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Applicability of a Surveillance Methodology for the Microbiological Safety of Well Water Supplies, in a Highly Vulnerable Hydrogeological Setting

——A Case Study Based Findings from the West Coastal Area of Sri Lanka

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ABSTRACT

A well surveillance study carried out in nine Divisional Secretariat Divisions on the west coast of Sri Lanka showed that 70.3% of 101 well sampling points were microbially contaminated with equal to, or greater than, faecal coliform grade C (11 - 100 cfu/100mL). Due to the very vulnerable hydro-geological setting of the coastal sand, laterite and alluvium aquifers occurring in the study areas, the recommended safe separation distance between an on-site sanitation system and a well could not be achieved. Hence, a cardinal rule of well protection was observed to be broken at almost every well study site. The existing excreta disposal systems need to be improved or replaced with more efficient ones before the impact of other sanitary hazards at the well, and wellhead area, on the microbial quality of well water, can be determined and addressed. The published (WHO, 1997) sanitary survey forms for open dug wells and tube wells need to be modified in the context of the study areas described. Based on a comparison of three different statistical methods used to assess the relative significance of each sanitary hazard modification to the methodology for determining the sanitary hazard index (SHI) was prescribed.

Keywords: Surveillance of Wells; Faecal Coliform Counts; Sanitary Survey; Sanitary Hazard Score

1. Introduction

The risk of groundwater contamination is significant where water borne on-site sanitation system is used compared with dry on-site sanitation system, unless the dry on-site sanitation system is constructed directly into the aquifer. The issue of microbial contamination of groundwater from on-site sanitation soakage pits becomes a more critical issue where shallow groundwater table presents.

On-site sanitation systems are widely used in Sri Lanka. For cultural reasons waterborne sanitation facilities are preferred in Sri Lanka with water used for anal cleansing. Large diameter wells, constructed basically with block work according to the local inhabitants' design, have been the only means of groundwater abstracttion until the recent introduction of small diameter tube wells.

Groundwater exploitation using open dug wells together with on-site sanitation practices may cause them to become high risk drinking water sources in the study areas selected in Sri Lanka. Therefore the selected study areas have a need for well surveillance and sanitation improvement programme for the protection of the groundwater resource. According to the information available to the lead author, there has been no systematic well surveillance programme in the study areas with the aim of groundwater protection. Therefore a pilot scale well surveillance study was carried out in the west coastal region of Sri Lanka to identify and assess the sanitary hazards associated with groundwater wells. The overall objective was the development of a medium to long term groundwater protection strategy to improve the microbial quality of groundwater point sources. This paper presents the findings from the field work carried out in Sri Lanka.

2. Study Area

The well study area (**Figure 1**) selected was the ninth Divisional Secretariat (DS) of the Government of Sri Lanka. This is sub-divided into Negombo, Katana, Divulupitiya, Minuwangoda, Dankotuwa, Wennappuwa, Nathandiya, Mahawewa and Udubaddawa, which belongs to three different districts (Gampaha, Puttalam and Kurunegala). Hereafter the study area is referred to as the Negombo region. The Negombo region is located on the west coast of Sri Lanka and **Table 1** summarizes some

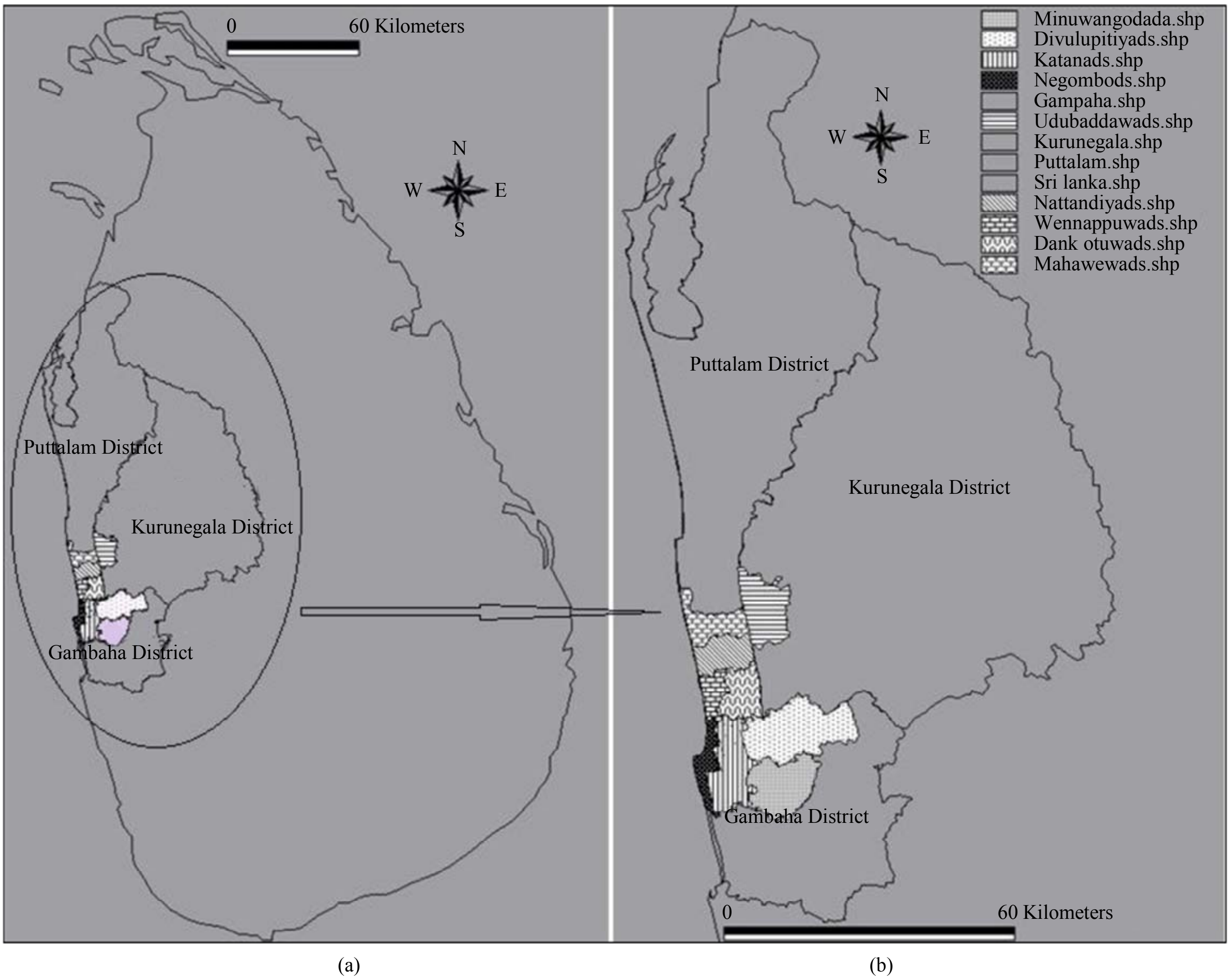


Figure 1. (a) Map showing the location of the study areas on the map of Sri Lanka and relevant districts; (b) Enlarged map of the study areas together with the relevant district boundaries.

