Deterioration in water quality from supply chain to household and appropriate storage in the context of intermittent water supplies

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ABSTRACT

Many water providers in urban developing country contexts have to supply the water intermittently due to the disparity between rapidly growing demand and investment in supply infrastructure. This can lead to water quality risks such as ingress of polluted groundwater and unsafe household storage. This study has investigated the common risks and possible alternative solutions down the supply chain in the Nagpur municipal piped network through quantitative and qualitative data collection. The water quality testing indicated a significant reduction in water quality between tap and point-of-use. Interviews and a sanitary survey indicated storage design, inappropriate extraction practice and children's access as the most frequent household storage risks. The people with socio-economically lower status were found to be in greatest need of interventions. The study leads to the following recommendations: there is a need for the evolution of a Water Safety Plan to enable supportive structures for good risk assessment which includes all stakeholders from source to point-of-use; community awareness of water quality risks needs to be raised; low cost 'improved' water storage at household level should be promoted; and the levels of residual chlorine should be investigated and adjustments made to assure potable water at point-of-use.

Key words │ intermittent supply, water quality, Water Safety Plan

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INTRODUCTION

Waterborne diseases are a substantial health burden in many rapidly growing cities in developing countries. Whilst 94% of the urban population in developing regions of the world get their water from improved sources (WHO/UNICEF 2010) it is less likely that such a proportion of such urban dwellers enjoy water that is of an acceptable microbiological quality. This could indicate a discrepancy between having access to improved water sources and having access to safe water at point-of-use (Nath et al. 2006). An explanation for the discrepancy is microbiological contamination along the supply chain from source to point-of-use (Wright et al. 2004).

This study investigates water quality change down the water supply chain from treatment to the point-of-use within the municipal piped network through household connections and public tap stands in Nagpur, India. This is a city of

three million people and the majority of the citizens in the central areas receive water through pipelines directly to households or to public tap stands. Water is supplied intermittently as a means of equitably allocating water in the context of an imbalance in the availability of supply relative to the growing demand. The duration of piped water provision varies from one to a few hours per day depending on area and time of year. To enable water access all through the day the consumers store the water in communal tanks or in small storage vessels in individual households. Access to water throughout the whole day is essential in Nagpur where the temperature during the dry season often rises above 45 °C.

Intermittent water supplies have the potential to lead to the deterioration of drinking water quality in three ways: by permitting the infiltration of polluted groundwater into pipes; by increasing the risk of biofilm growth

in stagnant water in distribution pipes; and by necessitating a requirement for storage which creates an opportunity for contamination due to lapses in hygiene (Coelho *et al.* 2003; Abu Amr & Yassin 2008). Coelho *et al.* (2003) suggest that of these mechanisms the deterioration of water quality in domestic tanks is by far the most significant, effectively negating the improvements obtained during treatment. This view was supported by Wright *et al.* (2004) who, in their systematic meta-analysis of 57 studies, demonstrated that microbiological contamination of water between source and point-of-use is widespread and often significant. Significant challenges exist in assuring safe drinking water quality in systems that are either wholly or partly community-managed (Howard 2003). The aim of this study was to investigate factors leading to post-source contamination in an intermittent water supply combining microbiological analysis and qualitative survey approaches and to consider the implications of the findings in terms of future drinking water quality management.

METHODS

Approach

The research approach incorporated both quantitative and qualitative data collection methods including water quality testing, semi-structured interviews and sanitation inspection forms. The research was facilitated by researchers from the National Environmental Engineering Research Institute (NEERI) who provided translation services and advice with regards to appropriate sampling locations and setting up key informant interviews.

