DOI 10.7343/as-2024-803

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

Initiative of EuroGeoSurveys' Urban Geology and Water Resources Expert Groups

Special Issue:
Groundwater in the cities of Europe

Groundwater resilience, security, and safety in the four largest cities in Denmark

Resilienza, sicurezza e protezione delle acquee sotterranee nelle quattro città più grandi della Danimarca.

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ARTICLE INFO

Ricevuto/*Received*: 5 July 2024
Accettato/*Accepted*: 7 September 2024
Pubblicato online/*Published online*: 30 September 2024

Handling Editor:
Stefano Viaroli

Citation:
Jørgensen, L.F., Troldborg, L., Ondracek, M., Seidenfaden, I.K., Kidmose, J., Vangsgaard, C., Hinsby, K (2024) Groundwater resilience, security, and safety in the four largest cities in Denmark - Acque Sotterranee - *Italian Journal of Groundwater*, 13(3), 25 - 41
https://doi.org/10.7343/as-2024-803

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Keywords: *: groundwater, water resilience, drinking water, urban water, water management, Denmark .*

Parole chiave: *Acque sotterranee, resilienza idrica, acqua potabile, acqua urbana, gestione delle acque, Danimarca.*

Riassunto

La completa dipendenza della Danimarca dalle acque sotterranee per l'approvvigionamento idrico rappresenta un caso di studio unico nella gestione delle risorse naturali, nella pianificazione urbana e nella resilienza idrica di fronte ai cambiamenti climatici. Questo articolo esamina le strategie di gestione delle acque sotterranee in Danimarca, concentrandosi sulle quattro maggiori città danesi (Copenaghen, Aarhus, Odense e Aalborg), ognuna delle quali affronta differenti sfide per le loro caratteristiche demografiche, geografiche, idrogeologiche ed economiche.

Attraverso l'analisi della gestione delle acque sotterranee di queste città, questa ricerca contribuisce alla definizione di un approccio globale ai sistemi di approvvigionamento idrico urbano sostenibili. In qualità di città costiere (CGC), devono affrontare le complessità del sostentamento della crescita della popolazione, della mitigazione degli impatti dei cambiamenti climatici e dei processi costieri, garantendo allo stesso tempo il mantenimento a lungo termine delle risorse idriche sotterranee. Copenaghen e Aalborg sono state costruite su un acquifero carbonatico fratturato, semi-confinate e localmente carsificato, mentre Aarhus e Odense sono state costruite su acquiferi glacio-fluviali. Le diverse sfide relative alle acque sotterranee in queste città evidenziano l'importanza dell'integrazione dello sviluppo urbano con la gestione delle risorse idriche e la sostenibilità ambientale, offrendo in questo modo preziose indicazioni per altre regioni che affrontano simili sfide.

Questo studio, quindi, non solo descrive le pratiche di gestione delle acque sotterranee in Danimarca, ma sottolinea anche la necessità di soluzioni innovative per garantire la resilienza dei sistemi di approvvigionamento idrico urbano stressati dal clima che cambia e dal crescente carico di contaminanti geogenici o organici emergenti.

Gli strumenti avanzati di monitoraggio e modellazione danesi sono utilizzati a supporto del processo decisionale e dell'innovazione nella gestione resiliente e sostenibile delle risorse idriche disponibili.

Abstract

Denmark's complete reliance on groundwater for water supply presents a unique case study in management of natural resources, urban planning, and water resilience in the face of climate change. This paper examines the groundwater management strategies in Denmark in general, focusing on Denmark's four largest cities- Copenhagen, Aarhus, Odense, and Aalborg - each facing distinct challenges due to their demographic, geographical, hydrogeological, and economic characteristics. Through analysis of these cities' approaches to groundwater management, this research contributes to the global discourse on sustainable urban water supply systems. As coastal groundwater cities (CGC), these urban areas must navigate the complexities of sustaining growing populations, mitigating climate change impacts, and coastal processes while ensuring the long-term viability of their groundwater resources. Copenhagen and Aalborg, built atop semi-confined fractured and locally karstic carbonate rocks, highlights the specific challenges associated with karstic groundwater systems, while Aarhus and Odense built on glaciofluvial aquifers face different issues. The different groundwater challenges in these cities underscore the importance of integrating urban development with water resource management and environmental sustainability, offering valuable insights and lessons learned for other regions facing similar challenges. This study, thus not only sheds light on Denmark's groundwater management practices, but also emphasizes the need for innovative solutions to ensure the resilience of urban water supply systems in a changing climate and increasing pressures of emerging organic contaminants as well as elevated concentrations of geogenic elements induced by water abstraction and fluctuating water tables. Advanced Danish monitoring and modelling tools applied to support decision-making and innovation within the water sector are continuously developed and improved to support resilient and sustainable management of the available water resources.

Introduction

Water supply for cities and nature is under serious pressure globally due to climate change and increasingly competing water and subsurface uses (Benz et al., 2024; Foster, 2022; Ingemarsson et al., 2022; United Nations, 2022; Grunfeld et al., 2024, Hinsby et al., 2024). Improved water resilience, security and safety require: “more integrative and ecologically-centred thinking in water governance” (Rodina, 2019). This is a relatively new challenge for urban water supplies requiring transdisciplinary collaboration to protect water resources and nature (Bjerre et al., 2023). In Denmark, the total reliance on clean groundwater for water supply (drinking water, industrial use, irrigation) is both a testament to natural resource management and a challenge e.g., future urban planning, water resilience and sustainable management in a changing climate considering groundwater legitimate uses and ecosystems/biodiversity according to EU policies (European Commission, 2009, 2015; Ingemarsson et al., 2022; Henriksen et al., 2021a, 2023a; Hinsby et al., 2008).

Before the industrial age, shallow manually dug wells were the main source of drinking water in Denmark, due to its favourable geological and climatic conditions (Jensen, 2013). Surface water was also a substantial source, both in rural areas as well as for urban drinking water supply, as evidenced by the onset of public water supply in Copenhagen and Odense in the late 16th century, where water was channelled from suburban freshwater lakes to the city centre through simple gravity flow (Barfod, 1977). After several cholera epidemics in the middle of the 19th century, the first modern water utilities were established in the larger cities based on groundwater as the resource for clean drinking water. Today, practically all water supply for Danish cities is supplied by groundwater resources. Consequently, the groundwater quantitative and chemical status, based on groundwater needs for legitimate uses and nature, is carefully monitored and modelled according to EU directives (European Commission, 1991, 2000, 2006, 2009, 2015, 2020; Thorling et al., 2024; Henriksen et al., 2023a; Troldborg et al., 2023). Historically, nitrate and pesticide pollution are the main concern for the chemical status of Danish groundwater and the well fields of the Danish water utilities (Thorling et al., 2023; Foster & Bjerre, 2023), but new emerging organic contaminants frequently appear in the monitoring programmes (Thorling et al., 2024).

The four largest cities in Denmark - Copenhagen, Aarhus, Odense, and Aalborg - are all situated at or close to the coast, and easy access to the sea has been a major factor in the geographical position of these cities. Each city, with its own distinct demographic, geographical, hydrogeological and economic characteristics, depends entirely on groundwater resources to meet (drinking) water needs. Meanwhile, the management of urban surface water, shallow groundwater and water table fluctuations potentially represents critical issues for buildings and infrastructure. Furthermore, the proximity to the coast poses a threat in terms of flooding from the seaside as well as exposure to saltwater intrusion to coastal groundwater bodies. In combination with shallow groundwater, this constitutes a high risk of flooding of buildings, infrastructure etc., and deterioration of the drinking water resources abstracted from coastal aquifers. These issues are projected to be more severe in the future because of climate change and rising sea levels (Colgan et al., 2022).

In Copenhagen, Denmark’s capital and largest city, the challenge is not only to sustain a growing population but also to innovate in the face of climate change impacts and rising sea levels. Aarhus, the country’s second-largest city, faces its unique set of challenges in managing groundwater resources amidst rapid urban expansion and agricultural influences. Odense and Aalborg, while smaller, confront similar issues of balancing growth with sustainable water resource management. Aalborg abstracts groundwater from fractured chalk/karst aquifers that are among the groundwater bodies most vulnerable to nitrate pollution in Denmark due to shallow water tables and high hydraulic conductivity (Nilsson et al., 2023; EGDI, 2024a). The aquifers supplying groundwater for the four cities and many other cities in Denmark are highly vulnerable to pollution from the surface according to the Drastic Index (EGDI, 2024b), which is a dimensionless score of vulnerability, based on the main hydrologic and geologic parameters of the setting (Aller et al., 1987.) This vulnerability is due, in part, to the relatively short groundwater travel times towards the water supply wells in which 50 % of the top of the intakes are above a depth of about 40 meters, and with typical lengths of less than 20 meters (Thorling et al., 2024). As a result, many Danish water supply wells are impacted by human activities (Hinsby et al., 2001, 2007; EGDI 2024c), and may contain pollutants above drinking water standards (Voutchkova et al., 2021), requiring careful monitoring in time and space of a long list of organic and inorganic groundwater quality indicators (Thorling et al., 2023, 2024). Recent studies found that the concentrations of nitrate and other pollutants as well as natural geogenic elements affect human health at concentrations much lower than the drinking water standards (Ahmad et al., 2020; Schullehner et al., 2018) and thereby affecting drinking water safety (Quevauviller et al., 2024).

