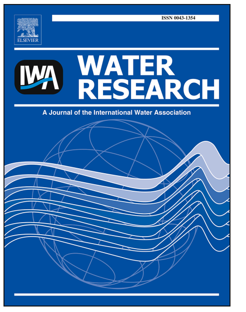

The public health significance of latrines discharging to groundwater used for drinking

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PII: S0043-1354(17)30622-X

DOI: 10.1016/j.watres.2017.07.049

Reference: WR 13092

To appear in: *Water Research*

Received Date: 18 April 2017

Revised Date: 17 June 2017

Accepted Date: 18 July 2017

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The Public Health Significance of Latrines Discharging to Groundwater used for Drinking

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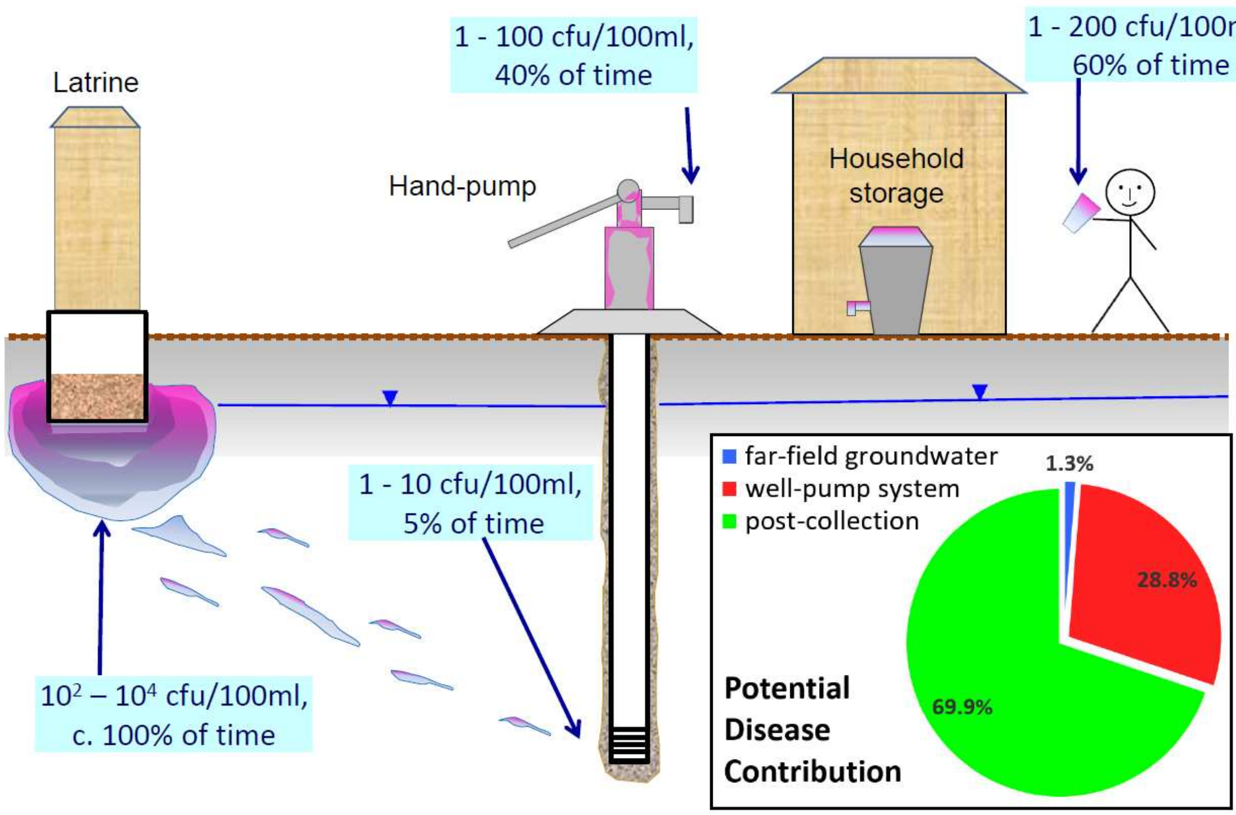
Abstract

Faecal contamination of groundwater from pit latrines is widely perceived as a major threat to the safety of drinking water for several billion people in rural and peri-urban areas worldwide. On the floodplains of the Ganges-Brahmaputra-Meghna delta in Bangladesh, we constructed latrines and monitored piezometer nests monthly for two years. We detected faecal coliforms (FC) in 3.3 - 23.3% of samples at four sites. We differentiate a near-field, characterised by high concentrations and frequent, persistent and contiguous contamination in all directions, and a far-field characterised by rare, impersistent, discontinuous low-level detections in variable directions. Far-field FC concentrations at four sites exceeded 0 and 10 cfu/100ml in 2.4 - 9.6% and 0.2 - 2.3% of sampling events respectively. The lesser contamination of *in-situ* groundwater compared to water at the point-of-collection from domestic wells, which itself is less contaminated than at the point-of-consumption, demonstrates the importance of recontamination in the well-pump system. We present a conceptual model comprising four sub-pathways: the latrine-aquifer interface (near-field); groundwater flowing from latrine to well (far-field); the well-pump system; and post-collection handling and storage. Applying a hypothetical dose-response model suggests that 1 - 2% of the diarrhoeal disease burden from drinking water is derived from the aquifer, 29% from the well-pump system, and 70% from post-collection handling. The important implications are (i) that leakage from pit latrines is a minor contributor to faecal contamination of drinking water in alluvial-deltaic terrains; (ii) fears of increased groundwater pollution should not constrain expanding latrine coverage, and (iii) that more attention should be given to reducing contamination around the well-head.

Keywords:

Faecal coliforms; latrines; groundwater pollution; Bangladesh; drinking water; risk

Graphical Abstract



INTRODUCTION

Graham and Polizzotto (2013) draw attention to the '*widespread global reliance on both pit latrines and groundwater …*' and estimate that 1.77 billion people worldwide use pit latrines, a figure that will increase in line with achieving Sustainable Development Goal (SDG) 6.2: safe sanitation for all. While expressing caution about the variable quality of previous studies of the risks of latrines to rural water supplies, they warn that areas with shallow groundwater and prone to flooding, conditions common in S and SE Asia, present the greatest risks to health. It is estimated that 38% of improved water sources globally are contaminated by faecal indicator bacteria (FIB; Bain et al. 2014), and that untreated groundwater is a major source of enteric disease globally and that the proven disease burden is only 'the tip of the iceberg' (Murphy et al. 2017). Bangladesh is a country that conforms to this pattern: untreated groundwater supplies >90% of the rural population, with FIB detected in around 40% of all supplies at the point of collection (PoC), rising to about 60% at the point of use (PoU; Hoque 1998; Ravenscroft et al. 2014; BBS/UNICEF 2015). Increases in contamination from PoC to PoU have been noted elsewhere and already drives hygiene education programmes (e.g. Trevett et al. 2005; UNICEF 2012). The many reviews of the effects of on-site sanitation on groundwater quality (e.g. Lewis et al. 1982; Cave and Kolsky 1999; Lawrence et al. 2001; Foppen and Schijven 2006; Graham and Polizzotto 2013 and references therein) draw heavily on short-term monitoring of existing water wells near existing latrines and equate, incorrectly we believe, the intrinsic quality of groundwater with the quality of the water collected from wells. The conventional wisdom that inadequate spacing of pit latrines and wells is a major contributor to faecal contamination of drinking water has long directed public health authorities to mandating spacing criteria, typically 10 to 50 m, although the scientific basis and efficacy of these rules are often open to question (Parker and Carlier, 2009; Graham and Polizzotto, 2013). We seek to show that the application of the precautionary principle to cases of uncertain attribution of the cause of faecal contamination in water wells leads to disproportionate attention being given to spacing as a control measure.

Concern over the severity of the risks of on-site sanitation polluting groundwater-sourced drinking water has fluctuated, mirroring renewed drives for safe water and sanitation such as the Millennium Development Goals, the SDG's and for example, India's Total Sanitation Campaign which aims to build 12 million latrines by 2019 but has been criticised for potentially increasing pollution of groundwater and drinking water. For example, on alluvial terrain in India's Odisha State, Daniels et al. (2016) report '*strong evidence of protozoa contamination of shallow groundwater from pour-flush latrines within 15m*' and conclude that contamination of groundwater used for drinking is correlated with faecal loading of latrines, literacy, livestock, damaged well-heads and antecedent rainfall. Daniels et al. (2016) predict that achieving 100% latrine coverage will result in a 1.9 – 4.1 times increase in protozoan contamination. Odagiri et al. (2016) also in Odisha State and Sorensen et al. (2016) in Bihar State both predict increased microbial contamination of shallow groundwater from increased adoption of latrines, suggesting a trade-off between sanitation and water supply objectives (i.e. SDG 6.1 and 6.2).

There is a potential contradiction between the conventional views that, on the one hand, perceive groundwater as being intrinsically safe and, on the other hand, perceive groundwater as being intrinsically at risk from latrines, although this difference may be partly explained by pit latrines by-passing the soil zone. It is a widely accepted norm that the immediate vicinity of hand-pumped tubewells are vulnerable to pollution, and much effort is given to reducing this risk through sanitary inspections and their incorporation into Water Safety Plans (WHO 2011). Unfortunately, sanitary inspection scores have little ability to predict bacterial contamination of well water (e.g. Hoque 1998; Luby et al. 2008; Ercumen et al. 2017; Misati et al. 2017). A possible explanation for this poor correlation is that the contents of the standard WHO sanitary inspection are necessary but not sufficient because it excludes factors such as well construction, the survival and growth of bacteria inside pipes and pumps, and the use of dirty priming water (Ferguson et al. 2011; Hoque 1998; Knappett et al. 2012a).