General context

Water is received from three surface water sources including an open reservoir (Pench, which supplies 77% of water to Nagpur) and then treated in one of five water treatment plants operated by private companies. They have an agreement with Nagpur Municipal Corporation (NMC) to put into supply potable water with a residual chlorine level of 1–1.5 mg/L leaving the treatment plant, 0.5–1.0 mg/L at

the Master Balancing Reservoir (MBR) and 0.2–0.5 mg/L at consumers' taps. After treatment the water is pumped to three MBRs and subsequently distributed to zone overhead service reservoirs by gravity and then different parts of the zone get water distributed to them according to a set daily scheme. NMC is responsible for the supply of safe water up to the point of distribution i.e. a consumer's tap or a public tap stand.

Stratification and site selection

Sampling sites from source to tap were chosen strategically at stages down the supply chain. Collection sites were chosen in agreement with NMC and NEERI (Figure 1). The zones Reshimbagh, Rambagh, Laxmi Nagar and Surendra Nagar were chosen for the variety in household standards, supply time and the presence of both public tap stands and household connections within these zones. Then actual study areas were chosen with advice from zone office personnel. Aiming to include a wide range of household types and supply types, households were selected in a convenient, non-randomized manner known as snowball sampling by talking to people in the streets and knocking on houses where people appeared to be at home. The test group was divided into three socio-economic categories according to the visual appearance of the dwelling and its contents (construction and state of repair of the dwelling, its size, and the nature of the household possessions). This categorisation was conducted in consultation with local experts and the categories were later corroborated by self-classification by the interviewees.

Water sampling

The sampling locations were as follows (numbers of sampling points at each location in parenthesis): A. Treatment
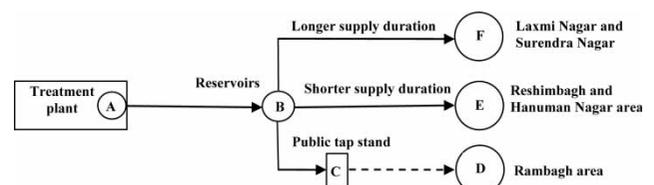

Figure 1 │ Schematic illustration of the sampling locations with the letters used for coding different types of sites.

plant (1); B. Reservoirs (2); C. Public taps (5); Area D – point of use (8); Area E – taps and point of use (16); Area F – taps and point of use (16). Each sampling point was visited once before the monsoon started and once following the commencement of the rains. Samples were taken in duplicate in sterile 1 l plastic bottles and transported to the NEERI laboratory in Nagpur for analysis within 4 h. In total 188 samples were taken for analysis. Due to intermittent supply, water was supplied to the sampling locations for short periods of time (as little as 1 h per day). Sampling was therefore arranged to coincide with these short periods of supply. The water samples were intentionally taken without sterilising the tap so the water quality could be determined from a user perspective. Samples were taken from household storage vessels without any additional hygiene procedures in a manner that was as natural a situation as possible. The limitation of this approach is that any contamination identified may originate from the water supplied or from the surfaces it has come into contact with post-supply. For this study, the aggregate effect of contamination was of interest.

Water quality testing

The levels of turbidity, pH and residual chlorine were determined. The number of presumptive thermotolerant coliform (TTC) colony forming units (cfu/100 ml) was enumerated by membrane filtration. 50 and 100 ml samples were filtered and the membranes were placed on m-FC agar (Difco) and incubated overnight at 44.5 °C. Differences in TTC means found at critical points of the water supply chain were compared through repeated measures ANOVA using the statistics software Statistica 9. The microbiological laboratory procedures were checked by using a sterile water control to detect extraneous contamination. These controls were negative.

Semi-structured interviews

12 consumer and 3 supplier interviews were held to establish a snapshot of stakeholder attitudes to water quality and its management. The number of interviews at each of the 3 socio-economic groups was equally distributed. The interviews were held in English and when translation was needed there was a female researcher who could translate to Hindi or Marathi (local language). The interviews began with a briefing, then either a written or spoken consent was taken. All interviews were digitally recorded, transcribed and then coded into topics in a spreadsheet and analysed systematically. They were also analysed as whole texts so individual user experiences did not get lost.

