthetic chemicals (Gwenzi et al., 2023). Alongside enhanced modelling efforts to simulate and predict future contaminant pathways, analysis of current contamination and sources of contaminants is essential in building a complete picture of contamination risks to groundwater in Malawi.

This model assumes a constant percentage of the population using pit-latrines. Whilst this was based on current trends in pit-latrine usage, future patterns of socioeconomic development will influence the extent of pit-latrine adoption. Further work will require greater trend analysis of sanitation usage and socioeconomic patterns to predict future trends in the extent of pit-latrine usage. In addition to further development for the Malawian context, 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 could also be used to target monitoring of groundwater quality in areas identified as at high risk of contamination. Future research should also explore the potential of interventions such as well deepening, pit latrine quality improvement, and enhancement of well head protection zones to cope with the challenges of growing sanitation requirements on Malawi's groundwater (Hinton et al., 2024b). Exploration of such solutions must take into account the hydraulic, social, and economic context.

5. Conclusions

- Using a novel high resolution spatial model of pit-latrine usage, we project microbial and chemical pit-latrine vulnerability.
- Under all modelled scenarios of population change, we project an 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 to 2070 under business-as-usual population growth
- Current annual national nitrogen loading in pit-latrines is comparable to nitrogen fertiliser application.
- Management of sanitary infrastructure is needed to navigate the growing risk of pit-latrine contamination of groundwater.

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).

CRediT authorship contribution statement

Rebekah G.K. Hinton: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Robert M. Kalin:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Modesta B. Kanjaye:** Writing – review & editing, Validation, Data curation, Conceptualization. **Prince Mleta:** Writing – review & editing, Data curation, Conceptualization. **Christopher J.A. Macleod:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Mads Troldborg:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Robert Kalin reports financial support was provided by Scottish Government Climate Justice Fund Water Futures Programme. If there are other authors, they 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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.122734.

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.

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