Journal of
Water, Sanitation & Hygiene for Development

© 2023 The Authors Journal of Water, Sanitation and Hygiene for Development Vol 13 No 10, 833 doi: 10.2166/washdev.2023.140

Review Paper

A historical and critical review of latrine-siting guidelines

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ABSTRACT

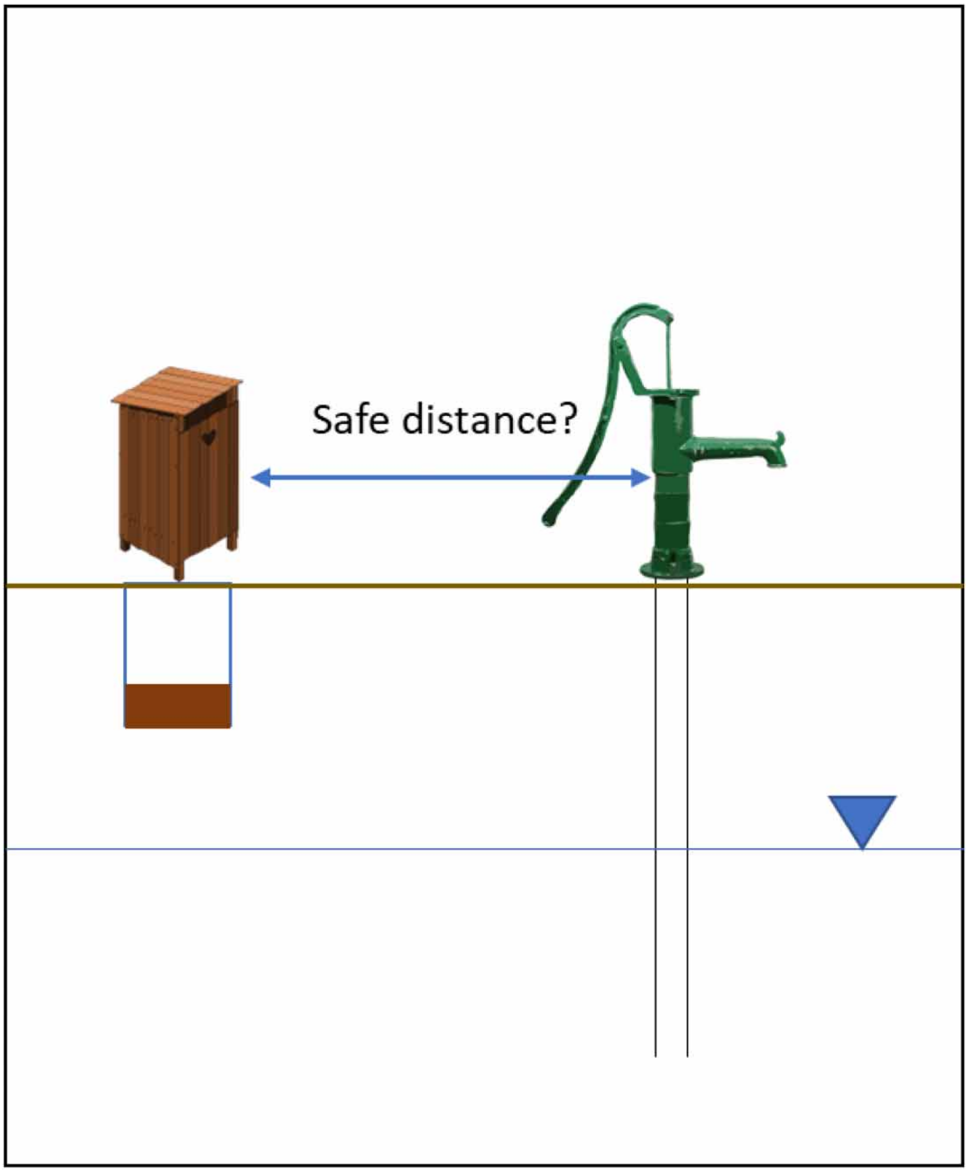
Latrines are an effective way for people in low- and middle-income countries to move away from open defecation. Guidelines are used to provide a recommended horizontal setback distance from a latrine to a downgradient well to ensure the safety of the well from subsurface contaminants. We collected 107 journal papers, books, and reports to critically review the recommended setback distances and how these recommendations are derived. It was discovered that the four most common guidelines/reviews are all based principally on just four field studies, all of which were conducted over 40 years ago, which casts doubt on a frequently used one-size-fits-all approach. More recent methods for latrine siting use both field data and some sort of modeling component to account for the different site conditions, but these models have not been verified for use outside their respective studies. They are also limited in how they consider the hydraulic connection between the latrine and the well. We recommend that future siting guidelines should focus more on vertical separation, include chemical contamination, and be based on models describing how latrines and wells are hydraulically connected, along with the fate and transport of potentially harmful contaminants.

Key words: groundwater, latrine, modeling, pollution, setback distance, toilet

HIGHLIGHTS

- Most common guidelines are based on four field studies, conducted over 40 years ago.
- Latrine-siting guidelines must account for the vertical transport of pollutants.
- Siting guidelines should account for the distinct features of loadings and transport of bacteria and viruses.
- In situ treatment technologies and resource recovery strategies may influence pollutant loadings.
- Models can assist with site-specific siting.

