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Analysis of the impact of domestic distribution systems on the dynamics of changes in tap water quality as a necessary element of risk management in the Warsaw Water Supply System - a case study, Poland

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ABSTRACT

The European Parliament adopted the new Directive 2020/2184 on the quality of water intended for human consumption, imposing an obligation on the Member States of the European Union to carry out a risk assessment in the entire water supply chain, from supply areas, to domestic distribution systems. A sensitive area that requires effective risk management by creating appropriate protective barriers based on the procedures of Water Safety Plans, where secondary water contamination most often occurs is the stage of water distribution, both in the water supply network and in internal installations in buildings. The article presents the results of research on secondary water contamination in a large system of collective water supply for the inhabitants of the capital of Poland, Warsaw. The assessment of the daily variability of water quality in terms of microbiological indicators, heavy metals (zinc, copper, nickel, chromium, cadmium), and parameters affecting water acceptability, that is, color, odor, turbidity, and iron and manganese content, showed that the risk of secondary contamination in domestic distribution systems is high. The most common (above 80% cases) and the greatest increase in the concentration of heavy metals in the tap was recorded after overnight stagnation for zinc (average 150%, max recorded concentration 170 μg/L) and copper (average 109%, max recorded concentration 24 μg/L).

Keywords: Domestic distribution systems; Drinking water quality; Secondary water contamination; Heavy metals; Water Safety Plan.

1. Introduction

Adopted on December 16, 2020 by the European Parliament, Directive (EU) 2020/2184 on the quality of water intended for human consumption introduces many important legal regulations in the water supply, in terms of consumer health protection against the undesirable effects of drinking water contamination. Effective control of the Water Supply System (WSS) and the water safety is ensured by the obligation, formulated in the Directive, to implement an approach based on risk assessment and risk management in the entire water supply chain, from catchment areas, through water treatment plants, distribution system, to domestic distribution (plumbing) systems (DDS) [1,2]. By imposing an obligation on Member States to carry out a risk assessment, the Directive also indicates an approach to this task, consisting in the development of the so-called Water Safety Plan, which together with the EN 15975-2:2013 standard on the safety of drinking water supply, constitute internationally recognized standards on which the production and distribution of water intended for human consumption are based.

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The Water Safety Plan is a multi-barrier system, made for minimizing potential threats to water quality, recommended by the World Health Organization (WHO), based on risk assessment and management, the purpose of which is to ensure effective control of the WSS to supply water of the right quality and quantity. Its crucial element is hazard assessment, determination of critical points and risk assessment in the entire water supply system [2–7]. A sensitive area that requires effective risk management by creating appropriate protective barriers based on the procedures of Water Safety Plan, where secondary water contamination most often occurs is the stage of water distribution, both in the water supply network and in internal installations in buildings [8–10].

The provisions of the new Directive as well as literature reports [11–13] indicate that the quality of water intended for human consumption can be significantly affected by plumbing system. Domestic distribution systems can be a significant source of contamination, and inadequate management of such systems can contribute to illness or ill health among consumers [14,15]. Health exposures particularly affect the elderly, people with reduced immunity and children, so increased attention in the Directive is given to facilities such as hospitals, health care facilities, nursing homes, child care facilities, schools and educational institutions [5,16]. These facilities have been defined in the Directive as priority facilities.

Among the risks associated with plumbing, there is a wide range of contaminants released from the water supply network during the transportation of water to the consumer [7] or as a result of installation defects [8,9,17,18]. In turn, inadequate plumbing fixtures and indoor plumbing materials can cause the release of chemicals whose content in the water can vary depending on the age of the material and the time of contact with the water [12].

Installations made of copper [15,19] carry a risk of discoloration of sanitary equipment and clothing, and when the copper concentration exceeds 5 mg/L, the color of the water and its undesirable, bitter taste increase significantly. galvanized pipes [20] (corrosion protection) can release zinc from the protective layer. Zinc does not pose a health risk in concentrations typically found in drinking water (less than 0.1 mg/L) however, once concentrations reach about 4 mg/L, it affects the acceptability of water by imparting an astringent taste [21]. As with zinc, increased chromium content in water can be affect by plumbing fixtures treated with a protective layer, which is supposed to provide them with greater resistance to damage and harmful agents such as corrosion [22]. Chromium taken in excess poses a threat to living organisms, and excessive doses can cause disorders of the circulatory and respiratory systems, allergies, skin diseases and cancerous changes. In addition, excessive amounts of chromium(III) can accumulate in the body, manifesting mutagenic properties [23]. Cadmium compounds are commonly used in the manufacture of tap faucets. Cadmium contamination of water can also come from galvanized pipes, from welds and some metal parts of water supply fittings [24–26]. Cadmium and its compounds have been classified as possibly carcinogenic to humans because there is evidence of carcinogenic effects of cadmium absorbed by inhalation, but there is no evidence of carcinogenicity of cadmium taken orally [27].

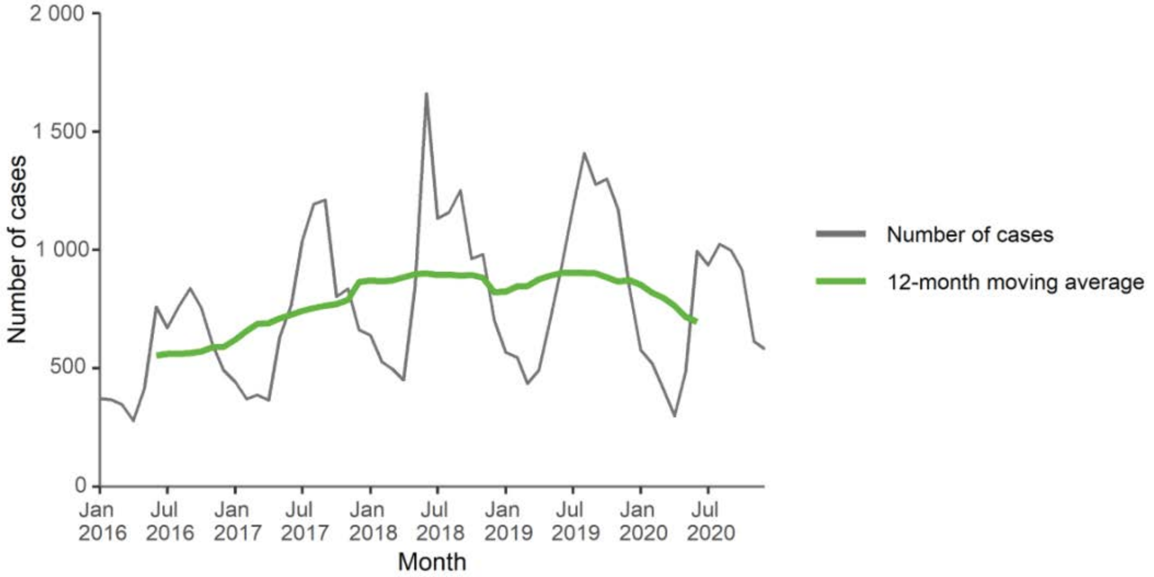
One of the most common abnormal changes in the quality of treated tap water sent to the consumer is increased iron content. High iron content in drinking water, leads to undesirable organoleptic changes, such as an increase in colour, turbidity, metallic taste, and the formation of ferruginous deposits in both the water supply system and indoor installations [8,18,28]. Secondary water contamination, as a result of dissolution of corrosion products as well as iron released from broken sediments in distribution system, is a common problem in WSS operation [29]. Secondary water contamination can also occur due to manganese [30], which occurs naturally in captured surface and groundwater, especially under anaerobic conditions and low water oxygenation. The presence of manganese in drinking water, as with iron, can lead to sediment deposition in the distribution system. In concentrations exceeding 0.1 mg/L, it imparts an undesirable taste to water and causes discoloration of sanitary appliances and clothes during laundering. The recommended value set for health reasons for manganese at 0.4 mg/L is higher than the acceptability threshold of 0.1 mg/L [31]. The presence of other metals, in the form of contaminants of natural origin or corrosion products, can also affect the increase of water colour, during the delivery process. For most people, water color is discernible when it exceeds 15 TCU (true color unit) [15].

