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How we assess water safety: A critical review of sanitary inspection and water quality analysis

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Abstract

Sanitary inspection is used in low-, medium- and high-income settings to assess the risk of microbial contamination at water sources. However, the relationship between sanitary inspection and water quality is not well understood. We conducted a critical literature review and synthesized the findings of 25 studies comparing the results of sanitary inspection and microbial water quality analysis. Most studies used sub-standard sanitary inspection and water quality analysis methods, and applied simplistic comparisons that do not characterize the complexity of the relationship. Sanitary risk score was used to represent sanitary inspection results in 21 (84%) studies; of which 12 (57%) found a significant association between score and microbial water quality and nine (43%) did not. Participatory sanitary inspection (12%) and reporting results back to communities (24%) were uncommon. Most studies relied on laboratory-based water quality analysis as an independently sufficient measure of safety, but reported inadequate quality control (52%) and/or sub-standard sample processing methods (66%).

We found that sanitary inspections could contribute to improving water safety through four mechanisms: guiding remedial action at individual water sources, allowing operators and external support programs to prioritize repairs, identifying programmatic issues, and contributing to research. The purpose of the sanitary inspection should be considered when planning sanitary inspection execution, data analysis and reporting to ensure appropriate methods are employed and results are fit for purpose. Further exploration should recognize that sanitary risk factors represent sources of contamination, pathways for contaminants to enter water supplies and breakdowns in barriers to contamination. These different sanitary risk factor types have different and inter-dependent effects on water quality.

Highlights

- Preventive, risk-based management is recommended to ensure drinking water safety
- Literature is divided on relationship between sanitary inspection and water quality
- Confusion about the purpose of sanitary inspection leads to flawed use
- Researchers trust water quality analysis results despite poor quality control
- Four mechanisms are identified through which sanitary inspection can improve safety

Keywords

microbial contamination; sanitary survey; water quality assessment; risk assessment; water source management; sanitary risk

1. Introduction

The baseline assessment for monitoring United Nations Sustainable Development Goal (SDG) 6 – to ensure access to water and sanitation for all - estimates that 89% of the global population uses a basic water service (WHO/UNICEF, 2017). Basic service is defined as use of an improved water source – one that is protected from contamination by the nature of its design – within a 30-minute round trip. Using an improved water source, however, does not guarantee water free of microbial contamination. It is estimated that at least one billion people worldwide use sources classified as an improved type that are contaminated (Bain et al., 2014a; Onda et al., 2012). National case studies in various settings suggest reductions of 7%-40% in estimates of the proportion of the population accessing safe water when water quality parameters are considered (Bain et al., 2012; Godfrey et al., 2011). Furthermore, one study estimated that one quarter of the people using water free from contamination at the time of sampling are using water sources with at least two sanitary risk factors. For water to be considered safe, it must be free of contamination at the time of sampling, as well as free from risk of future contamination. Using this definition of safe water, it is estimated that three billion people are using unsafe water (Onda et al., 2012).

The World Health Organization (WHO) Guidelines for Drinking-Water Quality (GDWQ) identify fecal contamination as the greatest risk to human health associated with drinking water quality (WHO, 2017). Fecal contamination is one of the most monitored water quality hazards because of the severity of its health impacts and high probability of occurrence, especially in areas without sufficient sanitation (Ashbolt, 2004; Hunter et al., 2002). The indicators of choice in microbial water quality analysis are *Escherichia coli* (*E. coli)* or thermotolerant coliforms (TTC), with specific pathogens monitored infrequently (Edberg et al., 2000; WHO, 2017). The WHO guidelines for *E. coli* and TTC state that neither should be detectable in a 100mL sample of drinking water. However, the WHO does not recommend sole reliance on water quality analysis (even if carried out frequently) to ensure water safety, because microbial water quality varies greatly in short periods and exposure can occur before the contamination is detected. Since 2004, the WHO have recommended risk-based water system management approaches to ensure water safety in all settings, in which sanitary inspection is promoted (WHO, 2004).

Sanitary inspection is defined by the WHO as "an on-site inspection of a water supply to identify actual and potential sources of contamination" (WHO, 1996). With a long history in public health (Lumley, 1859), sanitary inspection was emphasized in the 1976 WHO monograph *Surveillance of Drinking-Water Quality* and in every edition of the GDWQ (WHO, 2017, 2004, 1997, 1984). Sanitary inspection is widely applied to water system technologies ranging from large, complex piped systems to small, community wells. For more complex systems, it can be extensive and may include validation of microbial controls, assessment of catchment-level risks and checking the pressure in a distribution system (Bartram et al., 2009). For smaller, simpler water systems, sanitary inspection is often conducted using simplified forms based on those developed by the WHO in the 1990s. These are water source type specific, short (9-12 yes/no questions) and include diagrams depicting sanitary risk factors (WHO, 1997). During a sanitary inspection, each observed sanitary risk factor at a water sources (e.g. wells, springs) is scored with a "yes"; the sanitary risk score for a particular water source is the count of risk factors identified at that water source. A sanitary risk score of zero suggests that the source is at low risk of contamination, and a higher risk score is indicative of a water source at higher risk.