Thus, all four cities have significant issues with the chemical status of their groundwater bodies due to elevated concentrations of a wide range of contaminants including nitrate and pesticides according to the data reported to the European Environment Agency (EEA), while only Copenhagen, Odense and Aarhus reported problems with groundwater quantitative status (EEA, 2024). An overview of the EU member state assessments of both groundwater chemical and quantitative status as reported to the EEA has been compiled and displayed on an interactive Pan-European map viewer (https://europeanwaters.eu/). The map shows that Copenhagen especially has significant challenges with both groundwater quantitative and chemical status.

By focusing on the Danish experience, this research review contributes to the broader discourse on sustainable urban water supply systems, offering insights and lessons that can be applied in various global contexts. The total reliance on groundwater in Denmark presents a unique opportunity to explore the synergies between urban development, water resource management, and environmental sustainability. Knowledge that is indispensable for the implementation of the anticipated European Blue Deal (EESC, 2023).

The Danish area and management tools in use

Denmark (43,000 km^2, 5.9 million inhabitants) experiences a coastal temperate climate characterized by mild winters and cool summers, and annual rainfall between 650 and 1,150 mm. With a gentle topography and a maximum elevation of 173 meters above mean sea level, Denmark's surface water resources are limited, comprising smaller streams, lakes, and wetlands. As a consequence of a total coastline of 7,400 km and only a short border with Germany in the south of Jutland, the interaction with the marine environment is pivotal for (ground)water use and management.

The near-surface geology of Denmark bears the imprint of previous glacial periods, with Quaternary tills prevalent in the eastern and northern regions and sandy glacio-fluvial sediments in the western and southern areas. Deeper deposits include Tertiary sand and clay, and Cretaceous chalk and limestone, see Figure 1. Tertiary and Quaternary sands and fractured Cretaceous and Tertiary chalk and limestone constitute the most important aquifers in Denmark (Fig.1) with about two-thirds abstracted from sands and the remaining part abstracted from chalk and limestone (Pedersen & Gravesen, 2011). Sound geological modelling is a prerequisite for all assessments involving the subsurface including the planning and use of urban groundwater and infrastructure (La Bianca et al., 2023).

Groundwater management is mainly the task of the 98 municipalities in Denmark that act within the legislation and frames laid out by the Danish Ministry of the Environment based on EU Directives such as the Nitrate Directive, the Water Framework Directive, the Groundwater Directive and the Drinking Water Directive (European Commission, 1991, 2000, 2006, 2020). The Danish Ministry of the Environment issue laws and regulations to implement these directives while the municipalities set out plans for groundwater protection, issue abstraction licenses incl. monitoring programmes to water utility companies and are responsible for enforcement of legislation. Besides, the water utility companies have the licence to perform groundwater-protecting measures, mainly manifested in voluntary agreements with farmers to either reduce the use of pesticides and nutrients or to establish forests in former agricultural areas. On top of this, The Danish Environmental Protection Agency (EPA) under the Ministry of the Environment, has assigned areas in the close vicinity of groundwater abstraction wells where the use of pesticides, nitrate, and other contaminants are restricted. Similarly, the EPA can assign areas where groundwater resource is particularly important and/or where specific efforts are needed to secure the resource. For more details on the Danish groundwater management, protection, and monitoring, see Jørgensen et al. (2016).

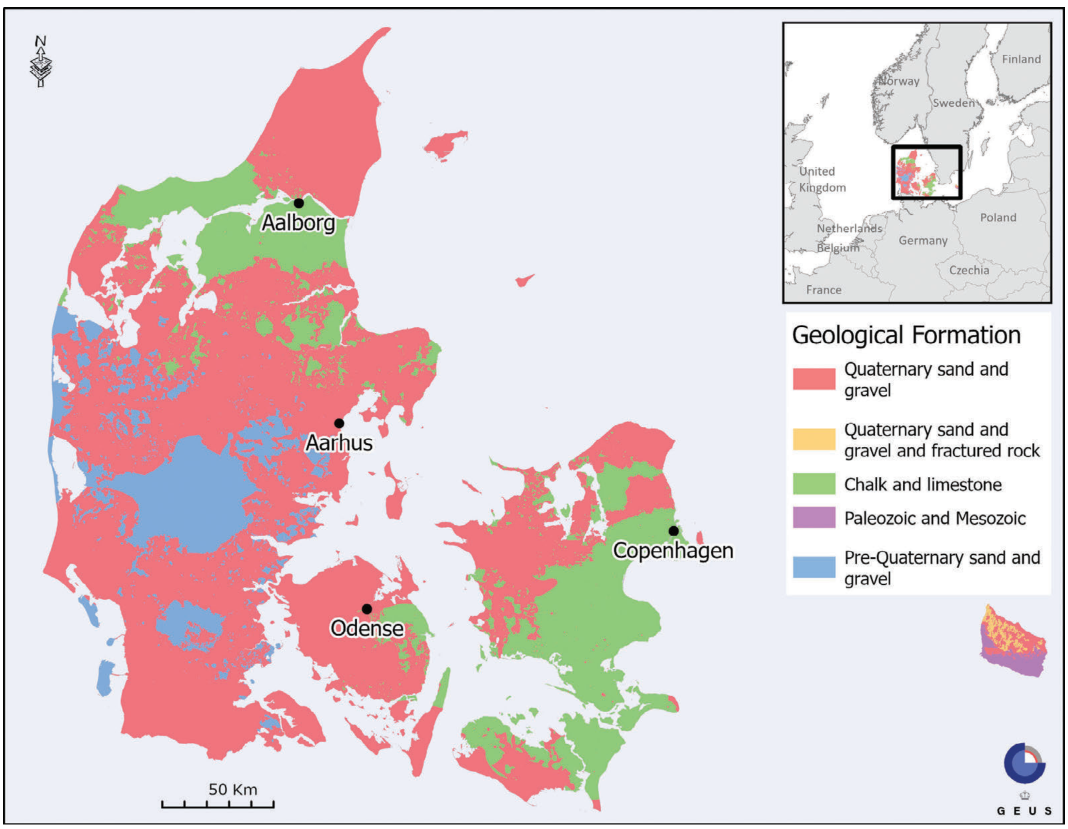

Fig. 1 - Location of the four case study cities in Denmark and the most important geological formations in relation to groundwater abstraction.

Fig. 1 - Ubicazione delle 4 città danesi analizzate in questo studio e le più importanti formazioni geologiche in relazione all'estrazione di acqua sotterranea.

Monitoring tools

Besides from the results from the monitoring programmes performed by the water utility companies, output from the National Groundwater Monitoring Programme, including observations from dedicated groundwater monitoring wells with short screens, are reported annually by the Geological Survey of Denmark and Greenland (e.g., Thorling, 2023, 2024). Another national funded monitoring programme, The Danish Pesticide Leaching Assessment Programme, where pesticides are tested under true farming practices, and thereby contribute to the regulation of pesticides both on a national scale as results are reported to the Danish Ministry of the Environment, but also to international knowledge as outputs are also published in peer-reviewed journal papers (Badawi et al., 2024). A dedicated programme for real-time groundwater level monitoring (https://groundwaterlevel.dk/) with more than 100 monitoring points providing information on the development in groundwater levels both on a short and longer term, supporting both climate change adaptation, urban development, management of water abstraction, knowledge on groundwater dependent ecosystems and biodiversity etc. These monitoring programmes support groundwater management and protection in Denmark as data and results are publicly accessible and available for free.

Modelling tools

The national modelling efforts on water management are centred around The Danish National Hydrological Model (DK-model; www.dennationalehydrologiskemodel.dk; Henriksen et al., 2003; Stisen et al., 2019; Højberg et al., 2013). The model is an integrated physically based hydrological model, covering both surface, soil, surface water and groundwater processes. It forms the backbone of:

- National Groundwater resources mapping (Troldborg, 2020)
- Resource sustainability assessment (Henriksen et al., 2023b)
- Climate change assessments (Seidenfaden et al., 2022)
- The National Nitrogen model (Højberg et al., 2021)
- Hydrological indexes for tracking extremes (Henriksen et al., 2022)

In recent years, the DK-model has become a part of the Hydrological Information Platform (HIP, https://hip.dataforsyningen.dk/help), where historical and future simulated model results, including high-resolution groundwater table maps (Koch et al., 2021), boundary conditions and setup information can be downloaded and used by consultancies and local authorities (Henriksen et al., 2021b). It, thus, often functions as a starting point for more detailed small-scale modelling. Furthermore, the DK-model is also operational in real-time, and hydrological indexes are updated daily showing the current status of soil moisture, groundwater and stream flow (https://dennationalehydrologiskemodel.dk/dk-modellen-i-anvendelse/hydrologiske-indeks).