The odour or taste of water, can be affected by a wide range of both microbiological and chemical factors and their deterioration can cause unacceptability of water to the consumer [32,33]. Deterioration of water odour in the distribution system, in addition to the corrosion products of pipes made of metals (steel, gray iron, ductile iron), can be influenced by the leaching of chemicals (antioxidants, plasticizers, solvents) from water pipes and systems made of plastic. Stagnant water conditions in infrequently used sections of water supply system and loss of oxygen can result in the reduction of sulfate(VI) by bacteria, most often resulting in the unpleasant odor of hydrogen sulfide.

During water distribution, an increase of turbidity may occur, as a result of organic and inorganic substances or a combination of both. An increase of the turbidity of water in the distribution system can be caused by, among other things, the penetration of corrosion products into the water, the fragmentation of biofilm, the resuspension of sediment accumulated on the walls of water pipes. The above-mentioned processes are favored by stagnant water, changes in flow and pressure in distribution or plumbing systems. A common phenomenon observed in water distribution systems is a short-term increase in water turbidity, resulting from a sudden release of sediment from the walls of water pipes, due to a sudden change in flow conditions. Turbidity is also an important indicator of potential microbiological contamination of water [18,34–36]. Secondary microbiological contamination of water may be a result of operational conditions of the distribution system (failures, leaks) and type of water treatment processes used at water treatment plant (selection of treatment processes, disinfection efficiency, organic matter reduction). In the distribution system, there can be an increase in the number of microorganisms, both in the watercourse (biomass clusters) and in the intra-pipe sediment and biofilm. Conditions conducive to bacterial growth are usually found at the ends of water mains and in oversized WSS, as well as in indoor installations of buildings [37,38]. The lack of microbiological stability of water is often associated with increased turbidity [8,18,39,40]. To assess the microbiological status of the water supply system, it is practiced to determine the total number of microorganisms at 22°C and 36°C in combination with monitoring of bacteria *Escherichia coli*, coliforms, turbidity and disinfectant concentration. In order to protect water against secondary microbiological contamination in extensive distribution systems, it is subjected to a disinfection process [41]. However, disinfection may also pose a potential threat of generating disinfection by-products (DBP) with carcinogenic properties for the water consumer [42], hence it is necessary in water supply risk management procedures to take into account the relationship between the microbiological stability of water and the potential to generate DBP in large water supply networks [40].

Bacterial proliferation in domestic distribution systems is facilitated by inadequate temperature, which can occur as a result of insufficient insulation or separation from hot water systems and as a result of improper operation, including the presence of stagnant water or previous colonization by bacteria. Opportunistic pathogens such as Legionella bacteria that multiply under the right conditions on surfaces and in water facilities can pose a significant health risk in plumbings, leading to the risk of infection by the droplet route as a result of inhalation of water-air aerosol. Literature data indicate that Legionella bacteria are the most common cause of water-dependent diseases [43–45]. According to the CDC's Waterborne Disease Outbreaks Annual Surveillance Report, Legionella is responsible for nearly half of recorded cases of illness and more than 90% of hospitalizations and deaths. The scale of Legionellosis pneumonia cases, in the countries keeping records, is shown in Fig. 1.

As mentioned above, the issue of secondary water contamination in water supply systems is an important study problem not only from a scientific point of view (analysis of the mechanisms and reason for secondary water pollution) but also from the aspect of health hazards to water consumers. However, there are no publications in the literature that would indicate how to select water quality parameters that strongly determine changes in the quality of water during transport to the consumer's tap, which should be taken into account in risk management not only for health reasons but also for the issue of acceptability the water quality by the consumer. Moreover, the group of these parameters should include water quality parameters, the dynamic in concentration variation of which should be taken into account in current operational decisions made by the operator. The purpose of the research, which consists of data obtained from distributed questionnaires and conducted studies of changes in water quality, was to identify potential factors and mechanisms determining secondary water contamination occurring in DDS of buildings in Warsaw's water supply system. Taking into account in this research the method of selecting the representative parameters of water quality in the assessment of its dynamics of changes from the intake to the consumer's tap, in conjunction with the identification of hazard factors in risk management, is an aspect of the novelty of conducted research. This research has a practical aspect, as it is part of the Water Safety Plan implemented by the Water Supply Company in 2022.



Source: Country reports from Austria, Belgium, Bulgaria, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden

Fig. 1. Distribution of Legionnaires' disease cases by month, EU/EEA, 2016–2020 [46].

2. Study subject

The objects that are the study subject are located in the capital of Poland - the city of Warsaw, where the water supplier is the Municipal Water Supply and Sewerage Company in Warsaw. The Warsaw agglomeration water supply system is supplied with water from two water treatment plants - the Central Plant, which includes two large water supply stations - Water Plant Filtry and Water Plant Praga, and the Northern Plant (Fig. 2). The source of water for the first two stations is infiltration water taken from the bottom of the Vistula River, and for the Northern Plant - surface water taken from the water reservoir Zegrze. Moreover, in the south-eastern part of the city, there are five small groundwater intakes supplying water to the Wawer and Wesoła districts.

The company supplies an average of about 340,000 m^3 of treated water per day to nearly 2.5 million consumers and operates a water supply network of about 4,400 km. The demand for water throughout the year is stable and does not fluctuate significantly.

Currently, Water Plant Filtry treats about 190,000 m^3 of water per day, which is more than half the demand of the Warsaw agglomeration. The station supplies water to the areas of the central and southwestern left-bank part of Warsaw (Fig. 2) and additionally to local towns: Pruszków, Piastów, Michałowice, Reguły, and parts of Raszyn. The Northern Plant, located in the suburban town of Wieliszew, is the second-largest source of water supply independent of the Vistula River's resources, providing about 30% of its total water demand. It supplies water to the northern districts of left- and right-bank Warsaw, including Białołęka, Bielany, Bemowo, Targówek, Praga Północ, part of Wola and Żoliborz. Water Plant Praga statistically supplies water to every fifth resident of Warsaw. It supplies water to Rembertów, Praga-Południe, Mokotów, Wilanów, Wawer and part of Wesoła and Powsin. The share of the plants in the total water demand is shown in Fig. 3.

