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Review: Urban Water Security and Safety

Review: Sicurezza e Protezione delle Acque nel contesto Urbano

Philippe QUEVAUVILLER[a], Klaus HINSBY[b,s] ✉ , Ida KARLSSON SEIDENFADEN[b,s], David PULIDO VELÁZQUEZ[c,s], Manuel SAPIANO[d,s], Rosario COELHO[e], Peter GATTINESI[f], Philipp HOHENBLUM[g], Vaclav JIROVSKY[h], Fatima MARINHEIRO[i], Luis SIMAS[l], Rui TEIXEIRA[m], Rita UGARELLI[n], Monica CARDARILLI[o], Sotirios PARASKEVOPOULOS[p], Stelios VRACHIMIS[q], Gertjan MEDEMA[p], Demetrios ELIADES[q], Francesco LA VIGNA[r,s]

[a] European Commission, DG HOME, Belgium
[b] GEUS, the Geological Survey of Denmark and Greenland, Copenhagen, Denmark
[c] IGME, the Geological Survey of Spain, Granada, Spain
[d] The Energy and Water Agency, Malta
[e] Aguas do Algarve, Portugal
[f] Advisor, United Kingdom
[g] Environment Agency Austria, Austria
[h] Czech Technical University in Prague, Department of Security Technologies and Engineering, Czech Republic
[i] Águas de Portugal, Portugal
[l] ERSAR, The Water and Waste Services Regulation Authority, Portugal
[m] Municipality of Barreiro, Water and Wastewater Department, Portugal
[n] SINTEF, Norway
[o] European Commission, DG Joint Research Centre, Italy
[p] KWR Water Research Institute, the Netherlands
[q] KIOS Research and Innovation Center of Excellence, University of Cyprus, Cyprus
[r] ISPRA – Geological Survey of Italy, Rome, Italy
[s] EuroGeoSurveys, Brussels, Belgium

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Correspondence to:
Klaus Hinsby ✉ :
khi@geus.dk

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Riassunto

Il termine “sicurezza idrica” può essere interpretato in modo diverso dando luogo a situazioni paradossali a seconda del contesto. In un contesto ambientale e di consumo umano, la sicurezza idrica si riferisce generalmente alla mancanza di risorse, vale a dire alla scarsità d’acqua che può essere correlata sia ad un eccesso di prelievo sia agli effetti della siccità (con evidenti collegamenti al cambiamento climatico). Inoltre, la sicurezza idrica è strettamente correlata alla sicurezza alimentare, alla sicurezza energetica, alla sicurezza sanitaria e alla sicurezza ecologica. Dal punto di vista della sicurezza (umana), tuttavia, la sicurezza idrica è intesa alla luce del possibile degrado intenzionale delle risorse, ad es. atto criminale o terroristico che porta ad una contaminazione deliberata (chimica o biologica). Quando si parla di “sicurezza dell’acqua”, il riferimento è alla qualità dei sistemi idrici per la salute ambientale o alla qualità dell’acqua potabile per la salute umana, che a loro volta si riferiscono a standard di qualità che stabiliscono i livelli massimi ammissibili di contaminazione o di contaminazione geogenica naturale di elementi come l’arsenico e il fluoro. Questa review fornisce una fotografia di varie questioni relative alla sicurezza e alla protezione delle acque (sotterranee), scritta da autori provenienti da diversi settori e discipline.

Abstract

“Water security” and “water safety” is defined differently. As the terms are related they may lead to confusion and misinterpretations, depending on the context. Water security generally refers to a lack of resources of an acceptable quality, i.e. water scarcity that may be related either to an excess of water demand or drought impacts (with links to climate change and e.g. salt water intrusion into coastal aquifers). Further, water security is closely related to food security, energy security, health security and ecological security. From a (human) security viewpoint, however, water security may also be understood in the light of possible intentional degradation of the resources, e.g. criminal or terrorist act leading to a deliberate (chemical or biological) contamination of water supply systems. Water safety on the other hand refers to the quality or chemical status of the water resources that has to comply with the defined quality standards for drinking water specifically to protect human health, both from elevated concentrations of contaminants and natural geogenic elements. This review gives a snapshot of various (ground)water safety and security issues written by authors from different sectors and disciplines. Illustrating and clarifying the many societal challenges related to water security and safety in cities.

Introduction

When discussing “water security” and “water safety,” it is important to clarify that these notions can be interpreted differently depending on the context. In an environmental and human consumption context, water security generally refers to a lack of resources of an acceptable quality, i.e. water scarcity that may be related either to an excess of water demand or drought impacts (with links to climate change). Further, water security is closely related to food security, energy security, health security and ecological security (Singh 2017) as illustrated by the Water-Energy-Food-Ecosystem Nexus (de Roo et al., 2021). From a (human) security viewpoint, however, depending on the context, water security is often understood in the light of possible intentional degradation of the resources, e.g. criminal or terrorist act leading to a deliberate (chemical or biological) contamination somewhere in the water supply system between the (ground) water resource and the tap. When speaking about “water safety”, the reference is about either the quality of the water bodies for environmental health or the drinking water quality for human health, which are themselves referring to quality standards setting the maximum permissible levels of contamination or of naturally occurring geogenic elements such as arsenic and fluoride (Hinsby et al., 2008; Giménez-Forcada, 2022). In a way, water contamination might be perceived as a combination of safety and security (in the sense of intentional contamination). In the cities’ environment the interplay among population growth, urban expansion, and resource utilization follows a non-linear trajectory, signifying the escalating non-linear impacts of urbanization on the broader environment (John et al., 2015). Additionally, human activities such as land-use change, substantial water withdrawals, and wastewater discharge can exert a more pronounced influence on the water cycle than climate change, leading to changes in both the chemical and quantitative states of both surface water and groundwater, thus impacting water safety and security as well (La Vigna, 2022; Bricker, 2013; Bricker et al., 2017, 2024). Still, standards are not established in the same spirit as discussed below.

Regarding (ground)water scarcity, security in an environmental sense is regulated by the Groundwater Directive (European Commission, 2006) which requests reaching a “good quantitative status” over the duration of a (6 years) River Basin Management plan, i.e. a balance between groundwater recharge and abstraction for different usages. The Water Framework Directive (European Commission, 2000) does not set any quantitative status for surface waters (focusing on chemical and ecological status) but a provision is set in its Article 4.7 regarding a temporary degradation of water resources that includes the possible occurrence of extreme droughts (possibly leading to water scarcity).