GRAPHICAL ABSTRACT



INTRODUCTION

Worldwide, about 1.6 billion people use latrines, with about 40 million new users each year (WHO/UNICEF 2021). The steady increase in latrine usage is in response not only to progress towards meeting Sustainable Development Goal #6 but also to the growing population in low- and middle-income countries (LMICs). Although increased latrine coverage is positive for the world's efforts to achieve adequate and equitable sanitation for all, latrine pits are not primarily constructed to prevent fecal contamination from entering subsurface soil or groundwater, only to physically separate humans from their waste (Orner *et al.* 2018). This means a pit latrine can act as a point source of chemical and/or microbial pollution to the subsurface, especially if soil properties do not provide sufficient assimilation of pollutants, and/or if the groundwater table is shallow. This may be particularly important where community members access shallow groundwater via hand-dug wells or handpumps (Smits & Sutton 2012; Butterworth *et al.* 2013).

To address the challenge of providing improved sanitation while also protecting easily accessible water supplies, governments, international agencies, and non-governmental organizations have published siting guidelines that provide recommended vertical distances between the bottom of a latrine and the water table, as well as horizontal distances between an individual latrine and nearby sources of water (known as the 'setback' distance). However, the recommended distances of these guidelines, specifically horizontal, are often based on a 'one-size-fits-all' approach that does not consider local conditions that influence the transport of microbial and chemical constituents from a latrine pit (Wilcox *et al.* 2010; Graham & Polizzotto 2013; Ngasala *et al.* 2021). Another limitation with many of the previously published recommended distances is that several of the guidelines have been passed down over the span of decades without critical re-evaluation of their validity or use of new knowledge.

Several previous papers have reviewed important aspects of latrine installation, usage, and/or maintenance. These include best emptying practices (Thye *et al.* 2011), latrine coverage and use (Garn *et al.* 2016; Igaki *et al.* 2021), usage and performance in urban areas (Nakagiri *et al.* 2016), attitudes towards latrines and culturally appropriate technologies in indigenous communities (Libby *et al.* 2020), groundwater pollution from latrines (Banks *et al.* 2002; Dzwairo *et al.* 2006; Templeton *et al.* 2015; Dzwairo 2018), technologies for in-situ treatment (Saxena & Den 2022), and potential of the technology for resource recovery (Orner & Mihelcic 2018). Although some of these studies briefly or tangentially discuss siting guidelines or safe setback distances, none of them critically evaluate the recommended horizontal distances that are commonly used or cited.

Graham & Polizzotto (2013) have provided what is, up until now, probably the most comprehensive review of latrine-siting guidelines. Important information provided by these authors includes an estimation of the number of people using latrines globally, the impact pit latrines have on groundwater, and gaps in our knowledge about the potential pollution pit latrines can have on groundwater. Notably, they also cite four prior latrine-siting studies (Lewis *et al.* 1982; Franceys *et al.* 1992; Sphere Project 2011; Water Aid 2011) that recommend distances of 15–50 m between a latrine and a nearby water source. However, despite the contributions of Graham & Polizzotto (2013), they do not look into the history of the recommended siting distances, nor do they evaluate how those guidelines have evolved over time. Therefore, appropriate siting for latrines cannot yet be considered a settled issue.

Furthermore, although providing sanitation for all is one end aim of Sustainable Development Goal #6, accomplishing this goal via increased latrine coverage and usage may have an unintended consequence of impeding the world's ability to provide universal and equitable access to safe and affordable drinking water for all. This may especially be true in contexts or communities where households employing on-site sanitation are also applying principles of self-supply to access shallow groundwater (Smits & Sutton 2012). In rural areas especially, there is a push not only to provide better quality of water, but also to improve accessibility of that water, because safely managed water is defined as an improved source that is 'accessible on [the] premise' and 'available when needed' (WHO/UNICEF 2021). Efforts to improve accessibility may therefore have the unintended consequence of bringing water sources closer to latrines that threaten the quality of the water. Thus, it is important to acknowledge the balance between providing equitable sanitation with providing safe and affordable drinking water for all. The provision of safe drinking water cannot be assured without careful consideration of where people dispose of their excrement.

Accordingly, in order to better inform more integrated decisions regarding the simultaneous provision of sanitation and safe water, the objectives of this critical and comprehensive review are to: (1) compile and summarize past papers recommending horizontal distances between a latrine and water source, (2) assess the most commonly used guidelines to determine the origin of each recommended horizontal distance, (3) critically assess the limitations or range of applicability of the most common guidelines, (4) discuss recent trends and advancements in properly locating latrines away from water sources, and (5) recommend actions that can be integrated into future latrine-siting guidelines. Our overall goal is to provide new insights that will assist the world in achieving multiple targets of Sustainable Development Goal #6, specifically the three targets of achieving universal and equitable access to safe and affordable drinking water for all, achieving access to adequate and equitable sanitation and hygiene for all, and improving water quality by reducing pollution.

METHODOLOGY

Stage 1: Database search

To obtain previously published books, journal papers, reports, or other documents recommending a horizontal setback distance, the search engines of Web of Science and Google Scholar were used. The different phrases and key words used in the search engines to gather literature were: 'latrine distances,' 'latrine siting guidelines,' 'latrine setback distances,' 'pit latrine safe distances,' 'on-site sanitation distances,' and 'latrine separation distance.' Manual searches were also performed using academic books the authors already had in their possession. For the search, we took any paper studying or discussing latrines, and considered a pit latrine and its various modifications to include a pit that collects and stores excreta as described by Feachem *et al.* (1981), Tilley *et al.* (2014), and Orner *et al.* (2018). All documents recommending or discussing a setback distance – whether those documents were review articles, research articles, reports, or 'gray' literature (pamphlets, documents issued by unknown organizations, etc.) – were included in the following analysis. We included gray literature as some investigators might use Internet search engines (like Google) instead of scholastic databases (e.g., Web of Science), and we wanted our review to include all potential possibilities.