Table 1. Basic facts about the Sri Lanka study area.

District	Study areas (divisional secretariat division)	Area (ha)	Population density/ha	No. of housing units	Estimated no. of latrine/ well density (/ha)
Gampaha	Negombo	3080	49	39,170	13
	Katana	10,800	22	57,142	5
	Divulupitiya	20,200	7	38,124	2
	Minuwangoda	13,050	12	45,814	4
Puttalam	Dankotuwa	7800	8	15,388	2
	Wennappuwa	3900	20	17,421	4
	Nathandiya	7200	9	16,205	2
	Mahawewa	7300	7	13,513	2
Kurunegala	Udubaddawa	13,030	4	13,824	1

Source: [2].

basic facts about the study areas.

Three different aquifers occur in the Negombo region, namely; Shallow aquifers on coastal sands, Laterite (Cabook) aquifers and alluvium aquifers [1]. A literature review highlighted the very vulnerable hydro-geological setting (with higher hydraulic conductivity values, **Table 2**) of these aquifers to contamination especially when the contaminants are released subsurface as in the context of on-site sanitation systems (discussed further in the methodology).

The Negombo DS division is supplied with piped water. All the other DS divisions in the study area are dependent on groundwater resources for day to day water consumption needs. This does not necessarily exclude the residents of Negombo DS division from owning a well for other water consumption purposes. Therefore groundwater exploitation using (open dug or tube) wells and on-site sanitation systems widely used in the study areas, together with very vulnerable hydrogeological settings of the aquifers to contamination, leave the wells at high risk of microbial contamination. According to the best knowledge of the lead author there was no previous systematic well surveillance study carried out in the Negombo region, to assess the sanitary risks associated with groundwater point sources.

3. Methodology

The surveillance methodology used in the Negombo region needed to be simple and efficient to be carried out with limited financial resources and technical support, and easily repeatable in future studies. The surveillance methodology, which was originally developed by Lloyd and Helmer [6] and later published in the WHO Guidelines for Drinking Water Quality [7], is relatively simple, yet robust, in identifying the sanitary hazards and associated faecal contamination in drinking water supplies.

This methodology is comprised of a survey of the sanitary conditions of the water supply and assessing the 44˚C thermo-tolerant (faecal) coliform (FC) counts of water samples at the same time. Sanitary survey observations and FC counts are compared to assess the relative microbial health risk in collections of wells, and to prioritize remedial actions to improve microbial well water quality.

Three different types of groundwater point sources were used in the study areas, namely, open dug wells, tube wells with hand pumps, and tube wells with mechanical pumps. Of the total 101 locations and wells studied, 88 were open dug wells, 7 were tube wells with hand pump and 6 were tube wells with mechanical pumps. The field work was carried out from January to May 2007. The sanitary survey forms published by WHO [7] were used to assess the sanitary conditions of the groundwater point sources in the Negombo region.

3.1. Faecal Coliform Counts

The FC counts of the well water were assessed in situ using the Del Agua field test kit and the membrane filtration technique [8]. At each study location samples were split in two, and processed for the FC counts. Based on the high (overall 92%) homogeneity levels (**Table 3**) of the observed FC grades (**Table 4**), the average of the two samples (split samples) was used in the analysis.

3.2. Sanitary Survey Forms

In this section the applicability of each sanitary survey question in the survey form is discussed and, where necessary, modified.

Open Dug Wells

*Q*1: *Is there a latrine within* 10 *m of the well*?

This question checks whether the safe separation distance between the groundwater point source (well) and an on-site sanitation system is maintained or not. The 10 m general guideline safe separation distance in the published [7] methodology is not specific to an individual study area. The British Geological Survey guideline for Assessing the Risk to Groundwater from On-Site Sanitation (ARGOSS) [9] when the separation distance between the on-site sanitation system and the groundwater point source is *less than* 25*-day groundwater travel time*, then the groundwater point source is at significant risk. The latter is more realistic, but more difficult to determine.

Table 2. Summary of hydraulic conductivity values and 25-day groundwater travel distance of three different types of aquifers occurring in the southwest coastal area of Sri Lanka.

Aquifer type	Hydraulic conductivity, K (m/day)			25-day groundwater travel distance (m)
	Todd & Mays (2005)	Jayasekera (2007), Sri Lanka	Bhosale and Kumar (undated), India	
Alluvial aquifer			65	1625 (K = 65)
shallow aquifers on coastal sands	45	49.5		1125 (K = 45) 1237.5 (K = 49.5)
Laterite (Cabook) aquifer			30	750 (K = 30)

Source: [3-5].

Table 3. Comparison of homogeneity levels of the observed FC grades of the split samples tested in Sri Lanka study areas.

Type of point source		AA	BB	CC	DD	EE	AB	BC	CD	DE	AC	BD	CE	AD	BE	AE	No. of samples
Dug wells	No. of samples	0	20	35	27	0	0	4	2	0	0	0	0	0	0	0	88
	Total (%)			82 (93)					6 (7)			0 (0)		0 (0)		0 (0)	
Tube well with hand pump	No. of samples	0	3	2	1	0	0	1	0	0	0	0	0	0	0	0	7
	Total (%)			6 (86)					1 (14)			0 (0)		0 (0)		0 (0)	
Tube well with mechanical pump	No. of samples	1	2	2	0	0	1	0	0	0	0	0	0	0	0	0	6
	Total (%)			5 (83)					1 (17)			0 (0)		0 (0)		0 (0)	
Overall	Total (%)				93 (92)					8 (8)			0 (0)		0 (0)	0 (0)	101

Table 4. Lloyd and Helmer's (1991) *E. coli*/faecal coliform classification scheme for water supplies.

Grade	Faecal coliform counts/100 mL	Risk
A	0	No risk; in conformity with WHO guidelines
B	1 - 10	Low risk
C	11 - 100	Intermediate to high risk
D	101 - 1000	Gross pollution; high risk
E	>1000	Gross pollution; very high risk

Source: [6,7].

Based on the hydraulic conductivity values summarized in **Table 2**, the safe separation distance between *an open dug well and an on-site sanitation system should,* conservatively, *be* 750 m (with the hydraulic conductiveity value of 30 m/day for the laterite aquifers, which is the lowest among the three) in the study area. Therefore the sanitary survey question 1 needs to be modified according to the safe separation distance appropriate for each aquifer type.

According to the estimated latrine/well densities in the study areas (**Table 1**), the maximum possible separation distance between a well and an on-site sanitation system can be 56.4 m in the Udubaddawa DS division which has the lowest estimated well/latrine density (1/ha). Therefore, based on the information available (**Tables 1** and **4**), *none of the study locations* in Sri Lanka *can safely build an on-site sanitation system maintaining at least a distance above* 25*-day groundwater travel distance from the domestic well*. Therefore the answer, even to the modified sanitary survey question regarding safe separation distance, will be "Yes" at all study locations.

