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Review

Comprehensive Control of Water Quality Deterioration in Building Water Supply Systems: A Review on Configuration, Purification and Regulation

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Abstract: The overall goal of urban water supply is to ensure the water quality from source to tap. As the "last mile", the building water supply system (BWSS) is the crucial part in ensuring tap water safety, and its deteriorating water quality has attracted increasing attention. In this work, we provide a comprehensive overview of the pollution, configuration, purification and regulation of BWSSs, with a focus on ensuring water quality safety. Periodic water usage in buildings is a unique feature that leads to intermittent water stagnation and reduced residual chlorine. Biological pollution has become a key focus of existing studies due to its acute effects on human health, compared to the chronic effects of chemical pollution. For new systems, water quality risks can be reduced at the source by optimizing pipe materials and reasonable layout. It is recommended to introduce secondary disinfection technologies, as they are important for ensuring biosecurity. Moreover, supervision and maintenance are the basis for long-term efficient operation of BWSSs. This review constructs a framework for controlling water quality deterioration based on the whole process, which is instructive for the design, operation, maintenance and management of BWSSs, and provides relatively clear research directions for improving water quality.

Keywords: secondary water supply; water pollution; biosafety; design and layout; disinfection strategy; management and maintenance

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1. Introduction

Drinking water safety is a critical issue closely related to human health, economic development and social stability that must be addressed at the national, regional and local levels. Since 1994, the World Health Organization (WHO) has developed a comprehensive risk assessment and risk management approach known as the water safety plan (WSP), which was globally recommended in the 2004 WHO Guidelines for Drinking-Water Quality [1]. The WSP is a proactive approach that ensures water safety through good management of all steps in the water supply chain. It involves understanding the complete system, identifying where and how problems could arise, putting barriers and management systems in place to stop the problems before they happen and making sure that all parts of the system continue to work properly [2]. Over the past two decades, the WSP has been widely implemented in more than 93 countries across low-, middle- and high-income regions [2,3], yielding numerous benefits such as improved water quality, strengthened system management and enhanced collaboration among water supply companies [4–6].

Urban water supply mainly consists of four links, including the water source, drinking water treatment plant, municipal distribution system and building water supply system

(BWSS), with the overall goal of achieving water quality assurance from source to tap (Figure 1a). Generally, the finished water from the drinking water treatment plant (DWTP) meets the drinking water quality and hygiene standards. However, it may undergo complex physical, chemical and biological changes that can occur during the transportation process, resulting in a 20% decrease in the qualified rate of water user terminals [7], which is not conducive to meeting the growing demand for high-quality tap water driven by rapid socioeconomic development and improved living standards. The water quality changes and microecology in the municipal pipeline network have been thoroughly studied over the years [8–10]. Recently, the BWSS as the "last mile" of the urban water supply and a key link in ensuring drinking water safety, has also attracted increasing attention [11,12], and WHO also provides recommendations for the application of a WSP in building drinking-water installations [13].

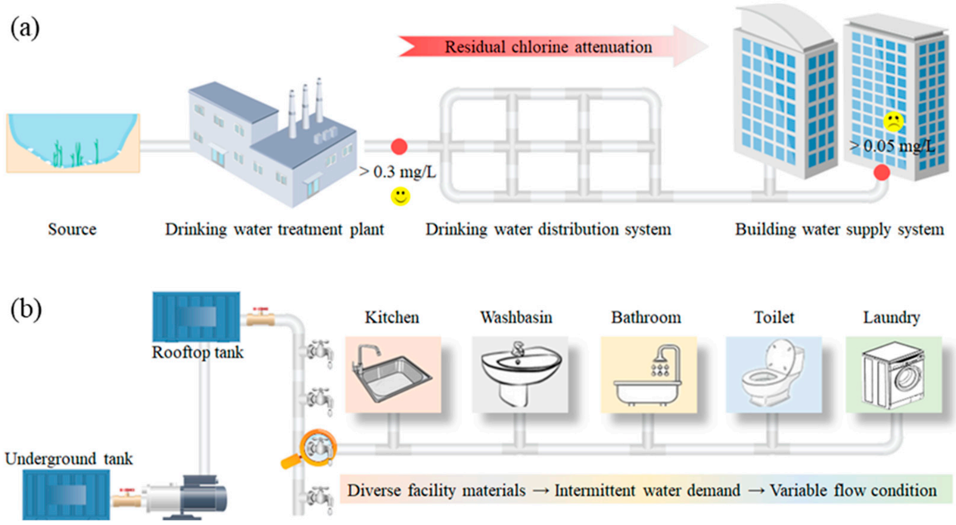

Figure 1. Schematic diagram of urban drinking water supply: (**a**) drinking water from source to tap; (**b**) secondary water supply system for buildings.

Municipal networks usually adopt low-pressure systems, for example, the municipal water supply pressure in China typically range from 0.15 to 0.35 MPa, which can satisfy the daily water consumption of residents on the third floor and below. With rapid urbanization, an increasing number of high-rise and super high-rise buildings have been constructed, putting forward a demand for adequate hydraulic pressure, which promotes the development of secondary water supply technology. Secondary water supply systems (SWSSs) consist of in-building infrastructures such as water tanks, pumps and pipes, and are employed to store, pressurize and transport water from the mains to the point of use (domestic taps) [14] (Figure 1b). Compared to municipal networks, SWSSs are typically characterized with diverse facility materials, intermittent water demand, variable flow condition and high water temperature, leading to a long hydraulic retention time (HRT) and attenuation of disinfectant residuals, which in turn cause a series of water quality issues [7,11,15], such as metal ion leaching, bacteria regrowth, biofilm formation and sediment accumulation. Therefore, it is necessary to take measures to ensure the water quality safety of BWSSs, meaning that the water quality meets national standards and is harmless to human health.

The choice of piping materials and the design of system layout are the sources that affect water quality. For example, the metal ions leached from pipes may pose health issues for consumers, the release of nutrients from polymeric materials can promote microbial growth, and excessive redundancy in system design (large water tank and pipe diameter) is likely to increase the HRT [7,16,17]. During long-term operation of the system, water pollution can hardly be completely avoided due to the above mentioned characteristics of BWSSs, and it is essential to set up (for new systems) and introduce (for existing systems) treatment technologies, especially secondary disinfection, which has been proved to be effective in guaranteeing the biosecurity of tap water quality [18–20]. However, the selection of disinfection types, the optimization of disinfection modes and the development of other applicable technologies still need to be explored in depth. Additionally, pollution incidents are common in BWSSs due to poor system monitoring and maintenance, such as "red water" or "yellow water" caused by aging and corrosion of pipelines, and exogenous pollution caused by pipeline leakage and misconnection [21–23]. It can be seen that improving the water quality in BWSSs by considering the entire cycle of system design, operation and maintenance is an effective and recommended way, as failures in any part of the system can lead to water quality issues at user terminals.

Currently, many studies have been conducted concerning BWSSs, focusing on the investigation, influencing factors and improving technology of water quality, but the understanding of BWSSs is still incomplete due to the scattered research directions [18,24–26]. A comprehensive review on control measures for water quality deterioration from the perspective of system configuration, purification and regulation is urgently needed, since no relevant review has been published, to the best of our knowledge. Based on previous reports, this study aims to summarize the measures for controlling the water quality deterioration in BWSSs from the following aspects: (1) delivering an overview of water quality pollution status and identifying the key control targets; (2) optimizing the system configuration to reduce pollution risks at the source; (3) enhancing purification technologies to improve water quality; (4) strengthening the system regulation to safeguard the water quality during operation. Due to the diverse and complex causes of water quality deterioration in BWSSs, it is challenging to draw generalized conclusions about specific implementations across various contamination scenarios. Therefore, we also aim to pinpoint gaps in knowledge and outline future research needs to enhance solutions for water security at user terminals. This study is of guiding significance for the design, operation, maintenance and management of BWSSs, and provides theoretical foundations and reasonably clear research directions for improving water quality in the future.

