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FOCUS ARTICLE

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Groundwater–surface water interaction in Denmark

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Abstract

The study of groundwater–surface water interaction has attracted growing interest among researchers in recent years due to its wide range of implications from the perspectives of water management, ecology and contamination. Many of the studies shed light on conditions on a local scale only, without exploring a regional angle. To provide a broad and historical overview of groundwater–surface water interaction, a review of research carried out in Denmark was undertaken due to the high density of studies conducted in the country. The extent to which this topic has been investigated is related to Denmark's physiography and climate, the presence of numerous streams and lakes combined with shallow groundwater, and historical, funding, and administrative decisions. Study topics comprise groundwater detection techniques, numerical modeling, and contaminant issues including nutrients, ranging from point studies all the way to studies at national scale. The increase in studies in recent decades corresponds with the need to maintain the good status of groundwater-dependent ecosystems and protect groundwater resources. This review of three decades of research revealed that problems such as the difference in scales between numerical models and field observations, interdisciplinary research integrating hydrological and biological methods, and the effect of local processes in regional systems remain persistent challenges. Technical progress in the use of unmanned aerial vehicles, distributed temperature sensing, and new cost-effective methods for detecting groundwater discharge as well as the increasing computing capacity of numerical models emerge as opportunities for dealing with complex natural systems that are subject to modifications in future triggered by climate change.

This article is categorized under:

Science of Water > Hydrological Processes
Science of Water > Water and Environmental Change
Water and Life > Nature of Freshwater Ecosystems

KEYWORDS

climate change, groundwater discharge, groundwater-dependent ecosystems, interdisciplinary research, nutrient issues

1 | INTRODUCTION

Groundwater–surface water interaction is the process in which the groundwater flowing in aquifers exchanges with the water in surface water bodies, such as streams, lakes, wetlands, and coastal waters. This interaction has received increasing attention in recent decades due to its implications for the integrated water management of water resources (groundwater and surface water) and valuable groundwater-dependent ecosystems within the Water Framework Directive (European Commission, 2000) and the Groundwater Daughter Directive (European Commission, 2006). There are several challenges when studying groundwater–surface water interaction, ranging from it being a highly variable process both in time and space (Duque & Rosenberry, 2022; Kalbus et al., 2006) to the problems of including flow exchange processes in integrated hydrological modeling considering two different types of water flow. The traditional approach has been to study surface water and groundwater separately (Barthel, 2014; Staudinger et al., 2019) because they have distinct characteristics from the physics of flow to the contaminant mechanisms. Even though studies focusing on groundwater and surface water are more common today, difficulties continue in addressing both systems holistically (Brunner et al., 2017). This includes the development of methods for detecting and quantifying where, when, and how this exchange takes place (Cook et al., 2018). Groundwater–surface water interaction takes place below the water, sometimes at great depths and, with rare exceptions, invisibly (Duque et al., 2020; Rosenberry et al., 2020). A full range of methods has been developed in the last few decades to track this process, from punctual techniques such as the application of the hydraulic gradient in Darcy's law (Freeze & Cherry, 1979) and seepage meters (Lee, 1977) to more integrative approaches such as radioactive tracers (e.g., radon, Ellins et al., 1990; radium, Burnett et al., 1990). Other tracers that allow researchers to identify the origin of the flow or quantify it are the use of heat (Lapham, 1989) and the detection of stable isotopes of water (Alpers & Whittemore, 1990). These are nonconventional but used increasingly (Schilling et al., 2019). They all provide partial information, but there is still a long way to go before they can directly unravel the frequent problems in detecting and quantifying groundwater–surface water fluxes (Schilling et al., 2017). Many of the difficulties encountered come from the geological complexity of natural systems (Brunner et al., 2017), and while theoretical processes are relatively well known, their implementation in real case studies with high-spatial and temporal resolution represents a technical and scientific challenge (Bouchez et al., 2021). Evolution in the knowledge, methods, and interest in this topic presents an exceptional example of the progress of the state-of-the-art, from the motivation behind the studies to the application of new technologies and techniques that were not initially imagined for this purpose, such as heat transport, remote sensing, radioactive tracers, and stable isotopes of water. Thus, even with the current level of knowledge, there are still many aspects that require further attention and will be an object of study for decades to come.

A review was undertaken of publications related to groundwater–surface water interaction in Denmark published up to the end of 2021. The first reason for carrying out this review is that Denmark has reasonably uniform physiographic characteristics and is of a moderate size, which allows the studies to be compared without differences between approaches or natural settings being too extreme. Second, groundwater–surface water interactions in a flat low-land area with a groundwater table close to the ground surface are found throughout Denmark and, in combination with a wet climate (temperate continental and oceanic, both without a dry season; Beck et al., 2018), generate many examples of these processes covering most regions of the country, despite several sites not being investigated. Third, and maybe most relevant, is that Denmark, after a slow start, has been a very active nation in research in the last few decades using or developing state-of-the-art methodologies and technologies to study the groundwater–surface water interaction. This study therefore also considers the reasons for this increase in focus on the groundwater–surface water interaction.

The objectives of this review were: (i) to present the evolution and state-of-the-art for all the studies completed in Denmark specifically related to the study of groundwater–surface water interaction; (ii) to show and interpret the themes and methods used, the geographical distribution, and links to the geology and physiographic characteristics of Denmark; (iii) to provide an overview of the cross-disciplinary perspectives and opportunities based on the work already developed; (iv) to assess the implications and future perspectives that can be foreseen in the years to come based on the current background; and (v) to specify the lessons learned and the limitations concerning the international status of groundwater–surface water interactions.

2 | CHARACTERISTICS OF DENMARK AND THE RELEVANCE OF ITS GROUNDWATER–SURFACE WATER INTERACTION

Denmark covers 43,000 km^2 and is geographically characterized by a soft topography, where the highest point is 170 m above sea level. It is divided into a continental part connected to Europe (Jutland) and 440 islands of variable sizes, from Zealand and Funen covering 7000 and 3100 km^2, respectively, to much smaller uninhabited islands. The shape of the coast has numerous inlets and outlets that enhance the generation of exchange areas between freshwater originating inland and the sea. These are called fjords locally because of their glacial origin and there are 81 of them that have a wide range of connectivity with the sea, generating implications for fjord salinity, water residence time, and ecological status (Conley et al., 2002).

The climate is coastal temperate, with annual average precipitation ranging between 600 mm (east) and 1000 mm (west). The geology is dominated by the glacial processes that took place in this region during the Quaternary, either with clay till or sandy meltwater deposits during the last two glaciations: the Weichselian, which covered most of Denmark, and the Saale for the south-western part (Houmark-Nielsen, 2011). The differences between these two areas in terms of hydrogeology determine the possibilities for identifying different types of groundwater–surface water interactions. For example, the largest rivers are in south-west Jutland in close contact with sandy meltwater deposits. Below the Quaternary deposits, Tertiary aquifers (sand and limestone), aquitards (clay), and Cretaceous chalk can also have a considerable impact on the hydrogeological processes (L. F. Jørgensen & Stockmarr, 2009). The combination of geology, climatic conditions, and topography generates 69,000 km of water courses in Denmark, most of them only a few meters wide (Danish EPA, 2022).

Denmark has 120,000 lakes larger than 100 m^2. Only 2% of them are more than 1 ha. There are another 75,000 ponds of less than 100 m^2. Most of the groundwater-dominated lakes are also found in the south-western part of Jutland. The high density of surface waters, easy access to most of them (since there are no remote uninhabited areas except for some islands), and the proximity of the water table to the topographic surface provide numerous opportunities and field settings for the study of groundwater–surface water interactions.

