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Review

Blockchain Technology and Sanitary Aspects of the Water Supply

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Abstract: Technological advances in the last decades have led to the realization of the concept of a smart environment. A significant part of this development is decentralized ledger technology and its variant, a blockchain. The blockchain database is immutable, open to all stakeholders, secure by architecture and robust. Applying a blockchain in water supply sanitary control creates opportunities for optimization, higher quality of service, cost reduction, better sanitary standards and public control. Physical, chemical, and biological water supply contamination is a great source of public health hazards. Implementation of a blockchain for water supply IoT, from the source point to the consumption point, enables effective response to changing environments, possible cross-contamination, stormwater management or disaster and emergency action. The chapter encompasses all fundamental elements and principles of water collection, distribution and consumption, with a focus on the health hazards and sanitary requirements for potable water. The chapter listed the main contaminants, methods of their registration and elimination, and requirements for drinking water in accordance with WHO, EU Drinking Water Directive and EPA standards. Blockchain technology solutions are described for smart water supply, including smart supply management, smart contracts, tokenization, smart compliance systems, and, most importantly, effective utilization of distributed ledger technologies for sanitary monitoring of water sources, water treatment, and water distribution systems.

Keywords: blockchain; IoT; smart environment; AI; water supply; public health

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1. Introduction

The definition of "well-being" usually refers to the quality of life of a person and society in general. It reflects physical and mental health and satisfaction with life. Water plays an important role in both individual and societal well-being. Its significance extends far beyond basic physiological hydration, sanitation and hygiene. Water comprises from 55% of body weight in senior adults to 75% in infants (Popkin et al., 2010). Sufficient daily water intake is essential for maintaining homeostasis and proper physiological functions. It comprises, on average, from 2.7 to 3.5 litres per person per 24 hours. It includes plain water, food, containing water and beverages, and depends on the individual's age, health condition, medications, climate and microclimate conditions and physical activity. Besides this, water is important for personal hygiene: handwashing, bathing, dental care and sanitary needs (Howard and Bartram, 2003). The usual water volume spent per person per day is from 35 litres to 400 litres (Beysens, and Milimouk, 2000), depending on the availability, climate, conversational and governmental practices. Higher volumes are used for agriculture, food and beverage processing. Industrial processes, from mining to end-product production, often require significant amounts of water. Power generation processes also require water, from hydropower to cooling of reactors. Transportation via navigable seas, rivers, lakes and channels is critical, comprising over 80% of international trade. Water bodies and artificial water attractions are important for tourism, leisure and recreation activities. The planetary water cycle and main natural water bodies are pivotal in forming both, local and worldwide, weather patterns. Weather and

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seismic activity often demand adequate disaster reaction in the case of flooding, typhoons, tsunamis, and other water-related public emergencies. Every aspect of water utilization and disaster mitigation or prevention requires an appropriate sanitary framework.

2. Water Supply Sources, Systems and Processes

2.1. Water Sources

The hydrological cycle comprises the largest water movement, delivering an estimated 110,000 cubic kilometres per year as precipitations, snow, rainfall and dew or condensate (Jackson et al., 2001). Typically, the Earth's atmosphere contains around 15,000 cubic kilometres of water at any time. Still, only around 2.5-3% of the water on Earth is fresh enough for drinking or agricultural usage. Most of these freshwater reserves, up to two-thirds of the total, are locked up and exist as ice caps, glaciers and permanent snow. Another 30% is groundwater. As little as 0.3% of all freshwaters is readily available from surface sources, rivers and lakes. Every type of water source requires a specific sanitary approach.

Water sources can be of three main types: surface natural or artificial reservoirs, groundwater sources, and specially collected or treated water. Some researchers prefer not to divide surface reservoirs and groundwater into two separate categories because of their interactions (Jackson et al., 2001). Surface flowing bodies of freshwater are comprised of rivers, streams, brooks, creeks, and canals. Natural or artificial bodies of standing water include lakes, ponds, collecting reservoirs, tanks and cisterns. Sometimes wetlands, marshes swamps and estuaries are also seen as surface sources or part of surface water systems.

Most of the groundwater, more than 8,000,000 cubic kilometres, is at a depth of up to 4,000 meters and is hardly available. Shallow and deep soul groundwater sources contain 67,000 cubic kilometres. They are usually aquifers, underground layers of permeable rock of sediments that contain water (Dodds, 2002). The shallow groundwater can be accessed through the springs, natural, dug or drilled wells below the water table. Artesian wells permit water delivery from confined aquifers.

Additional water sources include rainwater, stormwater, recycled water, desalinated water, water collected from the atmosphere, fresh ice and some other sources (Beysens, and Milimouk, 2000). Rainwater collection is an old technique, suitable for the widely geographically distributed settlements. The catchment area is usually supplemented by open or underground storage reservoirs, tanks or cisterns. Storm-water collection systems can be additional to usual rainwater collection and contain wadis, usually dry streams, and catch and retention basins. Storm water often requires additional treatment and purification before consumption or can be utilized for non-potable use.

Other types of water collection are desalination of seawater or brackish water, wastewater treatment and purification, atmospheric water generation, and ice and iceberg utilization. Some techniques, such as atmospheric water generation and ice utilization can produce potable water. Atmospheric water generation is usually used in arid and desert areas. It includes fog nets, dew condensers, dew “springs” and “ponds”, massive aerial condensers, radiative aerial condensers, seawater condensers and adsorption-desorption on desiccants (Beysens, and Milimouk, 2000). Desalination usually exploits evaporation, while ice-water desalination methods are proposed (Najim, 2022). Desalination is used for potable and non-potable water production. Wastewater recycling processes usually produce non-potable water. Ice water production is proposed for glacial ice, ice caps and icebergs.