The recent Directive on Critical Entities Resilience (Directive EU, 2022/2557) (European Commission, 2022) addresses natural and man-made threats affecting the drinking and waste water sectors, among others. Specifically, it provides an overarching framework for all hazards, whether accidental or intentional.

Recommendations to deal with criminal and/or terrorist threats are subject to non-binding statements under the CBRN (Chemical, Biological, Radiological, Nuclear) Action Plan and EU research projects. When dealing with water safety, environmental and/or drinking water standards are established according to identified contamination risks (to the environmental quality of ground and surface waters and/or the drinking water quality at the tap). The Groundwater Directive makes a link between the protection of groundwater abstracted for drinking water purposes (the so-called Drinking Water Protection Zones) and drinking water quality but it does not consider the intentional degradation as one of the regulated threats. In other words, the Drinking Water Directive (European Commission, 2020) regulates the quality of water intended for human consumption. While the logic of the Directive is to address all possible contamination causes, thus implicitly covering deliberate poisoning risks, the drinking water standards do not cover substances of criminal origin; it introduces a risk-based approach across the water supply in its entirety (from source to tap) and will promote/enforce preventive measures at source (including groundwater).

This paper discusses the following water security and safety facets of relevance to urban water supply, 1) water security aspects related to groundwater over-abstraction in urban and peri-urban areas illustrating both similarities and differences between southern and northern Europe, 2) water security from an intentional degradation viewpoint, 3) pathogen contamination in urban water networks, and 4) groundwater monitoring in cities as a fundamental action to prevent and manage some of the covered issues related to water security and safety; including the impacts of climate change and climate change mitigation and adaptation solutions (Ingemarsson et al., 2022) on water and Earth System resilience (Gleeson et al., 2020). The paper is structured in four main sections for each of the discussed topics mentioned above. The purpose of the discussion of water security and safety issues in urban settings is not to provide an exhaustive review of the relevant issues, but to highlight some of the main concerns for water resilience, security and safety to be considered to ensure a secure and safe urban water supply in a changing climate.

Discussion

Water security issues related to groundwater over-abstraction and droughts

Groundwater over-abstraction and water table decline

Groundwater over-abstraction, droughts and resulting water table decline, particularly in urban areas, presents a complex set of issues negatively affecting society and nature, potentially resulting in increasing risks of geohazards (land subsidence, flooding etc.), salinization, and biodiversity loss (Jasechko et al., 2024; Ohenhen et al., 2024; Zuccarini et al., 2024; Flörke et al., 2018, La Vigna, 2022; Foster, 2022; Li et al., 2023; Zektser et al., 2005).

Groundwater, representing 99% of Earth’s liquid freshwater resources, is vital in sustaining ecosystems, supporting agriculture, and providing potable water for billions worldwide (United Nations, 2022). "Groundwater underpins the development of agriculture, cities, and critical ecosystems" (Rodella et al., 2023). Yet, as cities expand and the demand for freshwater surges, unsustainable extraction of groundwater has led to severe environmental and socio-economic consequences, globally.

Groundwater abstraction in urban areas may result in land subsidence (Collados-Lara et al., 2020; Dinar et al., 2021). Cities built on these vulnerable grounds face an increased risk of infrastructure damage. For instance, Jakarta, Indonesia, Mexico City, Mexico, and Beijing, China (Li et al., 2023) are notorious examples where excessive groundwater pumping has led to sinking cities, with some areas experiencing subsidence rates of more than 10 cm per year. The implications are dire, ranging from cracked foundations and damaged buildings to disrupted water and sewage systems. Moreover, subsidence can alter surface water flow and increasing flood risks (Ohenhen et al., 2024).

Focusing on Europe, the continent presents a unique case study in groundwater over-abstraction, with distinct challenges emerging between southern and northern regions due to a large variation in precipitation and groundwater recharge (Martinsen et al., 2022). Europe's diverse climate, economic activities, and water management policies contribute to varying degrees of groundwater issues. These differences underscore the necessity for region-specific strategies to address the pressing challenges of groundwater sustainability. Issues related to water scarcity and over-abstraction are well known in Southern Europe (Collados-Lara et al., 2020; Dinar et al., 2021), but are less prominent and not well investigated in Northern Europe (Barthel et al., 2021).

Groundwater Issues in Southern Europe

Southern Europe, characterized by its Mediterranean climate, faces significant water scarcity issues, exacerbated by long, dry summers and increasing demand for agricultural and touristic uses. In the future, this issue will further exacerbate due to climate change. In Mediterranean regions, we anticipate significant reduction in precipitation alongside increasing temperatures and evapotranspiration leading to more frequent, prolonged, intense and severe droughts (Tramblay et al., 2020, 2021). If the currently irrigated crops are maintained, it will force higher pumping rates in aquifers which will be reflected in lower guarantees to meet the demands (Gomez-Gomez et al., 2022). The impact on groundwater status will especially be significant in those aquifers with lower mean residence time and higher vulnerability to pumping (Pulido-Velazquez et al., 2020).

A recently published global worldwide study of groundwater trend showed that the aquifer with the fastest rate of decline according to the data they collected is the Ascoy-Sopalmo (located in Segura Basin, Spain) with an average decrease of 2.95 meters per year (Jasechko et al., 2024).

Countries such as Spain, France, Italy, and Greece heavily rely on groundwater for irrigation, drinking water, and supporting their vital tourism industries., This reliance has led to extensive over-abstraction and land subsidence (Collados-Lara et al., 2020; Dinar et al., 2021; Herrera et al., 2009), resulting in several environmental and socio-economic challenges.

Coastal areas in Southern Europe are particularly vulnerable to saltwater intrusion, a problem intensified by groundwater over-abstraction, which will intensify in the future due to climate change and reduce water security due to deteriorating groundwater chemical status (Baena-Ruiz et al., 2021). For example, in Spain's coastal aquifers, such as those in the delta of the Ebro River, excessive pumping for agriculture has led to saltwater encroachment, rendering water sources unsuitable for consumption and irrigation, and threatening local ecosystems.