The anthropogenic impact plays a significant role in the growing interest in conducting these studies in Denmark. Farmland covers two thirds of the country and the use of fertilizers has resulted in numerous ecological problems in streams, lakes, and coastal waters (European Environment Agency, 2018). Regulations were imposed on the use of fertilizers for agriculture through environmental action plans in 1987, 2000, and 2006, coupled with the establishment of monitoring networks for groundwater and surface waters (Danish EPA, 2022; Miljøstyrelsen DCE, 2017; Svendsen & Norup, 2004). This gave rise to a growing interest in the processes occurring between groundwater and surface water since in-situ biogeochemical processes at the interface between the two domains can reduce nutrients efficiently, triggering the implementation of a national plan for wetland restoration (Land et al., 2016; Miljøstyrelsen, 1998). Presently, the rewetting of lowlands (following drainage in past decades) is on the agenda as a means for reducing CO_2 emissions (Sand-Jensen, 2020).

Thus, Denmark constitutes a study region in itself where groundwater–surface water interactions are extensive, monitoring and field accessibility are relatively easy, and there are strong practical interests in the topic. Considering the country's size, it is likely that this is the region with the highest density of groundwater–surface water studies in the world.

3 | OVERVIEW OF THE TYPE OF STUDIES AND TOPICS

Investigations about hydrology in catchments and groundwater associated with river discharge in Denmark have addressed issues related to agriculture, river flow forecasts, and the impact of groundwater abstraction on surface waters for several decades, starting in the late 1970s and early 1980s (Erup & Jacobsen, 1981; E. Hansen & Dyhr-Nielsen, 1982; Refsgaard & Hansen, 1982a, 1982b). Nevertheless, the study of groundwater–surface water interactions has only received attention from researchers more recently, starting in around the mid-to-late 1980s, as a consequence of the need to understand the links between them. However, research then was mostly targeted at groundwater–stream interactions, and it was not until around 2006 that there was an increase in new studies on groundwater exchange with lakes, fjords, and the sea.

A total of 106 research papers associated with the topic of groundwater–surface water interactions in Denmark (tables in Section S1) were identified. The criteria for defining "What is groundwater–surface water interaction?" were based on the fact that groundwater is a component that is often neglected in studies because it is the most difficult to identify (Lewandowski et al., 2015; Rosenberry et al., 2015). Thus, even though groundwater has an impact in most of the studies focusing on stream research, the studies had to specifically address groundwater to be relevant in this review. This might have led to the omission of studies with a strong focus on surface water hydrology and a biological perspective, especially if these studies did not address the issue of groundwater. Hydrologically, this involves the

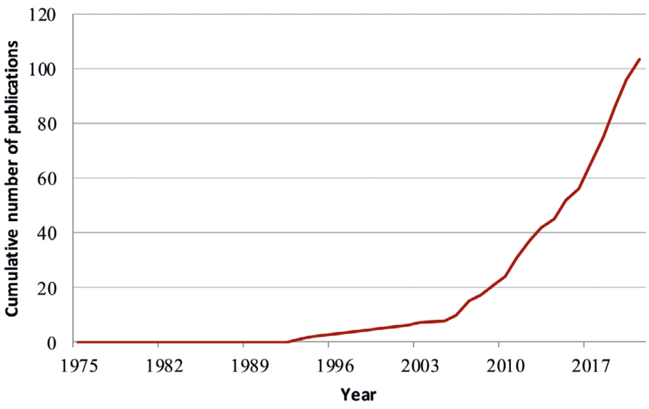

FIGURE 1 Cumulative number of publications related to the topic of groundwater–surface water interaction in Denmark.

exchange of both groundwater and surface water in both directions, even if for the case of Denmark the majority of case studies refer to groundwater discharging into surface water, often with an impact from a hydrochemical perspective. The range of interests in this topic varies from being a strong research focus to a side theme in a discussion of the consequences of groundwater on surface waters or vice versa. Based on the accumulated number of publications (Figure 1), the topic of groundwater–surface water interaction has garnered increasing interest in the research community. The first research papers were published in the mid-1990s and the number continued rising steadily until the mid-2000s, when the trend changed. This is the case internationally too. In the past 15 years in Denmark, 5–10 studies have been published annually, covering new study areas and alternative methodologies or improving general understanding of the physical and chemical processes involved.

These publications were scrutinized to identify patterns regarding the motivation of the study, the natural environment investigated, the scale of work and the methods applied in order to provide a general overview of the type of research undertaken in Denmark in the last 30 years.

3.1 | Classification results

The research topic was quite evenly split among modeling, chemistry, or water composition (involving taking and analyzing samples) and field methods (also including physically based methods such as the use of heat as a tracer; Figure 2). This can be seen as a sign of the parallel development of the state-of-the-art in each category, because each reinforces the others. Thus, monitoring processes by field methods and understanding the chemistry involved help develop more accurate models reproducing the natural systems. The criteria for the different categories are described in the Supporting Information (Section S2).

Within the modeling approaches, approximately half of the publications focused primarily on the groundwater component, while the remainder comprised integrative groundwater and surface water models or other forms of modeling (Figure 2). This suggests that groundwater is often the more unknown element that leads to the use of models to fill the knowledge gap. Most of the integrative groundwater–surface approaches were developed for catchment scales, and they are frequently focused on broader perspectives (e.g., rainfall-runoff) than on the exchange of water between groundwater and surface water compartments. Other types of models cover different tools from a variety of analytical and empirical models quantifying flow and trends in water quality, including hydraulic, hydrogeological and ecological themes.

The most common field method used was Darcy's law based on measured hydraulic gradients and, preferably, measured hydraulic conductivity. The other three methods (seepage meters, heat, and differential gauging) were found equally frequently (Figure 2). The use of differential gauging was less prominent than the other methods, but was related to the topic covered in this review. Time series of stream flow at a few points in a catchment (outlets of subcatchments) were used extensively when calibrating integrated groundwater–surface water models, and the data were often available from national databases. However, this gives little information about the spatial distribution of groundwater discharge to streams such as differential gauging, for example, because this method is best on a larger scale.

Water composition studies showed an even distribution between studies of the fate of nitrate, transport of chemical components (from nutrients to isotopes), and chemical budgets. These studies were selected based on their groundwater–surface

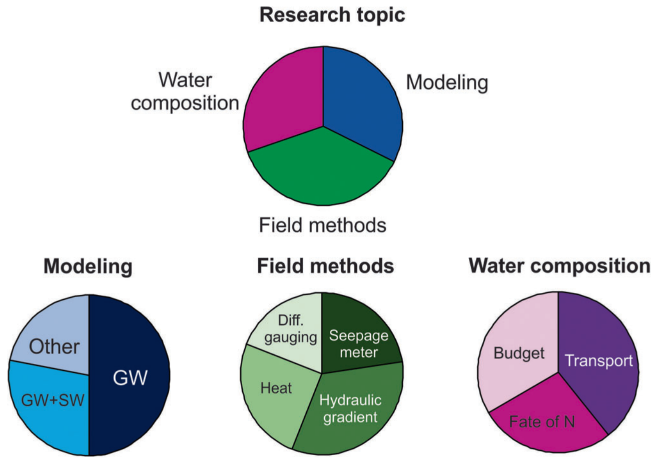

FIGURE 2 Results of the classification based on research topics ($n = 148$), modeling type ($n = 50$), field methods applied ($n = 84$), and water composition ($n = 51$).