2. Pollution of BWSSs: Identifying the Key Control Targets

Periodic use and intermittent stagnation are distinctive features of BWSSs that may affect water quality, making deterioration a common issue during the water supply process in buildings (Figure 2). Water pollution in BWSSs includes both physicochemical and biological contamination. There is a strong need to identify the key control targets based on existing investigations (Table 1), which is the basis for secondary water supply quality assurance.

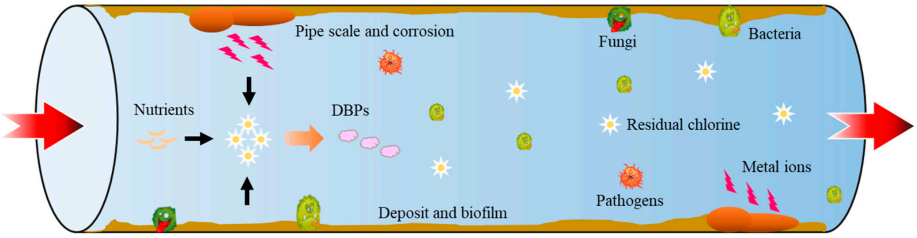

Figure 2. Schematic diagram of water quality issues in building water supply pipelines.

Table 1. Summary of reported water quality investigations for BWSSs.

Location	Building Type	Sample Type	Physicochemical Parameters	Biological Indicators	Reference
Beijing, China	Residential building	Tap water (*n* = 14)	Cu (0.069 ± 0.076 mg/L) Zn (0.10 ± 0.04 mg/L)	Class: *α-Proteobacteria* Family: *Hyphomonadaceae* Genus: *Phreatobacter, Porphyrobacter, Blastomonas Sphing-omonas*	[15]
	Office building	Tap water (*n* = 17)	Cu (0.005 ± 0.000 mg/L) Zn (0.40 ± 0.24 mg/L)	Class: *γ-Proteobacteria* Family: *Rhodocyclaceae* Genus: *Aquabacterium, Methyloversatilis, Hydrogenophaga*	

Table 1. *Cont.*

Location	Building Type	Sample Type	Physicochemical Parameters	Biological Indicators	Reference
Xiamen, China	Residential building	Input water ($n = 41$)	Turbidity (0.19 ± 0.10 NTU) Residual chlorine (0.57 ± 0.23 mg/L)	16S rRNA genes ($10^{3.08 \pm 0.91}$ gene copies/mL) *Legionella* spp. ($10^{0–3.87}$ gene copies/100 mL)	[11]
		Tank water ($n = 41$)	Turbidity (0.38 ± 0.33 NTU) Residual chlorine (0.44 ± 0.20 mg/L)	16S rRNA genes ($10^{3.63 \pm 1.10}$ gene copies/mL) *Legionella* spp. ($10^{0–6.71}$ gene copies/100 mL) *Enterococcus* ($10^{1.96–3.43}$ gene copies/100 mL) *Acanthamoeba* ($10^{1.91–2.38}$ gene copies/100 mL) *H. vermiformis* ($10^{3.43–4.01}$ gene copies/100 mL)	
		Tap water ($n = 39$)	Turbidity (0.28 ± 0.18 NTU) Residual chlorine (0.42 ± 0.21 mg/L)	16S rRNA genes ($10^{3.65 \pm 1.25}$ gene copies/mL) *Legionella* spp. ($10^{0–4.36}$ gene copies/100 mL) *Salmonella*, *Staphylococcus aureus* and *Aeromonas hydrophilia* ($10^{1.08–3.38}$ gene copies/100 mL)	
Fujian, China	Laboratory building	Tap water ($n = 24$)	Zn (7.716 mg/L) Fe (1.621 mg/L) Turbidity (1.02 ± 1.40 NTU) Residual chlorine (0.038 ± 0.036 mg/L)	*L. pneumophila* (Max: 1.95 × 10^5 copies/100 mL) *Salmonella* spp. (Max: 1.70 × 10^3 copies/100 mL) *Shigella* spp. (Max: 7.08 × 10^3 copies/100 mL) *E. coli* (Max: 7.24 × 10^3 copies/100 mL) *P. aeruginosa* (Max: 1.62 × 10^3 copies/100 mL)	[25]
	Teaching building	Tap water ($n = 24$)	Zn (6.378 mg/L) Fe (0.700 mg/L) Turbidity (0.20 ± 0.07 NTU) Residual chlorine (0.149 ± 0.132 mg/L)		
	Dormitory building	Tap water ($n = 24$)	Zn (3.082 mg/L) Fe (0.717 mg/L) Turbidity (0.23 ± 0.09 NTU) Residual chlorine (0.093 ± 0.074 mg/L)		
Taipei, China	Public and private buildings	Tank water ($n = 75$)	Turbidity (0.46 NTU) Residual chlorine (0.4 mg/L)	Total coliform (1/75) Total bacteria count (4/75)	[27]
		Tap water ($n = 87$)	Turbidity (0.44 NTU) Residual chlorine (0.3 mg/L)	Total coliform (3/87) Total bacteria count (8/87)	
Kaohsiung, China	Public and private buildings	Tank water ($n = 55$)	Turbidity (0.94 NTU) Residual chlorine (0.3 mg/L)	Total coliform (0/55) Total bacteria count (12/55)	
		Tap water ($n = 56$)	Turbidity (0.57 NTU) Residual chlorine (<0.1 mg/L)	Total coliform (4/56) Total bacteria count (24/56)	
Shanghai, China	Residential building	Tap water ($n = 17$)	Total chlorine (0.35 ± 0.36 mg/L) TOC (4.28 ± 1.48 mg/L)	Phylum: *Proteobacteria*, *Firmicutes*, *Bacteroidetes*, *Nitrospirae*, *Actinobacteria*, Genus: *Sphingomonas*, *Prevotella*, *Nitrospira*, *Novosphingobium*, *Methylobacterium* *Legionella* spp. (77–8.4 × 10^3 gene copies/mL) *Mycobacterium* spp. (61–2.1 × 10^4 gene copies/mL)	[12]
		Rooftop tank water ($n = 10$)	Total chlorine (0.48 ± 0.31 mg/L) TOC (4.28 ± 1.94 mg/L)		
		Underground tank water ($n = 8$)	Total chlorine (0.69 ± 0.36 mg/L) TOC (4.64 ± 0.38 mg/L)		
Amman, Jordan	Laboratory building	Tank water ($n = 68$)	Turbidity (0.3–1.7 NTU) Residual chlorine (0.0–0.30 mg/L) TOC ((1.94–4.28 mg/L)	Log mean plant count ((1.0–6.8 CFU/mL)	[28]
Shanghai, China	Residential buildings	Tank water ($n = 30$)	-	Bacteria Phylum: *Proteobacteria* Class: *α-Proteobacteria*, *γ-Proteobacteria* Genus: *Nitrospira*, *Pseudomonas* Eukaryotes Protists ((31.23% ± 19.83%) Metazoan (20.91% ± 16.41%) Fungi (9.14% ± 8.62%) Amoebae Amoebozoa (91.15% ± 17.02%) Rhizaria (6.62% ± 16.16%) Opisthokonta (1.29% ± 3.54%) Excavata (0.94% ± 3.60%)	[29]
		Tap water ($n = 16$)	-		
		Biofilm ($n = 27$)	-		
		Sediment ($n = 27$)	-		
Beijing, China	Unspecified	Tap water ($n = 22$)	Fe (0.04 ± 0.02 mg/L) Turbidity (0.19 ± 0.24 NTU) Total organic carbon (2.06 ± 0.48 mg/L) UV (0.01 ± 0.01 cm^{-1})	Phylum: *Proteobacteria* Class: *α-Proteobacteria*, *γ-Proteobacteria*	[24]

