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The technological development of drinking water treatment plants in the Czech Republic

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ABSTRACT

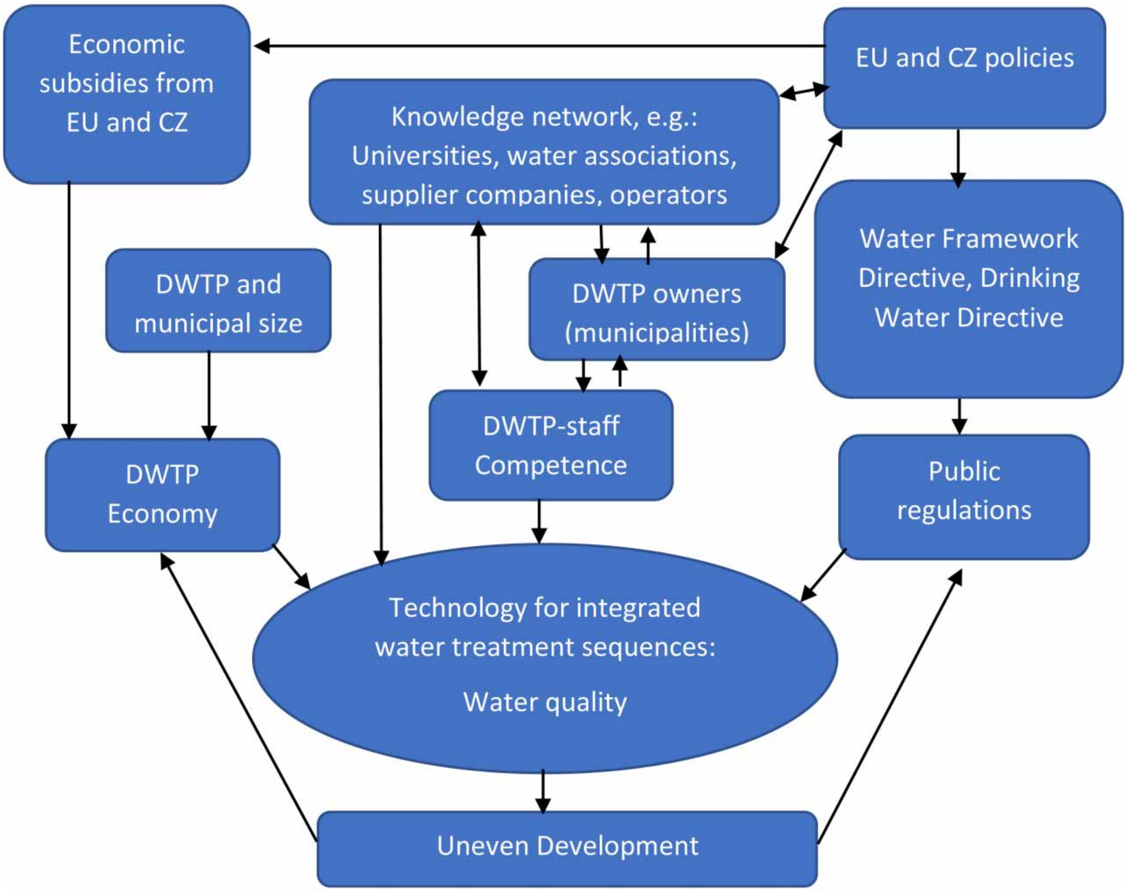
Several actors have an impact on the quality of drinking water, but ultimately drinking water treatment plants (DWTPs) play a decisive role in ensuring that water quality complies with public regulations. Several developing technologies are combined in water treatment processes. In this paper, we are analysing the technological development of DWTPs in the South Bohemian region of the Czech Republic. The empirical basis is five DWTPs of varying size, and data are gathered through semi-structured interviews with relevant staff inside and outside of the five DWTPs. This study identifies the interplay of factors driving technological development: public regulations, the economic capacity of local DWTP owners together with subsidies from the European Union and national authorities, political priorities by local authorities, and the knowledge network. The paper addresses learning–knowledge–change processes of DWTPs, thereby contributing to our understanding of developing competence in producing drinking water. Generally, large DWTPs are front-runners in introducing new technologies while the smaller ones are lagging. Still, private companies operating small plants on behalf of municipal owners ensure that those DWTPs are part of a wider knowledge network, aiding to introduce a necessary and cost-effective upgrade to treatment steps

Key words: Czech republic, Development support with economic subsidies, Drinking water treatment plants, Learning–knowledge processes, Technological development

HIGHLIGHTS

- Drivers and barriers to technological change in drinking water treatment plants (DWTPs).
- Differences in learning–knowledge–change processes within a tight knowledge network.
- Industry 3.0 roll-out of digital processors in water treatment technologies.
- Development trajectories differ between large and small DWTPs.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water is an essential commodity for human life and societal development, serving fundamental purposes within health, agriculture, industry, transportation, and recreation. The provision of clean drinking water is a global priority recognized by the United Nations, which is evident in its sustainable development goal 17, which emphasizes 'ensuring availability and sustainable management of water and sanitation for all'. In a European context, specific directives like the Water Framework Directive, Drinking Water Directive, and Wastewater Directive set clear aims and targets for water quality. The Czech Republic is relatively well-positioned in Europe regarding drinking water quality and has made commendable progress in improving the quality over the past decades (Ministry of Agriculture, 2021). Nevertheless, there is still potential for improvements in the Czech Republic, especially through the adoption of new water treatment technologies, the integration of digital technologies for more efficient operation, and the better protection of raw water sources. This protection involves making changes to land-use practices to safeguard crucial water resources. Despite the progress, new challenges arise due to changing drivers and pressures on water quality, such as increasing biomass in watersheds and declines in acid rain loads, as well as climate change leading to extreme weather events and variations in rainfall patterns

(Finstad *et al.*, 2016; Eikebrokk *et al.*, 2018; de Wit *et al.*, 2023). Such changes significantly impact the quality of runoff from catchments to the raw water sources of drinking water treatment plants (DWTPs) (Haaland *et al.*, 2010). Recent attention has been given to 'emerging contaminants' originating from pharmaceutical and personal care products, plasticizers, surfactants, fire retardants, nanomaterials, and pesticides (Najm & Trussell, 1999; Kumar *et al.*, 2022). Although wastewater treatment processes do not remove all harmful compounds, drinking water treatment technologies need to consider these contaminants to ensure the safety of drinking water. Moreover, traditional contaminants as input of organic matter, suspended matter, and nutrients from agricultural areas and fishponds, as well as legacy anthropogenic pollutants, continue to present challenges in developing and optimizing treatment processes for DWTPs, not only in the Czech Republic but also elsewhere.