Stage 2: Ancestry search

From each document obtained from Stage 1, we determined if that document contained a recommended latrine setback distance. If so, we recorded the distance recommended and the source (citation) on which that recommended distance was based, i.e., the 'ancestor' of the paper identified in Stage 1. Then, the process was repeated iteratively with each identified ancestor. A paper was only included as part of the citation history (ancestry) if it was explicitly cited when it discussed setback distances between a well (or another type of water source) and a latrine. The iterative ancestry search process continued until either an original reference (a paper doing its own field research without mentioning any other relevant papers) was reached, two consecutive sources were in a language other than English, a reference was reached that had already been identified in the ancestry of another paper, or a source listed no references and attempts to contact the authors to obtain the references they used in the document failed. Siting guidelines in relation to septic tanks (as opposed to latrines) were not reviewed; if the search led to a paper considering septic tanks explicitly, it was included in the literature gathered, but then there was no iteration after the septic tank paper was counted. The literature search ended on November 14, 2022.

Stage 3: Document classification and citation counts

Each of the documents identified in Stages 1 and 2 was assigned one of three classifications. *Field studies* are documents that conduct their own data collection and make a latrine-siting recommendation based wholly or in part on those data. *Reviews* are documents that do not conduct original research but synthesize previous work done by others. Any document not falling into one of these two categories was designated a *guideline document*. These are generally documents that focus on some aspect of latrine management and, as part of their analysis, refer to a recommended setback distance that had previously appeared in a separate document.

The final step was a citation count. We counted how many times each document in our overall set (from Stages 1 and 2) was cited by any other document within the set. Of particular interest is which field studies and/or guideline documents are cited most often, as this is likely to give an indication of the setback distances that are most commonly used in practice.

RESULTS AND DISCUSSION

Objective 1: Compile past documents

From the original database search (Stage 1), 51 documents were identified (see Supplementary material, Figure S2). From these 51 original documents, 56 additional 'ancestor' documents were found searching the reference history in Stage 2, for a total of 107 documents gathered. Any document that was identified in both the database search (Stage 1) and the ancestry search (Stage 2) was counted as part of the original database search. A complete list of the documents found from the search (and the phrase used to find each one) and reference history can be found in Supplementary material, Table S1. Breaking it down by category, there are 52 field studies, nine reviews, and 46 guideline documents.

Objective 2: Determine origin of common siting guidelines

After going into the citation history of each collected document, we were able to determine the most-cited pieces of literature, which are shown in Figure 1. Figure 1 shows the 26 most commonly cited field study papers, guideline documents, and reviews found in the citation history. That figure also provides a citation family tree that indicates from where the recommended distances are derived. The documents included in Figure 1 are those that were cited at least twice by other documents found in the literature search. The complete citation family tree (including all 107 papers, not just the 26 most common) can be found in Supplementary material, Figure S1.

