Water quality aspects related to domestic drinking water storage tanks and consideration in current standards and guidelines throughout the world – a review

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ABSTRACT

In many parts of the world, drinking water storage takes place in near-house or in-house tanks. This can impact drinking water quality considerably. International and numerous national standards and guidelines addressing the construction, installation and operation of domestic drinking water storage tanks are reviewed on their consideration of water quality aspects and the minimisation of health risks associated with drinking water storage. Several national and international standards and guidelines are reviewed in terms of drinking water quality requirements. Factors that have an impact on water quality in relation to the use of domestic drinking water storage tanks are summarised comprehensively. The impact of the domestic storage of drinking water on water quality, the points and locations of use, their positioning, the materials they are made of, their design and operation, as well as aspects of how they are operated and maintained is outlined and discussed in detail. Finally, the incorporation of aspects regarding water quality in drinking water storage tanks in standards and guidelines is presented and assessed. To make the use of domestic drinking water storage tanks safer and more efficient, recommendations for modifications, improvements and extensions of respective standards are made.

Key words | domestic storage tanks, drinking water quality, public health, standards, water supply

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HIGHLIGHTS

- A review of domestic drinking water storage tanks.
- Arrangement, construction, design, materials and operation are presented.
- Impact on drinking water quality is reviewed and discussed.
- Standards and guidelines are reviewed on consideration of water quality changes.
- Recommendations for improvements of standards and guidelines are made.

INTRODUCTION

The supply of drinking water always requires storage, as consumption is varying. Storage involves a risk of contamination before use. Especially in non-piped systems and piped systems with intermittent supply, storage is a crucial factor regarding water quality and thus public health. This is because in such systems the risk of a water quality impairment is especially high. Since the major part of the world's population obtains drinking water via in-house or near-house storage, impairment during domestic storage is of high importance and therefore requires a closer look.

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To protect public health, international and national guidelines and standards for drinking water quality do exist. Those regulations are intended, if properly implemented, to ensure drinking water safety through elimination, or, as far as possible, removal of contaminants that bring about a certain health risk potential. The guidelines and legislations include a basis for assessing drinking water quality and limits for potentially hazardous contaminants. Consequently, those regulations provide the fundamentals to assess the impact of drinking water storage systems on drinking water quality.

In-house or near-house storage means using storage tanks. These domestic drinking water storage tanks differ in size, position, construction, materials and operation. This is due to the differences in the location of their use. Domestic drinking water storage tanks can be found both in sparsely populated regions and in more densely populated regions. Moreover, their application includes cold climates as well as warmer regions. Furthermore, the respective situation of the local water supply also greatly affects their design and operation.

In Arctic regions, storage tanks are used in buildings because large distances between the water source, location of treatment and the consumer must be overcome there. In addition, these regions are at the same time characterised by an extremely low population density. Consequently, water demand is quite low and highly variable. Moreover, the prolonged low temperatures in such regions make the use of pipes and outdoor locations difficult or even impossible (Guyer 2013; Daley *et al.* 2018).

In warmer regions, domestic storage tanks are also used when the population density is very low and when long distances between the drinking water source and settlements must be overcome. By contrast, many other factors play a role in these parts of the world. The main reason for the need to use domestic storage tanks is the limited or scarce amount of water available. This limited water supply must be addressed by decentralised storage systems, mostly in the form of domestic storage tanks. Moreover, due to the water stress, in most cases there is no central water treatment. Consequently, for domestic drinking water storage systems, treatment or at least disinfection of the water is essential. This treatment directly before use is, in most cases, the best or only way to guarantee the required drinking water quality. Finally, interruptions to a central water supply, a water supply via wells and springs, as well as permanent, temporary or accidental contamination of water resources make drinking water storage close to or in households necessary.

In addition, in some places domestic storage tanks are used for historical reasons. This is, for instance, the case in the UK, where the water supply was intermittent at its beginning in the 19th century. Today, the historic domestic storage tanks still in operation are used to supply toilet cisterns and bathroom cold taps only (Kilvington *et al.* 2004).

All in all, the main purpose of domestic drinking water storage tanks is to guarantee a complete and uninterrupted water supply. Besides this main purpose, they can also serve the purpose of providing enough pressure and firefighting reserves, which, however, play a subordinate role. The crucial aspect to be considered when domestic water tanks are used is water quality as a key factor for public health. This is because the storage of drinking water always means a change in its quality, since chemical, physical and microbiological processes take place during its residence in such systems (USEPA 2002). Therefore, keeping the water quality as high as possible or – in other words – avoiding deterioration of the water quality is the main objective when using domestic drinking water storage tanks. This is crucial for the reduction of public health risks and it means to avoid anything hazardous to human health or that could contribute to a disease or an infectious condition in humans. Consequently, all efforts and measures must be directed towards that one objective. This means that, to prevent water quality problems, special attention must be paid to the construction, positioning, design, operation and maintenance of domestic drinking water storage tanks. Design and operation should aim at complete mixing, high exchange rates that result in short residence times and low temperature changes. Adverse conditions might bring about the consumption of disinfectants, cause the formation of disinfection by-products, and bacterial growth, as well as the formation of substances responsible for taste and odour.

In this review, special attention is paid to national and international standards and guidelines with respect to their specifications regarding drinking water quality in principle, and particularly with respect to their consideration of the use of domestic drinking water storage tanks. Issues regarding construction, positioning, materials as well as operation and maintenance of domestic drinking water storage tanks, and their impacts on water quality, are considered comprehensively. Moreover, the review contains an assessment of the suitability of current standards and guidelines, when applied properly, to prevent water quality deterioration in domestic drinking water storage tanks. The review is completed by recommendations concerning possible modifications, improvements and extensions of standards to make the use of domestic drinking water storage tanks safer and more efficient.

DRINKING WATER QUALITY REQUIREMENTS

WHO guidelines

Renwick (2013) explains the approach of the World Health Organization (WHO) with respect to the published Guidelines for Drinking Water Quality. These guidelines are not enforceable, but a basis and guiding principle for many governments and authorities worldwide in setting up their own national water quality standards. The WHO guidelines represent a ‘framework for safe drinking-water’ with the purpose of providing a ‘preventive, risk-based approach to managing water quality’ (WHO 2011). In the guidelines, three main issues are highlighted: (1) health-based targets, (2) Water Safety Plans and (3) surveillance and control. The health-based targets include the definition of a tolerable burden of disease, orientation values of water quality characteristics, as well as technology and performance targets. Water Safety Plans aim at the assessment, monitoring and management of water systems as well as associated communication to make the identification, defence against and prevention of health risks possible. The objective of surveillance is to make sure that Water Safety Plans are being fulfilled and that the targets for human health are being met. Successful surveillance and control require appropriate inspection concepts. The WHO Guidelines for Drinking Water Quality (WHO 1997) provide useful and very effective advice, recommending the application of a semi-quantitative approach that includes logical questions and a simple scoring system. This should be applied as complementary to targeted sampling with subsequent water quality analysis of the water samples (Robertson *et al.* 2006).

Since the WHO guidelines are sufficiently comprehensive and often more detailed than the national directives in developing countries, they are frequently used as the primary, if not the only, standard. This preferential application in developing countries also results from its good practicability.

North America

In the USA, authorities follow the Safe Drinking Water Act (SDWA 2002), which is the main federal law that ensures the quality of drinking water. Under the SDWA, the Environmental Protection Agency (EPA) sets standards for drinking water quality and oversees the states, localities and water suppliers who implement those standards. SDWA applies to every public water system in the United States, while the US EPA sets national standards for tap water, which help to ensure the quality of the water supply. Regarding water reservoirs, special attention is paid to the presence of *Legionella* sp. in water for consumption (Storey *et al.* 2004; Thomas *et al.* 2004; Marciano-Cabral *et al.* 2010).

In contrast, not all drinking water aspects are regulated at a national level in Canada. As stated in the Guidance for Safe Drinking Water in Canada: From Intake to Tap (DWS 2001), the provincial, territorial and federal governments have collaborated to establish the Guidelines for Canadian Drinking Water Quality. According to this guideline, ‘provincial and territorial authorities are responsible for the implementation of these guidelines within their jurisdictions. At the federal level, the guidelines provide a benchmark and set out the basic parameters that every water system (public, semi-public and private) should strive to achieve in order to provide the cleanest, safest and most reliable drinking water supply possible’. Moreover, the Canadian authorities work with national and international standard-setting organisations, mostly the NSF International and the American National Standards Institute (ANSI), to develop appropriate standards focusing on water quality aspects (Government of Newfoundland & Labrador 2011).