*Q*2: *Is the nearest latrine on higher ground than the well*?

This question checks the possibility of well water contamination, with leachate from on-site sanitation systems, due to the relative location of the well *down gradient* of on-site sanitation systems. Since the topography of the study area is almost flat, Q2 is redundant in the context of the study areas and will not be considered for further analysis.

All the other questions present in the published [7] sanitary survey form (**Text Box 1**) are applicable in the context of the Sri Lanka study areas.

Text Box 1. The modified sanitary survey form for open dug wells.

Open dug wells

1. Is there a latrine within the safe separation distance of the well?
2. Is there any other source of pollution (e.g. animal excreta, rubbish) within 10 m of the well?
3. Is the drainage poor, causing stagnant water within 2 m of the well?
4. Is there a faulty drainage channel? Is it broken, permitting ponding?
5. Is the wall (parapet) around the well inadequate, allowing surface water to enter the well?
6. Is the concrete floor less than 1m wide around the well?
7. Are the walls of the well inadequately sealed at any point for 3 m below ground?
8. Are there any cracks in the concrete floor around the well which could permit water to enter the well?
9. Are the rope and bucket left in such a position that they may become contaminated?
10. Does the installation require fencing?

For the same justifications made in the above sub-section, open dug wells, the sanitary survey question Q1 will be modified for tube well with hand pump and tube well with mechanical pump, and question Q2 in the sanitary survey form for tube wells with hand pump will not be considered for further analysis in the context of the study areas. All other questions are valid and applicable in the context of the study areas for tube wells with hand pump and tube wells with mechanical pump.

Therefore the modified sanitary survey form for open dug wells and tube wells in the context of the Negombo region would like the ones in **Text boxes 1**-**3**.

4. Results and Discussion

4.1. Microbial Well Water Quality

Table 5 summarizes the occurrence of the observed faecal contamination levels in the study areas whereas the faecal contamination levels of different groundwater point sources are presented in **Table 6**.

Text Box 2. The modified sanitary survey form for tube wells with mechanical pump.

The modified sanitary survey form for **tube wells with mechanical pump**

1. Is there a latrine or sewer within the safe separation distance of the pump-house?
2. Is the nearest latrine a pit latrine that percolates to soil, *i.e.* un-sewered?
3. Is there any other source of pollution (e.g. animal excreta, rubbish, and surface water) within 10 m of the borehole?
4. Is there an uncapped well within 15 - 20 m of the borehole?
5. Is the drainage area around the pump-house faulty? Is it broken, permitting ponding and/or leakage to ground?
6. Is the fencing around the installation damaged in any way which would permit any unauthorized entry or allow animals access?
7. Is the floor of the pump-house permeable to water?
8. Is the well seal unsanitary?
9. Is the chlorination functioning properly?
10. Is chlorine present at the sampling tap?

Text Box 3. The sanitary survey form for tube well with hand pump.

The sanitary survey form for **tube well with hand pump**

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

A majority (>50%) of the wells in all study areas, and a high proportion (70.3%) of the wells overall in the Negombo region had well water faecal contamination levels above C grade (11 - 100 cfu/100mL). Considering the whole Negombo region, only about 1% of the wells, solely from one study area (Katana DS Division), satisfy the WHO Guideline value (zero cfu/100mL) for drinking water quality. The extensive use of on-site sanitation systems, together with the very vulnerable hydrogeological conditions of the local aquifers, are the most likely major causes of the observed high levels of faecal contamination of well water in the Negombo region. However the impact of other identified sanitary hazards of the well and the well head area should not be overlooked and are discussed in the following sections.

Considering all three types of groundwater point sources, the microbial quality of tube well water was superior to that of open dug wells (**Table 6**). However, both tube wells and open dug wells share the same shallow aquifers and have on-site sanitation system built within the safe separation distance between the well and the on-site sanitation system. The depth of the dug wells in the study areas varied from a minimum value of 1.5 m to a maximum value of 20 m with an average of 8.7 m. The average tube well depth was 6 m, with minimum and maximum depths of 3.3 m and 8 m, respectively. In general, the depth of a (dug/tube) well was observed to increase approximately in proportion to the distance from the coast. When the thickness of the unsaturated zone between the point at which pollutants are released and the groundwater table increases, the attenuation of the pollutants will also increase. Therefore deep groundwater can be expected to have better microbial quality than shallow groundwater. However, even though the average depth of the dug wells in the Negombo region was greater than that of the tube wells, the microbial quality of tube well water was superior to that of the open dug wells. Therefore the reasons for the higher faecal contamination levels observed in the Negombo open dug well water could reasonably be associated with the sanitary conditions around them, adding contamination directly down the well to the more remote contaminants from sanitation systems.

4.2. Factors Affecting the Faecal Contamination Levels of Well Water

4.2.1. Population Density and the Extent of the Study Areas

The faecal contamination levels of the well water observed in the Negombo region showed no (with negative gradient) or very weak ($R^2 < 0.1$ with positive gradient) correlation with population density and the extent of the study areas in the Negombo region (**Table 7**). Since almost every house in the Negombo region owns an on-site sanitation system, the population density is proportional to the latrine density in the Negombo region. Therefore according to the estimated correlation values in **Table 6**, the latrine density is not a significant factor impacting on the faecal contamination levels in the well water in the Negombo region. However, the ubiquitous usage of the on-site sanitation system in the Negombo region could be

Table 5. Occurrence of the FC grades in the Negombo region, Sri Lanka arranged by study areas.

Study areas	Percentage of occurrence of FC grade					No. of samples	≥C grade	
	A	B	C	D	E			
Negombo	0.00%	46.15%	23.08%	30.77%	0.00%	13	53.85%	62.75%
Katana	4.55%	40.91%	45.45%	9.09%	0.00%	22	54.55%	
Divulupitiya	0.00%	20.00%	50.00%	30.00%	0.00%	10	80.00%	
Minuwangoda	0.00%	16.67%	33.33%	50.00%	0.00%	6	83.33%	
Dankotuwa	0.00%	33.33%	60.00%	6.67%	0.00%	15	66.67%	78.26%
Wennappuwa	0.00%	16.67%	33.33%	50.00%	0.00%	6	83.33%	
Nathandiya	0.00%	16.67%	41.67%	41.67%	0.00%	24	83.33%	
Mahawewa	0.00%	0.00%	100.00%	0.00%	0.00%	1	100.00%	
Udubaddawa	0.00%	25.00%	25.00%	50.00%	0.00%	4	75.00%	75.00%
Overall	0.99%	28.71%	42.57%	27.72%	0.00%	101	70.30%	

FC Grade A = 0 cfu/100mL; Grade B = 1 - 10 cfu/100mL; Grade C = 11 - 100 cfu/100mL; Grade D = 101 - 1000 cfu/100mL; Grade E ≥ 1000 cfu/100mL.

Table 6. Occurrence of FC grades in different types of groundwater point sources in the Negombo region, Sri Lanka.

