Potential impacts of changing supply-water quality on drinking water distribution
A review

Liu, Gang; Zhang, Ya; Knibbe, Willem Jan; Feng, Cuijie; Liu, Wentso; Medema, Gertjan; van der Meer, Walter

DOI
10.1016/j.watres.2017.03.031

Publication date
2017

Document Version
Final published version

Published in
Water Research

Citation (APA)
Liu, G., Zhang, Y., Knibbe, W. J., Feng, C., Liu, W., Medema, G., & van der Meer, W. (2017). Potential impacts of changing supply-water quality on drinking water distribution: A review. *Water Research*, *116*, 135-148. https://doi.org/10.1016/j.watres.2017.03.031

Water Research 116 (2017) 135–148

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Review

Potential impacts of changing supply-water quality on drinking water distribution: A review

Gang Liu [a, b, *], Ya Zhang [c], Willem-Jan Knibbe [a], Cuijie Feng [b], Wentso Liu [c], Gertjan Medema [b, d], Walter van der Meer [a, e]

[a] Oasen Drinkwater, PO BOX 122, 2800 AC, Gouda, The Netherlands
[b] Sanitary Engineering, Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA, Delft, The Netherlands
[c] Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL, 61801, USA
[d] KWR Watercycle Research Institute, P.O. Box 1072, 3430 BB, Nieuwegein, The Netherlands
[e] Science and Technology, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands

A R T I C L E I N F O

Article history:
Received 10 November 2016
Received in revised form
17 February 2017
Accepted 15 March 2017
Available online 19 March 2017

Keywords:
Drinking water distribution
Water quality switching
Destabilization
Transition effects
Evaluation framework

A B S T R A C T

Driven by the development of water purification technologies and water quality regulations, the use of better source water and/or upgraded water treatment processes to improve drinking water quality have become common practices worldwide. However, even though these elements lead to improved water quality, the water quality may be impacted during its distribution through piped networks due to the processes such as pipe material release, biofilm formation and detachment, accumulation and resuspension of loose deposits. Irregular changes in supply-water quality may cause physiochemical and microbiological de-stabilization of pipe material, biofilms and loose deposits in the distribution system that have been established over decades and may harbor components that cause health or esthetical issues (brown water). Even though it is clearly relevant to customers' health (e.g., recent Flint water crisis), until now, switching of supply-water quality is done without any systematic evaluation. This article reviews the contaminants that develop in the water distribution system and their characteristics, as well as the possible transition effects during the switching of treated water quality by destabilization and the release of pipe material and contaminants into the water and the subsequent risks. At the end of this article, a framework is proposed for the evaluation of potential transition effects.

Contents

---

* Corresponding author. Room 4.51, Stevinweg 1, Building of CiTG, TU Delft, 2628 CN, Delft, The Netherlands.

E-mail addresses: g.liu-1@tudelft.nl, gang.liu@oasen.nl, ganghow@gmail.com (G. Liu).

http://dx.doi.org/10.1016/j.watres.2017.03.031

1. Introduction

1.1. Drinking water supply system

Drinking water treatment makes water potable by removing contaminants present in the source water. Depending on the contaminants present, different technologies and their combinations can be used for drinking water production (Moel et al., 2006). In both developing and industrialized countries, a growing number of contaminants are entering water supplies due to human activity: heavy metals, pharmaceuticals, endocrine disruptors, perfluorinated compounds, flame retardants or biocides (Shannon et al., 2008; Schriks et al., 2010; Ternes et al., 2015). Public health and environmental concerns drive efforts to tighten water quality regulations (WHO, 1996; WHO, 2004; WHO, 2011; Qu et al., 2012) and further treat waters previously considered clean. These efforts have greatly promoted the development of water treatment science and technology and the upgrading of treatment plants over several decades (Pinheiro and Wagner, 2001; Miner, 2002; Shannon et al., 2008).

The treated drinking water is delivered to individual dwellings, communal buildings and other customers' through pressurized distribution networks (DNs), including drinking water distribution systems (DWDSs) and premises plumbing (Mays, 1999; Ainsworth, 2013). Those DNs - consisting of pipes, pumps, valves, storage tanks, reservoirs, meters, fittings, and other hydraulic appurtenances transport the drinking water from a centralized treatment plant or well to customers' taps (Moel et al., 2006; NRC, 2006). In general, DWDSs are buried underground, range in length of tens to several hundreds of kilometers (totaling 0.4 million kilometers in the Netherlands and1.6 million kilometers in the U.S.) with varying diameters and materials (metals, plastic, and cement pipes) in multi-loops (Verberk et al., 2007; Vreeburg, 2007; AWWA, 2012). Premise plumbing refers to the parts of DN that connect a building to the water main pipe and the pipes inside buildings, which are characterized by high surface area to volume ratio, long retention times, warmer temperature, and close contact with water (NRC, 2006; Nguyen et al., 2012; Wang et al., 2013; Proctor and Hammes, 2015). The DNs is the final barrier that protects drinking water from contaminants during distribution and ensures the quality of the supplied product (Mays, 1999). For the drinking water provision, distribution is as important as production, because the quality of tap water can only be as good as the condition of the pipes it flows through (Moel et al., 2006; Misko et al., 2010; Ainsworth, 2013).

1.2. Water quality stability and deterioration during distribution

There is a broad consensus that the ultimate goal of drinking water supply should be seen as providing good quality at the customer's tap rather than only at the point it leaves the treatment plant. The treated drinking water enters the distribution system containing physical loads (particles), microbial loads (cells) and nutrient loads (organic and inorganic nutrients) (Liu et al., 2013c; Prest et al., 2016). Given the occurrence the long retention times (also referred as “water age”) especially at the dead-end nodes (Ainsworth, 2013) and in premises plumbing the simultaneously impact of physiochemical and microbiological processes can result in the deterioration of the quality of the water that reaches customer's tap compared to the original water produced at the treatment plant (Vreeburg and Boxall, 2007; Liu et al., 2013c; Proctor and Hammes, 2015). Such water quality deterioration has been observed and reported worldwide: for example in higher turbidity and particle counts (Vreeburg et al., 2004; Verberk et al., 2007; Liu et al., 2016), larger cell numbers (Van der Kooij, 1992; Hammes et al., 2010; Liu et al., 2016), and greater presence of selected indicator micro-organisms (van der Wielen et al., 2016) at taps compared to treatment plants. In extreme cases, discolored water (also reported as dirty water, red water) (Sly et al., 1990; Vreeburg and Boxall, 2007; Li et al., 2010) was observed at the taps.

Those observed quality deteriorations are related to the accumulation of distribution network harbored material (DNHM) and ongoing processes such as pipe corrosion, biofilm matrix formation and detachment, loose deposit accumulation and resuspension, which occur in the DN pipes over decades (Lee et al., 1980; LeChevallier et al., 1987; Van Der Wende et al., 1989, Smith et al., 1997; Gauthier et al., 1999; Chaves Simões and Simões, 2013, Liu et al., 2014) (Fig. 2A). Consequently, to guarantee the delivery of high quality water to customers, the concept of water quality stability was proposed and set. The standards included: re-suspension potential measurements (RPM, turbidity < 0.8NTU) for physical stability (Vreeburg et al., 2008); a saturation index (SI, -0.2 to 0.3) for chemical stability (Verberk et al., 2009); and assimilable organic carbon limit (AOC, < 10 μg C/l for unchlorinated water) for biological stability (Van der Kooij, 1992). Achieving these stability standards has become another important driving force behind the upgrading of treatment processes (Pinheiro and Wagner, 2001; Miner, 2002; Qu et al., 2012).

1.3. Irregular supply-water quality changes and transition effects

At the operational level, the tightening of water quality regulations, the development of water purification technologies, and the awareness of the deterioration of water quality have led to the upgrading of treatments at water utilities and thus to a better-quality treated water at treatment plants worldwide (Pinheiro and Wagner, 2001; Miner, 2002). This upgraded treatment constitutes a cause of irregular changes in supply-water quality; other causes are the use of alternative source water (Zhang, 2009; Li et al., 2010; Utecht and McCoy, 2016) and variations in disinfectant strategies (Wang et al., 2014). Irregular changes therefore refer to situations that are qualitatively different from the regular operation of a DWDS. Accordingly, the accompanying transition effects refer to the often dramatic impact of these changes in the networks, and particularly on distribution network-harbored material (DNHM).

Under regular operations, DNs can function as sinks (contaminant accumulation, as in particle sedimentation) or sources (contaminant release, as in loose deposit resuspension) of trace contaminants in the bulk water (Vreeburg and Boxall, 2007; Liu et al., 2014; Makris et al., 2014). The material retained in DNs (pipe scales, biofilm matrix and loose deposits) develops and stabilizes under the historical environmental conditions when the supply water is continuously flushed out. If destabilized and mobilized, this DNHM will become a major source of contaminants, which can impact supply-water quality. The transition effects are defined as the physiochemical and microbiological water quality problems caused by the destabilization and mobilization of DNHM and its release into the bulk water. The transition effects are in turn the consequence of irregular changes in supply-water quality. Examples of transition effects include the water discoloration observed in 80% of the distribution area of Beijing, China, when the quality of supply water was improved in 2008 (Li et al., 2010); and the recent Flint (Michigan, U.S.) drinking water crisis, in which elevated lead levels were measured in children following changes in source water and treatment (Hanna-Attisha et al., 2016).

Transition effects have so far been poorly documented and their quantitative definition, based on measured parameters, requires further research on integral evaluation and a better understanding of the composition and characteristics of the corresponding DNHM. Supply-water quality is of course subject to regular fluctuations related to daily variations in source-water quality and treatment performance. In addition, there may also be periodic changes, such as operationally related changes (filter backwash), seasonal changes of surface-water quality, annual switching of water sources, and changes in the mixing ratio of multiple water sources. All of these periodic changes in supply-water quality fall under the rubric of regular changes, and are part of the environment in which the DNHM has developed and stabilized in the distribution system (biofilm, pipe scales and biofilm matrix). Such regular changes are not considered in this review paper because they do not lead to DNHM destabilization and mobilization.

1.4. Objective of this review

Water utilities pay close attention to the safety and quality of drinking water during distribution, focusing on various aspects and situations, such as pressure transients, cross-connection, deterioration of buried infrastructure, permeation and leaching, nitrification, microbial growth and biofilm, water storage facilities, water age, and pipe repair. Even the accumulation of chemical and biological material in DWDSs have become a widely accepted target of attention. However, the transition effects which can lead to esthetic and health problems have been neglected. The available literature on the characteristics of the material developed and contaminants harbored in DNs and the potential transition effects following the switching of supply-water quality were reviewed for this article, which also incorporates the authors' first-hand knowledge and research. The particular object of this critical review is development and destabilization of DNHM. In the conclusion, we propose a framework for the evaluation of potential transition effects before switching supply-water quality. The discussion emphasizes water quality improvements, but the review, knowledge, and proposed framework could also be applied to other irregular water quality changes produced by a variety of causes.