Both the location of water intakes and the extensive and oversized water distribution subsystem in Warsaw translate into hydraulic conditions for the operation of the

Fig. 2. Area of water supply by Municipal Water Supply and Sewerage Company in Warsaw.

water supply network. Simulations of the operation of the water supply system using a mathematical model showed that even with maximum water consumption, water flow velocities in the distribution water supply network do not exceed 0.1 m/s, and at its ends, it drops even below 0.03 m/s. Thus, the hydraulic conditions prevailing in the Warsaw water supply network in each of the above-mentioned supply zones may promote the phenomenon of secondary water contamination. In order to minimize the risk of deterioration of the water quality supplied to consumers, approximately 80,000 flushing operations are carried out annually on the water supply network. Their effectiveness is confirmed each time by measuring the water turbidity, which in the vast majority confirms the appropriate water quality. However, the mere fact of flushing the water may imply a temporary change in the network's operating conditions and result in a short-term deterioration of water quality.

The company supplies water to both, institutional (housing cooperatives and communities, universities, associations, companies and health care facilities) and individual customers (Table 1).

Water supply zones are also characterized by a wide variety of uses of the buildings to which water is supplied (Table 2).

3. Study method

3.1. Questionnaire survey

As part of the research work carried out, in order to obtain basic information on plumbing systems in the water supply area of the city of Warsaw, a survey questionnaire was conducted to managers of educational buildings and health care facilities, which, according to Directive 2020/2184 [16], constitute a group of priority facilities. The Directive defines priority facilities as large non-residential facilities where a large number of users may be exposed to water risks, particularly large public buildings. The survey process also included residential buildings managed by housing cooperatives located in the water supply area. The surveys were addressed to more than thirty administrations of multi-family buildings, ten city hospitals and more than forty educational institutions. To obtain information on the state of the domestic distribution system (DDS), the survey questionnaire included information on:

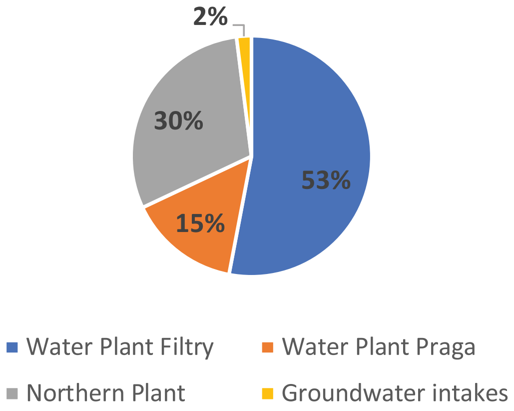


Fig. 3. Share of total water demand of Warsaw residents from individual water treatment plants.

Table 1
Basic qualification of the company water customers

Structure of customers	Water Plant Filtry	Water Plant Praga	Northern Plant
Individual	22,791	24,294	20,501
Institutional	9,985	3,779	4,619

- age, material and technical condition of water plumbing systems,
- operational problems identified most frequently in the installations,
- number of buildings requiring replacement of water installations,
- water quality tests performed at the consumer's tap,
- equipment of the installation with a non-return valve,
- additional water treatment in the building facility,
- tenant complaints about water quality in multi-family buildings.

3.2. Secondary water contamination of the WSS

Based on the survey process carried out for the study of secondary water pollution, a representative study object (SO) was selected from the group of multifamily buildings, characterized by good technical condition of the plumbing and an age of 13 y. A multi-family building is located in the Praga Północ district (Fig. 2), in the mixing zone of water pumped into the distribution system from two water treatment plants: the North Plant and the Central Plant Praga. The criterion for the selection of the building for the study was the location of the building in the water mixing zone due to the potentially greatest variability in the range of water parameters and the wide variety of materials used along the water transport route that can cause secondary water contamination.

Samples for laboratory tests were taken from 2 points (Fig. 4):

- Point No. 1 - internal cold-water installation in a multi-family building at ul. Tarchomińska – a tap in the apartment,
- Point No. 2 - a point on a DN 100 mm diameter water distribution network on Tarchomińska street – a fire hydrant.

Table 2
Selected categories of buildings in the supply area

Building categories	Water Plant Filtry	Water Plant Praga	Northern Plant
Multi-family buildings	10,213	1,469	5,837
Hospitals	50	6	15
Elementary school	98	16	82
Kindergartens	156	25	110

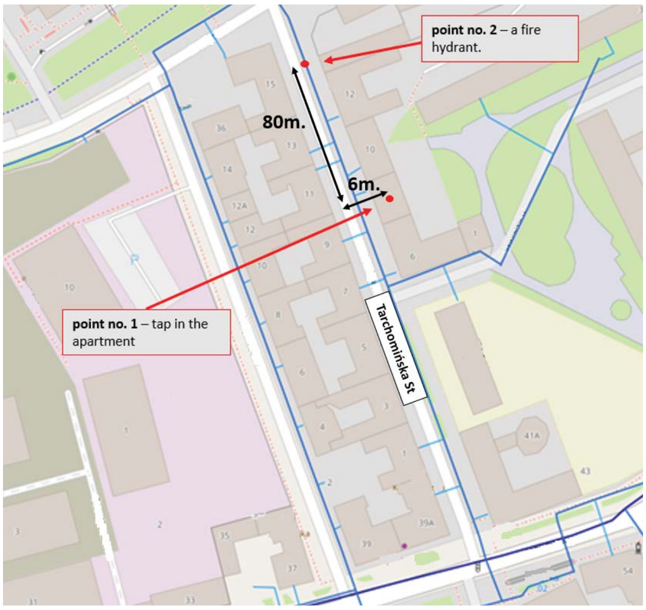


Fig. 4. Sampling points and a distribution network close to the building designated for testing.

The total distance between the hydrant (point no. 2) and the consumer's tap point (point no. 1) is 102.7 m and consists of an 80 m long distribution pipe, a 6 m long water supply connection and a 16.7 m long plumbing. The distribution network is a ductile iron pipe put into service in 2009. The water supply connection is a polyethylene pipe (PE) with a diameter of 63 mm in use since 2009. The material structure of the domestic distribution system (DDS), where the consumer's tap is located, is characterized by great diversity. It consists of:

- galvanized steel pipes with diameters DN 20 to DN 40 mm, in use since 1999. Its share in total length of the plumbing is 40%,
- polypropylene (PP) pipes with diameters DN 20 to DN 40 mm. The installation was made in 2019–2020, and its share in total length of the plumbing is 60%.

Water samples for chemical tests were taken in accordance with ISO 5667-5:2017-10, and for microbiological tests in accordance with ISO 19458:2007. Samples were taken twice a month according to the scheme:

- TE sample, was taken from the tap in the apartment, in the evening hours (6 pm),
- TM sample, representing a sample after an overnight stagnation of the water, was taken the next morning, from the tap in the apartment between 4:30–5:00 am,
- HM sample, was taken from a hydrant located on the water supply pipe feeding the building in which the apartment is located, in the morning from 4:30–5:00 a.m. a moment before the TM sample was taken.

Water quality tests were carried out for a period of 10 months from October 2020 to the end of July 2021. A total of 720 test results were carried out in accordance with the procedures presented in Table 3. The research work included the microbiological indicators such as colony count 22°C, colony count 36°C, heavy metals such as zinc, copper, nickel, chromium, cadmium, and water quality parameters affecting its acceptability by consumers: colour, odour, turbidity, iron and manganese content. The selection of psychrophilic and mesophilic bacteria in the conducted experiment was important for assessing the dynamics of changes in the microbiological quality of water in indoor installations. The adoption of selected heavy metals in the conducted study was due to the fact that there is a high risk of health hazards for the water consumer during prolonged exposure to elevated concentrations of these metals in drinking water. The selection of 5 heavy metals was based on the building material of the selected section of the Warsaw water supply network and the indoor installation under study. On the other hand, iron, manganese, turbidity odor and color were selected for the ongoing 10-month studies both as indicator parameters most noticeable to the water consumer and as parameters identifying the occurrence of the process of secondary water pollution in the water supply network and indoor installations.