2.2. Water Supply Systems

Water supply is characterized by quantity, quality, accessibility, continuity and affordability (WHO, 2022). Accessibility is the percentage of the population with access to a drinking water supply. Quantity signifies volume per person in the population, while quality depends on the ways and methods of validation by approved water supply providers. Continuity depends on the period when drinking water is available and affordability reflects the price as a fraction of income. Water

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supply systems are usually an important part of the infrastructure, designed to provide clean and safe drinking water. The specific components and complexity of these systems depend on the region, scale and resources.

Modules of fully-fledged water supply systems include water sources, intake structures, water treatment facilities, storage reservoirs and distribution networks (McGhee, and Steel, 1991). Primary water sources are described above. Intake structures collect water from the source and direct it into the supply system. Depending on the place, they can be on the bank side, on the surface or submerged. Usually, pipes, channels and pumps of intake structures are protected from debris by trash racks, screens, and gratings. Filters stop contaminants and aquatic life.

Water treatment facilities are designed for processes of coagulation and flocculation, sedimentation, filtration, and disinfection. They are described below in a more detailed fashion. Storage reservoirs hold water at different stages of its processing. It can store the water for future consumption during periods of low demand, releasing it during periods of higher demand (Mays, 2001). Some reservoirs work for the regulation of pressure in the system and all its parts. Some storages are designed to be involved at the time of emergency supply.

The distribution system also consists of various pumping stations, pipes and channels, hydrants, controlling valves and meters (Mays, 2001). The water distribution system is connected to customer facilities and water storage at the consumer end. The distribution network is supplied by facilities, valves, and devices to control overflow, backflow, cross-contamination and emergency inflow and outflow prevention.

2.3. Water Treatment

Water treatment includes several stages and processes: screening, aeration, coagulation and flocculation, sedimentation, filtration, chlorination, and supplementary treatment (McGhee, and Steel, 1991). Screens are employed on different levels of the system, usually at the source of water intake. Large, bulky objects are stopped and mechanically removed by coarse or bar screens. Fine screens, in surface water intake, often coupled with bar screens and placed behind them. More complex drum screens hold rotating cylindrical mesh structures. Solids are retained on the surface and removed mechanically by brushes or scrapers, while water flows through. Screw screens similarly lift and remove debris from the surface by use of an inclined screw. Besides the screening process itself, screens support appropriate water flow and handle filtered solids.

Water aeration is mainly performed for the removal of dissolved gases, volatile organic compounds, and certain contaminants (Spellman, 2008). It is done by the air introduction from blowers at the bottom of the in-reservoir aeration columns/towers, centrifugal pumps or mechanical bladed aerators in water tanks. Oxygen of the introduced air removes hydrogen sulfide, and carbon dioxide, converts dissolved ferrous iron and manganese into insoluble forms and removes some volatile organic compounds (VOCs) such as trihalomethanes (*THMs*).

Coagulation destabilizes suspended particles in water (Bratby, 2016). Coagulation and flocculation bring together suspended particles into aggregated particles by particle charge removal due to interaction with the coagulant. The last part of the process is called flocculation. Inorganic aluminium-based and iron-based salts and certain organic polymers are used as coagulants. Coagulants are added into the mixing tank and then treated water is moved to the flocculation basin, where it is slowly mixed by paddles or hydraulic flocculators (Spellman, 2008). Afterwards, water moves to settling or sedimentation basins. Macromolecules form sludge sediment, which is removed, while water with microfloccules is filtrated.

Filtration on a bigger scale is continued in the next stage. It involves the removal of suspended solids, particles, bacteria, parasites and impurities from water, percolated down the porous filtration bed. A properly operated water treatment facility shall reduce impurity load up to 99% of the coliform bacteria, protozoa, and viruses (Nemerow et al., 2009). For filtration media are usually used sand beds of specific depths and granular sizes, gravel, anthracite coal, and diatomaceous earth in various combinations. Filtration can be done with the help of the gravity force, as in slow sand and rapid sand plain filtration, or with the pressure in diatomaceous earth filters. In some medium or

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small water treatment plants successfully applied gravity-driven low-flow ultrafiltration with specific molecular weight cut-off (MWCO) (Stoffel et al., 2022). All filters require backwashing to dislodge and remove filtered out impurities.

Effective filtration can remove most of the bacterial, viral, protozoa or other pathogens. However, for safe water use additional methods of chemical or physical disinfection are applied. The traditional one includes water chlorination or more chloramination in various stages (Nemerow et al., 2009). The more advanced methods are oxidation processes (AOPs) for the production of highly reactive radicals. It includes ozonation, ultraviolet (UV) disinfection or peroxidation (McGhee, and Steel, 1991). These methods are also used in combination. Sometimes bromine, iodine, silver and chlorinated lime are applied (Spellman, 2008). As an additional method, mostly small and medium water treatment plants today, applied environment-friendly biofiltration (Hammes et al., 2010), mostly by various microorganisms, primarily bacterial. Biofiltration requires biomonitoring and support of the adequate environment by nutrient addition and oxidation control.