Storage sanitary inspection form

Sanitary surveys were conducted by the researcher together with the translator by asking questions and observing the storage facilities in 24 people's homes. The purpose of this was to relate this information to the water quality data and in a systematic way assess risks related to household water storage. The sanitation inspection form was developed based on eight criteria for safe water storage from Centers for Disease Control and Prevention (CDC) and the International Scientific Forum on Home Hygiene (IFH) (CDC 2003; Nath *et al.* 2006). The eight criteria relate to whether the storage vessel is dipped (and if so by what means); whether the vessel has a lid; the integrity of the vessel and its hygienic appearance.

RESULTS

Interviews with water providers in Nagpur

NMC officials placed a high emphasis on the effectiveness of source treatment. They explained how water is treated and chlorinated and chlorinated again at the zone reservoir because of chlorine depletion on the way there but at that point they only needed to add a minimal amount. One engineer said, regarding water quality changes:

> 'When we are monitoring we can see that the quality degrade to the consumers.' (B3)

The NMC officials further explained that the supply network suffered from occasional problems with groundwater intrusion, as pipelines leak, especially during the rainy season. During that time there could even be cross contamination between the water supply and the sewerage system. NMC monitors water quality daily and the interviewees stated that the water supplied is normally potable. NMC

officials said that they were aware that water quality may deteriorate post-supply. Their opinion was that behavioural change is needed to reduce such post-supply contamination and that consumers should clean their equipment more and stop washing their hands in the same vessels that they use for drinking water.

Interviews with consumers

Water quality and access

The consumers reported that they did not find the time limitations of the intermittent supply to be a substantial burden or to be the factor that determines the amount of water collected. Volumes collected were reported to be more related to storage limitations and personal preferences. 10 out of 12 of the consumers stated that they were satisfied with the water quality they get even though half of the interviewees claimed to have turbid water to some extent during the rainy season. Below are two positive comments from households without problems and a negative one from a young woman from the lower socio-economic status areas:

> '… There is no turbidity in water and the taste is very good so we do not have any treatment …' (D1)
> '… The water quality that we are receiving right now is the best …' (E7)
> 'Early in the morning when they start the tap the water quality is sometimes turbid, muddy and sometimes you can find some kind of worm, basically in the rainy season. For 3–4 pots it is like that after that it is good, the water is clear and taste is a bit sweet.' (D5)

But even some of those who did not believe they had any water related problem chose to treat it. Households use various treatment options, and they use them before storage. Technologies used are point-of-use water purification systems: boiling of water, household chlorination or filtration.

Water storage

All water storage vessels used by the interviewees were made of bronze, steel or clay. 11 out of 12 of the households cleaned their pots daily and some used soap. Whilst this

practice indicated a positive attitude towards hygiene, such wide mouthed vessels which allow entry of a hand are not recommended for safe water storage by CDC (2003) and IFH (Nath *et al.* 2006).

Point-of-use behaviour

A large majority of the users will extract water from storage with glasses or mugs. These extraction tools are what most people drink from but some use them to fill another glass which they drink from. Many children drink straight from the extraction tool. This is described as follows by two mothers in large families:

> 'The children take directly from the storage with small glasses and older will not dip directly with hand or glass they take it with a jug and transfer it for drinking purposes.' (D3)
> '… Children when they come after playing do not take those precautions and take water directly with their hands …' (F8)

Health

Knowledge of water-related illnesses and their causes are fairly common. There are a number of diseases that have affected the study areas that relate to water, even though they were reported to be quite rare. Jaundice, yellow fever, typhoid, diarrhoea, stomach ache and fever were the diseases mentioned by the interviewees as previously present but only the last three were reported to be present at the time of the interviews in the rainy season.