2. Material accumulation in DNs and its characteristics

Four elements have been defined and studied in DNs: 1) the bulk water that flows through the pipe networks; 2) the suspended solids which are particulate matter that is suspended in the water and transported through the network; 3) the pipe surface with the associated material, e.g., biofilm, extracellular polymeric substance (EPS), scaling; and 4) the loose deposits which are particulate matter that has accumulated and is retained in the pipes (Liu et al., 2014; Proctor and Hammes, 2015; Liu et al., 2016). The materials in the first two elements only present in the system for a relatively short period of time, i.e., the period it takes for the water to flow through. Additional forces, such as bio-adhesion, weight, and chemical bonds, effectively counter the regular hydraulic forces, resulting in the retention of the material over a longer period of time (i.e., years), under the last two elements.

Physically, the force can be the weight of suspended solids, if they become large and heavy enough due to (bio-)aggregation and precipitation (Vreeburg and Boxall, 2007) to the point that, once settled, they cannot be resuspended by the hydraulic turbulence in a DN; one example would be the sand and activated carbon particles collected from field networks as loose deposits (Camper et al., 1986; Brazos and O'Connor, 1996; Liu et al., 2014), as shown in Fig. 1B. Chemically, the forces can be chemical bonds of corrosion products, pipe scales (passivation layers), and association of iron-bonded oxidation products (e.g., ionic attractive force, hydrogen bonding, van der Waals interactions, electrostatic attractive forces, repulsive forces) (Mceneill and Edwards, 2001; Lytle et al., 2004; Flemming and Wingender, 2010; Peng et al., 2010) (Figs. 1C and 2). Microbiologically, the viscous forces between the adhering bacteria and substratum surfaces can be attributed to the self-produced extracellular polymeric substances which can help to harbor more material to form a biofilm matrix (Beech and Sunner, 2004; Flemming and Wingender, 2010; Chen et al., 2014; Fish et al., 2016), as shown in Fig. 1D and E and Fig. 2. The extracellular mineral scaffolds (bio-mineralization) contribute to the development of the structural organization of the biofilm matrix (Oppenheimer-Shaanan et al., 2016).

2.1. Drinking water distribution pipes: material used and aging problems

2.1.1. Pipe material

The pipe material is important because of its influence on water quality and its relationship to energy efficiency (Broo et al., 2001). For example, the release of lead will pose health risks for consumers (Rabin, 2008); the release of nutrients from rubber material will promote microbial growth in the distribution system (Broo et al., 2001); the presence of tuberculation will make the pipes rough inside, resulting in increased pumping costs and, in some extreme cases, leakages (Mceneill and Edwards, 2001). Worldwide, the traditional inorganic pipe materials are being replaced by organic pipe materials, even if the use of stainless steel is

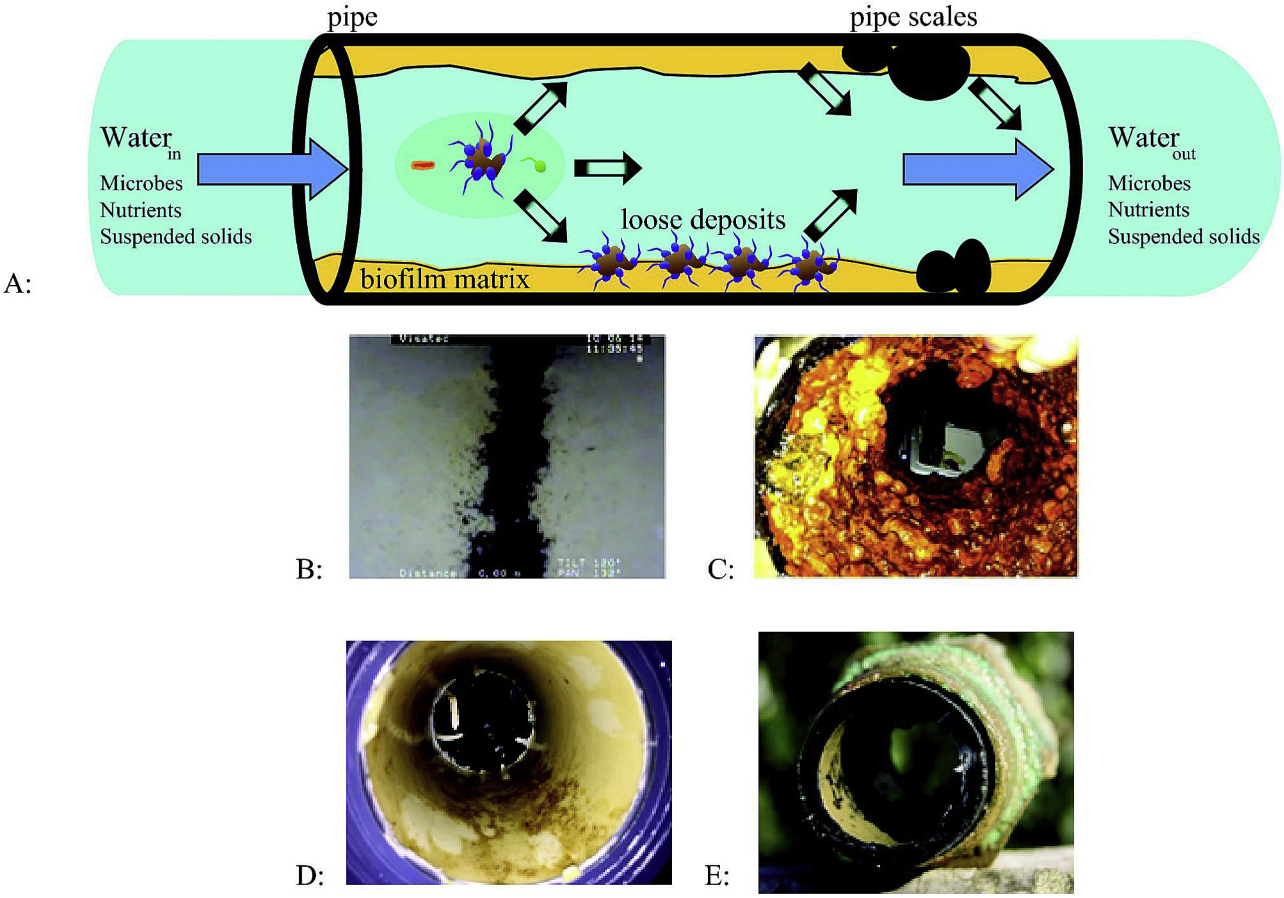

Fig. 1. The distribution system as a reactor and the micro-environments formed in the supply pipes over the timespan of years. A) material and phases developed in distribution pipes; B) inner view of a distribution pipe under normal operation (D = 110, PVC, loose deposits on the bottom, service time = 20 years) (Liu et al., 2016); C) CI pipe with scaling (D = 100 mm, service time = 20 years) (Ren et al., 2015); D) PVC pipe with bio-fouling (D = 110 mm, service time = 20 years); E) HDPE pipe with associated material (D = 25 mm, service time = 20 years). (The white surface in D and black surface in E are the surfaces after the removal of attached material.)

increasing. Iron pipes with interior cement-mortar lining and exterior plastic protection, as well as other cement-based materials, are still being installed (Broo et al., 2001). Although lead and asbestos cement-based material are being phased out and replaced, there are still substantial lengths being used in operational distribution systems (Rabin, 2008). An overview of the pipe material used in distribution networks in the Netherlands from 1955 to 2014 is shown in Fig. 3 (Vreeburg, 2007; Geudens, 2015).

2.1.2. *Aging pipes*

The design lifespan of distribution pipes, regardless of the material used, is 65–90 years (AWWA, 2012). The majority of the

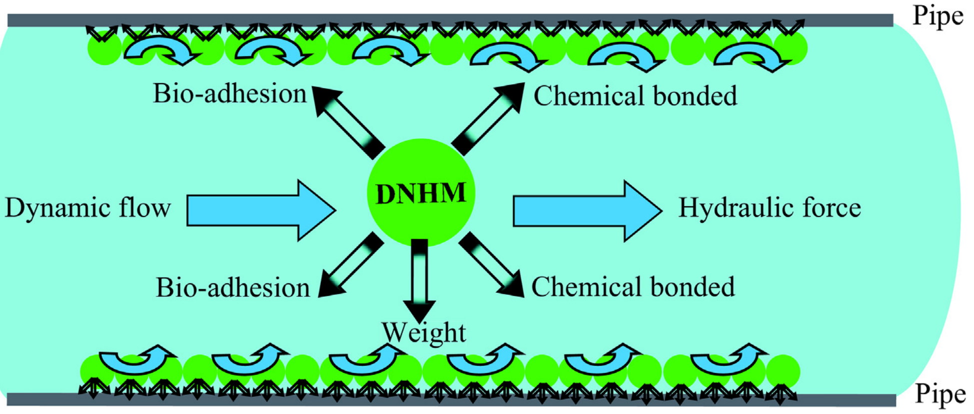

Fig. 2. Illustration of the balance of forces that allows material to be retained and developed in distribution networks in the form of distribution network-harbored material (DNHM).

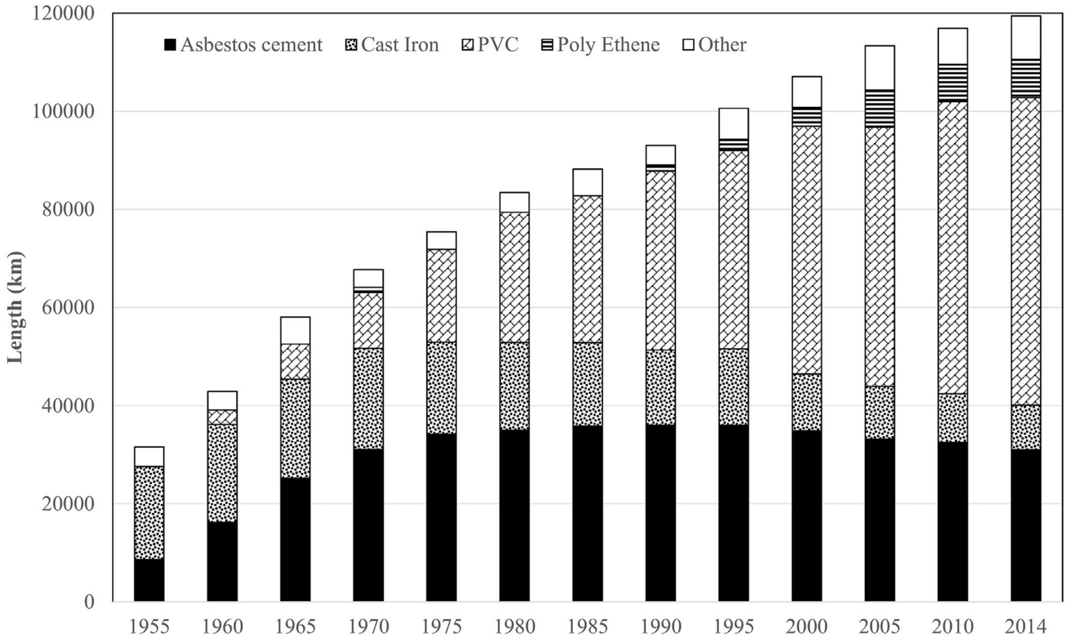

Fig. 3. Material used in distribution network in the Netherlands over time (1995–2014) (Geudens, 2015).

distribution pipes in developed countries (e.g., the U.S.) will reach the end of their lifespan in the coming 20 years (Moe and Rheingans, 2006). Therefore, a new era of water industry for pipe repairing and replacement is beginning. For the U.S., the estimated replacement cost will be at least $1 trillion in the coming 20 years (AWWA, 2012; Qureshi and Shah, 2014).