The primary objectives of this study were to understand the migration of faecal bacteria away from latrines under different hydrogeological settings and thereby produce better guidelines for siting and construction, at least for alluvial terrains. However, recognising that the causes of faecal contamination of drinking water are more nuanced than simple spacing, we also sought to isolate factors such as operation and maintenance and hygiene practices from the migration of contaminants in groundwater. To do this, we constructed and monitored new latrines and dedicated piezometers at households with no existing latrine at four sites in rural Bangladesh monthly over two years. We interpret these results in the light of drinking water surveys conducted by ourselves and others and studies of alternative pollution pathways to assess the relative contributions of different sub-pathways from the latrine to the point of water consumption.

METHODS AND MATERIALS

Study Sites

Following a pilot study on older (Pleistocene) sediments of the Barind Tract and Holocene sediments of the Chittagong Coastal Plain (Islam et al. 2016; Table S1), we selected four (Phase 2) sites on the Ganges – Brahmaputra – Meghna delta to reflect the diversity of recent floodplain environments in Bangladesh (Fig 1; Brammer 2012; Rahman and Ravenscroft 2003). The village and household selection were carried out considering social and logistical factors as detailed by Islam et al. (2017a) and included the requirement that collaborating households did not already have their own latrine and that shallow groundwater was not contaminated by arsenic above the national standard (50 µg/L). At our study sites, domestic water supplies are drawn dominantly from manually-drilled, privately-owned tubewells a few tens of metres deep and equipped with suctionmode (e.g. the UNICEF Nr 6) hand pumps. Most households use a latrine of the same type as constructed under the study; open defecation is rare at all sites. Pirganj, on the Tista Fan and Shambuganj on the Old Brahmaputra floodplain (Rangpur and Mymensingh districts respectively) have sandier, more permeable sediments with less organic matter and deeper water tables. Jajira (Shariatpur District) and Paikgachha (Khulna District) lie respectively on the River and the Tidal floodplains of the Ganges (Brammer 2012), formed of finer sediments, albeit with different internal sedimentary structures, and shallower water tables. All sites have surface aquitards 3 to 5 m thick within which the latrine was constructed. However, the grain sizes of the sediments to depths of 5m bgl differ: sandy at Pirganj and Shambuganj but dominated respectively by silt and clay at Jajira and Paikgachha (Fig S1). Only at Paikgachha (8m) is there a lower aquitard of sufficient thickness (> 0.5m) that might divide the upper 30 m of sediment into separate aquifers.

All sites are subject to a tropical monsoonal climate. Mean annual rainfall is typically around 2000 mm, and mean annual temperature is about 25°C with monthly means ranging from 18 to 30°C (Brammer 2012). There is significant pumping from shallow tubewells (tens of metres deep) for irrigation in the vicinity of the Shambuganj and Pirganj sites and may cause temporary changes in flow direction between February and April each year. No irrigation wells were identified that could affect either the Jajira or Paikgachha sites.

Monitoring Networks and Sampling and Analytical Protocols

New pit latrines were manually excavated to a depth of 2.5 m and completed with 1.5 m diameter concrete rings as per local practice. At each site, between 25 and 38 PVC piezometers (with 38 mm diameter, 3 m long screens) were installed using the local manual-percussive technique (e.g. Ali 2003) in a cruciform pattern in four layers at depths of 4 to 30 m and radial distances of 2 to 10 m. The first monitoring horizon was selected to be as close as practical to the water table to intercept any shallow pathway, should it exist, and was completed in a presumed low permeability (silt or sandy silt) layer since none of the latrines discharged directly into an aquifer. The second monitoring horizon, typically 5 – 10 m bgl, was selected to represent water quality at top of the first aquifer. The third horizon was selected to identify any significant vertical migration of bacteria into the aquifer. The deepest monitoring horizon, typically 25 – 30 m bgl, was selected to represent the deepest credible depth for bacterial migration, or to represent water quality in a second aquifer if encountered. Immediately after completion, the borehole annulus was sealed from the surface with a sand-cement slurry, and in any lower aquitard by carefully dropping hand-rolled balls of bentonite clay, to prevent percolation of surface water or inter-aquifer leakage. The layout of piezometers was based on a conceptual site model developed from a test borehole, water features survey, estimation of groundwater flow direction(s), examination of land use and discussions with residents. Concerns over possible cross-contamination in the Pilot Study prompted a change in the sampling procedure from a conventional hand-pump to a peristaltic pump. Between and/or immediately before sampling each piezometer, the hoses were flushed with water was hot enough to sterile the tube. and the outside of the pipe was also properly cleaned.

Water samples were collected in 500 ml autoclavable Nalgene plastic bottles which were autoclaved each time before sampling, and after sampling kept in insulated boxes with ice packs to maintain the temperature between 4 and 8 ^{0}C and transported to the Environmental Microbiology Laboratory of the International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b) at Dhaka. The collected water samples were analysed within 24 hours of collection following procedures described earlier (Islam et al. 2001, 2016). Analyses enumerated faecal coliforms (FC), *E. coli* and faecal streptococci; however, because the patterns of these parameters are essentially the same (Islam et al. 2017a) we restrict our presentation to faecal coliforms. Water samples were also tested in the icddr,b laboratory in Dhaka for pH and electrical conductivity monthly, and chloride and nitrate quarterly (Islam et al. 2017b). Sampling was conducted in 24, approximately monthly, sampling events. This interval is three times less than the putative maximum survival period of

FC's outside the gut (e.g. Lewis et al. 1982). During each sampling event, which required at least two days on site, the depth to groundwater was measured in every piezometer using a standard electrical dip meter. In categorising faecal risk, we follow the WHO (2011) classification where very low, low, medium, high and very high risk correspond to 0, 1-10, 11-100, 101-1000 and >1000 cfu/100ml.

Limitations

This paper does not describe the latrine-derived chemical contamination by nitrate and chloride or other FIB, which are discussed by Islam et al. (2017a, b) who also present a detailed analysis of the environmental factors that explain intra- and inter-site variations and hence siting criteria. The study did not consider the subsurface transport of protozoa, viruses or pathogens in general, the influence of pit emptying, or household water treatment.

RESULTS

Lateral and vertical head differences in monthly measurements of groundwater elevation within sites were generally negligible, rarely exceeding a few centimetres and usually within the measurement error. However, differences between sites are significant (Fig 2). At Paikgachha, the most down-basin site where the grain size is finest, the piezometric surface at all depths was always above the base of the latrine. At Jajira, the water table rises above the base of the latrine for about half the year, whereas at the northern sites with sandy soil and subsoil, Shambuganj and Pirganj, the water table intersects the base of the latrine for a short period in the monsoon, if at all.

Analyses of faecal coliforms for each sampling event at each piezometer at each site are presented in the Supporting Information (SI S3) and summarised in Table 1 and Fig 3. The spatial and temporal distributions of FC are illustrated in Figures 4 and 5 and the Supporting Information (SI S4). From north to south, there are progressive increases in the overall detection rate (3.3% at

Pirganj and 23.3% at Paikgachha) and the proportions of samples with medium, high and very high levels of contamination. Everywhere the magnitude and frequency of FC detections decline rapidly with distance from the latrines. In the shallowest piezometers, at a radial distance of 2m, FC concentrations typically ranged between 10^2 and 10^4 cfu/100ml and almost always detected, but beyond a straight line distance of about 5 m (including vertical and horizontal dimensions) FC are undetectable more than 90% of the time and rarely exceed 10 cfu/100ml. Beyond about 5m, such detections as occur are not continuous in space or time (SI S4). Moreover there are no consistent concentration gradients or dominant directions of contaminant transport.

Fig 5 illustrates the discontinuous, multi-dimensional spatial distribution of faecal bacteria around latrines, and in particular the very low levels of contamination beyond the inner ring of piezometers, even at the most contaminated sites and in the most contaminated events. At Paikgachha, the most contaminated site, FC were detected at least once at every piezometer but, beyond the shallowest layer the frequencies and maximum levels of contamination are very low, and in most of the deeper (≥10m) piezometers FC never exceed 10 cfu/100ml. At Paikgachha, the sampling event with the most detections occurred in the middle of the dry season (December 2014; Fig 5a). here, the shallowest piezometers at 2 m distance are severely contaminated, but the FC concentration was only 15 cfu/100ml at a 4m radial distance. At a depth of 10m, the maximum FC concentration was only 7 cfu/100ml, and at eight out of thirteen piezometers FC were not detected. Evidently, the distribution of FC detections in the far-field does not follow an obviously rational pattern. For example, more detections were found in the 20 and 27 m deep piezometers although the maximum concentration was just 6 cfu/100ml. By contrast with Paikgachha, the most-contaminated sampling event at Shambuganj occurred in the late monsoon (September 2015; Fig 5b). In the shallowest layer, FC concentrations were mostly a few hundred cfu/100ml at a 2m radial distance and in one piezometer FC’s were not detected. At depths of 8 and 18 m, FC’s were detected in only 4 and 3 out of the 13 piezometers in each horizon respectively; and at 25 m there were no detections. In the best instrumented horizons (10m at Paikgachha; 8 and 18 m at Shambuganj) there is no indication of either lateral concentration gradients or continuity of contamination, and on some limbs contamination was detected only in the most distant piezometer. The far-field monitoring results at Paikgachha, Shambuganj and the other sites indicate the distribution of faecal bacteria do not resemble the classical plume that is assumed in solute transport theory, whether in terms of direction, continuity or concentration gradient.

DISCUSSION

Monthly monitoring at four experimental latrines over two years revealed a consistent pattern of bacterial migration, characterised by what we term near-field and far-field contamination (Table 2). The near-field extends for only a few metres from the latrine and contains high concentrations of FC that are spatially and temporally continuous. In the far-field, by contrast, FC detections are rare, with concentrations mostly ≤ 10 cfu/100ml and where bacterial contamination is spatially and temporally discontinuous, displaying neither concentration gradients nor relation to either inferred flow directions or seasonal fluctuations. Transport in the far-field may involve periodic detachment of sediment-bound bacteria and/or the operation of ‘two populations’ as suggested by the column-modelling studies of Feighery et al. (2013) who inferred the presence of a minor second population which could be transported up to 10m. This is similar to the pioneering observations of Caldwell and Parr (1937), Dyer (1941) and Dyer et al. (1945) who found that the migration of faecal bacteria is quickly limited to a few metres, equivalent to our near-field. Longer-range migrations, much cited in literature reviews, may be equivalent to our far-field detections but capture neither the nature of risk nor adequately describe the nature of advective transport of bacteria through aquifers.