Over the years, many studies have extensively investigated specific water treatment technologies. However, there has been a lack of research on how these technologies can be effectively integrated and operated together to form complete treatment processes and how these processes evolve and improve over time. For instance, a recent special issue on advanced treatment technologies for drinking water featured seven contributions, all of which only covered partial aspects (Sun & Chu, 2021). This paper aims to address this gap in the literature by conducting a comprehensive analysis that combines insight from both natural and social sciences. The novelty of this paper lies in its theoretical approach, which revolves around learning, knowledge, and change processes, thus linking to innovation studies. Although not directly engaging with the policy, the analysis offers valuable insights that can be useful to formulate policies concerning DWTPs. Specifically, the goal of this paper is to achieve the following objectives:

- To chart the evolution and formation of unit process combinations into integrated treatment sequences across different DWTPs.
- Identify the key drivers that govern the technological development of DWTPs.
- Analyse the learning, knowledge, and change processes involved in implementing and operating technology combinations in different DWTPs.
- Establish a basis for explaining and understanding differences in the development of treatment processes and also for reflecting on drinking water policies.

In summary, this study aims to shed light on the combined technological advancements in DWTPs and their underlying drivers. It also offers valuable insights for policy formulation in the context of drinking water management.

To achieve our goals, we recognize that maintaining existing drinking water standards and meeting new ones requires the collaboration of multiple stakeholders, both within and outside of DWTPs. This integrated management perspective is crucial for effective water quality management. In this paper, our primary focus is on DWTPs. However, Najm & Trussell (1999) highlighted that the main drivers behind advancements in water treatment technologies 'have been the discovery of new rarer contaminants, the promulgation of new water quality standards, and costs'. Additionally, they emphasized the importance of testing and approval processes by regulatory authorities for new technologies. While these factors are indeed essential, it is important to recognize that water quality standards are just one component of the broader institutional regime. Public policies set specific aims and targets that need to be considered. Additionally, the regional and local context of water treatment plays a significant role. Economic conditions and political priorities at the local level influence how DWTPs meet regulations and respond to the demand for clean drinking water. The organization of the water industry also factors into the equation, with a mix of public and private actors involved in the Czech Republic, including local public owners of treatment plants and private or public operators. Furthermore, the quality of raw water is affected by contextual factors, such as natural conditions, land-use practices, and forecasted changes in environmental drivers and pressures. These factors significantly influence the design and optimization of treatment processes in individual DWTPs.

The technological development of DWTPs includes the integration of digital control systems. As in other industries, DWTPs are incorporating and customizing digital technologies to complement both existing and new non-digital water treatment methods. This involves utilizing digital monitoring systems to detect various substances in water and automatically adjusting the chemical dosing to improve water quality. This application of digital technologies can be seen as an innovation, introducing something new to the geographic area. Concurrently, the adoption of digital control systems may lead to innovative changes in the organization of work processes within DWTPs. Whether termed as innovation or simply considered as regular technological development, these advancements involve learning and knowledge-building processes. These processes have the potential to bring about positive changes, leading to improved water quality or more effective maintenance of existing water quality standards.

In our examination of learning and knowledge processes, we apply a typology that differentiates between three levels: (i) single-loop learning, which revolves around experiential or learning by doing, (ii) double-loop learning, which surpasses existing practices by questioning and adapting them, and (iii) triple-loop learning, which transcends the structural context of practices and seeks deeper changes and transformations (Argyris & Schön, 1978). Similarly, there is a three-tiered typology for ‘change’: incremental, transition, and transformation. Incremental change is often associated with business-as-usual, while transformation requires long-term complex learning on a systemic scale (Lonsdale *et al.*, 2015). While there may be an intuitive notion that associates single-loop learning with incremental change, double-loop learning with transition, and triple-loop learning with transformation, it is important to note that there is no inherent or necessary connection between them. Following the work of Park *et al.* (2012), and confirmed by Orderud & Naustdalslid (2020), we emphasize interlinked change cycles that may involve stages from problem structuring to monitoring and learning, thereby incorporating all three learning loops.

Additionally, to enrich this conceptual framework, a three-pronged typology of knowledge bases in innovation networks is instructive. It consists of (i) analytic knowledge bases, characterized by a small number of actors and high network density, involving knowledge exchange in epistemic communities and long-term cooperation between research units within globally configured networks; (ii) synthetic knowledge bases, involving a small number of actors and low network density, with knowledge exchange in communities of practice, cooperation along supply chains, and collaboration in nationally and regionally configured networks; and (iii) symbolic knowledge bases, featuring numerous actors and low network density, with knowledge exchange in interpretive communities, cooperation in short-term projects between companies, and the prevalence of regionalized and localized networks (Martin, 2013). Regarding the drinking water treatment industry, we primarily consider it to fall under the second category, which is characterized by a synthetic knowledge base.

In exploring learning, knowledge, and change processes, it may be instructive to consider the concepts of path dependency and lock-in (Martin, 2010), along with tacit and explicit knowledge (Polanyi, 1966). Commonly, advancements in knowledge build on existing knowledge, following established paths in a regional context, which may lead to lock-in to specific solutions. The knowledge of individuals is commonly shaped through the interaction of explicit (written) and tacit dimensions. Basic concepts can be learned through explicit knowledge, while further development and refinement occur through the acquisition of tacit knowledge gained through practice.

These learning–knowledge–change processes in DWTPs occur amidst broader industrial changes. In recent years, the emergence of ‘Industry 4.0’, the fourth industrial stage, has received increasing attention. While the third industrial stage (‘Industry 3.0’) focused on Supervisory Control And Data Acquisition (SCADA) and robotization, the fourth industrial stage is characterized by the industrial applications of artificial intelligence, the Internet of Things, machine/deep learning, and utilizing big data analytics (Bailey *et al.*, 2019). Here, we use the term ‘digitalization’ to encompass both Industry 3.0 and Industry 4.0. SCADA represents centralized systems of computers, networked data communication, and user interfaces, while Industry 4.0 is decentralized. We can also consider Industry 3.0 as the ‘weak’ version of digitalization and Industry 4.0 as the strong version. Reviewing the application of deep learning and algorithms in urban water management, Fu *et al.* (2022) concluded that such applications are still at an early stage, with most studies testing the performance of deep learning methods using benchmark networks, synthetic data, laboratory-based, or pilot systems. Deployed applications with measurable benefits are relatively scarce at this point. Therefore, digitalization in DWTPs appears to be related to ‘Industry 3.0’, but its advancement levels may vary depending on the specific implementation and utilization of digital technologies.