2.1. Physicochemical Pollution

In SWSSs, elevated levels of heavy metals like iron (Fe), zinc (Zn), copper (Cu) and lead (Pb) have been detected, with considerable variations among different functional areas. For example, Cu levels were relatively high in residential tap water (0.069 ± 0.076 mg/L), while a high Zn content was observed in office building tap water (0.40 ± 0.24 mg/L) [15]. The long HRT within SWSSs may promote the leaching of Zn^{2+} and Fe^{2+}/Fe^{3+}, resulting in lower Fe concentration in water from frequently-used taps than less-used taps [15], and the concentrations of Zn and Fe were found to dramatically exceed the standard values of drinking water (1000 µg/L and 300 µg/L) after an extremely long period of stagnation (COVID-19 pandemic) [25]. Long-term exposure to and consumption of drinking water with excessive metal content may lead to skin, gastrointestinal and neurological damage, so the heavy metal pollution issues should be given sufficient attention. Moreover, the residual chlorine concentration in water storage tanks is difficult to meet China's drinking water standard (0.05 mg/L) [14], especially in summer [11]. Compared with the input water, increased turbidity and reduced residual chlorine were observed in both tank and tap water [11,27]. The notable rise in turbidity may be linked to the total bacteria in water [11], corrosion of metal tank walls [30] and localized scaling caused by microbial metabolic products [31]. Moreover, drinking water turbidity has been confirmed to correlate with potentially preventable gastrointestinal illness risk in high-income regions, such as France and Spain [32]. Whereas, the reduction in residual chlorine is often accompanied by the increase of disinfection byproducts (DBPs), which may exacerbate toxic effects on human organs and increase the risk of cancer [33].

2.2. Biological Pollution

2.2.1. Microbe Count

Biological pollution is a more serious issue in BWSSs, and is closely related to the physicochemical parameters of water quality. A survey of tank and tap water from 178 buildings in Taipei, Taichung and Kaohsiung showed that 35% of the 323 samples failed to meet the drinking water standards. Most of the noncompliant samples were collected from taps, with the main parameters exceeding the standards being total bacteria counts and total coliform groups [27]. Water stagnation is a significant factor contributing to increased microbial growth, with large quantities of bacteria, fungi and other microorganisms detected in storage tanks worldwide [12,28,31]. As a result, customers utilizing the tap water from tanks or pools may be at a heightened risk of microbial exposure. Concretely, 16S rRNA genes were higher in taps and rooftop tanks relative to underground tanks and the distribution main ($p < 0.05$) [12], and a high microbial biomass was found in the spare tank [26]. Compared with short-term stagnation, a higher number of culturable bacteria were detected after the longer retention [25]. Notably, residual chlorine exhibited a significant correlation with heterotrophic plate count (HPC) ($p < 0.05$) [25], and could serve as a timely indicator for the microbiological safety of tap water with prolonged stagnation, since it is more easily detected in real time.

2.2.2. Microbial Community Characteristic

The microbial communities in BWSSs comprise mainly bacteria, dominated by *Proteobacteria*, with lower abundances of *Bacteroidetes* and *Actinobacteria*, while rare taxa are distributed across various phyla [15,34,35]. At the genus level, *Pseudomonas*, *Phreatobacter* and *Nitrospira* have been identified as the most dominant taxa [11,29], some of which exhibited season-dependent characteristics. For example, *Pseudomonas* became the dominant groups in summer water, while *Phreatobacter* was the abundant genus in autumn, winter and spring water [11]. Building type also affects the microbial community diversity, with higher values are detected in offices than residential buildings [15]. Moreover, biofilms on the tank and pipe walls create a suitable environment for a variety of microbes by supplying nutrients and offering protection [36]. The microbial community in biofilm is typically distinct from that in bulk water, with lower richness and evenness [34], although many shared taxa exist as a result of bulk water seeded with biofilms. Biofilm and sediments in BWSSs are key ecological niches for nitrifiers such as *Comammox*, playing a crucial role in drinking water nitrification [37]. In contrast, the eukaryotes in BWSSs have not been adequately studied. A survey of SWSSs in 23 residential buildings revealed that protists had the highest average abundance, followed by metazoan and fungi [29]. *Ascomycota* and *Basidiomycota* were identified as predominant fungal classes, and there was a notable proportion (48.58% ± 34.14%) of fungal sequences that could not be further classified [29].

2.2.3. Opportunistic Pathogen Distribution

BWSSs may harbor pathogens that can infect immunocompromised individuals, and many potential pathogens appear to be enriched within biofilms [34,38]. Consumers using the tap water from SWSSs may undertake higher risks of pathogen exposure, as opportunistic pathogens are more frequently detected in SWSSs [11,12,39]. Pathogenic bacteria typically possess the ability to grow at low dissolved oxygen and in nutrient-poor conditions, form biofilms, resist disinfectants and thrive within free-living amoeba, which make them well adapted to BWSSs [40].

Mycobacteria spp. and *Legionella* spp. were identified as the most abundant pathogenic bacteria in BWSSs [11,12,41]. *Mycobacteria* spp. exhibited the highest abundance in tap water, while *Legionella* spp. were detected more frequently in tank water (35%) than tap water (21%) and input water (9%) [11]. *Mycobacterium* spp. contain multiple species of opportunistic pathogens, with *Mycobacterium avium* being of particular concern, which has been detected in approximately 35% of showerhead biofilm samples in the US [38]. *Legionella* spp. includes 20 species associated with human disease, and it has been detected in up to 40% of homes in the US and over 60% of public buildings in Hungary [41,42], with *Legionella pneumophila* being the most well known. *Legionella* spp. has been proposed as an additional indicator for assessing the microbial safety in BWSSs [11]. A survey among the European Network of Drinking Water Regulators revealed that an upper limit of 10–100 CFU/L for *Legionella* is applied in 67% of the responding countries and regions [43]. Although the risk assessment by the WSP approach in some buildings has shown a lack of practical relevance, especially in determining the occurrence of risks related to microbial growth [43], exploring and utilizing advanced technologies to accurately identify more potential pathogens at the higher level (species or strains) remains a priority for future research.

3. Configuration of BWSSs: Reducing Pollution Risks at the Source

The water pollution sources in BWSSs mainly come from low-quality materials (pipes or tanks), aged facilities, pipeline corrosion, dust deposition, etc., and water supply strategy is also a crucial factor influencing water quality. To ensure tap water safety, the first priority is to mitigate water quality pollution at the source.

3.1. Characteristics of Facility Material

3.1.1. Water Tank

In the last few decades, a variety of materials have been employed to construct water storage tanks in SWSSs. It is well known that traditional roof tanks are made of reinforced concrete, but their inner walls are rough and prone to detachment. Lining these tanks with smooth and harmless materials such as polyethylene (PE) and stainless steel is a recommended strategy for renovating old buildings to alleviate the water pollution [44]. During the development of secondary water supply projects, poor heat dissipation performance of plastic steel water tanks and bad corrosion resistance of cast iron water tanks are gradually eliminated [45], and many environmentally friendly materials such as fiberglass and stainless steel have been promoted for commercial water tanks. Fiberglass is not easily corroded, but tanks made from this material need frequent cleaning due to rapid bacteria growth inside. Stainless steel tanks have the structural advantage of no translucency and are widely used in newly constructed residential buildings [17]. Various tank materials have different effects on water quality and microbial communities (Table 2). Among cast iron, fiberglass and PE tanks, the microbial taxa from tanks made of the same material showed higher similarity, with *Bacillus* spp. and *Moraxella* spp. being more abundant in cast-iron tanks, whereas *Arthrobacter* spp., *Pseudomonas–Alcaligenes* and *Aeromonas* showed higher proportions in fiberglass and PE tanks [28]. The relative abundances of certain amoeba genera, such as *Vannella*, *Stenamoeba* and *Vexillifera*, as well as the detection frequency of AOA *amoA* genes, were lower in stainless steel tanks compared to PE and ceramic tanks [29,37].