4. Results and discussion

4.1. Analysis of questionnaire survey

In the surveys, a total of 75 questionnaires were obtained regarding the condition of indoor cold-water systems in: 2,285 multifamily buildings, 33 educational buildings and 10 hospitals (Table 4).

The received surveys show that, the highest average age of indoor cold-water installations (24 y) was noted in educational institutions. In contrast, the average age of 21 and 20 y was characterized by installations in multi-family buildings and hospitals. The surveyed facilities differed significantly in the material of the plumbing (Fig. 5). In hospitals, the most common material was polyvinyl chloride (40%), which dominated the 20–50 y age group. In educational facilities, the largest number of cold-water installations were made of steel (45%), which was most common in buildings in the 20–50 y age (77%). Among educational buildings with an installation age of less than 20 y, the most common materials used are plastics PVC (polyvinyl chloride) (44%) and PP (polypropylene) (39%). On the other hand, in 1,500 multi-family buildings (66%), the predominant material of indoor plumbing systems, is polypropylene, accounting for 47%, 13% and 6% in multi-family buildings in the age range of 10–20 y, 20–50 y and under 10 y, respectively. The fewest installations were made of copper. This material is found only in the age group of buildings between 10 and 20 y, with a share of 3%.

DDS surveys in the three study groups showed the worst technical condition of steel plumbing systems in schools and kindergartens with an average age of 33 y (64% of surveyed educational institutions, range of variation from 10 to 60 y), while the best condition was in multi-family buildings (22%). In the group of multifamily buildings, the worst technical condition was reported in PVC installations (55%) with an average age of 23 y (range of variation from 3 to 30 y) and steel (46%) with an average age of 32 y (range of variation from 15 to 70 y). The most frequently reported by managers operational problems of all surveyed facilities

Table 3
List of methods of analysis of the studied parameters

Parameter	Method of analysis	Equipment	Standard	Parametric value
Total number of microorganisms at 22°C	Culture-based method	Incubator	ISO 6222:2004	No abnormal change
Total number of microorganisms at 36°C	Culture-based method	Incubator	ISO 6222:2004	No abnormal change
Turbidity	Nephelometric method	Nephelometer	ISO 7027-1:2016-09	Acceptable to consumers and no abnormal change. Recommended value range of up to 1.0 NTU
Colour	Spectrophotometric method	Spectrophotometer	PB-LCW-OC-test Hach no 8025	Acceptable to consumers and no abnormal change
Odour	Sensory method	–	EN 1622:2006	Acceptable to consumers and no abnormal change
Iron	Spectrophotometric method	Spectrophotometer	ISO 6332:2001	200 µg/L
Manganese	Flame atomic absorption spectrometry method	Spectrophotometer	PN-92/C-04570/01	50 µg/L
Zinc	Flame atomic absorption spectrometry method	Atomic absorption spectrometer	ISO 8288:2002 method A	3,000 µg/L
Copper	Atomic absorption spectrometry method with electrothermal atomization	Spectrophotometer	ISO 15586:2005	2,000 µg/L
Nickel	Atomic absorption spectrometry method with electrothermal atomization	Atomic absorption spectrometer	ISO 15586:2005	20 µg/L
Chromium	Atomic absorption spectrometry method with electrothermal atomization	Atomic absorption spectrometer	ISO 15586:2005	50 µg/L
Cadmium	Atomic absorption spectrometry method with electrothermal atomization	Atomic absorption spectrometer	ISO 15586:2005	5 µg/L

Table 4
Statistics of survey results regarding the condition of internal cold-water installations in selected categories of buildings

Representative group of buildings		Hospitals	Schools and kindergartens	Multi-family buildings
Number of buildings in a category		10	33	2,285
Average age of buildings (y)	average	20	24	21
	median	10	20	20
	min	5	1	3
	max	60	60	60
Percentage of buildings requiring replacement of indoor plumbing (%)		40	64	22
Percentage of buildings where water leaks have been identified (%)		60	55	44
Percentage of buildings in which periodic inspections f the installation condition are carried out (%)		100	100	100
Percentage of buildings where water quality tests are performed regularly (%)		100	100	5
Percentage of buildings equipped with anti-pressure valves (%)		100	67	90
Percentage of buildings with local, additional water treatment (%)		70	15	25

are corrosion and installation leaks which were reported in 60% of medical facilities, 55% of educational buildings and 44% of multifamily buildings.

Minor failures occurring at connections, on risers and in residential units - like valve scale overgrowth, were indicated in only a few residential facilities (19% of multifamily