The Doñana National Park in Spain, a UNESCO World Heritage site, exemplifies the ecological impact of groundwater over-extraction (González-Jiménez et al., 2023). The Upper Guadiana Basin is also a paradigmatic case of conflict between agricultural development (linked to groundwater overexploitation) and RAMSAR wetland environmental conservation, with increasing negative impacts on water security due to climate change (Pulido-Velazquez et al., 2023).

The park's wetlands have experienced significant drying, affecting the habitat of numerous bird species and leading to a decline in biodiversity. This issue is not isolated, but indicative of the broader environmental consequences faced by Southern Europe due to unsustainable groundwater use.

Over 30% of the total land area of the Maltese islands has been developed, where urban landscapes prevail in the eastern side of the main island of Malta (NSO, 2024). At 1,700 inhabitants per square km, Malta has by far the highest population density in Europe and can therefore be considered as an island city-state, presenting a mixed land-use scenario where urban, industrial, agricultural and natural areas intermix. The semi-arid Mediterranean climate limits the availability of natural water resources, and when coupled with the small size of the islands precludes the formation of surface water resources. In fact, groundwater is the only naturally renewable freshwater source present in the islands. (Sapiano, 2020).

Municipal water supply relies on desalinated water blended with groundwater in a 65:35 mix. (WSC, 2023) Groundwater, however, sustains water security for the demands of the agricultural and commercial sectors and as a whole contributes around 60% of the water demand of the islands.

In the island of Malta, the impacts of urbanization on the groundwater environment are twofold. The dense urbanized landscape, characteristic of the eastern side of the island, limits recharge to groundwater due to land sealing. The reduction in natural recharge has however over the years been compensated by an increased artificial recharge due to leakages from municipal water distribution networks as well as a reduction in groundwater abstraction for municipal and agricultural purposes which was shifted to inland areas (Sapiano, 2020). On the other hand, groundwater abstraction to sustain municipal and agricultural demand becomes more concentrated in the less-urbanised inland areas resulting in an increased pressure on groundwater resources in these areas. In fact, groundwater level monitoring stations located in the urbanized areas show a slow but steady increase since the 1960's, whilst in stations located in the inland areas a negative trend in water level prevails – highlighting the over-abstraction at the regional level (EWA, 2023). This illustrates the different facets of the impact of urbanization on groundwater systems.

Groundwater Issues in Northern Europe

Contrastingly, Northern Europe, with its generally cooler climate and higher precipitation rates, faces different groundwater-related challenges. Countries such as the United Kingdom, Germany, the Netherlands, and the Nordic countries (Denmark, Norway, Sweden and Finland) have more abundant water resources and shallow water tables (Schneider et al., 2022), but are not immune to the problems of over-abstraction (Barthel et al., 2021; Henriksen et al., 2021, 2023a,b,c; Jasechko & Perrone, 2021; Mielby & Henriksen, 2020; Seidenfaden al., 2022); and resulting land subsidence (Peduto et al., 2017) or impacts on groundwater dependent terrestrial and aquatic ecosystems (Danapour et al, 2021; Henriksen et al., 2023; Nilsson et al., 2023).

While less frequent than in Southern Europe, Northern European urban areas are also susceptible to the impacts of groundwater over-abstraction, including land subsidence and the exacerbation of geohazards. For instance, over-extraction has contributed to subsidence issues in parts of the UK (Agarwal et al., 2020) and Denmark, affecting infrastructure and residential properties.

Northern Europe experiences significant seasonal variability in groundwater levels due to its climate. However, climate change is altering precipitation patterns (Seidenfaden et al., 2022) and increasing the frequency of extreme weather events, such as droughts and floods. These changes can exacerbate groundwater scarcity during dry periods and challenge the existing water management infrastructure and water supply (Barthel et al., 2021), where wells are at risk of running dry in summer seasons e.g. in Norway and Sweden (Jasescko et al., 2021). Similar to Southern Europe, saltwater intrusion due to over-abstraction is an issue in many parts of Northern Europe, particullarly around larger cities with high water consumption such as Copenhagen, Denmark (Henriksen et al., 2023b) or coastal areas with high seasonal demands (Hinsby et al., 2011; 2024; Rasmussen et al., 2013). This phenomenon reduces water security in these areas due to elevated chloride concentrations above drinking water standards.

Chan et al. (2021) investigated future soil moisture, stream and groundwater droughts in a Danish catchment. While registering an overall groundwater table rise due to higher precipitation, they also found that the occurrence of the most extreme drought category doubled for both soil, stream flow and groundwater droughts. Furthermore, increasing irrigation demand led to a worsening of the most extreme groundwater drought.

Precipitation over the Danish area is unevenly distributed with the highest precipitation amounts in the west and the smallest in the east. Reversely, the pressure on the drinking water resource is largest around the capital (Copenhagen) located in Zealand to the east. These imbalances lead to severe overexploitation of 2.25 times the available robust water resource calculated by Henriksen et al. (2023b). They defined the robust water resource as the exploitation possible without i) degradation of the groundwater aquifers and ii) runoff required to ensure water security for ecosystems e.g. the required environmental flows supporting fish communities (Henriksen et al., 2021; Nilsson et al., 2023).

Abstraction in Copenhagen (Frederiksberg Waterworks) is believed to be a contributing factor to a slow increase in chloride content in the drinking water (Frederiksberg Municipalities, 2022), potentially worsening due to future sea level rise projected for the area (Colgan et al., 2022). Furthermore, the cost of removing contaminants is projected to increase (Archiland, 2018). However, terminating the abstraction is feared to cause other water security issues such as increasing flooding risks and damage to urban infrastructure due to increasing water tables.

Droughts and/or over-abstraction on the other hand frequently leads to water table decline causing damages to buildings and other infrastructure (Henriksen et al., 2022).

Regional Variations and Policy Responses

The European Union has recognized the critical importance of sustainable groundwater management, enacting policies like the Water Framework Directive (WFD) to address the above-mentioned water security issues. However, the effectiveness of such policies varies significantly between Southern and Northern Europe due to differences in enforcement, local governance, and public awareness.

In Southern Europe, the challenge lies in balancing water demand with a sustainable and diverse supply, necessitating investments in water-saving technologies and non-conventional water resources, promoting less water-intensive crops, and enhancing public awareness regarding water conservation. Managed aquifer recharge (MAR) projects, like those being explored in Spain and Malta, offer promising solutions to replenish depleted aquifers and combat salinization. Additionally, the substitution of groundwater with non-conventional water resources such as sea-water desalination and water reuse further reduces existing pressures on aquifer systems.