Groundwater availability and water security

Denmark is rich in groundwater resources, facilitated by excess net rainfall and robust aquifer systems dominated by sand and limestone. The temperate climate fosters low evapotranspiration rates and an average groundwater recharge of 300 mm/year (Stisen et al., 2012). However, groundwater recharge varies significantly across the country (Fig. 2) with higher recharge rates in western Denmark due to relatively high precipitation and unconfined aquifers, contrasting with the eastern region's lower precipitation and confined aquifers overlaid by till, leading to more surface and drain water runoff.

A recent study (Henriksen et al., 2023b) provides an estimate of the robust (sustainable) accessible groundwater resource in Denmark at catchment level (Fig. 3). Results show that although the country is in a good situation, the abstraction in some catchments is far larger than the robust resource, especially in the larger Copenhagen area and around the second largest city, Aarhus. High population density results in overabstraction of groundwater in the vicinity of these two large cities, especially southwest of Copenhagen (Fig. 3, Henriksen et al., 2021a, 2023b) although only 11 % of groundwater bodies in the eastern part of Denmark are reported to fail good quantitative status according to

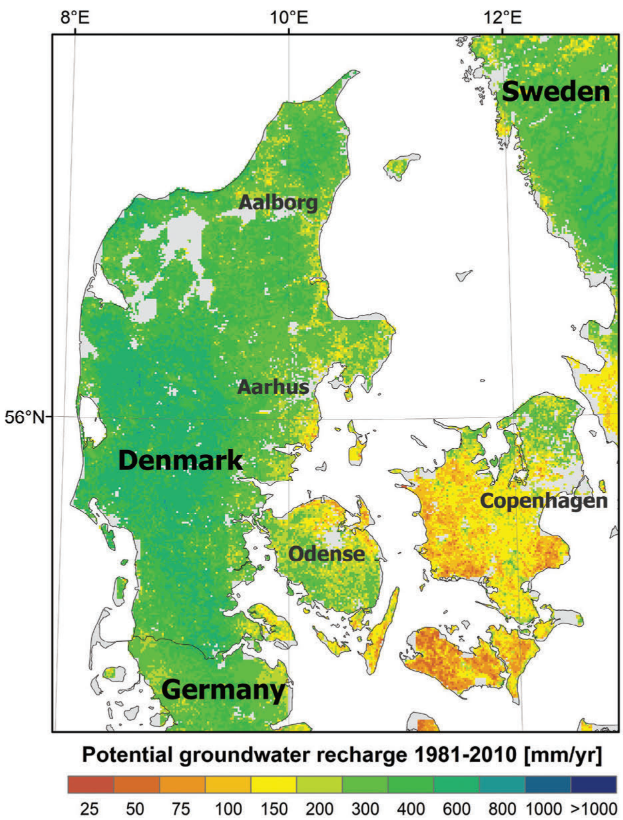

Fig. 2 - Potential groundwater recharge for Denmark, average 1981-2010. Adapted from the Pan-European groundwater recharge map developed by Martinsen et al. (2022) (EGDI 2024d).

Fig. 2 - Ricarica potenziale delle falde in Danimarca, valore medio per il periodo 1981-2010. Adattata dalla Carta Pan-Europea della ricarica delle falde realizzata da Martinsen et al. (2022), (EGDI 2024d).

 DOI 10.7343/as-2024-803

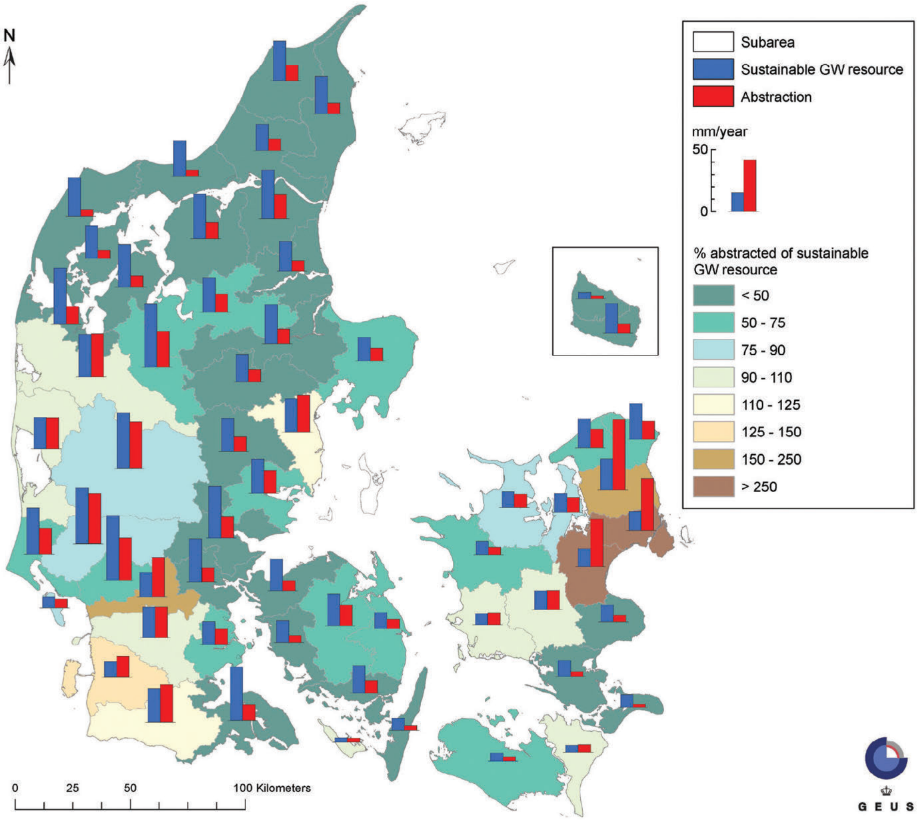

Fig. 3 - The robust groundwater resource (blue columns) in mm per year, compared to the actual abstraction (red columns) calculated on the level of 58 catchment areas. The background colours indicate the exploitation rate from less than 50 to more than 250%. Edited from Henriksen et al. (2023b) with permission.

Fig. 3 - La risorsa idrica sotterranea (colonne blu) in mm all'anno, confrontata con gli effettivi prelievi (colonne rosse). L'elaborazione è stata realizzata per 58 bacini idrografici. I colori di sfondo indicano il tasso di sfruttamento, da meno del 50 a più del 250%. Modificato con permesso da Henriksen et al. (2023b).

national reporting and the EEA (2024). The estimates are based on model calculations with the DK-model and pre-set assumptions such as abstraction patterns as the previous five years, a maximum abstraction of 30% to 50% of groundwater recharge to groundwater aquifers in different depths, minimum effect from abstraction on surface water systems as streams and wetlands etc.

"Potential groundwater recharge" as used in Figure 2 refers to the fact that the groundwater recharge depicted is not directly measured recharge to the water table, but instead an approximation obtained by multiplying the efficient precipitation by an estimated groundwater recharge coefficient that partitions the efficient precipitation into groundwater recharge and shallow runoff. In addition, regions without data are included in the map by using proxy (satellite) data and interpolations of data from regions with measured and modelled groundwater recharge data using machine learning techniques. For more details of the procedure see Martinsen et al. (2022).

As described in sections below, most of the groundwater abstraction for drinking water purposes in the four largest cities (and in most other cities in Denmark) takes place in the countryside, outside the densely populated areas. Groundwater infiltration in urban areas is limited and typically contaminated by human activities. Therefore, especially shallow groundwater poses a challenge in urban areas in terms of groundwater flooding, reduced infiltration capacity due to soil sealing (Quevauviller et al., 2024), high groundwater table etc. Mapping and interviews (Danish Ministry of the Environment, 2021; WSP et al., 2021) reveal that citizens, water utilities and authorities experience an increasing number of challenges and damages caused by rising groundwater tables. Ceased groundwater abstraction for drinking water production or for remediation of pollution as well as sealing of sewers that have previously worked as drains, can result in a rising groundwater table (Rasmussen et al., 2023). Finally, a naturally high groundwater table in combination with an increasing number of extreme precipitation events also results in groundwater flooding that can last for longer periods than earlier experienced, especially in clayey areas. A recent review study, prepared for a Danish insurance company concluded that there is a knowledge gap when it comes to urban groundwater and the associated risks. The study points out that as most Danish experiences and solutions hitherto were related to nature-based solutions associated with surface runoff from cloud bursts, the potential threats from rising groundwater are still to be faced (van der Keur & Henriksen, 2022).

Groundwater quality threats and water safety

As groundwater is continuously replenished by infiltrating rainwater, activities on the surface are often reflected in the chemical status of groundwater. Around 60% of the rural area is subject to mainly conventional agricultural practices which result in leaching of nitrate, pesticides and other agricultural contaminants to groundwater bodies. Other emerging organic contaminants, PFAS and PFOS being the latest recognized, arise from different anthropogenic activities both in rural and urban areas. Furthermore, natural geogenic components such as arsenic pose a challenge in some areas like in many other regions in Europe and southeast Asia (Giménez-Forcada et al., 2022; Ahmad et al., 2020; Postma et al., 2012; Sen & Biswas, 2013). Selected examples of groundwater quality indicators are shown in Figure 4, based on the annual reporting from the National Groundwater Monitoring Programmememe (Thorling et al., 2023, 2024), and will be described below.