2. MATERIALS AND METHODS

The analysis is primarily based on five DWTPs located in the Bohemian region, with four of them located in South Bohemia (Jihočeský kraj) and one in Pilsen (Plzeňský kraj). This research is part of the interdisciplinary TAČR KAPPA[1] project focused on drinking water quality, known as Drinking Water Readiness for the Future, DWARF. Three of the selected DWTPs were chosen because they actively participated in testing and optimizing water treatment processes as part of the DWARF project. The other two DWTPs were included in the study to broaden the investigation into technological development within the field. In Table 1, the selected DWTPs are ranked based on their technological state, capacity (litres of water produced), and economic capacity of municipalities that own them. In the Czech context, the ranking ranges from 1 (lowest) to 5 (highest). In short, the study consists of one DWTP with the lowest level of technology, capacity, and economic basis, and another DWTP at the second lowest level. Next, there is one DWTP at a generally mid-level, while the two remaining public plants are at a high level in terms of technology, capacity, and economics. Thus, the study encompasses DWTPs representing practically the whole span of technology, capacity, and economics in the Czech Republic.

The analysis is primarily based on interviews and document studies. The main data source is interviews conducted with professionals and skilled workers involved in running DWTPs. Additionally, interviews were held with municipal owners of WTPs and an association for private operators, providing valuable information. In total, the empirical basis consists of 17 interviewees, with four of them being interviewed twice, and follow-up questions were added through e-mails. The key characteristics of the informants, presented in Annex 1, are

Table 1 | The DWTP cases, ranking 1–5, with 5 highest and 1 lowest.

Place	Technology state	Capacity	Economic basis	Overall	Operator
Plav	5	5	4	5	Public
Plzeň	5	4	4	4	Public
Písek	4	3	3	3	Private
Sušice	2	2	2	2	Private
Karhov	1	1	1	1	Private

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[1] The Technology Agency of the Czech Republic, the KAPPA programme.

highlighting that the majority are male and hold university degrees related to water or agricultural disciplines, with about half in management positions, mostly technologists, and the majority affiliated with private companies. The document studies consist of printed descriptions of DWTP technologies at the five plants.

The interviews were conducted using a semi-structural method. This means formulating a set of main questions to be addressed but not necessarily posed in a strict order. Each main question had possible follow-up sub-questions that could be raised, pending the informant response. Informants were encouraged to elaborate on their answers. Moreover, interview guides were tailored to fit different categories of interviewees.

In the process of approaching potential informants, conducting interviews, and storing interview data, we adhered to the recommendations and instructions outlined by the General Data Protection Regulations (GDPR) of the European Union. Invitation letters and interview guides were approved by the Norwegian Data Protection (NSD) agency. The interviews were recorded and transcribed for further data analyses.

Although the five cases encompass different categories of DWTPs, as presented in Table 1, they are still cases embedded in particular institutional and socio-natural settings. As a result, significantly different settings may give rise to diverging processes. Consequently, it may not be feasible to draw wholesale conclusions that apply to all cases. Still, the study asserts that there are valuable lessons to learn across institutional and contextual settings.

3. RESULTS

The first part presents results on technology and the next on learning–knowledge–change processes. In the section on technology, we provide an outline of the basic drivers of technological development and the complexity of specific development trajectories. We then proceed to showcase the five cases that exemplify these concepts. Moving on to the next sub-section, we delve into knowledge sources and networks before exploring the processes of learning, knowledge acquisition, and change.

3.1. Explaining and understanding the technological development of DWTPs

3.1.1. Common factors

On one side, advancements in science unleash potential for effectively treating raw water and improving or upholding drinking water quality in the studied localities. Technology producers in the commercial sector strive to make these new processes applicable and persuade DWTP owners to adopt their technology and components. However, economic constraints are a significant obstacle to DWTP upgrading. The close connection to the economic factor and its intermediary position can be observed in policy-making at various levels, where different policy fields and objectives, including regulations on drinking water quality, compete for priority. These regulations potentially drive technological upgrades of DWTPs. Delving deeper into the matter reveals a more intricate picture:

- Although DWTPs are owned by municipalities, they can be run by either public or private entities. In the case of private operators, commercial companies may have informal influence over decisions regarding DWTP upgrades.
- Private consultancy companies may be engaged to design DWTP upgrades, and their staff, being knowledgeable professionals in water treatment processes, play a significant role in driving change.
- Professionals in the water sector commonly have educational backgrounds in water-relevant disciplines, with some even sharing the same university education. This common background fosters a shared understanding of achieving good water quality across private and public actors, including operators, technology producers, and consultancy firms, potentially impacting the content of technological development.

- Professional organizations like the Association of Water Supply and Sewerage of the Czech Republic (SOVAK CR) and the Water Association of the Czech Republic (CzWA) promote state-of-the-art technologies, potentially driving the technological development of DWTPs.
- Water quality regulations at national and European levels can also have an impact on technological development. The Czech Republic's stringent threshold levels, in certain cases exceeding EU regulations, suggest a stronger political commitment and capability to provide good water quality.
- The Public Procurement Act of the Czech Republic may impede technological development because municipalities, as owners of DWTPs, are obliged to invite all manufacturers in tender processes when assembling instruments at different stages of the treatment process, leading to a mix of systems that may not function optimally.
- Municipalities vary in economic resources, affecting their abilities to invest in water treatment technologies. Additionally, political priorities and willingness to allocate funds for water treatment may differ.
- Economic constraints at the municipal level may be eased by funds from higher administrative levels, such as the European Union and national funds administered by the Ministry of Agriculture and the Ministry of Environment.
- Large DWTPs owned by large cities and several municipalities provide better scope and scale for sound financial planning, including investments in technological upgrades.

Besides societal factors, natural conditions also play a role in the technological development of DWTPs. Some conditions are common for all, while others are contextual and differ between DWTPs. For instance, the lack of limestone in the geology of South Bohemia is a common natural condition, while land-use practices (e.g., forestry, agriculture, fish farms, and urban) may cause variations in raw water quality. Moreover, changes in environmental drivers and pressures, such as land use, may necessitate upgrading or changes in the treatment technology to address changes in water quality.

3.1.2. The institutional framework – regulations and economics

Before the year 2000, the Czech Republic had a standard for assessing drinking water quality, which was a regulation that should be adhered to, though non-compliance did not result in any penalties. However, with the introduction of the Public Health Act, regulations now define drinking water quality based on a range of indicators, leading to stricter monitoring and a stronger push for developing drinking water treatment technology.

Many municipalities that own DWTPs are outsourcing the operation of drinking and wastewater treatment plants to private companies. These companies are selected through competitive bidding for a specific period of years. Nonetheless, the final water prices for consumers are approved by the municipalities, considering documented actual costs of treatment processes, technology investment, and other factors. Consequently, political decisions at the municipal level play a decisive role, as any increase in water prices could impact re-election prospects and lead to reluctance to engage in ventures that require substantial investments, potentially hindering technological upgrades.