Storage sanitary inspection form

The result for each of the 8 sanitary aspects indicates that there are risks present due to inappropriate storage. The three most common risks are storage designed for dipping, use of short/no handle or hand for extraction and storage vessels accessible for children. The percentage of households where specific risks are present is shown in Table 1. A comparative analysis between areas with different socio-economical standards was made and there were

Table 1 │ Households answering yes to questions regarding sanitation related issues

Question asked	Yes answer (%)
Does the storage vessel design permit dipping?	88
Do they use dipper with short/no handle	67
Is the vessel accessible for children?	58
Do they pour back excessive water?	43
Is the vessel made of non-durable material?	33
Do they lack a lid on storage vessel?	17
Is the inside of the vessel hard to clean?	13
Are there signs of dirt around opening?	11

Table 2 │ Risk of re-contamination by socio-economic standard of the area

Socio-economic standard	Average risk score (maximum [most risky] possible score is 8)
Higher ($n = 4$)	1.8
Medium ($n = 8$)	2.9
Lower ($n = 12$)	4.1

indications that those with the largest risks are households with lower socio-economic standard (Table 2).

Water quality results

The risk categorisation developed by Lloyd & Helmer (1991) was used to classify the quality of water samples according to the presence of faecal indicator bacteria in the water samples. The microbiological water quality demonstrated both spatial and temporal differences. TTC counts at different locations are presented in Figures 2–4. These indicate a substantial water quality reduction down the supply chain, especially between tap and point-of-use. The differences in microbiological quality between public tap stands and point of use were significant at the 95% level and significant at the 90% level between tap and point-of-use in the other supply areas. The second set of samples was taken mainly after the rain started. The rains affected the proportion of samples assigned to the worst water quality category. For example, in the samples taken before the rains, only samples taken from Area D at point of use were found to be in this worst category. In the set of samples taken after the rains,
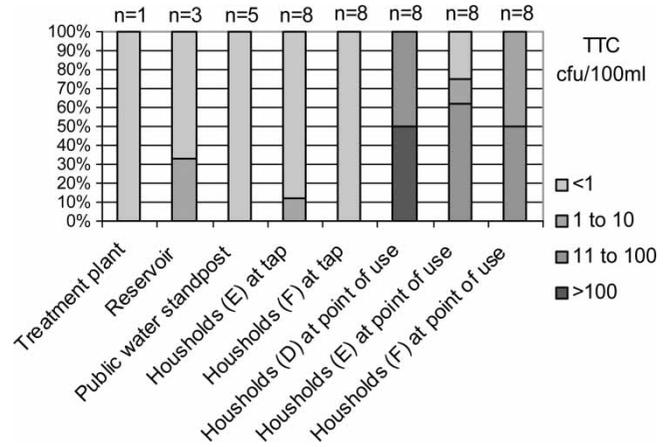

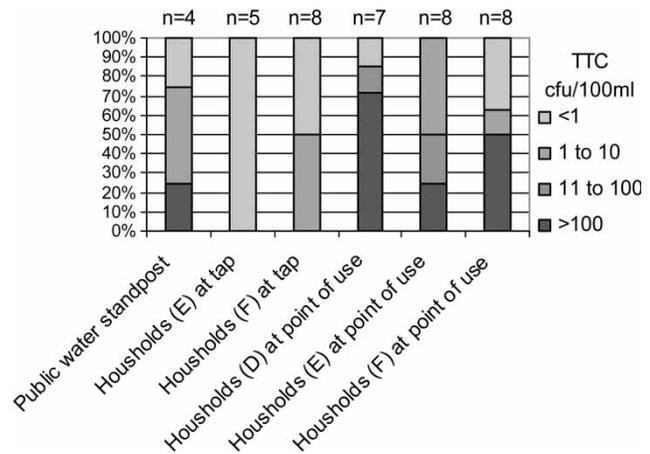**Figure 2** │ TTC counts down the supply chain for the 1st set of samples.