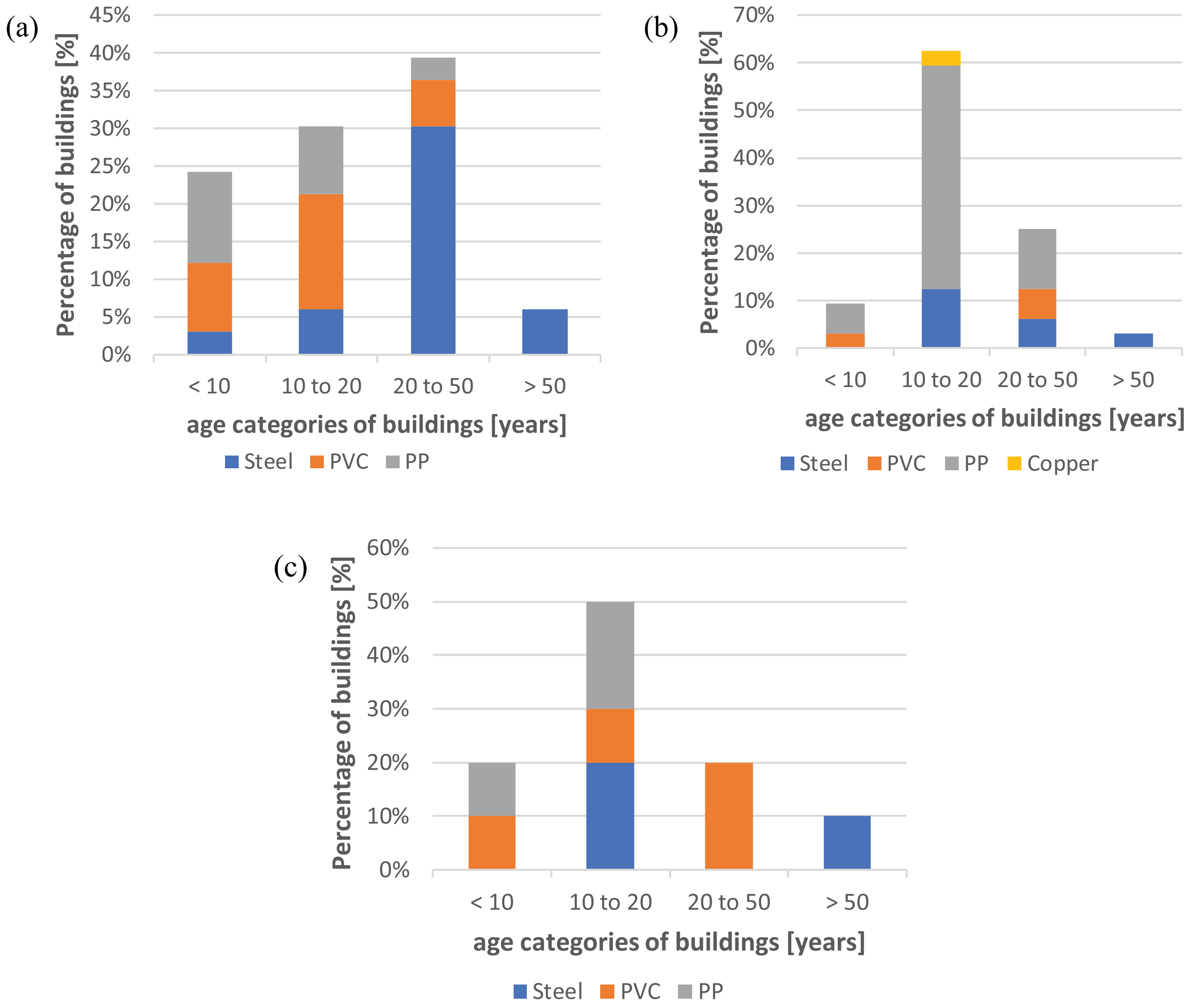


Fig. 5. Material structure of indoor installations in each building category as a function of age. (A) Education buildings, (B) multifamily buildings, and (C) hospital buildings.

buildings) as factors determining operational problems. Administrators of 37% of multifamily buildings reported no operational problems. The need to upgrade the plumbing due to poor technical condition (Table 4), was reported in 4 hospitals (40% of surveyed healthcare facilities), 21 schools and kindergartens (64% of educational facilities) and 503 residential facilities (22% of multi-family facilities). Surveys showed the lowest level of protection in the form of non-return valve on the cold-water system in educational facilities, which at the same time had the highest average service life.

Administrators of all surveyed healthcare facilities declared that periodic water quality tests are performed in the buildings, as well as regular inspections of the technical condition of the installations. Three hospital administrators reported supplemental water treatment which is used for local water purification at the dialysis station (1 facility) or water softening for sterilization and heating boiler feed (2 facilities). Information from surveys shows that chemical disinfection of cold-water systems is performed periodically in four of the ten hospitals. Supplemental water treatment (softening or use of tap carbon filters) was indicated by 15% of building administrators. In the group of multifamily buildings, only 25% of apartments use mechanical filters on the internal installation.

Administrators of all surveyed health and educational institutions (Table 4) declared regular water quality tests, which are most often performed for the presence of microorganisms: *Escherichia coli*, coliforms, Enterococci, colony count 22°C. In multifamily facilities, on the other hand, only 5% of facilities perform periodic quality tests. Circumstances for occasional water sampling, are works related to the replacement of installations or when a resident's complaint is received. Administrators of 63% of multi-family buildings reported that they periodically receive complaints from residents about the quality of the water supplied. In 50% of these complaints are related to water color and turbidity and in 13% to water pressure and interruptions.

Conducted surveys reported that multi-family facilities indicated the most non-compliance of water quality with the required parametric values specified in the Regulation of the Minister of Health on the Quality of Water Intended for Human Consumption [47], so this group was selected as representative for the research of secondary water pollution in the DDS.

4.2. Analysis of secondary water contamination

As part of the research work, the dynamics of daily variability of heavy metal concentrations, selected microbiological indicators and water quality parameters affecting its acceptability (colour, odour, turbidity and iron and manganese content) were assessed (Fig. 6).

4.2.1. Zinc

Test results of zinc in the analyzed water samples showed large fluctuations in concentration in the water after overnight stagnation (Fig. 6A sample TM), with variability noted from 10 to 170 μg/L (average 50 μg/L). The dynamics of changes in the concentration of zinc in water at testing distance from hydrant (sample HM, variation from 10 to 50 μg/L, average 20 μg/L) to tap of the consumer (sample TM), indicates significant secondary contamination of water, which occurs in internal water supply systems. In water samples from the tap at the consumer's home (sample TM), the average zinc concentration is 150% higher than the concentration in water in the water supply system (sample HM). The concentration of zinc in tap water in samples taken in the evening (sample TE) varied between 10 and 60 μg/L, with an average of 20 μg/L. The average percentage increase in zinc concentration observed in the TE and TM samples over the period of the study was 295%. The increase in zinc concentration was observed in 16 out of 20 cases. On 13/11/20, the largest increase in the concentration of zinc in the tap water (sample TM) was recorded at 750%, for which the concentration was 170 μg/L. In contrast, the smallest increase (33.3%) from a value of 30 μg/L (sample TE) to a value of 40 μg/L (sample TM) was recorded on 14.05.2020. During the study period, a 25% decrease in zinc concentration relative to evening values was observed twice in samples taken after overnight stagnation (26.03.2021, 30.07.2021). This decrease may be due to the measurement uncertainty for the result range of 20–90 μg/L of 40%. Similar to the study by Lytle and Schock [48] as well as Abedin et al. [17], the zinc contents of the water samples in Warsaw WSS clearly indicated the release of Zn ions from the indoor installation made of galvanized steel (leaching of the anti-corrosion coating). Despite the observed phenomenon of secondary water contamination, the level of zinc concentration did not exceed the parametric value (Table 3), which would constitute a reason for the unacceptability of the water and a health risk for the water consumer.

4.2.2. Copper

The tests carried out clearly indicated the variability of copper concentration (Fig. 6B,) in the water taken from the indoor installation both in the evening (sample TE, range of variation 1.5–9.2 μg/L) and in the morning (sample TM, range of variation 2.2–24 μg/L). The average percentage increase in copper concentration observed between the evening and morning intakes was 109.3%. Increase in copper concentration was observed in 17 out of 20 cases. On 13/11/2020, the largest increase in copper concentration in the consumer's tap water was recorded at 352.8%, for which the concentration was 24 μg/L (sample TM). In contrast, the smallest increase from a value of 6 μg/L to a value of 6.2 μg/L (3.3%) was recorded on 15/01/2021. In addition, during the study period, there were also three cases for which a decrease in copper concentration relative to evening values was observed in samples taken after overnight stagnation (04/12/2020, 26/02/2021, 26/03/2021), most likely due to measurement uncertainty. The results show that the dynamics of changes in the concentration of copper in water on distance from hydrant (sample HM, variation 0.5 to 4.6 μg/L, average 1.2 μg/L) to the tap of the consumer (sample TM, variation 2.2–24 μg/L, average 8.4 μg/L) is very high, 600%. The conducted study, similar to the results of Vargas et al. [49], indicates significant secondary contamination of water as a result of stagnation and high daily dynamics of variability. In addition, the results of the study showed a lack of complete knowledge of the building administrator regarding the materials that build the plumbing. According to the information obtained from the administrator, there are no sections of the installation made of copper in the building.