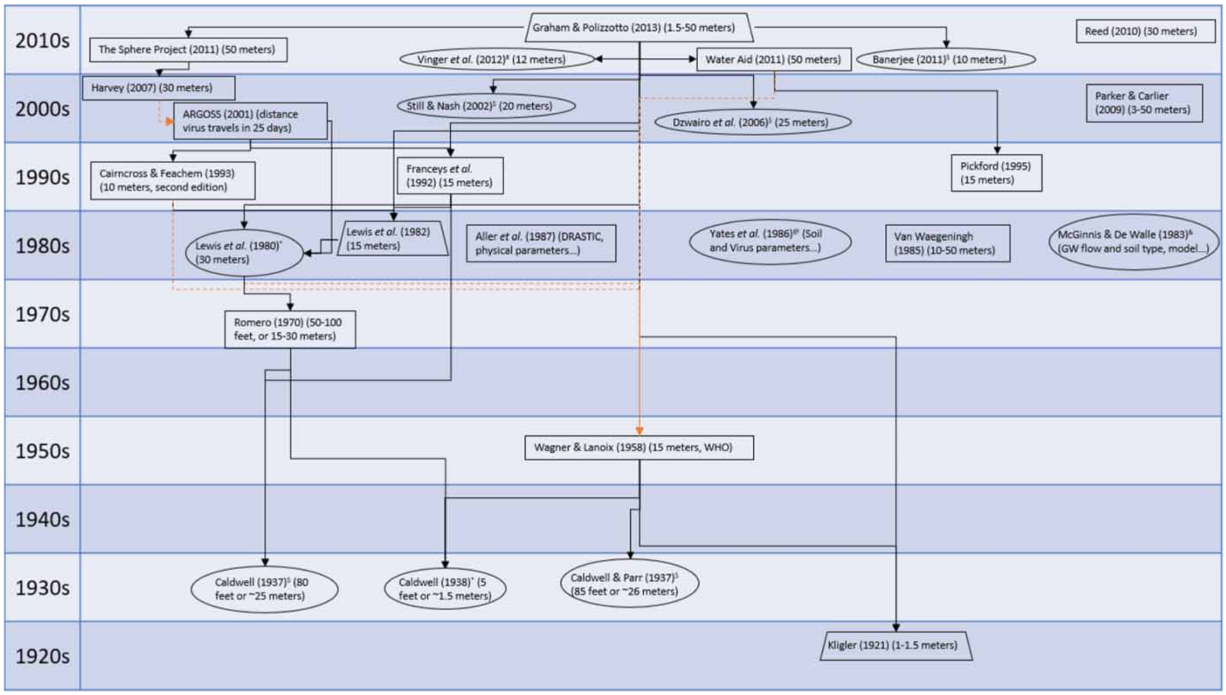


Figure 1 | Citation family tree for siting a latrine near a water source. Black lines represent direct citations while dashed orange lines mean there is one degree of separation in the citation history, with the intermediate reference not included in the figure. References placed in trapezoids are reviews, references in rectangles are guideline documents, and references in ovals are field studies. * denote field studies done on bacteria; @ denote field studies done on viruses; & denote field studies done on physical parameters; $ denote field studies done on both bacteria and chemicals; and # denote field studies done on chemicals only.

From Figure 1 it can be seen that 20 of the 26 most commonly cited documents are connected in some way. The four most commonly used guideline documents and reviews are those of Franceys *et al.* (1992, cited nine times), ARGOSS (2001, cited nine times), Lewis *et al.* (1982, cited eight times), and Wagner & Lanoix (1958, cited four times). These total citation numbers were obtained from the larger set of 107 papers provided in Supplementary material. Three of these four documents (Wagner & Lanoix 1958; Lewis *et al.* 1982; Franceys *et al.* 1992) recommend a horizontal setback distance of 15 m for placement of a latrine near a water source. The fourth of these (ARGOSS 2001) recommends that the latrine be placed at a distance equal to that which viruses can travel in the subsurface in 25 days (based on local soil type and decay rate).

Of the 46 identified guideline documents, 34 were found to be connected to the four most cited documents in their ancestry (this includes the four most cited documents themselves). From Figure 1, it can be seen some of the four most cited papers even cite each other (e.g., Franceys *et al.* (1992) citing Lewis *et al.* (1982), and ARGOSS (2001) citing Franceys *et al.* (1992)). The field papers most commonly cited are those of Lewis *et al.* (1980, cited eight times), Dzwairo *et al.* (2006, cited six times), Caldwell & Parr (1937, cited six times), Caldwell (1938, cited four times), and Still & Nash (2002, cited three times).

Objective 3: Critically assess common guidelines

From the analysis of the collected literature, we noticed three key limitations of existing siting guidelines. First, the four guideline documents or reviews most often cited for latrine distance siting – those of Franceys *et al.* (1992), Lewis *et al.* (1982), ARGOSS (2001), and Wagner & Lanoix (1958) – were found to directly cite a total of only four field studies concerning latrine pollution (Caldwell 1937; Caldwell & Parr 1937; Dyer *et al.* 1945; Lewis *et al.* 1980). These four field studies are summarized in Table 1 and resulted in recommended distances of 25, 26, 15, and 30 m, respectively. Although the field studies are diverse in location and local conditions (the U.S. study (i.e., the Caldwell papers) covers a clay to coarse sand (e.g., silty loam), the India study (Dyer *et al.* 1945) covers clay to sand, and the Botswana study (Lewis *et al.* 1980) covers a clay soil type), four field papers is probably not enough for strict guidelines to be established. These field papers are also old enough to likely be outdated, with three of the four field papers being at least 78 years old, so it would be wise to include newer field studies

Table 1 | Field papers directly cited by the four most cited latrine-siting documents

Paper	Location	Site description	Recommended distance, and how it was determined	Directly cited by
Caldwell & Parr (1937)	Alabama, USA (rural)	Study includes soil content, soil pH. Soil type ranged from clay to coarse sand Wells drilled to ~4 m (12 ft)	85 ft (or ~26 m) Found by measuring and observing the concentrations of a chemical stream consisting of nitrate, nitrite, and chloride at monitoring wells of certain set distances	Wagner & Lanoix (1958)
Caldwell (1937)	Alabama, USA (rural)	Study includes soil content, soil pH. Soil type ranged from clay to fine gravel Wells drilled to ~4 m (12 ft)	80 ft (or ~25 m) Found by measuring and observing the concentrations of *B. coli* at monitoring wells of certain set distances	Franceys *et al.* (1992)
Dyer *et al.* (1945)	India (location unknown)	Study includes soil content, measuring water table depth, ground water temperature, conductivity, acidity, free ammonia, BOD Soil type ranges from clayey at top decreasing in clay content to sand at the bottom Wells drilled to ~8 m (27 ft)	50 ft (or ~15 m) Found by measuring bacteria and chemical concentrations in wells placed away from latrine. Only found contamination (chemical) to travel as far as 15 ft, but says 50 ft to try to account for different soil content	Wagner & Lanoix (1958)
Lewis *et al.* (1980)	Botswana (peri-urban)	Study includes measuring electrical conductivity, bacterial concentration, pH, transmissivity, storage coefficient. Soil type is clay with exposed bedrock Wells drilled up to 22 m	30 m Bacterial and chemical measurements were obtained from observation wells and pumping tests. Found bacterial contamination as far as 25 m, but most likely gives 30 m to serve as a buffer	ARGOSS (2001), Lewis *et al.* (1982)

(preferably from this century) for establishing recommended guidelines. It is therefore problematic that the four most commonly cited documents are based on just a small number of probably outdated field studies.