Northern Europe focuses more on adapting to climate change's impacts on groundwater resources and managing urban development to prevent geohazards and impacts on the built infrastructure. Policies aim to improve water use efficiency, delineate water protection areas to protect both groundwater quantitative and chemical status accord to the WFD & GWD, and invest in green infrastructure to enhance natural recharge and mitigate flood risks.

It is important to not only address the issue of over-abstraction of water in terms of availability, but also to consider groundwater quality in future water management policies to promote sustainable development. For instance, the lack of potable water is significantly affected by nitrate contamination and this problem is expected to worsen in the future (Wang et al., 2024). Recent research on water safety issues and the relation between groundwater, drinking water and human health in Denmark indicate that the current drinking water quality standards may be too high for some typical pollutants including nitrate, pesticides or naturally occurring trace elements (Ahmad et al., 2020; Schullehner et al., 2018, 2019). Some elements may also affect human health positively (Schullehner, 2019). These findings should be considered when evaluating water security in general as elevated concentrations of harmful elements may also affect food security and industrial uses. Reducing the concentration of even naturally occurring element as e.g. arsenic may reduce health risks and costs (Ahmad et al., 2020).

Lessons learned

Groundwater over-abstraction and resulting water table and runoff decline pose significant threats to water security, urban stability, salinity balance, and biodiversity globally. Its implications extend beyond the immediate environmental impact, affecting socio-economic conditions and public health. Addressing this challenge requires a holistic approach encompassing regulatory frameworks, technological innovations, climate change, and community participation in transdisciplinary collaboration.

Groundwater over-abstraction in Europe presents a complex tapestry of challenges that vary significantly from the arid south to the wetter north although both southern and northern Europe can be severely affected by droughts. The continent's experience underscores the need for tailored, region-specific approaches to groundwater management that consider each area's unique climatic, geographical, and socio-economic conditions. By fostering cooperation across national borders and investing in sustainable water management practices, Europe can address the pressing issues of groundwater over-abstraction, ensuring the resilience and water security of its water resources in the face of climate change and increasing demand.

Innovative solutions like managed aquifer recharge and conjunctive groundwater-surface water use can play a pivotal role in replenishing depleted aquifers (Ohenhen et al., 2024) and conjunctive use management models might help to identify and assess potential management alternatives (Pulido-Velazquez et al., 2008). MAR involves the intentional recharge of aquifers with surface water during periods of surplus, thus restoring groundwater levels and counteracting the effects of over-abstraction. Additionally, raising public awareness about the importance of groundwater conservation and encouraging water-saving behaviours can contribute to the sustainable management of this precious resource.

Water security planning for drinking water infrastructure

Overview

Drinking water systems face both unintentional threats, such as those arising from accidents, and deliberate actions that can lead to significant disruptions. While the likelihood of such events is low, incidents affecting drinking water infrastructures highlight the real nature and high impact of deliberate activities on water supply systems and interconnected services, such as hospitals, schools, and industry (Galbusera et al., 2021).

Drinking water systems are vulnerable to deliberate malicious actions from source to tap. For instance, physical equipment sabotage, cyberattacks on information and operational systems, and water contamination (Hassanzadeh et al., 2020). These hostile acts have the potential to compromise the physical integrity of water supply systems and the quality of supplied water.

Recognizing the importance of drinking water supply to national security, some governments have entrusted security intelligence services with the responsibility for surveillance and threat assessment, enforcing security requirements (Gonçalves, 2020).

The new Critical Entities Resilience Directive (CER) (European Commission, 2022), which replaced the European Critical Infrastructure Directive of 2008 (European Commission, 2008), includes the water sector. This is being transposed into the national legislation of all Member States, requiring entities that are considered critical to take appropriate and proportionate technical, security and organisational measures to ensure their resilience (European Commission, 2022).

Safety and Security of Drinking Water Systems

Water safety and security for drinking water systems are distinct but interconnected concepts (Batlle Ribas et al., 2022). Water safety concerns maintaining the quality of drinking water with the goal of providing clean and safe water for public consumption. This includes measures to prevent contamination occurring in the catchment, during water abstraction, treatment and distribution, which could be caused by accidents, natural disasters or systemic failures.

On the other hand, water security pertains to safeguarding the drinking water supply (including groundwater) from deliberate acts of tampering or toxic release with malicious purposes or discharging wastes in the environment that threaten water resources (e.g. illegal drugs), potentially resulting in severe impacts on public health and order (Teixeira et al., 2023).

Both are essential for ensuring adequate supply of drinking water, but it is important to consider different levels of criticality and needs, which may lead to divergent priorities and resource allocation, although generally complementary.

Water Security from source to tap

It is crucial to implement security measures to strengthen the resilience of drinking water infrastructure against malicious actions. It necessitates a thorough planning process involving strategies and measures to protect water infrastructure, prevent unauthorized access to water facilities, and mitigate the risk of intentional harm to the water supply.

Water security planning provides drinking water utilities with the essential information and tools to formulate and execute strategies in the event of deliberate chemical or biological contamination of the drinking water supply system.

In this context, the Water Security Plan (WSecP), developed within the European Reference Network for Critical Infrastructure Protection (ERNCIP) (Hohenblum, 2013), is designed to expedite the response and recovery in the event of contamination affecting the drinking water supply system. By doing so, the plan aims to minimize the severity of potential disruptions and mitigate the risk of disease outbreaks with potentially catastrophic consequences (Teixeira et al., 2019; Teixeira et al., 2022).

Water Security Plans are therefore suitable for implementing the new CER Directive (European Commission, 2022), as they offer a comprehensive approach to resilience planning for critical entities. Additionally, response and recovery for deliberate water contamination can also enhance resilience for other unexpected incidents, especially when integrated with Water Safety Plans (WHO, 2009; WHO, 2014).