Arsenic

Arsenic generally of natural geogenic origin (Smedley & Kinniburgh, 2002; Postma et al., 2012; Giménez-Forcada et al., 2022) is one of the most problematic groundwater and drinking water quality issues globally considered to be responsible for the largest mass poisoning in history (Sen & Biswas, 2013). The Danish drinking water quality standard (DDWQS) for Arsenic is 5 µg/L or half of the EU and WHO DWQS of 10 µg/L (European Commission, 2020; WHO, 2022). Concentrations above the DDWQS are found in many parts of Denmark, also around the larger cities, constituting significant health issues (Ramsey et al., 2021; Richter et al., 2022). Studies in the Netherlands have demonstrated that lowering the contents of Arsenic to less the 1 µg/L by treating groundwater at water supply plants has considerable economic benefits due to improved water safety (Quevauviller et al., 2024) and health conditions by reducing incidences of lung cancer in the Netherlands (Ahmad et al., 2020).

Arsenic is detected in most (92%) of the 6,102 Danish water supply wells analysed in the period 2017-2021 and above the DDWQS in 12% (Thorling et al., 2023), see Figure 4. Balanced abstraction schemes (dilution) and treatment at the water supply plants in most cases solve this challenge.

Nickel

Nickel in Danish groundwater primarily arises from natural geological sources, released by oxidation of pyrite accelerated by a lowered groundwater table as a result of groundwater abstraction for drinking water production (Larsen & Postma, 1997). The DWQS for Nickel is 20 µg/L as established in the European Drinking Water Directive (European Commission, 2020) or significantly lower than the WHO DWQS of 75 µg/L (WHO, 2022). Elevated nickel levels in drinking water can lead to health issues, including allergic reactions, dermatitis, and potential kidney and liver toxicity. Long-term exposure to nickel has been linked to an increased risk of

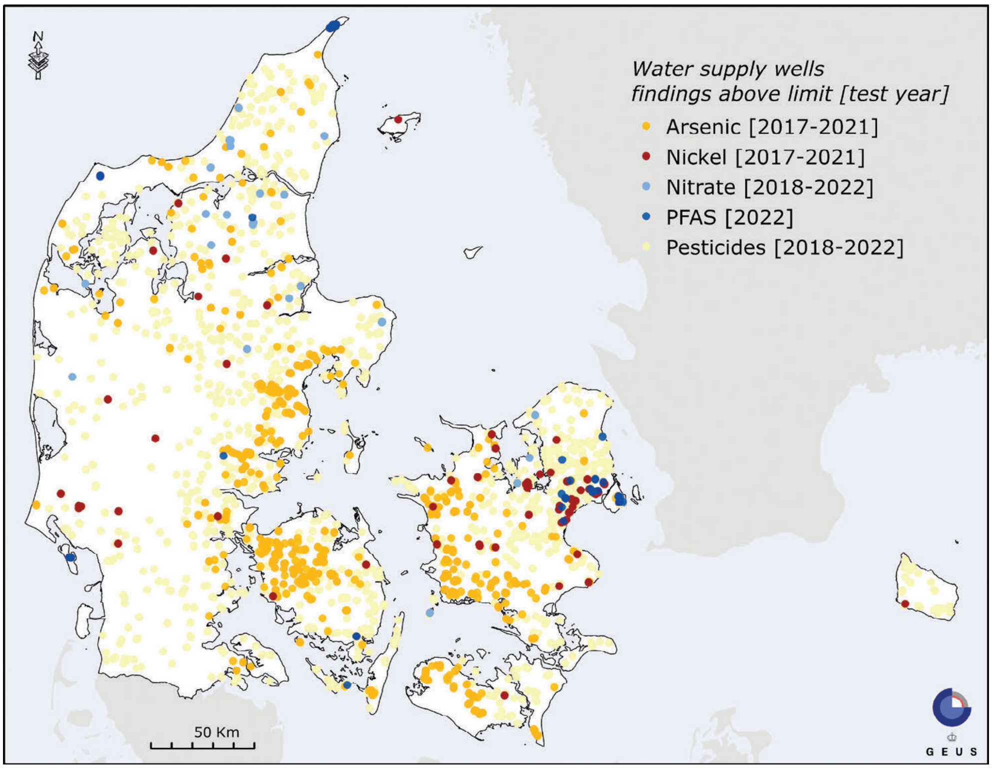

Fig. 4 - Arsenic, Nickel, Nitrate, PFAS, and Pesticides and their metabolites, all above (Danish) drinking water standards (DWQS) in active Danish water supply wells. Arsenic above the DDWQS of 5 µg/L in the period 2017-2021. Nickel above the DWQS of 20 µg/L in the period 2017-2021. Nitrate above the DWQS of 50 mg/L in the period 2018-2022. Pesticides and/or their metabolites above the DWQS of 0.1 µg/L in the period 2018-2022. The sum of four PFAS substances (PFOS + PFOA + PFHxS + PFNA) above the DWQS of 0.002 µg/L in 2022. Numbers in brackets indicate the monitoring period (Thorling et al., 2023, 2024).

Fig. 4 - Pozzi attivi per approvvigionamento idrico in cui sono stati riscontrati valori di Arsenico, nichel, nitrati, PFAS e pesticidi e loro metaboliti, al di sopra degli standard per l'acqua potabile (DWQS). Arsenico al di sopra del DWQS di 5 µg/L nel periodo 2017-2021. Nichel superiore al DWQS di 20 µg/L nel periodo 2017-2021. Nitrato superiore al DWQS di 50 mg/L nel periodo 2018-2022. Pesticidi e/o loro metaboliti superiori al DWQS di 0,1 µg/L nel periodo 2018-2022. La somma di quattro sostanze PFAS (PFOS + PFOA + PFHxS + PFNA) al di sopra del DWQS di 0,002 µg/L nel 2022. I numeri tra parentesi indicano il periodo di monitoraggio (Thorling et al., 2023, 2024).

cancer (WHO, 2022).

Nickel was detected in 79% of the 6,102 Danish water supply wells analysed in the period 2017-2021 and above the DWQS in less than 2% (Thorling et al., 2023), Figure 4. Balanced abstraction schemes (dilution) solve this challenge.

Pesticides and their metabolites

Pesticides and their metabolites are in general undesirable in groundwater and drinking water, and the concentrations should be kept as low as possible (WHO, 2022). Denmark follows the EU DWQS of 0.1 μg/L for a single pesticide, metabolite, degradation, or reaction product and 0.5 μg/L for the sum of pesticides and metabolites (European Commission, 2006, 2020). The monitoring programme for Danish water utility companies includes up to 45 different pesticides and metabolites, depending on their relevance. The list has changed over time since pesticides were introduced into the monitoring programmes for both groundwater and drinking water in Denmark in 1989-90. Initially, only eight different active pesticide products were included. Pesticides or their metabolites were detected at least once in 40% of the 6,386 wells analysed in the period 2018-2022. The DWQS was exceeded in 11% of the analyses, and the parameter for the sum of pesticides and metabolites in 2% (Thorling et al., 2024).

PFAS+

Contamination of the environment with novel entities (Persson et al., 2022) including PFAS contamination of groundwater and drinking water (Sunderland et al., 2019; Cousins et al., 2022) is a growing concern in the EU (Sonne et al., 2023) and globally (Richardson et al., 2023). This is also the case for Denmark (Fig. 4), and a range of different PFAS substances were therefore included in the Danish groundwater and drinking water monitoring programmes (Johnsen et al., 2023; Thorling et al., 2023). Figure 4 clearly illustrates that the Copenhagen area is a hotspot for PFAS contamination of water supply wells. Data on other emerging contaminants such as those defined by the Voluntary Watch List of Working Group Groundwater within the Common Implementation Strategy for Water Framework Directive (European Commission, 2019) e.g., pharmaceuticals, are currently unavailable or very limited.

Four Cases of Urban Water Management

The following review of urban water in the four largest cities in Denmark is mainly based on municipal or national reports and notes. Maps with the location of water supply wells are retrieved from the Danish National Well Database (Jupiter) hosted at www.geus.dk. All four cities investigated in this study are categorised as coastal groundwater cities (CGC) according to the classification scheme of La Vigna (2022). Aalborg and Copenhagen are built on top of semi-confined fractured and locally karstic carbonate rocks and hence may be classified as HRGC-KGC, while the cities of Aarhus and Odense are Alluvial Groundwater Cities (AGC) (Table 1). Groundwater is the only source of drinking water in all four cities, both for citizens and for industry. Some general facts on the population and location of the cities are summarised in Table 1.

The City of Copenhagen

Copenhagen is situated in the east-central part of the island of Zealand (Figs. 1 and 5). Around 1,500,000 citizens live in the Greater Copenhagen area, a little less than half of these in the municipalities of Copenhagen and Frederiksberg.