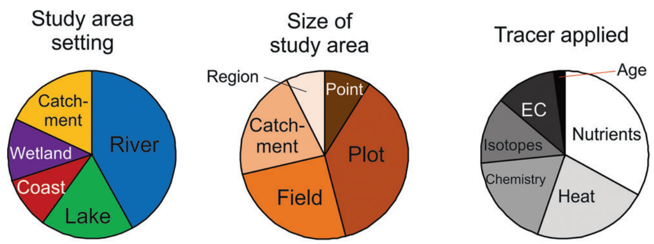

FIGURE 3 Results of the classification of articles by study area setting ($n = 118$), size of the study area ($n = 122$) and tracer applied ($n = 94$).

water interaction implications, and while there is much more literature related to specific biogeochemical processes, detailed laboratory and field experiments, and links between biological and physicochemical interactions, they were deliberately excluded from this review. Overall, this is a field of research with a wide range of perspectives to deal with the excess of nutrients in natural environments, not just in Denmark but also in most countries where there is intensive agricultural activity.

An additional classification for the papers selected was made considering the setting studied, the study area size and the type of tracer, here including any parameter or compound that can be useful for tracking water. The study area setting analysis (Figure 3) indicated a dominance of studies associated with streams, owing to their frequent presence in the Danish landscape and because over the years hydrologists have mostly worked with streams. The study of lakes comprised ca. 20% of the studies, almost double the number of coastal and wetland studies. There were more studies on coastal and wetland settings, but this review relates to publications that have focused on the interaction between groundwater and surface water. Some of the wetland studies could be included in the river category, as wetlands are nearly always associated with streams and/or other surficial currents of water. Catchment was the third most frequent setting.

The scale of work analysis indicated that most of the studies were performed on plot, field, and catchment scales in that order (Figure 3). This seems logical as these are the scales where groundwater–surface water interactions can be assessed and quantified (plot scale) and have a major impact on the hydrology and water quality (field and catchment scales). Often the field scale perspective is required, for example, how lakes are "natural integrators," recording and archiving lake–catchment–climate relationships and where lake water and chemical budgets can be established. Catchment scale studies have stronger implications from a management perspective, as they allow a more integrative and holistic perspective even if details are not included, for example, relating to the spatially distributed interactions of groundwater–surface water exchanges.

From the water tracer perspective, there was a clear dominance of nutrient tracers, such as nitrate and phosphate (Figure 3). These are not conservative tracers, but tracing their changes and reaction products can be a way to investigate sources of groundwater. Furthermore, removal processes taking place at the interface between groundwater and surface water can be investigated and an age assigned to that water. For instance, nitrate was not found in groundwater in Denmark until the 1950s, when the use of fertilizer increased dramatically (B. Hansen et al., 2012). Temperature (heat) as a tracer was the second-most used method, closely followed by stable isotopes of water (^{18}O and deuterium). Despite these having only been used in Denmark in the last 10–15 years, they are well integrated as part of routine investigations nowadays. Electrical conductivity (EC) is especially relevant in coastal area settings as a tracer of seawater. Age tracers (e.g., CFCs, tritium-helium) were only present in a few published articles, probably due to their high cost and technical difficulties when it comes to sampling and analysis.

4 | GEOGRAPHICAL DISTRIBUTION OF STUDIES

Geographically, there is an uneven distribution of groundwater–surface water studies in Denmark (Figure 4). The main islands are less represented than the middle part of the peninsula of Jutland. This is due to geological differences directly linked to the effects of the last glaciation. The western part of the peninsula of Jutland is covered by sandy fluvioglacial sediments, and the eastern part of it is covered by glacial tills separated by the main stationary line where the latest glacial advance in Weichselian ended (Figure 4). Areas with a good hydraulic connection between surface water and groundwater (i.e., sandy regions in central Jutland) are overrepresented compared with areas dominated by clay that are typically drained. Central Jutland was the object of research in long-term projects in the period 2006–2018. It is characterized by the presence of many lakes (called the "high lake area" because many lakes are located near the topographical divide running approximately north–south following the main stationary line) and is of high ecological value. The survey also identified areas with surprisingly few investigations considering their ecological situation and impact: north and south of Limfjorden, the fjord that connects the Kattegat in the east with the North Sea in the west, areas in the south-east of Jutland, and the south of the island of Zealand. In addition, there are several studies on a national/island scale with a regional perspective (i.e., climatic changes, implementation of new regulations in agriculture, and land-use changes).

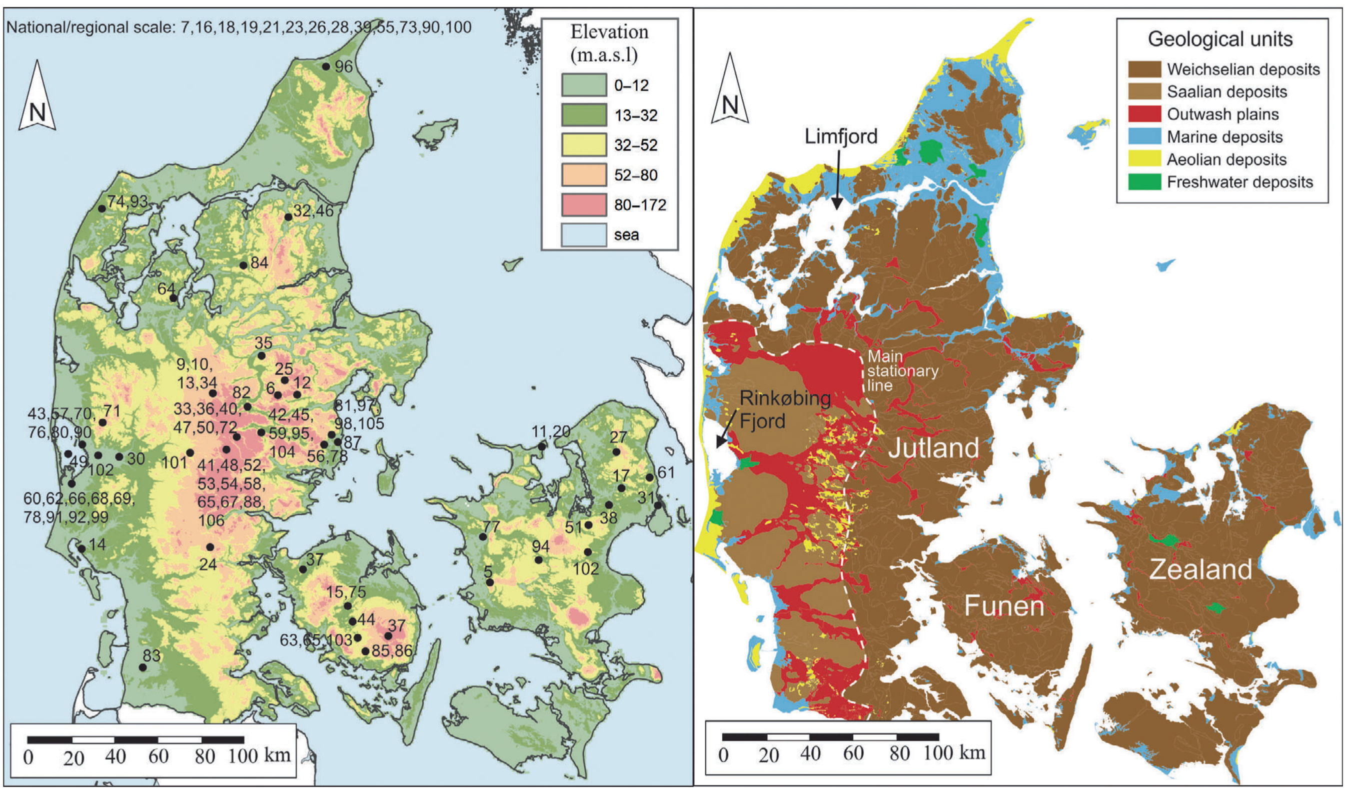

FIGURE 4 Left: Topographical map of Denmark and location of the studies (ID in the tables of Section S1). Right: Geological map of Denmark with topographical names referred to in the text.