Table 2. Impact of facility materials on the water quality of BWSSs.

Facility Material	Facility Type	Key Findings	Reference
Cast iron, PE and one fiberglass	Tank	(1) Relative abundance of *Bacillus* spp. and *Moraxella* spp.: cast iron > fiberglass and PE (2) Relative abundance of *Arthrobacter* spp., *Pseudomonas–Alcaligenes* and *Aeromonas*: fiberglass and PE > cast iron	[28]
SS and ceramic	Tank	(1) Relative abundances of some amoeba genera: SS < ceramic (2) Significant differences were observed in amoeba communities among water samples collected from SS and ceramic tanks	[29]
SS, PE and ceramic	Tank	(1) Detection frequency of AOA *amoA* genes: SS < PE < ceramic	[37]
Galvanized steel vs. steel plastic	Pipe	(1) Color degree (CU): 11.8 vs. 8.1; (2) Turbidity(NTU): 8.2 vs. 0.74 (3) Fe (mg/L): 0.455 vs. 0.175; (4) Residual chlorine (mg/L): 0.25 vs. 0.28	[7]
PPR, SS and copper	Pipe	(1) Biofilm biomass: PPR > copper > SS; (2) EPS content: copper > PPR > SS (3) *B. cereus* grown displayed more biofilm biomass in PPR and SS pipes (4) *Acinetobacter* displayed more biofilm biomass in SS and copper pipes	[46]
Copper and PE	Pipe	(1) Biofilm formation rate: copper < PE (2) Number of virus-like particles in water and biofilm: copper < PE	[47]
Copper, PVC-C, PE and PVC-P	Pipe	(1) ATP concentration in water and biofilm: copper < PVC-C < PE < PVC-P (2) Gene copy numbers of *Legionella* spp., *Mycobacterium spp.*, *Pseudomonas* spp., *Aeromonas* spp., fungi and *Vermamoeba vermiformis* were higher for PVC-P and PE than for copper and PVC-C	[48]
PPR, PVC and SS	Pipe	(1) HPC in biofilm: PVC > PPR > SS; (2) *Escherichia coli* in biofilm: PVC > SS >PPR	[49]
Copper and PEX	Pipe	(1) Number of *L. pneumophila* (< 41 °C): copper < PEX (2) Differences between copper and PEX diminished with elevated temperature	[50]

Note: PPR (polypropylene random); SS (stainless steel); PVC-C (chlorinated polyvinyl chloride); PVC-P (plasticized polyvinyl chloride); PE (polyethylene); PEX (crosslinked polyethylene); EPS (extracellular polymeric substance); ATP (adenosine triphosphate).

3.1.2. Pipeline

Compared to municipal pipelines, the building water supply pipelines are typically smaller and have a greater surface area to volume ratio between pipe wall and bulk water, which increases the impact of materials on water quality (Table 2). Pipe materials may affect the attenuation of disinfectants and formation of DBPs [51,52]. For plastic pipes, the release of microplastics caused by hydraulic shock may contribute to DBP formation [53], and the haloacetic acids (HAA) formation rate was highest in high-density PE (HDPE) pipes, followed by polypropylene (PP) and polyvinyl chloride (PVC) [54]. For metal pipes, varying degrees of corrosion can occur during transportation, leading to the release of metal ions (e.g., Fe^{2+}/Fe^{3+}, Cu^{2+}, Pb^{2+} and Zn^{2+}) [7,55], which was identified as the main risk at the consumption point in a risk assessment study of a drinking water supply system [56]. These ions may participate in continuous chlorination, altering the formation of DBPs and posing health issues to consumers. The formation of trihalomethanes (THMs) in stainless steel pipes was higher than PE pipe [57].

Moreover, the release of nutrients from polymeric materials, such as phosphorus and organic carbon, can promote microbial growth [16]. The biofilm biomass in polypropylene random (PPR) pipes was found to be higher than in copper and stainless steel pipes [46], and the bacteria in PE pipes reached steady state faster than in copper pipes [47], which is perhaps due to the antimicrobial properties of copper pipes [48]. The growth of the same bacteria can vary greatly depending on pipe materials, with *Escherichia coli* being detected more frequently in stainless steel pipes than in PPR pipes [49]. Chlorine-resistant bacteria can still form biofilms and grow with varying efficiency in pipes at chlorine concentrations above 0.6 mg/L, such as *Pseudomonas*, *Acinetobacter*, *Mycobacterium*, *Bacillus*, *Acidovorax* and *Sphingobium* [58]. Their proportion in biofilms varies between plastic and metal pipes [48,59], which may lead to different security hazards. Additionally, it should be noted that the impact of facility materials on water quality was also related to water stagnation time and temperature. Under conditions where bulk water can be continuously refreshed, there are only minor discrepancies in residual chlorine, turbidity, biomass and microbial community structure between the concrete tile and stainless steel tanks, and biological contamination is not severe [11]. At temperatures below 41 °C, copper pipes supported fewer *L. pneumophila* compared to PEX pipes, and the differences in microbial community composition between pipe materials decreased with rising temperatures [50]. Currently, PE, PPR, stainless steel, copper, etc., are widely applied in building plumbing throughout the world [49,60]. Taking into account the height, function and structure of buildings, as well as the water quality and water usage patterns, selecting the appropriate material for pipes, tanks and accessories is essential to ensure clean and stable tap water.

3.2. Design and Layout Form

3.2.1. Water Tank

The water supply strategy of SWSSs is mainly reflected in the layout of the water storage tank, which can be categorized into three forms (Figure 3), including rooftop-only systems, underground-only systems and underground–rooftop systems [11,12]. The tap water microbiome differed significantly depending on the water supply strategies, even if the fitting materials and intrabuilding environment were consistent [15]. In rooftop-only systems, the microbial community underwent a similar degree of change during transmission from the mains to the rooftop tank and then to the taps [12]. In underground-only systems, there was less community shifts in the water supply transfer process [12]. For the special mode of double tanks, the spare tank showed higher levels of bacterial 16S rRNA gene abundance, pathogens-like sequences and antibiotic-resistant genes than the used tank due to the longer HRT [11]. In underground–rooftop systems, higher variance was observed in the similarity levels between the rooftop tank and the tap water, compared to levels between the rooftop tank and the underground water ($p < 0.05$) [12]. Moreover, the mode of water supply significantly affected some opportunistic pathogens. Compared to underground-only and underground–rooftop systems, household taps served by rooftop-only systems had lower *Legionella* numbers ($p < 0.05$) and higher mycobacterial densities ($p < 0.05$) [12,29]. However, the layout of water tanks had no significant impact on pathogenic eukaryotes [29].