After disinfection, water undergoes chemical treatment to adjust pH and to remove excess of some minerals lowering its hardness. Acidity is regulated by lime or sodium carbonate. Calcium and magnesium bicarbonates, sulfates and chlorides can form insoluble deposits and scales in the pipes, boilers and on the bottom of pots. These deposits reduce flow in the piping or create insulation heat in boilers. Lime and potassium aluminium sulfate are commonly used in this phase (Nemerow et al., 2009). Piping corrosion and potential release of metal ions are prevented by the addition of orthophosphate or polyphosphate. For dental health reasons, a small amount of fluoride can be added into the water. However, high levels of fluoride can be destructive for teeth enamel (Spellman, 2008).

2.4. Quality Control

2.4.1. Normal Requirements

Quality standards divide water in accordance with its purity and possible use. There are four categories of health risks: potable water, palatable water, contaminated (polluted) water, and infected water (WHO, 2022). There are also Water Quality Indices (WQIs), which consider physical and chemical water parameters. There are general WQI, agricultural index, recreational index and ecological index. The main parameters in WQI are turbidity, pH, level of dissolved oxygen, nitrogen and phosphorus, heavy metals, biopathogens and specific chemical contaminants, such as pesticides, organic compounds, antibiotics, and some others (Spellman, 2008). Besides possible direct toxicity, pharmacological, physiological, and clinical effects are taken into account.

While water quality standards can differ significantly from country to country, ehere are thoroughly worked-through standards for physical conditions and many chemical compounds. Normal turbidity in Europe for potable water under the Drinking Water Directive (98/83/EC, amended) is 1 NTU (Nephelometric Turbidity Units). The U.S. Environmental Protection Agency (EPA) NTU standard turbidity “must be less than or equal to 0.3 NTUs in at least 95% of the samples in any month." EPA pH range is from 6.5 to 8.5, while in EC is from 6 to 8. EPA standards for some inorganic chemicals are: lead (Pb): level of 0.015 mg/L; arsenic (As): 0.010 mg/L; cadmium (Cd) 0.005 mg/L; chromium (Cr) 0.1 mg/L; mercury (Hg): 0.002 mg/L; nitrate-nitrogen (NO3-N): Maximum Contaminant Level (MCL) of 10 mg/L; fluoride (F): MCL of 4.0 mg/L. For pesticides, atrazine: the MCL is 0.003 mg/L or 3 μg/L; simazine: 0.003 mg/L (3 μg/L). For some other organic compounds: benzene MCL 0.005 mg/L; total trihalomethanes (TTHMs): MCL 0.080 mg/L. Microbiological most common contaminants are set by EPA at zero level for E. coli (Escherichia coli) and total coliform bacteria, Cryptosporidium, enteric viruses, and Giardia lamblia in 100 milliliters of sample. Radiological parameters for radon (222Rn are set by the EPA at 4,000 picocuries per litre (pCi/L). Gross Alpha and Gross Beta radioactivity are set to zero.

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2.4.2. Methods of Detection

Water quality monitoring is a number of practical methods, designed to assess and maintain the cleanliness and safety of water sources and water in processing and delivery systems, up to the end user point (WHO, 2022). It comprises of systematic collection and analysis of physical, chemical and biological water characteristics. The main goals of the evaluation are public and ecological health and safety. To achieve these targets, water samples are collected from various locations and depths within the water body or source (McGhee, and Steel, 1991). The measurement of parameters can be periodical or continuous. Collected samples are analyzed in situ, with the transfer of data, or delivered to the laboratory. Collected data is processed and compared to the standards described above. Real-time monitoring employs sensors with telemetric data transfer. Besides standard laboratory methods, ecological biomonitoring of water bodies may include quantitative and qualitative assessment of water biota. Data is reported to stakeholders and the public in accordance with agreed standards and programs (Behmel et al., 2016).

Traditional organoleptic practices are today supported by a wide range of more developed methods (WHO, 2022). Chemical inorganic substances are detected by: the volumetric method, colorimetric method, electrode method, ion chromatography, high-performance liquid chromatography, flame atomic absorption spectrometry, electrothermal atomic absorption spectrometry, inductively coupled plasma atomic emission spectrometry, inductively coupled plasma mass spectrometry. For organic chemicals employed: high-performance liquid chromatography, gas chromatography, gas chromatography–mass spectrometry combination, headspace gas chromatography–mass spectrometry, purge-and-trap gas chromatography, purge-and-trap gas chromatography–mass spectrometry, electrolytic conductivity detection. gas chromatography with a capillary column and gas chromatography with a detector (Nemerow et al., 2009). A more advanced method is high-performance liquid chromatography (HPLC). Radiological control can include alpha, beta and gamma ionizing radiation detection, if necessary.

Biological control is done for different types of biota, biomarkers and pathogens. Some pathogens are transit ones, while others grow in the specific water environment, and can be facultative and obligate (WHO, 2022). For bacteria are used presence/absence tests, membrane incubation in specific conditions, aerobic or anaerobic, with tests for spores and bacterial cells; acid and gas from lactose detection or the production of the enzyme β-glucuronidase after membrane filtration. The classical culture method is Heterotrophic Plate Count (HPC), Colonies, grown on the agar plate are counted, regardless of particular bacterial form. Membrane filtration allows identification and quantification of specia (Hammes et al., 2010). Most Probable Number (MPN) method also allows the estimation of a number of cells, based on growth in a sample. Molecular methods are: Polymerase Chain Reaction (PCR) for genetic material, which allows the specification of bacteria (Yaradou et al., 2007); Quantitative qPCR checks the number of specific cells. Another genetic method is Fluorescence In Situ Hybridization (FISH) uses DNA probes, complementary to bacterial DNA. Enzyme-Linked Immunosorbent Assay (ELISA) helps to detect and quantify the presence of specific bacterial antigens or antibodies.