In the literature, authors report mixed results with regard to correlation between sanitary risk score and microbial water quality. Some studies demonstrate a significant correlation (Cronin et al., 2006; Howard et al., 2003; Snoad et al., 2017; Usha et al., 2014), while others do not (Bain et al., 2014b; Ercumen et al., 2017; Lloyd and Bartram, 1991; Misati et al., 2017). These findings have made some practitioners doubt the utility of sanitary inspection and question its validity and utility as a surveillance tool.

The objectives of this critical literature review are to evaluate the use of sanitary inspections and their findings, and to identify how they can be used to contribute to water safety. We examine the following research questions:

- Is there a significant association between sanitary inspection and microbial water quality?
- What is the role of sanitary inspection in water safety assessment and management?

To answer these questions, we reviewed studies that assess the association between water quality analysis and sanitary inspection.

2. Material and Methods

The literature search strategy was broad to find all relevant studies; the preliminary search string used *"water" AND "sanitary" AND ("inspection" OR "survey")*. Snowball sampling was used to expand search terms when relevant terms were found in the searched literature. PubMed, Web of Science and Google Scholar were used to identify articles. Papers were included if: (1) both sanitary inspection and water quality analysis were carried out on the same drinking water sources, (2) sanitary inspection and water quality results were directly compared and (3) the article was written in English. Papers were excluded if the study assessed water only used for a purpose other than drinking. There were no geographic or water source type inclusion criteria. The citations of every included paper were searched to identify further studies for inclusion.

Metadata, sanitary inspection results, water quality analysis results and identified correlations between sanitary inspection and water quality were extracted from each included study . Information was collated and analyzed using Microsoft Excel (2016). See Supplemental Materials for data table.

3. Sanitary Risk and Water Quality

Twenty-five studies are included (Table 1.) The largest number were conducted in sub-Saharan Africa (n=12, 48%) and Asia (n=10, 40%), study locations also included two (8%) countries in South

America and one (4%) in Europe. The studies examined sanitary inspection and microbial contamination in various water source types, including improved sources (piped systems, boreholes/tubewells, protected hand-dug wells, protected springs and rainwater harvesting systems) and unimproved sources (unprotected wells and unprotected springs). Twelve studies were longitudinal (48%) and 13 were cross-sectional (52%).

Table 1 Characteristics of 25 studies included in critical review

Study	**Country**	**Type of water source[a]**	**Water quality indicator[b]**	**Statistical model[c]**
Lloyd and Suyati, 1989	Indonesia	PW, CW, OW, RWH, PS, BH, SW	TTC	NS
Lloyd and Bartram, 1991	Java	BH, CW, OW	TTC	Linear associations, SHI
Howard et al., 2003	Uganda	PS	TTC, FS	Logistic regression, OR
Haruna et al., 2005	Uganda	PS	TC, TTC, FS	Pearson product-moment correlation coefficients
Godfrey et al., 2006	Mozambique	BH, OW	TTC, *Enterococci*	Logistic regression
Magrath, 2006	Sierra Leone	CW, BH, OW, PS	TTC	NS
Cronin et al., 2006	Mozambique	BH, CW, OW, SW	TTC	Linear associations
Luby et al., 2008	Bangladesh	BH	TC, TTC, EC	OR
Vaccari et al., 2010	Thailand	CW, OW	TC, EC, TTC	Linear associations
Aldana, 2010	Nicaragua	BH, CW, PS, PW, RWH	TTC, FS	Mantel-Haenzel statistical test
Parker et al., 2010	Uganda	BH, PS, CW, OW, SW, RWH	TTC	Kolmogorov–Smirnov two sample test, Kruskal–Wallis test, Spearman's rank correlation coefficient
S. Barthiban and Lloyd, 2011	Maldives	OW	TTC	Linear associations, SHI
Bacci and Chapman, 2011	Ireland	BH	TTC	NS
Barthiban et al., 2012	Maldives	OW	TTC	Linear associations, SHI
Mushi et al., 2012	Tanzania	CW, OW	TC, EC, CP,SFB	Spearman rank correlation analysis
Akoachere et al., 2013	Cameroon	CW, OW	TC, *Vibrio, Staphylococcus*	Pearson's Chi-square test