The differences in faecal contamination between sites are open to various environmental explanations that are discussed in detail by Islam et al. (2017b). We consider that differential faecal loading is an unlikely explanatory factor because each latrine received the product of a single family. Near-field contamination is greatest where the unsaturated zone below the latrine is thin, transient or absent, suggesting that bacterial survival or transport is facilitated in the saturated zone. However, any causal interpretation is subject to confounding by inter-related factors including higher clay and organic matter content of sediments and, at Paikgachha, by saline pore water which favours preservation of bacteria (e.g. Miller et al. 1984). Conversely, the sites with deeper water tables are also underlain by sandier sediments (Fig 1) and less organic matter.

Much was learned about latrines and groundwater pollution 70 to 80 years ago through the detailed field investigations of Elfreda Caldwell and colleagues in the southern USA and Brian Dyer and colleagues in the Indian Subcontinent. Notwithstanding mention in some reviews (e.g. Lewis et al. 1982), this knowledge, which remains valid, has unfortunately been 'lost' to recent researchers. Our findings replicate and revalidate the findings of both groups regarding the very limited transport of bacteria in the subsurface. Caldwell and Parr (1937) and Caldwell (1937; 1938a, b) tested about 20,000 water samples from around five experimental bored latrines on the coastal plain of Alabama. Initially, *E. coli* reached radial distances of 3 and 5 m in a few days. After two months, *E. coli* were detected in 90% of 5 m wells; 40% of 8 m wells for one month; and occasionally at 11 m for 10 days. After five months, *E. coli* was not detected at 3 m, and after 7 months was not detected 1.5 m from the latrine, excepting temporary resurgences following rises in the water table. The authors hypothesised an attenuation mechanism equivalent to a schmutzdecke in parallel with the changes inside the latrine. Their work included an early discovery of hand-pumps acting as bacterial reservoirs (Parr and Caldwell, 1933). At experimental bored latrines on alkaline-alluvium at Lahore (Pakistan), Dyer (1941) monitored hand-pumped wells at radial distances of 1.5 to 10 m, concluding that faecal bacteria travelled > 1.5m but < 3m in the direction of flow. Extending these investigations to an alluvial site near Kolkata (India), Dyer and Bhaskaran (1943, 1945) and Dyer et al (1945) found that *E. coli* were detected at radial distances of 3m for 2 months and abundant at 1.5m, but virtually absent by the end of a year.

Recent studies in Bangladesh (Table 3) enhance the significance of our findings. Irrespective of whether pump spouts are disinfected, 20-50% of tubewell water samples are contaminated by low levels of FC (and other FIB) at the point of collection, and significantly more at the point of use. Moreover, a high proportion of these wells were a few tens to a few hundreds of metres deep; depths to which faecal bacteria could not survive if transported by normal groundwater flow. Correlations of tubewell contamination with sanitary inspections scores have low explanatory power. Some correlations with distance to latrines (e.g. Escamilla et al. 2013) suggest associations over tens of metres, although our data do not support such inferences. Greater faecal contamination in the wet season appears to be near universal (Kostyla et al. 2015) and a few studies infer that heavy antecedent rainfall promotes contamination events (e.g. Wu et al, 2016). Although there is some indication of greater near-field contamination in the monsoon, we find no correlation between contamination events and 3-day or 7-day antecedent rainfall (SI-S4).

Parr and Caldwell (1933), Hoque (1988), Knappett et al. (2012a) and Ferguson et al. (2011) draw attention to the role of the borehole - well - pump system in contaminating drinking water (Table 3) including: (i) dirty priming water; (ii) leaking casing joints; (iii) cement grouting of the borehole annulus reducing contamination of shallow wells; and (iv) elastomeric components of hand-pumps acting as bacterial reservoirs. The high frequencies of faecal contamination in the pilot study tubewells (Islam et al. 2016; SI-1) and piezometers compared to piezometers in this study (sampled with a peristaltic pump) support the conclusion that the in-situ microbiological quality of groundwater is much superior to that of well water. The impersistent effect of spot chlorination (e.g. Luby et al. 2006) may thus be explained by factors other than pervasive contamination of the aquifers.

Combining our study data for near- and far-fields with published data supporting pervasive recontamination, we propose (Fig 6) an extended conceptual model of faecal contamination of drinking water that distinguishes four sub-pathways: (P1) leakage and biofiltration of faecal waste at the latrine-aquifer interface and near-field; (P2) leachate migration through the far-field to the borehole; (P3) from the face of the borehole to the pump spout; and (P4) from point of collection to point-of-use. The overall source-pathway-receptor route is characterised by a large and rapid decline of faecal bacteria in the near-field followed by slow-attenuation of low-level contamination in the far-field and then progressive increases in faecal bacteria between the point of entry to the well and the point of consumption due to recontamination from non-latrine sources. Sub-pathways P2 and P4 have long been recognised and have given attention through siting criteria and hygiene education respectively. On the other hand, sub-pathway P3 has been largely neglected and comprises at least four sources of contamination: (a) dirt or drilling fluid additives such as cow dung introduced during construction; (b) faecal contamination infiltrating beneath platforms and along the borehole annulus to enter through the screen or leaking joints; (c) dirty priming water ; and (d) biofilms on elastomeric components of hand-pumps that can harbour faecal bacteria for more than a hundred days.

Estimation of Potential Disease Burden

Extreme contamination in the near-field is well-known although the rate of attenuation is less well appreciated. The public health significance of the subsequent sub-pathways is indicated by the increasing frequency and magnitude of contamination from far-field groundwater to the point-of-use. Actual morbidity risks will depend on the particular pathogens present, the frequency of occurrence, concentration, and their dose-response functions. For illustrative purposes, we use the degree of faecal contamination on each sub-pathway to estimate the corresponding relative disease burden by comparing the behaviour of real pathogens to that of the hypothetical enteric bacterium,

Bacterium experimentus of Briscoe (1984) which follows a perfect log-linear dose-response function with a probability of infection ($P_{inf.}$) defined as

$$P_{inf.} = 0.5 * \log_{10} (\text{dose})$$

where the dose is the concentration of the pathogen and $P_{inf.}$ is limited to a maximum value of 1.0. We assume that the dose of *B. experimentus* in a given time unit (e.g. a day) is directly proportional to the median concentration of FC in each sub-pathway, where we estimate a hypothetical 'dose' by summing the products of the proportions of samples contaminated and the median FC concentration in each WHO risk class. The input data on the proportions and concentrations in each risk class and for each sub-pathway are taken either from this study or the quality control data set (n = 109) of the 2013 Multiple Indicator Cluster Survey (BBS/UNICEF 2015; Table 4).

For each sub-pathway, we sum the weighted probabilities to calculate an attributable risk (AR) for the sub-pathway of interest (P_i) as:

$$AR_i = pn_i * P_{(inf.)i}$$

where pn_i is the proportion of samples in that risk class. Thus AR_{i-1}, the attributable risk from the preceding sub-pathway, is subtracted from AR_i to calculate the incremental attributable risk (IAR) arising from sub-pathway P_i alone. Dividing the increment of attributable risk by the total attributable risk at the point of consumption provides an estimate of the proportion of diarrhoeal disease attributable to bacteria originating in each of sub-pathways P2 to P4.

The calculated proportions of attributable disease for the base case are 1.3%, 28.8% and 69.9% (Table 5). A sensitivity analysis was conducted, initially applying 50% increases and reductions to the proportions of samples contaminated, median concentrations, and ±200% variations in P_{inf}. Subsequent checks considered reducing the dose by a factor of ten, and adjusting the infectivity of Briscoe's putative pathogen ($P_{inf.}$ $0.2*\log_{10}(\text{dose})$) to result in a 100% probability of infection when consuming 2L of water containing 5000 cfu/100ml of FC. The resulting ranges of disease risk attributable to each sub-pathway were: 0.3-4.1% in the far-field, 27.4-32.6% at point of collection and 66.0-71.0% at point of use.

The use of Briscoe's hypothetical pathogen in our calculations does not contradict our questioning of his argument about the interaction of different transmission routes (Cairncross 1987). Our calculations make the conservative assumption of no bacterial die-off on subsequent sub-pathways which, if included, would reduce the risks originating from the upstream sub-pathways even further. Uncertainty arises because we combine our site data with national data; nevertheless, we consider the sensitivity analysis renders the qualitative conclusions robust and serves the purpose of driving improvements in sanitary practice.

Policy Implications

Recent reviews and studies (e.g. Graham and Polizzotto 2013; Daniels et al. 2016; Odagiri et al. 2016; Sorensen et al. 2016) have re-ignited an old debate as to whether increasing latrine coverage increases diarrhoeal disease due to increased groundwater contamination. Our results suggest that such warnings conflate the low-risk from groundwater contamination in the far-field with much higher risks associated with contaminated well water, and therefore fail to target the principal sources of microbial risk, which arise close to the well and post-collection. Thus, while recent initiatives to improve post-collection water handling (e.g. UNICEF 2012) are fully justified, the attention given to well-latrine spacing is not proportionate to the associated risks. Further, increased groundwater contamination from expanding latrine coverage poses only a modest threat to drinking water quality compared to the risks associated with sub-pathways P3 and P4. To translate the benefits of improved post-collection hygiene practices into reduced mortality, more attention must also be given to reducing contamination at the well (cf. VanDerslice and Briscoe 1995). Moreover, the rare and low level of contamination found at depths of 10 m or more confirms that the traditional attention given to horizontal spacing is not only unwarranted but fails to understand the pathways of the widespread contamination of tubewells tens to a few hundreds of metres deep. Hence, provided modest vertical and horizontal spacing criteria are adhered to, measures to increase natural attenuation during groundwater flow from latrines will have little impact on the prevalence of diarrhoeal disease. Only measures that reduce contamination along the P3 and P4 sub-pathways will have a major impact on disease burden.