Flow cytometry is a technique of rapid analysis of individual bacterial cells in a water sample by laser beams. It provides information about cell size, shape, and fluorescent staining patterns. The method is quantitative and qualitative. Next-generation sequencing (NGS), such as 16S rRNA gene sequencing, is a high-throughput identification of bacterial types in samples (Hammes et al., 2010). Another group of rapid methods with the ability for real-time monitoring use biosensors, devices with biological molecules or organisms in the detector – antibodies, receptors, enzymes, nucleic acids, living cells or organisms, etc. (Wlodkowic and Karpiński, 2021). They detect and quantify the presence of specific types of bacteria by metabolic byproducts (Gerhardt, 2006). Sometimes, these metabolites can be used as chemical indicators, for example, adenosine triphosphate (ATP). They can indirectly measure bacterial contamination by detecting the presence of bacterial metabolic activity (Dodds, 2002). Distant methods of water body control by space satellites or UAVs include IR, UV and visual spectrum analysis (Yang et al., 2022). It can signal in real-time and in progress about algae growth or other detectable contaminants.

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Viruses are harder to detect. For concentration, various methods of ultrafiltration, ultracentrifugation, or adsorption to solid particles can be used to increase the viral load in the sample. Viruses can be detected with the help of electronic microscopy or culture cultivation. Usually, cytopathogenic effect (CPE) in cell culture is observed, which yields results within 3–12 days; plaque assays, which yield results within 24 hours – signs in cell culture by virus cell infection. ELISA, PCR and NGS, mentioned above, are additional methods. **Loop-mediated isothermal amplification (LAMP)** is similar to PCR but simpler, faster and performed at lower temperatures. However, LAMP is less sensitive. Whole-Genome Sequencing (WGS) is more precise. In addition, mass-spectrometry can be used for viral proteins (capsid and enzymes), DNA and RNA. Flow optometry is used for viruses as well. Immunologic arrays and biosensors also can be employed (Hrdy and Vasickova, 2022).

For bacteria, viruses and protozoa, public health methods – epidemiological control, clinical information analysis and reports are used. Establishing buffer zones around water sources can reduce the risk of cross-contamination from agriculture, industrial activities and human settlements. Sewage treatment, stormwater management, and rapid disaster response are important for water supply health and safety control.

2.5. Health Hazards and Contaminants

There are physical, chemical, and biological pathogenic contaminants which can be brought in with water. These substances and organisms are carcinogenic, toxic, or infectious. Detection, monitoring and control of these hazardous substances and biota are important in the sanitary observation of water supply (WHO, 2019; WHO, 2022). Water safety plans (WSP) and Sustainable Development Goals (SDG) include it. The main contaminants are shown in Table 1 and discussed in more detail below.

Table 1. The main contaminants in water supply.

Physical contaminants	Inorganic chemicals	Organic chemicals	Biological contaminants
Solid particles from nature (soil, rocks, dead trees, animal corpses, etc.)	Sodium, calcium, potassium, magnesium	trichloroethylene, tetrachloroethylene	Bacteria (E. Coli, Salmonella, Shigella, Legionella, etc.)
Organic material (algae, faeces, etc.)	Antimony, arsenic, mercury, cadmium, chromium, iron	Cyanides, phenols, volatile organic compounds, petroleum products	Viruses (Hepatitis A and E, enteroviruses, noroviruses, adenoviruses, etc.)
Solid particles resulting from human activity (paper, plastic, glass, etc.)	Sulfate, chloride, nitrate	Algae toxins (cylindrospermopsins, microcystins, saxitoxins)	Protozoa (lamblia, cryptosporidium, entamoeba histolytica, toxoplasma, etc.)
	Uranium, Radon & other radioactive elements	Pesticides and fertilizers (atrazine, glyphosate, etc.)	Helminths (schistosoma, dracunculus medinensis, fasciola hepatica, etc.)

2.5.1. Chemical Aspects

There are several inorganic pollutants that pose risks to human health while consumed with water and can cause acute or chronic toxicity in concentrations higher than the accepted threshold. They can be naturally occurring or from industrial sources. Antimony is toxic to the skin and digestive system. Chronic exposure to lead- arsenic- and mercury-contaminated water may cause neurological, dermatological or cancer problems. Cadmium in high concentration is a carcinogen for the urinary system. Another carcinogen is chromium, used in metal works or tannery (Nemerow et al., 2009). Fluoride, beryllium, nickel, thallium, and some others are also elements-toxic contaminants. Uranium is toxic, besides its radiologic effect. Radon is mainly mutagen due to ionizing radiation. Other rare radioactive contaminants in water include plutonium, technetium, radium, caesium, strontium, thorium, lead-210, iodine-131, and tritium (WHO, 2022).

Obvious toxic chemical compounds are cyanides, phenols, and Volatile Organic Compounds (VOCs) such as benzenes, toluene; petroleum products (WHO, 2022). Phenols and benzenes are also carcinogenic. Many of them are persistent organic pollutants (POPs). They can accumulate in the food chain of aquatic organisms. Disinfection byproducts (DBPs) such as chloramines, trihalomethanes and haloacetic acids are toxic in chronic intake. Pesticides, soil fumigants, fertilizers such as ammonia, rodenticides and herbicides, are other groups of contaminants with adverse effects. Water contamination by fertilizers can lead to algal bloom (Spellman, 2008). Algal toxins are routinely checked in water bodies, especially in warm times of the year. Cyanotoxins from cyanobacteria, microcystins and cylindrospermopsins, domoic acid can be neurotoxic or cause indigestion or liver damage. Saxitoxins are neurotoxic, and they can come from different types of algae. Endocrine-disrupting chemicals (EDCs), such as bisphenol A (BPA) and phthalates, have an adverse influence on the endocrine system of vertebrates after chronic intake (Falconer et al., 2006).