Figure 3 │ TTC counts down the supply chain for the 2nd set of samples.
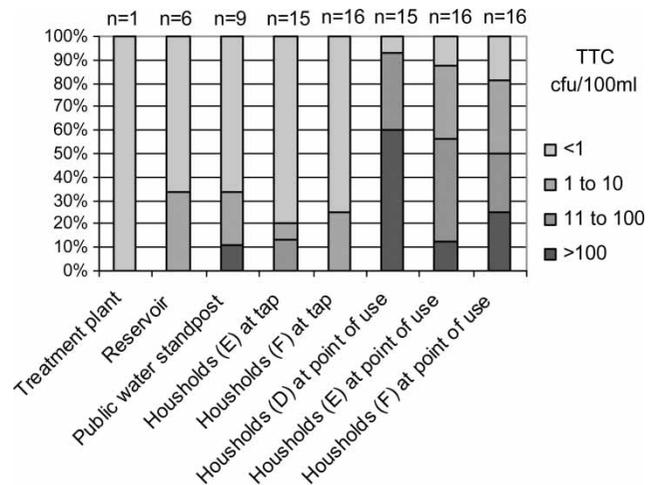

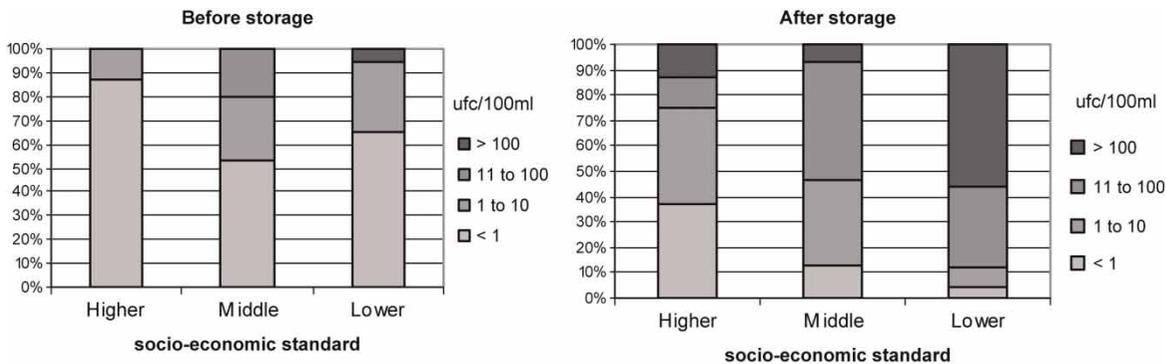**Figure 4** │ TTC counts down the supply chain for the whole period.

Figure 5 │ TTC in the water supply for different socio-economical standards.

samples from the public standpost, and samples from all of the point of use sampling locations were found to exhibit poor microbiological quality.

Socio-economic status was compared with the TTC levels in the water before and after storage. The result is presented in Figure 5 and shows that the TTC levels both before and after storage is clearly different. Further, it was apparent that samples taken from households assigned a lower socio-economical status tended to have higher TTC levels although this was not confirmed statistically due to the relatively small sample size. No residual chlorine was found in household storage vessels. Residual chlorine was found in one of the 6 samples taken in the zone reservoirs, the level at that time being 0.1–0.2 ml/L, which suggests that very little chlorine made it to the reservoirs. The pH values were quite stable and all samples taken had values that varied between 7.6 and 8.6. The average value of turbidity was 1.6 Nephelometric Turbidity Units (NTU) but there were a few peaks especially when water samples were taken in the morning, reaching a maximum 22 NTU.

DISCUSSION

Water quality deterioration

The NMC staff interviewed said that the network had problems with broken pipes and consumers spoke about foul water at the beginning of the supply time. The problem with ingress is most likely contributing to point-of-use water quality reduction in Nagpur and is likely to be exacerbated by intermittent supply. The sanitary inspection form showed that unimproved storage is another reason for quality reduction as well as poor handling habits. Interviewees like D3 and F8 confirmed that there are cases of unsafe extraction and that children access the water storage unsupervised which could be a pathogen entrance route. There are also temporal aspects of the water quality: turbidity increases during the rainy season and some interviewees said that they noticed that people in their area are more likely to get sick at that time. The worsened water quality situation during the rainy season is likely to be also caused by a more difficult hygiene situation during that wet period which may not be uniquely related to drinking water quality. Intermittent supply, unimproved storage and poor handling within households are identified as the direct risks to water quality reduction by this study, which accord with existing research (Mintz *et al.* 2001; Nath *et al.* 2006; Persson 2009).