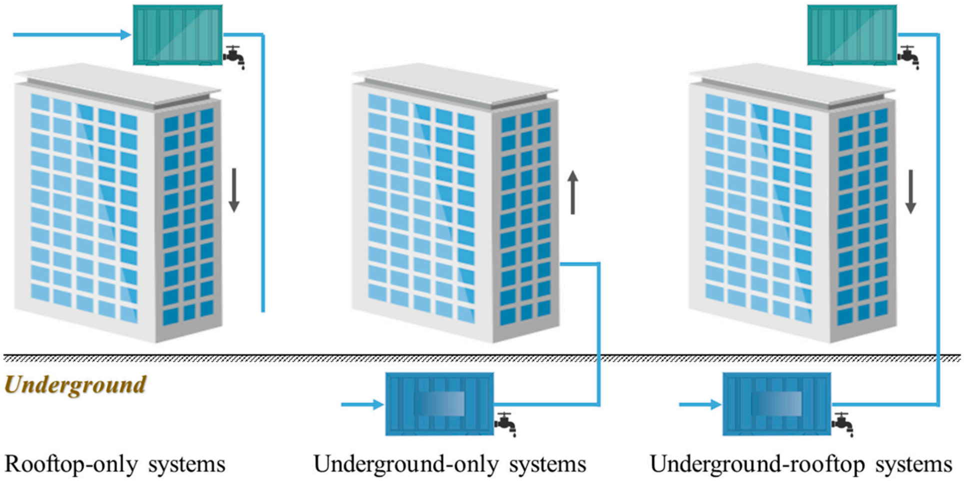

Figure 3. Schematic diagram of water storage tank layout in secondary water supply systems.

The mismatch between water demand and storage tank size is the main cause of low water turnover and prolonged stagnation [17]. Prior to 2004, fire demand and domestic water share the storage tank, resulting in excessive tank volume, long HRT and the presence of a dead water region [7]. In order to solve these problems, a series of optimized designs were taken on water storage tanks. For instance, the fire water tank and domestic water tank are separated to reduce the volume of domestic water tank and so as to shorten the HRT; the deflector plate is set up in the domestic water tank to avoid a dead water region and short-circuiting; and the location of the manhole is changed from the upper part to the side of the water tank to reduce water tank contamination by the external environment.

3.2.2. Pipeline

Currently, the building water supply network is mainly arranged in the form of branches. Low flow velocity and branched pipes lengthen the HRT of water, which may result in occasional turbidity exceedances and chlorine residuals falling below 0.05 mg/L, ultimately leading to elevated microbial indicators [7]. Water consumption in a low-occupancy residential community located at the end of a branched network is always very low. It is recommended to flush the taps for 5 min before use for low-occupancy floors, which can basically discharge the water retained in the building pipes and eliminate the impact of stagnation on tap water quality [61]. A better strategy to solve this issue is to design the building water supply network in a reasonably circular form, so that the "stagnant water" inside the pipe can be turned into "flowing water", effectively reducing the HRT of the drinking water. The looped pipeline layout form at the end of the water supply has been widely applied in various buildings in developed countries of the European Union (Figure 4), and the relevant technical regulations, design standards, maintenance and management systems have been relatively complete and mature [62,63].

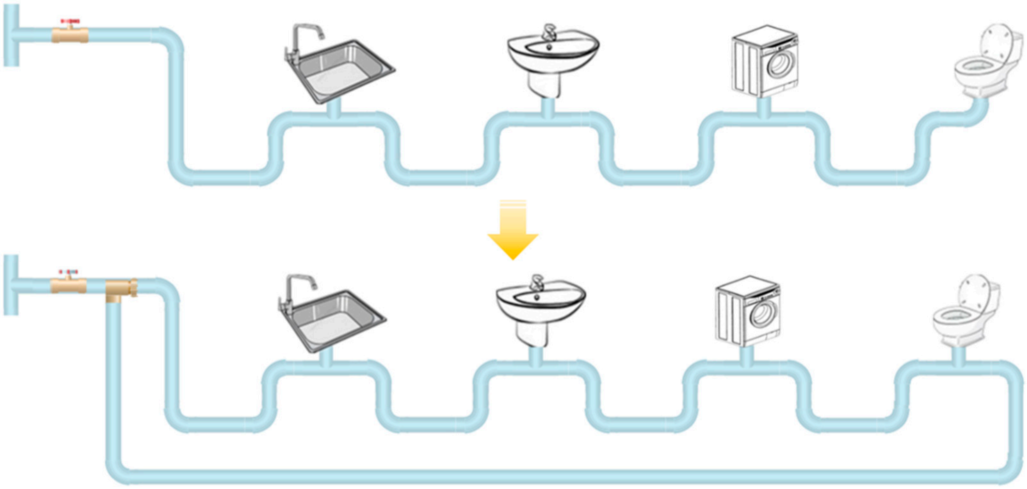

Figure 4. Evolution of the pipeline layout form at the end of the water supply.

4. Purification of BWSSs: Improving Water Quality by Introducing Treatment Technology

An extended stagnation period during low water consumption and the detached biofilm from the pipe wall can exacerbate water quality deterioration in the BWSSs [11,20]. Considering the stability and microbial safety of tap water quality, some water treatment technologies are commonly required to be introduced to BWSSs, such as membrane filtration and disinfection (Table 3) [20,64,65].

Table 3. Summary of the treatment technologies for improving water quality in BWSSs.

Treatment Technology	Operating Condition	Treatment Effect and Economic Benefit	Reference
Ultrafiltration (UF)	Flux: 10 L/(m^2•h) without residual chlorine	(1) Total organic carbon (TOC) and UV_{254} were reduced in the effluent (2) Successfully achieved zero fouling of UF membrane	[64]
Ultraviolet (UV)-UF	UV dose: 40 mJ/cm^2 UF membrane effluent rate: 40 mL/min	(1) *Legionella* spp., *Legionella pneumophila*, *Mycobacterium* spp. and *Acanthameoba* spp. were undetected in the water (2) Mitigate biofouling of UF membranes	[65]
Chlorine	Short-term chlorination 0.1 and 0.2 mg/L	(1) Biofilm: inactivation rate over 98% at 2 h (2) Water: regrowth of bacteria was effectively controlled within 24 h.	[20]
	Continuous chlorination 0.1 and 0.2 mg/L	(1) Continuous secondary chlorination significantly enhanced the inhibition of bacterial regrowth in biofilm and water (2) Bacterial diversity and potential pathogens reduced after continuous secondary chlorination	
	Shock disinfection (3 mg/L)	(1) 3.0 mg/L, CT = 300–400 mg•min/L: biofilm inactivation rate > 95% (2) Biofilm structure is disrupted and thickness is reduced	[19]
Chloramine	Shock disinfection (3 mg/L)	(1) 3.0 mg/L, CT = 300–400 mg•min/L: biofilm inactivation rate > 95% (2) Biofilm structure is disrupted and thickness is reduced	[19]
UV	6-lamp UV disinfection reactor Various lamp operation modes for different time periods	(1) The economical-running strategy for the UV disinfection reactor was predicted to reduce 32% of energy, corresponding to a daily electrical energy cut of 4.8 kWh	[66]
UV–Chlorine	UV: 40–100 mJ/cm^2 Chlorine: 1–5 mg/L	(1) The technology has been applied in a residential district of Suzhou, China, and the qualified rate of water quality increases from 61% to 100%	[67]

4.1. Ultrafiltration

At present, some BWSSs incorporate water treatment units to improve water quality and reduce microbial risks, among which ultrafiltration (UF) is a commonly applied technology [64,65]. UF exhibits excellent purification effects for a variety of organic and inorganic substances, as well as for microorganisms. Even for hard-to-remove micropollutants such as antibiotics and hormones, it may achieve retention efficiencies of 60–90%, with the specific effectiveness depending on the molecular structure of residual compounds and the characteristics of the membrane material [68,69]. The permeate of UF is usually stored in the circulation tank and can be directly supplied to the users after appropriate disinfection [70]. During the operation of UF, the intercepted substances can lead to membrane fouling, such as microorganisms and their metabolic byproducts [71], requiring frequent physical and chemical cleanings to control the increase of fouling resistance [72]. The need for maintenance-intensive cleanings conflict with the low-maintenance requirements for BWSSs, given their small scale, low capacity and lack of dedicated maintenance personnel [73]. Existing research reported that zero fouling can be achieved either at a flux of 10 L/(m^2 h) without residual chlorine, or at a higher flux with intermittent filtration [64], advancing the development of cleaning-free and low-maintenance membrane processes. Additionally, ultraviolet (UV) pretreatment was found to effectively reduce the ultrafiltration biofouling in BWSSs [65].