3.1.3. Development of DWTP technologies and digitalization

In the Czech Republic, modern water treatment technologies began to emerge in the 1990s, and the pace of modernization accelerated after 2000. Over the past two decades, there have been significant advancements in drinking water treatment technology. While the fundamental processes have remained unchanged, the focus has shifted to improving efficiency and optimizing the treatment process under current and future (socio-) natural conditions. This includes selecting new chemicals for coagulation, flocculation, and disinfection processes. Recent technological advances in water treatment include flotation as a separation process, dual or multi-media filtration, membrane filtration with nanomaterials and ceramic membranes, ultraviolet (UV) disinfection, granular or powdered activated carbon (PAC), and advanced oxidation processes.

The introduction of digital automation through SCADA systems started around the year 2000, gradually replacing manual processes. Larger DWTPs now have a fully operational SCADA system, while smaller ones are still in the process of implementing them. Although the days of ‘adding buckets’ are gone, there may still be some (semi-) manual processes left, e.g., within lime management. Moreover, as one of the interviewees stated, ‘although DWTPs may be equipped with a sufficient number of sensors and analysers for functioning on its own, we are reserved to let it completely go unattended, at least for plants treating surface water – groundwater is more fit because the water quality is more or less the same. Nevertheless, there is a bid for making parts of the water treatment process fully automated, based on in-line monitoring measurements and dosing by digital processors’.

Digital control systems have improved accuracy and reduced human errors in dosing chemicals, making the work less physically demanding for the operator. Still, digitalization has also brought new challenges. Understanding the effects of consecutive actions in treatment processes has become more complex, and issues may arise due to changes in operational conditions. A process may appear to fail, but the problem is due to a change in an up-flow operation.

Digitalization has broader impacts on water treatment companies. The transition from paper to electronic documents started around the year 2000, and the use of database technology for various systems, such as geographical, technical, and customer information, started in 2010. In 2015, the system was extended to enable online data transmission to cell phones operated[2] by technical staff, providing real-time distribution network data to all operators.

3.1.4. The technological development of the five DWTPs

At the studied DWTPs, the treatment process of raw water typically commences with preparatory steps, including increasing the pH and adding a coagulant to remove dissolved organic matter (DOM), allowing time for flocculation. Subsequently, the water undergoes a two-stage separation process by sedimentation and filtration. The treatment process concludes with the addition of carbon dioxide (CO_2) and lime for pH stabilization and corrosion control, followed by a final disinfectant treatment before the water is directed into the distribution network.

The ***Plav DWTP***, receiving an overall top rating of 5 (Table 1), began operating as a two-stage plant in February of 1982. The initial setup comprised 15 settling tanks for the first stage and 14 sand filters for the second stage. Over the years, the technology in both stages underwent modernization, including the addition of a lime farm, retrofitting of the settling tanks and the pipe equipment, and the implementation of digital control and automation systems for all 14 filters. Offline measurements were performed by the laboratory. However, despite these upgrades, the raw water quality deteriorated due to an increase in the frequency and intensity of floods and drought episodes. To address this, a third and final stage was added in 2015, utilizing granular activated carbon (GAC) filtration, to remove DOM (Table 2). The recent upgrade also included the rehabilitation of settling tanks and sand filters. Future upgrades are planned to modernize existing sand filters, reconstruct the lime preparation process and optimize lime water with the right concentration for automatic dosing. Additionally, chloramine is used for disinfecting the water. Since Plav is not connected to any wastewater treatment plant, it must handle and process sludge remains after water treatment.

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[2] This may require technology for protection against hacking.

Table 2 | Technologies of DWTPs.

	Plav	**Plzeň**	**Písek**	**Sušice**	**Karhov**
River	Malše	Úhlava	Otava	Roušárka/Otava	Studenský potok
Pretreatment/pH control	$Ca(OH)_2$ option	$Ca(OH)_2$	$Ca(OH)_2$ option	$Ca(OH)_2$ option	$NaHCO_3$
Oxidation					Ozonation
Coagulation	$Fe_2(SO_4)_3$ (Kemifloc PIX-313)	$Al_2(SO_4)_3$	$Al_2(SO_4)_3 \times nH_2O$	$Al_2(SO_4)_3 \times nH_2O$	$Al_2(OH)_xCl_{6-x}$ (PAX-18)
Flocculation	Rapid and slow mixing	Rapid and slow mixing	Magnafloc LT-20	Pressure vessel	Magnafloc
Separation	Sedimentation	Sedimentation	Dissolved air flotation		Sedimentation
		$KMnO_4$			
Filtration 1	Sand	Filtralite	Filtralite	Sand, pressurized filtration	Sand
		Ozonation		Flocculation option, Superfloc	$KMnO_4$
Filtration 2	GAC	GAC	GAC	Sand, pressurized filtration	Sand
		UV disinfection			
Corrosion control and hardening	$CO_2 + Ca(OH)_2$	$CO_2 + Ca(OH)_2$	$CO_2 + Ca(OH)_2$	$CO_2 + Ca(OH)_2$	$CO_2 + Ca(OH)_2$
Disinfection	$Cl_2 + (NH_4)_2SO_4$	Cl_2	NaOCl	NaOCl + Cl_2	Cl_2

$Al_2(SO_4)_3$, aluminium sulphate; $Al_2(OH)_xCl_{6-x}$, aluminium hydroxide; $Ca(OH)_2$, calcium hydroxide; Cl_2, chlorine; $Fe_2(SO_4)_3$, ferric sulphate; GAC, granular activated carbon; $NaHCO_3$, sodium bicarbonate; $(NH_4)_2SO_4$, ammonium sulphate; UV, ultraviolet.

The Plav DWTP was designed for a capacity of 1,400 litres per second (l/s), but the current standard operation is 550 l/s, with a peak operation of 900 l/s under the maximum capacity utilization of GAC. Raw water is sourced from the nearby state-owned Římov reservoir. The plant is publicly owned and run by the South Bohemian Water Association, which has more than 200 municipalities as members, including the regional centre České Budějovice. Over 400,000 residents of the South Bohemian Region, in 156 towns and villages, including all district towns, receive water from the Plav DWTP. Moreover, Plav serves as a backup for other DWTPs in the region.

The total investment in the 2015 upgrade amounted to 271 million Czech crowns (CZK), with 70% (189 million CZK) provided by European Union funds. Over the years, the entire water system, comprising the treatment plant and 550 km of pipelines, has amounted to an investment of 1.45 billion CZK (6.15 million EUR). Of this, 0.67 billion has been funded nationally by the Czech Republic and the European Union (Naše Voda, 2022), indicating a significant contribution from the local level.