South America

In Brazil, there is a standard of the Brazilian Health Ministry for water treatment, distribution and storage – the Ordinance n. 5, formerly n. 518 (Brazil 2004, 2017). This standard includes recommendations and threshold values for drinking water quality parameters such as turbidity, iron and the residual free chlorine concentration. The limits and requirements also apply to water stored in domestic drinking water storage tanks.

Europe

The European Union Council Directive 98/83/EC of 1998 is the higher-level law for national sanitation and distribution system standards of the European member states related to water quality. In this directive, the quality of water intended for human consumption is addressed irrespective of its origin and whether it is supplied via a distribution network, from a tanker, in bottles or containers. The directive comprises parameters and parameters for water quality, that must be complied with. The requirements apply to the point at which drinking water emerges from the taps, from a tanker, and at which the water is filled into bottles or containers (Council Directive 98/83/EC 1998). The Directive 98/83/EC specifies that, in cases where water quality does not meet the requirements, the obligations of the responsible authorities are nevertheless considered as fulfilled if non-compliance is due to the domestic distribution system or the maintenance thereof. However, there is still the requirement to ensure that the necessary remedial action to restore water quality is taken by the responsible person as soon as possible.

The German implementation of the Council Directive 98/83/EC of the European Union in a national law is the Drinking Water Ordinance (TrinkwV 2001). The purpose of this regulation is to protect human health from adverse effects of any contamination of water intended for human consumption. The basic requirement of the Drinking Water Ordinance (TrinkwV 2001) is that the water intended for human consumption must be free from pathogens, palatable and clean. Following the principles of the Council Directive 98/83/EC, there is no distinction regarding the origin of water for human consumption.

The German Drinking Water Ordinance (TrinkwV 2001) regulates that, in cases of non-compliance with quality threshold values, which can be attributed to domestic installations or their inadequate maintenance, appropriate orders must be issued by the national authority concerned. In such cases, the owner or operator of the domestic distribution system must take appropriate measures to eliminate or minimise health risks.

In the United Kingdom (UK), regulations on water quality also follow the European Union Council Directive 98/83/EC of 1998. For the implementation in national law, the application of domestic storage tanks had to be considered. This was done by the Water Supply (Water Fittings) Regulations from 1999 (HMSO 1999) – a specific standard including recommendations for storage cisterns. Moreover, the process of implementation resulted in the adoption of a series of standards such as the Water Supply (Water Quality) Regulations from 2000 and 2001. A special feature of these regulations is the specific regularity framework for the countries England and Wales, Northern Ireland, and Scotland.

Africa

In South Africa there is a national standard that gives guidance with respect to the quality of water for domestic use (South African Water Quality Guidelines – Domestic Use (DWAF) 1996). The document is primarily for water quality managers and provides information to assess water quality aspects with respect to human consumption and other domestic purposes. Included in the guidelines are definitions of water quality concepts, information regarding the application of the guidelines and information on different water quality constituents. The latter cover aspects of occurrence, interactions and measurement. In addition, information on data interpretation is given and treatment options are mentioned. To guarantee a high degree of transparency and reasonability, in addition comprehensive source information is given.

Renwick (2013) discussed the Ghana Standard No. 175-1:2008, which outlines water quality standards for both municipal drinking water and packaged (bottled) drinking water (Ghana Standards Board 2008). The Ghana standard refers to the WHO Guidelines for Drinking Water Quality

(WHO 2011) in connection with the standard methods for the examination of water and wastewater of the American Public Health Association (2012). In this standard, a minimum free chlorine residual of 0.2 mg/L is specified and for *Escherichia coli* the demand is that none should be detected in a 100 mL sample. Renwick (2013), furthermore, states that 'there are no requirements listed for sanitary surveys or operator certifications, but during conversations with GWCL staff it was apparent that staff were aware of the WHO framework for drinking water quality'.

Middle East and Asia

In Oman, a country which also uses storage tanks in buildings, there is a standard for drinking water – the Omani Standard No. 8/2012 (DGSM 2012). This standard is also based on the International Guidelines for Drinking Water Quality of the World Health Organization. It includes requirements for aesthetic characteristics, total residual chlorine, biological and microbiological characteristics. There is no standard regarding criteria for water quality in domestic storage tanks or other aspects of water distribution and storage. However, there is a general use of total and faecal coliforms as quality indicators for drinking water, as stated by Al-Bahry *et al.* (2011).

The legal basis in Japan is the Waterworks Law published by the Japan Ministry of Health, Labour and Welfare. This includes articles on private water supply facilities, hygiene measures and water quality standards (Japan Ministry of Health Labour & Welfare 1957-1, 1957-2, 1957-3).

IMPACTS OF DOMESTIC WATER STORAGE ON WATER QUALITY

Relevant water quality aspects

In principle, water quality aspects can be categorised as chemical, physical and microbiological issues, as shown in Table 1. Quality changes associated with chemical reactions include the loss of disinfectant residual, disinfection by-product formation, development of taste and odour, increase in pH, corrosion, build-up of iron and manganese, the occurrence of hydrogen sulphide, and leachate from internal coatings (Kirmeyer *et al.* 1999). Microbiological problems occur in cases where microorganisms are introduced into storage facilities, grow and proliferate. As identified by Smith *et al.* (1990), microbial growth is supported by increases in water temperature, the availability of nutrients and minerals, the occurrence of corrosion products, a lack of disinfection residual and stagnation periods (low or no flow). The impacts of physical processes on water quality are related to the accumulation of sediments, contaminant entries and temperature effects like thermal stratification. Moreover, changes in temperature can cause chemical or microbiological problems in turn.

Table 1 | Causes of changes in water quality in drinking water storage tanks

Chemical	Microbiological	Physical
Disinfection agent decay	Microbial growth	Sedimentation
Chemical contamination	Nitrification	Contaminant entry
By-product formation	Pathogenic agent contamination	Thermal stratification
Corrosion	Taste and odour formation	Warming
Taste and odour formation		

Adapted from USEPA (2002).

The decay of the disinfection agent and the formation of by-products are the most common chemical problems that can cause microbiological processes which may result in water quality deterioration. Factors such as the concentration of organic material, the presence and state of biofilms, nitrification processes, conditions regarding ultraviolet radiation and temperature can affect disinfectant consumption. Regarding domestic storage tanks, wall effects are of special importance due to the bigger suface-to-volume ratio when compared with large central storage reservoirs. The loss of disinfectant residual is often intensified by oversized storage volumes, poor water mixing rates, inappropriate maintenance (cleaning) and structural defects (lack of sealing), which can cause contamination (e.g., Grayman & Clark 1993; Clark *et al.* 1996; Kirmeyer *et al.* 1999; USEPA 2002; Hannoun *et al.* 2003; Grayman *et al.* 2004; Mahmood *et al.* 2005; Basile *et al.* 2008; Schafer & Mihelcic 2012; Matsinhe *et al.* 2014; Miyagi *et al.* 2017).

The formation of disinfection by-products (DBPs) results from chemical reactions of the disinfectant with organic substances. Different kinds of by-products formed can be attributed to the type of disinfectant used. The DBP formation depends on the contact time, disinfectant residual, temperature, pH, precursor concentration and bromide ion concentration (Kirmeyer *et al.* 1999).

The presence of disinfectant residuals and their by-products, biological activity, emissions from materials in contact with water and external contamination may contribute to the development of taste and odour (Burlingame & Anselme 1995). In a study by Rigal (1992), impairments of the taste of drinking water in contact with thermoplastic materials were described and attributed to the release of phthalates, aldehydes, ketones, alkanes and fatty carboxylic acids from the materials investigated.

Changes in pH are of special importance regarding corrosion, since effective corrosion control passivating layers require stable pH conditions. Otherwise, corrosion can occur and particles as well as other corrosion by-products can be released into the water. As a result, additional chemical and microbiological processes may take place and the corrosion itself can be accelerated. There is also the possibility of microbial induced corrosion by iron-oxidising and sulphur-reducing bacteria, which often coexist and establish a biofilm on exposed metal surfaces (Little 1990). In contrast, biofilms on storage tank walls can represent a kind of barrier to corrosion processes (O'Conner *et al.* 1975; Abernathy & Camper 1998).