4.2. Disinfection

Chlorine residual is the most important factor in inhibiting bacterial regeneration and controlling microbial risk in drinking water. Its concentration at the end of the pipeline network shall not be less than 0.05 mg/L and 0.2 mg/L according to "Standards for Drinking Water Quality" issued by China [14] and Drinking Water Quality Guidelines issued by the World Health Organization [1]. As is well known, maintaining chlorine residuals in BWSSs is challenging due to water stagnation [17,28], and a reliable method is secondary disinfection. At present, diverse disinfection strategies have been implemented at the building level, such as chlorine, chloramine, UV and so on (Figure 5) [18–20,67].

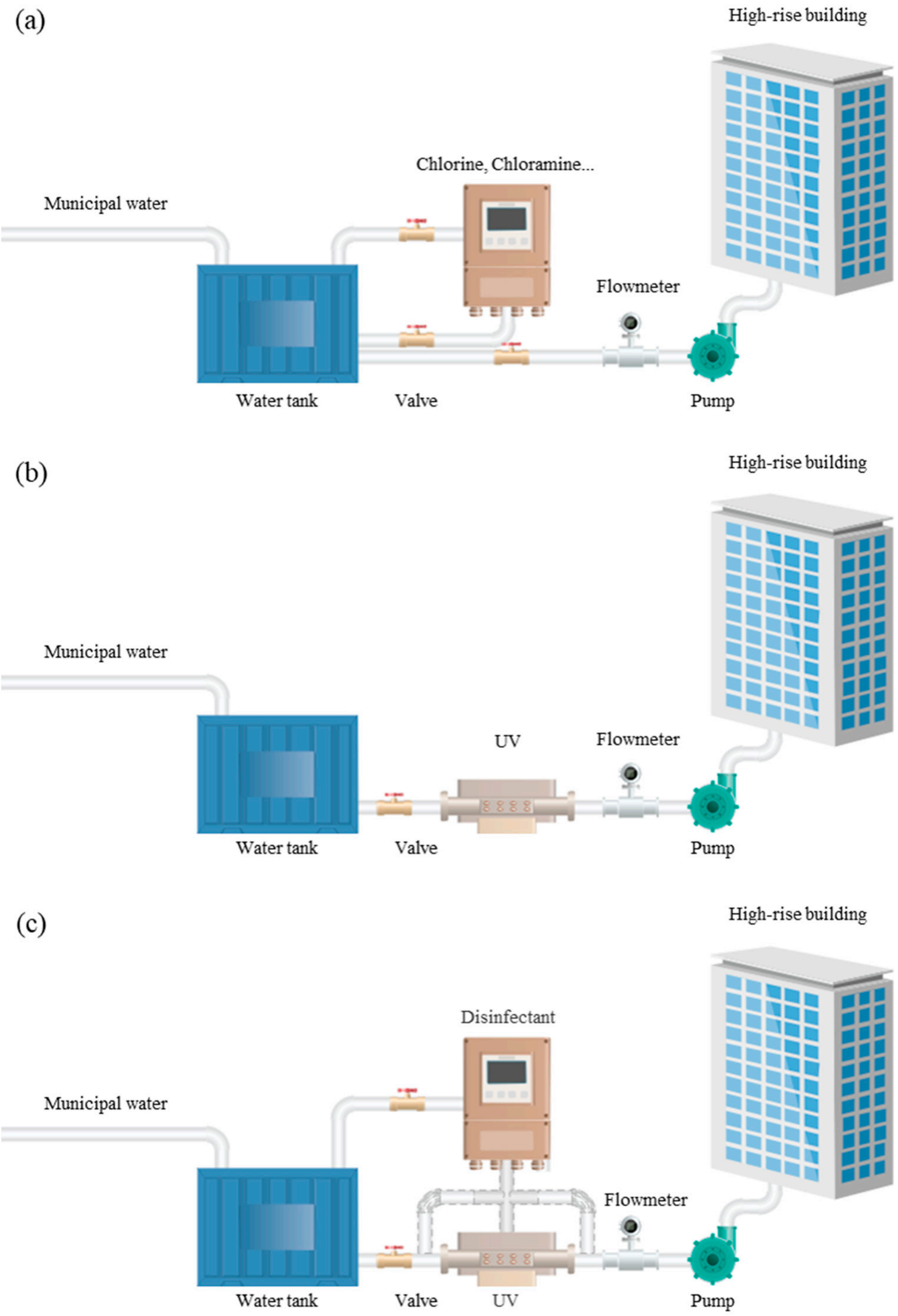

Figure 5. Secondary disinfection strategies for BWSSs: (**a**) chlorine or chloramine disinfection; (**b**) UV disinfection; (**c**) compound disinfection.

4.2.1. Chlorine

Chlorine in the forms of chlorine gas, sodium hypochlorite or calcium hypochlorite, is a widely used for primary and secondary disinfection of drinking water, as well as for controlling pre-established biofilms. Chlorine can react not only with cell walls and membranes, but can also penetrate the cytoplasm and act on DNA. Additionally, it is effective for micropollutants having electron-donating aromatic group and amines [74]. The main adverse effect of residual disinfectants is the formation of DBPs through their reaction with residual natural organic matter, and several DBPs have been recognized as carcinogens [75].

When supplementing chlorine in BWSSs for secondary disinfection, concentration control is crucial since high concentrations can negatively affect the taste, while low concentrations may fail to exert antibacterial effects. The residual chlorine concentration at the inlet of water tanks is recommended to be no less than 0.35 mg/L in winter and 0.45 mg/L in summer [76], and the compliance rate of tap water can reach 95% when the residual chlorine concentration at the outlet of water tank is 0.13 mg/L [77]. In recent years, intelligent sodium hypochlorite replenishment equipment has been developed and applied to BWSSs [78]. When chlorine was added jointly at the inlet of the high and low water tanks, the residual chlorine concentration at the outlet of the water tank was maintained at 0.2–0.45 mg/L during the chlorine supplementation period and above 0.05 mg/L at all times of the day, providing assurance for drinking water safety [78].

Chlorine plays a significant role in shaping bacterial and eukaryotic communities [79,80], despite a rich microbiome existing in drinking water regardless of the presence of disinfectant residuals. Continuous chlorination was more effective at controlling biofilms and bacterial regrowth in water than short-term chlorination, and distinct responses were observed between abundant and rare taxa [20]. Furthermore, chlorine was reported to have a strong negative impact on the richness of the eukaryote community [80]. After chlorination, *Proteobacteria*, *Firmicutes*, *Actinobacteria* and *Bacteroidetes* continued to dominate the biofilm bacterial communities in BWSSs [81,82], and the species richness of the genera *Mycobacterium*, *Pseudomonas*, *Sphingomonas*, *Undibacterium*, *Phreatobacter* and *Methylobacterium* increased [10,83].