4.2.3. Nickel

The nickel concentration in the evening samples from the sample TE ranged from 0.6 to 2.3 μg/L with an average value of 1.0 μg/L. The concentration of nickel in the water samples taken in the morning from the internal installation (sample TM) ranged from 0.6 to 2.5 μg/L (average 1.2 μg/L), reaching the median of 1.0 μg/L. As in the case of zinc and copper, the nickel content in water taken from the consumer's tap (samples TM, TE), especially after overnight stagnation, was clearly higher than the value determined in water samples taken from the hydrant (sample HM), which indicates significant secondary water contamination in internal water supply systems (Fig. 6C). The average concentration of nickel in water in the water supply network (sample HM) reached the value of 0.9 μg/L and the variability was from 0.6 mg/L to 1.3 μg/L. The average percentage increase of nickel concentration in the consumer's tap water observed between the evening and morning intake was 64.9%. Increase in nickel concentration was observed in 12 out of 20 cases. On 02/07/2021, the largest increase in nickel concentration in the consumer's tap water was observed at 166.7%, for which the water concentration in the sample after overnight stagnation (sample TM) was 1.6 μg/L. The smallest increase of 11.1% was recorded on 12/02/2021 and 26/02/2021. The obtained results of testing the concentration of nickel in the tap water of the Warsaw WSS were consistent with the results of studies carried out in France [50], Islamabad in Pakistan [51], and in the Guanzhong Plain region in China [52]. Whereas, the research by Abedin et al. [17] showed that in tap water in the central region of Bangladesh (Mirpur, Dhaka) the content of nickel was an order of magnitude higher and exceeded the concentration of 10 mg/L. Noted daily changes in nickel concentration are consistent with the study conducted by Asami et al. [53] in which a marked decrease in nickel concentration was observed after draining the tap water. In addition, there were five cases during the study period for which a decrease in nickel concentration was observed in samples taken after overnight stagnation relative to evening values. The average decrease was 35.8% with variability in the range of 0.1–1.2 μg/L. The reported decreases in concentration may be due to measurement inaccuracy of 40% for the 0.1–0.9 μg/L result range and 25% for the 1.0–3.0 μg/L range. In 3 of the 20 cases, nickel concentrations did not change after overnight stagnation. The concentration of nickel in water in the water supply network (sample HM) and in water taken from the tap (samples TM, TE) during the study period was at levels well below the parametric value of 20 μg/L.

4.2.4. Chromium and cadmium

The concentration of chromium as well as cadmium in the water taken from the hydrant (sample HM) and in the consumer's tap (samples TM, TE) remained below the limit of quantification which is 0.5 μg/L for chromium and 0.05 μg/L for cadmium. The water in the Warsaw WSS in terms of the content of these elements met the requirements set out in both Directive (EU) 2020/2184 [16] and in Polish legislation (Regulation of the Minister of Health of 7 December 2017 on the quality of water intended for human consumption (Dz.U. 2294) [47]), in which the parametric value for chromium was set at 50 μg/L. The concentrations obtained for chromium are also many times (50 times) lower than the parametric value of 25 μg/L, to be in effect under Directive 2020/2184 from January 12, 2036. Similar trace concentrations of chromium in water intended for human consumption have been reported in France [50], Noakhali in Bangladesh [52] and Atonsu-Kumasi in Ghana [54]. However, studies by Abedin et al. [17], Mohammadi et al. [55], Zakir et al. [56] and Kumar et al. [57] showed chromium content in drinking water at the level of several micrograms per liter.

4.2.5. Iron

Analysis of the concentration of iron in the tap water showed daily variability of the content of this element in the water (Fig. 6D). Iron concentration in samples taken in the evening (sample TE) fluctuated between 46 and 152 μg/L (average 99 μg/L), while in water samples taken in the morning (sample TM), it ranged between 64 and 170 μg/L (average 96 μg/L). During the study period, 10 cases showed an increase in iron content in the morning water stream (sample TM) relative to evening values (sample TE) by an average of 26.9%. In these samples, the dynamics of variation in iron concentrations in samples TM relative to samples TE were characterized by a minimum increase of only 7.5% recorded on 26/02/2021. The maximum increase in iron concentration was recorded on 29/01/2021 and amounted to 71.7%. In the next 10 cases of the conducted measurement series, an average decrease of 22.7% was recorded in the iron content after the overnight stagnation (sample TM) against the evening values (sample TE). On 27/11/2021, the lowest decrease in water iron concentration of 8.3% was recorded from 120 μg/L (sample TE) to 110 μg/L (sample TM).

The results of the study of iron content in water in the water distribution system (sample HM) were characterized by a much lower dynamics of variation during the period of the research (variation of 79 to 150 μg/L, average 108 μg/L). Relating the values of iron concentrations in water network (sample HM) to the values in water samples taken from the tap in building (sample TM), it can be seen that the concentration of iron in distribution (sample HM) in 70% of cases was higher than the value after overnight stagnation (sample TM). Average value by 12% (min. variability of 3.9% on 09/04/2021, maximum variability of 61.3% on 28/05/2021). The reduction of the average iron content was probably influenced by the FCPP100 string filters mounted on the internal cold-water system.

There are two periods visible in the analyzed research: (period I) from 15/10/2020 to 15/01/2021 and from 22/04/2021 to 30/07/2021 (period II), in which higher iron concentrations were observed in all measurement points. The average concentration of iron in morning samples (sample TM) was higher than the average value from the entire research period by 8.3% and 10.8%, respectively, in period I (variability from 81 to 132 μg/L) and period II (variability from 74 to 170 μg/L). On the other hand, in water samples taken in the evening (sample TE), the average concentration of was higher than the average value from the entire research period by 6.5% and 23.9%, respectively, in period I (variability from 78 to 152 μg/L) and period II (variability from 96 to 150 μg/L). The variability of iron content in water samples from the distribution system (sample HM) in period I of the study was characterized by a minimum concentration of 88 μg/L and a maximum concentration of 140 μg/L. In this period, the average value of iron concentration (sample HM) was higher by 2.3% compared to the value from the entire research period and reached the level of 110.7 μg/L. In the second period, the concentration of iron in water (sample HM) varied from 97 to 150 μg/L, with an average value of 123.8 μg/L, which was 14.4% higher than the average iron concentration in HM water samples throughout the research period. The periodically higher iron content in the water in the spring/summer season (period II) was influenced by the temperature, the increase of which is conducive to increasing the dynamics of corrosion processes. In winter (period I), exploitation works were carried out on the water supply network close to the research area, which resulted in the disturbance of sediments and, as a result, increased iron transmission to water. A large daily variability of iron in drinking water in the range from 2 to 450 was noted in their studies by Abedin et al. [17]. Similarly, studies by Abdeldayem [58] in WSS in Egypt, Abeer et al. [51] in Bangladesh and Zakir et al. [56] in northern Pakistan showed iron concentrations in tap water above 100 μg/L.

Throughout the research, the concentration of iron in the water in WSS of Warsaw did not exceed the parametric values set by European and Polish Legislation [16,48] at level of 200 μg/L.