5 | HISTORICAL OVERVIEW OF STUDIES

5.1 | 1990s

The first published article specifically focusing on groundwater–surface water interactions in Denmark was motivated by the need to assess the potential of denitrification of riparian zones (Brüsch & Nilsson, 1993). Previous international literature (Gambrell et al., 1975; Jacobs & Gilliam, 1985) had already shown similar potential in aquifers, and the authors combined this knowledge with the influence of flow patterns of groundwater and overland flow in a riparian-wetland area. The site-specific results were extrapolated to similar and extensive areas in Denmark, demonstrating great potential for removing nitrate at this interface between aquifers, riparian zones and streams. They indicated that this potential would change from area to area for geological reasons. At the same time, researchers were interested in how pumping affects stream flow (Christensen, 1994) and in regional groundwater flow to streams (Christensen et al., 1998). These early studies showed the variability in groundwater flow to streams, both seasonally and spatially, using extensive geological information. Iversen et al. (1998) published an overview of the issues associated with nutrients in Denmark in the context of European regulations and actions to combat these problems in groundwater, surface water systems and coastal areas. Some of the implementations were directly or indirectly linked to the processes in which groundwater and surface water interact (i.e., wetland restoration and groundwater protection areas). This highlighted how the management of nutrient issues should consider groundwater–surface water interactions as part of an integral plan to tackle pollution on a national scale.

5.2 | 2000s

The practical implications of studying the interaction between streams and groundwater boosted the analysis of how pumping affects streamflow (Christensen, 2000; Nyholm et al., 2002, 2003). These authors analyzed the hydraulic connection between aquifers and streams and the impact of pumping relative to baseflow. Their application to field conditions was especially relevant since there were no precedents of published studies considering the physical processes in outwash plains in Denmark (Nyholm et al., 2002). All three studies were based on synchronic measurements of flow in the stream as observations to adjust the models. The first comprehensive study of groundwater flow paths in riparian zones was completed by Langhoff et al. (2006). They monitored flow paths from direct groundwater flow through the streambed (seepage meters), stream banks and over-bank flow at several sites along a headwater stream in Jutland. Based on their measurements, they proposed the use of the C ratio (apparent relative width), calculated as the width of the riparian zone divided by the effective stream width (where effective width is stream sinuosity multiplied by stream width). When the C ratio was small, streambed seepage dominated, and when the C ratio was large, groundwater seeped to the surface. Flow patterns were thus linked to landscape and stream geomorphology. While the use of seepage meters to measure streambed seepage has been used continuously by other researchers since the 2006 study, stream bank seepage and overland flow are often neglected.

The first studies investigating the interaction between the sea and the groundwater were completed at this time (M. Andersen et al., 2005; M. S. Andersen et al., 2007; N. O. Jørgensen et al., 2008). They focused on the geochemical impact when seawater is mixed with groundwater. The topics covered seawater intrusion in general and the impact of storm-flood events (M. Andersen et al., 2005) plus the discharge of nitrate to coastal areas (M. S. Andersen et al., 2007). From a methodological perspective, these works developed different sampling schemes and combinations of geophysical and geochemical methods, taking advantage of the impact of the presence of high-salinity water. N. O. Jørgensen et al. (2008) were the first researchers in Denmark to use stable isotopes of water, investigating mixing between sea and groundwater with different tracers. Deuterium and O^{18} have been used intensively and their range of applications has grown considerably since then.

Wetlands were still in focus in this period due to their ability to remove or retain nutrients. These investigations ranged from detailed hydrogeological studies in combination with groundwater sampling to estimate the removal and retention of nitrate and phosphate (Hoffmann et al., 2006) to general overviews of characteristics of different restored wetlands (Hoffmann & Baattrup-Pedersen, 2007). The restoration of wetlands in Denmark started as a national program in 1998 to reduce the load of nutrients to streams (Hoffmann et al., 2004) and included multiple locations all over the country, and therefore provides a unique overview of the impact thanks to intense monitoring efforts.

The first example of the use of heat as a tracer was in 2007 (Pedersen & Sand-Jensen, 2007) in a study that observed that the temperature of groundwater-fed streams was buffered relative to streams where groundwater inputs were nonnegligible.

The different case studies gave way to a more holistic and integrative approach, with the classification of different hydrogeological types based on the degree of connection between aquifers and streams (Dahl et al., 2007). A key element in these typologies is that the type of flow path depends on whether the water flows diffusely overland, directly, or through manmade drainage systems. Large-scale groundwater–stream models were developed during this period, and the impact of climate change was evaluated by comparing the effect on streamflow in two areas in Denmark that have a distinct geology (van Roosmalen et al., 2007). The differences in regional geological characteristics were the main controls of how climate affects streamflow, despite small heterogeneities not being included in these simulations. Another example of an integrative approach was the study of Henriksen et al. (2008) who discussed the ratio between groundwater abstraction and recharge (usually the amount of recharge was considered the amount of renewable water that could be extracted), considering environmental and ecological perspectives relative to streamflow. The study was based on the national-scale groundwater model (Henriksen et al., 2003). Boegh et al. (2009) developed regional-scale models using remote sensing techniques to estimate evapotranspiration linked to runoff in order to identify the variability of streamflow on the island of Zealand, where agricultural activities and drainage systems have a significant impact on the surface hydrology.

The first study investigating the interaction of groundwater with a lake was completed in 2009 (Nilsson et al., 2009) and applied many of the methods already developed for streams. This was also the first time that temperature in lakebeds was measured using heat as a tracer to quantify seepage in Denmark, and it showed a relatively good agreement with other techniques (seepage meters and application of Darcy's law).

5.3 | Early 2010s

Investigation into the effect of wetlands on the fate of nutrients continued, but now over longer periods, and different monitoring strategies were tested (Hoffmann et al., 2011). Additional perspectives were added to this topic, such as the fate of pesticides in wetlands (Kidmose et al., 2010). Groundwater played a fundamental role in wetland water balances and became a requirement when developing nutrient budgets (Hoffmann et al., 2012). In other cases, as presented in Dalgaard et al. (2012) in which six European locations were studied (one of them in Denmark), groundwater can disturb the correlation between nitrogen (N) applied in farming and the content measured in streams.

Publications on groundwater–lake interactions increased dramatically during this period. Lake Hampen in Central Jutland received attention in successive studies since it is a groundwater-dominated lake. The development of a groundwater flow model, supported by different field measurements (seepage meter, water stable isotopes and apparent CFC age-dating of groundwater) and on-land and off-shore geophysical investigation allowed researchers to identify the main areas of inflow and outflow (Kidmose et al., 2011). This was followed by studies on the effects of groundwater seepage on the growth of submerged macrophytes (Frandsen et al., 2012) and studies on nutrient balances in the lake, as this is an oligotrophic lake (Ommen et al., 2012). Local-scale modeling demonstrated how plant cover on the lakebed changed its hydraulic properties and therefore the seepage patterns (Karan et al., 2014b). Other angles of research connected to lake-groundwater studies discussed the role of groundwater on the carbon balance in a lake on Zealand (Staehr et al., 2010) and the focused inputs of phosphorous to a eutrophic lake (Kidmose et al., 2013). Taking a more general perspective, Nielsen et al. (2012) analyzed 210 lakes in Denmark and showed that the impact of non-point sources of nutrients on lake water quality was determined not only by land use near lakeshores, but also by land use in the whole watershed of the lake. Geophysics was also applied in this period to detect, for example, the groundwater discharge to a coastal lagoon, using electromagnetics methods to differentiate fresh water from salty water discharge (Kinnear et al., 2013).