The ***Plzeň DWTP*** has a long history, with the first plant opening in 1924, followed by a two-step plant that was put into operation in 1970. The current DWTP, which includes an ozone treatment step, was inaugurated in 1997. Subsequently, reconstruction was completed in 2015, adding UV disinfection and some carbon filtration, which has since been expanded to a full GAC treatment. Presently, the Plzeň DWTP, with an overall rating of 4 (Table 1), operates with coagulation using aluminium sulphate and flocculation is achieved by changing from rapid to slow mixing of the water (Table 2). Lime water is dosed to optimize the coagulation process, maintaining an acidity (pH) of 6.4. For the removal of inorganic and organic particles, the DWTP uses 12 parallel sedimentation tanks. The first step of filtration involves six parallel filters using Filtralite as filter media, and the second step employs GAC filtration. Ozone is used between the two filtration steps to provide the first disinfection barrier. A second disinfection step is achieved by UV radiation applied after GAC filtration to minimize bacterial contamination from the GAC filters, especially when temperatures increase above 22 °C. Finally, chlorine is dosed as a final disinfection step. Between the UV and chlorine disinfection, corrosion control takes place, including an increase in pH and alkalinity, as well as calcium (Ca^{2+}) concentration (hardening). The 1970 plant serves today as a backup and can be restarted in case of an emergency.

The maximum capacity of Plzeň DWTP is 1,000 l/s, but it currently operates at 500 l/s, despite the guaranteed capacity being 400 l/s. The DWTP serves nearly 230,000 people in the Plzeň region. Before the last upgrade, the plant was under the ownership of a French company, but the city of Plzeň took full control in connection with the reconstruction from 2013 to 2015 to ensure compliance with rules of local control to be warranted economic support from the EU and national sources.

The current ***Písek DWTP***, with an overall rating of 3 (Table 1), was put into operation in 2019 and was located a few hundred metres uphill from its previous site adjacent to the raw water source, the Otava River. The old plant, dating back to 1900, underwent modernizations in 1943, 1968, and 1982. It is operated using four parallel gallery clarifiers with the sedimentation of sludge coagulated with ferrous sulphate[3]. The coagulated and settled water then run through six parallel sand filters. In addition, CO_2 and lime water were applied for pH and corrosion control. However, by the 2010s, the technology of the old plant reached its end-of-life due to capacity limitations and repair costs outweighing its benefits. As a result, a new DWTP with state-of-the-art treatment processes to provide better water quality became necessary.

In the preparatory step of the new DWTP, a flotation technique is employed, where DOM, algae, microorganisms, colloids, and other particles are attached to air bubbles introduced at the bottom of the tank. These bubbles rise to the surface of the flotation unit, where a skimmer wipes off the sludge. Aluminium sulphate is used as a DOM coagulant, as it was found to work better than ferrous sulphate for flotation. The DWTP's filtering process consists of three units, with Filtralite filter media made from burnt clay and three absorbents based on activated carbon (GAC) (Table 2). The GAC provides additional DOM removal, including microorganisms' exudates that cause taste and odour, as well as drug residues and fertilizers.

Some automation was already introduced at the old DWTP in the form of timed relays, with filters turned on and off at certain time intervals, followed by automatic filter backwashing cycles. The new DWTP is highly automated, with all processes digitally controlled, monitored, and overseen by the operator. It achieves faster stabilization of water quality parameters compared to the old plant, where stabilizing parameters requires long time. Furthermore, the new DWTP successfully removes 70% of the undesired substances like DOM, microplastics, fertilizers, and nitrates, a significant improvement compared to the old treatment plant's 20% removal.

The decision to construct the new DWTP was based on an assessment of three options: (i) reconstructing the existing plant, (ii) building a new plant, or (iii) acquiring water from the Plav DWTP/Římov reservoir. The last option, which was the cheapest, was rejected due to water security concerns, such as accidents in the distribution network over long distances. Instead, the new plant option was chosen. However, the current plant faces challenges under certain conditions, such as during autumn fishpond draining and spring floods. In such

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[3] Aluminum sulphate was used as a coagulant until about 1990 and then was replaced by ferrous sulphate because the latter worked better under sedimentation.

situations, the municipality obtains water from the Plav DWTP, accounting for 20% of the municipality's annual water provision. The Písek DWTP serves around 35,000 people, with a maximum capacity of 75 l/s and currently operating at 55 l/s.

The total costs of constructing the new DWTP amounted to 200 million CZK. This investment was not eligible for European Union funds, but the owner, Písek City, included the annual lease of 60 million CZK paid by the current operating company. The reason for the ineligibility of EU funds was the length of the contract between the city and the then-operating company.

Before 1990, the ***Sušice DWTP*** operated as a groundwater collection well located next to two rivers, with merely a chlorine gas treatment. In 1990, an additional well based on gravity outflow was incorporated, along with one borehole, but the treatment process remained limited to chlorine gas. A new DWTP began operation in 2003, with an overall rating of 2 (Table 1). Since 2003, some technological improvements have been implemented, such as the addition of lime water (suspended lime hydrate) and CO_2 after filtration, along with digital control systems, monitoring, and additional analysers. However, chemical oxygen demand values, which reflect the content of DOM, still require manual analysis beyond the indicative values displayed by the monitoring system.

Currently, the plant employs coagulation filtration with aluminium sulphate as a coagulant. The process starts with an aggregation tank, followed by the Culligan® OFSY Series Omni-Filtration Systems (Culligan.cz) with two filtration stages in series using pressure vessels with several layers of filtering sand. The first stage involves coagulation filtration, followed by the second stage for the final separation of the suspension. Between the two stages, flocculation can occur based on the dosage of a polymeric flocculant (Superfloc, Kemwater ProChemie, Czech Republic). The last phase of the process is corrosion control/hardening, followed by chlorine disinfection.

The municipality plans to introduce activated carbon pressure filters and UV lamps to ensure hygienic barriers. They also intend to implement a process of carbonation process with lime water and CO_2 addition into filtered water, thereby increasing pH and stabilizing the water prior to entering the drinking water reservoir and the distribution network. Currently, during critical situations of odour development, PAC is metered together with aluminium sulphate at the first coagulation step.

The Sušice DWTP has a maximum capacity of 55 l/s and normally operates at 25 l/s, serving approximately 11,000 people. A recurring challenge for the water treatment is that after 2–4 days of continuous rain, the raw water becomes brown due to DOM being washed out from the watershed. Beaver dams also cause similar issues. Moreover, the devastating hurricane of 2007, coupled with increasing bark beetle attacks in Šumava mountain, has made the area more susceptible to erosion during rainfall.