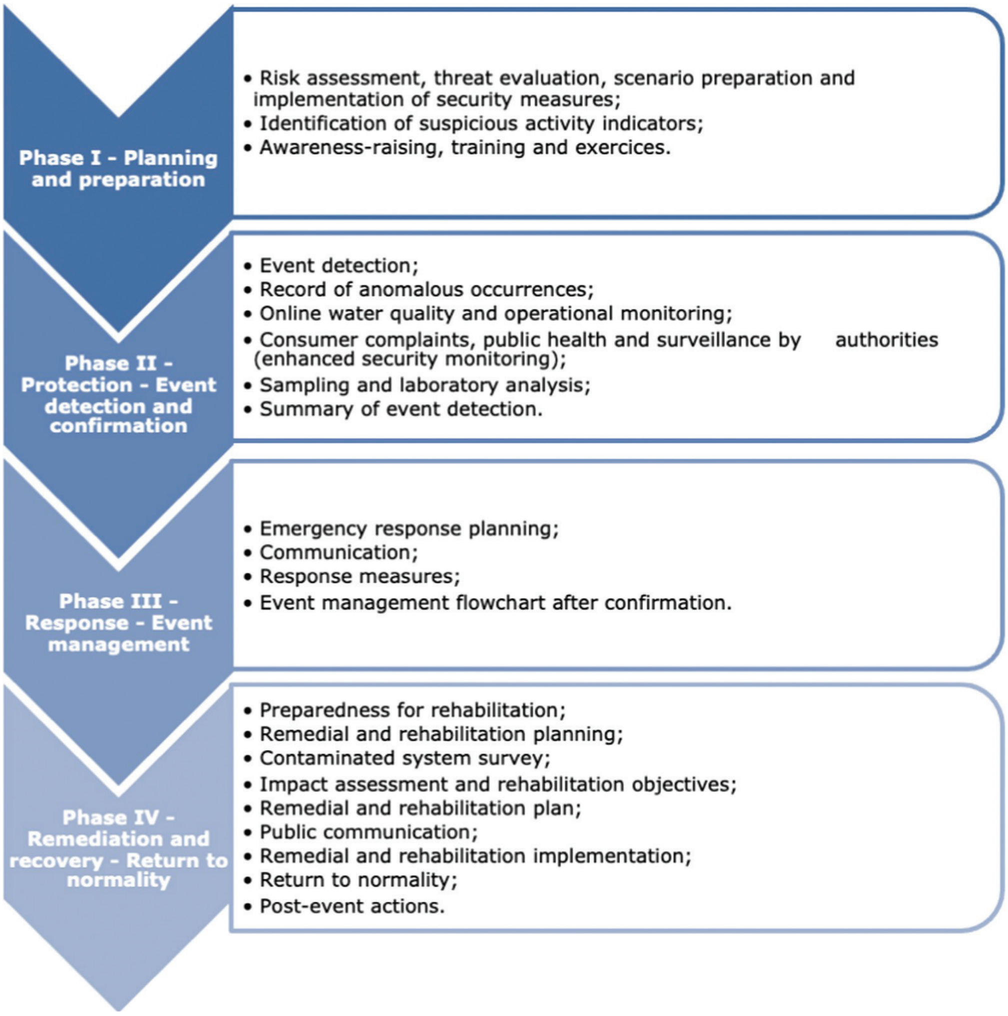
Lifecycle of Water Security Plan

The Water Security Plan is organized into four phases, which are characterized by regular revision and continuous updating by water utilities. These phases (Fig. 1) are based on the timeline of a potential contamination and include (European Commission, 2020):

1. Planning and preparation;
2. Protection: event detection and confirmation;
3. Response and event management;
4. Remediation, rehabilitation, and recovery.

Planning and Preparation

As the first action, water utilities should prioritize planning to mitigate water security incidents. This involves team building, assigning roles and tasks at the senior management level, and conducting risk assessments to evaluate potential threats and infrastructure vulnerabilities. Assessing the potential impact of incidents, particularly on essential services and customers, such as hospitals and schools, is crucial. Part of this planning process includes defining scenarios of attack to anticipate and prepare for



Phase I - Planning and preparation

- Risk assessment, threat evaluation, scenario preparation and implementation of security measures;
- Identification of suspicious activity indicators;
- Awareness-raising, training and exercices.

Phase II - Protection - Event detection and confirmation

- Event detection;
- Record of anomalous occurrences;
- Online water quality and operational monitoring;
- Consumer complaints, public health and surveillance by authorities (enhanced security monitoring);
- Sampling and laboratory analysis;
- Summary of event detection.

Phase III - Response - Event management

- Emergency response planning;
- Communication;
- Response measures;
- Event management flowchart after confirmation.

Phase IV - Remediation and recovery - Return to normality

- Preparedness for rehabilitation;
- Remedial and rehabilitation planning;
- Contaminated system survey;
- Impact assessment and rehabilitation objectives;
- Remedial and rehabilitation plan;
- Public communication;
- Remedial and rehabilitation implementation;
- Return to normality;
- Post-event actions.

Fig. 1 - Water Security Plan lifecycle (Teixeira et al., 2019; Teixeira et al., 2022).

Fig. 1 - Ciclo di vita dei Piani di Sicurezza dell'Acqua (Teixeira et al., 2019; Teixeira et al., 2022).

various types of deliberate malicious actions that could occur. Implementing security measures, including risk assessment checklists, communication channels, and screening methods, is essential to protect drinking water systems against deliberate contamination. Additionally, establishing security protocols and conducting training and exercises are important components of emergency preparedness.

Protection: Event Detection and Confirmation

During event detection and confirmation, it is crucial to quickly determine the existence and level of risk of a suspected contamination, including the type to assess potential public health impacts.

The WSecP should integrate real-time event detection from online monitoring systems. Early detection sensors, parameter analyses, and contamination warning systems are pivotal in safeguarding water supply systems and distribution networks and should be seamlessly integrated into regular operations. Water utilities should prioritize the installation of sensors and establish a clear verification and maintenance process to ensure data reliability.

Additionally, laboratories should have rapid detection technologies to quickly determine if a contaminant is toxic. They should provide water utilities with analytical capabilities to support monitoring, surveillance, response and recovery in contamination events. These data will inform decision-makers on necessary control and remedial actions.

Staff engagement in real-time detection of suspicious activity, vandalism, or sabotage is crucial. Furthermore, feedback from consumers, health authorities, regulators, civil protection, local government, environmental agencies, and police authorities is valuable.

Response and Event Management

The WSecP aims to expedite the response to confirmed contamination events and outlines procedures for addressing water supply disruptions, including identifying alternative water sources. Operators must have an effective emergency communication plan for timely notification of contamination, as well as response measures such as isolating the contaminated area, disinfecting the system, and issuing 'boil water' advisories.