Sorlini et al., 2013	Chad; Cameroon	BH, OW, PW, SW	EC, *Enterococci, Salmonellae*	NS
Usha et al., 2014	India	CW	EC	Fischer's exact test, OR
Engström et al., 2015	South Sudan	BH, CW	TTC	OR, Chi-square tests
Okotto-Okotto et al., 2015	Kenya	CW, OW	TTC	Interval regression
Gerges et al., 2016	Haiti	BH, CW, OW	EC	Logistic regression
Dey et al., 2017	Bangladesh	BH	EC, TC, TTC	Multiple logistic regression
Ercumen et al., 2017	Bangladesh	BH	EC	Linear associations
Misati et al., 2017	Kenya	BH, RWH, OW, CW, NS, SW, PW	TTC	Wilcoxon rank sum test
Snoad et al., 2017	India	BH, OW, PW, US	TTC	Logistic regression

NS = not specified
a: BH = borehole/tubewell, CW = covered dug well, NS = not classified spring, OW = open dug well, PS = protected spring, PW = piped water source, RWH = rain water harvesting, SW = surface water, US = unprotected spring
b: CP = Clostridium perfringens, EC = E. coli, FS = fecal streptococci, SFB= sorbitol fermenting Bifidobacteria, TC = total coliforms, TTC = thermotolerant coliforms
c: SHI = Sanitary hazard index

The included studies examined either the relationship between water quality and overall sanitary inspection risk score (n=11, 44%), water quality and individual sanitary risk factors (n=4, 16%), or both (n=10, 40%). Comparisons of sanitary risk score and microbial contamination were based on the assumption that the relationship between the two is generally positive and linear because a larger number of sanitary risk factors would lead to a higher-risk source and a greater likelihood and/or severity of contamination (Lloyd and Bartram, 1991). However, of the studies that analyzed overall risk score (n=21, 84%), only 12 (57%) found a significant association between sanitary risk score and water quality while nine (43%) did not find a significant association.

Table 2 Numbers of studies (n) that found significant association between individual sanitary risk factors and microbial water quality, by water source type

Handpumps	**n=**	**%**	**Dug Well**	**n=**	**%**	**Spring**	**n=**	**%**
Apron damaged	4	50	Latrine nearby	1	10	Fence missing	2	66
Latrine nearby	3	38	Parapet inadequate	1	10	Masonry faulty	1	33
Other pollution	2	25	Apron damaged	1	10	Backfill eroded	1	33

Standing water	2	25	Improper bucket storage	1	10	Standing water	1	33
Handpump loose	2	25				Latrine uphill	1	33
Latrine uphill	1	13				Surface water uphill	1	33
Fence missing	1	13				Other pollution	1	33
Apron less than 1m	1	13				Outlet dirty	1	33
Drainage channel broken	1	13						

Fourteen studies compared individual sanitary risk factors with water quality. This type of analysis was often carried out to determine which sanitary risk factors have a stronger correlation or a greater effect on contamination. Eight studies compared water quality and sanitary risk factors for boreholes with handpumps. Damage to the concrete apron was the risk factor most frequently associated with poor water quality at handpumps (n=4, 50%) (Table 2). Association between water quality and the proximity of the nearest latrine was demonstrated in three studies (38%). Interestingly, one study found that short proximity to the nearest latrine was associated with *worse* water quality, and the other two found an association with *better* water quality. It was suggested that a nearby latrine may improve water quality if it is associated with less open defecation (Godfrey et al., 2006). Presence of a source of pollution other than latrines within 10 meters, loose hardware at the base and the presence of standing water were associated with water quality in two (25%) studies each.

Ten studies compared water quality and individual sanitary risk factors for dug wells (covered and open) and three studies looked at springs (protected and unprotected). For dug wells, either zero or one study found correlation between individual sanitary risk factors and water quality. In springs, two (66%) studies found a correlation between water quality and the absence of a fence. One of those studies also found that the springs reacted quickly to rainfall, and identified poor protection of the backfill area as a major contamination risk (Howard et al., 2003).