The second limitation of the four most commonly cited guideline documents is that three of them (Wagner & Lanoix 1958; Lewis *et al.* 1982; Franceys *et al.* 1992) provide a recommended setback distance of 15 m, but the distances traveled by the pollution in the field studies listed in Table 1 are greater than this, in the range of 25–50 m. To be protective of health, we would expect the recommended setback distance to be greater than – not lower than – the distance traveled by pollutants of concern. To explain this surprising observation, we note that the four commonly cited guidelines are often based on just one particular pollutant from a field study, and did not consider all of the pollutants measured (like chemical) in the study, even if it is found those pollutants travel further than the pollutant they considered in their respective document.

The third limitation of the four most commonly cited guidelines is that three of them (Wagner & Lanoix 1958; Lewis *et al.* 1982; Franceys *et al.* 1992) use a 'one-size-fits-all approach' for developing a recommended setback distance. Specifically, these three guideline documents all recommend a horizontal setback distance of 15 m, with little to no consideration of the local site conditions. However, it is known that local site conditions can be important towards proper siting of a latrine near a water source. For example, WEDC (2023) identified at least six factors that vary from site to site and can affect proper latrine siting (Figure 2). We therefore contend that a blanket recommendation of 15 m as a setback distance is over-simplified and may not apply in many contexts.

To elaborate on just two such locally varying factors in Figure 2, we consider the importance of soil type (factors 2 and 4 in Figure 2) and depth of the vadose zone (factor 3 in Figure 2). It is known that soil type affects how microbial contaminants travel (Yates *et al.* 1988). Fewer studies have investigated the removal of microorganisms in vadose zones compared with removal in groundwater and soils (Schijven *et al.* 2017). However, it appears that in soil media, pumice sand and uniform sand are reported to have better rates of microbial removal (Pang 2009). Estimates on the removal rate of various microorganisms for distance traveled ($\log_{10}$/m) are also reported for different subsurface media (Pang 2009). Chemical contaminants such as nitrate that can adversely affect human health are often considered to travel at the same rate as water (Templeton *et al.* 2015). Considering the four most cited papers for latrine siting, Franceys *et al.* (1992) and Lewis *et al.* (1982) both

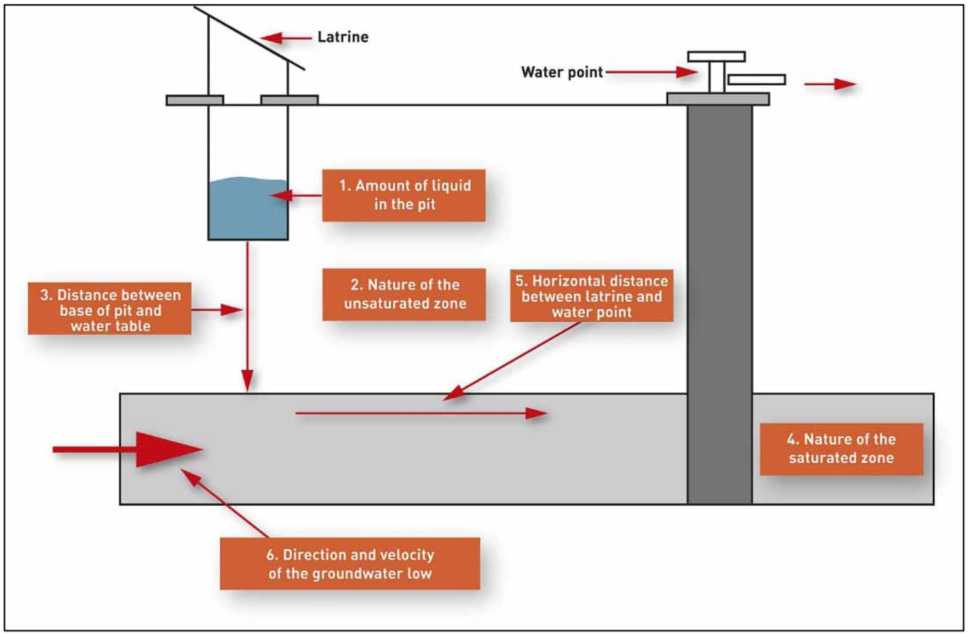


Figure 2 | Parameters to consider when siting a pit latrine to protect local groundwater resource (reprinted with permission of WEDC, Loughborough University (2023), based on Sugden (2006)).

suggest that in finer soils, latrines can be placed closer to wells as finer soils do a better job of limiting pathogen movement. ARGOSS (2001) does not provide a recommended distance but instead provides a risk level and states the distance should be based on how far viruses are expected to travel in 25 days. Wagner & Lanoix (1958) give 15 m as a general distance to avoid bacterial contamination.

Except for Lewis *et al.* (1982), none of the other most cited guideline documents considers the depth of the water table in their siting guideline. If the water table is deep enough, it may take too long for pathogens to reach there before they either die off or reduce in concentration. This could play a large role in latrine siting in situations where a household or community hand pump (or shallow well) that accesses shallow groundwater is placed close to house(s) and latrines. Assuming a flat ground surface, the flow of liquids and contaminants from a latrine is primarily vertical and not horizontal. This is especially important when the water table is high. Templeton *et al.* (2015) had previously made the important point that depth to the vadose zone (and not the horizontal distance between a latrine and a well) is actually the most important parameter when it comes to latrine placement and siting. Much of the data provided by other studies supports this contention of Templeton *et al.* (2015); for example, Islam *et al.* (2016) found that pollution traveled only a short horizontal distance of 4.5 m when the vertical distance between the latrine and water table was large (7.5–20 m). Also important is the knowledge that hand pumps are only effective in lifting water down to 10 m (Marshall 2017).