Type of structure		Occurrence (%) of FC grade					No. of samples
		A	B	C	D	E	
Dug wells	No. of samples	0 (0.0%)	23 (26.1%)	36 (40.9%)	29 (33.0%)	0 (0.0%)	88
	Above C-grade			65 (73.9)			
Tube well with hand pump	No. of samples	0 (0.0%)	3 (42.9%)	3 (42.9%)	1 (14.3%)	0 (0.0%)	7
	Above C-grade			4 (57.1)			
Tube well with mechanical pump	No. of samples	1 (16.7%)	3 (50.0%)	2 (33.3%)	0 (0.0%)	0 (0.0%)	6
	Above C-grade			2 (33.3)			
Overall	No. of samples	1 (0.99%)	29 (28.7%)	41 (40.6%)	30 (29.7%)	0 (0.0%)	101
	Above C-grade			71 (70.3)			

Table 7. Summary of estimated correlations between different faecal contamination levels and the population density, and extent of the study areas, in the Negombo region.

Correlation	Gradient	R^2
Mean FC counts vs. Population density	Positive	0.0021
Percentage of occurrence > FC grade B vs. Population density	Negative	0.0288
Percentage of occurrence > FC grade C vs. Population density	Negative	0.4097
Percentage of occurrence > FC grade D vs. Population density	Positive	0.0121
Mean FC counts vs. Area	Negative	0.0111
Percentage of occurrence > FC grade B vs. Area	Negative	0.0010
Percentage of occurrence > FC grade C vs. Area	Negative	0.0243
Percentage of occurrence > FC grade D vs. Area	Positive	0.00009

a reason why a very weak correlation is observed between the population density and the faecal contamina tion levels.

Therefore the major impact on the microbial well water quality seems to be very local in the Negombo region, potentially from the sanitary conditions of the wellhead area.

Nevertheless, due to the very vulnerable hydrogeological conditions, and bearing in mind the fact that it is not feasible to maintain a safe separation distance between the on-site sanitation system and the well, faecal contamination of well water from on-site sanitation system, (similar to the context of the Maldives islands [10]) can also considered to be local.

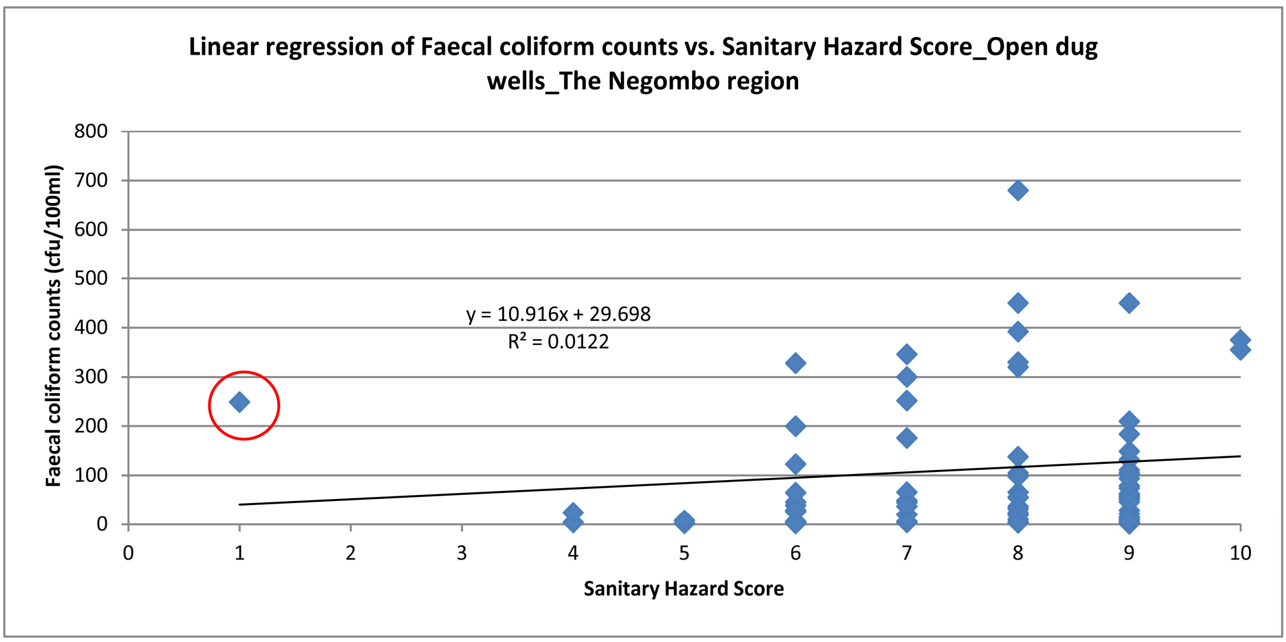
4.2.2. Sanitary Hazards

The Sanitary Hazard Score (SHS) is the summation of the number of sanitary hazards present at each well in the wellhead area. A linear regression analysis (**Graphs 1** and **2**) was carried out between the faecal contamination levels and the SHS to test the preliminary hypothesis that increasing levels of faecal contamination will positively correlate with increasing number of sanitary hazards observed.

Graph 1 shows that, in the Sri Lankan study area, it was rare to find wells with few or no hazards and, unlike previous studies in Thailand [11] and Indonesia [6], the great majority of wells are characterized by large number of identifiable hazards and, unsurprisingly, high levels of FC contamination. It has already been pointed out that all of the wells have latrines discharging unacceptably close to a well.

As highlighted in **Graph 1** with red circle, the well at sampling location ID71 showed higher faecal contamination level (Grade D = 101 - 1000 cfu/100mL) with SHS equal to 1, which is the presence of an on-site sanitation system within the safe separation distance. This fact clearly highlights the impact of an on-site sanitation on the microbial quality of well water as being far more important than the presence of other, more localized pathways of contamination. The intensity of faecal pollution (10^4 - 10^6 FC/100mL) at the point of effluent discharge from an on-site sanitation system is much higher than the intensity of pollutants which will be introduced by the presence of other localized pathways. When the leachate leaking from the on-site sanitation system reaches the well water through the aquifer pathway, over a distance comparable to the safe separation distance, the impact of the presence of the on-site sanitation system and localized pathways may become comparable. However, in the context of the Negombo region where, due to the very vulnerable hydrogeological conditions present, and where it is not feasible to achieve the required safe separation distance presence of on-site sanitation system, this also becomes a localized pollutant source to the well water. In this scenario the contaminant loading from the on-site sanitation system is not comparable with that from localized pathways. This is what is clearly identified at sampling location ID 71.

In the previous sections it was hypothesized that the causes of the faecal contamination of the well water are local, and, potentially due to the sanitary conditions of



Graph 1. Linear regression of the faecal coliform counts vs. sanitary hazard score for open dug wells in the Negombo region. The point (ID 71) which had Grade D level faecal contamination with SHS = 1 is circled in red.