2.5.3. Biological Aspects

Microorganisms and vertebrates are significant water biological contaminants and pathogenic agents. They are bacteria, viruses, protozoa and helminths (Magana-Arachch and Wanigatunge, 2020). Each group includes relatively long compendiums of pathogens. Here are listed the most important ones.

Bacterial infections caused by contaminated water intake are mostly with gram-negative Escherichia coli (E. coli), O157:H7 strain and some others. Gastrointestinal illness with usual symptoms of diarrhea can be brought by several types of Salmonella. Another form of salmonellosis is typhoid fever. Classical haemorrhagic dysentery or shigellosis is triggered by one of the four serotypes of Shigella. The most profuse and lethal diarrhea is called cholera and is caused by Vibrio cholerae. This bacterium can be transmitted even in seawater or river sea estuaries. Diarrheal campylobacteriosis is often originated from Campylobacter bacteroideus infection or other campylobacter species (Hutton and Chase, 2017). Yersinia enterocolitica also causes enteric infection. A typical waterborne infection with high temperature is leptospirosis, after contamination of water source by infected urine. Legionella pneumophila can cause pneumonia. It can reproduce in warm water springs or boilers of end-users. Some other frequent bacterial contaminants are Burkholderia, Francisella, and Aeromonas hydrophila (WHO, 2022).

Viruses are widespread in water bodies, but most of them are not pathogenic for humans (Dodds, 2002). At the same time, a number of viral infections, known to be primarily spread by the fecal-oral route, are well-known. Hepatitis A virus affects the liver, as well as another enteric virus of hepatitis E, widespread in South-Eastern Asia. Classical diarrhea viral groups are Rotaviridae and Caliciviridae, such as noroviruses or sapoviruses, and enteric adenoviruses (Magana-Arachch and Wanigatunge, 2020). Neurotropic poliovirus is also transmitted through the fecal-oral route, including contaminated water. Coxsackievirus and echovirus belong to the enterovirus group. They cause infections, including hand, foot, and mouth disease. Astroviruses can cause gastroenteritis, mainly in children (Hutton and Chase, 2017).

Protozoal pathogens spread via the water route cause a number of infections (WHO, 2022). Giardia lamblia causes giardiasis, a diarrheal illness, and is extremely widespread.

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Cryptosporidium is another cause of specific infection with diarrhea, cryptosporidiosis. Due to spore formation, it is highly resistant to chlorine disinfection. Entamoeba histolytica causes amoebiasis with severe haemorrhagic diarrhea and, in some cases, liver abscesses (Magana-Arachch and Wanigatunge, 2020). Cyclospora cayetanensis is responsible for causing cyclosporiasis. Naegleria fowleri, or "brain-eating amoeba", can lead to primary amoebic meningoencephalitis (PAM). Toxoplasma gondii can potentially enter with contaminated water. Toxoplasmosis results in flu-like symptoms. Acanthamoeba is a free-living single-cell protozoa which can rarely cause eye infection or, in some cases, encephalitis (WHO, 2022). Other potential pathogens are Ballantidium coli, microsporidia, and Dientamoeba fragilis.

Helminthiases are caused by adult or larval forms of waterborne helminths. Schistosomiasis, or bilharzia, is caused by several forms of Schistosoma. The larval form, or cercariae, penetrates the skin or mucosa. The adult form lives in pelvic blood vessels. Dracunculiasis is infection by nematode Dracunculus medinensis (WHO, 2022). The larval form is consumed with water-containing host copepods. An adult worm later emerges through the skin. Fascioliasis is caused by flatworms Fasciola hepatica or Fasciola gigantica. Larval form, metacercariae migrates to liver bile ducts, where the adult form develops. Dioctophymiasis: is caused by Dioctophyme renale. The adult form primarily affects the kidneys. Ascaris lumbricoides, Trichuris trichiura, hookworms such as Necator americanus and Ancylostoma duodenale, and Cestoda tapeworms such as Taenia species, can be transmitted through the water (Dodds, 2002).

3. Blockchain Technologies

3.1. Main Elements

Blockchain is a technology of distributed ledger databases with peer-to-peer connections and necessary cryptographic security (Morabito, 2017). A ledger is a type of historical/economic record which is supposed to be immutable after registration. Every new ledger entrance, a batch of transactions, is a block "chained" to the previous one by the previous block hash. Blockchain is a sequential linear ledger, while Directed Acyclic Graph (DAG) is a directed network ledger where no cycles or repetitions are possible, and transactions are represented as graph nodes (Kasahara et al., 2023). Distributed ledger is decentralized across a number of computing "nodes". Transactions are validated by these network nodes through consensus algorithms. Usual multi-agent system consensus mechanisms are proof of work (PoW), proof of stake (PoS), delegated proof of stake (DpoS), proof of authority (PoA), proof of space, proof of time, proof of luck and hybrids (Bouraga, 2021). Blockchain can be open to the public or be limited only for wetted users access or private. Mixed forms are also in use.