The challenges of aging pipes:

1) Aging pipes are more vulnerable to contaminants (Moe and Rheingans, 2006; AWWA, 2012; Qureshi and Shah, 2014). As recorded by a Midwestern water utility in the U.S., pipe breaks sharply increased from 250 breaks/year in 1970 to 2200 breaks/year in 1989 (Moe and Rheingans, 2006). The challenge is especially serious in developing countries where maintenance of the distribution system infrastructures is lacking due to inadequate resources. Water loss level (as a percentage of water supplied) for developed countries, middle-income countries, and developing countries, are 5–24%, 15–24% and 25–45% respectively (Moe and Rheingans, 2006). In cases of low or negative pressures in the pipes, the contaminated water, wastewater, and other contaminants surrounding the pipes can be drawn into the pipes through cracks. In such cases, even if measures are taken to improve water quality at the treatment plant, customers will not fully benefit from them.
2) The material accumulated in a distribution system (biofilm, scaling and loose deposits) develops over time. Therefore, the older the pipes the greater the accumulation of material in the form of pipe scales, biofilm matrix and loose deposits (Makris et al., 2014).
3) Because the long design lifespan and limited accessibility, the DN consists of pipes installed at different times. As a result, it is a variegated reflection of both past and present knowledge, strategies, technologies, and operations related to drinking water distribution.

2.2. Loose deposits

Despite the application of different treatment processes, certain (varying) amounts of particles remain present in treated and distributed water. These particles may be particles present in the raw water that were not removed by the treatment (Clark et al., 1992; Tobiason et al., 1993), or may have been introduced during the treatment for example, powdered activated carbon particles (Camper et al., 1986; Brazos and O'Connor, 1996) or aluminum micro-flocs (Gauthier et al., 2001). Particles can also be generated during distribution as a result of precipitation and flocculation processes, biofilm detachment and corrosion phenomena (Sly et al., 1990). While travelling in distribution systems, the particles can be transported throughout the network by the water flow or be deposited as loose deposits which can be re-suspended by daily hydraulic turbulence, depending on their characteristics and the flow conditions (Vreeburg and Boxall, 2007; Liu et al., 2013c; Liu et al., 2014; Liu et al., 2016).

Sedimentation and resuspension are two-way continuous processes until the loose deposits have accumulated to a degree that they can no longer be resuspended by daily hydraulic variations. Then, niches are created characterized by a high surface area and micro-environments that may lead to the formation of biofilm and the accumulation of different elements (Ca, Fe, Mn, and As) (Liu et al., 2014). Even anoxic and anaerobic conditions can occur in such circumstances. Gradually, the accumulated material may develop into pipe scales (Makris et al., 2014).

Therefore, the presence and development of loose deposits involves a combination of physical and bio-chemical processes. Amounts of loose deposits ranging from 30 to 24,500 mg/m have been found in distribution systems worldwide (Barbeau et al., 2005; Carrière et al., 2005; Vreeburg et al., 2008; Liu et al., 2014) containing high amount of biomass (Zacheus et al., 2001; Liu et al., 2013c; Liu et al., 2014), organic matter (Gauthier et al., 1999; Lehtola et al., 2004) and inorganic matter (Echeverría et al., 2009). Previous studies have mainly focused on discoloration problems (Vreeburg and Boxall, 2007). Recently, however, loose deposits have attracted renewed attention due to the high volume and diverse of the microbes they harbor (Liu et al., 2013c; Liu et al., 2014; Proctor and Hammes, 2015; Prest et al., 2016; van der Wielen and Lut, 2016). The reported composition of loose deposits is summarized in Table 1.

2.3. *Biofilm matrix*

Biofilm refers to the structures formed by microorganisms via adhesion, nucleation, and growth on surfaces. Specifically, biofilm is defined as matrix-enclosed bacterial populations adhering to each other and/or to surfaces or interfaces, including microbial aggregates and floccules and populations within the pore spaces of porous media (Costerton et al., 1995). In most biofilms, the microorganisms account for less than 10% of the dry mass, whereas the matrix can account for over 90%. The matrix is extracellular material, mostly produced by the organisms themselves, which consists of a conglomeration of different types of biopolymers and is known as EPS (Flemming and Wingender, 2010). In addition to EPS, the mineral scaffolds (bio-mineralization) also play a crucial and conserving role in the biofilm, providing resistance to environmental stresses and increasing the overall fitness of the microbial community (Oppenheimer-Shaanan et al., 2016). The research has found that, the biomineralization media promotes the resilience of biofilm and limits the penetration of antibacterial agents into biofilms.

In DNs, the inner surfaces of the pipes support biofilm formation. The biofilm establishes itself through the formation of cell aggregates and attaches itself to the surface with the aid of the EPS. The self-produced EPS, in return, accumulates organics and inorganics in the biofilm matrix (LeChevallier et al., 1987; Van Der Wende et al., 1989; Costerton et al., 1995; Flemming and Wingender, 2010; Wang et al., 2012b). The pipe-wall biofilm harbors 10^4-10^8 cells/cm^2 (Liu et al., 2013c; Makris et al., 2014; Proctor and Hammes, 2015) and the associated organic and inorganic matter (Peng et al., 2010; Peng and Korshin, 2011; Liu et al., 2014), which include heavy metals (e.g., As) (Schock et al., 2008; Liu et al., 2014) and (opportunistic) pathogens have (Norton et al., 2004; Pryor et al., 2004; Vaerewijck et al., 2005; Feazel et al., 2009). The reported composition of biofilm matrix is summarized in Table 2.

2.4. *Pipe scales*

The presence of scales (passivation layers, corrosion products, and associated contaminants) in water pipes has attracted both scientific and societal interest (Renner, 2008; Schock et al., 2008; Makris et al., 2014). Scales form on drinking-water pipes as a result of a combination of in situ processes or upstream corrosion, post-treatment deposition of solid materials, and deposits formed through the reaction of the treated water and the pipe material with natural substances that pass through the treatment process (Schock et al., 2008). The pipe scales formed in DNs consist mostly of tubercles formed via precipitation and re-precipitation mechanisms of pipe-originating nucleating elements, e.g., aluminum (Al), copper (Cu), iron (Fe), and lead (Pb) (Makris et al., 2014). Their formation has been primarily attributed to electrochemical surface corrosive phenomena, and to the dissolution and precipitation of metal salts in the pipe networks (Mceneill and Edwards, 2001; Makris et al., 2014).

Various types of pipe scales have been found, with metal pipes being especially susceptible (Prest et al., 2016). The nature and composition of scales in depend on both the water quality and the pipe material. Thin manganese oxide was found in PVC pipes, and was much easier to detach compared to metal pipe scales (Cerrato et al., 2006). In addition, the water source (Yang et al., 2012) and disinfectant residuals (Wang et al., 2012a) present in distributed water are also important factors in the reported variations in formed pipe scales. Lead (Pb) and copper (Cu) pipes rely upon the chemistry of supply water to develop passivating or immobilizing solid phase on the pipe surfaces (Schock et al., 2008). Other trace elements in water, such as aluminum (Al), radium (Ra) and arsenic (As), also accumulate in scales on DN pipes. The most commonly observed and studied pipe scales are alkaline/calcareous scales, iron scales, aluminum scales, corrosion-induced asbestos scales, and lead scales: these are reviewed and summarized in Table 3.

3. Destabilization of distribution network-harbored material and transition effects

3.1. *Destabilization of DNHM*

Transition effects can occur when the balance of forces are destabilized (Fig. 2) as a result of the irregular changes in supply-water quality. This destabilization leads to the mobilization of

Table 1
Summary of reported information on loose deposits developed and accumulated in DNs (N.A.: not available).

Types	Mass	Biomass	Community Composition	Inorganic Composition	Reference
water flushing		1.0–1.4 × 10^{11} cells/g	N.A.	FeOOH, $CaCO_3$, SiO_2, MnO_2	(Barbeau et al., 2005)
water flushing		2.7 ± 1.3 × 10^8 CFU/g	N.A.	FeOOH, SiO_2, $Al(OH)_3$, $CaCO_3$, MnO_2	(Gauthier et al., 1999)
pigging		*Mycobacterium*: 1.8 × 10^5 CFU/g	targeted at *Mycobacterium* spp.	N.A.	(Torvinen et al., 2004)
pigging		3.0 × 10^2 CFU/g	N.A.	FeOOH, $Al(OH)_3$, MnO_2, $CaCO_3$	(Zacheus et al., 2001)
water flushing	280-1400 mg/m	780-3900 ng ATP/g	Phyla: *Proteobacteria* (77%), *Actinobacteria* (8%), *Chloroflexi* (5%) Genera: *Sphingomonas* (21%), *Alkanindiges* (12%), *Pseudomonas* (9%)	Al, Ca, Fe, Mn, Mg, As	(Liu et al., 2014)
water flushing	10-13650 μg As/g loose deposits	N.A.	N.A.	α-FeOOH, γ-FeOOH, Fe_3O_4, $FeCoO_3$, $CaCO_3$, $Fe_2(AsO_4)(SO_4)(OH)\cdot 7H_20$	(Lytle et al., 2004)

Table 2
Summary of reported information on biofilm matrix developed and accumulated in DNs (N.A.: not available).