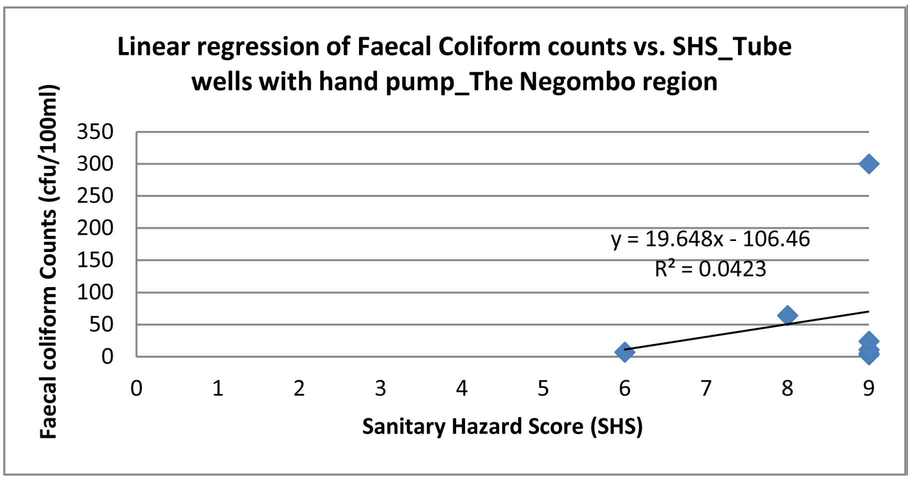
the well and the wellhead area (including the on-site sanitation system where maintaining safe separation distance was not feasible due to very vulnerable hydrogeological conditions). However the correlation between the FC counts and the SHS was very weak ($R^2 < 0.1$) or not present (**Graphs 1** and **2**); this might be because the major unknown is the FC contribution of each hazard source in the well water. The contribution of each hazard to FC contamination should be identified by the SHI (see below).

4.3. Relative Significance of Sanitary Hazards

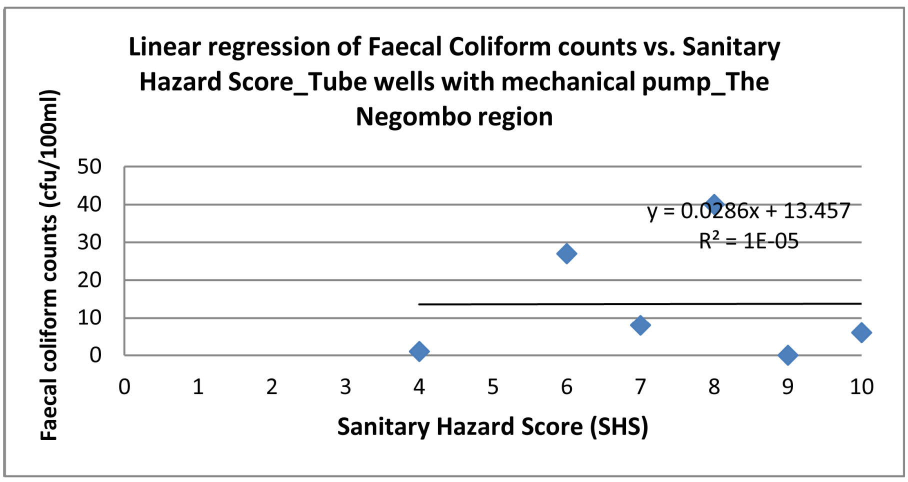
Different statistical methods [11-13] have been used in the past to assign weights to each observable sanitary hazard. The impact of sanitary hazards based on the occurrence of the sanitary hazards with the FC grades above and below an observed FC grade for each type of groundwater point source is summarized in **Table 8**.

In this method [12] of statistical analysis of the occurrence of the sanitary hazards,

- when a sanitary hazard is abundant, the impact of that hazard on the microbial quality of well water cannot be readily identified
- Therefore, even though the sanitary hazard ID 01 (on-site sanitation system present within the safe separation distance) of all types of groundwater point source can be a major source of faecal contamination of well water, its significance is not identified in this methodology because of the very frequent occurrence of it in the Negombo region.
- When the occurrence of a hazard decreases from one FC grade (e.g. FC Grade D) to one grade lower (FC Grade C), the impact of that hazard can be said to be the higher grade (e.g. FC Grade D).
- When the occurrence of a hazard increases from one FC grade (e.g. FC Grade D) to the next lower FC



(a)



(b)

Graph 2. Linear regression of the faecal coliform counts vs. sanitary hazard score for tube wells with (a) hand pump, and, (b) mechanical pumps in the Negombo region.

grade (e.g. FC Grade C), this will imply that the impact level of the hazard is the lower FC grade (e.g. FC Grade C).

- When the difference in occurrence of a hazard in two consecutive grades (e.g. FC Grades D and C) of faecal contamination is negative, the impact level of that hazard is either FC Grades D or C.

The percentage occurrence of each sanitary hazard with different FC grades (**Table 8**) implies that in the case of open dug wells in the study areas described:

Table 8. The relative significance of the sanitary hazards assessed based on the percentage occurrence of the sanitary hazards with different faecal contamination grades in the Negombo region.

Hazard ID	Percentage occurrence with FC grade ≥ FC Grade D	Percentage occurrence with FC grade < FC grade D	Difference	Hazard ID	Percentage occurrence with FC grade ≥ FC Grade C	Percentage occurrence with FC grade < FC Grade C	Difference
Open dug wells							
1	100.0%	100.0%	0.0%	1	100.0%	100.0%	0.0%
2	82.8%	86.4%	–3.7%	2	86.2%	82.6%	3.5%
3	86.2%	84.7%	1.5%	3	87.7%	78.3%	9.4%
4	86.2%	81.4%	4.9%	4	86.2%	73.9%	12.2%
5	6.9%	5.1%	1.8%	5	7.7%	0.0%	7.7%
6	75.9%	94.9%	–19.1%	6	87.7%	91.3%	–3.6%
7	86.2%	79.7%	6.5%	7	81.5%	82.6%	–1.1%
8	89.7%	76.3%	13.4%	8	84.6%	69.6%	15.1%
9	79.3%	57.6%	21.7%	9	67.7%	56.5%	11.2%
10	96.6%	100.0%	–3.4%	10	98.5%	100.0%	–1.5%
Tube with hand pump							
1	100.0%	100.0%	0.0%	1	100.0%	100.0%	0.0%
2	100.0%	83.3%	16.7%	2	75.0%	100.0%	–25.0%
3	100.0%	100.0%	0.0%	3	100.0%	100.0%	0.0%
4	100.0%	100.0%	0.0%	4	100.0%	100.0%	0.0%
5	100.0%	100.0%	0.0%	5	100.0%	100.0%	0.0%
6	100.0%	100.0%	0.0%	6	100.0%	100.0%	0.0%
7	100.0%	83.3%	16.7%	7	100.0%	66.7%	33.3%
8	100.0%	83.3%	16.7%	8	100.0%	66.7%	33.3%
9	100.0%	83.3%	16.7%	9	100.0%	66.7%	33.3%
Tube well with mechanical pump							
Hazard ID	% occurrence with FC grade ≥ FC Grade C	% occurrence with FC grade < FC Grade C	Difference	Hazard ID	% occurrence with FC grade ≥ FC Grade B	% occurrence with FC grade < FC Grade B	Difference
1	100.0%	100.0%	0.0%	1	100.0%	100.0%	0.0%
2	100.0%	100.0%	0.0%	2	100.0%	100.0%	0.0%
3	100.0%	75.0%	25.0%	3	80.0%	100.0%	–20.0%
4	50.0%	50.0%	0.0%	4	60.0%	0.0%	60.0%
5	100.0%	75.0%	25.0%	5	80.0%	100.0%	–20.0%
6	100.0%	75.0%	25.0%	6	80.0%	100.0%	–20.0%
7	100.0%	75.0%	25.0%	7	80.0%	100.0%	–20.0%
8	0.0%	50.0%	–50.0%	8	20.0%	100.0%	–80.0%
9	50.0%	75.0%	–25.0%	9	60.0%	100.0%	–40.0%
10	0.0%	75.0%	–75.0%	10	40.0%	100.0%	–60.0%