General hydrogeological setting

The geology is dominated by Quaternary glacial deposits of varying thickness, typically 10-30 m, including both tills as well as meltwater deposits as clay, silt, sand, and gravel (Gravesen et al., 2017). The groundwater aquifers are mainly chalk or limestone of Cretaceous or Danien age, fractured by pressure of overlying glacial ice during the Quaternary period to a depth of about 80 meters. In some areas, overlying sandy meltwater deposits are hydrologically connected with these aquifers (Troldborg, 2020; Troldborg et al., 2023).

Groundwater uses:

The Greater Copenhagen Utility, HOFOR, annually supply around 50 million m^3 of drinking water to 1 million citizens and to industries in the central City of Copenhagen (consisting of the municipalities of Copenhagen and Frederiksberg, marked by shading in Figure 5) as well as neighbouring municipalities in the Greater Copenhagen area. In most of these municipalities, Copenhagen excluded, small local water utilities are operating and extract minor amounts

Tab. 1 - Facts and groundwater city classification according to La Vigna (2022).

Tab. 1 - Dettagli e classificazione degli acquiferi urbani secondo La Vigna (2022).

City	Population	Precipitation {mm/yr}	Drinking water production per year {mill. m^3]*	City classification 1	City classification 2
Aalborg	150,000	790	7	CGC[a]	HRGC-KGC[b]
Aarhus	300,000	810	15	CGC	AGC[c]
Copenhagen	1,500,000	660	50	CGC	HRGC-KGC
Odense	180,000	870	9	CGC	AGC
*By the major water utility company. [a]Coastal Groundwater City, [b]Hard Rock – Karstic Groundwater City, [c]Alluvial Groundwater City					

of groundwater for drinking water supply. However, most of the drinking water needs are covered by HOFOR due to challenges related to quality at the local level. HOFOR operates seven larger utilities situated far (up to 50 km) from the city centre where groundwater is abundant in the needed amounts (www.hofor.dk), (Fig. 5). The relatively small volume of groundwater in the low-lying and coastal area of central Copenhagen has for centuries been considered too contaminated, and the quality is also threatened by saltwater intrusion due to pumping. This was recognized already centuries ago where hand-dug wells were the main source (in combination with surface water) for drinking water supply in historic Copenhagen. In 1859, Copenhagen Water Supply Company (today HOFOR) was established with drinking water production based on suburban groundwater. Accordingly, most abstraction in central Copenhagen was abandoned (Copenhagen Municipal Council, 1959).

The location of wells and treatment plants in a number of suburban municipalities, which do not receive drinking water from HOFOR, requires particular attention when it comes to administration, management and protection as the municipality with the largest interests at stake (Copenhagen) has no jurisdiction in the abstraction areas. This has historically resulted in challenges and even conflicts which eventually have been solved by political and administrative cooperation across municipality borders (Copenhagen Municipal Council, 1959; Copenhagen Municipality, 2012).

Groundwater quantity issues:

Both increasing and decreasing water tables may cause problems depending on the location. Some well fields operated by HOFOR goes back more than a century since when the supply structure and number of customers have grown, which together with rapidly developing water-demanding industries resulted in a growing volume of drinking water production during the 1960s and 1970s. However, this development in increasing abstraction ceased in the 1980s and 1990s due to regulations, water levies, measures to minimize water losses etc. It is estimated that the water use has been halved during the last five decades (Skov- og Naturstyrelsen, 1999; Jørgensen et al., 2016). Historically, wells were situated in lower-lying areas and often close to streams or brooks, hence pumping caused lowered groundwater tables resulting in reduced baseflow which again led to deteriorated ecosystems (Henriksen et al., 2021a). Rising groundwater tables as a result of reduced pumping or abandoned wells have, on the other hand, caused problems for buildings and infrastructure that were established previously during decades of intense pumping and lower water tables (Copenhagen Municipality, 2021).

As illustrated in Figure 3, the groundwater resources are in general over-exploited in the eastern parts of the Island of Zealand, where Copenhagen is situated. Henriksen et al. (2023b) estimate that the present abstraction in the Greater Copenhagen area exceeds 250% of the sustainable groundwater resource, resulting in desiccated wetlands and low stream flows affecting the ecological status of the ecosystems (Gejl et al., 2020; Henriksen et al., 2021a) as well as quality problems, described in the next paragraph. Climate change impacts are expected to increase the number of climate extreme events including extended periods of droughts in summer and winter seasons (Schneider et al., 2022; Seidenfaden et al.,

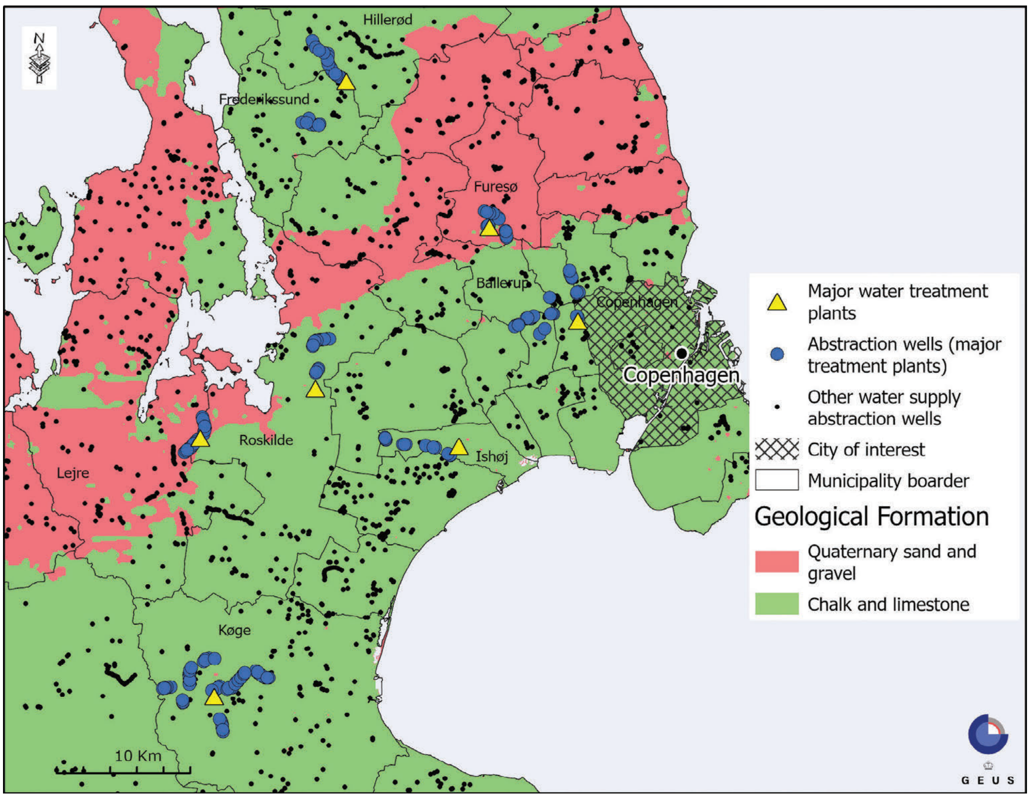

Fig. 5 - Greater Copenhagen area (most of the area is populated, the central part of Copenhagen city is shaded) and the central-eastern part of Zealand with primary geology. The location of water supply wells and main water treatment plants, all HOFOR, is also shown.

Fig. 5 - Geologia dell'area metropolitana di Copenaghen (la maggior parte dell'area è popolata, il centro città di Copenaghen è ombreggiata) e della parte centro-orientale della Zelanda. Viene anche riportata l'ubicazione dei pozzi di approvvigionamento idrico e dei principali impianti di trattamento delle acque gestiti da HOFOR.

2022), which will increase pressures on water resources for industry, households and nature.

Groundwater quality issues:

Geogenic nickel as well as pesticides and their metabolites (Albers et al., 2023), and PFAS are found in and around Copenhagen (Fig. 4). Nickel is especially a challenge in an area southwest of Copenhagen where previous high abstraction rates have lowered the groundwater table, resulting in pyrite-oxidation (Larsen & Postma, 1999). The groundwater quality issues are handled by adjusting abstraction schemes and by dilution/mixing of different water types at the water treatment plants.

The City of Aarhus

Aarhus is situated in the eastern and central part of Jutland (Figs. 1 and 6). Around 360,000 citizens live in the city centre.

General hydrogeological setting

The geology is dominated by a thick layer of Quaternary glacial deposits, mainly clayey tills 20-50 m or even thicker. The sandy aquifers are of either Quaternary glacial origin (sandy meltwater layers) or deltaic deposits of Tertiary age, starting 25-100 m below the surface, and usually well-protected by overlying layers with low permeability (Larsen & Kronborg, 1994; Troldborg, 2020; Troldborg et al., 2023).

Groundwater uses

Most of the City of Aarhus and its suburbs are supplied with drinking water by the large water utility Aarhus Vand which annually produces around 15 million m^3 supplying both the city and the entire municipality of Aarhus (Aarhus Municipality, 2015) from eight main treatment plants, see Figure 6. The municipality covers a large area (compared to the municipality of Copenhagen), and all wells and plants are mainly situated in rural areas outside the city limit but (almost all) within municipality borders. This makes groundwater management, protection and monitoring more manageable as decisions are centralised in one administrational unit at the municipal level in the same municipality.