Types	Mass	Biomass	Community Composition	Inorganic Composition	Reference
water meter	N.A.	N.A.	Phyla: *Proteobacteria* (98%) Genera: *Methylophilus* (49%), *Acidovorax* (25%), *Lysobacter* (18%), *Sphingomonas* (6%)	N.A.	(Hong et al., 2010)
metal pipes	1.96–140.79 mg/cm^2	10^4-10^6 CFU/cm^2	DCIP: Phyla- *Proteobacteria* (71%), *Cyanobacteria* (7%), *Bacteroidetes* (6%); Genera- *Hyphomicrobium* (28%), *Rhizobium* (9%) GCIP: Phyla- *Proteobacteria* (93%); Genera- *Desulfovibrio* (17%), *Afipia* (8%), *Rhodanobacter* (6%) GSP: *Proteobacteria* (99%), Genera- *Pseudomonas* (43%), *Sphingomonas* (30%), *Limnobacter* (8%), *Delftia* (6%) SSCP: Phyla- *Proteobacteria* (98%), Genera-*Sphingomonas* (72%), *Pseudomonas* (14%)	Mn: 0.2 mg/cm^2 Fe: 9.0 mg/cm^2	(Ren et al., 2015)
plastic pipes	N.A.	90-160 pg ATP/cm^2, 1.2–3.2 × 10^5 cells/cm^2	PVC (chlorinated): Phyla- *Proteobacteria* (99%); Genera- *Brevundimonas* (22%), *Aeromonas* (5%) PVC (unchlorinated): Phyla- Proteobacteria (99%); Genera- Sphingomonas (85%)	Al, Ca, Fe, Mn, Mg, As	(Ren et al., 2015) (Liu et al., 2014)

DNHM and the release of contaminants into the water column.

3.1.1. *Physical destabilization*

Under normal water distribution operations, the phenomenon of discoloration has been attributed to the disturbance of equilibrium between weight and the hydraulic resuspension force (weight = hydraulic force) of loose deposits as a result of sudden hydraulic peaks (increasing hydraulic resuspension force, hydraulic force > weight) (Vreeburg and Boxall, 2007). This principle is also applied, for instance, in resuspension potential measurements (Vreeburg et al., 2008), self-cleaning networks (Vreeburg et al., 2009), hydraulic flushing and loose deposits sampling (Liu et al., 2014). In the event of irregular change in supply-water quality, a similar destabilization can occur: weight decreases through particle dissolution which makes the particles smaller and transferable to the water column. This weight decrease is caused by the destabilization of chemical forces, for example the process in Equation (1) (Moel et al., 2006) and applies to other compounds associated with loose deposits, biofilm matrix and pipe scales.

3.1.2. *Chemical destabilization*

Chemical destabilization is mostly caused by the differences of pH, redox potential, and ion composition in the supply water. This is especially relevant in the remobilization of contaminants bound by pipe scales on metal pipes via desorption and/or dissolution (Peng et al., 2010). For example, large amounts of Fe rich particulates (>300 mg/l) were released after a change was made from non-disinfection to chlorination (Equation (2)) (Reiber and Dostal, 2000); and in another study, the switch in source water caused Fe concentration peaks (>10 mg/l) in the first month because of the presence of high SO_4^{2-} concentration (Equations (3) and (4)) (Wang et al., 2009). Moreover, the replacement of chlorine for monochloramine caused the release of up to 4800 μg/l Pb (Equation (5)) (Edwards and Dudi, 2004). There have been several reports of serious red-water complaints following switches in source water in Southern California, Tucson (Arizona), Tampa (Florida), in the United States; and, in a northern city in China (Brodeur et al., 2006; Tang et al., 2006; Yang et al., 2012). It is believed that the pipe material and supply-water quality determine the characteristics of the pipe scales, and that different pipe scales adapt differently to supply-water quality changes (Yang et al., 2012).

$$\mathrm{CaCO_3 + CO_2 + H_2O \leftrightarrow Ca2^{+} + 2HCO_3^{-}} \tag{1}$$

$$\mathrm{Fe(OH)_3 + 3HCl \leftrightarrow FeCl_3 {+} 3H_2O} \tag{2}$$

$$\mathrm{FeOOH + SO_4^{2-} \leftrightarrow (FeO)_2SO_4 + 2OH^{-}} \tag{3}$$

$$\mathrm{(FeO)_2SO_4 + 2H_2O \leftrightarrow 2Fe^{3+} + SO_4^{2-} + 4OH^{-}} \tag{4}$$

$$\mathrm{Pb_3(CO_3)_2(OH)_2 + 2H^{+} \leftrightarrow 3Pb^{2+} + 2CO_3^{2-} + 2H_2O} \tag{5}$$

3.1.3. *Microbiological destabilization*

Microbial community composition and function can be potentially impacted by the changes in environmental conditions (Allison and Martiny, 2008; Shade et al., 2012). The drinking water microbial communities are sensitive to physiochemical and microbiological water quality changes (i.e., disinfectants, nutrients concentration and composition, inorganic elements), which could

Table 3
Summary of reported information on pipe scales developed and accumulated in DNs (N.A.: not available).

Types	Inorganic Composition	Reference
alkaline/calcareous scales	$CaCO_3$, FeOOH, Fe_3O_4, $Fe(OH)_{12}(CO_3)(H_2O)_3$ or $Fe_6(OH)_{10}(CO_3)(H_2O)_3$, and amorphous Fe phases	(Edwards, 2004; Hodgkiess, 2004)
iron scales	Fe_3O_4, Fe_2O_3, $Fe(OH)_2$, $Fe(OH)_3$, α-FeOOH, β- FeOOH, γ- FeOOH, $FeCO_3$, $Fe_2(CO_3)(OH)_2$, $Fe(OH)_{12}(CO_3)(H_2O)_3$, $Fe_6(OH)_{10}(CO_3)(H_2O)_3$, $Fe_6(OH)_{12}(SO_4)(H_2O)_8$	(Ewing, 1935; Makris et al., 2014)
aluminum scales	Al_2SiO_5 and $AlPO_4$	(Kvech and Edwards, 2001; Kvech and Edwards, 2002)
corrosion-induced asbestos scales	release Ca and asbestos fibers into water	(Axten and Foster, 2008)
lead scales	PbO,PbO_2, $Pb_3(CO_3)_2(OH)_2$, $Pb_5(VO_4)_3Cl$	(Schock, 1980; Schock et al., 2008; Gerke et al., 2009)

induce specific selection pressure on microbial population and drive community diversification (Gomez-Alvarez et al., 2016). For example, the temporary switch between chlorination and chloramination revealed reversible shifts in microbial communities (Hwang et al., 2012; Wang et al., 2014). The response of microbial community composition and function to water quality changes can lead to the microbiological destabilization of DNHM. In extreme case, discoloration (and associated health concerns) may arise; for example, the increased sulfate levels in feed water have caused significant increase of sulfur-oxidizing bacteria, sulfate-reducing bacteria and iron-oxidizing bacteria, which are associated with severe iron corrosion scale release and red water (Yang et al., 2014). In cases of water quality improvements achieved through the input of better source water or upgraded treatment, the available nutrients (e.g., AOC) are reduced, which leads to a decrease in the biological activity in the water and the biofilm (Van der Kooij, 1992; Van der Wielen and Van der Kooij, 2010; Liu et al., 2013b). Furthermore, the lower nutrient concentration and resulting decrease biomass production will also lead to a lower production of EPS and therefore a reduction of the bio-adhesion to the pipe surface (Hsieh et al., 1994; Laspidou and Rittmann, 2002).

In practice, the physiochemical and microbiological destabilization will occur simultaneously. The mineral dissolution as mentioned above in accordance with Equations (1)–(5), will gradually result in the loss of biofilm structure stability (biofilm mineral scaffolds) and a diminished ability of biofilm to resist environmental condition changes, such as those associated with the changes in physiochemical characteristics of the contacting water (Oppenheimer-Shaanan et al., 2016). On the other hand, the loss of biofilm matrix protection will increase the contact of the water with pipe scales, which will further accelerate desorption and dissolution of inorganic contaminants. Meanwhile, the changes of water characteristics will influence the microbial community composition and function that result in bio-destabilization of DNHM. This has been illustrated by the red water events in Beijing, where increased sulfate in supply-water caused microbial community composition changes revealed by increase in sulfur oxidizing bacteria, sulfate reducing bacteria and iron oxidizing bacteria and red water events associated with high iron concentrations (Yang et al., 2014).

3.1.4. Timeline of destabilization processes

Although the issue is obviously important, no study explicitly focuses on the timeline of transition effects. Once destabilization occur, the chemical bonds and forces may be weakened faster than the microbiological forces, owing to the stability provided by the entanglement of biopolymers within the biofilm matrix (Flemming and Wingender, 2010) and to the viscous bond between the attached surface and bacteria (Chen et al., 2014). From the microbial community perspective, changes of community composition were not observed in the studies over short periods (0.2 years on average), but the studies covering significant longer periods (4.9 years on average), indicate that there is a lag in the responses of microbial communities to water quality changes (carbon amendments in this case) (Allison and Martiny, 2008). This means that there will be a lag in the case of bio-destabilization caused by microbial community composition and function changes. Therefore, it is hypothesized that if the transition effects are dominated by chemical destabilization, they will happen and be detected over short periods (i.e., weeks), and evidenced by reported pipe scales dissolution and release (Reiber and Dostal, 2000; Edwards and Dudi, 2004; Wang et al., 2009). In contrast, if the transition effects are dominated by microbiological destabilization, they will only be detected and observed after a longer period of time following the switching (i.e., months to years). This is illustrated by the reported water meter clogging that occurred two years following switching in the supply area of the Oasen drinking water company in the Netherlands, where the distribution system consisted mainly of PVC pipes without corrosion problems (Fig. 4, results not published).

3.2. Problems associated with transition effects

3.2.1. Aged pipes

As discussed above, aging pipes are vulnerable to the intrusion of contaminants because of the increased number of pipe breaks and negative pressure events (Moe and Rheingans, 2006). In the case of transition effects caused by physiochemical and microbiological destabilization, the corrosion, pipe material leaching, and pipe scale release caused by the irregular changes in supply-water composition, may accelerate the pipe damaging process. Paradoxically, the irregular changes of supply-water quality (e.g. improved quality due to switching source water and to upgraded treatment) may raise the risk of contaminant intrusion by increasing the chances of pipe damages.

3.2.2. Tap water quality and safety

Physically, the release of DNHM can cause problems, such as blue water (high copper concentration) (Edwards et al., 2000) and red water (high iron concentration) (Wang et al., 2009; Li et al., 2010; Yang et al., 2014), and in some cases water meter clogging which leads to pressure loss at the taps (Fig. 4). Chemically, the release of heavy metals (Pb, As, Cu, Fe, Mn) may pose health risks to customers (Lytle et al., 2004; Liu et al., 2010; Lytle et al., 2010; Hanna-Attisha et al., 2016; Utecht and McCoy, 2016). Microbiologically, the detachment of biofilm and the release of cells may lead to high cell densities in the water column (Makris et al., 2014). As (opportunistic) pathogenic microorganisms have been frequently detected in biofilms and loose deposits in DNs (Pryor et al., 2004; Torvinen et al., 2004; Feazel et al., 2009; Chaves Simões and Simões, 2013, Falkinham et al., 2015), their release into water column can, in principle, constitute a pathogen mobilization process and pose health risks to consumers (Beuken et al., 2008; Schwake et al., 2016). An overview of reported water quality problems associated with water quality changes is summarized

Fig. 4. Picture of particulate matter that clogged the water meter in Oasen's Hendrik Ido Ambacht supply area.

in Table 4; most problems relate to discoloration and Pb. However, knowledge about the influence of such a transition on microbial ecology and bacteria release is lacking.