Blockchain widely uses the hash function for data encryption and integrity, transaction security and validation of multi-agent consensus protocols (Morabito, 2017). A hash function is a deterministic type of cryptographic algorithm that translates input into a highly specific fixed-size hash value, which is usually a hexadecimal number or a sort of binary sequence. Typically, the Secure Hash Algorithm SHA-256 is used in blockchain, a member of a cryptographic MD5-based family of hash functions. Some blockchains utilize more secure algorithms from the newer SHA-3 family. These hash values are called "hash nodes." The binary hash tree, or a Merkle Tree, is a way to effectively control data consistency and integrity. The leaf nodes are paired to create a new layer. Every new hash is produced by concatenating the two nodes' values and consulting the hash root. The so-called Merkle root guarantees data integrity in the whole dataset. Each block bears a header, previous block hash (block address) function, timestamp, Merkle root and nonce (Morabito, 2017). The header identifies the entire block in the blockchain. Merkel root is a digital fingerprint of the entire function in the Merkel Tree. The nonce number is usually produced by a deterministic pseudo-random number generator (DPRNG). Please see Figure 1.

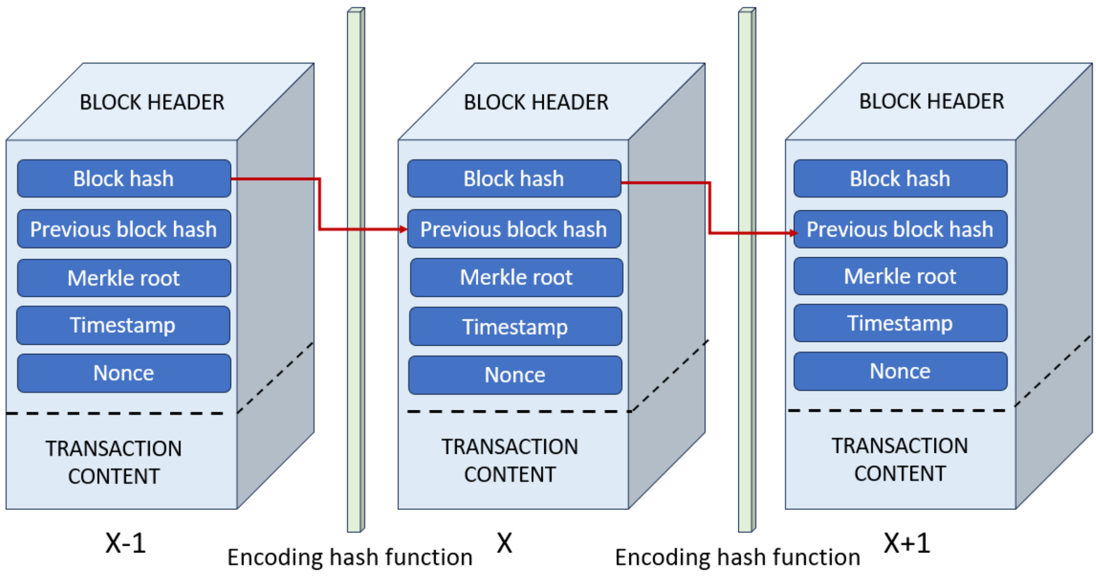

Figure 1. Block structure in a blockchain.

Blockchain applications are smart compliance, smart supply chains, smart contracts, and tokenization (McMeel and Sims, 2021). The main features of these applications are decentralization, security, tamper-resistance, transparency across the blockchain and immutability. Smart contracts are the core mechanism for many blockchain implementations, such as decentralized finances, smart supply chains, resource trading, the insurance industry, smart healthcare, and legal services. There is no necessity for the intermediary party in a smart contract. The conditions are predefined and immutable after the start of execution. Smart contracts can require authentication and/or digital signatures for parties. Tokenization is one of the elements of the blockchain mechanism, which allows the conversion of many types of assets or rights into tokens (Morabito, 2017). Blockchain environment permits secure transactions, tokens liquidity, fractional ownership or responsibility.

3.2. Applications for Water Supply

Information technologies enable water supply systems with additional possibilities (Stankovic et al., 2020). Smart cities, smart environments, and smart water contracts trading platforms are important developments (Asgari and Nemati, 2022). "Smart" water supply means a wide variety of data-driven optimization solutions (Oberascher et al., 2022). It encompasses all stages, from water body control to water distribution and consumption, to make it more efficient, reliable, and sustainable (Mattila et al., 2022). Smart water supply includes a specific IoT-focused smart environment, with sensors and actuators, permanent data monitoring and analysis (Ighalo et al., 2021). Blockchain is instrumental in every stage where ledger immutability, reliable data transparency and distribution, smart compliance, smart contracts and tokenisation can be helpful. Real-time monitoring of water quality, quantity, low rate, and infrastructure conditions requires continuous reporting to the corresponding stakeholders and is supported by real-time data analysis (Ikeda and Liffiton, 2019). It helps with water source planning, water leak estimation, water pricing in times of scarcity, and peak water usage monitoring and control (Oberascher et al., 2022). Machine Learning (ML) and Deep Learning (DL) AI tools are part of many real-time monitoring systems (Asgari and Nemati, 2022). Urban water cycles with the ability to reuse wastewater or integrate stormwater are also important goals for smart water management.