- The impact of sanitary hazard ID 1 cannot be assessed due to its abundance.
- Sanitary hazards ID 6 and 10 have no impact on microbial well water quality at FC Grades D and C levels.
- The impact of the hazards ID 7 and 9 on the well water quality is at FC Grade D.
- Sanitary hazards ID 2, 3, 4, 5 and 8 are associated with FC Grade C levels of microbial contamination of well water.
- In the case of tube wells with hand pump,
- The impact of sanitary hazards ID 1, 3, 4, 5 and 6 cannot be assessed due to their abundance.
- Only, the hazard ID 2 is associated with D level faecal contamination.
- Hazard IDs 7, 8 and 9 are associated with Grade C level of microbial contamination of well water.
- In the case of tube wells with mechanical pump,
- The sanitary hazards 1 and 2 are abundant with FC Grades C and B and hence their impact cannot be assessed.
- Hazards ID 3, 5, 6 and 7 cause FC Grade C level of microbial contamination.
- Sanitary hazard ID 4 causes FC Grade B level of impact.
- Hazards ID 8, 9 and 10 cause neither C nor B grade faecal contamination.

The Sanitary Hazard Index (developed by Lloyd and Boonyakarnkul [11]) is another measure of the relative significance of the sanitary hazards causing faecal contamination of well water (**Table 9**). The SHI values were shown to be efficient in prioritizing remedial actions by systematically removing the sanitary hazard in order to improve tube well microbial well water quality in Thailand [11]. This study is the only published practical demonstration of substantial FC improvement using a follow-up evaluation following specified remedial work at the well head. It is important to note that, in rural central Thailand, sanitary hazard question (ID 1), the latrine within 10 m of the well, occurred rarely, although when it did occur it was often the major source of faecal contamination according to the SHI!

According to the SHI values (**Table 9**), sanitary hazard (ID 5), parapet wall inadequacy, is the crucial hazard causing a significant level of well water faecal contamination, followed in descending order of significance by hazards (ID) 9, 8, 4, 3 and 7 (well walls inside the well inadequate sealed for a depth of 3 m). Sanitary hazards ID 10, 2 and 6 are not significant in the microbial contamination of open dug wells.

However the Cronin *et al.* [12], statistical method showed that hazards ID 7 and 9 cause FC Grade D level of contamination while hazards ID 2, 3, 4, 5 and 8 cause FC Grade C levels of microbial contamination of well water. Therefore the SHI values were recalculated with median FC counts (mean values were used by Lloyd and Boonyakarnkul [11]) and summarized in **Table 10**. The SHI values recalculated based on the median FC counts closely agree with the findings from the previous statistical method. However, this way of SHI assessment needs to be field checked to assess its competence when used in prioritizing remedial actions to improve the microbial well water quality.

Table 11 shows that the SHI values did not differ significantly whether mean or median FC counts were used in the assessment. The SHI values resemble some of the findings from the method of Cronin *et al*., (based on comparison of occurrence of sanitary hazards with different FC grades). However, the hazard ID 2 was causing FC Grade D in the Cronin *et al*., method, whereas it is not

Table 9. Sanitary Hazard Index (SHI) values for each sanitary hazard of open dug wells observed in the Negombo region.

Sanitary Hazard ID	5	9	8	4	3	7	1	10	2	6
SHI	**0.412**	0.085	0.078	0.040	0.038	0.011	0.000	–0.009	–0.013	–0.039

Table 10. Sanitary Hazard Index (SHI) values recalculated based on median faecal coliform counts, for each sanitary hazard of open dug wells observed in the Negombo region.

Sanitary Hazard ID	9	5	8	7	2	3	4	1	6	10
SHI	0.1387	0.1216	0.0700	0.0497	0.0333	0.0333	0.0115	0.000	–0.011	–0.01149

Table 11. Sanitary Hazard Index (SHI) values calculated based on mean and median faecal coliform counts, for each sanitary hazard of tube wells with hand pump observed in the Negombo region.

Using mean values	ID	7	8	9	1	3	4	5	6	2
	SHI	0.067	0.067	0.067	0.000	0.000	0.000	0.000	0.000	–0.093
Using median FC values	ID	7	8	9	1	3	4	5	6	2
	SHI	0.169	0.169	0.169	0.000	0.000	0.000	0.000	0.000	–0.098

significant according to the SHI values.

Other than the status of sanitary hazard ID 4, the SHI values of hazards for tube wells with mechanical pump are similar to the findings from the method of Cronin *et al*. The SHI values presented in **Table 12**, demonstrate an identical rank order for the mean and median FC counts except for sanitary hazard ID 4 which is replaced by ID 3 in the top position using the FC median value.

The contingency table analyses of the FC grades and sanitary hazards proposed by Howard *et al*. [13] are summarized in **Figures 2-4**. This was carried out using GraphPad Prism statistical software. The odds ratios imply that for.

4.3.1. Open Dug Wells

Hazards ID 4, 7, 8 and 9 are causing Grade D level of faecal contamination. Hazards ID 3, 4, 6, 8 and 9 are causing Grade C level of faecal contamination.

Even though hazard ID 9 contributes to FC Grades C and D, the odds ratio of hazard ID 9 with FC Grade D is higher than that with FC Grade C. Similarly the odds ratio of hazard IDs 4 and 8 are higher with FC Grade C than Grade D. Hazard ID is only contributing to FC Grade D. Therefore the contingency table analysis implies that:

Table 12. Sanitary Hazard Index (SHI) values calculated based on mean and median faecal coliform counts, for each sanitary hazard of tube wells with mechanical pump, observed in the Negombo region.