The impact of pumping from aquifers near streams was still an area of focus in the early 2010s as Denmark has a great dependency on groundwater for water supply, and the large number of streams makes it likely that pumping is located close to one. For example, the effects of considering the unsaturated zone during pumping were investigated by S. E. Poulsen et al. (2011). Pumping changes how regional flow discharges to riparian zones and streams (as streambed seepage, drainage, or groundwater-fed surface flow or springs). Johansen et al. (2011, 2014) were the first studies on how groundwater seepage affects fen ecosystems (groundwater-dependent ecosystems). A pumping experiment in a shallow chalk aquifer showed that outflow through springs was reduced, while the shallow water table in the fen ecosystems was relatively unaffected (Johansen et al., 2011) and the effect on vegetation was minimal (Johansen et al., 2014). Many of these studies were supported by numerical modeling. Refsgaard et al. (2010) pointed out that it would be a much more powerful tool for the future of integrated groundwater–surface water management if national databases were merged and the challenge of geological heterogeneity and model uncertainty were addressed.

Several studies from this period take advantage of the use of heat as a tracer. Jensen and Engesgaard (2011) estimated fluxes based on month-long time series of 2 m deep temperature profiles in the streambed, and compared them with seepage meter measure fluxes. Milosevic et al. (2012) used a similar heat-tracing approach and, combined with hydrochemical data, were able to quantify the contaminant discharge to a stream. Karan et al. (2013) used temperature profiling methods to validate seepage fluxes estimated with a 2D numerical flow model. Karan et al. (2014) extended this analysis using a 3D streambed temperature array as a calibration target in an inverse optimization of a coupled flow-heat model. They were able to analyze the dynamic exchange that develops between streams and groundwater during streamflow increases due to rainfall. Sebok et al. (2013) were the first to apply distributed temperature-sensing fiber optic cables (DTS-FO) to identify zones of high groundwater discharge to a lake.

While most of the studies focused on natural environments, one study was undertaken in the urban area of Copenhagen (J. Jeppesen et al., 2011). The authors showed how massive groundwater extraction in this zone decreased the interaction between groundwater and surface waters, but also how natural streams were replaced by pipe systems that can leak/drain depending on the water table elevation.

5.4 | Recent works

In recent years, publications (57 during the period 2015–2021, Table S4) have focused on the development of new methods and optimization of established techniques. These technical advances are divided into three categories—identification and quantification tools, use of water composition, and modeling—and are explained below.

5.4.1 | Identification and quantification tools

The use of DTS as an identification tool has continued. Matheswaran et al. (2015) combined DTS with a 1D stream temperature model along a 1.8 km stream section to identify sections with significant groundwater discharge. J. R. Poulsen et al. (2015) combined DTS with point estimations of fluxes from temperature profiles and differential gauging along a 2.5-km reach of stream with the same objective. Sebok et al. (2015a) added a twist to the use of DTS by being the first to use it to understand dynamic sedimentation-scouring processes in streams. They analyzed the thermal DTS signal and related it to the sedimentation-scouring processes measured by a GPS system. A later study focused on the vertical temperature changes associated with sedimentation erosion processes (Sebok et al., 2017). Typically, for the quantification of fluxes using heat as a tracer, uncertainty in the thermal conductivity is of little concern and a standard value is applied. However, Duque et al. (2016) and Sebok and Müller (2019) showed that thermal conductivity measured in situ can be critical when it comes to obtaining reliable flux estimates. Furthermore, Tirado-Conde et al. (2019) included the effect of heterogeneity in thermal conductivity for inferring fluxes based on temperature profiles. Karan et al. (2017) picked up on the use of stream temperatures as a proxy for groundwater discharge introduced earlier by E. Jeppesen and Iversen (1987) and Pedersen and Sand-Jensen (2007), using a dual-depth method to record temperatures of air, 10 cm below the water level, and above the streambed sediments. They identified sections of the stream where the temperature was buffered by groundwater discharge.

Remote sensing with unmanned aerial vehicles (UAV) has shown promising results with the use of recent technical advantages to map larger areas. Bandini et al. (2017) and Jiang et al. (2020) used a UAV to determine continuously the water stage along a stream which, in combination with an integrated hydrological model, achieved a substantial improvement in the model results to predict spatial patterns of groundwater–surface water exchange. An evolution in the use of drones was presented by Bandini et al. (2021) in a way that determined both discharge and Manning's roughness for several streams in Denmark. Covering extensive areas with low-cost methods is one way of tackling the spatial variability in groundwater discharge to streams due, for example, to spatial and temporal variations in streambed hydraulic conductivity (Sebok et al., 2015b) or local geology in inland catchments (Frederiksen et al., 2018) and coastal waters (Duque et al., 2018).

The development of new devices for measuring flow requires validation and testing in field conditions and a comparison with other established methods. Cremeans and Devlin (2017) developed a new option for measuring groundwater discharge to surface water bodies called the streambed point velocity probe. It was based on a small-scale tracer test using salt. Applications of this system were undertaken to estimate the contaminant discharge to a stream (Rønde et al., 2017) to work specifically with the groundwater–surface water interaction (Cremeans et al., 2018) or quantify differences between this new method and temperature probes, seepage meters and the application of Darcy's law (Cremeans et al., 2020).

5.4.2 | Use of water composition

Water composition is an indicator of the processes and history behind a simple sample; different components of water can be used as tracers. Among the tracers frequently presented in studies in recent years are stable isotopes of water. This is due to the simplicity of sampling, their accuracy and the relatively low cost. Müller et al. (2018) used stable isotopes of water to analyze seasonal dynamics in the interaction between groundwater and a saline lagoon. In the same study area, Duque, Knee, et al. (2019) showed how combining them with sampling of nitrate and phosphate can be used to identify chemical and hydrogeological processes affecting the delivery of nutrients to coastal areas. Carstensen et al. (2016) used ^{18}O and deuterium in addition to ^{15}N to track the impact of controlled drainage on the delivery of nutrients to streams on agricultural land. Hajati et al. (2018) detected flow reversals in the interaction between a lake and an aquifer based on changes in the stable isotopes of groundwater. Engesgaard et al. (2020) used ^{18}O in combination with electrical conductivity to propose a fast and easy method to detect groundwater–lake interactions.

The study of nutrient transport continues to be one of the major reasons for investigating groundwater–surface water interactions, not just to assess the contaminant load to a surface water body, that is, a lake, by combining conservative and nonconservative tracers (Kristensen et al., 2018), but also to quantify the effects of redox conditions in groundwater on the fate of nitrate before discharging to streams (Jensen et al., 2021; Nilsson et al., 2017; Ribas et al., 2017). In the field of wetland restoration, problems due to the release of phosphate are a new concern (Audet et al., 2020). Previous studies on water–ecosystems interactions (Johansen et al., 2011, 2014) were followed by a nationwide survey of relations between vegetation and water level in 35 wetlands, demonstrating that absolute water level and water level variability affect species diversity (Johansen et al., 2018). Anthropogenic effects on the chemical characteristics of water were studied, for example, the implementation of controlled drainage to generate anoxic conditions to minimize the impact on harvest yields (Carstensen et al., 2019), the implications of human-made drain management on stream-riparian zones (Steiness et al., 2019), and the bypass effect of drains or geological conditions (Steiness et al., 2021). Studies specifically focusing on the transport of nutrients and geological characteristics have also demonstrated the preferred methodologies in clay till areas (Petersen, Prinds, Iversen, et al., 2020; Petersen, Prinds, Jessen, et al., 2020).

Groundwater loading of nutrients to surface water is not only associated with the use of fertilizers; geogenic sources of phosphorous in groundwater beneath lakes can also be a problem. This has been demonstrated by numerous studies at Lake Væng, where anoxic groundwater below the lake triggers mobilization of iron hydroxides reduced by organic matter (Kazmierczak et al., 2016, 2021). Lake Nørresø on Funen presented similar problems with phosphate levels in the lake, where the high phosphate concentrations predated the practice of intensive agriculture, thus pointing to a geological origin (Nisbeth, Jessen, et al., 2019). These studies demonstrated how groundwater can play an essential role in the phosphorous budget of lakes, both as a driver for transport and as a mobilization source of P accumulated in the lake sediments (Nisbeth, Kidmose, et al., 2019).