4. A Critical Analysis of Study Methods

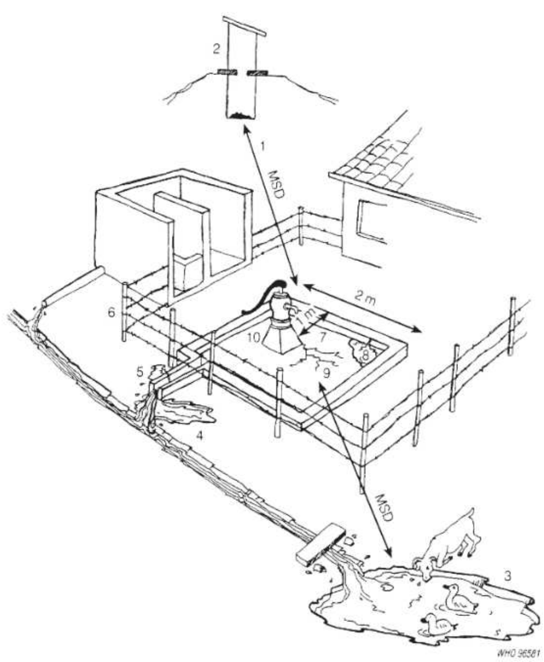
In the next three sections, we critically analyze at the sanitary inspection, water quality analysis and statistical analysis methods described in the 25 included studies. We aim to assess the validity of the results presented in those studies both in terms of analytical data quality and in terms of the comprehensiveness of the representation of the water source. We then highlight opportunities for improvement in data collection and analysis.

4.1. Sanitary Inspection

GUIDELINES FOR DRINKING-WATER QUALITY — ANNEX 2

Fig. A2.5 Example of sanitary inspection form for tubewell with hand-pump

Note: MSD = minimum safe distance determined locally; see section 6.2.2.



I **Type of facility** TUBEWELL WITH HAND-PUMP

1. General information: Health centre ....
   Village ....
2. Code no.—Address ....
3. Water authority/community representative signature ....
4. Date of visit ....
5. Water sample taken? .... Sample no. .... Thermotolerant coliform grade ....

II	**Specific diagnostic information for assessment**	**Risk**
1.	Is there a latrine within 10 m of the hand-pump?	Y/N
2.	Is the nearest latrine on higher ground than the hand-pump?	Y/N
3.	Is there any other source of pollution (e.g. animal excreta, rubbish, surface water) within 10 m of the hand-pump?	Y/N
4.	Is the drainage poor, causing stagnant water within 2 m of the hand-pump?	Y/N
5.	Is the hand-pump drainage channel faulty? Is it broken, permitting ponding? Does it need cleaning?	Y/N
6.	Is the fencing around the hand-pump inadequate, allowing animals in?	Y/N
7.	Is the concrete floor less than 1 m wide all around the hand-pump?	Y/N
8.	Is there any ponding on the concrete floor around the hand-pump?	Y/N
9.	Are there any cracks in the concrete floor around the hand-pump which could permit water to enter the well?	Y/N
10.	Is the hand-pump loose at the point of attachment to the base so that water could enter the casing?	Y/N

Total score of risks .... /10

Contamination risk score: 9–10 = very high; 6–8 = high; 3–5 = intermediate; 0–2 = low

III **Results and recommendations**

The following important points of risk were noted: .... (list nos 1–10) and the authority advised on remedial action.

Signature of sanitarian ....

Figure 1 Sample WHO sanitary inspection form for tubewell (borehole) with handpump including checklist and illustrative diagram (WHO, 1997)

All included studies used sanitary inspections that consisted of a checklist of yes/no questions. Two (8%) did not specify which sanitary inspection form was used, nor did they list the sanitary risk factors assessed. Many included studies used the WHO sanitary inspection forms without modification (n=12, 48%) (example in Figure 1) (WHO, 1997). Some studies did not specify the source of the forms (n=8, 32%), but assessed sanitary risk factors similar to those included in the WHO forms. Two such studies (8%) used sanitary inspections prescribed by the government of Bangladesh (Ercumen et al., 2017; Luby et al., 2008) and another used the Government of India Uniform Drinking Water Quality Monitoring Protocol (UDWQMP) forms (Snoad et al., 2017). Three studies (12%) used sanitary inspection forms based on the WHO forms, modified with country-specific information.

The importance of sanitary inspection form standardization is discussed by Lloyd & Suyati (Lloyd and Suyati, 1989), who piloted early versions of the WHO forms in Indonesia in the 1980s. In the first phase of piloting, sanitary inspectors were instructed to judge the sanitary status of a source as “good” or “bad” without further guidance. The investigators determined that this method was too subjective, preventing comparison between sources. They then developed the sanitary inspection form types we recognize today, providing a sanitary risk score and enabling district surveillance coordinators to compare sources and “decide priorities for remedial action…for supervision purposes and for urgent re-sampling” (ibid). An advantage of standard forms, therefore, is the ability to compare sources with one another (Howard, 2002). The choice and/or design of sanitary inspection form is dependent on the intended use of the results: standard forms might be more appropriate for a national survey of water sources, for example, but a modified form may be more useful for a local area operator looking to make repairs or improvements. The uses of sanitary inspection reported in the studies are explored in Section Six.