Possible low-cost interventions to reduce faecal pollution along the P3 sub-pathway include: (i) replacing cow-dung with bentonite clay as a drilling additive; (ii) cement grouting of the borehole annulus after sand packing; (iii) overnight shock chlorination on the day of well completion; (iv) maintaining a container of chlorinated water for priming purposes; (vi) regular removal and cleaning of the pump head with disinfectant and a brush; (vii) more microbiological testing; and last but not least (viii) incorporation of the above into awareness raising in caretaker training and water safety plans.

Conclusions

Severe and spatially or temporally continuous faecal pollution of groundwater from pit latrines is largely restricted to a near-field that extends for a very few metres and passes rapidly into a far-field (FC typically <10 cfu/100ml and <10% of the time) where faecal pollution is spatially and temporally discontinuous, lacks concentration gradients and is poorly correlated with groundwater flow. Contamination of far-field groundwater is less frequent and less severe than water collected from hand-pumped tubewells. Faecal contamination along a sequence of four-sub-pathways comprising the latrine-groundwater interface or near-field (P1); flow through the far-field (P2); well screen to pump outlet (P3); and collection-to-consumption (P4) drops to a minimum in the far-field and then is progressively re-contaminated up to the point of use. Invoking the hypothetical pathogen Bacterium *experimentus*, we estimate that sub-pathways P2, P3 and P4 respectively contribute of the order of 1-2%, 29% and 70% of faecal risk at the point of consumption.

Tactically, the goal of safe drinking water (SDG 6.1) will only be realised if parallel action is taken to control risks in the much-neglected well-pump sub-system as well as reducing post-collection contamination. Strategically, our findings suggest that recent warnings of the reality and public health significance of increased groundwater pollution resulting from expanding latrine coverage appear exaggerated. Our findings are expected to apply to all alluvial-deltaic terrains, but may not apply in areas with fractured or fissured aquifers and thin soil cover.

Acknowledgements. The study was funded by the UK Department for International Development (DFID), through the Sanitation and Hygiene Applied Research for Equity (SHARE) Consortium led by the London School of Hygiene and Tropical Medicine (LSHTM) and WaterAid Bangladesh. icddr,b acknowledges with gratitude the commitment of these agencies to the research. icddr,b is grateful to the Governments of Bangladesh, Canada, Sweden and the UK for providing unrestricted support. We thank Professor Richard Carter for helpful comments on an early version of the script. We also thank two anonymous reviewers for their valuable and constructive suggestions. The authors declare no conflicts of interest.

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ACCEPTED MANUSCRIPT

LIST OF TABLES

Site	GPS Coordinates	Elevation (m asl)	Nr of Piezometers	Nr of Samples	Faecal Coliforms (cfu/100ml)		
					Median	>0	>10
Pirganj, Rangpur	E: 89.20513 N: 25.29444	26.4	30	626	0	3.3%	0.8%
Shambuganj, Mymensingh	E: 90.27130 N: 24.455778	13.5	34	842	0	10.5%	2.5%
Jajira, Shariatpur	E: 90.14381 N: 23.24308	7.2	32	737	0	13.7%	6.7%
Paikgachha, Khulna	E: 89.18509 N: 22.36135	1.4	27	575	0	23.3%	19.0%

Table 1. Faecal Coliform detections at four sites. All measurements are units of colony forming units per 100 ml of water (cfu/100ml) analysed at the icddr,b Environmental Microbiology laboratory in Dhaka. The number of samples excludes baseline and duplicate samples.

	Near-field				Far-field				
Site	Typical high and median FC conc’n	Typical frequency		Lateral & vertical extent (m)	max. FC (cfu/100ml)	FC frequency		Migration distance, m	
		FC >0	FC >10			FC >0	FC >10	FC >0	FC >10
Pirganj, Rangpur	100; median 0	16%	8.0%	< 1.7 m	20	2.4%	0.2%	11	4.4
Shambuganj, Mymensingh	200 – 600; median 0	17.1%	9.4%	L<2.2m; (7m*)	500	9.4%	1.3%	28	6.5
Jajira, Shariatpur	4,000 – 20,000; median 0	69%	59%	L<2m; (8m*)	92	9.6%	2.3 %	23	11
Paikgachha, Khulna	1,500 - >80,000; median 560	93%	92%	c. 5m	56	7.0%	1.6%	28	8.7

Table 2. Summary of Near- and Far-Field contamination characteristics at four sites. All detections refer to faecal coliforms in cfu/100ml. Note, in the far-field, all median FC concentrations are zero. At Pirganj and Shambuganj the true near-field does not reach the 2m (radially) distant piezometers; there is a zone with slightly elevated frequencies of detections (≤20%) extending about 4 and 8m respectively. Also, breakthrough time at these sites were probably affected by the fall in the water table in the dry season below the shallowest piezometers causing downward migration of pollution that did not reach the second monitored horizon.

Subject	Findings / Observations	Reference(s)
FIB in water wells	With or without sterilisation of the pump spout: • 30-50% of shallow tubewells are contaminated at point of collection; • 27-50% of deep tubewells (>150m) are contaminated at point of collection (authors suggest dirty pump priming water as a factor); • 76-94% of ring wells contain FIB are contaminated by FIB at point of collection, and much more frequently in higher risk classes than in tubewells.	Ahmed et al. (2005); Ercumen et al. (2017); Hoque (1998); Leber et al. (2010); Ravenscroft et al. (2014); BBS/UNICEF (2015)
Platforms and annular space sealing	The presence of a platform made no difference to *E. coli* detection, but cement sealing of the annulus significantly reduced the frequency and magnitude of contamination.	Knappett et al. (2012a)
Handpumps as bacterial reservoirs	Hand-pumps removed from the field and a new handpump spiked with *E. coli* were flushed with sterile water; the field pumps produced FIB for at least 29 days, and the spiked pump for 125 days.	Ferguson et al. (2011)
Well disinfection	Disinfection by shock chlorination does not prevent the recontamination / regrowth of FIB.	Luby et al. (2006); Ferguson et al. (2011)
Latrine and site drainage.	Associations regarding distance to latrine or pollution source are weak, absent or have improbably large correlation distances. Correlations with Sanitary inspection scores generally absent. However, at 12 sites in West Bengal, FC migrations of 7m laterally and 6.5m vertically were inferred.	Banerjee (2011); Hoque (1998); Ercumen et al. (2017); Escamilla et al. (2013); Wu et al. (2016).
Impact of contaminated ponds on groundwater.	Low-permeability, biologically active 'skins' greatly restrict leakage to groundwater except following heavy rain and in the early monsoon.	Knappett et al. (2012b)
Rainfall and seasonality	Contamination of tubewells is greatest during the monsoon. One study reported a small but significant relationship with heavy antecedent rainfall.	Lawrence et al. (2001); Ahmed et al. (2005); Luby et al. (2008); Leber et al. (2010); Wu et al. (2016)
Transport of FIB through soil columns	An average decay rate of 0.03 $\log_{10}$/day was measured in Column experiments and modelling required a two-population model where most bacteria are removed in the first metre but the second population could migrate up to 10m.	Feighery et al. (2013)
Sediment binding of FIB	In a peri-urban area, sediments adsorbed $10^3 – 10^4$ cfu/g of FIB to a depth of at least 10 m.	Lawrence et al. (2001)

Table 3. Key Findings from recent studies of water well pollution and latrines in Bangladesh and West Bengal (India)

WHO Risk Class	Far-field Groundwater		Point of Collection		Point of Use	
	Median FC	Prop'n	Median FC	Prop'n	Median FC	Prop'n
Very low	0	93%	0	77%	0	30%
Low	2	5.7%	3	10%	4	28%
Medium	20	1.3%	18	8%	60	26%
High	350	0.1%	300	3%	294	13%
Very High	0	0%	2300	2%	1800	3%

Table 4. Input data for the base case for pathogenic disease burden estimation. Data for the far-field are taken from this study; and other data are taken from quality control data set from BBS/UNICEF (2015). All samples were collected by ICDDR,B staff and analysed in the ICDDR,B Environmental Microbiology Laboratory in Dhaka

Sub-pathway	Attributable Risk	Incremental Attributable Risk	Attributable Risk at PoU
Latrine to Well entry	0.017	0.017	1.3%
Well entry to PoC	0.385	0.368	28.8%
PoC to PoU	1.276	0.892	69.9%

Table 5. Relative risks for *Bacterium experimentus* in the aquifer – well – household system.

FIGURES

1. Location of Study Sites
2. Water table hydrographs at the four experimental sites
3. Histogram of faecal coliform detections at piezometers at four sites
4. Pseudo-sections illustrating faecal contamination along one axis of piezometers at Paikgachha
5. Distribution of FC in the most contaminated sampling events at Paikgachha and Shambuganj.
6. Cartoon depicting an extended conceptual model of faecal contamination of groundwater-derived drinking water.