Especially during stagnation periods, compounds can be released from tank materials to the drinking water, depending on the chemical composition, the rate of migration and the water temperature (Kirmeyer *et al.* 1999). If the leachates contain organic compounds, bacterial growth can be supported. Otherwise, changes in pH and ion composition can result. A study indicating the bacterial growth-promoting effect of nutrients leached from coatings on storage facilities was performed by Ellgas & Lee (1980). Van der Kooij (1993) and Schoenen & Wehse (1988) also attributed the observed bacterial growth to the release of growth-promoting substances from materials being in contact with drinking water.

Since the loss of disinfectant residual and increases in temperature are typical of domestic drinking water storage tanks, the propensity for regrowth and biofilms is increased. This is further supported by the high surface-area-to-volume ratio and by stagnation and long residence times, respectively. The water age can be higher due to oversizing of tanks and short circuit flows between the inlet and outlet. Poor mixing (including thermal stratification, swirls, zones without flow – dead zones) can exacerbate water quality problems by creating zones within the storage tank where the water age significantly exceeds the average water age throughout the facility (Grayman *et al.* 1999; USEPA 2002). Long residence times and higher temperatures of up to 22 °C are optimal for microbiological growth (Kerneis *et al.* 1995; Uhl *et al.* 2002; Uhl & Schaule 2004). An increase in heterotrophic plate counts, as a consequence of an increased temperature and the concentration of biodegradable organic matter that resulted in decreases in free chlorine residual, was shown by Ndiongue *et al.* (2005). The impact of nutrients available for bacterial growth and of the level of disinfectant residual on bacterial biomass and production was investigated by Prévost *et al.* (1998), who showed that bacterial growth was slower at low nutrient levels.

In systems where free ammonia is present, nitrification can occur. The nitrification process can cause a degradation of chloramine residuals, a consumption of dissolved oxygen, a slight decrease in pH and increases in the heterotrophic bacterial populations as well as in the concentrations of nitrite, nitrate and organic nitrogen. Sufficiently high flow rates and mixing are suitable measures to avoid stagnation and long retention times and thus nitrification.

In water distribution systems, poor mixing promotes sediment accumulation, leading to increased disinfectant demand, microbial growth, DBP formation and increased turbidity within the bulk water (USEPA 2002). These effects are not just reductions in quality by themselves, but they can also cause further quality problems. For example, Egorov *et al.* (2003) assumed a relation between turbidity and gastrointestinal illness due to the consumption of non-boiled tap water. Quality problems especially arise at low concentrations of the disinfectant. Beuhler *et al.* (1994) reported on elevated levels of coliforms associated with accumulated sediment.

If there is a temperature difference between the water entering a tank or reservoir and the water inside, stratified layers will form (USEPA 2002). This should be prevented by an optimised mode of reservoir operation, or techniques should be applied to promote mixing, respectively. Using hydraulic simulations that consider mixing in drinking water storage tanks (Clark *et al.* 1993; Mau *et al.* 1995; Hannoun *et al.* 2003) and the thermal stratification (Gualtieri *et al.* 2004), conclusions can be drawn on measures to minimise adverse effects on water quality. A simple method in design to prevent or minimise stagnation and poor mixing is to separate the inlet and outlet (Clark *et al.* 1993). Moreover, the application of turbulent jet inflow with a long path can promote better mixing inside the tank (USEPA 2002).

The water temperature is also of special importance, since it can accelerate chemical processes (USEPA 2002). Chemical reactions can lead to changes in pH, alter taste and odour, and promote disinfectant decay and disinfection by-product formation, as well as leaching of substances from reservoir or tank materials.

The entry of contaminants can directly affect water quality. In cases of uncovered storage facilities or due to missing caps and closures, it will be possible for worms or insects to enter storage tanks. Microorganisms can also be introduced in storage systems from windblown dust, debris and rainwater. Moreover, leakages present a potential risk of contamination from animal excrement, as reported by Geldreich (1996), who could trace back a *Salmonella* contamination to birds defiling a storage facility.

Health risks due to domestic drinking water storage

The most relevant health-based target in relation with drinking water quality is to prevent the introduction, growth and spread of pathogens. The majority of studies and investigations by far focus and deal with aspects referring to the presence and growth of bacteria and pathogens in domestic drinking water storage systems. Health effects of relevant pathogens are listed in Table 2. Table 3 provides a supplementary summary of results from literature studies focusing on water quality in relation to bacterial presence and associated health risks.

Impact of domestic storage tank position

Position and materials of domestic drinking water storage tanks have a strong impact on water quality since they determine the chemical, physical and microbiological processes taking place during storage. With respect to position, domestic drinking water storage tanks can be connected directly to a public water supply network via a pipeline. Otherwise, they can be arranged completely independently of public networks. In cases where domestic drinking water storage tanks are connected by a pipeline to a public water supply network, they can be installed at house service connections or integrated into residential buildings. Depending on the installation site at or in the house, the storage tanks can be classified into street-level tanks and roof-level tanks. In some cases, combinations of both exist. Roof-level tanks, as shown in Figure 1 (left), are located on the highest part of a building and are connected to the internal house installations by pipes. In the case of combinations where storage tanks interact, the street-level

Table 2 | Health effects of relevant pathogens associated with domestic storage

Organisms isolated from domestic storage tanks	Effects on public health	References
Acanthamoeba keratitis	Sight-threatening infection related to ocular contact lens wearers (inflammatory corneal ulcer), and granulomatous amoebic encephalitis (GAE)	Kilvington *et al.* (2004), Winck *et al.* (2011)
Aeromonas spp.	Intestinal and extra-intestinal infections (gastroenteritis, skin, urinary tract, and eye infections)	Al-Bahry *et al.* (2011)
E. coli and *Enterococcus* sp.	Faecal contamination indicators	Oswald *et al.* (2007), Völker *et al.* (2010), Matsinhe *et al.* (2014)
Legionella spp.	Pneumonia (legionnaires' disease), immunosuppressed users risks	Völker *et al.* (2010), Al-Bahry *et al.* (2011)
Pseudomonas spp.	Negative health effects on newborn babies (gastroenteritis)	Al-Omari *et al.* (2008), Völker *et al.* (2010), Al-Bahry *et al.* (2011)
Salmonella spp.	Salmonellosis, immunosuppressed users risks	Al-Bahry *et al.* (2011)

Table 3 | Summary of literature studies with focus on the presence and growth of bacteria and pathogens in domestic drinking water storage systems

Study	Study area	Bacteria and pathogens considered	Aspects of tank usage considered	Results and findings regarding water quality and health risks
Miyagi *et al.* (2017)	Okinawa Prefecture, Japan	Total viable count	Positioning	Higher concentration of bacteria when residual chlorine was <0.1 mg/L and at water temperature was $>20\,^{\circ}$C
		Faecal coliforms		Decreases in residual chlorine resulted from increasing water temperature due to increased solar radiation
		Aeromonas		
		Enterobacteriaceae		
		Non-fermentative Gram-negative rods		
Matsinhe *et al.* (2014)	Maputo, Mozambique	Total bacteria	Design	Bacterial ingress and frequent presence due to poor maintenance, cleaning and disinfection measures, missing coverage as well as oversizing
		Faecal coliforms	Maintenance	Bacterial growth resulted from combined effects of sediments, low disinfection capacity and long retention time
		E. coli	Operation	
Aish (2013)	Middle Governate in the Gaza Strip, Palestine	Total coliforms	Maintenance	Biological contamination in 75.7% of the domestic drinking water storage tanks due to insufficient cleaning and improper implementation of water disinfection
		Faecal coliforms		
Akuffo *et al.* (2013)	Nyankpala Community, Ghana	Total coliforms	Material	Presence of coliform bacteria in all the storage tanks investigated, with the highest levels being observed in polyethylene barrel containers
		Faecal coliforms		In metallic containers, violations of the WHO limits (WHO 2011) for the parameters colour, turbidity and total iron
Schafer & Mihelcic (2012)	Tiquipaya, Bolivia	Total coliforms	Material	Statistically higher *E. coli* and turbidity in storage tanks cleaned less than three times per year
		E. coli	Maintenance	Highest *E. coli* counts were found in polyethylene tanks when compared to fibre cement and fibreglass
			Positioning	Increases in *E. coli* and total coliforms could be attributed to increases in temperature and losses in chlorine residual, conditions which were especially pronounced in black polyethylene tanks
			Operation	
Al-Bahry *et al.* (2011)	Muscat, Oman	*Pseudomonas*	Material	Physicochemical characteristics of holding tank systems support microbial regrowth, which in turn, affects the drinking water quality
		Aeromonas		
		Iron and sulphur bacteria		