Objective 4: Review recent trends and advancements

The four most commonly cited documents – those of Franceys *et al.* (1992), Lewis *et al.* (1982), ARGOSS (2001), and Wagner & Lanoix (1958) – are all at least 20 years old. In the past two decades, there has been a lot of additional work on developing latrine-siting guidelines. Based on our literature review, we identified three trends and advancements that are prevalent in much of the recent literature.

Firstly, within the past 20 years, there has been a shift regarding how the recommended setback distance is found. This is because studies originated in the new millennium that included a modeling component to determine a safe distance between a latrine and a water source. These water sources range from drilled wells, to canals and lakes. Modeling enables a user or researcher to account for physical, chemical, and biological processes while making estimates for a setback distance. These modeling papers also move away from the one-size-fits-all latrine-siting approach used by older papers and discussed above to a site-specific approach. However, it should be noted that Lewis *et al.* (1982) is the earliest identified paper that considered the hydrogeological environment while developing a five-step decision tree (something that could be considered a 'model' in Figure 6.2 in their paper) for proper latrine distancing. Specifically, they looked at the hydraulic loading rate of the latrine, groundwater depth below the latrine, and soil type. Their paper looked at the relationship between a single latrine and a shallow borehole.

Four representative papers involving modeling are further highlighted in Table 2. What is also of note is the parameters found in the field and used in their respective models in Table 2 tend to be more and of greater detail than the parameters found in Table 1. For example, the porosity is considered in each of the models which can play a significant role in the transport of microbial contaminants. A couple of the models evaluate the different dispersivities expected in the subsurface which play a part in the fate and transport of both microbial and chemical contaminants.

Compared to the distances provided in Table 1, all the distances in Table 2 except one are greater than the Table 1 distances. Table 1 distances range from 25 to 30 m and Table 2 distances range from 22 to 75 m, some of which are more than two times greater than in Table 1. Specifically, distances from the latrine to the water source were found to be 22, 75, 34, and 48 m from the four references covered in Table 2 (in order they appear). Although the references in Table 2

Table 2 | Papers using modeling to determine a safe, horizontal setback distance, and the type of model they used

Paper	Location	Field parameters gathered/used in model	Study area description	Model used and distance derived	Mechanisms (and microbial/chemical species) considered in model
Megha *et al.* (2017)	India (urban)	Soil content, pH, conductivity, bulk density, saturated soil permeability, effective porosity, sorption capacity of soils	Study is based around the Canoli Canal in Kozhikode City. Varying soil types ranging from sandy to sand clay (11 sites total)	Freundlich isotherm modeling, two-way ANOVA analysis, linear regression between adsorption capability and minimum safe distance Minimum distance of 22 m in sandy soil, less in other soils (6.5 m in sandy clay)	Sorption (lambda phages)
Molin *et al.* (2008)	India (peri-urban)	Hydraulic conductivity, porosity, hydraulic gradient, latrine injection rate, well extraction rate	Study is based in areas of the state of Kerala. Soil type is not specifically stated	Dose response model ~75 m	Inactivation (Hepatitis A virus)
Ngasala *et al.* (2021)	Tanzania (urban)	Soil material, hydraulic conductivity, vertical anisotropy, horizontal anisotropy, depth of different layers, porosity, recharge, longitudinal dispersivity, horizontal transverse dispersivity, vertical transverse dispersivity	Study is based in the city of Dar es Salaam. Took samples from 63 wells. Soil types were fine sand (top 10 m), clayey sand (10–30 m deep), and sandy clay (30–60 m deep)	MODFLOW and MT3DMS used for groundwater and transport modeling, then a linear regression model Distance of at least 34 m	Advection, dispersion, source/sink mixing (NO_3^-)
Pang *et al.* (2003) (septic tank)	New Zealand (peri-urban)	Longitudinal dispersivity/distance ratio, longitudinal dispersivity, vertical dispersivity, depth of aquifer, effective porosity of aquifer, bulk density, hydraulic gradient, hydraulic conductivity, pore water velocity	Study is based around an open water lake. Looks at two septic tank systems in different areas. Soil type is pumice	AT123D. Distance of 48 m	Advection, dispersion, irreversible filtration, and die-off (enteric viruses)

Distances are all site-specific for each paper.

all performed extensive modeling work at their respective sites, these models have not been tested in other locations or with other contaminants (besides the ones in the original study). Something else the authors do not consider is how *in situ* treatment technologies (e.g., permeable reactive barriers (Rao & Malini 2015; Naser *et al.* 2019; Suhogusoff *et al.* 2019)) or adding additional resource recovery infrastructure (e.g., a urine diverting component (Tilley *et al.* 2014; Mkhize *et al.* 2017; Naughton *et al.* 2018)) to the latrine could help reduce the recommended distance. Even though recent papers have made advancements with the methods used to get a setback distance, there is no clear consensus on what mechanisms of contaminant growth and removal to consider.

The large range of distances in Table 2 may result from the second recent advancement identified: improved estimation of microbiological behavior in the subsurface. This leads to a better understanding of the mechanisms of microbial contaminant growth and removal a specific model considers, building more robust models. However, the biggest factor affecting these distances is likely inactivation of the respective microbial contaminant. The modeling paper with the largest distance (Molin *et al.* 2008) modelled two viruses and one bacterium and determined the inactivation rate is likely the cause of why one virus (Hepatitis A) had such a higher travel distance than the other two pathogens (Rotavirus and *E. coli*).