Recently, Aarhus Vand has agreed with Aarhus Municipality and the Danish State to establish groundwater parks with the ambition of serving public well-being, nature, and groundwater protection at the same time by transforming agricultural areas into forest or nature with no use of nutrients, pesticides etc. The parks are planned to cover 80 km^2, around 17% of the area of the municipality and almost 30% of the present agricultural area (Aarhus Vand, 2024).

Groundwater quantity issues:

The aquifers are estimated (Henriksen et al., 2023b) to be slightly overexploited, as abstraction amounts to 110-125% of the sustainable resource in the catchment area enclosing Aarhus Municipality (Fig. 3). Depleted baseflow in streams and brooks as well as effects on lakes, biodiversity etc. are recognized as challenges to be addressed (Aarhus Municipality, 2015) according to requirements of the Water Framework and Groundwater directives and related guidelines.

Groundwater quality issues:

As illustrated in Figure 4 and addressed by Aarhus Municipality (2015), pesticides are a challenge in an increasing number of water supply wells, demonstrating that the groundwater is affected by surface activities.

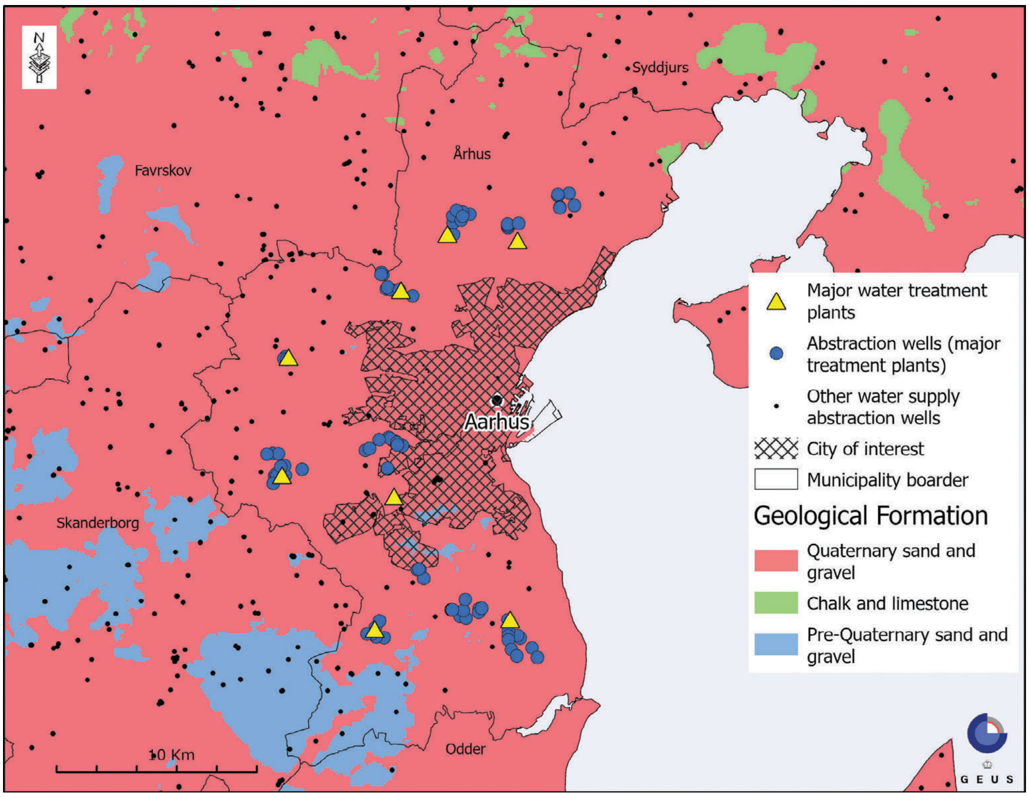

Fig. 6 - The city (shaded) and municipality of Aarhus with primary geology and wells supplying groundwater for drinking water production. The eight largest treatment plants and abstraction wells belonging to Aarhus Vand (the major water utility company for Aarhus) are also marked.

Fig. 6 - Geologia della città (ombreggiata) e del comune di Aarhus e i pozzi per la captazione di acqua potabile. Sono contrassegnati anche gli otto maggiori impianti di trattamento e pozzi di estrazione appartenenti ad Aarhus Vand (la principale società di servizi idrici di Aarhus).

Geogenic Arsenic is also detected in an increasing number of abstraction wells; however, this is removed during water treatment to ensure that the DDWQS is met. Elevated chloride concentrations arising from aquifers in contact with tertiary marine deposits are also mentioned; this is solved by dedicated abstraction schemes. (Aarhus Municipality, 2015). Groundwater dating tracers (environmental tracers) were recently used to estimate groundwater age and travel times and improve the understanding of the vulnerability of the investigated water supply wells and the exploited groundwater bodies towards pollution from the surface, (Broers et al., 2021; EGDI, 2024c). Poorly constructed wells may create short-circuiting that enables fast migration of pollutants e.g. along casings, increasing the vulnerability of the well and the groundwater body towards pollution from the surface. In contrast to flow models the environmental tracers may identify poorly constructed wells with badly developed sealing or damaged casings that make both the wells themselves and the groundwater bodies they exploit more "vulnerable" to pollution from the surface. Occasionally, poorly constructed or damaged wells can be repaired instead of just closed down depending on the construction issues causing the problem.

The City of Odense

Odense is situated in the central part of the island of Funen and connected to the sea by a fiord (Figs. 1 and 7). Around 180,000 citizens live in the city centre.

General hydrogeological setting

The geology in this area consists of Quaternary clayey tills with embedded smaller sand and silt layers and lenses in the shallow horizons while the deeper sandy aquifers are thicker, 10-20 m (Larsen, 2002). Groundwater is typically abstracted from depths between 40 and 60 m below the surface (Troldborg, 2020; Troldborg et al., 2023).

Groundwater uses

Drinking water demand of most of the citizens in and around the City of Odense derives from well fields located in the vicinity of the city limits towards the south and east. A large part of the City of Odense is supplied with drinking water from the utility company VCS Denmark.

Groundwater quantity issues:

The original water supply for the City of Odense (from the 19th century) was based on an artesian aquifer in what is now the central part of the city.

As water demand increased due to urbanization, this primary, confined aquifer became non-artesian as the groundwater level was lowered due to abstraction. The urban groundwater level was the lowest in the 1970s at the time of the largest groundwater abstractions for the city (Laursen & Linderberg, 2017).

Figure 8 shows the changes in water abstraction from this aquifer under the City of Odense as well as the response in piezometric level of the shallow groundwater in a monitoring well inside the city. The overexploitation resulted in a deterioration of groundwater quality (e.g., elevated sulphate and chloride concentrations) of the aquifer leading to the

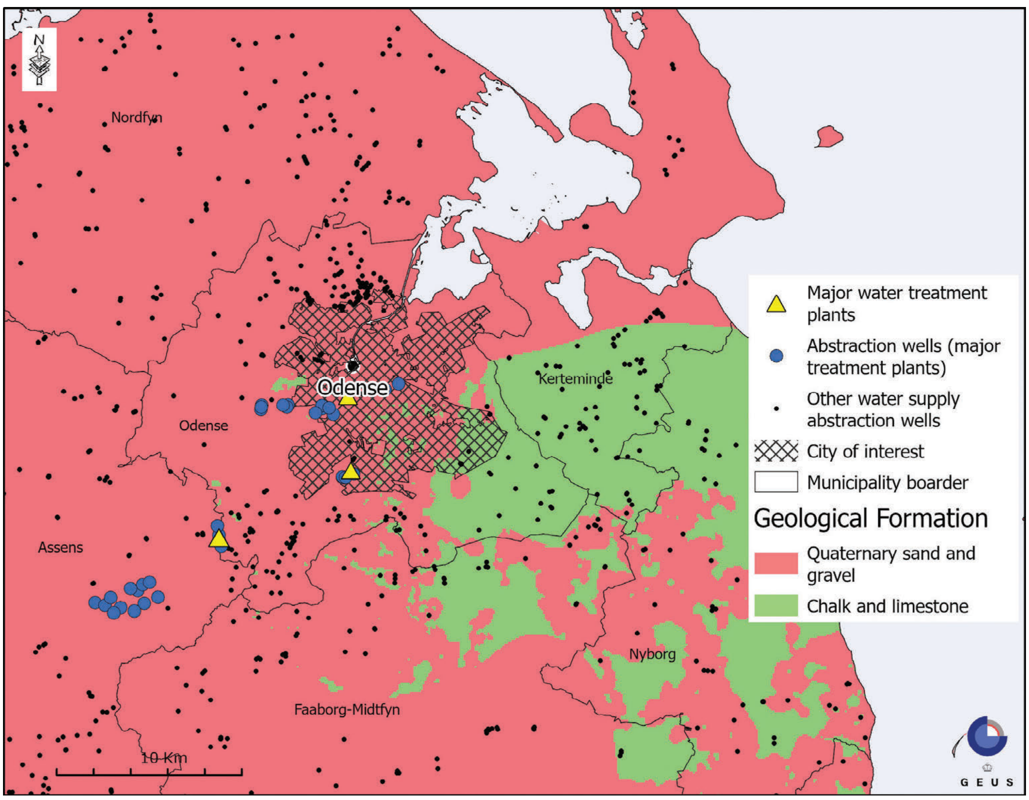

Fig. 7 - The city (shaded) and municipality of Odense with primary geology and wells supplying groundwater for drinking water production. Three major treatment plants belonging to VCS Denmark are marked as well as their abstraction wells. (VCS Denmark operates more treatment plants and wells supplying neighbouring municipalities in separate distribution systems, not illustrated on this map.)