The ***Karhov DWTP*** dates to 1973, with most of the technology from that time in service today, earning it the nickname of a 'waterwork museum', still using some hydraulic control systems. However, there has been some modernization over the years. After the turn of the century, an ozonation unit was installed, and in 2012, the DWTP was converted to a two-stage treatment comprised of oxidation (ozone) and sedimentation, with polyaluminium chloride (PAX-18) as a coagulant, followed by sand filtration. The treatment process concludes with hardening and chlorine disinfection steps. Recently, the DWTP has been testing flotation as a potential replacement for conventional sedimentation, and it has also introduced ceramic filters and activated carbon adsorption. However, a reduction in the subsidy rate from 70 to 30% by the Ministry of Agriculture has posed a significant challenge, making the required investment of 65 million CZK a considerable obstacle. The municipality is rather small, with only about 2,500 inhabitants. Consequently, the DWTP operates at a capacity of about 6 l/s, with a maximum capacity of 17 l/s and a backup pump providing 22 l/s. In recent years, the raw water quality has deteriorated mainly due to bark beetle attacks and forest clearing in the catchment area. This has resulted in the flushing of DOM and an increase in the water's colour.

3.2. Learning–knowledge processes and change

The study's main focus is on the development of water treatment technologies, particularly related to professions involved in water treatment. However, other fields such as economics, communication, and law also play important roles. Our emphasis, accordingly, will be on learning, knowledge, and change processes associated with drinking water treatment technologies and, if needed, incorporating insight from other professions. One essential aspect we highlight is the role of public regulations in determining water quality standards and specifying acceptable levels of various substances. Here, natural science plays an important role in identifying harmful substances, leading to the development of new and improved treatment processes. These advancements are eventually adopted and adapted by local water treatment companies in the South Bohemian Region.

Knowledge sources and networks are integral to learning, knowledge, and change processes. To better comprehend these processes, our initial focus is on examining the knowledge sources and networks of DWTPs in the southwestern part of the Czech Republic. Subsequently, we enter the learning–knowledge–change processes at the level of DWTPs.

3.2.1. Knowledge sources and networks

In short, the knowledge network on water treatment technologies is well developed, and the water profession appears highly interconnected. The central elements of these networks are

- *Water associations*: SOVAK publishes a monthly magazine and conducts workshops and committees comprising specialists who produce reports on wastewater and drinking water treatment topics. Additionally, the association arranges annual conferences for the water sector and participates in meetings of water associations at the European level. CzWA shares similar activities with a stronger focus on wastewater subjects, though they also address drinking water topics. Both associations engage with relevant ministries to discuss new acts and regulations and subsequently inform their members about the outcome of these interactions.
- *Universities*: Shorter courses are offered by universities to update DWTP technicians on water treatment processes and technologies. These technicians collaborate with university scientists in testing and optimizing specific treatment technologies. The interaction is further strengthened through university alumni meetings and student internships at DWTPs.
- *Academic and professional journals, and conferences*: Scientific papers on water treatment, mostly in open access, can be assessed on digital platforms such as ScienceDirect. Additionally, there are professional (Czech) journals and national conferences that address topics related to drinking water quality and provide access to relevant research articles.
- *Parent companies*: Some private operators of DWTPs are subsidiaries of large international companies. The staff of these daughter companies in the Czech Republic may attend training courses organized by the parent company.
- *Supplier companies*: Companies offering water treatment technologies and components provide visits to equipment-producing plants and training courses, in addition to regular maintenance or urgent repair services.
- *Consultants*: Independent water treatment professionals who offer consultancies on water treatment technologies serve as valuable brokers of knowledge for DWTPs.
- *DWTPs*: Visits and communication between DWTPs enable learning and exchanging experiences in operating specific water treatment technologies, both regularly and during technology upgrades.

3.2.2. Learning–knowledge–change processes

The knowledge network plays a decisive role in fostering learning, knowledge acquisition, and driving change at DWTPs, alongside internally organized processes. It is useful to distinguish between *learning and knowledge* on one hand and *change* on the other. Learning–knowledge at the individual level may not always translate into technological development at the DWTP level, particularly when experienced employees are replaced by newcomers. Still, learning and knowledge can lead to optimization and potentially invention (or innovation[4]) at the plant level. Learning–knowledge and change also differ according to several other categories, such as educational background, job position, phase of career, type of company or DWTP, and stage of technological development. On this basis, the following summarizes the main pathways for learning, knowledge, and change processes:

- *Training* (learning–knowledge) is an ongoing activity at all DWTPs, but its organization varies according to the plant size. Larger DWTPs tend to have more explicit knowledge through written manuals for different positions and treatment processes, whereas smaller ones rely more on tacit knowledge gained through learning by doing.
- *External training* is more common among technologists with higher education than among operators with vocational education, leading to the formation of external networks primarily among technologists.
- *Internal mentoring*. Young technologists are mentored by experienced ones, especially if the newcomer does not have a background in water science. Operators are trained and supervised by technologists, and new operators work alongside those they are replacing, thereby enabling the transfer of tacit knowledge through learning by doing.
- *Cooperation with other DWTPs* and visiting other DWTPs of similar size and location facilitate knowledge exchange about water treatment technologies.
- *Supplier companies' training.* When new water treatment technologies are implemented, supplier companies conduct training session(s) for the staff, promoting learning and knowledge processes for optimization. Supplier companies also conduct maintenance and repair at the plant, which may thereby convey skills in optimizing treatment processes. However, if suppliers monopolize maintenance and repair, it may impede competence building.
- *Private operator companies*. Smaller DWTPs run by private operator companies serving multiple WTPs (both drinking water and wastewater) engage technologists who are responsible for designated areas. They make regular visits to WTPs, and these visits may occur more frequently during emergencies. While these visits primarily serve as monitoring activity, they also play an important role in facilitating learning–knowledge processes.
- *Transition to digital automation*. In the last few decades, there has been a shift towards digitalized automation, known as 'Industry 3.0', which has led to a growing need for abstract reasoning among technologists and operators. Particularly for operators, this shift may necessitate changes in their learning–knowledge processes.
- *Employee-driven improvement ideas*. Technologists and operators present ideas for improving water treatment processes. DWTPs may incentivize this by offering economic rewards for the best ideas. Many technologists are highly educated, with a PhD in water treatment or related topics, and often present ideas that have the potential to become innovations.

Turning to the change component, it is necessary to distinguish between operators and technicians.

At the *operator* level, transformations might manifest as experiential learning, where employees enhance their workflow based on insight gained from their daily tasks. Subsequently, they share this knowledge informally with their operator colleagues as tacit (undocumented) knowledge, which eventually becomes evident through the final output. Operators acquire competence through observation and experience, for instance learning how long time it takes before water from heavy rainfalls reaches the DWTP, as well as the quality of that water. They are then prepared to take appropriate measures, such as adding and dosing chemicals. Similar experiences

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[4] Innovation means an invention becoming commercialized.

relate to cleaning of filters, coping with clogging of pipes, and from observing the functioning of pumps, possibly recommending the installation of a different type of pump.