Few studies described the methods for conducting the sanitary inspection beyond choice of sanitary inspection form. Seven (28%) described strategies to reduce inter-inspector bias, including consistent training of inspectors or using only one inspector for all sources. Although some risks are easy to identify (e.g. whether the fence is missing) and would likely be reported consistently among inspectors, others are more subject to inspector interpretation (e.g. presence of "other sources of pollution" within 10 meters). Measures should therefore be taken to ensure inter-enumerator agreement if sanitary inspections performed by different enumerators are to be compared. Proper and consistent training has been shown to improve learning and individual outcomes in similar fields (Crocker et al., 2016) and may improve sanitary inspection data quality and inter-enumerator agreement.

Most papers reviewed did not report collaboration with or reporting of results back to the operators. Three (12%) included water source operators or users in a participatory sanitary inspection process. Six (24%) reported sanitary inspection results directly to the operators or users. Sanitary inspection is recommended by the WHO as a tool to help system operators identify and remediate risks at their systems. If sanitary inspection is conducted with the purpose of informing remedial action, the water system operator responsible for making repairs would need to be informed of the results. For sanitary inspection to be part of a larger risk-based management approach, "it is essential that responsible community members both assist the official in making the [sanitary] survey and learn how to conduct the survey independently" (WHO, 1997, Page 44). Two of the three papers that reported participatory sanitary inspection methods were Lloyd & Bartram (1991) and Lloyd & Suyati (1989); these studies led to the development of WHO sanitary inspections. Although not all sanitary inspection is intended to directly inform repair (see Section 6), it is beneficial to the water system users to participate in inspection in order to better understand risks.

4.2. Water Quality Analysis

Bain et al. (2014b) propose 13 criteria to assess the quality of studies analyzing microbial water quality. When the criteria we applied to 319 studies involving microbial water quality analysis, only 35% qualified as "high quality" studies (met 8-13 quality criteria). In our current review, two method quality criteria were used to assess the studies: whether a study met minimum sample handling requirements and described quality control measures (Table 3).

Table 3 Frequency of water quality analysis quality control/quality assurance (QA/QC) measures

	Count	Percent		Count	Percent
Method			*Processed within*		
Laboratory-based	19	76%	6 hours	8	42%
Field-based	6	24%	24 hours	5	26%
QA/QC Described			Not specified	6	31%
Yes	10	40%	*Transportation method*		
No	15	60%	On ice/ice packs	11	57%
			Cool conditions	2	10%
			Not specified	6	31%

In most studies, water samples were collected in the field, transported to laboratories, and analyzed using established laboratory methods (n=19, 76%). The WHO GDWQ recommend that water samples for microbiological analysis be processed within six hours of collection, with an absolute maximum of 24 hours in order to be considered valid (1997). Processing within 6 hours is difficult in areas with dispersed water sources, poor road conditions and/or few laboratories. The 6 hour processing time includes storage time within the laboratory, and samples delivered to the laboratory in the late afternoon may be stored overnight before processing (Wright et al., 2014). Of the studies that analyzed samples in a laboratory, eight (42%) reported that samples were processed within six hours of sample collection, five (26%) reported processing between 7 and 24 hours after collection and six (32%) did not report the time between sampling and processing.

Water samples should be transported to the laboratory in a lightproof, insulated box with either ice or ice packs. If these conditions cannot be met, the GDWQ recommend that samples be discarded (WHO, 1997). Eleven studies (58%) reported transporting samples on ice or ice packs and two (11%) referred to transportation in cold, dark conditions. The remaining six (32%) studies did not specify transportation procedures.

Seven (37%) studies reported both processing within the recommended 6 hours and transporting samples on ice. The majority of included studies that analyze water quality samples in a laboratory, therefore, did not meet basic handling and analysis recommendations of WHO.

Six studies (24%) used field-based water quality tests exclusively. Field-based tests have an advantage over laboratory analysis because water samples can be analyzed immediately after collection, eliminating sample degradation during transport and storage. There is a long history of field-based test methods in microbial water quality monitoring (Bartram, 1996; WHO, 1997), and studies report comparable accuracy to laboratory tests (Wright et al., 2011) and potential reduction in monitoring costs (Crocker and Bartram, 2014).

Of the 25 included studies, ten (40%) described quality control measures such as the analysis of field blanks or replicate samples. Eight (42%) studies using laboratory-based water quality analysis and two (33%) using field-based analysis reported quality control methods.