Schafer (2010)	Cochabamba, Bolivia	Total coliforms	Material	Difference in microbial water quality in storage tanks with respect to the material they are made of, since the material has an impact on the water temperature inside the storage tanks
		E. coli	Maintenance	In black polyethylene tanks, water temperatures even reached 34 °C, in contrast to 20 °C and 23 °C in the fibreglass and fibre cement tanks, respectively
				Evidence, even if not statistically significant, that cleaning of the storage tanks resulted in less positive findings of *E. coli* when it was performed three or more times per year
Schafer (2010), LeChevallier *et al.* (1996), Donlan *et al.* (1994), Smith *et al.* (1989), Donlan & Pipes (1988), Fransolet *et al.* (1985)	Bolivia	Total bacteria	Operation	Increased microbial growth in storage tanks above a temperature of 15 °C
	Canada	Coliforms		
	USA	*Pseudomonas*		
	France	*Azobacter*		
		E. coli		
Al-Omari *et al.* (2008)	Amman, Jordan	*Pseudomonas aeruginosa*	Operation	Drop down of residual chlorine below the threshold value given by the Jordanian standards
		Total coliforms	Maintenance	All samples taken tested positive for total heterotrophic plate counts and, in some cases, even *P. aeruginosa* were found
		Faecal coliforms	Positioning	Free and total coliforms were not detected
		HPC bacteria		To keep heterotrophic plate counts at low levels, frequent cleaning of the roof storage tanks is recommended
Graham & VanDerslice (2007)	El Paso County, Texas, USA	Total coliforms	Operation	In the first set of measurements, coliforms were detected in 54% of the samples, whereas the results nine months later showed an increase of up to 82%
		E. coli	Design	This adverse effect was attributed to the longer storage times resulting from the larger volume, which favour chlorine decay
				In small containers (less than ten gallons), considered as reference, chlorine decay and bacterial contamination in terms of total coliforms was less
				It was supposed that the habit of refrigeration of the small containers and the small headspace prevented a stronger chlorine decay
				Active disinfection effect due to the higher chlorine residuals
				The use of contaminated containers and mixing conditions of old and fresh water had a considerable effect on water quality

(*continued*)

Table 3 | continued

Study	Study area	Bacteria and pathogens considered	Aspects of tank usage considered	Results and findings regarding water quality and health risks
Oswald *et al.* (2007)	Lima, Peru	*E. coli*	Operation	*E. coli* was detected in 28% of the 93 storage tanks considered
				Although drinking water was boiled in most of the households studied, almost one-third of the water samples were faecally contaminated
Kilvington *et al.* (2004)	UK	*Acanthamoeba keratitis*	Operation	The storage of water in domestic tanks can promote *Acanthamoeba* colonisation and consequently increase the risk of disease for contact lenses users
Tokajian & Hashwa (2004)	Lebanon	Total coliforms	Operation	A significant positive correlation between the level of heterotrophic bacteria in domestic tanks and the temperature of the stored water was identified
		Faecal coliforms		
		E. coli		
		HPC bacteria		
		Proteobacteria		
Tokajian & Hashwa (2003)	Lebanon	Total coliforms	Material	The study focused, inter alia, on the effect of storage on the microbial quality in 500 L domestic storage tanks made of galvanised cast iron and black polyethylene, respectively
		Faecal coliforms	Operation	There was a significant increase in the mean bacterial count in both tank types after 7 days of storage
		E. coli		The results showed a positive correlation between heterotrophic plate counts and pH, temperature and storage time
		HPC bacteria		
Campos *et al.* (2003)	Brazil	Coliforms	Operation	In samples taken from storage tanks, the iron concentration and turbidity were higher than recommended by the Brazilian standard for drinking water
				In 27% of the cases the residual chlorine concentration was below the minimum value required according to this standard
				Moreover, 19% of the samples were contaminated by coliforms
Coelho *et al.* (2003)	Jordan, Lebanon and Palestine	HPC bacteria	Material	During storage, a dramatic increase in the heterotrophic plate counts with a simultaneous reduction in chlorine residual was observed
			Operation	Relations between the heterotrophic plate counts and pH, temperature, turbidity and tank material could not be identified
Momba & Kaleni (2002)	South Africa	HPC bacteria	Material	Indicator microorganisms were present in both types of domestic storage tanks, polyethylene and galvanised steel, and growth of coliforms during storage was observed
		Total coliforms		However, in the galvanised steel containers no faecal coliforms were found and the levels of HPC bacteria were lower compared to the polyethylene containers
		Coliphage		
		E. coli		
		Salmonella		

		Clostridium perfringens		
Evison & Sunna (2001)	Amman, Jordan	*P. aeruginosa*	Operation	Increases in heterotrophic plate counts in association with decreases in chlorine residual
		HPC bacteri		During storage there were also changes in pH, turbidity and TOC as well as trihalomethane concentrations
		Coliforms	Material	However, no coliforms or *P. aeruginosa* were detected
Schoenen (1990), Schoenen & Scholer (1985), LeChevallier *et al.* (1981), Schoenen & Dott (1977), Grabow *et al.* (1975)	Canada, Germany, South Africa	Total bacteria	Operation	Increased likelihood of microbial growth at long retention times, low or no residual chlorine and high water temperatures within domestic storage tanks
		Total coliforms		
		E. coli		
Sutton & Mubiana (1989)	Zambia	Faecal coliforms	Operation	There were no faecal coliforms in 85% of the samples from storage vessels.
				Only 4% of the samples contained >10 faecal coliforms per 100 mL

tanks are operated to feed roof-level tanks by a pumping system (USEPA 2002). The roof-level tank then provides the drinking water for the individual tapping points. An example of a combined system is shown in Figure 1 (right).

In many cases roof water tanks are used as a kind of backup due to the intermittent public water supply. According to Tamari & Ploquet (2012), roof tanks are most commonly used in Latin America, South Asia, the Middle East, Mediterranean countries and in Africa. For roof positions, shading is relevant to prevent bacterial growth due to heating by direct sunlight (Miyagi *et al.* 2017). Water storage tanks with continuous water flow bypassed from the public water main were developed in Japan to deal with interruptions of water supply caused by earthquakes (Ishizuka *et al.* 2006). Edwards & Maher (2008) considered water quality in storage facilities and recommended focusing on planning aspects regarding the location of storage facilities relative to the distribution system besides water mixing within tanks and a maximum turnover to maintain water quality. Table 4 provides an overview of different situations regarding positioning of drinking water storage tanks as described in the literature.

Regarding the tank position, the most important impact factor on water quality is the temperature. Increasing temperatures due to warm ambient conditions or direct sunlight result in increased bacterial growth and accelerate chemical processes.

Impact of domestic storage tank material

The storage tanks used mainly consist of plastic material (polyethylene and glass-fibre reinforced plastic). This includes regions in Nicaragua and Bolivia (Macy & Quick 1998), rural Thailand (Mintz *et al.* 1995), Bangladesh (Sobsey *et al.* 2003), South Africa (Momba & Kaleni 2002) and Zambia (Mintz *et al.* 1995) as well as Native American village homes (Faubion 1994). In addition, a variety of other materials are used for domestic drinking water storage tanks, as summarised in Table 5.