Water utilities should also have the necessary chemicals, equipment, and procedures ready for emergency response. In the event of waterborne contamination, the water utility must promptly notify customers in coordination with health, security authorities, and regulatory agencies.

Remediation, Rehabilitation and Recovery

The WSecP also includes a recovery phase to promptly restore the drinking water system to normal functioning. The remediation and rehabilitation process aims to minimize exposure to contaminated water and begins once a contamination incident is confirmed. All activities to restore the provision of uncontaminated drinking water should be identified, evaluated, and implemented quickly.

Documentation of these activities serves to confirm that remediation goals have been met. Effective internal and public communication using official and trustworthy channels remains crucial during this phase. Monitoring after remediation ensures that the drinking water system operates normally in the long term and that business continues as usual. This includes periodic sampling, inspection, and maintenance of water distribution system components and treatment equipment, along with public communication of monitoring activities and results. Lastly, proper protocols and procedures for the discharge of contaminated water should be integral parts of the drinking water decontamination treatment process.

Cyclical Revision, Improvement and Dissemination

Water utilities need a well-structured and maintained Water Security Plan to reduce the risk of waterborne disease outbreaks during disruptive events.

Regular updating of the plan is crucial, including annual inspections of the water system infrastructure and testing of backflow prevention devices. Continuous review and improvement of the plan, validation of early warning and response measures, and involvement of regulatory agencies, emergency services, and public health authorities are recommended (Teixeira et al., 2022). Lessons learned from past events and external expert consultancy should also be considered.

Information-sharing among all involved parties is essential, with a "need-to-know" basis for sensitive information. Additionally, the plan should include criteria for dissemination to new employees, including evaluation and vetting before access is granted (Teixeira et al., 2022).

Recommendations

Protecting drinking water systems (including groundwater) is crucial. They should be prepared for deliberate threats to water infrastructure that might affect businesses' daily activities. Water utilities should incorporate specific measures to improve resilience of drinking water systems against potential intentional disruptions.

The WSecP emphasizes the need to establish a coordinated approach for assessing risks and implementing security measures for water supply systems. The plan supports water utilities in preventing contamination and improving detection capabilities. Collaboration between public and private sectors is encouraged, including the development of a communication strategy to ensure a rapid and efficient response.

Security planning can therefore also provide water utilities and relevant authorities with better planning and faster response to suspicious contamination of drinking water.

Furthermore, the spread of fake news and misinformation concerning drinking water supply can have serious consequences. They may lead to unwarranted panic and fear among the public, as well as a loss of trust in the water supply. Yet, they may divert resources and undermine decision-making, hindering timely and effective response to incidents.

Therefore, it is crucial for competent authorities and water utilities to provide accurate and timely information to the public regarding contamination events, being aware that they can be targeted as part of a hybrid threat campaign.

If a Water Safety Plan already exists, it is essential to integrate water security planning for a more comprehensive approach to risks that combines unintentional and intentional contamination. Despite water safety falls under the responsibility of water utilities and competent authorities, the security aspect of drinking water systems is often overlooked or underestimated, making the WSecP a comprehensive strategy designed to maintain vital societal functions.

Pathogen contamination in urban water networks *overview*

The provision of safe drinking water is essential for every society, as it determines people's health and quality of life. Urban Water Distribution Systems (WDS) are vital for this purpose but are susceptible to pathogen contamination due to infiltration of contaminated substances (e.g., wastewater, raw water), due to cascading events after natural disasters, infrastructure failures, human errors, or malicious attacks. Contamination exposes populations to significant health risks by introducing pathogens such as Cryptosporidium, Escherichia coli O157:H7, and norovirus into the water supply.

Notable incidents, such as the sewage contamination in Nokia, Finland (Laine et al., 2011), the infection with the Cryptosporidium pathogen in the town of Skellefteå in Sweden (Bjelkmar et al., 2017), an outbreak in Antwerp, Belgium by surface water infiltration during firefighting (Braeye et al., 2015), as well as wastewater infiltration events in France (Beaudeau et al., 2008), in Italy (Giammanco et al., 2018), and in Denmark (Kuhn et al., 2017), all demonstrate the vulnerability of those systems. These events highlight the necessity of regarding urban water systems as critical entities, as underscored by the USA Presidential Policy Directive 21 (PDD-21) , and the Directive (EU) 2022/2557.

Risk assessment

Water utilities are beginning to adopt a risk-based approach, driven by the EU Directive 2020/2184 on the quality of water intended for human consumption, as well as the WHO's Guidelines for Drinking Water Quality (WHO, 2022), which describe the Water Safety Plan (WSP) approach. WSPs aim to help water authorities to prepare for and manage emergencies that could impact their systems. Risk assessment is crucial to creating and executing a WSP (WHO, 2016). This process helps identify potential hazards to water systems, including microbiological, chemical, or radiological threats. Risk assessment is vital for evaluating health risks linked to water supply contamination and aids authorities in managing and reducing the impact of such events.

A particular type of risk assessment, known as Quantitative Microbial Risk Assessment (QMRA), has gained prominence over the past two decades and is included in the WHO's water-related guidelines (WHO, 2022). QMRA employs a mathematical approach to estimate infectious risks by integrating scientific data about pathogens — their fate, movement, exposure pathways, and the health effects they can have on humans. It also considers the effectiveness of physical and mechanical barriers and mitigation measures to reduce these risks (WHO, 2016). Overall, the methodology deals with the exposure assessment, the health effects assessment as well as the risk characterization.

To mitigate the risks, WDS require effective operation and maintenance, including ensuring physical (pressure) and structural integrity, consistent monitoring, timely and hygienic infrastructure repairs. Additionally, employing residual disinfectants helps maintain water safety, particularly when standard operational conditions are compromised.

The Need for Water Security Planning

Despite these preventive measures, pathogen contamination crisis can occur. This calls for the preparation of effective management and emergency response plans. The importance of rapid response is paramount to protect the health of drinking water consumers, as pathogen contamination rapidly spreads and leads to acute health impacts. One of the first efforts to standardise contamination response procedures and protocols, was through the Drinking Water Utility Response Protocol Toolbox by the US EPA (EPA, 2006), as well as through the standard EN 15975-2:2013. For malicious attacks on drinking water infrastructure or criminal activities that can contaminate drinking water systems, the European Commission's Joint Research Center (JRC) proposed the establishment of "Water Security Plans" for drinking water supply (Teixeira et al., 2019), and identified four operational phases, (see previous section) each with a different set of possible actions.