Technologists employed at specific DWTPs can partake in experiential learning and change processes that resemble what is described above for operators. However, due to their formal education, technologists are also involved in more complex optimization of treatment processes. This can include actions such as adjusting the dosing of CO_2 and lime in treated water to modify its alkalinity. For technologists overseeing several DWTPs, their role extends to facilitating change processes by addressing issues as they arise and disseminating newfound knowledge throughout the network of DWTPs.

4. DISCUSSION

The study's overall findings confirm disparities within the drinking water industry in the South Bohemian Region. These differences are observed in terms of the extent of advanced treatment technologies and the degree of integration into 'Industry 3.0', which are characterized by the adoption and adaption of digitally driven automation in water treatment processes. This uneven development aligns with literature, suggesting that regional inequalities are an inherent effect of capitalism, with such disparities intensifying concurrent with the rise of neoliberalism becoming hegemonic in the early 21st century (Smith, 1984; Harvey, 2005; Hudson, 2007; Peck *et al.*, 2022). Our study demonstrates that DWTPs in smaller municipalities are trailing behind, reflecting a certain territorial unevenness. Nevertheless, the provision of drinking water in the Czech Republic does not conform to a typical market model. Water prices for consumers are regulated, investments in new DWTPs receive substantial subsidies from national and EU funds, and DWTPs are owned by municipalities, which are often managed by private companies as operators. This regulatory structure suggests a version of variegated capitalism (Peck & Theodore, 2007) that mitigates the inherent uneven nature of capitalism. Furthermore, water provision is regarded as an integral part of the infrastructure that facilitates capital accumulation (Harvey, 1985), making the allocation of public funds towards water infrastructure a reasonable step. The specific spatial pattern of unevenness then becomes a struggle between opposing forces: market dynamics and the extent and direction of the public reallocation of resources. Within the European context, robust regulations are rooted in the concept of 'water as a right', leading the European Union to issue a revised and more stringent Drinking Water Directive, taken into effect in January 2021.

The literature on unevenness provides valuable insights into overarching macro-forces and how these forces translate into spatial realities. Our study, however, is addressing micro-forces; these are the forces and processes that give rise to local and intra-regional disparities and potentially contribute to a kind of spatial uneven development among DWTPs. Here, the size of municipalities[5] becomes a significant factor, shaping their economic standing and hence their capacity for investments. The concept of agglomeration economics comes into play as we also discover that many small municipalities are members of the association that owns the large Plav DWTP. This collaborative approach, where resources are pooled, has the potential to counteract to some extent the centre–periphery dimension of spatial uneven development. However, as demonstrated by the case of Písek, the distance to the Plav DWTP can introduce uncertainties and significant risks. Písek's decision in this respect to construct a new plant and source water from Plav during periods with high watershed runoff seems reasonable. It is important to note that Písek is not a small municipality, and the smaller one faces even greater economic challenges. Introducing wastewater treatment to the equation adds another layer of complexity,

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[5] It should be noted that in the beginning of 1990s, just after the communist regime fell, the Czech Republic allowed many very small municipalities to be formed.

as exemplified by the small Studená municipality, which owns the Karhov DWTP. The municipality prioritized upgrading its wastewater treatment plant under pressure from a local meat-producing plant. However, subsequently, the company owning the plant reduced its activity, leaving the municipality with considerable excess wastewater treatment capacity. This illustrates the challenges encountered by peripheral regions.

In this article, our primary focus has been on the learning–knowledge–change processes taking place at DWTPs. A counterargument to this focus in relation to technological development could be that it is more likely believing the tail to wag the dog compared to the more foundational roles played by economics and regulations representing the dog wagging its learning–knowledge tail. For sure, economic considerations might render upgrading or establishing new plants unfeasible, as illustrated by the case of Karhov DWTP. Similarly, regulations specifying limits for harmful substances in drinking water could ultimately necessitate investments. However, we contend that learning–knowledge processes have a more significant impact than the dog–tail analogy suggests, especially when adopting a process-oriented perspective.

To begin with, the learning–knowledge processes within DWTPs are interconnected with a wider knowledge network. As underlined by Najm & Trussell (1999), the testing of new technologies involves small-scale pilots as well as real-world trials, wherein DWTPs can have a role. These tests create windows of opportunity for enacting stronger regulations and securing funds to introduce new technologies.

Secondly, in-house learning–knowledge processes at individual DWTPs contribute to improve water quality by optimizing treatment processes based on the local context. The competence in running the DWTP is enhanced, potentially leading to more cost-effective production. This efficiency could, in turn, assist in funding necessary upgrades of treatment technology. Moreover, the emergence of ideas for new technologies may also arise within these processes, eventually entering the broader knowledge network and potentially securing funding for commercial production.

Hence, there are valid reasons for acknowledging the significant role that learning–knowledge processes play in the technological development at DWTPs. Still, there are complexities associated with the knowledge dimension. Our study reveals a close-knit regional and national learning–knowledge network embedded within wider European and international/global networks, also encompassing commercial suppliers of water treatment technology. Furthermore, the study indicates that new technologies, albeit to varying extents and speeds, are making their way into DWTPs. From this, we may infer that the knowledge dimension does not appear to pose a substantial barrier nor cause significant disparities in the potential for technological change among various DWTPs. Nonetheless, decisions regarding technological upgrades rest with the DWTP owners, who are primarily municipalities. This involves administrative staff and politicians representing different parties. Overall, larger municipalities and DWTPs tend to possess higher competence compared to their smaller counterparts. This enhanced competence facilitates better communication with decision-making politicians and the ability to formulate applications for public funds. Again, the case of Plav, along with private operator companies serving smaller municipalities, may mitigate the influence of size as a driving force behind uneven technological development.

Shifting the focus towards learning–knowledge and *change*, we applied typologies that categorize various aspects of these processes. The analysis unveiled a merging of these categories, blurring the boundaries between the theoretical typologies of learning, knowledge, and change. This blending brings to light the criticism raised by Markusen's (1999) about the ambiguous nature of concepts within regional science, stemming from the presence of multiple alternative meanings, inadequate standards of evidence, and thereby the weakening of policy relevance. The criticism was especially aimed at case studies. In a later response, Peck (2003) argued for methodological pluralism, advocating for both the in-depth exploration offered by qualitative case studies and the traditional replicability inherent in quantitative studies. Hudson (2003) argued that case studies within critical theory and political economy could better address policy needs. Adding to this, the concepts and categories applied in this paper's study are analytically distinct, and their blending is context-dependent, contingent on the specific cases at hand, which aligns with Peck's call for depth.