The materials of which storage tanks are made are of special relevance with respect to water quality. This relates primarily to the leaching of compounds from the tanks into the stored drinking water. For quality aspects, not

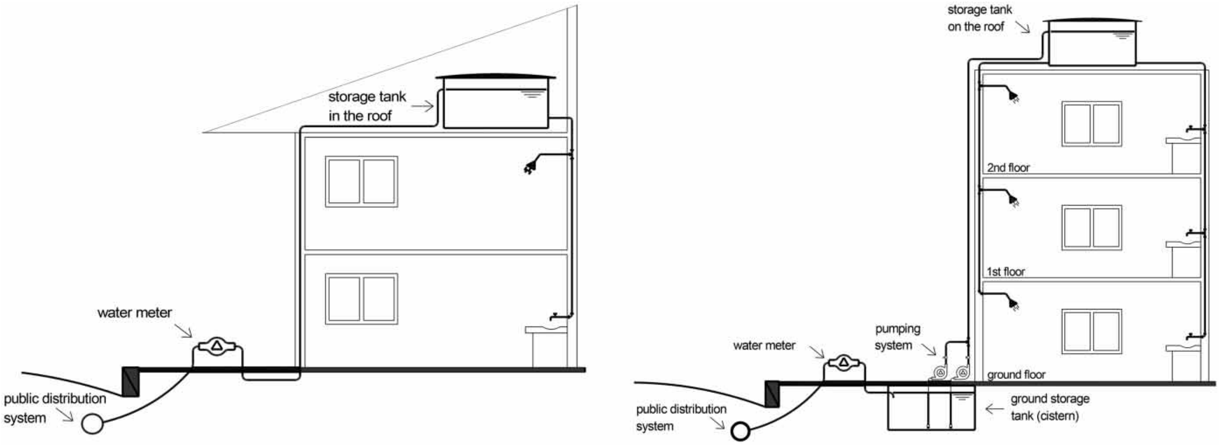

Figure 1 | Concepts of domestic water supply: (Left) supply from a roof-level tank; (Right) supply from a combined system consisting of a street-level tank, a pumping system and a roof-level tank.

Table 4 | Overview of different situations regarding positioning of drinking water storage tanks

Underground to house	Ground-level	Roof-level	Combined
Morocco: Water for drinking and cooking is stored in a kind of traditional cistern that is buried in the ground. The cisterns are filled by river water and/or rainwater via simple channels. From there, the water is consumed without any treatment (Aziz *et al.* 2016)	Mozambique: Domestic tanks are mainly located at ground level, 'from where stored water is further pumped to roof tanks or supplied directly to taps in the domestics' (Matsinhe *et al.* 2014)	Japan: Roof tanks are used for storing water in case of temporary restriction of the public water supply (Miyagi *et al.* 2017)	Japan: Water storage tanks with continuous water flow bypassed from the public water main were developed to deal with interruptions of water supply caused by earthquakes (Ishizuka *et al.* 2006)
Rural Zambia: Water is fetched from wells and carried to the houses, where it is stored in small vessels (Sutton & Mubiana 1989)	USA: In Texas, settlements exist which do not have a piped water supply system (Crowder 2003). There, drinking water is delivered by water delivery trucks and stored in open or closed domestic water storage tanks outside the home (Graham & VanDerslice 2007)	Lebanon: Storage of water in domestic storage tanks of 500 L capacity due to an intermittent water supply (Tokajian & Hashwa 2003)	Bolivia: Underground cisterns store water before it is pumped to water storage tanks located on the roofs of the homes in order to have a constant supply (Schafer 2010)
	Spain: For multi-apartment buildings the location is the basement (Cobacho *et al.* 2008)	Mexico: Roof water tanks are filled with tap water from the public water supply (Chaidez *et al.* 1999)	Brazil: Street-level tanks and roof-level tanks are connected by pumps (Campos *et al.* 2003; Hua *et al.* 2018)
		Spain: Tanks are located on the roof in the case of single-family houses to compensate service interruptions (Cobacho *et al.* 2008)	USA: In Arizona, drinking water storage tanks are used in conjunction with domestic water wells. Booster pumps collect well water before it is delivered to homes (Artiola *et al.* 2012)

Table 5 | Overview of different materials used for domestic drinking water storage tanks

Plastic material	**Metallic material**	**Mineral-based material**
Oman: Reinforced plastic and polyethylene as roof tank material (Al-Bahry *et al.* 2011).	Oman: Galvanised iron as roof tank material (Al-Bahry *et al.* 2011)	Jordan: Commonly used domestic storage tanks are made of fibreglass (Evison & Sunna 2001)
Jordan: Commonly used domestic storage tanks are made of polyethylene (Evison & Sunna 2001)	Jordan: Commonly used domestic storage tanks are made of cast iron (Evison & Sunna 2001), while Al-Omari *et al.* (2008) report on steel tanks	Egypt, El Salvador, India: Traditional water storage vessels made of earthenware and ceramic (Mintz *et al.* 1995)
Palestine: Plastic and stainless-steel storage tanks are used (Aish 2013)	Lebanon: The main types of storage tanks consist of galvanised cast iron or black polyethylene (Tokajian & Hashwa 2003)	Japan: Roof tanks are constructed from fibre-reinforced plastic, reinforced concrete or stainless steel (Miyagi *et al.* 2017)
Lebanon: The main types of storage tanks consist of galvanised cast iron or black polyethylene (Tokajian & Hashwa 2003)	Palestine: Plastic and stainless steel storage tanks are used (Aish 2013)	Ghana: Different kinds of domestic storage tanks can be found, which include earthen pots, metallic containers and polyethylene barrel containers (Akuffo *et al.* 2013). The materials of domestic drinking water storage tanks include polyethylene or similar plastic, steel, cement and ceramic (Renwick 2013)
Japan: Roof tanks are constructed from fibre-reinforced plastic, reinforced concrete or stainless steel (Miyagi *et al.* 2017). Glass fibre reinforced plastic tanks to deal with interruptions of water supply caused by earthquakes (Ishizuka *et al.* 2006)	Japan: Roof tanks are constructed from fibre-reinforced plastic, reinforced concrete or stainless steel (Miyagi *et al.* 2017)	Mozambique: Materials like concrete, plastic (pre-fabricated black PVC) and asbestos cement are mostly used for the construction of domestic drinking water storage tanks (Matsinhe *et al.* 2014)
Ghana: Different kinds of domestic storage tanks can be found, which include earthen pots, metallic containers and polyethylene barrel containers (Akuffo *et al.* 2013). The materials of domestic drinking water storage tanks include polyethylene or similar plastic, steel, cement and ceramic (Renwick 2013)	South Africa: Galvanised steel containers (Momba & Kaleni 2002)	Bolivia: Elevated storage tanks are constructed of fibreglass or fibre cement (Schafer 2010)
Mozambique: Materials like concrete, plastic (pre-fabricated black PVC) and asbestos cement are mostly used for the construction of domestic drinking water storage tanks (Matsinhe *et al.* 2014)	Ghana: Different kinds of domestic storage tanks can be found, which include earthen pots, metallic containers and polyethylene barrel containers (Akuffo *et al.* 2013). The materials of domestic drinking water storage tanks include polyethylene or similar plastic, steel, cement and ceramic (Renwick 2013)	USA: (Arizona): Galvanised steel, fibreglass and polyethylene are the typical materials of domestic water storage tanks in use (Artiola *et al.* 2012)
Nicaragua: Use of 80 L plastic, lidded storage vessels equipped with a spigot for extracting water (Macy & Quick 1998)	Malawi: Traditional water storage vessels made of tin (Mintz *et al.* 1995)	
Bolivia: Elevated storage tanks are constructed of polyethylene (Schafer 2010)	USA: (Arizona): Galvanised steel, fibreglass and polyethylene are the typical materials of domestic water storage tanks in use (Artiola *et al.* 2012)	
USA: (Arizona): Galvanised steel, fibreglass and polyethylene are the typical materials of domestic water storage tanks in use (Artiola *et al.* 2012)		

only the tank material itself has to be taken into consideration, but also fittings, coatings and re-lining products. The leached substances can be harmful themselves or can adversely affect odour and taste. In addition, they can act as nutrients for microorganisms and thus cause bacterial growth, which in turn, increases the potential health risk. As a result of corrosion, harmful particles can be formed or at least provide a habitat for microorganisms, and consequently support microbial growth as well. According to Al-Bahry *et al.* (2011), special attention must be paid to styrene, an integral solvent used in Oman for the manufacturing of glass-reinforced plastic tanks. This is due to the proven carcinogenicity and mutagenicity of styrene to humans (Manolis *et al.* 1994). In addition, Al-Bahry *et al.* (2011) mention a problem in Oman regarding a lead-containing paint used to coat the inner surfaces of glass-reinforced plastic tanks to prevent sunlight penetration and to inhibit algal growth. This paint is used despite paints and coatings containing lead being prohibited according to the American standard on paints, related coating and aromatics (ASTM 1992) and WHO guidelines for drinking water quality (WHO 1997).