4.2.2. Chloramine

Chloramine is also a commonly used disinfectant in drinking water systems, and has good diffusion ability within the biofilm matrix due to its greater stability and lower reactivity than chlorine [84,85]. Additionally, chloramine is beneficial in preventing high levels of DBPs [86]. Wang et al. studied the chloramine shock disinfection of secondary water supply pipelines and found that 3 mg/L chloramine had a heterotrophic bacteria inactivation rate of over 95% on the pipe wall biofilm [19]. Plumbing systems treated with chloramine showed lower levels of *Legionella* than those treated with chlorine [87]. Additionally, the *Mycobacterium* spp. and nitrifying microbes (*Nitrosomonas* and *Nitrospira*) were the main genera that were prevalent and enriched in chloraminated systems due to the formation of ammonia during chloramine decay [88,89]. There were also several other prevalent genera, including *Methylobacterium*, *Escherichia*, *Desulfovibrio*, *Desulfomonile*, *Yersinia*, *Desulfuromonas* and *Geobacter* [89,90].

4.2.3. UV Irradiation

UV disinfection is common in water treatment across a range of systems, from small to large scale. UV radiation can penetrate cellular components and directly affect microbial DNA and RNA, forming pyrimidine dimers that prevent replication and transcription [91], while bacteria may undergo photoreactivation and dark repair after UV irradiation [92]. Existing studies have shown that low-pressure UV reduces cell counts determined by HPC and flow cytometry, and medium-pressure UV alters the microbiome in drinking water, resulting in a decrease in *Proteobacteria* and a predominance of *Actinobacteria* [93,94]. Even low doses of UV radiation (1 mJ/cm^2) can effectively inactivate cells, but UV irradiation can be negatively affected by water turbidity [95], leading to a significant reduction in UV effectiveness at high biomass concentrations.

In recent years, as high-rise buildings have proliferated in urban areas, the employment of UV disinfection in BWSSs has been recommended and prevalently practiced in China [96], due to the merits of minimal byproducts, a compact footprint, ease of operation and low maintenance cost. Compared with the conventional UV disinfection applications for municipal water and wastewater [97,98], the BWSS has its own characteristics, such as fluctuating flow rates, seasonal variations in water temperature, and frequent issues with inadequate quartz sleeve cleaning for UV reactors. It is crucial to recognize that substantial daily fluctuations in water flow rate and/or water temperature can cause considerable variations in the practical output fluence of UV reactors, and reliable online monitoring is essential for ensuring energy efficiency and safe operation. A tri-parameter online monitoring system was developed to measure the real-time fluence of UV reactors [99] and has been successfully deployed in a residential community located in Zhengzhou, China [18]. After long-term of monitoring (6 months), it was discovered that the traditional operating mode of UV reactors was unsuitable for high-rise buildings since there was significant energy loss during low-flow periods and insufficient disinfection during peak-flow periods [18]. The flow rate of BWSSs in high-rise residential communities fluctuates on a 24 h cycle [18], due to the differing real-time water usage by residents at different time periods of the day. Therefore, UV disinfection facilities should preferably be intelligently controlled according to its running status. Li et al. developed a cost-effective operating strategy for multilamp UV reactors in BWSSs, which was predicted to cut energy consumption by 32%, equating to a daily electrical energy savings of 4.8 kWh [66].

4.2.4. Combined Chlorine and UV Disinfection

A composite secondary disinfection method consisting of chlorine and UV is an effective choice for guaranteeing the water quality safety in BWSSs, since it not only leverages the benefits of both chlorination and UV irradiation but also has the potential to generate free radicals, such as hydroxyl radicals and reactive chlorine species, through the photolysis of chlorine [100]. During combined UV and chlorine treatment, different micropollutants can be degraded via diverse mechanisms. For example, chlorination (>60%), direct UV photolysis (>80%) and radical oxidation (>90%) contributed the most to the degradation of bisphenol A, diclofenac and caffeine, respectively [101]. Typically, secondary disinfection facilities are installed at the water tank outlet. By integrating reliable UV sterilizers with chlorine, the water quality compliance rate can be increased from 61% to 100%, and this technology has been successfully implemented in a residential community in Suzhou, China [67]. Chlorine and UV can be combined in different ways based on their relative positions, including sequential disinfection (Cl_2-UV or UV-Cl_2) and simultaneous disinfection (UV/Cl_2). However, the processing effects and applicable conditions of these different methods have yet to be thoroughly explored and elucidated for BWSSs.

5. Regulation of BWSSs: Ensuring Water Quality During Operation and Maintenance

During the long-term operation of BWSSs, poor management and bad maintenance are also important aspects leading to water quality deterioration. Although many developed countries have water safety control regulations until the point of use, water quality monitoring is often lacking in most buildings, especially private residences [102]. For example, in many European countries, it is not feasible to fully monitor the quality of drinking water within buildings due to restrictions imposed by drinking water authorities on accessing the interior spaces of people's houses [61]. Therefore, strengthening and optimizing the regulation of BWSSs is an indispensable measure to improve water quality.

5.1. Contingency Event Handling

5.1.1. Exogenous Pollution

Exogenous pollution is the main issue in SWSSs. Exogenous substances can enter storage tank due to poor management, such as drinking water pipelines were cross-connected with reclaimed water pipelines in toilets, rainstorm lead to wastewater to pour into buried storage tank, and the leakage of domestic sewage contaminated the water tanks [21]. Among them, domestic sewage pollution is the most severe type, as even low levels of domestic sewage intrusion can introduce various pathogens, posing a serious threat to water safety [21,103]. Once a perceptible change in water quality is detected, a series of emergency measures need to be taken as soon as possible, including stopping the water supply, increasing the doses of disinfectants and cleaning the storage tank. However, not all domestic sewage pollution comes with perceptible sensory properties or changes in turbidity that humans can detect, and it is these imperceptible contaminations that may exacerbate the health issues to consumers. Thus, early detection of sewage pollution is crucial for ensuring water safety, and intestinal bacteria represented by *E. coli* and *Enterococcus faecails* can serve as warning indicators, even at imperceptible levels [21].

5.1.2. Water Supply Interruption

Premise plumbing is characterized by start–stop flow patterns with highly variable velocities, making it more susceptible to biofilm detachment and resuspension of loose deposits, especially during water supply restoration following interruptions caused by power outages, long vacations, technical maintenance or pandemic lockdown [104,105]. The sudden hydraulic disturbances induced by water supply restoration can disrupt the stability of scales, biofilms and loose deposits formed in pipelines, resulting in sharp increases in turbidity, metal elements, adenosine triphosphate and number of amplicon sequence variants (ASVs) [22]. Generally, small pipes and low velocity accelerate the accumulation of particles and metals. Large pipes and high velocity facilitate flow regulation, reduce chronic load and help prevent discoloration [106], but promote biofilm growth [22]. To solve the conflicts when managing physiochemical and microbiological indicators, it is possible to consider proactively increasing flow rates on a controlled basis to achieve the so-called self-cleaning effect [106,107].

5.2. System Periodic Maintenance

5.2.1. Pipeline Aging

Aging pipes often adversely affect the delivery of drinking water to consumers, as they are more vulnerable to contaminants [108], and may lead to increased concentrations of metal ions and organic substances [8,109]. The longer the service life of the pipeline, the more substances accumulate in the form of biofilm matrices, pipeline scale and loose deposits [110], and these accumulations can directly affect the formation of DBPs. Turbidity, zeta potential, pH, bacterial abundance and microbial diversity have been successfully correlated with pipe age [24]. It is estimated that 22% of pipelines in the United States have been in use for over 50 years, and only 43% of pipelines are in good condition [111]. The average pipe age is estimated to be 75–80 years in the UK [112], while it is estimated overall to be at least 60 years for pipes in China, and "red water" issues have attracted the attention of responsible authorities [23,113]. The WSP approach can be considered for application as it shows more significant advantages for complex and older buildings [43]. Water utilities/authorities have proposed plans for upgrading aging pipelines to address water quality issues [114], but the implementation requires substantial and ongoing investment.