Using mean values	ID	4	3	5	6	7	1	2	9	10	8
	SHI	0.475	0.124	0.124	0.124	0.124	0.000	0.000	–0.274	–0.693	–0.730
Using median FC values	ID	3	4	5	6	7	1	2	9	10	8
	SHI	0.062	0.062	0.062	0.062	0.062	0.000	0.000	–0.452	–0.841	–0.952

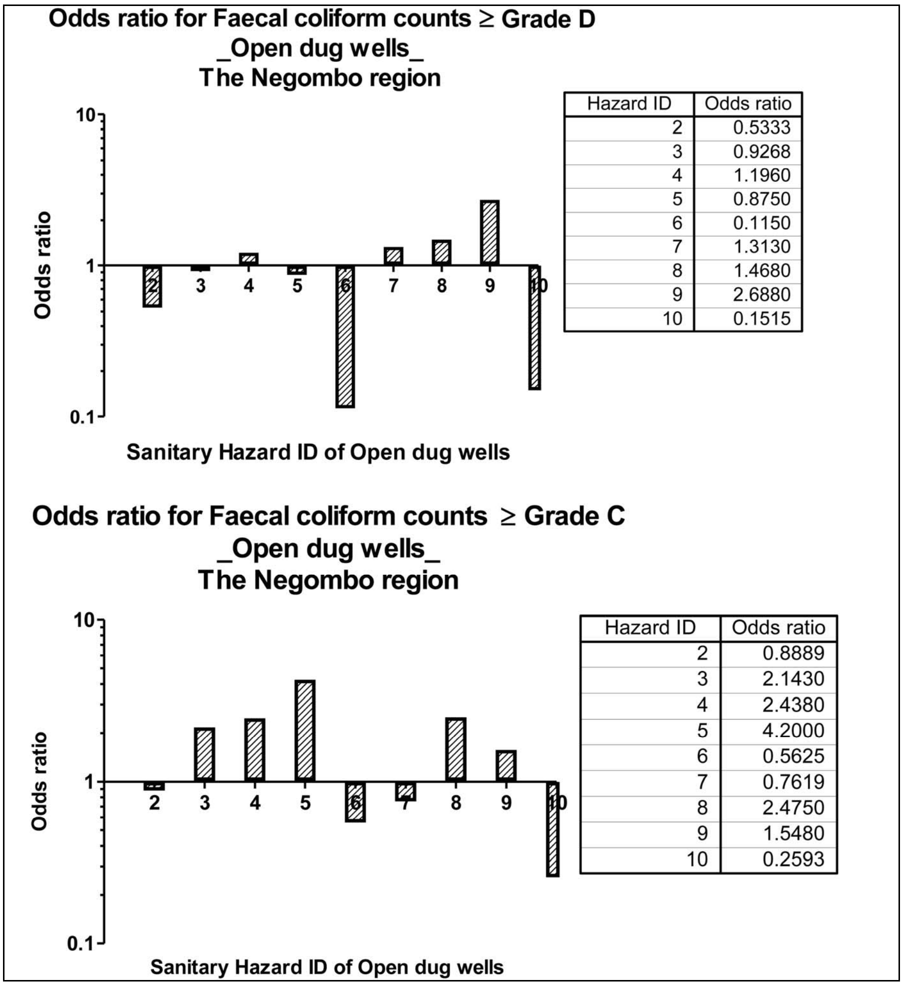


Figure 2. The plots of odds ratios from the contingency table analysis of the sanitary hazards and the faecal coliform counts of the open dug wells in the Negombo region.

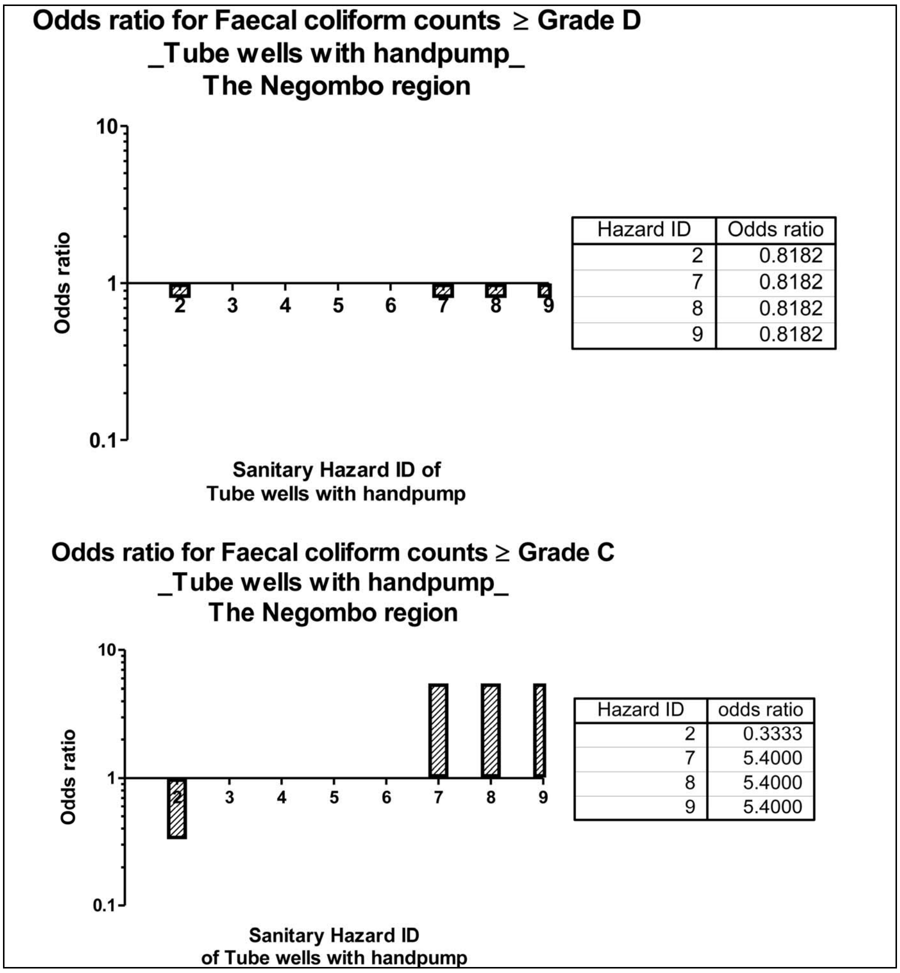


Figure 3. The plots of odds ratios from the contingency table analysis of the sanitary hazards and the faecal coliform counts of the tube wells with hand pump in the Negombo region.

- Hazards ID 7 and 9 are contributing to Grade D level of faecal contamination of well water Hazards ID 3, 4, 6 and 8 are contributing to Grade C level of feacal contamination.
- Hazard IDs 2 and 10 are not contributing to FC Grades C and D.
- The impact of hazard ID 1 cannot be assessed with this method due to its abundance.

4.3.2. Tube Wells with Hand Pump

- Hazards ID 7, 8 and 9 are causing Grade C level of faecal contamination.
- Hazard ID 2 is not contributing to FC grades C or D level of contamination.
- The impact of other hazards cannot be assessed with this method due to their abundance.