Safeguarding the water at household level

During the study period the maximum deterioration in water quality seemed to be due to household handling. Clasen *et al.* (2009) drew a similar conclusion and recommended household interventions for safeguarding water. Two measures that can be taken to prevent quality loss are improved hygiene and improved household water technology. Improved hygiene requires heightened awareness and the promotion of behavioural change related to water collection, storage and use practices. Improved attitudes to hygiene need to be accompanied by an enabling environment such as ready access to soap for handwashing and detergent for storage vessel cleansing. Access to

affordable hygienic storage vessels and promotion of affordable point of use household treatment devices are also relevant here. Regarding the storage improvement, a vessel design is needed that prevents dipping and access by children's hands (Nath *et al.* 2006). The problem with children in particular is that they often do not take hygiene precautions. An education programme for them and their families would be appropriate (Nath *et al.* 2006). If pathogens enter the supply pipes or during collection then point-of-use treatment is needed to assure safe water, especially if the centrally added residual chlorine is depleted before reaching the households. Presently it seems that the central addition scheme does not add enough chlorine solution to make the effect last down to household storage level, which it needs to do. It would be appropriate to investigate the levels in the system and make appropriate adjustments where necessary. One option may be to promote the addition of chlorine solution to household storage directly. Chlorine addition at household level could be more efficient than the present method, especially during the rainy season, if combined with appropriate storage.

Affordability

This study, albeit based on a small sample size, suggests a link between poverty and inferior water quality in both the quantitative and qualitative data. To enable as many people as possible to gain access to safe storage, the accessible intervention must be affordable. But the drive for cost effectiveness should be balanced because any intervention can fail and leave the user exposed. Solutions should be robust and if possible have more than one barrier for safeguarding the water quality. The price of NMC water is lowered up to a certain volume to enable the poor to cover the basic water needs. Another attempt to supply water for all is the free water in public tap stands for people living in slum areas. Since the completion of the fieldwork, the authors have learned that as well as subsidies for supply to the urban poor, consideration is now being given by NMC to identify ways of intervening to promote water quality protection at the point-of-use. The issues surrounding extension of a utility's remit for water quality management beyond the point of supply will be considered in the next section.

Appropriate framework and responsibility of governance

Intermittent supply was one of the factors affecting water quality in the area covered by this investigation. The supplier interviews indicated that NMC want to gradually increase the supply time in Nagpur and eventually to be able to provide a continuous water supply to the entire population. NMC has embarked upon a 24×7 water supply system and about 15,000 households are connected in the pilot phase. They have now received approval from Government of India to cover the entire city with a 24×7 water supply system. This is an excellent long term aim but the pressures of rapid urban population growth and the continuing development of unauthorised townships make the logistics of such a goal increasingly challenging.

The findings of this study corroborate those of previously-published research which demonstrate that where water is stored in the home, one can expect significant water quality deterioration. In these circumstances the good work done by a utility to supply water of a high microbiological standard may be partially or completely offset by hygiene behaviours that introduce faecal contamination to the drinking water. There are several pathways for drinking water contamination in this environment and as such the risk assessment and management approaches required to minimise contamination necessitate an overarching or 'holistic' approach from source to point-of-use. This suggests a role for the WHO recommended framework for risk assessment and management known as the Water Safety Plan (WSP) (WHO 2005, 2008). WHO assert that the most cost-effective and protective means of consistently assuring a supply of acceptable drinking-water is the application of some form of risk management based on sound science and supported by appropriate monitoring. It is essential that such risk management is inclusive and, therefore, needs to cover the whole system from catchment to consumer. A WSP therefore comprises system assessment and design, operational monitoring and management plans (including documentation and communication) (WHO 2005).