On the other hand, the extent of light penetration and thus of changes in temperature also depends on the material. As described by Evison & Sunna (2001), the light penetration was higher in fibreglass tanks than in tanks made of polyethylene, whereas no light penetrated cast iron tanks. Since increases in temperature promote bacterial growth, light penetration should be prevented through the choice of an appropriate material when positioning of the storage tanks in a dark place is not possible.

When considering the materials of which storage tanks are made, the compatibility with physical and chemical agents has to be taken into consideration in cases of on-site treatment performed within the tanks. In the case of the use of oxidising disinfectants (e.g., chlorine), the tank material must not exert an oxidant demand or take part in chemical reactions forming excessive concentrations of toxic DBPs (Sobsey 2002). When solar or heat treatments are applied, the tank material must be capable of withstanding high temperatures and must allow, if necessary, the penetration of UV radiation and/or the absorption of heat energy (Sobsey 2002).

Impact of design and operation of domestic storage tanks

Mixing and volumetric exchange

Since the tank geometry has a significant impact on the residence time and mixing, and consequently on the water quality, the design of storage tanks is of high importance. It is known that mixing is best achieved in spherical or cubic tanks. As described by Kennedy *et al.* (1993), the higher the height-to-width ratio of a storage tank, the poorer the mixing characteristics will be. In such cases, the tanks rather behave as plug-flow vessels. Also, Mahmood *et al.* (2005) regard mixing in storage tanks as particularly important to maintain water quality. An optimisation to achieve good mixing characteristics should focus on the tank configuration, inlet pipe diameter and orientation, adequate volume turnover, fill time and inflow rate. Grayman *et al.* (2004) also focused on the mixing and ageing of water in storage facilities and their effects on water quality. The authors recommended minimising the retention time and avoiding dead zones. Since the operation regime also has an impact on the mixing characteristics, the flow regime in storage tanks can behave somewhere between these two extremes. Grayman *et al.* (2004) furthermore state that ‘tanks operated under plug-flow conditions will generally lose more disinfectant than tanks operated under mixed-flow conditions’. Therefore, storage tanks should be designed to encourage good mixing. According to Mahmood *et al.* (2005), the key design parameters for complete mixing are the inlet pipe diameter and its orientation. As key operational parameters they mention adequate volume turnover and fill time. Considering design and operation with respect to mixing characteristics, also the water depth in the tank at the time of filling must be considered, since complete mixing is more difficult at high water levels. Better mixing should be possible when the tanks are of smaller size (Evison & Sunna 2001).

Not only should tanks be designed to ensure the best possible mixing and maximum volumetric exchange, but also the operation mode should focus on this by means of the fill–drain cycle. When there is no possibility of emptying domestic tanks completely, the remaining sediments can act as a long-term habitat for microorganisms (Tokajian &

Hashwa 2004). Consequently, incoming water will immediately be contaminated and thus increase the potential health risk.

Design

Also, with respect to (re)contamination, an appropriate design of storage tanks, especially in-house vessels and roof tanks, may help to maintain water quality. Some traditional models of in-house vessels make contamination less likely due to their narrow-necked form and when they are equipped with a faucet or spouts as well as tightly fitting lids (Mintz *et al.* 1995). Without pouring devices, hands, cups and dippers are used, which bring a higher risk of faecal contamination (Sobsey 2002). Having these devices, however, can be even more effective in reducing waterborne diseases than chemical disinfection by using chlorine tablets in these traditional models (Deb *et al.* 1986). However, there are still some disadvantages of the traditional models that can be overcome by modern design, as proposed by the Centers for Disease Control and Prevention (CDC) and the Pan American Health Organization (PAHO) and summarised by Mintz *et al.* (1995). These design criteria include an appropriate standard volume, a stable base, an appropriate handle, a single opening (5 to 8 cm in diameter) with a strong, tightly fitting cover, a cleanable spigot, devices that allow air to enter as water is extracted, as well as volume indicators and illustrations of safe water handling practices. According to Chaidez *et al.* (1999), for roof tanks, a cover to avoid contamination of the stored water by bird excrement and organic debris is especially important. Graham & VanDerslice (2007) also recommend 'the use of small-mouthed containers, that provide for easy fill-up and dispensing, and prevent people from contaminating the drinking water during storage'. The advantage of narrow nozzles in comparison to wide openings with respect to observed levels of coliform bacteria is stressed by Akuffo *et al.* (2013) as well. Special attention should always be paid to all tank openings, as emphasised by Artiola *et al.* (2012). In addition to openings for entry and exit of water, there is a need for inspection hatches and ventilation ports for larger domestic storage tanks. Since ventilation ports serve the purpose of allowing air to enter and escape the tank with decreasing or rising water levels, respectively, appropriate covers or screens are needed. These covers should at least keep out rodents and other small animals, as well as insects. Special filters can even prevent the entry of dust and microorganisms. However, they are hardly, if ever, used in domestic drinking water storage tanks. Consequently, the contamination of water stored near domestic settings by dust entry is more likely if the storage tanks are located in dry and therefore dusty environments. Without special filters, green algae, bacteria, viruses, protozoa, fungi, pollen and spores can enter the tanks via dust (Artiola *et al.* 2012).

The impact of size is highlighted by Miyagi *et al.* (2017), who explain the causal relationship between a mismatch in tank size and water demand with low turnover and stagnation, and the resulting loss of residual disinfectant that can, in turn, allow the growth of bacteria. The authors also describe a reason for and effects of the installation of oversized domestic storage tanks in Okinawa. Especially families with children install large roof tanks to secure their water supply. However, when the grown-up children have left the household, the tanks remain despite decreasing water demand. Furthermore, cleaning the water storage tanks at the recommended intervals becomes increasingly difficult for the now-elderly residents and may even be neglected. Due to the observed low concentrations of residual chlorine when the tank size per inhabitant is greater than 1 m^3, the authors recommend smaller tank sizes than this volume.

On-site treatment

However, the operation of domestic storage tanks not only means the filling and emptying regime. For the purpose of maintaining or even improving microbiological water quality and consequently keeping the potential health risk low, an on-site or point-of-use treatment in combination with safe storage in appropriate vessels or tanks is particularly important. Effective treatment of household water includes 'filtration with ceramic filters, chlorination with storage in an improved vessel, solar disinfection in clear bottles by the combined action of UV radiation and heat, thermal disinfection (pasteurisation) in opaque vessels with sunlight from solar cookers or reflectors and combination systems employing chemical coagulation-flocculation, sedimentation, filtration and chlorination', as summarised by Sobsey (2002). Sobsey *et al.* (2003) report on a study performed in settlements in Bolivia and Bangladesh, where storage tanks were operated in combination with a disinfection step. Based on such studies, systems aiming to improve the microbiological quality of collected household water by treatment in combination with a protected storage in appropriate tanks are being implemented worldwide. These include combinations of chlorination and storage in narrow-mouth plastic tanks (Mintz *et al.* 1995, 2001; Reiff *et al.* 1995; Quick *et al.* 1996) and solar disinfection in clear, plastic, disposable beverage bottles prior to in-house storage (Conroy *et al.* 1996, 1999). In Japan, storage tanks (with a capacity of 5 m^3) equipped with an electrolysis system to control bacterial growth have been developed (Ishizuka *et al.* 2006). In this system, chlorine is produced intermittently by electrolysis and acts as a disinfectant to secure the supply of drinking water when long-term storage (up to six months) is necessary. The authors conclude that an application is possible in countries or regions that do not have good water treatment and supply systems, since the electrolysis system can be run by using a normal car battery.

Impact of maintenance and control of domestic storage tanks

The main objective of maintenance and control measures is to guarantee that the water quality after storage is sufficient. Therefore, monitoring should, in any case, include the final point of water supply, i.e., the household tap or spout. For integrated monitoring regarding quality control, in addition, appropriate sample points placed in the entire distribution system are recommended. The control of water quality in domestic storage tanks should focus on the presence of a disinfectant residual and the concentration of bacteria and pathogens. This alignment ensures the timely detection and recognition of health risks and makes effective and timely action possible. The relevance of appropriate monitoring is emphasised by Tokajian & Hashwa (2004), who conclude that 'proper and continuous monitoring of the quality of water stored in domestic tanks would effectively reduce any potential health hazards to consumers in countries employing domestic storage systems to overcome water shortage problems'. Lautenschlager *et al.* (2010) recommend including spot tests for in-house drinking water installations in routine monitoring plans. Due to the authors' reference to Switzerland, this will only be applicable in countries rich enough to afford this monitoring. Schafer (2010) also points out that guidelines for water quality and, based on this, monitoring programmes mainly focus on source water or water leaving treatment facilities, respectively, but not the point of consumption. Consequently, the quality of the consumed water is rather unknown and with it the potential health risk. A test for total coliform bacteria and *E. coli* after cleaning and disinfection of domestic storage tanks is recommended by Artiola *et al.* (2012). In cases where there are long distances between the sampling point and a laboratory for analysis of the water samples, the use of on-site testing kits is reasonable (Bartram & Balance 1996). An important point to produce reliable results is professional handling by trained personnel (Robertson *et al.* 2006).