It should be realized that material release may occur without being apparent in visible/noticeable changes in color and pressure for the end-users; this could include the leaching of certain compounds or the presence of (opportunistic) pathogens, phenomena that involve even higher risk to customers than do discoloration and pressure loss. For example, the Pb problem in the Flint water triggered a serious public health crisis, as evidenced by high Pb levels in children's blood; these levels were detected before the contamination was recognized (Hanna-Attisha et al., 2016; Schwake et al., 2016). Even if the precise mechanisms are unknown, the field result collected at Flint also suggested high Legionella numbers in premise plumbing: a consequence of the interruption of distribution system corrosion control (Schwake et al., 2016).

Once the transition effects occur, the DN no longer functions as a sink but rather as a source of material leached into water. It is important to quantify the level to which this can impact water quality, in order to decide whether actions should be taken to guarantee the quality and safety of drinking water at customers' taps. This maximal quality deterioration potential (QDP) can be determined by assuming the DNHM is immediately released into the contacting water column, as presented in Equations (6) and (7) below:

$$T_{DNHM} = \sum_{1}^{n} \text{Niches} \tag{6}$$

$$QDP = T_{DSHM}/V_{water} \tag{7}$$

T_{DSHM}: total material harbored by certain length of DN pipe (e.g. 1 m).
Niches: different niches available in DN pipes, e.g. biofilm, loose deposits, pipe scales, etc.
QDP: quality deterioration potential in the selected pipe.
V_{water}: volume of water in contact with DNHM in the selected length pipe.

Taking the reviewed data sets from reported distribution system study as an example (Liu et al., 2013c), the biofilm formed on 110 cm water main pipe can lead to a QDP for microbiological quality of 0.4×10^7 cells/ml and 200–1600 ng ATP/l. These numbers increase further when the contribution of niches of loose deposits are also taken into account (by 60–600 ng ATP/l). Such assessment can be done on different parameters and multiple niche environments within DN pipes.

3.2.3. Distribution process

The destabilized and mobilized DNHM may be retained in the DNs as loose deposits instead of flowing out at customers' taps if the generated particulate matter has a weight that can balance the hydraulic force. In this situation, the organic components, which were previously protected by pipe scales and biofilm matrix from contacting disinfectant residuals in the water column will, when release, cause faster decay of disinfectant residuals and form disinfection by-products (DBP) in the system where the disinfectant residuals maintained during distribution. The mobilized but retained particulate matter also offers more surface area and available nutrients for bacterial growth.

3.3. Control strategies for preventing potential transition effects

The potential transition effects and the associated problems will seriously discourage customers from directly using tap water and can easily counteract the numerous efforts devoted to source-water switching and treatment upgrading. In extreme cases, there can be esthetic and health risks. Therefore, attention and effort should be focused on developing strategies to prevent potential transition effects.

3.3.1. Reconditioning the treated water

The potential transition effects are caused by irregular changes in the physiochemical and microbiological characteristics of the produced water. Therefore, properly reconditioning the treated water can be helpful to prevent transition effects during distribution. The critical parameters to be adjusted should be determined according to the properties of aged pipes, pipe scales, loose deposits and biofilm matrix in the downstream DNs (e.g. PH, redox, SI, corrosion inhibitors). However, the reconditioning option should be carefully examined to make sure treated water will not be recontaminated. One example of such a reconditioning is the remineralization of reverse osmosis permeate by adding the required minerals for health reasons and to meet regulatory requirements (Withers, 2005; Liang et al., 2013; Luptáková and Derco, 2015).

Table 4
Historical problems associated with transition effects in distribution systems.

Problems	Reasons & Changes	Location	Pipe material	Year	Reference
Discoloration	Source water switch	Tucson, U.S.	galvanized steel; unlined cast iron	1992	(Basefsky, 2006)
Discoloration, high concentration of As, Cu, Fe	Starting up of chlorination	Midwestern U.S.	unlined cast iron	1996	(Reiber and Dostal, 2000)
Discoloration	Source-water switch	Tampa, U.S.	galvanized steel; unlined cast iron; lined cast iron; PVC	2001	(Tang et al., 2006)
Discoloration (red-brown colored water), Pb release	Disinfection strategy switch from free chlorine to chloramine	Washington D.C., U.S.	solder, brass, lead	2004	(Edwards and Dudi, 2004)
Discoloration (red water), high number of iron-related bacteria	Source-water switch	Beijing, China	cast iron	2008	(Li et al., 2010)
Discoloration (brown water)	Source-water switch	North China, China	cast iron	2009	(Wang et al., 2009)
Release of Pb, As, Al	Changes in coagulant in drinking water treatment	Ontario, Canada	lead	2007–2010	(Kim et al., 2011)
Release of Pb, high concentration of Legionella	Source and treatment switch	Flint, U.S.	lead	2015	(Schwake et al., 2016; Utecht and McCoy, 2016)

Similarly, in the Flint case, the addition of corrosion inhibitors to the treated water following switching might have prevented the crisis; while for the Beijing case, strategies to deal with the potential influences of high sulfate concentration could have prevented the red water events during the switching.

3.3.2. Cleaning the pipe network beforehand

As the distributed drinking water quality can only be as good as the condition of the distribution network, one of the proposed control strategies is to clean the pipe network before switching supply-water quality. The commonly used method for distribution pipe cleaning is known as 'unidirectional flushing', which employs a large water volume at sufficiently high velocity (1.5 m/s) water to mobilize the sediments and carry away the loose deposits through fire hydrants (Ellison, 2003). The problem with the method is that it can be wasteful of water and ineffective in removing adherent contaminants (e.g., tuberculation, scale, biofilm), especially when there are difficulties in achieving required velocity (Ellison, 2003; Quarini et al., 2010). Air scouring is similar to water flushing, except that the air is introduced into the fluid column to create a high-velocity, turbulent flow. It is generally more efficient in removing biofilm and soft scales than flushing, but it is at least twice as costly as flushing. An alternative technique is pigging, which propels or pulls (pigs, a bullet-shaped object) through the pipelines using water pressure. Hard pigs have a higher cleaning efficiency than soft pigs. Recently, ice pigging has been introduced and become established, providing the advantages of high cleaning efficiency, no sticking, water saving and reduced costs (Bellas and Tassou, 2005; Quarini et al., 2010; Dang et al., 2014). In extreme cases, when the above-mentioned cleaning techniques are not sufficient, the pipes should be rehabilitated or replaced.

From a practical perspective, considering the complexity and costs of each method, the water flushing and air scouring options are more appropriate compared to pigging and pipe replacement. This especially true for the mega-cities, such as New York and Beijing. In instances where regulations allow for quality variations and exemptions, and the transition effects pose no health risks to customers, the temporary exceeding of water quality requirements, and subsequent compliance, maybe acceptable (EPA 1998a,b).

3.3.3. Monitoring

Another strategy involves monitoring the transition effects after switching supply-water quality, so that proper action can be taken in a timely manner by the water utilities if any destabilization occurs. Generally, there are three challenges to monitoring the release of contaminants during transition effects. Namely, 1) the uncertainty concerning whether and when the release is going to happen; because the contaminant-release events often go undetected since the release is episodic and non-periodic (Makris et al., 2014); 2) the released contaminants might be under the detection limits, because any released contaminants are diluted in a large volume of water which flow through the DN and cannot, therefore, be detected; 3) the sampling artifacts and analytical limitations in the currently used protocols exclude suspended colloidal or particulate material, such as for Pb, As, and Cr, from detection (Parks et al., 2004; Triantafyllidou et al., 2007).

To overcome the first challenge mentioned above, one suggestion would be to monitor water quality parameters in real time, for instance by online particle counting (Verberk et al., 2007) and online cell counts using flow cytometry (Hammes et al., 2012; Besmer et al., 2014). Measurements taken at multiple locations in the distribution system before the water quality changes can provide a background database; new measurements would then be taken at the same locations during and after the supply-water quality changes. A data comparison obtained at these different instances will offer valuable information on the transition effects. However, online detection is limited. There are no available online devices for heavy metals (such as As, Pb) and pathogens. In addition, if the contaminant-releasing events are too low to be noticed by comparing the background and transition period measurements, online monitoring will give no significant results.

As a solution to both the second and third challenges, it is proposed that suspended particles be studied, as we have described previously (Liu et al., 2013a; Liu et al., 2016) be studied. In short, this method consists of a pre-concentration step for the suspended particles by filtrating about 200 L of water through 1.2 μm filters with a multiple particle filtration device. The collected particles can then be analyzed on physiochemical (e.g., total suspended solids and elemental composition) and microbiological parameters (biomass quantification and bacterial identification). In this way, the particulate contaminants can be pre-concentrated and the contaminant-releasing events can be detected, captured and characterized (Liu et al., 2016). As a combined solution to all the three challenges, an online particle sampling, concentrating, and monitoring system would have to be developed.

For the purposes of summary, an overview of the aging pipes and the harbored material retained in the pipe systems, types of potential destabilization, associated problems, and timeline for the releasing events to occur, and various cleaning methods is given in Table 5.

4. Conclusions and outlooks: transition effects evaluation framework

Until now, no information has been available on the evaluation of the potential transition effects of the planned switching of supply-water quality, nor are there any proper guidelines for the avoidance of potential esthetic and health risks. Based on this review, and bearing in the mind the WHO's outlined Water Safety Plans (Davison et al., 2005), the following framework comprising a system assessment, management plans and operational monitoring is proposed as a means of evaluating the potential transition effects before the switching of supply-water quality (Fig. 5).

- System assessment:

Step 1 involves the parallel evaluation of: 1.1) water quality changes and 1.2) the current situation of the distribution system. If there is no change in the produced water quality nor fouling in the distribution system, the supply water can be switched directly. Otherwise, the evaluation should be continued with Step 2. The research questions in Step 1 can be summarized as follows:

Q1) Are there quality improvements/changes as a result of the new treatments/sources?
Q2) Is there DNHM in the DN?
Q3) What is the composition of the DNHM material?
Q4) Where is the DNHM present?

Step 2 involves an assessment of whether the transition effects will occur or not.

Q5) Will the transition effects occur?
Q6) What will be released into water from DNHM during the transition period?
Q7) What risks does the released material present?

If there are no transition effects observed, the supply water can be switched safely. If transition effects are observed, the evaluation should continue to the next step.

Table 5
Potential contribution of DNHM as contaminants.