4.3. Models of the Relationship between Sanitary Inspection and Microbial Water Quality

Twenty-one (84%) of included studies specified the statistical analysis used to relate sanitary inspection and water quality. The choice of statistical analysis depended on the structure and distribution of the data, but also reflected the purpose of the analysis.

The included studies used diverse statistical analyses: logistic regression, non-parametric tests and non-statistical, linear comparisons to examine the relationship between microbial water quality and sanitary inspection risk scores. All used water quality as the dependent variable, and sanitary risk score, individual sanitary risk factors, or both as the independent variable(s). No studies used linear regression, which is an appropriate decision: linear regression relies on a continuous dependent variable and assumes normal distribution of variables, which would be inappropriate for microbial water quality data (Tillett, 1993). Some studies used logistic regression to assess the association between sanitary inspection and water quality results (n=4). Logistic regression is limited in requiring a large sample size, but does not assume normal distribution. Binary logistic regression (Godfrey et al., 2006) and ordinal logistic regression (Snoad et al., 2017) were used when water quality was categorized into a safe/unsafe binary variable or ordinal health risk categories, respectively. Multiple logistic regression was used in two studies where individual sanitary risk factors were included as independent variables (Dey et al., 2017; Howard et al., 2003).

Many studies used non-parametric tests such as Chi-square (Akoachere et al., 2013; Engström et al., 2015), Wilcoxon rank sum (Dey et al., 2017; Misati et al., 2017) or Kruskal-Wallis tests (Parker et al., 2010). These do not require normal distribution and can be used for small sample sizes.

Some studies described the relationship in terms of non-statistical relationships (n=6) and/or analyzed and represented results in a sanitary hazard index (SHI) (n=3). Lloyd and Suyati (Lloyd and Suyati, 1989) developed the SHI and an example is shown in Graphical Abstract. The SHI is proposed for prioritization of sources for remedial action by combining sanitary risk score and water quality. It is therefore most useful to support programs or water source operators who manage multiple water sources. The authors who chose to use either the SHI or non-significant linear relationships emphasized the accessibility of these methods to decision-makers in low-resource settings. While statistical analysis is appropriate for answering research questions, it is not needed for prioritizing water sources for repair or rehabilitation.

5. Critical Analysis of the Role of Sanitary Inspection

Studies that compare individual sanitary risk factors and water quality provide insight into factors contributing to water source contamination. In comparison, there is little clarity afforded by the studies that compare overall sanitary risk score and water quality, as their findings are inconsistent (Section 3). Here, we suggest that this inconsistency derives from flaws in the implicit model underpinning these analyses. The flaws arise from confusion over the purpose of sanitary inspection and unsound assumptions about water quality analysis.

5.1. Independent Sufficiency of Sanitary Inspection and Water Quality Analysis

Some of the included studies suggest that sanitary inspection can predict or even replace water quality analysis. However these tools are distinct and complementary. The first edition of the GDWQ states:

> “While drinking-water standards provide authoritative criteria concerning the acceptability of water for human consumption, the prescription of standard in no way obviates the need for sanitary surveys…No bacteriological or chemical analysis of samples, however carefully it is carried out, is a substitute for a complete knowledge of conditions at the source and within the distribution system.” (WHO, 1984)

In order to be considered “safe,” a water source should be free of both contamination and the threat of contamination. Therefore, neither sanitary inspection nor water quality analysis is independently sufficient to determine water safety.

5.2. *Interpretation of a Sanitary Risk Score.*

Comparisons of sanitary risk score and microbial contamination are based on the intuitive assumption that the relationship between the two is generally positive and linear (Lloyd and Bartram, 1991).

However, a sanitary inspection carried out using a short, standard form is not comprehensive; and the 9-12 question checklist used in the 25 studies cannot reasonably include every factor that might contribute to microbial contamination of the source type considered. This is particularly the case for technologies such as boreholes/tubewells where contaminants may derive from outside the area covered by the sanitary inspection and relate to wider aquifer contamination.

Many included studies sum the results to derive a sanitary risk score. This approach suffers two principal deficiencies: weighting-related and component-type-related.

Sanitary risk scores do not weight the included risk factors, despite evidence that some are more strongly associated with water quality or have a greater magnitude of effect in particular settings (Howard et al., 2003). However, there is insufficient evidence to weight sanitary risk factors in such a way that is generalizable, and it is reasonable to assume that setting-specific factors would modify such weighting substantively. Weighting, therefore, could potentially be included in comprehensive, local sanitary inspection, but not in the standard forms used by most of the included studies.