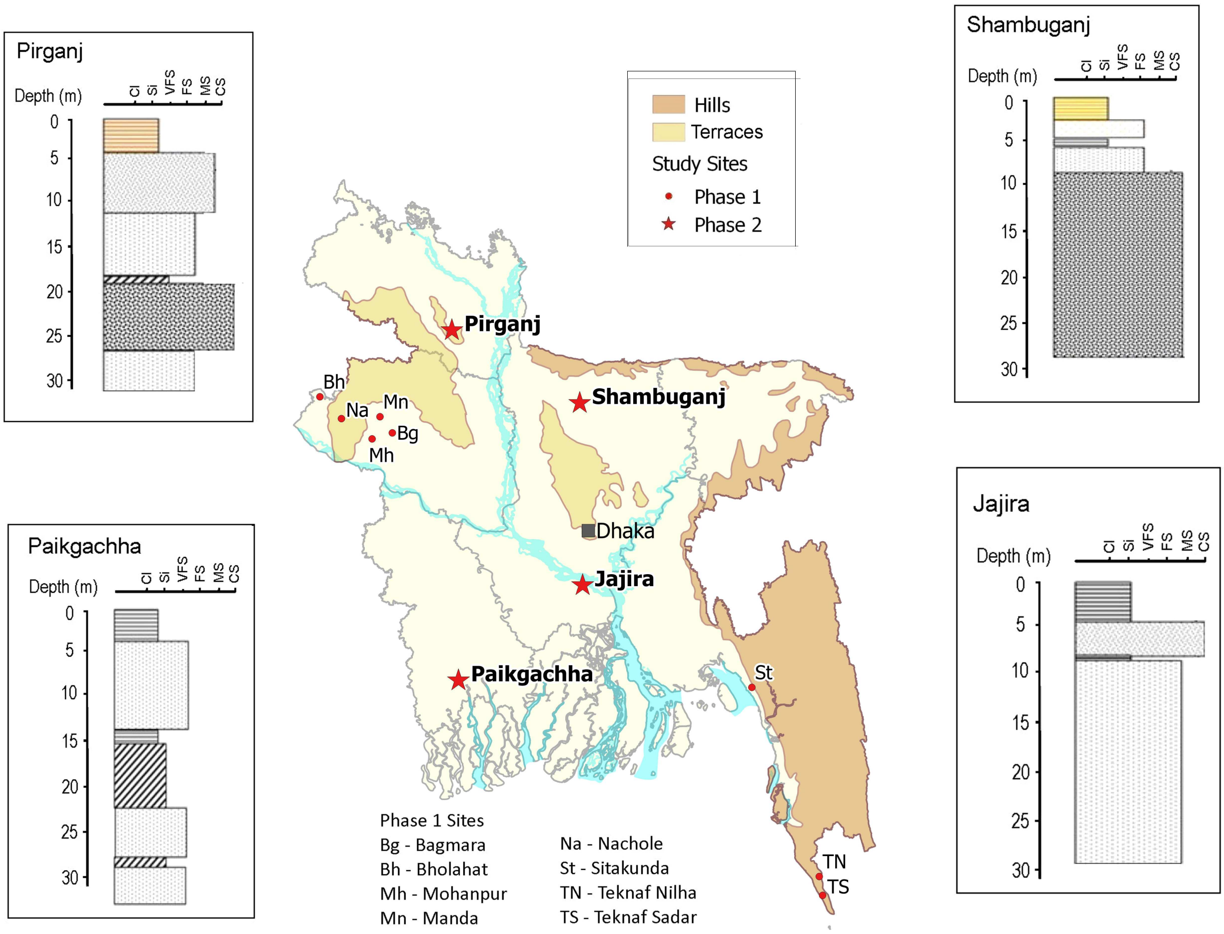


Fig 1. Location of study sites. The Phase 1 (Pilot Study) sites are located either on or around the Pleistocene Barind Tract or on the Chittagong Coastal Plain; the Phase 2 sites are located on the floodplains of the main Ganges – Brahmaputra – Meghna river system. The annotations show the lithological profiles at one of the deepest piezometers at each site where lithological codes are Cl – clay, FS –fine sand, MS- medium sand, CS – coarse sand.

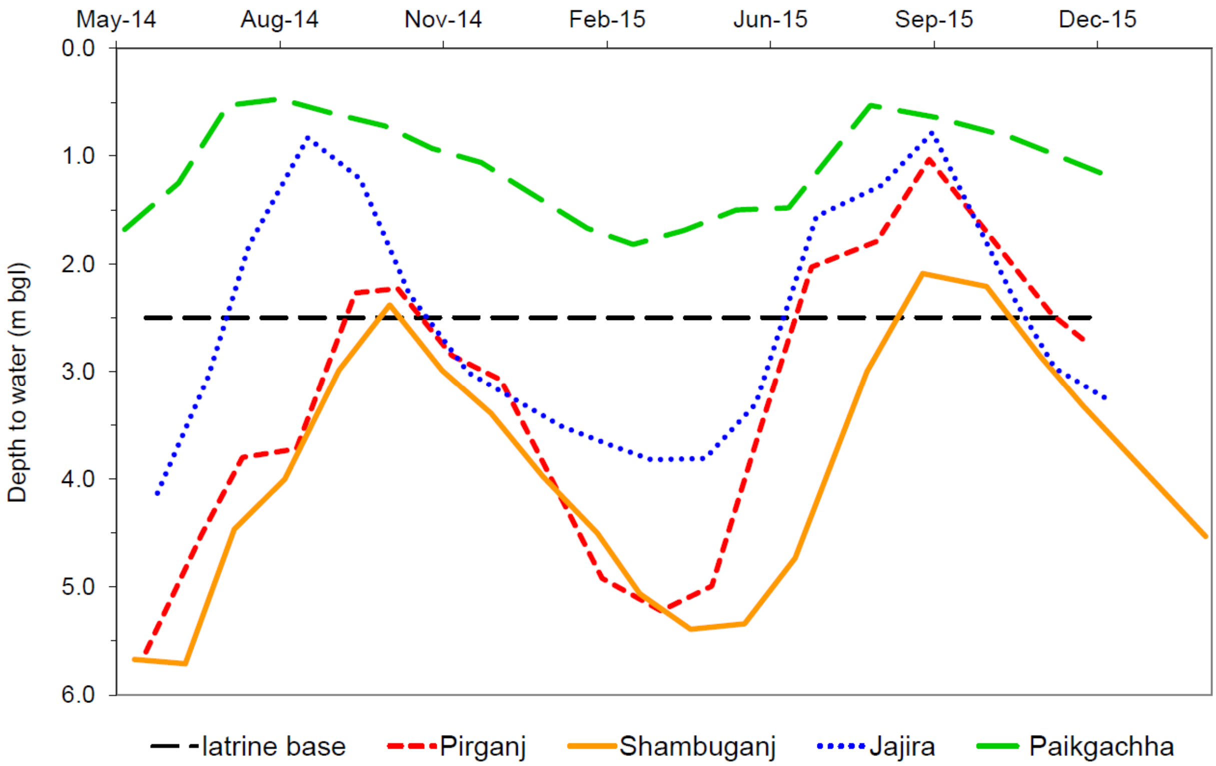


Fig 2. Water table hydrographs at the four experimental sites. Each hydrograph represents monthly measurements of the depth to water in a 10 m deep piezometer at a radial distance of 2 m from the latrine. Except in a few very shallow piezometers which briefly run dry in the dry season, the choice of piezometer makes a difference of no more than a few centimetres and usually less. The depth of the latrine base is approximately the same at all sites.

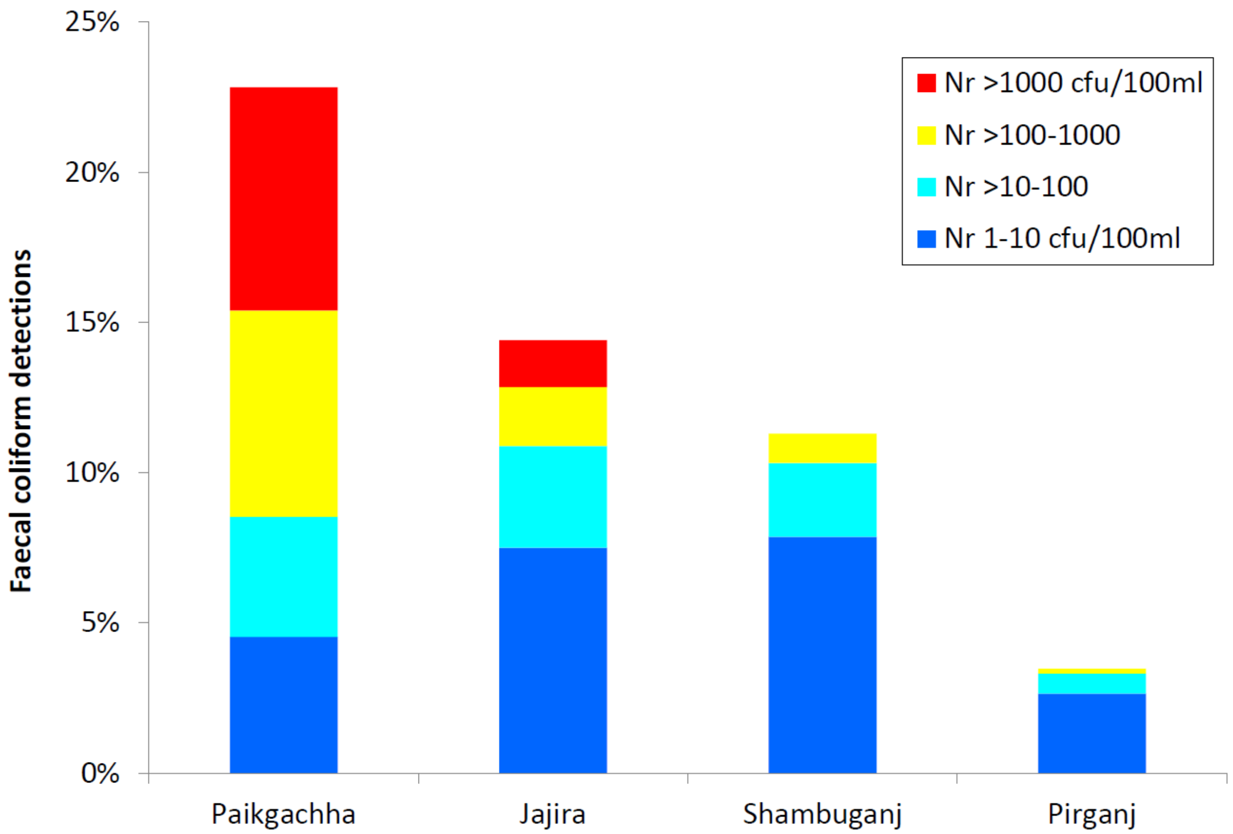


Fig 3. Histogram of faecal coliform detections at piezometers at four sites. The four concentration classes correspond to the WHO classification of low, medium, high and very high microbial risk.