The type of contaminant modelled also may play a part in the large differences between the distances in Tables 1 and 2. The papers in Table 1 either considered bacteria or chemicals while the paper in Table 2 with the longest distance (Molin *et al.* 2008) also considered viruses (while also considering chemicals and bacteria). When considering both bacteria and virus fate in the subsurface and the risk they pose to infectious disease, the following features are important in influencing environmental transmission: (1) the pathogen needs to be excreted in high numbers, (2) it must persist in the environment, and (3) it must also be highly infectious (Aw 2018). Concentrations of viruses and bacteria measured in human feces are typically 10^6–10^9 per gram of feces. Concentrations of protists (and helminths) though are much, much lower. Latrines located in developing regions of the world, where diarrheal diseases and intestinal parasites are more prevalent, are expected to experience a higher loading of pathogens versus developed regions (Fletcher *et al.* 2013). In general, it is reported that for the same media, virus and bacteria removal rates are in the same order of magnitude, though they can be lower or higher (Schijven *et al.* 2017), and while helminths are known to persist in the environment, their excretion in feces is relatively low and because of their size are thought to pose a low risk from transport out of the latrine pit (except during improper management of fecal sludge). The risk to a water supply associated with the excretion of viruses and bacteria is thus higher than for other classes of pathogens.

Furthermore, there are multiple parameters affecting both bacteria and viruses such as temperature, microbial activity, moisture content, pH, and organic matter (Yates *et al.* 1988). Yates *et al.* (1988) and Matthes & Pekdeger (1981) determined the one factor most affecting the survival of viruses was temperature, where the length of time (in days) for virus survival ranging from a short time period of days (higher temperatures) to months (colder temperatures). The temperature in the subsurface is known to vary throughout the day (Saito *et al.* 2006) from 7 to 25 °C in the upper 12 cm of soil. However, Holden & Fierer (2005) point out that the temperature range of the vadose (unsaturated) zone decreases considerably as depth increases as it becomes more insulated. With many pit latrines already being dug ~2 m deep, there might not need to be a need to consider this temperature variation.

There are many similar ways bacteria and viruses travel within the subsurface. They both move better in more saturated soils, and with higher hydraulic loading rates (i.e., rainfall recharge). In the case of latrines, much of the hydraulic loading would come from urine, unless there was a pour-flushing mechanism involved as well (or the latrine also accepts effluent from water-based hygiene). An average human excretes anywhere between 0.6 and 1.1 L of urine a day (up to 0.45 m^3/year) (Franceys *et al.* 1992). Assuming the average person adds 0.060 m^3/year of fecal matter (Franceys *et al.* 1992) with water content 75% (UMass n.d.), an additional 0.045 m^3 of water is annually added into the pit from fecal matter. Thus, the presence of a urine collection system (e.g., Tilley *et al.* 2014; Trimmer *et al.* 2016; Mkhize *et al.* 2017) to collect valuable nutrients (Mihelcic *et al.* 2011) will significantly reduce the hydraulic loading of the latrine pit into the subsurface. Another important factor in hydraulic loading associated with latrine usage is the number of household members using the latrine or whether the latrine is shared amongst several households. Besides Molin *et al.* (2008), these modeling papers do not consider the varying degree of hydraulic loading. There also does not seem to be much conversation relating to the hydraulic connection between the latrine and the water source. If someone has an understanding of the hydraulic connectivity (or the lack thereof which would be best) between the latrine and the water source, they can make better siting decisions.

Because viruses are smaller compared to bacteria (about 0.02 μm for viruses to 0.4 μm for the smallest bacteria), some mechanisms affecting transport from a latrine pit to groundwater will be different. For example, the mechanism of filtration is expected to be more effective with bacteria than viruses with bacteria being more easily filtered out due to their larger size. Matthess *et al.* (1988) states another reason for bacteria filtering better could be due to their motility adding to diffusion and their tendency to aggregate more, increasing the diameter and thus allowing better filtration.

The third trend revised recommended setback distances, is a result of modeling, improved estimation of microbial behavior, and accounting for site-specific factors like soil type. Whereas the four old field papers said 15 m, now there are new field papers suggesting greater than 15 m, so the recommendations have changed in the past 20 years. This trend also comes from comparing the papers in Tables 1 and 2. There are three overarching differences identified: (1) The timeline of the studies varies. For example, the field papers in Table 1 range from a few months to 1.5 years, while no timeline is specified in modeling papers in Table 2. (2) Although the methods used in Table 1 appear adequate, the newer methods used in Table 2 tend to result in more conservative approaches and larger setback distances. (3) The field papers in Table 1 did not consider multiple locations, unlike the modeling papers reviewed in Table 2. Specifically, the field papers (Caldwell (1937) and Caldwell & Parr (1937)) only visited one site and looked at soil log profiles while the modeling papers (Megha *et al.* (2017) and Ngasala *et al.* (2021)) looked at a range of soil types and included those soil types when they calculated the recommended horizontal distance in their models.