Maintenance actions are also aimed at avoiding the deterioration of water quality. This primarily means regular cleaning of the tanks and controlling the integrity of all storage tank components. By cleaning, sediments, biofilms and other deposits are removed and, with this, microorganisms and their habitats, as well as other harmful substances. Al-Omari *et al.* (2008) report that cleaning of roof storage tanks in Jordan guarantees low levels of total heterotrophic plate counts. In a study by Schafer (2010), it was found that *E. coli* counts and turbidity were lower in storage tanks that were cleaned at least three times per year compared to storage tanks cleaned less frequently. Cleaning in this study area in Bolivia meant chemical treatment by using bleaching agents, detergents or disinfectants. Aish (2013) also recommends frequent cleaning of drinking water storage tanks in conjunction with proper disinfection to minimise bacterial contamination. In most cases, quality problems arise when cleaning and disinfection are insufficient, which unfortunately is the case very often. Maputo, Mozambique, can be taken as an example. According to Matsinhe *et al.* (2014), the maintenance of domestic storage tanks there 'is often poor, cleaning and disinfection is hardly done'. Moreover, lids were missing, or the tanks were 'locked for long periods, meaning that they were hardly opened for cleaning, maintenance and repair work'.

As described in detail by Artiola *et al.* (2012), cleaning and disinfection procedures depend on the size of the domestic storage tank. The procedures described by these authors include (1) scrubbing and washing of internal surfaces with soapy water and a brush, (2) rinsing and flushing to remove all of the soap as well as all bottom sediments and residues, (3) filling with fresh water with added disinfectant that is left for a sufficient period of time to take effect and (4) drainage of all the disinfected water and refilling with potable water. For large outdoor tanks with full access to the inner surface, the filling step can be replaced by a procedure where sprayers and soft brushes are used to wet all the inner surfaces of a tank with a highly concentrated disinfecting solution. After a certain period of exposure, the surfaces are washed with clean water using a hose and the wash water is drained off. This wash and drain step must be repeated at least once.

In addition, Artiola *et al.* (2012) recommend to include the following aspects in maintenance plans: the replacement of electrical components, inspections of level indicators and control devices, visual inspections of the water surface and the bottom of the tank with respect to pollution and sediment accumulation, inspection of access hatches, inspections with respect to corrosion of tank materials, as well as the identification and repair of leaks.

Impact of stagnation in in-house installations

Apart from these considerations on water quality due to domestic drinking water storage, there is research that focuses on stagnation in in-house installations and its impact on drinking water quality monitored at the water taps. In Brazil, where domestic storage tanks are generally used, the occurrence of *Acanthamoeba* in tap water was investigated by Winck *et al.* (2011) in municipal schools of the State of Rio Grande do Sul. From the 136 tap water samples analysed, 23% tested positive for free-living amoebae. In studies by Mazieri *et al.* (1994) and Levin *et al.* (1991), the occurrence of *Legionella* sp. in tap water of Brazilian hospitals was demonstrated. Since the favourable temperature range for *Legionella* growth is 25–42 °C (ASHRAE Standard 2000), there is a potential for contamination in cold water systems in tropical, subtropical and desert regions. The increase in temperature is supported by stagnation.

Lautenschlager *et al.* (2010) investigated the impact of stagnation periods in domestic water supply systems in Switzerland on the bacterial cell concentrations and the cells' composition. From the determination of the cell concentrations, the adenosine tri-phosphate (ATP) concentrations and heterotrophic plate counts, it was concluded that bacterial growth mainly occurred during overnight stagnation periods of between 8 and 20 hours. After a 5 min flushing of the taps, the cell concentrations and water temperature decreased to levels generally found in drinking water networks.

In Germany, Völker *et al.* (2010) investigated warm water systems inside buildings and found *Legionella* sp., *Pseudomonas* sp., *Enterococcus* sp. and *E. coli*. The number exceeded the threshold values set by the German Drinking Water Ordinance (TrinkwV 2001).

CONSIDERATION OF WATER QUALITY WITH RESPECT TO DOMESTIC STORAGE IN NATIONAL AND INTERNATIONAL LEGISLATION

With the knowledge of the aspects and relationships regarding water quality in drinking water storage tanks as discussed above, it is of special interest how this knowledge is incorporated in national and international legislation relevant for the use of these facilities for water supply. For this purpose, numerous standards, guidelines and specific recommendations of local authorities were comprehensively reviewed with respect to presence and applicability of demands and requirements that support or focus on the prevention of water quality deterioration during domestic storage. However, a direct assessment of the usefulness of the reviewed standards and guidelines in terms of water quality in domestic drinking water storage tanks only was possible to a limited extent, since drinking water storage in on-site water tanks and cisterns is mostly taken into account in a more general way instead of specific consideration.

WHO guidelines

The World Health Organization (WHO) Guidelines for Drinking Water Quality serve as a basis for national water quality standards or even as the only standard for drinking water quality. Since the WHO guidelines represent a 'framework for safe drinking-water' with the purpose of providing a 'preventive, risk-based approach to managing water quality' (WHO 2011), they do not include any detail with relation to domestic storage of drinking water. Consequently, authorities can only have an influence on domestic water storage by monitoring and controlling drinking water quality and public health. In such cases, guidance for appropriate drinking water storage is rather reactive than proactive.

North America

To be applied for water storage tanks in the USA, the American Water Works Association (AWWA) published the following standards, including:

- minimum requirements for the design, construction, inspection and testing of
  - new welded carbon steel tanks for the storage of water at atmospheric pressure (ANSI/AWWA D100-11)
  - new cylindrical, factory-coated, bolted carbon steel tanks for the storage of water (ANSI/AWWA D103-09)
  - composite elevated tanks that use a welded steel tank for watertight containment and a single pedestal concrete support structure (ANSI/AWWA D107-10)
  - wire- and strand-wound, circular, prestressed concrete water-containing structures (ANSI/AWWA D110-13)
  - concrete tanks using tendons for prestressing (ANSI/AWWA D115-06)
  - thermosetting fibreglass-reinforced plastic (FRP) tanks for the storage of water (ANSI/AWWA D120-09)
  - bolted above-ground thermosetting fibreglass-reinforced plastic (FRP) panel-type tanks for potable water storage (ANSI/AWWA D121-12)
- coating systems for coating and recoating the inside and outside surfaces of steel tanks used for potable water storage in water supply service (ANSI/AWWA D102-14)
- automatically controlled, impressed-current cathodic protection systems intended to minimise the corrosion of interior submerged surfaces of steel water storage tanks (ANSI/AWWA D104-11)
- sacrificial anode cathodic protection systems intended to minimise the corrosion of interior submerged surfaces of steel water storage tanks (ANSI/AWWA D106-16)

Thus, concrete and detailed guidelines to guarantee drinking water quality during domestic storage are thus available and practically applicable.

In Canada the B126 SERIES-13 – Water cisterns standard is intended to ensure the proper design, installation and location of drinking water storage systems to help prevent health risks from contaminated drinking water and accidents. As highly concentrated excerpts of this standard, fact sheets exist (e.g., Scott & Corkal 2006; Manitoba Conservation & Water Stewardship 2014) to provide basic information on how to maintain safe drinking water in onsite storage systems (tanks and cisterns). These fact sheets include information on construction material, basic design components, placement and installation, maintenance, disinfection and cleaning, inspection and monitoring.