Khulna, Paikgacha

Low level faecal contamination

FC (>**0** CFU/100ml)

WEST											EAST
Depth (m)	-10	-8	-6	-4	-2	0	2	4	6	8	10
3					90%		90%	86%			
10				10%	24%		10%	5%	14%	5%	5%
20					10%		5%				
27							10%				

	Latrine
	> 50% contaminated
	20 - 50% contaminated
	> 10-20% contaminated
	1 - 10% contaminated
0	Never contaminated

Medium level faecal contamination

FC (>**10** CFU/100ml)

WEST											EAST
Depth (m)	-10	-8	-6	-4	-2	0	2	4	6	8	10
3					86%		90%	86%			
10				0%	14%		5%	0%	5%	0%	0%
20					0%		0%				
27							0%				

Maximum faecal contamination

Max. FC (cfu/100ml)

WEST											EAST
Depth (m)	-10	-8	-6	-4	-2	0	2	4	6	8	10
3					32000		64000				
10				7	50		56	2	30	1	1
20					3		6				
27							10				

	Latrine
	> 1000 cfu/100ml
	101 - 1000 cfu/100ml
	> 11-100 cfu/100ml
	1 - 10 cfu/100ml
0	0 cfu/100ml

Fig 4. Pseudo-sections illustrating faecal contamination along one axis of piezometers at Paikgachha, the most contaminated site. The top row of numbers shows the distance in metres from the latrine and corresponds to the fixed lateral spacing of piezometers. The rows correspond to the pre-defined depths at which piezometer screens are installed. Blank cells on the figure are where no piezometer is installed. Contamination is represented in three alternative ways: (a) the percentage of monthly samples exceeding 0 cfu/100ml; (b) the percentage of monthly samples exceeding 10 cfu/100ml; and (c) the maximum value of FC determined at each piezometer on any occasion.

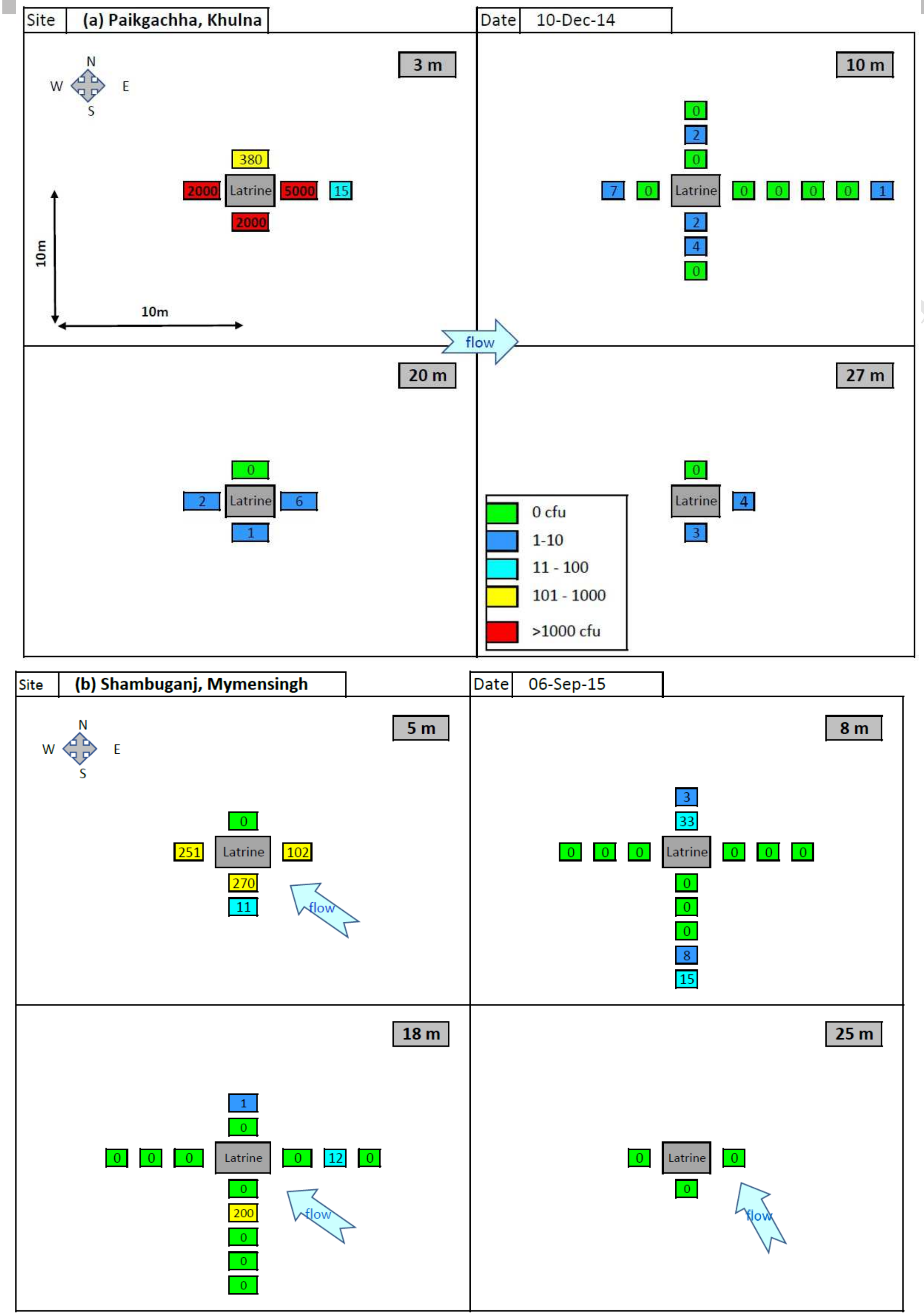


Fig 5. Distribution of faecal coliforms (in cfu/100ml) in the most contaminated sampling events at (a) Paikgachha in December 2014 and (b) Shambuganj in September 2015. The four quadrants show the four depth horizons at which piezometers are installed. The geometric alignment in the figure follows the nominal (north, south, east west) arrangement of the axes of the piezometer nests.

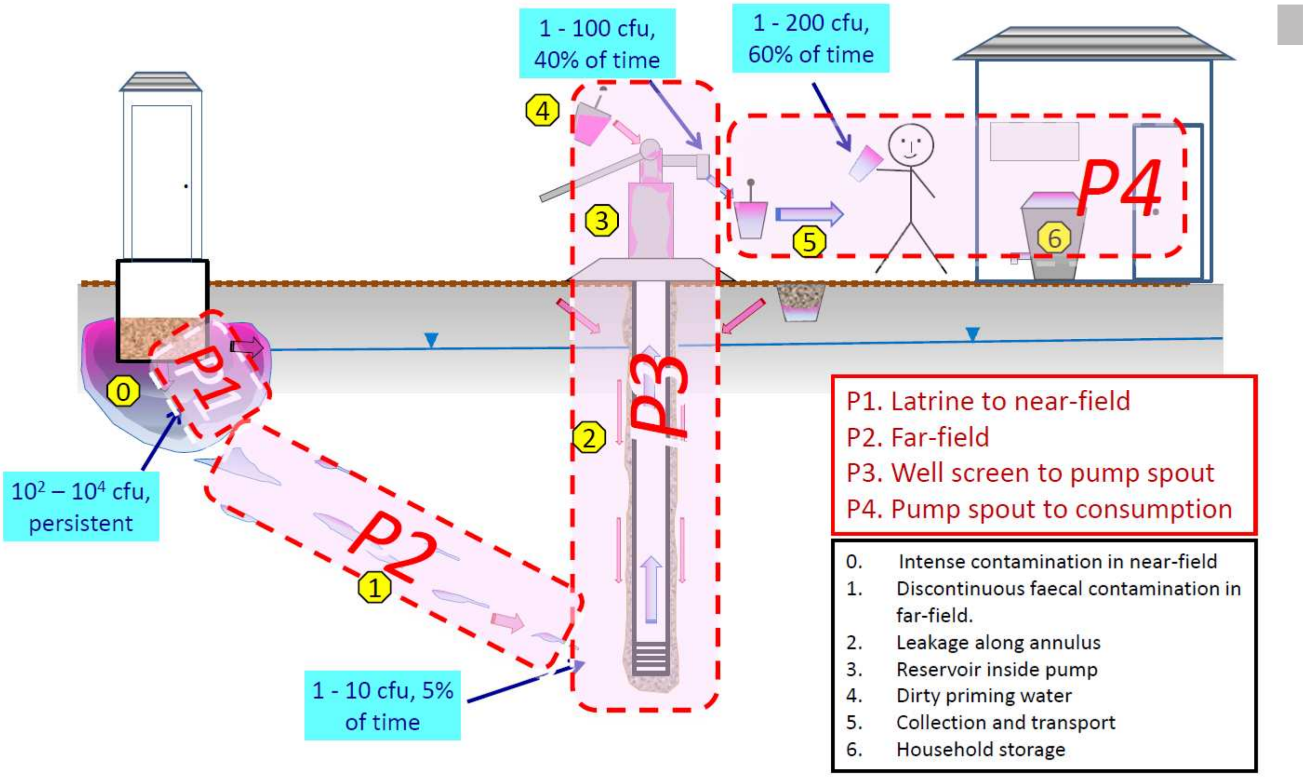


Fig 6. Cartoon depicting an extended conceptual model of faecal contamination of groundwater-derived drinking water. See text for explanation.