4.2.6. Manganese

Studies of manganese concentrations in water in the Warsaw WSS showed a similar trend of variability as was observed for iron. The largest range of variability was noted in water samples taken in the evening hours (Fig. 6E), from the indoor installation (sample TE), for which the minimum concentration of 9.6 μg/L occurred in water on 29/07/2021 and the maximum concentration of 91.4 μg/L was observed in a sample from 03/12/2020. On the other hand, in water samples taken from the indoor installation in the morning (sample TM), the variation in manganese concentration ranged from 2.5 to 42.5 μg/L reaching an average value of 24.1 μg/L. In contrast, manganese in samples taken at the water mains (sample HM) was characterized by concentrations in the range of 2.5–50.9 μg/L (average 23.1 μg/L). In addition, the evening samples had the highest average concentration of manganese (28 μg/L), which was 2.9% and 19.1% higher than the average values for water samples taken in the morning from the tap (sample TM) and hydrant (sample HM), respectively. During the 10-month period of the ongoing study, manganese concentrations in samples TE exceeded twice the parametric value of 50 μg/L. Elevated above the permissible threshold values, at 58.2 and 91.4 μg/L, were found in samples TE taken on 12/11/20 and 03/12/20. The period of high manganese concentrations was consistent with period I, the high iron concentrations in sample TM. It should be noted that in samples taken the following morning (sample TM), manganese concentrations were lower by 34.7% (sample TM - 38.0 μg/L) and 57% (sample TM - 39.3 μg/L), respectively, and did not exceed the parametric value of 50 μg/L. Also, on the distribution network point (sample HM), the concentration of manganese was lower by 37.5% and 53.9% and was 36.4 μg/L on 13/11/20 and 42.1 μg/L on 04/12/2020. The occurrence of manganese in tap water at concentrations ranging from several up to several dozen micrograms per liter (with a median of 26 mg/L), was also noted in studies by Abedin et al. [17]. However, studies conducted in various regions of Bangladesh [52,56,59], Egypt [58], as well as in Mandalay Region of Myanmar [60] showed manganese concentrations in drinking water at several up or even twenty orders higher, exceeding the permissible concentration, that is, 50 mg/L.

Taking into account the dynamics of manganese concentration variability in water and the fact that the water pumped into the Warsaw WSS (water from Northern Plant and Praga Plant) was characterized by concentrations below the parametric value, it seems that the elevated manganese concentration in the evening samples (sample TE) was caused by the release of manganese from sediments, deposited mostly in the water connection pipe.

4.2.7. Colour and odour

The results of colour testing in water samples at all measurement points (samples TE, HM and TM), throughout the 10-month study period, remained in compliance with Directive (EU) 2020/2184 [16] and Polish Regulations [47] in which it is required the colour to be acceptable to consumers and without abnormal changes. The results of water odour samples were similar. In all samples tested (samples TE, HM and TM), the water odour was marked as acceptable, below the level of perceptibility (<1 A).

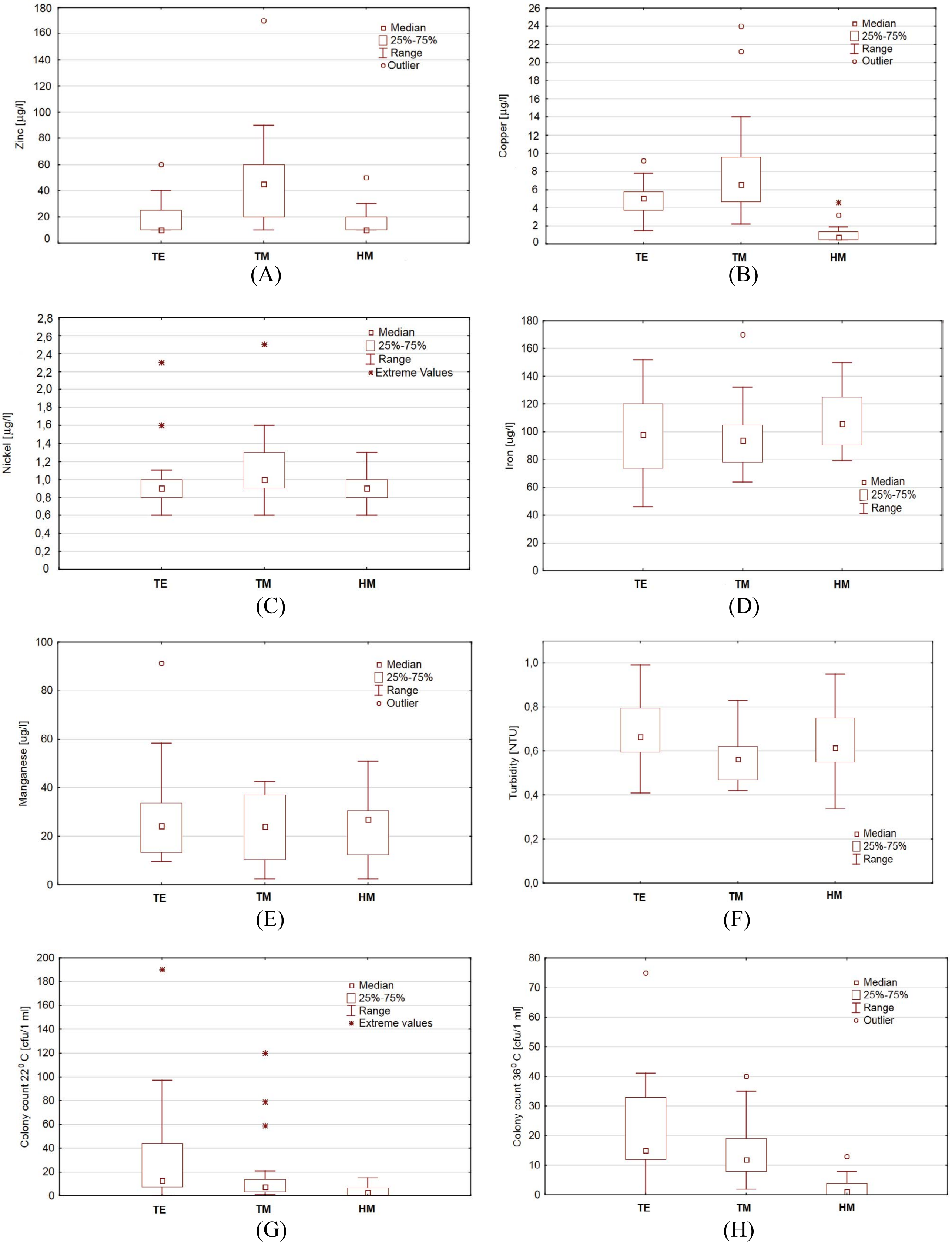
4.2.8. Turbidity

The turbidity of the water (Fig. 6F) in samples taken in the evening from the indoor installation (sample TE), varied from 0.41 to 0.99 NTU, reaching an average value of 0.69 NTU. The average turbidity of the water samples taken in the morning from the indoor installation (sample TM) was 17.4% lower than that of the evening samples (sample TM from 0.42 to 0.83 NTU). At the same time, the results obtained from water samples taken from the water supply network (sample HM) had the highest variation from 0.34 to 0.95 μg/L, for which the average turbidity was 0.64 NTU. During the study period, as many as 15 out of 20 cases (75% of samples) showed a decrease in turbidity (sample TM) relative to evening values (sample TE) by an average value of 24.3%. On the other hand, in 5 test series an increase of turbidity was recorded after overnight stagnation, relative to evening values characterized by average value of 17.2% (min increase of 1.5% on 23/04/2021, max increase of 53.7% on 12/03/2021). Analysis of the magnitude of turbidity in the morning at the consumer's tap (sample TM) in relation to the values obtained in samples from the water supply network (sample HM) showed that the turbidity in distribution system in 66% of cases (16 of 20 cases) was on average 8.8% higher than the value determined in the sample TM. The smallest increase of 3.6% was recorded on 04/12/20 for turbidity of 0.57 and 0.55 NTU in the network water (sample HM) and consumer tap (sample TM), respectively. Throughout the study period, in all water samples, turbidity remained at a level consistent with European [16] and Polish Legislation [47] not exceeding the parametric value of 1 NTU. Based on the study of 14 independent water supply systems, de Roos et al. [61] demonstrated the need to maintain water turbidity below 1 NTU. These studies, as well as studies conducted in the Silesian agglomeration, Poland [18] showed that turbidity is a practical indicator of microbiological risk and the occurrence of Acute Gastrointestinal Injury (AGI). In the systems studied by de Roos et al. [61] where the turbidity was well below 1 NTU, in most cases below 0.5 NTU, no AGI was recorded.