3.2.1. Smart Compliance System

Constant monitoring and reporting are important for the smart compliance system (Oberascher et al., 2022). It ensures that water supply system infrastructure and operations effectively comply with regulatory standards, safety and security protocols, and environmental requirements (Ikeda and Liffiton, 2019). It remotely registers water quality parameters, water treatment processes, and its real-time compliance with regulations. This includes automatic and semi-automatic testing for contaminants in all stages of water collection, purification and delivery, disinfection levels, and other quality standards (Ighalo et al., 2021). If water quality falls below a threshold, the smart system can trigger shutting off contaminated water sources collection and distribution and inform stakeholders. All these events will be recorded in the Digital Ledger database (Asgari and Nemati, 2022). Blockchain guarantees tamper-resistant, immutable record-keeping data integration from various sources, registration of real-time alerts, long-time sustainability based on data, predictive analysis, reliable stakeholder reporting and public notification (Stankovic et al., 2020). Comprehensive audit logs should be maintained on the blockchain database, enabling higher accountability.

3.2.2. Smart Contracts

Smart contracts are self-executing, with predefined procedures, rules and conditions. The authorized parties have the right to access the blockchain, often private (Furones and Monzón, 2023). They are usually water utility operators, auxiliary water supply service providers, service users, regulatory bodies, and end-consumers. Data is transparent for blockchain users. Smart control systems and smart meters trigger automated billing and generate invoices in accordance with data about the quality and quantity of consumed water or services. Smart contracts can be used for supply chain management in any utility besides water, which is used for water supply system functions and inventory control with automatic resupply: pipes replacement, spare fitting, water quality testing and monitoring equipment, tools, personal protective gear equipment, energy supply and backup generators. Smart contracts are useful for routine service contracts for asset management (McMeel and Sims, 2021). It enables contracts for regular examinations and support of infrastructure, pipe cleaning and water tank maintenance (Oberascher et al., 2022). Smart contracts system works together with smart compliance system. Data and automatic documentation are often shared in a real-time manner between involved stakeholders (Ikeda and Liffiton, 2019). Overall control allows effective resource allocation, easier dispute resolution and effective emergency response. Billing and payment for end-users is streamlined by blockchain and facilitates micro-transactions, if necessary. Remote areas can receive better service if they are part of the smart water supply system with a smart contracts option (Stankovic et al., 2020).

3.2.3. Tokenisation

Digital tokenization is an effective tool in blockchain's smart system of supply. Water can be acknowledged as a public or communal utility, managed by levels of government, municipal, private or public companies or partnerships. Water sources, water quantities, water rights or water-related assets can be tokenized, for example, as eWater tokens (Ikeda and Liffiton, 2019). It can help to recognize shares and allocate resources in communal water supply systems and water rights for agricultural, industrial or municipal use. Token-based incentives, such as tradable water credits or specific digital tokens for water conservation and pollution control, help to optimize control of water resources. Incentive tokens can be redeemed through the discounts (Ikeda and Liffiton, 2019). Smart contract shares, rights and contracts themself can also be tokenized as well. Licenses can be controlled by tokens with a certain time limit (Morabito, 2017). All these tokens are placed in the distributed ledger or blockchain associated with the water supply system. Blockchain with tokens gives it a higher degree of efficiency, flexibility, transparency, accessibility and governance.

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4. Smart Water Quality Control

4.1. Sensors, Networks, Systems

Smart water contamination control is reactive, with swift response to incidents, and proactive, with the help of data analysis and predictive model constructions (Oberascher et al., 2022). It integrates IoT technologies, data-driven decision-making and continuous smart infrastructure maintenance, Supervisory control and data acquisition (SCADA) system with IoT and AI for water quality control refers to several conceptual elements in smart water supply and distribution (Shahra and Wu, 2020). Telemetric data collection from various sensors placed in water sources, water tanks and delivery systems, have to constantly obtain real-time data. Integrated inline sensor-based monitoring (ISBM) includes various types of specifically calibrated sensors (Lambrou and Anastasiou, 2014). Measurement of pH, turbidity, total dissolved solids (TDS), chemical composition and biological content is sometimes a non-trivial task in conditions of permanent contaminated water contact, especially at water sources. Sensors are mostly optical, electrochemical, and spectrophotometric. While some techniques allow real-time reporting, others are possible only as near-real-time or semiautomatic. For example, real-time PCR or routine quantification of L. pneumophila is available, but in some cases, the method is laboratory-dependent (Yaradou et al., 2007). Flow cytometry allows quantitative and qualitative control for pathogenic bacteria (Clausen et al., 2018). Disinfection control is possible in some forms of real-time dynamic monitoring flow cytometry (Arnoldini et al., 2013). Other real-time methods for faecal contamination use ATF monitoring (Højris et al.,2018) or other metabolites, like tryptophan, by in-situ tryptophan-like fluorescence (Sorensen et al., 2018). Various biosensors use fluorescent-labelled, fluorogenic, immunomagnetic and radio-labelled antibodies or antigens and other proteins, such as enzymes, cell structures or organisms (Gunter et al., 2023). Biosensors are usually electrochemical, optical or fluorescent. For viral contamination, quantitative reverse-transcriptase PCR method is proposed (La Rosa et al., 2010) or bioluminescence and flow cytometry.

Every sensor has to be connected by an appropriate network medium to the nodes or computing units. It depends on the proximity of the sensor, frequency of the data reporting, transmission interval and necessary quality of information. Proximity Wireless Network (PWN) usually takes up to tens of meters and exploits Radio Frequency ID (RFID), which works in ultra-high frequency diapason (Oberascher et al., 2022). Zigbee protocol and Wi-Fi are effective up to a hundred meters. Local Area Network (LAN) covers up to a thousand meters and can be serviced by wireless Wi-Fi, wireless point-to-point radio protocol WM-Bus and wired Broadband Powerline Communication (BB-PLC). Over one kilometre distance, Wide Area Network (WAN), Low Power Wide Area Networks (LPWAN) and long-range wide area network (LoRaWAN), various cable connections, a fiber-optical passive optical network (PON), wireless options such as 4-5G are effective. Another protocol for distant fiber-optical data transfer is Wavelength Division Multiplexing (WDM).