We observe that the categories encompassing employees, generational differences, educational background, and the size of DWTPs may fall into different categories within the typologies of learning and change. Consequently, the scale of analysis becomes pivotal in determining which learning or change typologies should be used – whether at the region level, the entire DWTP, or intra-DWTP levels. Neglecting such differences may undermine our understanding of the processes that shape diverse and uneven technological development trajectories. What holds significance is often the interplay and intersection among different categories of learning and change. In aiming for an efficient and technologically up-to-date DWTP operation, it is unlikely that reliance solely on experiential learning would suffice. Typically, a DWTP will also engage in transitional learning. However, after or during a transitional learning process, the optimization of treatment processes would require experiential learning. Similar interactions apply for other knowledge and change typologies. These interactions may manifest differently in large and small DWTPs, as underscored earlier.

None of the DWTPs have transitioned from the SCADA system to any form of the decentralized artificial intelligence (AI)-governed system, aligning with the observations made by Fu *et al*. (2022). This is not indicative of a lack of awareness about AI's potential; rather, it reflects concern about the technology's ability to effectively manage all the intricately interconnected parameters that influence the quality of the water in a specific context. The responsibility of providing clean water to both people and industries contributes to a conservative stance within the water industry when it comes to implementing new technologies. The water industry's reluctance to swiftly adopt novel technologies stems from considerations about whether these technologies can reliably address the wide array of parameters that impact water quality. Economic constraints further compound this hesitancy, particularly for DWTPs in smaller municipalities. These limitations prompt careful deliberation before introducing new technologies, whether they pertain to water treatment technologies or any form of digitalization. Consequently, progress is gradual, and the implementation of any decentralized AI system at present appears to be a distant possibility.

Although commercial operator companies run DWTPs, the sector is significantly regulated by public authorities, underscoring the influence of politics. As one of the better-performing European countries in terms of water quality, the Czech authorities, supported by economic assistance from the EU, appear to prioritize the provision of clean water. Still, our mapping of the combinations of unit processes in DWTPs revealed varying development trajectories, mainly along the axis of small to large municipalities and DWTPs. The question of whether the resulting inequalities are politically endorsed or not falls beyond the scope of this paper. Our inquiry revolves around strategies to bridge these gaps through levelling-up policies.

Broadly speaking, we may distinguish between policies that accept the existing DWTP structure and employ economic incentives in a technological levelling-up approach to help smaller DWTPs address critical technology gaps. This first strategy is more feasible in situations of economic growth and increasing funds for the water sector, whereas it faces challenges when total funds remain stagnant or decrease. Nevertheless, a targeted reallocation of resources towards the neediest smaller DWTPs should be attainable. The second strategy involves establishing a new larger DWTP or a few medium-sized DWTPs, which presents more complexities, especially in terms of selecting suitable locations for the new facilities. In addition, issues regarding ownership structure, economic costs, and responsibilities may cause political struggles. Although a larger plant would enhance water safety, it might render water provision more vulnerable to significant interruptions compared to a system composed of many small plants. In summary, there is a trade-off between higher risk and reduced water security on the one hand, and a more competent staff with the capacity to manage failures, along with the financial capacity to set up backup systems against power disruptions and similar challenges, on the other hand.

On a smaller scale, regional authorities could facilitate or mandate formal collaboration between DWTPs, thereby enhancing their competence through learning–knowledge processes and potentially resulting in improved drinking water quality. Another consideration could be a revision of procurement regulations, allowing municipalities to develop integrated treatment processes and avoid incorporating treatment units that do not function effectively within the overall system.

5. CONCLUSIONS

The main overarching conclusions drawn from this study into technological development and knowledge networks across five DWTPs of different sizes can be summarized as follows:

- A well-developed regional and national DWTP-knowledge network, coupled with strong international connections, serves as a driving force for improving drinking water quality through the advancement of more effective water treatment technologies.
- The bulk of the knowledge base falls within the realm of synthetic knowledge, with knowledge exchange taking place within communities of practice and cooperation along supply chains. Still, there are elements of analytic knowledge present, which is evident through knowledge exchange within epistemic communities and globally configured networks, as well as traces of symbolic knowledge, involving numerous actors and cooperations in short-term projects among companies.
- More effective treatment technologies may lay the basis for stronger public regulations related to drinking water quality. This also facilitates improvements within individual DWTPs, contingent upon political backing and the economic capacity of the municipal owners of the DWTPs.
- Larger DWTPs are at the forefront of the water treatment technologies, while smaller ones are trailing behind, materializing in uneven patterns and development trajectories. This discrepancy is mainly attributed to economic disparities but is also mediated by the full-time technologists at larger DWTPs.
- In many smaller municipalities, commercial companies are responsible for operating DWTPs, which assists them in staying better connected to the drinking water technology network. Still, larger DWTPs possess an advantage in learning–knowledge processes, fostering good drinking water production through an ongoing interaction between technologists and operators.
- Generally, despite differences between larger and smaller facilities, DWTPs within the region predominantly employ mature treatment technologies. The central task and challenge lie in optimizing these technologies to suit local conditions.
- The DWTPs have not progressed beyond the SCADA system, with some of the smaller ones still in the process of implementation – a phase characterized as a form of limited digitalization. Notwithstanding, smaller DWTPs may leap-frog and partially introduce digitally autonomous sections within the treatment process.
- The incorporation of digital equipment has made treatment processes less susceptible to human errors. However, this shift has concurrently presented challenges in pinpointing errors since digital indicators can obscure the true location of errors. Hence, a comprehensive understanding of treatment processes is necessary, and operators might need to acquire more profound theoretical knowledge.
- Targeted economic subsidies emerge as a suitable policy measure for levelling-up small DWTP lagging in treatment technology. Conversely, building a large plant to replace many smaller ones poses more substantial challenges but could be considered as a long-term strategy.

Future research: Discussing policies, the paper argues that targeted economic subsidies could be an effective way of levelling-up lagging DWTPs. Related to this discussion, further research should reveal the allocation of EU/Czech funds to different types of WTPs and municipalities. In addition, the research should assess how much funding is necessary for levelling-up needy DWTPs, also considering the development of other plants. Moreover, comparing water quality in different plants should be part of research, also addressing threshold levels of harmful substances according to public regulations.

The analysis of learning–knowledge–change processes found that categories within learning, knowledge, and change commonly combine and interact when studying real-world cases. More research is needed to understand how such combinations are spelled out. Linked to this is a discussion on the development of new categories. New research studying other cases, also outside of Europe, may help identify commonalities and the role of context.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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