4.2.9. Colony count 22°C and 36°C

The highest variability of colony count 22°C, in the range from 0 to 190 CFU/mL was noted in water samples collected at the consumer's tap in the evening (sample TE) in the entire variable population (Fig. 6G), for which the average value was 34 CFU/mL. The average total number of microorganisms at 22°C at the consumer's tap in the evening (sample TE), during the study period, was higher by 78.9% compared to the value in samples taken in the morning (TM - average 19 CFU/mL). The smallest range of variables was found in water samples from the water supply network (sample HM), where sample results were 11.7% and 7% smaller than those taken in the consumer's tap in the evening (sample TE) and in the morning (sample TM), respectively. The total number of microorganisms at 22°C in tap water (sample HM) took values from 0 to 15 CFU/mL (average 4 CFU/mL).

Only in 25% of cases the colony count 22°C after overnight stagnation (sample TM) was higher than the value from the evening hours (sample TE), and the average increase was 52.3%. On 11/06/2021, the increment was the largest at 53 CFU/mL (79.1%, an increase in sample TE from 67 to 120 CFU/mL, while on 23/04/2021 the increment was the smallest at 1 CFU/mL (33%, an increase from 3 CFU/mL sample TE to 4 CFU/mL sample TM). On the other hand, for 14 samples (70% of cases), the opposite phenomenon was



(A) (B)

(C) (D)

(E) (F)

(G) (H)

Fig. 6. Variability of (A) zinc, (B) copper, (C) nickel, (D) iron, (E) manganese, (F) turbidity, (G) colony count 22°C, and (H) colony count 36°C in sampling points: tap evening (TE), tap morning (TM), hydrant morning (HM).

observed, characterized by a higher number of microorganisms in samples TE relative to samples TM by an average of 48.6% (range of variation from 12.2% to 93.8%). The smallest decrease of 12.2% in the total number of microorganisms in 22°C after overnight stagnation was recorded on 16/07/2021 (decrease from 90 CFU/mL in the sample TE to 79 CFU/mL in the sample TM) and the largest 93.8% on 29/01/2021 (decrease from 48 CFU/mL in sample TE to 3 CFU/mL in sample TM). Throughout the period of the study, the colony count 22°C had higher values in the consumer's tap water (samples TE and TM) than in the water in the water supply network (sample HM). The highest increase above 900% was recorded on 11/06/2021, in which the water in distribution system (sample HM) contained 11 CFU/mL and the water in the consumer's tap contained 120 CFU/mL. In addition, in the period from 10/06/2021 to 30/07/2021 relative to the period 15/10/2020 to 27/05/2021, a very high increase (700%) in the colony count 22°C was observed in samples taken from the building's indoor installation. This increase is most likely related to an increase in water temperature that promotes biofilm development in the system. The average temperature of water pumped into the water supply system in June and July 2021 was 21.8°C and 24.6°C, respectively, while in April and May it varied between 9.3°C and 15.0°C.

The results of the colony count 36°C (Fig. 6H) collected from the consumer's tap both in the morning and in the evening were less differentiated. In the evening samples (sample TE), the number ranged from 0 to 75 CFU/mL (average 26 CFU/mL), while in the samples after overnight stagnation (sample TM) the number ranged from 2 to 62 CFU/mL (average 18 CFU/mL). Similarly, to the colony count 22°C, results in the samples taken from the water supply network (sample HM) were significantly lower than those of tap water samples at the consumer's (samples TM and TE). The average value in TE and TM tests was 12 and 8 times higher, respectively, in relation to the sample HM value, for which the variability of the total number of microorganisms at 36°C was 0–13 CFU/mL (average 2 CFU/mL). In addition, a higher value was more often recorded in water samples in the evening than after overnight stagnation (13 out of 20 cases). Increased water intake in the evening (at 6:00 p.m.) could have favored the migration of bacteria from the biofilm to the water flowing in the system and resulted in an increase in the number of bacteria in the water sample, compared to the result obtained in the sample after overnight stagnation (at 4:30 a.m.).

The dynamics of changes in the colony count 22°C and 36°C in water at the test section: from network to consumer tap, indicates significant secondary water contamination occurring in internal water supply systems. The correlation observed between surface area to volume ratio and bacteria levels found in water after overnight stagnation suggests that biofilm is a major contributor to water contamination Similar observations of deterioration of water quality in internal water supply systems were observed by Bedard et al. [62], Lipphaus et al. [63] and Lautenschlager et al. [64].

5. Conclusions

The questionnaire survey indicated that in each of the analyzed categories of buildings, a significant percentage of them (especially educational buildings – 64%), require replacement of the internal installation. Attention is drawn to common problems reported by building managers, such as water leaks from the system (65%, 55%, 44% in hospitals, schools and multi-family buildings, respectively) and corrosion of pipes.

The questionnaire survey results also indicate that in a significant group of multi-family buildings (63%), service recipients report deterioration of water parameters related to its acceptability (colour, turbidity – 50% of consumer complaints). However, the results of the water surveys obtained at the measurement points do not allow a clear indication in which section the most frequent contamination occurs, that justifies the need for further study.

Assessment of the condition of internal water supply systems based on a questionnaire survey and research involving inspection of selected water quality parameters at a representative point of the WSS of Warsaw, showed a high susceptibility of water supplied to the consumer to secondary contamination in the internal water supply system. In the case of heavy metals such as zinc, copper and nickel, although the obtained values do not exceed the parametric values, a strong impact of the materials used on the change in the quality of water in the recipient's tap is visible. There was an increase in the concentration of zinc (150%), copper (600%) and nickel (27%) in the tap water stream compared to the water stream in the water supply network. However, the occurrence of cadmium and chromium in drinking water at the WSS in Warsaw was not recorded.

The variability in the content of iron, manganese and turbidity of water found at both test points (a tap Fe: sample TM 64–170 μg/L, sample TE 46–152 μg/L; Mn: sample TM 2.5–42.5 μg/L, sample TE 9.6–91.4 μg/L; turbidity: sample TM 0.42–0.83 NTU, sample TE 0.41–0.99 NTU and a hydrant sample HM: Fe 79–150 μg/L; Mn 2.5–50.9 μg/L; turbidity 0.34–0.95 NTU), indicates the presence of these elements deposited in the form of sediment both in the water supply network and in the connection and internal installation, from where they are released into the water depending on the changing conditions of water flow. The above may be the cause of exceedances of the aforementioned parameters in the future and result in the unacceptability of the water by the residents of the building in question.

The results of microbiological water quality tests show that in the summer period, characterized by higher water temperature and reduced water consumption (weekend water consumption decreases), there is a significant increase in the number of microorganisms in the tap water (5 and 9 times for psychrophilic bacteria and 12 and 8 times for mesophilic bacteria in samples TM and TE, respectively).

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