There seems to be a gap between the EU Directive 2020/2184, which focuses on water safety: delivering excellent water to consumers and adopting procedures and protocols for handling water safety and security emergencies. Past contamination incidents teach critical lessons in preparedness for both water safety and water security threats and the importance of communication among water authorities, health services, emergency responders and criminal investigators. Strengthening WDS resilience involves developing comprehensive emergency plans, conducting regular single or multi-agency training exercises, investing in monitoring technologies, threat assessment and decision support tools to enhance the preparedness and ability to respond rapidly and effectively to immediate threats and also contribute to the long-term sustainability and safety of urban water systems.

Technologies for Responding to Pathogen Contamination Emergencies

To address the challenge of pathogen contamination, a wide spectrum of technologies and tools are required to contribute to the different water security phases (Eliades et al., 2023). In the context of the Horizon 2020 Pathogen Contamination

Emergency Response Technologies (PathoCERT) project, a number of these technologies were developed and demonstrated in the field, by water authorities as well as first responders.

During the preparation phase, computational models, sensors, actuators, as well as monitoring and control software need to be put in place to process data and estimate the state of the system. In practice, this would include installing water quality sensors at strategic locations throughout the network and designing estimators of water quality indices in locations without sensors. A software that combines models and measurements to provide estimations of the system state is generally referred to as a Digital Twin (DT) (Karmous-Edward et al., 2019). DTs vary in form, from well-calibrated models of hydraulics and quality processes to DTs capable of real-time state estimation analysis and decision support. For instance, they can optimise infection processes to minimize the contamination risks considering changes in water quality. DTs can be used to support preparations: How (fast) will the contamination spread? What is the potential impact? What are effective mitigation strategies? Moreover, the exchange of information between different stakeholders can be achieved through the use of Data Spaces (Curry et al., 2022). It's important to note that risk assessment can be conducted during all the different phases.

During the event detection phase, early warning systems need to be in place to continuously monitor and provide alerts when abnormal measurements arrive, which could be due to a possible contamination event. These alerts could be due to changes in the sensor measurements, as well as due to other sources of information, such as satellite images of water reservoirs, smart cameras detecting increased turbidity in surface water, as well as customer complaints or social media posts reporting water quality issues (Papadimos et al., 2023). From this point, it's crucial and time-critical to have tools available that help operators diagnose the event, localize its source, identify the type of contaminant, assess the threat to public health, estimate its impact and plan an effective response. For example, portable sensors (e.g., digital rapid tests) which can detect high concentrations of pathogens within a few minutes (Canciu et al., 2021, 2022), can assist in isolating the contaminant source within a short time when combined with DTs and iterative on-the-field manual sampling (Paraskevopoulos et al., 2022). As another example, drones with water sampling mechanisms can be used for collecting water samples from reservoirs, for fast analysis (Panetsos et al., 2022, 2023).

During the response and event management phase, tools can assist water operators in reconfiguring the disinfection controls or using booster disinfection, segmenting the network into smaller sections for isolating the contamination and reducing the exposure, as well as rerouting the contaminated water out of the WDS through flushing. These require the use of calibrated water-quality models which consider the dynamics in the systems.

Case study: Investigating pathogen contamination events

A tool to help investigations during pathogen contamination events is the PathoINVEST software, developed as part of H2020 PathoCERT project. It is a DT that assists responsible authorities in responding to such emergencies using realistic water demands, and up-to-date modelling of reactions between different substances (pathogens, chlorine, organic compounds) in the WDS (Paraskevopoulos et al., 2022). PathoINVEST has been applied in three European case studies (Cyprus, Granada, and the Netherlands), each with distinct network hydraulic characteristics, demonstrating its applicability and diverse functionalities in real-time events. In both Granada and Cyprus, the case studies focused on earthquakes resulting in sewage infiltration into the WDS. Conversely, in the Netherlands, the tool was used in response to a suspected intentional contamination following customer complaints.

In each instance, responsible authorities formed emergency response teams comprising individuals from all relevant sectors (water utilities, civil protection, and health care) and utilised the tool to mitigate the events and aid in decision-making effectively. Specifically, PathoINVEST was employed in Granada and Cyprus, among others to visualise contamination spread, recommend optimal sampling locations, assess the impact using the QMRA framework, and suggest the closure of valves to isolate and prevent further spread of contamination. In the Netherlands, following customer complaints, the tool facilitated the identification of the suspected contamination source, enabled impact calculation (QMRA), and guided the implementation of mitigation measures, including valve manipulation.

The case studies demonstrated that the use of PathoINVEST enhanced the situational awareness and understanding of the emergency response teams. Using the tool they were able to locate the source of contamination significantly faster than traditional approaches and prioritise effective mitigation scenarios.

Policy implications

Resolving the gap in water security planning involves strengthening the role of technologies in the relevant EU directives and bridging the gap between water safety and water security. Below, we identify 11 policy implications, which will improve water incident preparedness and effective response:

1. Promote the integration of Water Security Plans in the Water Safety Plans, and develop Standard Operating Procedures for responding to contamination emergencies.
2. Promote the adoption of innovative sensors measuring various chemical and biological characteristics.
3. Promote the widespread deployment of continuous monitoring technologies, using online sensors for various chemical and biological parameters, as well as hydraulics.
4. Promote the use of smart actuators to enable control and system reconfiguration in case of crisis.

5. Facilitate data sharing with different stakeholders through a Water Security Data Space.
6. Establish Early Warning Systems for detecting events as they occur, or forecasting emergencies.
7. Promote the adoption of Digital Twin technologies for decision support before, during, and after emergencies, including developing optimal response strategies, optimizing sensor placement, enhancing contamination detection, source isolation techniques, and improving disinfection control.
8. Use computational models for estimating the impact on human health.
9. Develop models, tools and data management systems to estimate the health and economic impacts of water contamination events, supporting rapid response and guiding informed decision-making.
10. Support procurement of innovative water solutions.
11. Improve the alignment and collaboration of different response agencies (first responders, law enforcement, water utilities, and public health) through joint protocols, training and exercises.