SUPPORTING INFORMATION

S1 The 'Safe Distances' Pilot Study

S2 Sediment Grain Sizes at Four Experimental Latrine Sites

S3 Faecal Coliform Monitoring around Four Experimental Latrines

S4 Seasonal Trends of Faecal Contamination and Antecedent Rainfall

SUPPORTING TABLES

Table S1. Faecal coliform detections in Pilot Study tubewells and piezometers

Table S2. Faecal coliform monitoring around four experimental latrines: (a) Pirganj; (b) Shambuganj; (c) Jajira; (d) Paikgachha.

SUPPORTING FIGURES

Figure S1. Sediment grain size distribution.

Figure S2 Antecedent Rainfall and Faecal Contamination at Paikgachha

Figure S3 Antecedent Rainfall and Faecal Contamination at Jajira

S1. The 'Safe Distances' Pilot Study

A pilot study (Islam et al. 2016) examined two contrasting hydrogeological environments: the Pleistocene Barind Tract in western Bangladesh and the Chittagong Coastal Plain (Fig 1). The former is characterised by stiff clayey soils, lower rainfall and deeper water tables; the latter by recent poorly consolidated sandy Holocene sediments with shallow water tables. The results are summarised in Table S1. At the Barind sites, FC were detected in between 0 and 50% of samples from the first aquifer; and at any given site the percentages tended to be higher from tubewells than piezometers. High values (10^2 – 10^4 cfu/100ml) were recorded exclusively in tubewells, while the maximum value recorded in any Barind piezometer was just 17 cfu/100ml. On the Chittagong Coastal Plain, FC were detected in between 14 and 78% of samples in the first aquifer. Although the frequencies of detection were not greatly different, the maxima were much greater in tubewells than piezometers. In all areas, where a second aquifer was encountered both the frequency and maxima of contamination were much lower in both tubewells and piezometers.

The differences between the Barind Tract (Pleistocene 'terrace') and the Chittagong Coastal Plain demonstrate the geological control of aquifer vulnerability and the advantage of including such environmental factors in siting criteria. The differences in high-level contamination between tubewells and piezometers led to the adoption of a peristaltic pump for sampling (and more rigorous cleaning of well materials and annular sealing) in the main study.

		Latrine depth (m bgl)	Water table (m bgl)	First Aquifer							Second Aquifer						
				Tubewells				Piezometers			Tubewells				Piezometers		
Upazila	Physiography			Depth(m)	n/n*	Detection	Max.	n/n*	Detection	Max.	Depth(m)	n/n*	Detection	Max.	n/n*	Detection	Max.
Bholahat	Barind	1.5	4-10	6 – 24	10,22	25% * (32%)	19* (2000)	6,18	11%	7	>33	5,7	14%	19	2,6	50%	8
Manda	Barind	3.0	3-8	7 – 24	15,28	40%	32,000	6,18	50%	17	>27	4,4	0%	0	2,6	17%	4
Nachole	Barind	2.0	13-24	>25	11,16	25%	31,000	2,6	0%	0	n.e.	0	-	-	0	-	-
Mohanpur	Barind	2.5	5-14	23-30	4,5	0%	0	3,9	10%	8	>35	9,11	9%	56	1,3	0%	0
Bagmara	Barind	2.5	2-11	>18	10,22	30%	267	8,24	30%	11	n.e.	0	-	-	0	-	-
Sitakunda	Coastal plain	1.5	7-8	5 – 20	19,19	14%	4000	6,18	29%	45	n.e.	2,2	0%	0%	0	-	-
Teknaf Sadar	Coastal plain	2.0	-	0 - 8	9,13	46%	10,000	6,18	76%	194	n.e.	0	-	-	0	-	-
Teknaf Nilha	Coastal plain	1.0	-	16-24	6,9	78%	2000	4,12	30%	3	>50	0	-	-	2,6	0%	0

Table S1. Faecal coliform detections in Pilot Study Tubewells and Piezometers

Notes: (1) All concentrations in cfu/100 ml; (2) figures marked with and asterisk exclude the samples taken after installation of the new pump; (3) 'n/n*' is the number of sampling point and the number of measurements; (4) 'n.e.' - not encountered; (5) the Barind is a slightly elevated terrace-like Pleistocene alluvial landform with stiff clay surface aquitard and a deep water table in the dry season, whereas shallow aquifers on the Chittagong Coastal Plain are of Holocene age generally overlain by more sandy soils and with a shallow water table. The ranges of water table depths were obtained from the nearest BWDB monitoring well.

S2 Sediment Grain Sizes at Four Experimental Latrine Sites

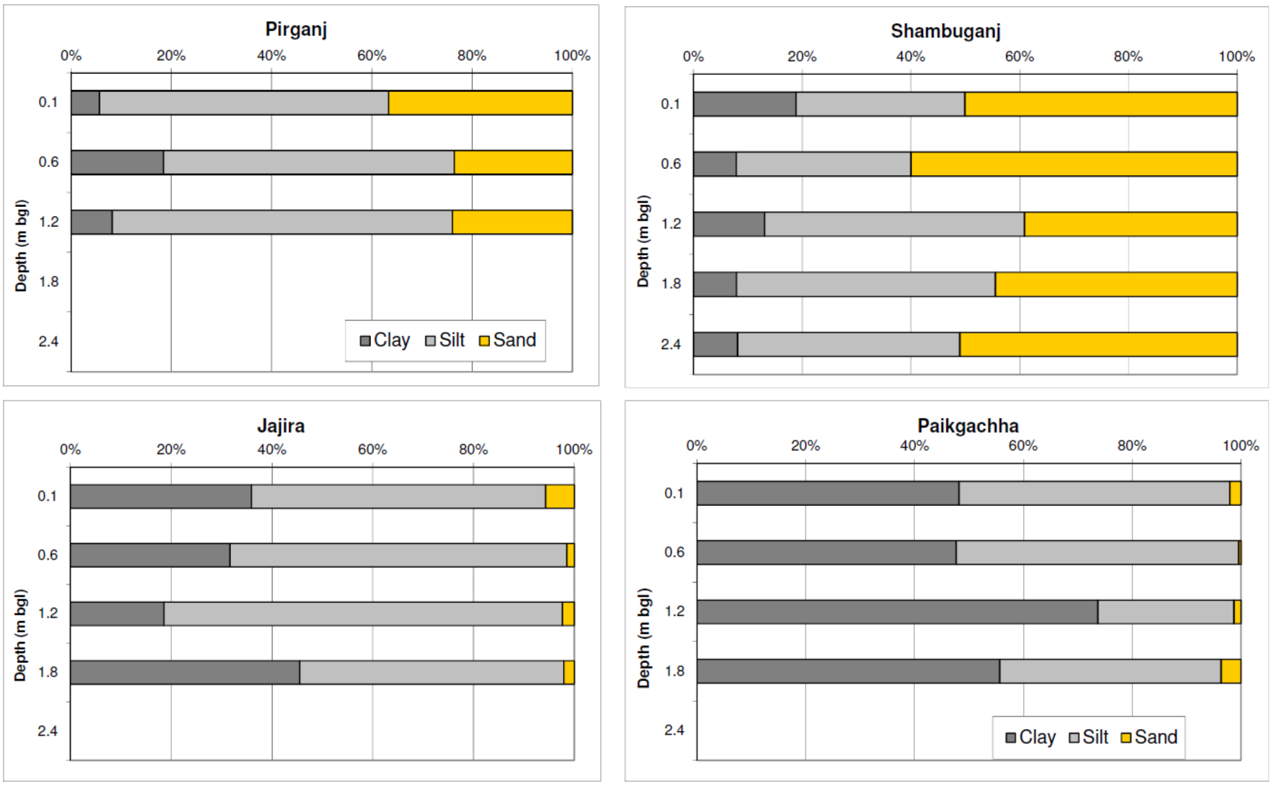


Fig S1. Sediment grain size distribution. The samples show the analyses of sediment samples collected at the time of excavation of the latrines and measured using standard laboratory methods (Gee et al. 1986)

Reference

Gee, G., Bauder, J. and Klute, A. (1986) Particle-Size Analysis, Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, Soil Since Society of America. Inc., Madison, WIS, USA.