Data is transferred to analytical nodes or computing devices. Some sensors are capable of primary data transformation (Oberascher et al., 2022). Fog and edge distributed computing concepts in IoT move data processing closer to data collection points. Cloud applications, on the other hand, are architecturally maximally distant from the sensors. Raw data from various sensors has to be integrated, cleaned and prepared for analysis. Preprocessing includes handling of missing data, outliers' removal and verification. Data processing today is highly automated and often employs AI techniques. Machine Learning algorithms compare big data flow against pre-labelled models with clearly set boundaries of sanitary indicators. Data loaded into the model can hold real spiking events by some sort of monitored contaminants (Czyczula Rudjord, et al., 2022). Anomaly detection enables a set of actions, such as actuators' activation, water treatment adjustment, notification report sending or emergency alarm. Some approaches take into account several non-specific biologically-connected changes together to produce analytical results with the help of neural network (Tinelli and Juran, 2019). Long-term trends and comparisons with historical records add in-depth understanding. Analytical data from several water sources and water treatment stations can be compared or integrated for wider analysis and predictions (Richards et al., 2023). Graphical visualization is an effective way for human-machine data interaction. Predictive and correlative analytics help to create

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more sophisticated models and optimize sanitary control efforts. Virtual water supply control can be virtually emulated for system planning, working protocol improvement or disaster response training.

4.2. Blockchain Applications

Blockchain provides a distributed tamper-proof system for data recording of water sanitary quality (Xia et al., 2022). The immutability of acquired data is important for every step, from sensors raw data and anomaly detection to final analytical reports (Alharbi et al., 2021). Blockchain prevents unauthorized data tampering for any stakeholder. At the same time, information about sanitary conditions or specific events is transparent inside of the system. Data events can be traced backwards due to specific timestamps and a unique cryptographic signature (Xia et al., 2022). Blockchain helps to recover lost data by its distributed nature (Mattila et al., 2022). Digitalized water quality certificates can be produced and represented automatically after appropriate validation by blockchain nodes (Asgari and Nemati, 2022). It ensures higher compliance with sanitary norms and easier auditing. Tokenization allows a specific system of rewards for water cleanness and standards upheld. Specific smart contracts in the case of water supply quality support or emergency response can also be activated via blockchain. For additional details, please consult Table 2.

Table 2. Blockchain applications in sanitary control of water supply.

Water supply system management and service	Distributed ledger database	Smart contracts	Tokenization	Automatic reports to stakeholders
Smart water quality control	✓	✓		✓
Planned sanitary events	✓	✓		✓
Emergency sanitary events	✓	✓		✓
Supply chain management for water quality control	✓	✓	✓	✓
Supply chain management for water delivery system	✓	✓	✓	✓
Clean water conservation	✓	✓	✓	✓
Auditing process	✓	✓		✓
Regulation compliance	✓	✓		✓
End-consumer sanitary control	✓	✓	✓	✓

5. Conclusion

Sanitary quality of water supply is an important part of public health preventive and protective efforts to prolong human life and improve its quality. There are multiple facets in pursuing the highest standards of consumed water, primarily the drinkable and used for food and beverage processing. The quality of water sources depends on the environmental factors, natural and artificial. Pollutants can enter the water source as part of an intrinsic system due to natural changes in weather, geology, biosphere, or a part of human biological, agricultural or industrial activity. Part of the contaminants result from less than adequate water treatment processes or deficiencies in the water distribution system. Hence, water supply monitoring, besides the quantitative dimension of sanitary measures, includes a significant part of qualitative control—the range of measures applied to upholding standards of drinkable water. Traditional water supply system treatment and monitoring includes control and management of water sources, effective water treatment and safe delivery to the end-consumer. Regular water testing is important for the constant quality of potable water. A wide range of sensors, from real-time devices and biosensors to near-real-time or laboratory appliances, are employed for qualitative and quantitative control. Telemetry and big data processing allow the creation of specialized IoT systems for water supply integrated into smart cities or smart environment. Distributed ledger technologies, and one of its forms, blockchain, are instrumental for the potent smart water supply. This chapter describes basic blockchain-related and other modern IT technologies applied for sanitary quality of water collection and distribution. Blockchain is effective for the immutable distributed timestamped ledger database. In the case of sanitary water control, blockchain is helpful for the registration and storing of all water supply-related events broadcasted to every stakeholder with an approach to the blockchain. Besides water quality data, blockchain holds a technical ability for smart contract enactment, compliance reporting and action activation. Tokenization helps to optimize water usage, improve initiatives in water conservation and safety, and allow higher flexibility for water supply management and use. Blockchain is considered to be a robust, secure, transparent and dynamic instrument for applications in utilities management. However, there are issues related to the types of security of blockchain and the integrity of data in it.

In this chapter, most of the cryptography and security-related issues were understandably left outside of the main topic discussion. The limited space permits us to focus solely on the key aspects of blockchain applications in the vast domain of sanitary water monitoring and management. To conclude, we can state that distributed ledger technologies, particularly the blockchain, are important for the effective contemporary water supply system and have to be implemented as a part of IoT and smart environment technologies for a higher degree of sanitary standards of potable water.

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