5.2.2. Water Tank Cleaning and Pipeline Flushing

The water storage tanks in SWSSs are usually not cleaned and disinfected regularly, especially in some old residential neighborhoods, which may lead to sediment accumulation [115,116], microbial growth and biofilm formation in the tanks [31]. High levels of heterotrophic bacteria were observed in PE tanks before cleaning and disinfection, posing a water-use risk [117]. Deterioration of water quality by sensory, chemical and biological indicators in SWSSs becomes more serious over time. In view of this, it is necessary to carry out regular cleaning and disinfection of the secondary water supply tanks. Disinfection time is usually not less than 30 min, and the disinfectant dosage is an important factor affecting the disinfection effect. The brand cleaning agent (Moesslein, TOPIX) with standard disinfection dose (25 L, 200 mg/L) to one-half of the standard disinfection dose (25 L, 100 mg/L) was reported to be effective in removing microorganisms, sediments and biofilms in the tank (volume 20 m^3) [117]. Optimizing cleaning and disinfection methods, reducing the disinfectant dosage while ensuring disinfection effectiveness, and improving economic benefits are the focus of future research.

For pipeline systems, regular flushing can reduce the net accumulation of particulate matter and keep water turbidity below standard levels, particularly in network endpoints, drainage valves and fire hydrants. A flushing procedure should be well defined based on the characteristics of the buildings, such as plumbing layout, pipe size and device features [118]. With the advancement of the Internet of Things (IoT), wireless sensors and remotely controllable devices equipped with preprogrammed flushing settings can now be installed [119,120]. Furthermore, there is an urgent need to establish protocols for implementing proper flushing procedures and for issuing official advisories. After flushing, adding a corrosion inhibitor is recommended to promote protective film formation inside the pipeline. Notably, flushing activities alone are insufficient to prevent water quality issues in complex plumbing systems, so routine water quality testing should be conducted to identify and mitigate potential health risks throughout the service life of buildings.

5.3. Intelligent Monitoring and Management

In recent years, the concept of a "smart water" proposal based on IBM's smart planet has gained popularity, which can provide real-time monitoring of SWSSs through advanced data acquisition and transmission technologies [67]. Correspondingly, a secondary water supply management information platform has been developed to make the BWSS operation more reliable and the management more intellectual, standardized, technical and user-friendly. The platform integrates advanced technologies including a geographic information system (GIS), IoT, remote communication and information science, to realize unified management, sharing and mining of data. Several subsystems with distinct functions including supervisory control and data acquisition (SCADA), comprehensive data query, project management, operation and maintenance, billing system, asset management, customer service and emergency alarming are consolidated into a monitoring and management system that can offer a diverse array of water supply services (Figure 6). The advantages of the intelligent management information platform include cost reduction, response time reduction and data publicity, among others. Such intelligent platforms have been deployed in several residential communities in downtown Shanghai [121], providing water utilities with comprehensive and reliable water-related information and offering a basis for scientific scheduling and decision-making.

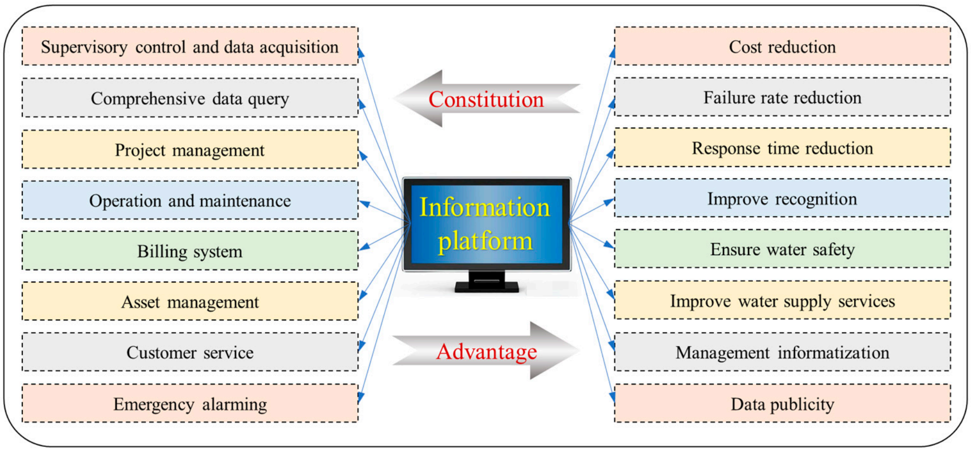

Figure 6. Constitution and advantages for integrating an intelligent water management information platform.

6. Conclusions and Outlook

In this work, a framework for mitigating water quality deterioration throughout the entire process was established (Figure 7), including risk factor identification, system design optimization, secondary purification application and management enhancement. Biological pollution may be more common and acute than physicochemical pollution in BWSSs and is affected by a variety of factors such as residual chlorine, stagnation time and temperature. In addition to potential pathogens, other risk factors present in deteriorating water quality, such as chlorine-resistant bacteria, antibiotic resistance genes (ARGs) and microbial metabolites, still require urgent attention. The selection of facility materials should comprehensively consider the height, function and structure of buildings, as well as the water quality and water usage patterns to minimize the water contamination at the source. Excessive redundancy in system design will directly affect HRT, which in turn leads to a series of water quality issues. The design of the water supply system should be based on the law of water usage, and it is essential to explore the looped pipeline layout form at the end of the water supply and optimize the water age through modeling to reduce the water stagnation time in the system. Introducing additional purification and disinfection technologies can help to address the pollution issues in existing systems and ensure the safety of tap water in new systems. The combined application scheme of continuous supplemental disinfection and periodic shock disinfection need additional investigation, and the response mechanisms of DBPs, microbial metabolites, ARGs removal and spread, etc., to different disinfection strategies have not yet been fully clarified. During the operation process, the timely handling of sudden pollution and the periodic maintenance of the system are indispensable. Expanding efficient and accurate online detection methods for water quality indicators to obtain timely information and feedback, and improving the module functions of the intelligent water management information platform are of great significance for pollution early-warning and guaranteeing water supply safety.

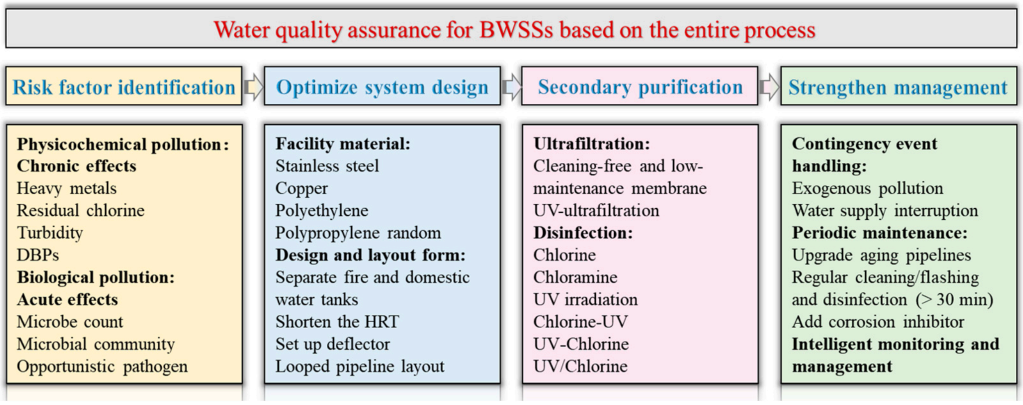

Figure 7. A theoretical framework for ensuring water quality in BWSSs throughout the entire process.

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