The dynamics of groundwater–surface water interaction also affect the transport of contaminant substances (Sonne et al., 2017) including pharmaceutical compounds (Balbarini et al., 2020). The discharge of contaminants driven by groundwater and its effect on the ecological status have also been investigated (Sonne et al., 2018), as has the natural attenuation occurring before groundwater is discharged to a stream reach (Ottosen et al., 2020), which was undertaken by monitoring a real case study in the area of Grindsted.

5.4.3 | Modeling

Most of the models applied have focused on groundwater or integrating groundwater and surface water, but some additional foci, including ecology, hydrochemistry, and socioeconomics, are starting to appear more often in the Danish literature. The challenge for models reproducing groundwater–surface water systems lies in feeding them with enough relevant information to reproduce the complexity of natural systems. This has sometimes been solved by supporting the model with geophysical information. Haider et al. (2015) studied fresh submarine groundwater discharge (FSGD) using airborne geophysical campaigns to reproduce the inferred salinity distribution, and from that the FSGD. A similar approach was taken by Meyer et al. (2019). Sebok et al. (2018) used off-shore electrical resistivity tomography and ground-penetrating radar investigations to delineate the connectivity between groundwater and a lake.

Applications of models to study the processes associated with groundwater–surface water interaction in more detail have been developed and have many uses. These include quantifying the nutrient load to lakes due to catchment land uses (Kidmose et al., 2015), studying denitrification in groundwater due to seasonal flooding of riparian zones (Jensen et al., 2017), examining the impact of river morphology (Balbarini et al., 2017), analyzing the impact of multiple stressors (industry, urban development, agriculture and climate change) at catchment scale (Kaandorp et al., 2018), assessing the effect of tile drainage on nitrate loading to streams and fjords (A. L. Hansen et al., 2019), evaluating groundwater pumping combining groundwater and surface water models (Molina-Navarro et al., 2018), and assessing the impact on ecology by adding biota empirical models to water flow models (Liu et al., 2020).

Simulating the impacts of climate change on groundwater–surface water systems is challenging as there are uncertainties about what the future climate will look like, but also because changes in the climate can affect the systems themselves. For example, a greater amount of precipitation can generate new stream paths or changes in the groundwater catchments, affecting the definition of boundaries and making them different from current ones. To deal with this issue, assembly of a variety of methods and modeling techniques would be needed to provide reliable estimates of the changes. One option is to take advantage of improved model performance by data assimilation (He et al., 2019) because this increases the accuracy when reproducing systems with strong interactions between groundwater and surface water. Uncertainties in the model design itself are also a theme that needs further exploration. Karan et al. (2021) showed how a change in discretization has a direct impact on the quantification of the groundwater–surface water exchange. This fact might also need to be considered when downscaling models to obtain detailed results (Noorduijn et al., 2021). The prediction of future scenarios also requires consideration to be given to changes in society, as Olesen et al. (2019) showed by using different socioeconomic pathways to estimate the impact of climate change on nutrient discharge to the sea in coastal catchments. Ultimately, the interest in climate change is closely linked to the impacts the climate will have on nature and human activity. A good example of this is the study conducted by Trolle et al. (2015), which estimated an increase in the load of nitrogen and phosphorous in 909 Danish lakes due to runoff intensification, thus triggering several biological processes harmful to ecosystems and human activity. Similarly, Henriksen et al. (2021) simulated the effect of climate change over two hydrological systems and linked them to the ecological quality of fish, highlighting greater uncertainty in biological processes than in hydrological processes.

6 | DISCUSSION

6.1 | Climate change and groundwater–surface water interactions

In the near future, the climate in Denmark will be wetter and warmer. Precipitation is projected to increase by 1.6%–6.9% by 2100 (DMI, 2014) based on IPCC projections (IPCC, 2014). The climate has already become wetter and warmer in the past >100 years, with precipitation increasing by 26%, temperature by 4°C, and recharge and river discharge by 86% and 52%, respectively (Karlsson et al., 2014). In outwash plain landscapes, groundwater fluxes to the riparian zone will increase in the winter and riparian zones will become wetter, probably because of groundwater-fed surface flow to streams dominating direct groundwater seepage into them. This could have a negative effect on wetland buffer efficiency. In addition, more frequent and longer periods of flooding of riparian zones are expected. This will affect the riparian flow path type. For example, Jensen et al. (2017, 2021) have shown that flooding leads to groundwater upwelling near the flood limit and groundwater-fed surface flow to the stream. This can have positive and negative effects on nitrate removal, depending on whether there is a top organic peat layer. If a peat layer is present, nitrate is likely to be reduced quickly in the organic and anoxic layers; if not, then nitrate will be transported to the surface and will reach the stream. Increased winter stream flow will increase erosion of the streambed and sediment material will be deposited downstream, leading to spatiotemporal changes in the vertical hydraulic conductivity of the streambed and thus in groundwater–stream interactions (Rosenberry et al., 2021; Sebok et al., 2015a, 2015b).

The same is true for groundwater-dominated lakes. Fluxes will increase in the winter and water levels will rise. During the summer, fluxes can be low and the lake stage critically low. Lakes in the "high country" can be especially vulnerable to climate change because they are located near the water divide running north–south in the center of Jutland. For example, Hajati et al. (2018) showed that in 2009–2010, when precipitation was well below normal, mainly falling as snow and remaining on the ground without melting for 2–3 months, the water divide moved and so a flow reversal took place. Normally, groundwater discharges to the northern and north-eastern lakeshore, but $\delta^{18}O$ showed that during this period the lake recharged groundwater. Lake stage was close to 0.5 m below normal. The generation of and changes in hydrological water divides (Duque et al., 2011; Winter et al., 2003) are hydrogeological problems rarely considered from a water management viewpoint, but they have significant practical implications, for example, in the transport of contaminants into or out of surface water bodies.

Numerous studies have shown climate change to mainly enhance seawater intrusion and change submarine groundwater discharge patterns as the battle between increased freshwater flux from the regional upland and sea level intensifies (Haider et al., 2015; Meyer et al., 2019; Rasmussen et al., 2013). In the case of Denmark, the potential increase of recharge increasing heads in coastal aquifers could be seen as a natural barrier to sea level rise, but the lowland nature of most of the coastline establishes a limit on this parallel potential protection (Duque et al., 2022) or, as classified by Michael et al. (2013), is topographically limited, being representative of 70% of the coast of the world. Sea level rises (up to 1 m) can also have a profound effect on lakes near the coast. For example, in Lake Tissø during peak sea levels, seawater could intrude through the stream outlet.

6.2 | Ecological processes linked to groundwater–surface water interaction

The study of ecological processes linked to the interaction between groundwater and surface water bodies is one of the drivers of the development in this research branch from early studies pointing to nutrients and their impacts on ecosystems (Søndergaard et al., 1990). Groundwater has ecological roles within aquifers and in ecosystems located close to the discharge zone or water table in lakes, rivers and coastal waters, referred to as terrestrial or aquatic groundwater-dependent ecosystems (GDEs). Ecohydrological studies are increasingly being recognized in international literature dealing with various topics such as: (i) multiscale conceptualization and classification of GDEs (Bertrand et al., 2012); (ii) the ecological function, structure, and classification of connected aquifer-surface water ecosystems (Gilbert et al., 1990); (iii) the impact of climate change on GDEs (Klöve et al., 2014); and (iv) nature-based solutions (Altamirano et al., 2021). There are not many examples of ecohydrological studies from Denmark that take into account groundwater–surface water interaction, even though several groundwater studies are linked to ecological processes and many groundwater systems have a great impact on ecosystems. One of the most significant examples is the research conducted at Lake Hampen, with a strong interaction between biological and hydrogeological studies.