4.3.3. Tube Wells with Mechanical Pump

- Hazards ID 3, 5, 6, and 7 are causing FC grade C level of contamination.
- Hazards ID 2 and 4 are causing FC grade B level of contamination.
- Hazards ID 8, 9 and 10 are not causing FC Grades B or C level of faecal contamination.
- The impact of Hazard ID 1 cannot be assessed with this method due to its abundance.

5. Summary and Conclusions

The published [7] sanitary survey forms for open dug wells and tube wells need to be modified according to the context of the Negombo study areas. Barthiban *et al.* [10] showed that the published [7] surveillance form needed to be modified to be applied in the context of the Maldives islands which was characterized by:

- Very vulnerable hydrogeological conditions aquifer with shallow groundwater table (at about 2 m on average),
- Limited land space and failure of maintaining safe separation distance between the on-site sanitation system and open dug wells,
- Extensive usage of on-site sanitation system (which are basically pit latrines with water used for flushing).

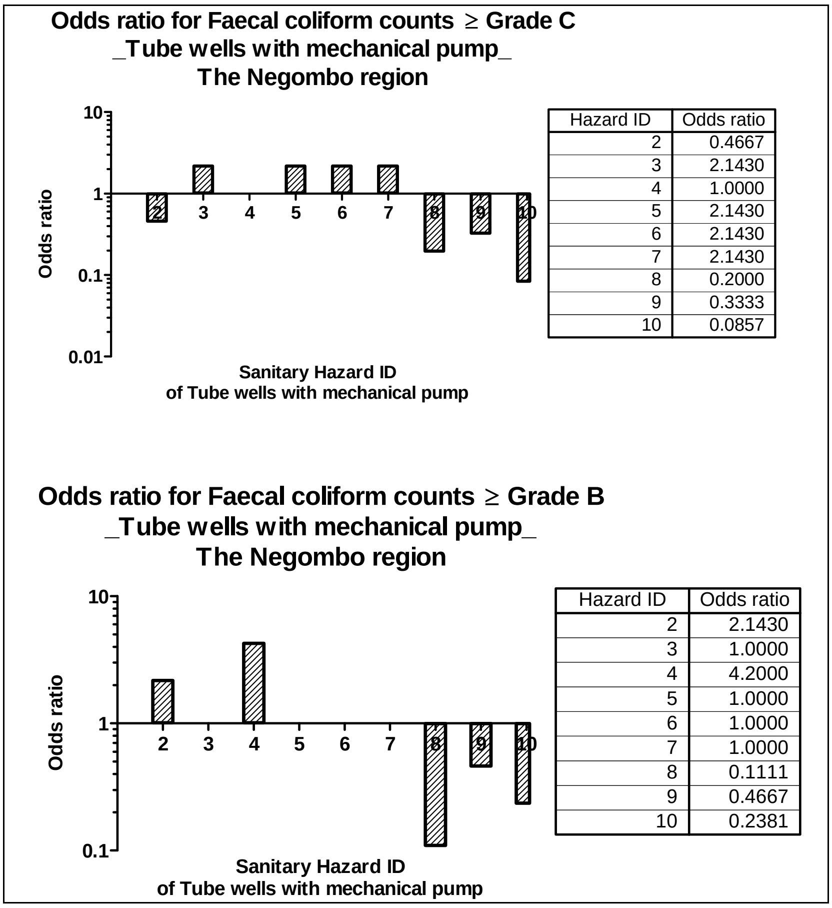


Figure 4. The plots of odds ratios from the contingency table analysis of the sanitary hazards and the faecal coliform counts of the tube wells with mechanical pump in the Negombo region.

Therefore, in conclusion, the published surveillance forms need revision based on the specific hydrogeological and sanitation densities of the study area.

The relative significance of sanitary hazards on the microbial contamination of wells was assessed using three different statistical approaches using a) compareson of the occurrence of sanitary hazards with specific FC grades, b) SHI values calculated based on the median FC counts (slightly different from the original method by Lloyd and Boonyakarnkul, [11] which used mean FC counts), and, c) contingency table analysis for different FC grades. Although several anomalies regarding the relative significance were noted between the different methods used, overall the results were comparable. This gives confidence in the statistical approaches used in assessing the relative significance of the sanitary hazards. However, the only method which has been *practically verified* by systematically removing the hazards and assessing the corresponding well water quality improvement is that described by Lloyd and Boonyakarnkul [11]. They achieved a 94% success rate in Thailand in reduceing FC grades from C and D to Grades A and B by a judicious selection of well head hazards for remedial action. However, they did not have to address the problem of 100% of wells being exposed to sanitation system effluxents within the safe separation distance.

SHI values calculated based on median FC counts more closely complied with the findings from the other two statistical methods rather than the original SHI values based on the mean FC counts. Therefore it is of practical importance to carry out a field based study to understand whether the SHI values calculated based on the median FC counts are efficiently identifying the relative impact of each sanitary hazard, in the Negombo region. Assessing the reliability of the SHI values based on the median FC counts will also help to deduce the reliability of the other statistical approaches used in this paper in estimating the relative significance of each sanitary hazard on the microbial well water quality, because the findings from all three are closely agreeing with each other.

The following conclusions were made based on the well surveillance study carried out in Sri Lanka.

- The published [7] sanitary survey forms for open dug wells and tube wells need to be modified according to the context of the study areas.

- Due to the very vulnerable hydro-geological setting occurring in the study areas (West Coastal Area of Sri Lanka), the negative impact from on-site sanitation system on microbial well water quality was widespread. This, also, overwhelmed the impact of other sanitary hazards observed at the well and in the wellhead area, on the microbial quality of well water.
- Therefore, the impact from on-site sanitation systems need to be reduced, or eliminated, before the impact from the other sanitary hazards can be quantified. It was shown that, under the prevailing vulnerable hydro-geological conditions achieving a safe separation distance between a well and on-site sanitation system is not practical in the study areas. Therefore the existing on-site sanitation systems need to be upgraded to reduce or eliminate the microbial pollution of well water.
- Water-tight septic tanks are required together with tile field treatment. Alternatively, the septic tank system may be replaced with sewered sanitation facilities, such as small bore sewerage system or a conventional sewerage system.
- Overall, microbial quality of tube well water is superior to that of open dug wells. Furthermore, tube wells with mechanical pumps had better microbial quality than that of the tube wells with hand pumps.
- The relative significance of sanitary hazards assessed using three different statistical approaches gave closely tallying results. This provided confidence in the methodology used and the relative significance values estimated. However, to fully ensure the reliability of the estimated values of relative significance, a systematic field based study needs to be carried out. Bearing in mind that the faecal contamination of wells in the study area from the on-site sanitation system is widespread due to the reasons mentioned above, any field study to be carried out to assess the relative significance of each hazard needs to begin with the removal of the impact of the on-site sanitation system.

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Abbreviations

ARGOSS—Assessing Risk to Groundwater from On-Site Sanitation.