Objective 5: Recommend future actions for latrine siting

More authors are now incorporating modeling in their analysis to recommend a setback distance, oftentimes combining different software and techniques to the data obtained in the field. This methodology appears to be the best way to identify a safe distance between a latrine and a water source. However, not all models are constructed the same and have limitations as shown in Table 2 with the mechanisms of microbial growth and removal they consider. So, an important question is, what is the most optimal method to estimate site-specific distances between a latrine and a water source? The different mechanisms of microbial growth and removal will be affected by the local site conditions, so it is important to first understand those. Figure 2 previously showed several local conditions to consider when looking to properly site a latrine that will protect a local water source (in this case a water point or shallow well accessing groundwater). Therefore, it is imperative to understand what mechanisms of growth and removal to include in a model and just as importantly exclude different pollutants at different field locations.

Additionally, there needs to be a greater effort to understand the fate and transport of chemical pollution from latrines. Many of the latrine studies focus on microbial contaminants which can be chemically disinfected at the household level. However, treatment of chemical contaminants at the household or small utility level is much more complex for species such as nitrate, antibiotic residues, and other chemicals such as pharmaceuticals previously mentioned by Graham & Polizzotto (2013). Accordingly, future research needs to look more deeply not only into the fate and transport of chemical contaminants from a latrine to the subsurface, but also at what levels pose an unacceptable risk to users of an impacted water supply.

Something else to consider in the development of a model is the issue of when certain field parameters are not determined in the field but are instead obtained from established values in the literature. This is likely to happen in parts of the world that lack established subsurface data or the resources to make site-specific subsurface measurements. Yates *et al.* (1986) have addressed this issue for the siting of septic tanks by using a kriging method, but only for a localized location. What is needed is the establishment of a global database for soils anyone can access to look at the ranges for different physical characteristics of soils for a particular area or region. The Food and Agriculture Organization of the United Nations has a soil portal leading to some physical data for soils worldwide, but it still lacks important data (such as hydraulic conductivity) to use for modeling. There will also be additional uncertainty in the use of any model because of changes in local weather and influences of climate change on local weather which can change groundwater table depth, vadose zone moisture content, and regional flow; however, models have the ability to account for these changes.

The parameters given the most attention when considering proper latrine siting should be reevaluated. As previously discussed, there is a compelling argument that the vertical distance from the bottom of the latrine to the top of the water table is the most important parameter to consider when siting a latrine near a downgradient well. However, previous studies and guidelines mostly focus on the horizontal distance between the latrine and the well and do not give enough attention to siting guidelines based on the vertical distance. Therefore, future research should look more closely at how the depth of the vadose zone affects the minimum acceptable horizontal setback distance.

Future research should also consider the context of where a latrine is being sited, that is, in a rural, peri-urban, or urban area. Latrine siting in areas that do not have piped water may already pose a greater risk to groundwater due to latrine density and physical space constraints. This must also consider informal settlements and slums. The presence of a piped water source may alleviate this risk; however, piped water systems that are not maintained at sufficient pressures can be contaminated from the surrounding subsurface due to transient intrusion and backflow (WSDOH 2006; Kumpel & Nelson 2014). The impact of latrine technologies design to capture nutrients or decrease pathogen or chemical concentrations exiting a pit need to also be considered as was addressed previously. Such technologies could be especially useful in peri-urban and urban areas.

CONCLUSION

The overall goal of our critical and historical review is to move towards global achievement of access to adequate and equitable sanitation and hygiene for all, while also ensuring that local water resources are not impacted by the placement of onsite sanitation via the construction of latrines. A citation tree showed that the four most common latrine-siting documents directly related to four field studies that investigated groundwater pollution from latrines with 20 of the 26 most commonly used papers are connected in some way. These four field papers recommend a distance ranging from 15 to 30 m, with three of these papers having a greater distance than any of what the four most cited guidelines and reviews recommend (i.e., 15 m). More recent field papers looking into proper latrine siting often incorporate a modeling component to provide a more sophisticated setback distance. Several modeling papers suggest the safe distances from a latrine to a water source should be 22–75 m, depending on chemical pollutants and if the pathogen of concern is a bacteria or virus.

We therefore conclude that new ways to estimate a low-risk setback distance of latrines from a water source are needed in order to better understand the impact the vadose zone has on pathogen fate and transport. There also needs to be a better understanding of the impact of technological advances on latrines that aid pathogen destruction or resource recovery influence pathogen and chemical loading into the subsurface. Other factors that influence this process of finding appropriate setback distances are locations where self-supply is used to access shallow groundwater or piped water systems that are not maintained at sufficient pressure. The endgame of proper latrine siting is likely some sort of model accounting for site-specific conditions and the hydraulic connection between the well and latrine. As previously stated, there will always be some uncertainty with modeling as it is difficult to account for seasonal variation due to climate change as well as space constraints depending on whether the area is urban, peri-urban, or rural, but modeling appears to have the highest ceiling to solve this problem.

Although much literature was gathered during this review, it is not all-encompassing. Future research should look at other on-site technologies other than latrines. One example is critically reviewing similar papers that evaluate the safe distance of a water supply to a sited septic tank, a more advanced technology to a latrine more commonly associated with water-flushed toilets. Though we were careful in searching for literature that covered our definition of what a latrine was in regard to the objectives of this review, we are also aware that some investigators use wording such as toilet, septic tank and latrine interchangeably, potentially leading to some missed literature by the authors. We believe our search methods have accounted for a sizeable majority of key papers. However, future efforts may consider not only latrines, but also septic tank siting guidelines to see what the distances are for each.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 13 June 2023; accepted in revised form 21 September 2023. Available online 30 September 2023