On a national level, in the last few decades Denmark has shown a commitment to restoring lost ecosystems due to past activities. This includes the re-establishment of lakes after being drained to gain land for agriculture, and lake restoration by taking action to increase the quality of water and ecosystems. In the last two centuries, about 70% of lakes and ponds were lost by drainage in Denmark and converted to agricultural land. In the past 25 years, due to greater concern about environmental issues and a desire to increase biodiversity, about 50 large (>10 ha) Danish lakes have been re-established in former lake basins (B. Hansen et al., 2012). Comprehensive studies of a few of these lakes (Kragh et al., 2022; Sø et al., 2020) show that rewetting of drained low-lying organic-rich agricultural areas to wetlands and lakes improves biodiversity and water quality, and changes greenhouse gas emission at the same time (Baastrup-Spohr et al., 2016). Despite the economic impact of losing agricultural land, lake restorations have generated other values such as natural areas for recreation, improved conditions for biodiversity, and reduced nutrient transport to downstream coastal waters (Hoffmann & Baattrup-Pedersen, 2007), which might also be converted into economic benefits. Lakes, and especially wetlands, are often strongly connected with groundwater, but it is not common practice to involve hydrogeological expertise in their restoration. That has sometimes led to short-term action, of lakes and wetlands with significant groundwater inputs of nutrients. This has been the case with Lake Væng, where lake eutrophication due to maintained P loading has been examined since the mid-1980s. Multiple attempts to biomanipulate fish communities in the lake have had a limited effect on the lake's ecological status after a short period (Kazmierczak et al., 2021; Kidmose et al., 2013). The geogenic input associated with groundwater has proven to be a constant input of P that has made biomanipulation activities inefficient in the long term.

Another cause for concern related to ecological processes is the effects of groundwater abstraction on gaining reaches of rivers and groundwater-dependent wetlands, since alteration of the streamflow regime can potentially have an adverse effect (Danapour et al., 2021). It remains unclear whether the magnitude of these changes can be comparable with natural variations (Johansen et al., 2011, 2014), and ultimately it will depend on the amount of groundwater extracted and the hydraulic connectivity between groundwater and wetlands/streams. These studies can also be seen in the context of climate change, as variations in recharge conditions would lead to modifications of the groundwater-dependent ecosystems.

Several studies (Henriksen et al., 2021b; Liu et al., 2020) have combined groundwater models with quantitative ecological tools, aiming to develop integrative solutions. This is a promising technique, despite common uncertainties in model outputs presenting a significant challenge. In other cases, such as Trolle et al. (2015), changing climate conditions (rising temperatures) can be a general indicator of ecosystem changes, assuming that the groundwater–surface water interaction remains the same.

6.3 | From Denmark to the rest of the world

The density and frequency of studies featuring groundwater–surface water interaction in Denmark have generated some useful lessons on methods and technical knowledge (Table 1), but can they be applied to other regions? The physiographic and climate characteristics of Denmark often make the water table proximal to the surface, facilitating sampling and investigation. This relates to the topography, recharge, and hydraulic properties, as has been demonstrated analytically and with spectral analysis for unconfined aquifers (Haitjema & Mitchell-Bruker, 2005; Marklund & Wörman, 2011). Based on these criteria, Denmark would only be comparable regionally with other similar regions (i.e., the east coast of the United States; Gleeson et al., 2011). However, the majority of groundwater–surface water interaction studies conducted in Denmark have been focused on a smaller scale (Figure 3). These studies mainly involve measurements taken at locations where the water table outcrops, such as rivers and lakes (as described by Bresciani et al. (2016)), which are often equivalent regardless of the regional context. Groundwater–surface water interactions are very sensitive to local effects. Peaks of stream discharge can flood areas, changing the interaction with groundwater, but simultaneously the modifications of the recharge vary the groundwater flow and patterns. The establishment of a truly dynamic model considering surface water and groundwater remains a research area that is not addressed very frequently. Two examples of studies that have addressed it are J. R. Poulsen et al. (2015), who simulated the changes in surface water, but kept groundwater the same, and Jensen et al. (2017), who changed groundwater flow, but kept surface water stable for all the simulations. Geology can also have effects on a local scale. Peat layers can have a significant impact both on groundwater discharge (Duque et al., 2018) and nitrate attenuation (Jensen et al., 2017, 2021). These layers are frequently not identified on geological maps as they have small dimensions and when looking at the bigger picture can be viewed as irrelevant or only of local interest, despite their frequent identification. The heterogeneity of aquifer systems is another factor that adds complexity to local studies. Several examples have addressed this issue in Denmark (Duque et al., 2018; Sebok et al., 2015b), but there are many more examples in other regions (Duque, Jessen, et al., 2019; Lewandowski et al., 2015; Schmidt et al., 2006).

Implementing small-scale changes in properties or boundary conditions in groundwater numerical models can be a complex process. The grid size would determine whether these could be inserted (Karan et al., 2021), raising the need for upscaling/downscaling (Noorduijn et al., 2021) depending on the base model used. All these complexities involve solving a key challenge, namely how to integrate local observations into regional models or vice versa: can regional models help in the methodology when collecting local-scale data? Possibilities for data collection are currently being expanded with the use of nonconventional measurements. This set of alternative techniques have been tested with variable results, depending on the characteristics of the local-scale data (Bouchez et al., 2021; Delsman et al., 2016; Schilling et al., 2019). Other modeling advances dealing with data involve computational growth and combining it with information from remote sensing and UAV. Current examples of their application in Denmark (Bandini et al., 2017, 2021) and internationally, along with integration of the information directly into hydrological models (Kurtz et al., 2017; Tang et al., 2018), bring new opportunities to this research field. The integration of these advances will pave the way for the provision of more accessible models, continuously updated and readily applicable by authorities in contexts where the groundwater–surface water interaction has significant societal implications.

One of the issues in the development of integrative models is the availability of data. There is also the possibility that the data may not be available or researchers are unaware of previous studies and that researchers have difficulty reproducing previous models. In this sense, Denmark has a powerful set of tools with which to share and publish information, including a physically based national water resources groundwater–surface water model (Henriksen et al., 2003b) and multiple platforms with databases (such as JUPITER-boreholes and GERDA-geophysics) that include

TABLE 1 Lessons learned and limitations of the study of groundwater–surface water interaction in Denmark applicable to other international settings.