	Types of destabilization	Potential problems	Time to occur	Cleaning methods
Aging pipes	chemical	pipe corrosion, heavy metal release, pipe breaks	days - weeks	rehabilitation and replacement of problematic pipe
Loose deposits	physiochemical & microbiological	contaminants release and discoloration	days - weeks	unidirectional water flushing, air scouring, soft-swab pigging
Biofilm matrix	bio-chemical & microbiological	cell release, particle generation, water meter clogging and discoloration	months - years	ice pigging
Pipe scales	(bio-)chemical	hazardous metal release and discoloration	days - weeks	chemical cleaning/ice pigging

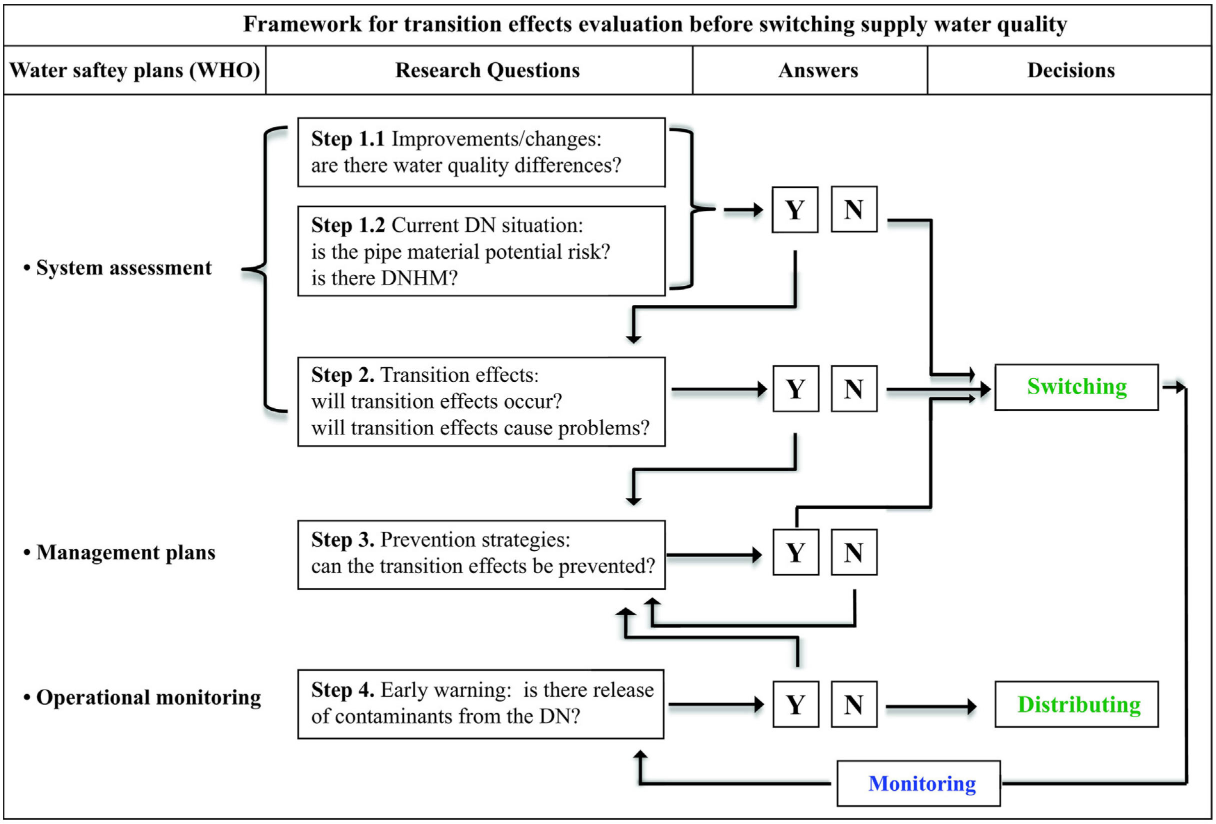

Fig. 5. Framework for potential transition effects evaluation before switching the supply-water quality.

- Management plans

Step 3 involves an evaluation of the control strategies to avoid transition effects. The possible strategies include flushing the distribution pipes (water, water and air), ice pigging, and the addition of required agents to stabilize the quality improved water (e.g., corrosion inhibitors).

Q8) Can the transition effects be prevented by pre-cleaning the DN?
Q9) How should the distribution pipes be cleaned?
Q10) Are there any essential compounds that should be added to the quality-improved water, for instance for reconditioning, to maintain stabilization of the DN and DNHM?

If the transition effects can be prevented by pre-cleaning the pipes or by reconditioning the quality-improved water, the supply water can be switched safely. The monitoring program should be carried out as described in Step 4 after the switching of the supply water. In case transition effects are observed, and no strategies succeed in controlling them, the supply water should not be switched until effective control strategies are developed.

- Operational monitoring

After the decision is made to switch the supply water, the distribution of quality-improved drinking water should be continuously monitored for material releases from the DWDS into the water. If material releases are detected, the evaluation should return to Step 3, with a search for cleaning and control methods, unless the material releases are minor and have no harmful effects on consumers. In no material releases are detected, the distribution of quality-improved drinking water may continue. This monitoring program/method can be used as an early-warning system, so that appropriate actions can be taken in time to prevent any undesired transition effects.

In the event of the application of the framework to the situation of Beijing, the system assessment will be able to diagnose: 1) the composition of pipe scales and biofilm community; 2) differences of supply-water quality regarding the sulfate concentrations; 3) potential transition effects of community-composition changes regarding sulfur-oxidizing bacteria, sulfate-reducing bacteria and iron-oxidizing bacteria, and 4) possible red-water events associated with high iron concentrations. The management plans should be able to prevent discoloration, either through the effective cleaning of DNs or by proper adjustment of treated-water quality, for example, through efficient sulfate removal. The monitoring program should cover bacterial community composition, suspended particle load, and sulfate and iron concentrations, all of which can offer valuable information on what is happening in the DNs after switching supply-water quality.

References

Ainsworth, R., 2013. Safe piped water: managing microbial water quality in piped distribution systems. Water Intell. Online 12, 9781780405841.

Allison, S.D., Martiny, J.B., 2008. Resistance, resilience, and redundancy in microbial communities. Proc. Natl. Acad. Sci. 105 (Suppl. 1), 11512–11519.

AWWA, 2012. Buried No Longer: Confronting America's Water Infrastructure Challenge. American Water Works Association.

Axten, C.W., Foster, D., 2008. Analysis of airborne and waterborne particles around a taconite ore processing facility. Regul. Toxicol. Pharmacol. 52 (1), S66–S72.

Barbeau, B., Gauthier, V., Julienne, K., Carriere, A., 2005. Dead-end flushing of a distribution system: short and long-term effects on water quality. J. Water Supply Res. Technol. AQUA 54 (6), 371–383.

Basefsky, M., 2006. Issues of aging infrastructure: the tucson experience. Southwest Hydrol. 24–25. March/April 2.

Beech, I.B., Sunner, J., 2004. Biocorrosion: towards understanding interactions between biofilms and metals. Curr. Opin. Biotechnol. 15 (3), 181–186.

Bellas, I., Tassou, S., 2005. Present and future applications of ice slurries. Int. J. Refrig. 28 (1), 115–121.

Besmer, M.D., Weissbrodt, D.G., Kratochvil, B.E., Sigrist, J.A., Weyland, M.S., Hammes, F., 2014. The feasibility of automated online flow cytometry for in-situ monitoring of microbial dynamics in aquatic ecosystems. Front. Microbiol. 5.

Beuken, R., Reinoso, M., Sturm, S., Kiefer, J., Bondelind, M., Aström, J., Lindhe, A., Losén, L., Pettersson, T., Machenbach, I., 2008. Identification and Description of Hazards for Water Supply Systems: a Catalogue of Today's Hazards and Possible Future Hazards.

Brazos, B.J., O'Connor, J.T., 1996. Seasonal effects on generation of particle-associated bacteria during distribution. J. Environ. Eng. 122 (12), 1050–1057.

Brodeur, T., Davis, F.S., Florence, R., Kim, M., Craig, M., Gianatasio, J., Sharp, D., Lowe, P., 2006. From red water to pump failures-corrosion control activities & related studies. Fla. Water Resour. J. 12, 42e48.

Broo, A.E., Berghult, B., Hedberg, T., 2001. Pipe material selection in drinking water systems-a conference summary. Water Sci. Technol. Water Supply 1 (3), 117–125.

Camper, A.K., LeChevallier, M.W., Broadaway, S.C., McFeters, G.A., 1986. Bacteria associated with granular activated carbon particles in drinking water. Appl. Environ. Microbiol. 52 (3), 434–438.

Carrière, A., Gauthier, V., Desjardins, R., Barbeau, B., 2005. Evaluation of loose deposits in distribution systems through unidirectional flushing. J. Am. Water Works Assoc. 97 (9), 82–92. +12.

Cerrato, J.M., Reyes, L.P., Alvarado, C.N., Dietrich, A.M., 2006. Effect of PVC and iron materials on Mn (II) deposition in drinking water distribution systems. Water Res. 40 (14), 2720–2726.

Chaves Simões, L., Simões, M., 2013. Biofilms in drinking water: problems and solutions. RSC Adv. 3 (8), 2520–2533.

Chen, Y., van der Mei, H.C., Busscher, H.J., Norde, W., 2014. Viscous nature of the bond between adhering bacteria and substratum surfaces probed by atomic force microscopy. Langmuir 30 (11), 3165–3169.

Clark, S.C., Lawler, D.F., Cushing, R.S., 1992. Contact filtration: particle size and ripening. J. Am. Water Works Assoc. 61–71.

Costerton, J.W., Lewandowski, Z., Caldwell, D.E., Korber, D.R., Lappin-Scott, H.M., 1995. Microbial biofilms. Annu. Rev. Microbiol. 49 (1), 711–745.

Dang, P., Jayaratne, A., Wilson, G., 2014. Ice Pigging–a Better Way to Clean Water Mains. Yarra Valley Water, Australia.

Davison, A., Howard, G., Stevens, M., Callan, P., Fewtrell, L., Deere, D., Bartram, J., 2005. Water Safety Plans: Managing Drinking-water Quality from Catchment to Consumer. In: Water Safety Plans: Managing Drinking-water Quality from Catchment to Consumer.

Echeverría, F., Castaño, J.G., Arroyave, C., Peñuela, G., Ramírez, A., Morató, J., 2009. Characterization of deposits formed in a water distribution system. Caracterización depósitos formados U. N. Sist. Distrib. agua potable 17 (2), 275–281.

Edwards, M., 2004. Controlling corrosion in drinking water distribution systems: a grand challenge for the 21st century. Water Sci. Technol. 49 (2), 1–8.

Edwards, M., Dudi, A., 2004. Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials. J. Am. Water Works Assoc. 96 (10), 69–81.