A critical question in the context of a water supply system such as that described in this study is whether there is any realistic prospect of a WSP being effective

across the whole system from source to consumer. Where WSPs have been implemented in the developed world they are normally undertaken by a well-funded and regulated utility. The responsibility for water quality normally ceases at the point of supply. What is needed in situations such as those represented in this case by Nagpur, is an extension of the WSP remit beyond the point of supply to the point of consumption. One possibility may be for NMC to take on a broader responsibility of governance, including household water quality. Such a solution may appear attractive in theory but in practice this raises considerable questions about the resourcing and skills needs for a utility more used to water engineering than the promotion of behavioural change. Organisational cultural change will almost certainly be needed. Before implementing a holistic WSP there needs to be an acceptance of a more bottom-up user perspective approach which in the context of India is unusual (van Heel 2001). Recent promotion of the WSP concept in Bangladesh by WaterAid has highlighted ways in which awareness raising of hygiene practices relating to household water storage and use may go forward in this environment (Akter & Jahan 2009).

Subsequent to the completion of the fieldwork study in 2010, NMC began to prepare a WSP, with assistance from WHO and NEERI, including material for behavioural change at household level. WSP preparation is at a preliminary stage; however, risk assessment has been carried out for the catchment's three water sources. The major source (Pench Reservoir which meets about 80% of the water demand of Nagpur) is surrounded by thick forest and therefore has very few risk factors. Risks at water treatment plants, mass balance reservoirs and elevated service reservoirs (ESRs) have been identified and NMC is taking steps to identify and eliminate/minimise the risks. However, the majority of the contamination is thought to occur beyond the ESRs due to unauthorised connections, pipeline tampering and low water pressure, leading to unauthorised installation of booster pumps in sumps and to cross contamination. Risk of water contamination at households is considered to be very high as compared to other stages of water supply and can be eliminated/minimised by way of awareness building. It is presumed that if a WSP is implemented as a framework in an effective way it would likely lead to better control over the water supply, to

improved water quality for the end users and to regular revision of the measures taken. This will also lead to a greater confidence in the water for all stakeholders, as well as health and long term economical gain.

Limitations of the study

The study has some limitations due principally to field visit time constraints. Ideally, more than two sets of water quality data would have been collected to detect temporal differences over a whole year and to provide a dataset which would permit more in-depth statistical analysis. Similarly a larger sanitation inspection survey and interview programme would have been desirable. Opportunities for detecting relationships between temporal variation in water quality and illness through investigations of hospital records and municipal water quality data records would have added to the study.

CONCLUSION

There is a reduction in water quality between tap and point-of-use, which indicates that the contaminants principally enter post supply. The present water quality reduction risks were confirmed by the sanitary inspection form as well as by the interviews and the inspection form indicated that storage design, inappropriate extraction practice and children's access are the most frequent household storage risks. No household was found to practice safe storage according to the CDC recommendations. There is also quality reduction during the rainy season due to groundwater ingress probably exacerbated by the intermittent supply but only a few take appropriate measures to safeguard the water quality. Those with socio-economically lower status are in greatest need of interventions. Residual chlorine is added early in the distribution but is depleted at point of storage so household chlorination needs to be considered and further investigated. From a user perspective the water quality in Nagpur has the potential to improve significantly. The water that NMC distributed was, under the test period, mostly of good quality but the water that the consumers actually drank was of a much lower quality. This could imply that the health and subsequently economical gain of centralized source treatment could be significantly compromised.

These following four points are recommendations to stakeholders, to safeguard the point-of-use water quality:

1. Investigate the levels of residual chlorine down the whole supply chain and make appropriate adjustments to assure potable water from a point-of-use perspective, and further investigate the need of additional household treatment.

2. Promote affordable 'improved' water storage at household level with a design that lives up to the previously mentioned CDC recommendations.

3. Include household water in the water monitoring schemes as well as evolve it into a WSP together with the other stakeholders.

4. Further raise awareness and promote behavioural change related to water risks and appropriate water habits.

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