Fig. 7 - Geologia della città (ombreggiata) e del comune di Odense e i pozzi per la captazione di acqua potabile. Sono riportati i tre grandi impianti di trattamento appartenenti a VCS Denmark e i loro pozzi di estrazione. (VCS Danimarca gestisce anche altri impianti di trattamento e pozzi che riforniscono i comuni vicini tramite sistemi di distribuzione separati, non riportati in questa figura.)

establishment of new wellfields outside the city. As water use in general decreased in the 1980s and 1990s, the shallow groundwater levels slowly recovered.

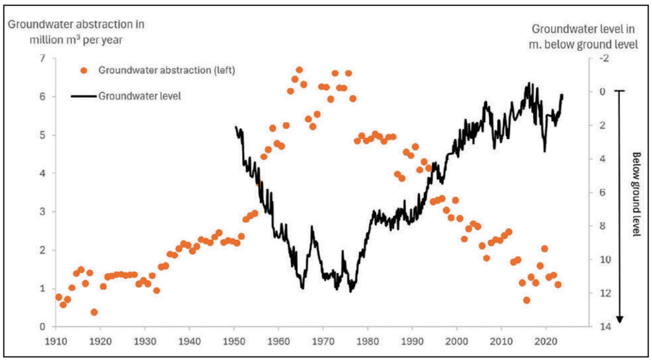

Fig. 8 - Shallow groundwater level and groundwater abstraction in Odense city (borehole DGU no. 145.16) and abstracted millions m³ groundwater per year from the urban well-field. Left axis is groundwater abstraction at the well-field with maximum groundwater abstraction in late 1960s and 1970s. With maximum abstraction, shallow groundwater levels (the most upper unconfined groundwater head) were 12 m below ground level. From the 1970s until 2010, groundwater levels rebound to a level just below the surface/ground level corresponding to 0 at the right-side axis. (-2 indicate 2 meters above ground level).

Fig. 8 - Livello di falda e quantità di prelievo di acque sotterranee (in Mm^3) nella città di Odense (pozzo DGU n. 145.16). L'asse sinistro del grafico corrsiponde all'estrazione di acque sotterranee nel campo pozzi con la massima estrazione di acque sotterranee compresa tra la fine degli anni '60 e gli anni '70. In corrispondenza della massima estrazione, i livelli delle acque sotterranee poco profonde erano 12 m sotto il livello del suolo. Dagli anni '70 fino al 2010, i livelli delle acque sotterranee risalgono a un livello appena sotto il livello della superficie/suolo corrispondente a 0 sull'asse destro.

The present groundwater abstraction is estimated to be lower than the sustainable groundwater resource in the catchment embracing the Municipality of Odense (Henriksen et al., 2023b), see Figure 3. In line with this, the municipality does not report any quantitative issues (Odense Municipality, 2018). However, increasingly shallower groundwater levels are experienced because of sealing of sewers that have previously worked as drains as well as the partly abandoned groundwater abstraction in the urban area, causing damage to buildings and infrastructure. Rising groundwater levels caused by decreasing groundwater abstraction, more precipitation especially in fall and winter periods, and rising sea level because of climate change, have also been reported as the main challenges for the City of Odense (e.g., Laursen & Linderberg, 2017; WSP et al., 2021). La Bianca et al. (2023, 2024) recently analyzed the impact of urban geology model simulations of groundwater levels and flow paths and the use of machine learning for predicting shallow water levels in urban areas.

Groundwater quality issues:

The main threat towards the groundwater around the City of Odense are pesticides and their metabolites, see Figure 4. VSC Denmark reports that as of spring 2024, one specific pesticide residue (Desphenyl Chloridazon) has been detected in two thirds of all their abstraction wells (VCS Denmark, 2024a). This is handled by active coal filtering to ensure safe drinking water with no exceedances of the DWQS.

To protect future groundwater quality, VCS Denmark, the municipality, and the Danish State are establishing afforestation in areas with groundwater recharge by entering agreements with farmers to abandon intensive agriculture. Positive side effects are enhanced biodiversity, carbon fixation, less leaching of nutrients, and creating more suburban recreative space (VCS Denmark, 2024b).

The water utility company of Odense has a long history of international collaboration on the use of environmental tracers for assessment of groundwater age and travel times, contaminant transport, vulnerability of water supply wells and the exploited aquifers or groundwater bodies (as explained above in the Aarhus section), and efficacy and timescale of contaminant remediation measures (Alvarado et al., 2005, Hinsby et al., 2006, 2024; Troldborg et al., 2008; Musy et al., 2023; EGDI, 2024c).

In addition, the City of Odense continuously explores new and efficient ways to protect groundwater quantity and quality for households, industry, agriculture, and nature (Laursen & Lindberg, 2017; Foster & Bjerre, 2023).

Recently, VCS Denmark and the Odense municipality established multi- and transdisciplinary collaboration to initiate afforestation and other mitigation measures to protect groundwater resources and ecosystems in and associated to the largest VCS well field (Bjerre et al, 2023).

The City of Aalborg

Aalborg is situated in the northern part of Jutland, at the fiord Limfjorden (Figs. 1 and 9). Together with the City of Nørresundby at the northern bank of the fiord, around 145,000 citizens live in the city centre.

General hydrogeological setting:

In general, the groundwater aquifers in this area are poorly protected by thin clayey or sandy glacial or postglacial layers above glacial sand and fractured chalk of Cretaceous and Danien age that constitutes the aquifers, or without any protective top layers at all. Abstraction takes place 20-50 m below the surface (Andersen & Sjørring, 1992; Troldborg, 2020; Troldborg et al., 2023).

Groundwater uses:

The main part of the city is supplied from well fields north and south of the city limits, operated by Aalborg Forsyning, the largest water utility in the area. Aalborg Forsyning annually distribute around 7 million m^3 of drinking water to the City of Aalborg and the surrounding areas (Aalborg Municipality, 2021).

Groundwater quantity issues:

The present groundwater abstraction is estimated to be well within the range of sustainability (Henriksen et al., 2023b), see Figure 3. However, the municipality foresees that the need for irrigation in the rural areas may increase as climate changes will result in higher evaporation rates during more dry summer periods, and potential droughts (Schneider et al., 2022). As irrigation is based on groundwater, and the wells for drinking water production are also located in rural areas, competition on the resources may be a future challenge, also taking the groundwater dependent ecosystems and biodiversity into account (Aalborg Municipality, 2020).

Groundwater quality issues:

The main threats toward groundwater quality in this area arises from agricultural practises, primarily nitrate and pesticides (incl. metabolites), see Figure 4. The fractured carbonate aquifers of the area are vulnerable to pollution from the surface due to the limited extend and high hydraulic conductivity of protective layers above these (EGDI, 2024a).

Already in the 1980s, the Municipality of Aalborg started the establishment of groundwater parks as they experienced quality issues, especially related to nitrate and pesticides from agricultural practices. The parks were mainly established by buying agricultural areas from farmers and planting forest, but in a few cases, land was expropriated to secure specific vulnerable areas and contiguous areas. Today, these areas cover around 12 km^2 but the municipality plans to further establish 6 km^2 to ensure clean groundwater for future generations. For comparison, the agricultural area in the municipality covers around 700 km^2 (Aalborg Municipality, 2024). However, an online monitoring station recently completed more than two years of near real-time nitrate measurements (September 2021 – April 2024) just downstream the most famous Danish chalk spring, St. Blaakilde, about 25 km south of Aalborg (EGDI 2023e). The measurements indicate agricultural impact of the underlying chalk aquifer despite most of the areas around the spring are protected, demonstrating that the springs integrate groundwater quality variability in time and space including areas with leakage from agricultural land uses and protected nature areas.

Discussion

The challenges described above clearly demonstrate the increasing pressure on groundwater quantity and quality in Denmark. As highlighted by the examples above, the highest groundwater resource demand may not be located close to the largest resource, meaning that even though the national groundwater resource for Denmark may be more than sufficient, the demand and supply do not necessarily balance locally or regionally. These challenges are linked to legitimate water uses such as drinking water, irrigation, and industry, but increasingly also to the need to preserve good ecological status of groundwater-dependent terrestrial and associated aquatic ecosystems. At the same time, already known as well as new emerging contaminants and pollutants can cause the abandonment of existing groundwater abstraction sites. Groundwater quantity and quality are also under increasing pressure due to climate change, climate change mitigation and adaptation measures, especially around the larger cities and in areas with intensive agriculture and shallow vulnerable aquifers.