Edwards, M., Jacobs, S., Taylor, R.J., 2000. The blue water phenomenon. Am. Water Works Assoc. J. 92 (7), 72.

Ellison, D., 2003. Investigation of Pipe Cleaning Methods. American Water Works Association.

EPA, 1998a. Announcement of small system compliance technology lists for existing national primary drinking water regulations and findings concerning variance technologies. Fed. Regist. 63 (151), 42032–42048.

EPA, 1998b. Revision of existing variance and exemption regulations to comply with requirements of the safe drinking water act. Fed. Regist. 63 (157), 43834–43851.

Ewing, F., 1935. The crystal structure of lepidocrocite. J. Chem. Phys. 3 (7), 420–424.

Falkinham, J.O., Pruden, A., Edwards, M., 2015. Opportunistic premise plumbing pathogens: increasingly important pathogens in drinking water. Pathogens 4 (2), 373–386.

Feazel, L.M., Baumgartner, L.K., Peterson, K.L., Frank, D.N., Harris, J.K., Pace, N.R., 2009. Opportunistic pathogens enriched in showerhead biofilms. Proc. Natl. Acad. Sci. U. S. A. 106 (38), 16393–16398.

Fish, K.E., Osborn, A.M., Boxall, J., 2016. Characterising and understanding the impact of microbial biofilms and the extracellular polymeric substance (EPS) matrix in drinking water distribution systems. Environ. Sci. water Res. Technol. 2, 614–630.

Flemming, H.-C., Wingender, J., 2010. The biofilm matrix. Nat. Rev. Microbiol. 8 (9), 623–633.

Gauthier, V., Gérard, B., Portal, J.M., Block, J.C., Gatel, D., 1999. Organic matter as loose deposits in a drinking water distribution system. Water Res. 33 (4), 1014–1026.

Gauthier, V., Portal, J.M., Yvon, J., Rosin, C., Block, J.C., Lahoussine, V., Benabdallah, S., Cavard, J., Gatel, D., Fass, S., 2001. Characterization of Suspended Particles and Deposits in Drinking Water Reservoirs, vol. 1, pp. 89–94.

Gerke, T.L., Scheckel, K.G., Schock, M.R., 2009. Identification and distribution of vanadinite (Pb5 (V5+ O4) 3Cl) in lead pipe corrosion by-products. Environ. Sci. Technol. 43 (12), 4412–4418.

Geudens, P.J.J.G., 2015. Dutch Drinking Water Statistics 2015. Vewin: association of Dutch water companies.

Gomez-Alvarez, V., Pfaller, S., Pressman, J., Wahman, D., Revetta, R., 2016. Resilience of microbial communities in a simulated drinking water distribution system subjected to disturbances: role of conditionally rare taxa and potential implications for antibiotic-resistant bacteria. Environ. Sci. Water Res. Technol. 2 (4), 645–657.

Hammes, F., Berger, C., Köster, O., Egli, T., 2010. Assessing biological stability of drinking water without disinfectant residuals in a full-scale water supply system. J. Water Supply Res. Technol. AQUA 59 (1), 31–40.

Hammes, F., Broger, T., Weilenmann, H.U., Vital, M., Helbing, J., Bosshart, U., Huber, P., Peter Odermatt, R., Sonnleitner, B., 2012. Development and laboratory-scale testing of a fully automated online flow cytometer for drinking water analysis. Cytom. Part A 81 (6), 508–516.

Hanna-Attisha, M., LaChance, J., Sadler, R.C., Champney Schnepp, A., 2016. Elevated blood lead levels in children associated with the Flint drinking water crisis: a spatial analysis of risk and public health response. Am. J. public health (0), e1–e8.

Hodgkiess, T., 2004. Inter-relationships between corrosion and mineral-scale deposition in aqueous systems. Water Sci. Technol. 49 (2), 121–128.

Hong, P.Y., Hwang, C., Ling, F., Andersen, G.L., LeChevallier, M.W., Liu, W.T., 2010. Pyrosequencing analysis of bacterial biofilm communities in water meters of a drinking water distribution system. Appl. Environ. Microbiol. 76 (16), 5631–5635.

Hsieh, K.M., Murgel, G.A., Lion, L.W., Shuler, M.L., 1994. Interactions of microbial biofilms with toxic trace metals: 1. Observation and modeling of cell growth, attachment, and production of extracellular polymer. Biotechnol. Bioeng. 44 (2), 219–231.

Hwang, C., Ling, F., Andersen, G.L., LeChevallier, M.W., Liu, W.T., 2012. Microbial community dynamics of an urban drinking water distribution system subjected to phases of chloramination and chlorination treatments. Appl. Environ. Microbiol. 78 (22), 7856–7865.

Kim, E.J., Herrera, J.E., Huggins, D., Braam, J., Koshowski, S., 2011. Effect of pH on the concentrations of lead and trace contaminants in drinking water: a combined batch, pipe loop and sentinel home study. Water Res. 45 (9), 2763–2774.

Kvech, S., Edwards, M., 2001. Role of aluminosilicate deposits in lead and copper corrosion. J. Am. Water Works Assoc. 93 (11), 104–112.

Kvech, S., Edwards, M., 2002. Solubility controls on aluminum in drinking water at relatively low and high pH. Water Res. 36 (17), 4356–4368.

Laspidou, C.S., Rittmann, B.E., 2002. A unified theory for extracellular polymeric substances, soluble microbial products, and active and inert biomass. Water Res. 36 (11), 2711–2720.

LeChevallier, M.W., Babcock, T.M., Lee, R.G., 1987. Examination and characterization of distribution system biofilms. Appl. Environ. Microbiol. 53 (12), 2714–2724.

Lee, S.H., O'Conner, J.T., Park, S.J., 1980. Biological mediated corrosion and its effects on water quality in distribution systems. J. Am. Water Works Assoc. 72 (11), 636–645.

Lehtola, M.J., Nissinen, T.K., Miettinen, I.T., Martikainen, P.J., Vartiainen, T., 2004. Removal of soft deposits from the distribution system improves the drinking water quality. Water Res. 38 (3), 601–610.

Li, D., Li, Z., Yu, J., Cao, N., Liu, R., Yang, M., 2010. Characterization of bacterial community structure in a drinking water distribution system during an occurrence of red water. Appl. Environ. Microbiol. 76 (21), 7171–7180.

Liang, J., Deng, A., Xie, R., Gomez, M., Hu, J., Zhang, J., Ong, C.N., Adin, A., 2013. Impact of seawater reverse osmosis (SWRO) product remineralization on the corrosion rate of water distribution pipeline materials. Desalination 311, 54–61.

Liu, G., Bakker, G., Li, S., Vreeburg, J., Verberk, J., Medema, G., Liu, W., Van Dijk, J., 2014. Pyrosequencing reveals bacterial communities in unchlorinated drinking water distribution system: an integral study of bulk water, suspended solids, loose deposits, and pipe wall biofilm. Environ. Sci. Technol. 48 (10), 5467–5476.

Liu, G., Ling, F., Magic-Knezev, A., Liu, W., Verberk, J.Q.J.C., Van Dijk, J.C., 2013a. Quantification and identification of particle associated bacteria in unchlorined drinking water from three treatment plants by cultivation-independent methods. Water Res. 47 (10), 3523–3533.

Liu, G., Ling, F., van der Mark, E., Zhang, X., Knezev, A., Verberk, J., van der Meer, W., Medema, G., Liu, W., van Dijk, J., 2016. Comparison of particle-associated bacteria from a drinking water treatment plant and distribution reservoirs with different water sources. Sci. Rep. 6.

Liu, G., Lut, M.C., Verberk, J.Q.J.C., Van Dijk, J.C., 2013b. A comparison of additional treatment processes to limit particle accumulation and microbial growth during drinking water distribution. Water Res. 47 (8), 2719–2728.

Liu, G., Verberk, J.Q.J.C., Dijk, J.C., 2013c. Bacteriology of drinking water distribution systems: an integral and multidimensional review. Appl. Microbiol. Biotechnol. 97 (21), 9265–9276.

Liu, H., Schonberger, K.D., Korshin, G.V., Ferguson, J.F., Meyerhofer, P., Desormeaux, E., Luckenbach, H., 2010. Effects of blending of desalinated water with treated surface drinking water on copper and lead release. water Res. 44 (14), 4057–4066.

Luptáková, A., Derco, J., 2015. Improving of drinking water quality by remineralisation. Acta Chim. Slov. 62 (4), 859–866.

Lytle, D.A., Sorg, T.J., Christy, M., Lili, W., 2010. Particulate arsenic release in a drinking water distribution system. J./Am. Water Works Assoc. 102 (3), 87–98.

Lytle, D.A., Sorg, T.J., Frietch, C., 2004. Accumulation of arsenic in drinking water distribution systems. Environ. Sci. Technol. 38 (20), 5365–5372.

Makris, K.C., Andra, S.S., Botsaris, G., 2014. Pipe scales and biofilms in drinking-water distribution systems: undermining finished water quality. Crit. Rev. Environ. Sci. Technol. 44 (13), 1477–1523.

Mays, L.W., 1999. Water Distribution System Handbook. McGraw-Hill Professional Publishing.

Mceneill, Lauries S., Edwards, M., 2001. Iron pipe corrosion in distribution systems. J. Am. Water Works Assoc. 93 (7), 88–100.

Miner, G., 2002. Upgrading water treatment plants. Am. Water Works Assoc. J. 94 (1), 123.

Misko, A., Pena, S., Song, J., Lee, K., Kim, V., Fagan, J.M., 2010. Aging Pipe Infrastructure.

Moe, C.L., Rheingans, R.D., 2006. Global challenges in water, sanitation and health. J. water health 4 (S1), 41–57.

Moel, P.J., Verberk, J.Q., Van Dijk, J., 2006. Drinking Water: Principles and Practices. World Scientific Singapore.

Nguyen, C., Elfland, C., Edwards, M., 2012. Impact of advanced water conservation features and new copper pipe on rapid chloramine decay and microbial regrowth. Water Res. 46 (3), 611–621.

Norton, C.D., LeChevallier, M.W., Falkinham Iii, J.O., 2004. Survival of Mycobacterium avium in a model distribution system. Water Res. 38 (6), 1457–1466.

NRC, 2006. Drinking Water Distribution Systems: Assessing and Reducing Risks. National Academies Press.

Oppenheimer-Shaanan, Y., Sibony-Nevo, O., Bloom-Ackermann, Z., Suissa, R., Steinberg, N., Kartvelishvily, E., Brumfeld, V., Kolodkin-Gal, I., 2016. Spatio-temporal assembly of functional mineral scaffolds within microbial biofilms. npj Biofilms Microbiomes 2, 15031.

Parks, J.L., McNeill, L., Frey, M., Eaton, A.D., Haghani, A., Ramirez, L., Edwards, M., 2004. Determination of total chromium in environmental water samples. Water Res. 38 (12), 2827–2838.