The assumed relationship between sanitary risk score and water quality analysis also presumes the effects of individual sanitary risk factors to be additive. However, risk factors interact and it is the specific combination of risk factors that predicts the likelihood and severity of contamination. The WHO sanitary inspection forms include questions that represent sources of contamination, pathways for contamination, and breakdowns in the barriers that prevent contamination. Sources of contamination are reservoirs of feces such as latrines or fertilized fields; carriers of contamination, such as standing water, transport feces from sources of contamination into the water source; and barrier breakdowns are weaknesses and failures in the system infrastructure that may allow feces to enter, such as cracks in the concrete apron of a handpump. Logically, contamination will be most favored if all three types of sanitary risk factor (source, carrier and barrier breakdown) are present – because, for example, a source of contamination need not lead to contamination if there is no carrier or the water source is well protected. One phenomenon which illustrates this is seasonal variation in water quality (Kostyla et al., 2015; Kumpel et al., 2017) – although the same sources of contamination and barrier breakdowns may be present in wet and dry seasons, the addition of rain as a carrier leads to increased contamination.

While sanitary risk scores are useful for making management comparisons between sources and compiling evidence on prevalent deficiencies, the hypothesis that a summative sanitary risk score should predict water quality is unsound.

5.3. *Rigor of Water Quality Analysis.*

Assessing the validity of sanitary inspection by comparing it to water quality analysis implies that water quality analysis is an independently sufficient measure of water quality. This review and other studies have shown that most water quality monitoring is conducted using laboratory-based or centralized analysis (Crocker and Bartram, 2014; Delaire et al., 2017), and indeed this is identified as preferable by WHO (1997). Although laboratory-based water quality analysis was common, less than half of included studies reported using any QA/QC methods and only seven (28%) studies met WHO recommendations for sample handling and transportation. Such a lack of methodological rigor and reporting calls into question the validity of the water quality analysis results; and the inferences/conclusions derived from comparison with them. Furthermore, laboratory water quality analysis faces serious challenges in many settings due to inconsistent availability of electricity, low-quality technology or unspecialized staff (Bartram, 1996; Patrick et al., 2011), even when samples are collected and transported according to WHO recommendations.

5.4. *Interpretation of Water Quality Analysis.*

Analysis of a single water quality sample provides a snapshot of the source water quality without context. Microbes are not evenly distributed throughout a water source; thus, repeated 100ml samples tested from the same source at the same time yield different results. In addition, microbial water quality can change rapidly, for example, due to rainfall patterns (Stukel et al., 1990). Water quality, therefore, is not directly comparable to sanitary inspection, which provides insight about the lasting condition of the water source.

6. Sanitary Inspection to Improve Water Safety

One source of confusion around sanitary inspection is a diverse understanding of its *purpose*. Clarity about purpose is important because it helps resolve conflict over topics such as sanitary inspection form standardization, the importance of community participation and the use of statistical or non-statistical analysis. For example statistical analysis of sanitary inspection and water quality data supports research into the optimal design and application of the tool, while, a non-statistical analysis such as the SHI maybe more useful in communicating findings, tracking progress in improvements and prioritizing action. Thus, it is important that the purpose of the sanitary inspection is determined beforehand, and influences tool selection or design before data collection, as different purposes demand different methods.

We propose four distinct purposes of sanitary inspection:

Individual water source improvement*:* Sanitary inspection is conducted at a single water source. Its conduct and its reporting inform system operators about water safety risks and facilitate repairs.

Water source prioritization*:* Sanitary inspection is conducted on multiple sources. Doing so allows operators and support programs to identify higher-risk sources and prioritize remedial action.

Systemic information*:* Sanitary inspection is conducted on multiple sources (on the same scale or more broadly than in water source prioritization). This allows identification of systemic responses in water supply planning and implementation.

Research*:* Sanitary inspection is carried out at large scale and results are analyzed to expand general understanding.

6.1. *Sanitary Inspection for Water Source Improvement*

In this mechanism, sanitary inspection informs system operators about the risks to the water source and operators can then make repairs or improvements. The role of sanitary inspection in educating water source operators and facilitating immediate repair response is cited frequently in the studies included in this review and elsewhere (Bartram, 1996; Lloyd and Suyati, 1989; Lloyd and Bartram, 1991; Luby et al., 2008). For this purpose, water quality analysis cannot replace sanitary inspection, because water quality results provide no information about the causes of contamination or the condition of the source.

Either a standard or locally specific sanitary inspection is appropriate for this purpose because the mechanism does not require generalization of findings across sources or comparison of sources with one another. The complexity of the form will depend on the complexity of the system in context and the level of training and expertise of the water source operator. Lloyd and Suyati (1989), for example, conducted sanitary inspection for small systems in Indonesia where operators had little system maintenance training; in this setting, they recommended a simple form with a graphical component such as in Figure 1. They recommended tearing off the completed graphical component of the WHO sanitary inspection form and handing it to the operator when the inspection was complete. Operator participation and training in sanitary inspection are especially important for this mechanism. Training operators to conduct sanitary inspections helps ensure that they are aware of sanitary risk factors and encourages them to take remedial action without reliance on occasional inspections by visiting inspectors.