S3 Faecal Coliform Monitoring around Four Experimental Latrines

Table S2(a). Pirganj Upazila, Rangpur District

Table S2(b). Shambuganj, Mymensingh District

Table S2(c). Jajira Upazila, Shariatpur District

Table S2(d). Paikgachha Upazila, Khulna District

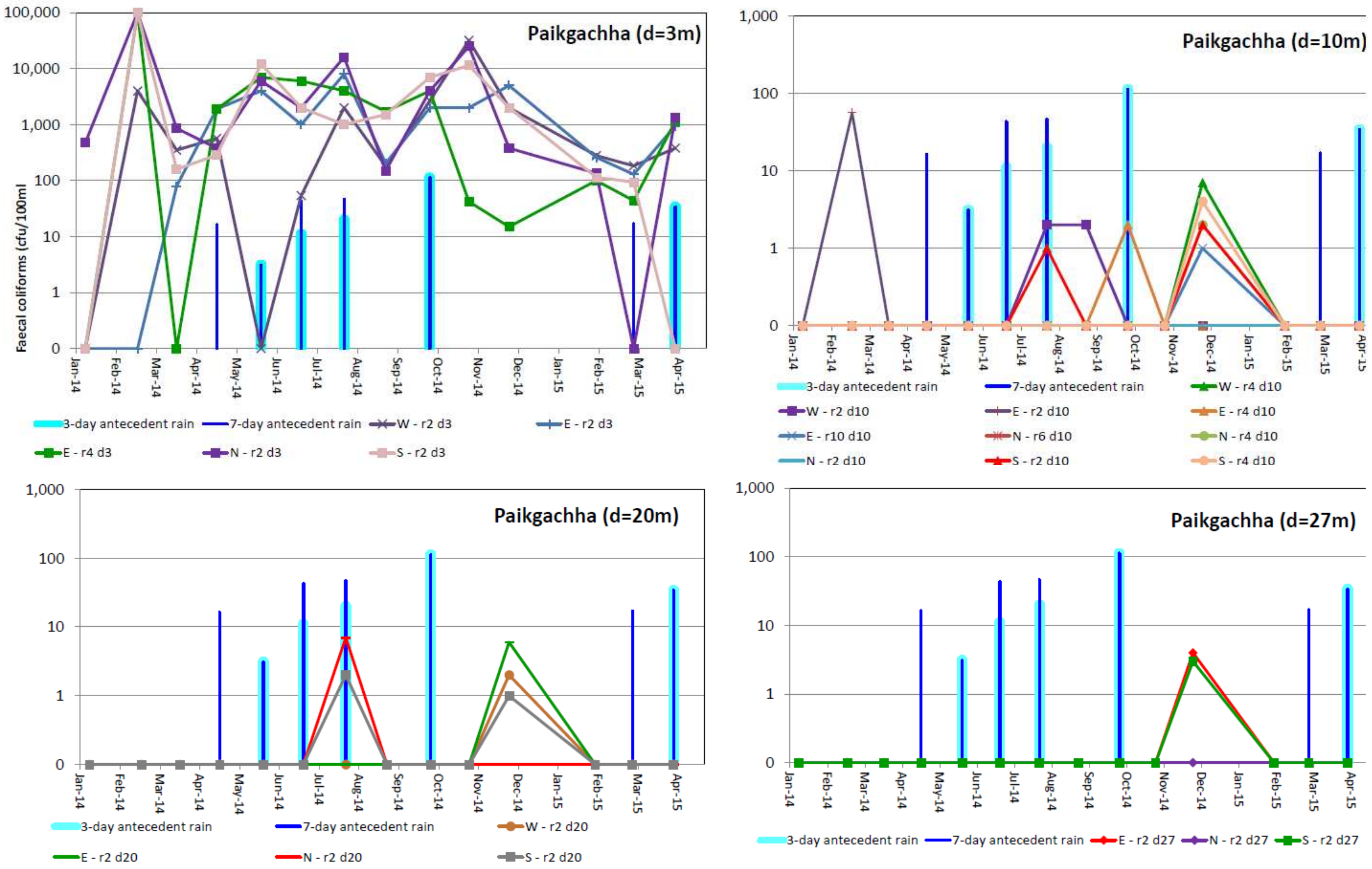
Tables S2(a) to S2(d) present that part of the raw monitoring data that are used in this paper including the piezometer ID, depth, distance and direction, date of sampling and the faecal coliform count.

S4. Seasonal Trends of Faecal Contamination and Antecedent Rainfall

The presence or absence of seasonal or other systematic temporal variations in bacterial detection is important for the evaluation of the many surveys with limited time frames, and which are frequently biased towards the dry season for logistical reasons. The international literature indicates the general increase in faecal contamination during the wet season (Kostyla et al. 2015), and in Bangladesh Wu et al. (2016) inferred positive correlations with heavy antecedent rainfall over periods of 3 to 30 days but strongest for 3-day antecedent rainfall. To test whether antecedent rainfall influences our results at the two most contaminated sites, Jajira and Paikgachha, we collected daily rainfall totals from Bangladesh Water Development Board stations in Paikgachha upazila and at Palong upazila, which is adjacent to Jajira. Figs S2 and S3 compare the monthly analyses of faecal coliforms (showing every FC detection at each site) with the 3-day and 7-day rainfall totals antecedent to the sampling event. The microbiological monitoring results are shown as continuous traces, except where there is a gap in the data. The 3-day and 7-day antecedent rainfall totals are shown as enveloping light and dark blue bars respectively; i.e. where the bars are coincident all rainfall in the preceding 7 days fell in the last 3 days. For clarity, the microbiological results at each site are divided between four graphs, one for each depth slice. The nomenclature of the piezometers listed in the legend indicates their direction, radial distance and depth; e.g. “E-r2d10” denotes a piezometer that is on the eastern line, at a radial distance of 2m and 10m deep. At Paikgachha, high-level contamination of the near-field persists without any obvious relation to antecedent rainfall. In the far-field, the many low-level detections are concentrated on two dates: August 2014 (mid-monsoon) which is preceded by heavy rain, and December 2014 (dry season) when there was no rain in the previous 7 days. Conversely, antecedent rain was accompanied by just one detection in October 2014 and no detections in April, May and June 2014 or March or April 2015.

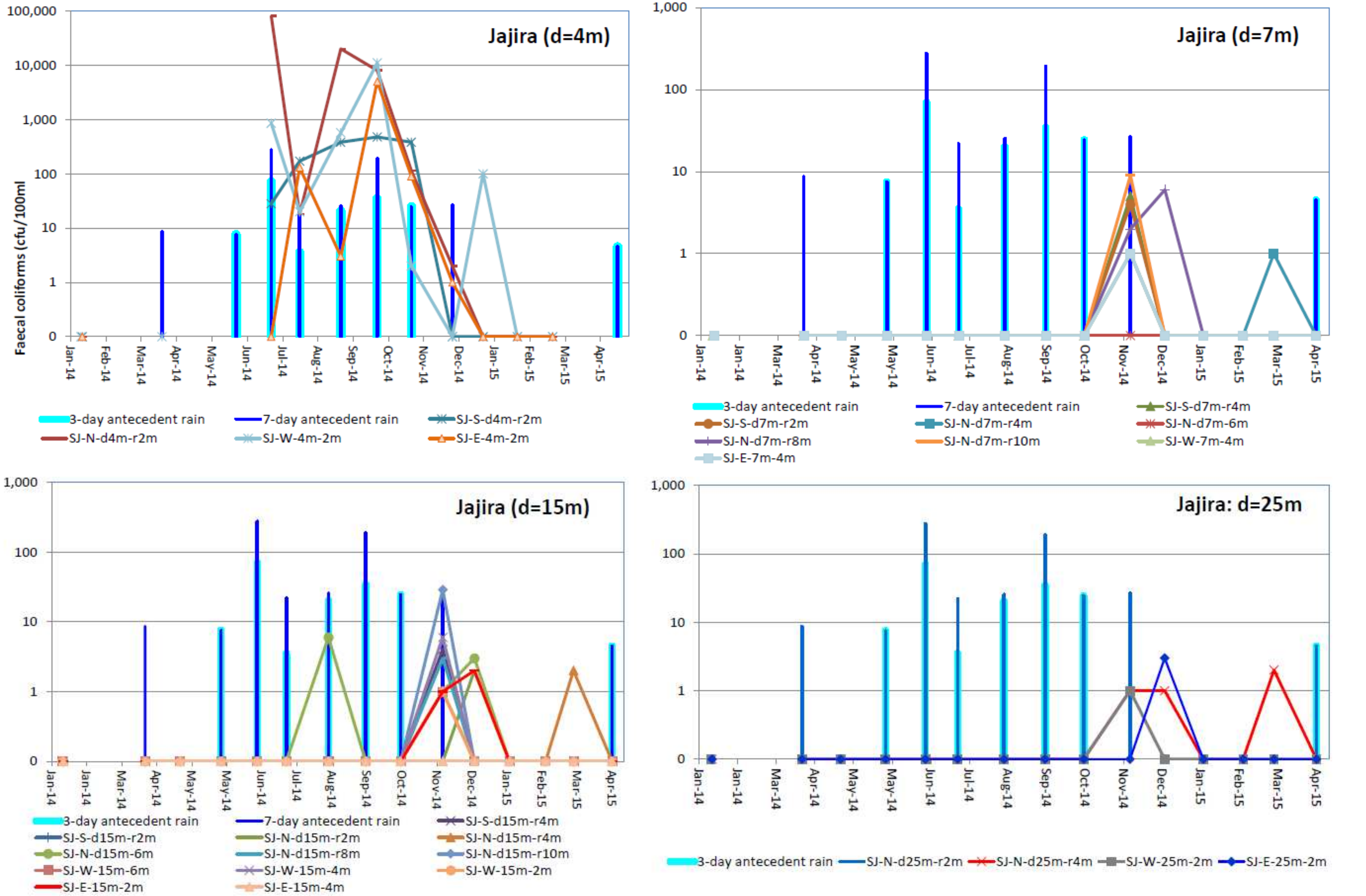
Jajira has the most piezometers with at least one FC detection. High-level contamination of the near-field is discontinuous over time because for part of the dry season the water table drops below the screened interval but otherwise is not obviously related to antecedent rainfall. In the far-field, low-level contamination (only one sample exceeded 10 cfu/100ml) is strongly concentrated in a few sampling events, notably the 2nd and 29th December 2014, following no detections in October when there was the same antecedent rainfall as on 2nd December, whereas on 29th December there was no antecedent rainfall. By contrast, significant antecedent rainfall in every month from May to October 2014 produced only one detection. Three far-field detections in March 2015 were not preceded by rain, but rain in April 2015 resulted in no detections. On the other hand, it is noted that the two major far-field contamination events occur when shallow contamination was 'disappearing' due to the declining water table.

In summary, we find no consistent relationship between antecedent rainfall and FC detections.



Note: Every well listed in the legend showed at least one detection of faecal coliforms between Jan. 2014 and Apr. 2015.
The vertical lines show the total rainfall in the preceding 3 (thick) and 7 (thin) days.

Fig S2. Antecedent Rainfall and Faecal Contamination at Paikgachha. The vertical axis shows the faecal coliform count in cfu/100ml.



Note: Every well listed in the legend showed at least one detection of faecal coliforms between Jan. 2014 and Apr. 2015.
The vertical lines show the total rainfall in the preceding 3 (thick) and 7 (thin) days.

Fig S3. Antecedent Rainfall and Faecal Contamination at Jajira. The vertical axis shows the faecal coliform count in cfu/100ml.

HIGHLIGHTS:

- Severe faecal pollution of groundwater from latrines is limited to a near-field
- In the far-field, faecal pollution is low-level, discontinuous and impersistent
- Latrine pollution of groundwater is a minor contributor to diarrhoeal disease
- Expanding latrine coverage will have little impact on groundwater used for drinking