Groundwater monitoring in cities

Overview

To prevent the previous treated issues, groundwater monitoring is a common fundamental need in modern urban areas. The vigilance over groundwater reservoirs stands as a pivotal stride in protecting urban water systems and mitigating water overexploitation and deterioration. Moreover when the monitoring is visible and openly accessible, it serves as a potent tool for bolstering public awareness; the expression "what you can't measure, you can't manage" aptly underscores the significance of monitoring groundwater and urban aquifers (Bonsor et al., 2017). Diverse strategies for groundwater management are deployed across metropolitan regions globally. Consequently, hydrogeological surveillance becomes imperative for manifold objectives, such as safeguarding groundwater reservoirs, delineating protection zones in newly urbanized sectors, appraising groundwater productivity, identifying vulnerability, assessing infrastructure leaks and their relative aquifer recharge function, and mapping the flow paths of urban aquifers. The crux lies in pinpointing the triggers and temporal patterns of groundwater fluctuations. Thus, tailor-made monitoring networks must be devised for specific objectives, such as (e.g.) distinguishing between shallow (normally not for drinking water supply) and deep urban aquifers (sometimes also used as drinking water source). Furthermore, given the dynamic nature of city landscapes, precise elevation determination for monitoring stations becomes paramount to avert inaccuracies in delineating groundwater flow gradients (La Vigna & Baiocchi, 2021) which can be really important to be known especially in presence of contaminated groundwater.

Existence of city-scale groundwater monitoring networks

Despite a plethora of boreholes and water wells in many cities, not all possess dedicated groundwater monitoring networks, though the abundance and wide dispersion of these installations are typical. Conversely, in certain instances, city-wide groundwater surveillance is a reality. For instance, Miami, Florida (USA), boasts a real-time monitoring network overseen by the US Geological Survey (Prinos et al., 2002). In Beijing, China, a monitoring network has operated since the 1960s, furnishing comprehensive insights into water table dynamics over monitored periods (Zhou et al., 2013). Seoul's metropolitan government (South Korea) inaugurated a local groundwater monitoring network in 1997, comprising 119 monitoring wells, to track changes in groundwater quantity and quality (Lee et al., 2005). Several examples are also present in the European context. Rome's Municipality (Italy), recently integrated more than 150 of its irrigation wells into the city's monitoring framework (Roma et al, this volume, La Vigna et al., 2021), with also focused monitoring activities in heritage sites (Mastrorillo et al., 2016). The city of Cardiff (UK), monitors groundwater levels and temperatures to regulate variations induced by ground-source heat pumps (Patton et al., 2020), but also Bucharest (Romania) (Gaitanaru et al., 2017); Glasgow (UK), Zaragoza (Spain), Hamburg (Germany) and Basel (Switzerland) (Bonsor et al., 2017) implemented city-scale groundwater monitoring networks. Generally, Dutch and German cities boast robust monitoring networks, with notable setups in Amsterdam (The Netherlands), boasting over 2500 bimonthly monitored stations (Bonsor et al., 2017), and Munich (Germany), equipped with nearly 500 monitoring wells (Menberg et al., 2013). Groundwater monitoring in cities is often oriented to specific objectives as reported by Bonsor et al. (2017) for some Dutch cities and municipalities:

- the protection of wooden pile foundations related to leaking/draining sewers and controlling high water levels in (Amsterdam- NL);
- subsidence control and groundwater flooding (Gouda - NL);
- groundwater flow patterns in relation to the spreading of groundwater contamination (Breda - NL).

Addressing the urban water security starting from monitoring

Groundwater and aquifers provide several essential services to cities, both directly and indirectly. These services include maintaining Groundwater Dependent Ecosystems (GDEs), supplying water for irrigating green areas, cooling buildings, providing drinking water, and facilitating urban surface water infiltration and retention. All of these contributions help make our cities more resilient (La Vigna, 2022) and safer.Therefore, monitoring of groundwater quantity and quality including near real-time monitoring of water tables and temperature etc. should be a common practice carried out in every urbanized area. This would help address some of the issues presented previously such as groundwater levels depletion and groundwater flooding, together with any kind of contamination detection. Understanding and visualizing groundwater overexploitation and competing uses can assist decision-makers in comprehending what is happening and acting accordingly. The frequent presence of surveyors in the field for monitoring activities, as well as the existence of a kind of "Public Engagement Centers for Groundwater Management and clear, open, and visible data for the public, are key actions to guaranteeing more control in the territory, also facilitated by a more aware public, thus preventing malicious or incorrect behaviour which can be detected more quickly. Moreover, the presence of a groundwater monitoring network is crucial for assessing the potential presence of pathogens in groundwater, as it serves as a "window" to this invisible resource (Kofinas et al., 2018).

Conclusions

This paper provides some facets of the water security and safety "paradox" as perceived by the diverse parts of the water system. At present, no agreed common understanding covers what could be referred to as overall water security and safety notions, i.e., clarifying the various meanings and prerogatives. It is to be expected that such an overall framework related to water resilience will become a high political focus in the years to come in line with the upcoming EU water resilience strategy (European Commission, 2024), owing to the increasing threats to water resources and the risks that they pose to society. This review discussed some aspects of the water security and safety "paradox", focusing on groundwater and drinking water in an urban context. By "paradox", it is meant that the words "security" and "safety" may be used differently depending upon the sectors and disciplines, hence leading to misunderstandings with consequences in scientific and legal interpretations. The paper illustrates various streams of research covering groundwater over-exploitation, water resilience (related to drinking water infrastructures), pathogen contamination and groundwater monitoring, all areas that would require an enhanced coordination to reach a better holistic view of risks potentially affecting (ground) water resources.

Author contributions

Philippe Quevauviller – The water security and safety paradox – Introduction. Klaus Hinsby, Ida Karlsson Seidenfaden, David Pulido Velázquez, Manuel Sapiano – Groundwater over-abstraction and water table decline. Rosario Coelho, Peter Gattinesi, Philipp Hohenblum, Vaclav Jirovsky, Fatima Marinheiro, Luis Simas, Rui Teixeira, Rita Ugarelli, Monica Cardarilli – Enhancing Resilience: Water Security Planning for Drinking Water Infrastructure. Sotirios Paraskevopoulos, Stelios Vrachimis, Gertjan Medema, Demetrios Eliades – Pathogen contamination in urban water networks. Francesco La Vigna – Groundwater monitoring in cities.

All authors have read and agreed to the final version of the manuscript.

Competing interest

The authors declare no competing interests.

Additional information

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