Sanitary risk score has little relevance to this mechanism, as every risk factor should be addressed. It may serve for tracking over time and a review of the score and remedial measures with visiting inspectors may serve to reinforce training, although we found no evidence for this.

6.2. Sanitary Inspection for Water Source Prioritization

This mechanism requires that sanitary inspection be carried out on multiple sources. Many studies cite prioritization of water sources for rehabilitation or repair as a major benefit of sanitary inspection and it is the main objective of the SHI (Bacci and Chapman, 2011; S Barthiban and Lloyd, 2011; Lloyd and Suyati, 1989; Lloyd and Bartram, 1991). Monitoring for the purpose of intervention prioritization can significantly improve water supply service quality (Bartram, 1996). The SHI is considered a robust tool for prioritizing investments as it accounts for sources where either sanitary inspection or water quality analysis might mischaracterize the source; sources with a low sanitary risk score but high levels of contamination would still be prioritized, for example.

The included studies suggest or assume that water sources with higher sanitary risk score or SHI should be prioritized. However, no studies discuss whether this is in fact optimal or whether the type of repair needed, community capacity to sustain the source or other factors might affect decisions. Water sources with specific types of breakdowns may be prioritized despite sanitary risk score, for example, because those breakdowns are more closely associated with poor water quality or because the repair is easier or cheaper.

6.3. Sanitary Inspection for Systemic Information

In this mechanism, sanitary inspection does not directly lead to remedial action of individual water sources, rather is used at a planning level to identify and respond to common deficiencies. It also requires sanitary inspection to be carried out at multiple water sources. For example, if sanitary inspection is conducted on boreholes with handpumps across a region and the majority of sources have loose hardware at the base, this would benefit from action at higher level than that of the system operator, such as by changing hardware specification, amending installation procedures or improving training of installation teams. To inform such decisions, the sanitary inspection should be standard across the water sources.

One program that used sanitary inspection for this systemic information mechanism is the Rapid Assessment of Drinking Water Quality (Aldana, 2010; WHO/UNICEF, 2012). In Nicaragua, for example, the investigators were able to make broad statements about the relative sanitary risk in water sources managed by different local water departments and make recommendations for departments to improve.

6.4. Sanitary Inspection for Research

Although research can affect remedial action or planning, the objective of this mechanism is to improve knowledge and thereby indirectly enhance the preceding mechanisms. Unlike the previous mechanisms, sanitary inspection is not used directly in a decision-making process. Sanitary inspection results can be used to examine water quality and safety (as is done in this review), understand the effect of natural disasters on water supply (Ferretti et al., 2010), map household water quality (Oloruntoba, 2008), assess seasonal variations in water safety (Kostyla et al., 2015; Kumpel et al., 2017) or address other topics. These analyses can be conducted using a simple sanitary risk score, but typically provide more insight if results are considered in the broader framework of water source risk and contamination prevention.

7. Study Limitations

Limitations of this study include potential screener bias, as only one researcher carried out title, abstract and full-text screening. Some relevant articles may have been missed, as only studies published in English were included. Monitoring results are often unpublished or published in non-peer-reviewed literature such as conference proceedings; although one RADWQ report was included, the majority of the included studies are peer-reviewed and some non-peer-reviewed publications could have been missed.

8. Conclusion

Managing water safety requires a commitment to an ongoing, day-to-day effort to protect the water s supply. Operators must continuously identify risks and manage the system appropriately. The value of sanitary inspection is not derived from its ability to *predict* risks to water quality, but from its utility in the ongoing effort to *protect* water safety. The scientific literature largely relies on the simplistic sanitary risk score, leading to inconsistent conclusions concerning whether sanitary inspection and water quality analysis are significantly associated. We conclude that a definitive interpretation is obstructed by the way that researchers think about water quality and water safety. Sanitary inspection and water quality analysis are distinct and complementary tools, and both serve important purposes in the on-going process of ensuring water safety. In this review we identify four mechanisms through which sanitary inspection contributes to improving water safety: individual water source improvement, water source prioritization, systemic information gathering, and research. Policy-makers, water source operators and researchers encourage use of sanitary inspection as an effective and useful tool. Care must be taken to reflect on their intended purpose of sanitary inspection and water quality analysis in design and before implementation of data collection efforts in order to ensure that data is fit-for-purpose and leads to improvements.

9. Conflict of Interest

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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