Peng, C.Y., Korshin, G.V., 2011. Speciation of trace inorganic contaminants in corrosion scales and deposits formed in drinking water distribution systems. Water Res. 45 (17), 5553–5563.

Peng, C.Y., Korshin, G.V., Valentine, R.L., Hill, A.S., Friedman, M.J., Reiber, S.H., 2010. Characterization of elemental and structural composition of corrosion scales and deposits formed in drinking water distribution systems. Water Res. 44 (15), 4570–4580.

Pinheiro, R., Wagner, G., 2001. Upgrading Water Treatment Plants. CRC Press.

Prest, E.I., Hammes, F., van Loosdrecht, M.C., Vrouwenvelder, J.S., 2016. Biological stability of drinking water: controlling factors, methods, and challenges. Front. Microbiol. 7.

Proctor, C.R., Hammes, F., 2015. Drinking water microbiology—from measurement to management. Curr. Opin. Biotechnol. 33, 87–94.

Pryor, M., Springthorpe, S., Riffard, S., Brooks, T., Huo, Y., Davis, G., Sattar, S., 2004. Investigation of opportunistic pathogens in municipal drinking water under different supply and treatment regimes. Water Sci. Technol. 50 (1), 83–90.

Qu, W., Zheng, W., Wang, S., Wang, Y., 2012. China's new national standard for drinking water takes effect. Lancet 380 (9853), e8.

Quarini, G., Ainslie, E., Herbert, M., Deans, T., Ash, D., Rhys, D., Haskins, N., Norton, G., Andrews, S., Smith, M., 2010. Investigation and development of an innovative pigging technique for the water-supply industry. Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng. 224 (2), 79–89.

Qureshi, N., Shah, J., 2014. Aging infrastructure and decreasing demand: a dilemma for water utilities. J. Am. Water Works Assoc. 106 (1), 51–61.

Rabin, R., 2008. The lead industry and lead water pipes “A modest campaign”. Am. J. public health 98 (9), 1584–1592.

Reiber, S., Dostal, G., 2000. Arsenic and old pipes-a mysterious liaison. Opflow 26 (3), 1.

Ren, H., Wang, W., Liu, Y., Liu, S., Lou, L., Cheng, D., He, X., Zhou, X., Qiu, S., Fu, L., 2015. Pyrosequencing analysis of bacterial communities in biofilms from different pipe materials in a city drinking water distribution system of East China. Appl. Microbiol. Biotechnol. 99 (24), 10713–10724.

Renner, R., 2008. Pipe scales release hazardous metals into drinking water. Environ. Sci. Technol. 42 (12), 4241–4241.

Schock, M.R., 1980. Response of lead solubility to dissolved carbonate in drinking water. J. Am. Water Works Assoc. 695–704.

Schock, M.R., Hyland, R.N., Welch, M.M., 2008. Occurrence of contaminant accumulation in lead pipe scales from domestic drinking-water distribution systems. Environ. Sci. Technol. 42 (12), 4285–4291.

Schriks, M., Heringa, M.B., van der Kooi, M.M., de Voogt, P., van Wezel, A.P., 2010. Toxicological relevance of emerging contaminants for drinking water quality. Water Res. 44 (2), 461–476.

Schwake, D.O., Garner, E., Strom, O.R., Pruden, A., Edwards, M.A., 2016. Legionella DNA markers in tap water coincident with a spike in legionnaires' disease in Flint, MI. Environ. Sci. Technol. Lett. 3 (9), 311–315.

Shade, A., Peter, H., Allison, S.D., Baho, D.L., Berga, M., Bürgmann, H., Huber, D.H., Langenheder, S., Lennon, J.T., Martiny, J.B., 2012. Fundamentals of Microbial Community Resistance and Resilience.

Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Marinas, B.J., Mayes, A.M., 2008. Science and technology for water purification in the coming decades. Nature 452 (7185), 301–310.

Sly, L.I., Hodgkinson, M.C., Arunpairojana, V., 1990. Deposition of manganese in a drinking water distribution system. Appl. Environ. Microbiol. 56 (3), 628–639.

Smith, S.E., Bisset, A., Colbourne, J.S., Holt, D.M., Lloyd, B.J., 1997. The occurrence and significance of particles and deposits in a drinking water distribution system. J. N. Engl. Water Works Assoc. 111 (2), 135–144.

Tang, Z., Hong, S., Xiao, W., Taylor, J., 2006. Characteristics of iron corrosion scales established under blending of ground, surface, and saline waters and their impacts on iron release in the pipe distribution system. Corros. Sci. 48 (2), 322–342.

Ternes, T., Joss, A., Oehlmann, J., 2015. Occurrence, fate, removal and assessment of emerging contaminants in water in the water cycle (from wastewater to drinking water). Water Res. 72, 1.

Tobiason, J.E., Johnson, G.S., Westerhoff, P.K., Vigneswaran, B., 1993. Particle size and chemical effects on contact filtration performance. J. Environ. Eng. 119 (3), 520–539.

Torvinen, E., Suomalainen, S., Lehtola, M.J., Miettinen, I.T., Zacheus, O., Paulin, L., Katila, M.L., Martikainen, P.J., 2004. Mycobacteria in water and loose deposits of drinking water distribution systems in Finland. Appl. Environ. Microbiol. 70 (4), 1973–1981.

Triantafyllidou, S., Parks, J., Edwards, M., 2007. Lead particles in potable water. Am. Water Works Assoc. J. 99 (6), 107.

Utecht, K.R., McCoy, W.F., 2016. Water management lessons from Flint, mich. ASHRAE J. 58 (5), 88.

Vaerewijck, M.J.M., Huys, G., Palomino, J.C., Swings, J., Portaels, F., 2005. Mycobacteria in drinking water distribution systems: ecology and significance for human health. FEMS Microbiol. Rev. 29 (5), 911–934.

Van der Kooij, D., 1992. Assimilable organic carbon as an indicator of bacterial regrowth. J./Am. Water Works Assoc. 84 (2), 57–65.

Van Der Wende, E., Characklis, W.G., Smith, D.B., 1989. Biofilms and bacterial drinking water quality. Water Res. 23 (10), 1313–1322.

van der Wielen, P.W., Bakker, G., Atsma, A., Lut, M., Roeselers, G., de Graaf, B., 2016. A survey of indicator parameters to monitor regrowth in unchlorinated drinking water. Environ. Sci. Water Res. Technol.

van der Wielen, P.W., Lut, M.C., 2016. Distribution of microbial activity and specific microorganisms across sediment size fractions and pipe wall biofilm in a drinking water distribution system. Water Sci. Technol. Water Supply 16 (4), 896–904 ws2016023.

Van der Wielen, P.W.J.J., Van der Kooij, D., 2010. Effect of water composition, distance and season on the adenosine triphosphate concentration in unchlorinated drinking water in The Netherlands. Water Res. 44 (17), 4860–4867.

Verberk, J.Q.J.C., O'Halloran, K.J., Hamilton, L.A., Vreeburg, J.H.G., Van Dijk, J.C., 2007. Measuring particles in drinking water transportation systems with particle counters. J. Water Supply Res. Technol. AQUA 56 (5), 345–355.

Verberk, J.Q.J.C., Vreeburg, J.H.G., Rietveld, L.C., Van Dijk, J.C., 2009. Particulate fngerprinting of water quality in the distribution system. Water SA 35 (2), 192–199.

Vreeburg, J.H.G., 2007. Discolouration in Drinking Water Systems: a Particular Approach. TU Delft, Delft University of Technology.

Vreeburg, J.H.G., Blokker, E.J.M., Horst, P., Van Dijk, J.C., 2009. Velocity-based self-cleaning residential drinking water distribution systems. Water Sci. Technol. Water Supply 9, 635–641.

Vreeburg, J.H.G., Boxall, D.J.B., 2007. Discolouration in potable water distribution systems: a review. Water Res. 41 (3), 519–529.

Vreeburg, J.H.G., Schaap, P.G., Van Dijk, J.C., 2004. Particles in the drinking water system: from source to discolouration. Water Sci. Technol. Water Supply 4 (5–6), 431–438.

Vreeburg, J.H.G., Schippers, D., Verberk, J.Q.J.C., van Dijk, J.C., 2008. Impact of particles on sediment accumulation in a drinking water distribution system. Water Res. 42 (16), 4233–4242.

Wang, H., Edwards, M.A., Falkinham III, J.O., Pruden, A., 2013. Probiotic approach to pathogen control in premise plumbing Systems? A review. Environ. Sci. Technol. 47 (18), 10117–10128.

Wang, H., Hu, C., Hu, X., Yang, M., Qu, J., 2012a. Effects of disinfectant and biofilm on the corrosion of cast iron pipes in a reclaimed water distribution system. Water Res. 46 (4), 1070–1078.

Wang, H., Proctor, C.R., Edwards, M.A., Pryor, M., Santo Domingo, J.W., Ryu, H., Camper, A.K., Olson, A., Pruden, A., 2014. Microbial community response to chlorine conversion in a chloraminated drinking water distribution system. Environ. Sci. Technol. 48 (18), 10624–10633.

Wang, Y., Zhang, X., Chen, C., Pan, A., Xu, Y., Liao, P., Zhang, S., Gu, J., 2009. Case study of red water phenomenon in drinking water distribution systems caused by water source switch. Environ. Sci. Chin. 30 (12), 3555–3561.

Wang, Z., Hessler, C.M., Xue, Z., Seo, Y., 2012b. The role of extracellular polymeric substances on the sorption of natural organic matter. Water Res. 46 (4), 1052–1060.

WHO, 1996. WHO Guidelines for Drinking Water Quality 2nd Edition.

WHO, 2004. Guidelines for Drinking-water Quality: Recommendations. World Health Organization.

WHO, 2011. Guidelines for Drinking-water Quality.

Withers, A., 2005. Options for recarbonation, remineralisation and disinfection for desalination plants. Desalination 179 (1), 11–24.

Yang, F., Shi, B., Bai, Y., Sun, H., Lytle, D.A., Wang, D., 2014. Effect of sulfate on the transformation of corrosion scale composition and bacterial community in cast iron water distribution pipes. Water Res. 59, 46–57.

Yang, F., Shi, B., Gu, J., Wang, D., Yang, M., 2012. Morphological and physicochemical characteristics of iron corrosion scales formed under different water source histories in a drinking water distribution system. Water Res. 46 (16), 5423–5433.

Zacheus, O.M., Lehtola, M.J., Korhonen, L.K., Martikainen, P.J., 2001. Soft deposits, the key site for microbial growth in drinking water distribution networks. Water Res. 35 (7), 1757–1765.

Zhang, Q., 2009. The south-to-north water transfer project of China: environmental implications and monitoring strategy. J. Am. Water Resour. Assoc. 45 (5), 1238–1247.