South America

Besides the general limits and requirements of the Brazilian Ordinances (Brazil 2004, 2017), cold water installations in buildings, including drinking water storage tanks, are addressed in the standard NBR 5626 (ABNT 1998), a technical standard from the Brazilian Association of Technical Standards (ABNT). The NBR standard includes recommendations on the dimensioning and maintenance of storage facilities and installations inside buildings, which may have an impact on water quality and can therefore contribute to prevent deterioration of drinking water quality. NBR 5626 recommends as the best solution a combined supply system, in which both water taps outside buildings and storage tanks are connected to the public distribution system, whereas taps inside buildings are supplied from the individual in-house storage tanks. This standard defines how the flow rate and the pipe diameter must be calculated. However, it does not describe exactly how the tank volume needs to be determined. It is recommended to consider the demand pattern, although this is often unknown. Consequently, the common volume stored is two times the daily consumption. Although some considerations related to the inlet and outlet of storage tanks are given, there is no technical specification on the design, construction or operation of storage tanks in order to prevent stagnation in practice.

Europe

In Germany, the continuously provided drinking water is almost exclusively stored in central service reservoirs.

Consequently, drinking water supply from small units and non-stationary plants plays a subordinate role. The areas of application are restricted to substitute or emergency supplies due to reconstruction work, failures or interruption of the public supply or even crisis situations and disasters. There is only one guideline that deals with the aspects of drinking water supplied from small units and non-stationary plants: DIN 2001 (2015). Part 3 provides guidance for the supplied water, planning, construction, operation and maintenance of these units. The standard includes, inter alia, system requirements depending on raw water quality, requirements for planning and construction, demands on water abstraction, treatment and supply, requirements for weather protection and energy supply, as well as requirements for the materials in contact with water. Quality aspects are also addressed. The quality requirements of the Drinking Water Ordinance (TrinkwV 2001) apply. In the case of an emergency supply, the provisions of the law on securing water supply and associated ordinances (WasSiG 2005) shall be taken into account. According to this law, water must be such that consumption and use does not constitute a health risk. The water must be free of substances in a concentration harmful to health. In contrast to the limits given in the Drinking Water Ordinance (TrinkwV 2001), the standard values of selected chemical parameters aim at a limited period of a maximum of 30 days.

In the United Kingdom, the Water Supply (Water Fittings) Regulations from 1999 consider the general maintenance of quality, the positioning and isolation of storage tanks, the capacity as well as materials and design aspects to avoid overflow and stagnation. Inspection and redundancy are not included in this standard. With the implementation of the Water Supply (Water Fittings) Regulations (1999) (1999 No. 1148), a requirement arose that cisterns should be covered with a ‘rigid, close fitting and securely fixed cover which is not airtight, but which excludes light and insects from the cistern’. Unfortunately, the regulations are not retrospective. This means that they do not have to be applied to storage cisterns that were installed before this legislation was set into power (Kilvington *et al.* 2004).

Africa

For African countries, to our knowledge, only the WHO guidelines as general water quality requirements are available. There is neither a legislation nor a specific standard or guideline available that focuses on the use of domestic drinking water storage and related aspects of drinking water quality.

Middle East and Asia

The Omani Standard No. 8/2012 (DGSM 2012) only focuses on general water quality requirements. There is no standard regarding criteria for water quality in domestic storage tanks or other aspects of water distribution and storage.

To guarantee high drinking water quality in domestic storage tanks, Japanese law requires the inspection and cleaning of tanks larger than 10 m^3 at least once a year, with notification of water supply quality (Miyagi *et al.* 2017). A correct management is also required for storage systems smaller than 10 m^3, but notification is not enforceable in such cases. These legal regulations are, furthermore, complemented by a notification regarding handling procedures for private water supply facilities (Japan Ministry of Health Labour & Welfare 1985).

CONCLUSIONS AND RECOMMENDATIONS

Domestic drinking water storage is required:

1. when there is no piped water supply,
2. when available raw water resources cannot be used due to contamination and/or missing treatment,
3. when there is an intermittent water supply,
4. to ensure water supply in cases of temporary restrictions due to emergency situations (e.g., power blackouts, earthquakes or accidental contamination).

Since storage always means a deterioration in water quality, the use of domestic drinking water storage tanks poses a serious threat to human health and consequently requires special efforts with respect to tank design, operation and maintenance, as well as quality control. The deterioration of water quality due to domestic storage can be attributed to long residence times of the water in such systems in conjunction with poor mixing. Consequently, the disinfectant residual will decrease, which may result in microbiological growth. Moreover, corrosion processes will be supported, as well as the leaching of compounds from the materials in contact with the drinking water. Further causes and factors for changes in drinking water quality are the formation of disinfection by-products due to reactions of the disinfectant chlorine with the material of the tank, the development of taste and odour, increases in pH and temperature, the precipitation of iron and manganese, the formation of hydrogen sulphide, nitrification processes, sediment build-up, and the introduction of contaminants. The major conclusion is that storage is always accompanied by an increasing risk of contamination and quality deterioration.

In order to minimise the impacts on water quality, measures with respect to the design and construction, operation and maintenance of drinking water storage facilities must be taken. For drinking water suppliers, it would be advantageous for these measures to be offered and described in national or international standards and guidelines. However, notably in countries where domestic drinking water storage tanks are intensively used, the available and applicable standards mainly focus on the water quality parameters that have to be met, but do not give advice or specifications on aspects of design and construction or the operation and maintenance of these special storage facilities or storage systems in general. Consequently, an international standard, similar to the Guidelines for Drinking Water Quality of the World Health Organization (WHO 2011), but regarding the aspects mentioned above, is recommended.

With respect to design and construction, an international standard should address possibilities for dealing with the specific disadvantages of drinking water storage. Advice should be given on the installation of baffles, recirculation and pumping systems, inflow diffusers, mechanical mixers, risers on outlet pipes, as well as aeration and ventilation systems. Moreover, the coverage and sealing of storage tanks needs consideration. The same applies to suitable sizing, the location of inlet and outlet pipes, and the provision of overflow and drainage pipes. In addition, the selection of the materials in contact with the drinking water should be taken into account.

Regarding the operation of domestic drinking water storage tanks, the turnover and exchange rate, respectively, and the fluctuation of the water level must be considered. In addition, water treatment needs to be addressed to reduce biodegradable organic compounds and the ammonium concentration as well as the bacterial input, and to prevent corrosion and the loss of disinfectant residual. In water distribution systems, the pump operation is automatically controlled on the basis of storage tank levels, and distribution pressures relative to programmed set points: as consumption increases, the levels and pressures drop, and pumps are turned on (Jentgen *et al.* 2007). According to Clark *et al.* (1993), the water level in most domestic reservoirs does not vary a great deal, remaining at 70–75% of the tank capacity. This analysis underscores the importance of concrete specifications regarding the fluctuation of the water level in a drinking water storage tank. The specifications should also include situations where several tanks interact. In Brazil, for example, it is common for hydraulic systems to consist of a street-level storage tank connected to another storage tank on the roof, which distributes the water to each floor of the building. Such systems are usually operated by pump control. Whenever the water level of the roof tank changes, it is refilled from the street-level tank with a float switch control. Consequently, the water level in the storage tanks may not change significantly. Moreover, for domestic drinking water storage tanks, an appropriate fluctuation of the water conflicts with the purpose of those storage facilities, which is to guarantee an uninterrupted supply for households within periods of non-supply from the main public water stations. Therefore, the determination of the minimum reserve necessary to be maintained in the tank and the pumping regime are of special importance. For example, pumping could be performed at longer time intervals and last longer compared to current practices, where pumps are switched on and off again and again for short periods of time.

For the maintenance of domestic drinking water storage tanks, advice and specifications can be based on Technical Note No. 3 of the World Health Organization (WHO 2005) on 'Cleaning and disinfecting water storage tanks and tankers'. Maintenance aspects should include cleaning, disinfection and inspection procedures. The publication by Artiola *et al.* (2012) represents a good basis for maintenance guidance. It seems reasonable to transfer the measures mentioned and explained there into an appropriate standard.

With respect to the application of national and international standards and guidelines, it is of special importance to make binding specifications about who is responsible for compliance and verification. In this context, it is of special importance to take the water quality at the consumers' taps into account. This brings the owners of houses into play, since they are mostly responsible for the water supply within a building. This means that the responsibility for many actions essential to control drinking water quality in buildings is often outside the mandate of the local drinking water supplier. Moreover, even if the responsibilities for managing building water supplies are clear, awareness and application of drinking water standards and guidelines are often limited. Consequently, initiating and setting up educational supporting programmes are considered as necessary.

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