Measures like specific protection zones around abstraction wells are routinely used in Denmark, and in total, the Danish Environmental Protection Agency (EPA) has assigned 4.850 of these areas in the close vicinity of these wells. The areas are protected via restrictions on use of pesticides, nitrate, and other contaminants. Similarly, the EPA strikes to appoint areas where the groundwater resource is particularly important and/or where specific efforts are needed to secure the resource, however, with less restrictive measures. In Denmark, the construction of groundwater parks and afforestation also is

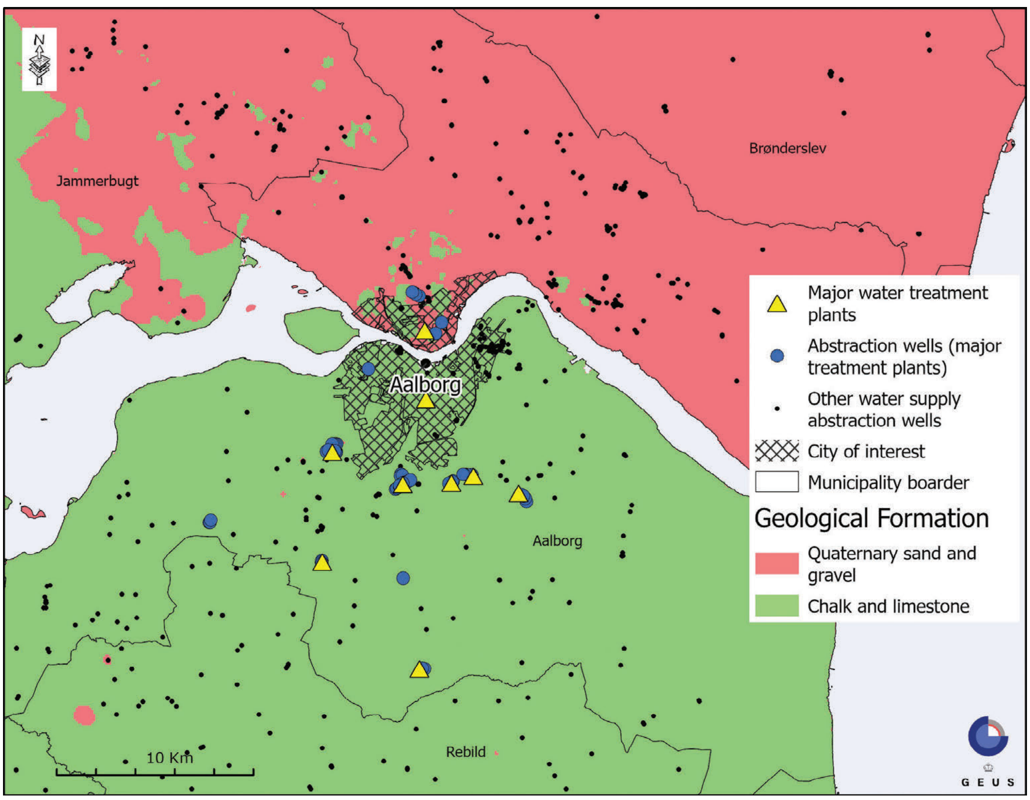

Fig. 9 - The city (shaded) and municipality of Aalborg with primary geology and wells supplying groundwater for drinking water production. Treatment plants belonging to Aalborg Forsyning are marked as well as their abstraction wells.

Fig. 9 - Geologia della città (ombreggiata) e del comune di Aalborg e i pozzi per la captazione di acqua potabile. Sono riportati gli impianti di trattamento appartenenti ad Aalborg Forsyning e i loro pozzi di estrazione.

well underway, as mentioned in the examples above, and the resulting positive effect on groundwater quality seems logical (due to the reduction or cessation of pesticides and nitrate use in the recharging area). The effect on groundwater quantity is, however, not well established, and groundwater recharge may increase or decrease due to afforestation (e.g., Allen & Chapman, 2001; Gustard & Wesselink, 1993; Sonnenborg et al., 2017; Zhang & Hiscock, 2010).

Consequently, there is a growing recognition that stronger and integrated spatial planning tools, e.g., as hydrological digital twins (Henriksen et al. 2022) are needed to improve the sustainable governance of water and natural resources in general at the national (Vangsgaard, 2023), European (EGS, 2023; Hinsby et al., 2024; Vangsgaard & Hinsby, 2021), and global level (Ingemarsson et al., 2022; United Nations, 2022); also to support the green transition and implementation of UN SDGs (Hinsby et al., 2024).

The Danish Water and Wastewater Association (DANVA) has recently argued that a national water authority is urgently needed due to the many and increasing pressures on water resources from climate change and other societal challenges (DANVA, 2024). Considering that most of the freshwater resources are stored in aquifers or groundwater bodies across Europe and globally (United Nations, 2022), this aligns well with a new initiative by the EuroGeoSurveys (EGS) arguing for the need of an integrated surface and subsurface spatial planning directive at the European level to prioritize the use of competing and sometimes conflicting (sub)surface uses (EGS, 2023).

Besides the groundwater issues described for the four largest cities in the sections above, many other Danish cities face significant challenges in providing sufficient freshwater resources for legitimate uses besides drinking water such as water for agriculture and industry. New groundwater quantity challenges are related to new industries requiring pristine or recycled water resources for large data centres, for production, for Power-to-X or other activities for the green transition that requires freshwater. Although e.g., Power-To-X facilities are looking into alternative water sources as wastewater, mildly polluted water or sea water, some areas are anticipated to face increasing pressure on the groundwater resources.

The geographical structure of groundwater abstraction moving away from the cities because of overexploitation and urban pollution can affect shallow groundwater in contact with infrastructure and buildings as seen in the example at the City of Odense. The example shows a drawdown (Fig. 8) in the shallow groundwater in the city of more than 10 m. During the period (1960-1980) with the highest drawdown, large areas of the present-day city were urbanized (developed) under "dry" conditions with groundwater levels 5-10 meters below the surface. These areas are today threatened by flooding because of the rebound of the shallow groundwater levels to more natural levels just below the surface but in contact with basements, road trenches, railroads and other critical infrastructures. National assessments of climate change impact on shallow groundwater (Seidenfaden et al., 2022) show far less impact in urban areas than changes in groundwater abstraction beneath the cities.

Besides a changed groundwater abstraction pattern, several interventions in urban hydrology can affect the urban groundwater levels. One is forced infiltration of rainwater often used as a climate change adaption measure to the groundwater thereby increasing groundwater levels and possibly polluting aquifers with pollutants from roofs, pavements and roads. Another known adaptation practice (to reduce the volume of sewer water needed to be cleaned) is to repair old and leaky sewers that in practise acts a groundwater drains. This increases groundwater levels but reduces cost of cleaning sewer water.

Of lessons learned from the management strategies in the four Danish cities we would like to emphasize the following: 1) The value of open (FAIR) access to groundwater and subsurface data in general for integrated and sustainable management of the (urban) subsurface; 2) The need for and value of integrated groundwater – surface water monitoring and modelling for groundwater quantitative and chemical status assessments, delineation of protected areas (including areas for afforestation), evaluation of contaminant migration and projection of climate change impacts; 3) The value of environmental tracers in combination with flow models for estimation of groundwater travel time distributions, assessment of the efficiency of remediation measures and vulnerability of aquifers and specific water supply wells (e.g. identification of poorly constructed or damaged wells that may be repaired); 4) The value of nature-based solutions for mitigating and adapting to climate extreme events in urban areas.

Conclusions

The growing pressures on groundwater quantity and quality in Denmark mirror broader challenges faced by many European countries. These pressures stem from contamination issues, legitimate uses such as drinking water, irrigation, and industry, as well as consideration of the ecological needs of groundwater-dependent ecosystems. Climate change and associated mitigation and adaptation measures further exacerbate these pressures, particularly around larger cities, and agricultural areas with vulnerable aquifers. Mitigation measures like groundwater parks is a powerful tool, but jurisdiction on the recharge area may be problematic as abstraction sometimes takes place outside the municipality that receives the resource.

Overall, addressing these challenges requires comprehensive, integrated approaches to spatial planning and resource management to ensure sustainable water governance, and to prioritize competing uses of the subsurface while facing climate change and urbanization pressures. In this context the use of advanced and integrated geological, groundwater-surface water and climate monitoring and modelling techniques considering sea level rise, hydrological extreme events (floods and droughts) is imperative for assessing and projecting the future of urban groundwater and societies especially in coastal areas.

Acknowledgments

Two anonymous reviewers are kindly acknowledged for their useful comments and suggestions.

Funding source

This work required no external funding.

Competing interest

The authors declare no competing interests.

Author contributions

Data processing and visualisation: LT, MO, JK; Writing-original draft preparation: LFJ, LT, MO, IKS, JK, CV, KH.

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

Additional information

DOI: https://doi.org/10.7343/as-2024-803

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