Topic	Lessons learned	Limitations so far	Examples
Climate change and adaptation	• Examples of issues related to increasing water input due to climate change to hydrological systems for nutrients, saltwater intrusion, droughts, and floods	• Uncertainties in the magnitude of the changes in comparison with other human activities • Highly dependent on climate forecast	van Roosmalen et al. (2007) Karlsson et al. (2014) Hajati et al. (2018) Meyer et al. (2019) Olesen et al. (2019)
Ecohydrology	• Ecological and hydrological methods can be combined for cross-disciplinary objectives	• Difficulties in adjusting the scale of work, objectives and terminology for interdisciplinary teams	Johansen et al. (2011) Frandsen et al. (2012) Kidmose et al. (2013) Karan, Kidmose, et al. (2014)
Integrated groundwater–surface water (GW–SW) modeling of water systems	• Powerful for multiple scales from local to regional • High potential in combination with remote sensing and unmanned aerial vehicles (UAV) • Possible to combine with biological models	• Difficulties matching the different scales of work • Problems matching local direct observations	Karan et al. (2021) Bandini et al. (2017, 2021) Henriksen et al. (2021)
Geology's impact on systems	• The regional setting defines the general dominant trends • Regional characteristics hinder comparisons between zones, but local measurements of GW–SW interaction can be analogous • Potential of geogenic pollutions of surface waters (e.g., P)	• Local impacts hinder the identification of general trends • Presence of thin layers of clay and organic matter, frequent in nature, affects the interaction GW–SW	Dahl et al. (2007) van Roosmalen et al. (2007) Duque et al. (2018) Sebok et al. (2015b) Nisbeth, Jessen, et al. (2019)
Hydrochemistry	• Nutrient transport and fate are key topics fostering research into nature-based solutions to deal with anthropogenic contamination	• Multiple scales of work and local processes in a highly heterogeneous setting complicate the definition of well-established protocols of research	Brüsch and Nilsson (1993) Hoffmann et al. (2006, 2011) B. Hansen et al. (2012) Jensen et al. (2017, 2021)
Hyporheic flow	• Barely mentioned in the studies selected for this review	• Lack of applications and examples in the Danish research landscape	—
Stable isotopes of water	• Potential application to multiple natural locations in addition to regional settings • Provides information with high-density sampling too	• Need to be combined with other methods • Uncertainties related to reduced differences for small-scale work	Hajati et al. (2018) Duque, Jessen, et al. (2019) Engesgaard et al. (2020)
Use of heat as a tracer	• A possible routine tool for quick and cheap estimation of discharge flow • Possible to apply at point, plot and field scale	• Uncertainties in thermal properties • Problems as a non-conservative tracer	Nilsson et al. (2009) Sebok et al. (2013) Karan et al. (2014) Duque et al. (2016)

physical and chemical measurements. For example, any new drilling in Denmark, whether for private or public purposes, is required to report and provide drilling samples for analysis to the Geological Survey of Denmark and Greenland (GEUS) in order to update the databases. Moreover, there are programs in place for sampling water quality and monitoring water tables following a FAIR protocol (GEUS, 2022; M. Hansen & Pjetursson, 2011). Data-sharing platforms and integrative publications such as this review, together with the current trend in open-source publications, would increase the opportunity to access data from different fields of research (surface/groundwater, geology/engineering, biological/earth sciences) and promote integrative cross-disciplinary studies.

The use of stables isotopes of water or heat as tracers in multiple studies has facilitated their inclusion as routine tools that are complementary to other methods. In the case of stable isotopes of water, their application has been demonstrated in a wide range of settings, from coastal to lakes in a local context (Duque, Knee, et al., 2019; Engesgaard et al., 2020; Hajati et al., 2018) beyond the more classical regional context (Blasch & Bryson, 2007). The use of heat as a tracer has allowed a high-density assessment of groundwater discharge to be undertaken with several examples (Duque et al., 2016; Karan et al., 2014; Sebok et al., 2013), despite uncertainties about thermal properties. This fact has been also discussed in an international context both for field studies and the modeling of integrative approaches (Bravo et al., 2002; Masbruch et al., 2014), and it has been suggested that while the error is minimal for shallow depths under stream beds (Munz et al., 2017; Schilling et al., 2019), it can have dramatic impacts on regional studies (Delsman et al., 2016). As the studies in Denmark often have a local character (Figure 3), this explains why, despite the intrinsic error of using heat as a tracer, the results are conclusive. Hyporheic flow is rarely a topic of research in Denmark when dealing with groundwater–surface water interaction. This is in contrast to the relevance that has been accorded in previous studies, including review papers (Boano et al., 2014; Conant et al., 2019; Fleckenstein et al., 2010; Lewandowski et al., 2020). This is a surprising outcome, considering that hyporheic flow could have an impact on the conceptualization and results that are frequently obtained in Danish territory. The importance of hyporheic flow to regional-scale surface water–groundwater interaction conceptualization has been shown by Mojarrad et al. (2022), for example, in a regional analysis in Sweden.

Due to the density of studies, the question arises as to whether the study of groundwater–surface water interaction is reaching its limit, as most of the major themes are now well known in Denmark. Nevertheless, in terms of research, improved knowledge of groundwater–surface water interaction has produced the opposite effect. When studies are conducted, more information is available, research infrastructures have already been constructed, and there is increased research interest. In addition, in the last few decades, the majority of the investigations were published in broadly accessible media, which is different from the 1960s and 1970s when many reports remained focused on a local scale, and projects with relevant output were not that accessible or well known. Today, publication in international journals has increased the visibility of and access to information generated even by local projects.

7 | CONCLUSIONS

Studies investigating the groundwater–surface water interaction in Denmark have increased in the last 30 years due to growing interest in this topic. There is a balance between the topics addressed; they are divided equally between field, modeling and water composition themes. The methodologies applied are evenly distributed for field studies with the use of seepage meters, Darcy's law, flow gauging and heat as a tracer, and for the water composition theme with the fate of N, chemical budget and transport. In the case of modeling, there is a preference for the use of standard groundwater models over other more integrative groundwater–surface water modeling approaches. Studies on groundwater–surface water interaction focus more frequently on rivers and streams; in fact, there are twice as many studies on rivers and streams than on lakes or catchments, and four times as many than on coastal areas or wetlands. In the studies for these publications, the dominant size of the study area is on the scale of 10 s m followed by 100 s–1000 s m and catchment studies, which reveals the scale at which the variations of groundwater–surface water exchange are detectable, but also the experimental nature of many of these studies.

Successive research has shown how methods have been enriched and refined, on many occasions driven by the institutional need to safeguard groundwater for human supply and protect natural settings threatened by an excess of nutrients. Currently, the use of temperature, stable isotopes of water and seepage meters are routine techniques, even though research on how to optimize their application is ongoing. Studies in Denmark on the transport, attenuation and discharge of nutrients to surface water bodies by groundwater are a key part of national strategies dealing with the eutrophication of lakes and streams, but the studies are also important sources when it comes to methodology and knowledge at an international level.

The geology of Denmark plays a fundamental role in the general type of interaction between groundwater and surface water. However, even with a clear distinction between the areas dominated by outwash deposits (sandy) and moraine (till), local heterogeneity is one reason to require specific studies for each location. Multiple attempts have been made to systematize the characterization and irregularities of discharge to streams and lakes, but the extrapolation of results to larger areas is still a challenge that needs to be addressed in future. The use of integrative models has provided results that match lumped measurements, but they rarely fit with local observations. The evolution in modeling techniques could change this, due for example to growing computing capacities and increased access to field data.

A future climate will bring different groundwater–surface water interactions, probably leading to a greater need for integrative approaches. The combination of disciplines in Danish studies has primarily taken place in the field of ecohydrology, which merges techniques from different areas of expertise. The combination of hydrological and ecological models emerges here as a promising multidisciplinary task that would require model uncertainties to be decreased on both sides to achieve direct application possibilities.

The use of new techniques and technologies, such as improvements in geophysical data collection and resolution, the use of UAV, cost-efficient applications using heat or stable isotopes of water as tracers, distributed temperature sensing or new devices to quantify groundwater discharge, could offer solutions to persistent problems in the field, and may provide the basis for a new generation of research collecting current knowledge and boosting future studies. Despite all the work undertaken in recent years, challenges in the study of groundwater–surface water interaction remain, not only in Denmark, but also in all the regions in the world where this exchange occurs.

AUTHOR CONTRIBUTIONS

Carlos Duque: Conceptualization (lead); formal analysis (lead); funding acquisition (equal); investigation (equal); methodology (lead); writing – original draft (lead). **Bertel Nilsson:** Conceptualization (supporting); investigation (equal); methodology (supporting); validation (lead); writing – original draft (equal); writing – review and editing (equal). **Peter Engesgaard:** Conceptualization (equal); formal analysis (equal); funding acquisition (equal); investigation (equal); methodology (equal); validation (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

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