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RESEARCH ARTICLE

Saltwater intrusion in Denmark

Intrusión de agua salada en Dinamarca

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ABSTRACT

Key points

Multiple factors that can induce the salinization of coastal aquifers have been found for Denmark

Saltwater intrusion can jeopardize fresh groundwater resources in coastal areas

Questions about the magnitude of these issues and the future perspectives with climate changes are discussed

The studies investigating saltwater intrusion in Denmark have been reviewed to identify the main characteristics and features that have an impact on coastal aquifers interacting with the sea. Traditionally, in regions with wet climate, saltwater intrusion is not appointed as a frequent problem and it is more commonly linked to areas affected by water scarcity. Nevertheless, multiple factors that can induce the salinization of coastal aquifers have been found for Denmark such as the presence of coastal drained lowlands with the water table below the sea level or karstic features and buried valleys in carbonate and detrital systems respectively that can act as preferential flow paths for saline water. Eustatic changes have been also played an important role in the salinization of aquifers, in deep aquifers saline ancient connate water can be identified and in small islands, a delicate equilibrium of freshwater lenses is generated over saline water. As the water supply in this country depends almost exclusively on groundwater, saltwater intrusion can jeopardize fresh groundwater resources in coastal areas. An overview of the cases already studied, questions about the magnitude of these issues and the future perspectives with climate changes are discussed to put into context what is already known and what are the next challenges.

Keywords: Coastal aquifers; Saltwater intrusion; Fractured aquifers; Freshwater lenses; Aerial electromagnetic methods.

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RESUMEN

Puntos clave

Se han identificado múltiples factores que pueden generar la salinización de acuíferos costeros en Dinamarca

La intrusión marina podría poner en riesgo los recursos subterráneos de agua dulce en las zonas costeras

Esta revisión plantea cuestiones acerca de la magnitud de los problemas existentes y las perspectivas considerando cambios climáticos

Se han revisado los estudios que han investigado la intrusión marina en Dinamarca para identificar las principales características que afectan a los acuíferos costeros en su interacción con el mar. Tradicionalmente, en regiones con clima húmedo, la intrusión marina no es considerada como un problema frecuente ya que se suele asociar con áreas afectadas por la escasez de agua. Sin embargo, se han identificado múltiples factores que pueden generar la salinización de acuíferos costeros en Dinamarca como la presencia de tierras bajas drenadas a lo largo de la costa con niveles freáticos por debajo del nivel del mar o el flujo preferente a través de morfologías kársticas o paleovalles en acuíferos carbonatados o detríticos respectivamente. Los cambios eustáticos han jugado también un papel importante en la salinización de acuíferos, en acuíferos profundos se pueden llegar a identificar aguas connatas antiguas y en islas de reducido tamaño, se establece un delicado equilibrio con lentes de agua dulce sobre aguas salinas. Debido a que este país depende casi exclusivamente de las aguas subterráneas para el abastecimiento de la población, la intrusión marina podría poner en riesgo los recursos subterráneos de agua dulce en las zonas costeras. La revisión de casos estudiados plantea una serie de cuestiones acerca de la magnitud de los problemas existentes y las perspectivas futuras considerando cambios climáticos. Con esta revisión se ha puesto en contexto el estado actual de conocimiento acerca de la intrusión marina en el país y se han identificado los desafíos que podría ser necesario acometer en el futuro.

Palabras clave: Acuíferos costeros; Intrusión marina; Acuíferos fracturados; Lentes de agua dulce; Métodos electromagnéticos aéreos.

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1. Introduction

Denmark is the country in the world (except for islands and archipelagos states) with the second longest coastline relative to areal extension (CIA, 2020). The maximum distance from any point in land to the coast is 52 km (Conley *et al.*, 2002). It is also the country in Europe with the highest use of groundwater: water supply and irrigation are based entirely on groundwater (IWA, 2018). In coastal aquifers, fresh groundwater from land meets highly saline groundwater from the sea. An equilibrium between the two water types establishes over long time (Cooper, 1959; Drabbe and Badon Ghijben, 1889), but increasing pumping or changes in climate can disturb this balance and cause saltwater intrusion (Bear *et al.*, 1999; Houben and Post, 2017), making fresh groundwater salty and unusable (Ayers and Wescot, 1985). Once started, saltwater intrusion is lengthy, expensive, and sometimes impossible to reverse (Bear *et al.*, 1999). Because of the proximity to the coast, many valuable aquifers in Denmark could be, in principle, at risk of saltwater intrusion now and/or in the future.

Denmark is characterized by a temperate wet climate with annual precipitation up to 1000 mm with moderate temperatures and incoming solar radiation that do not provoke extreme evapotranspiration. The net recharge is therefore relatively high, and groundwater resource assessments can present a good status regarding the amount of water stored (Henriksen *et al.*, 2003). This is quite different from regions where the climate can be classified as arid or semiarid, where saltwater intrusion is a common process that can take place almost on annual basis because of dry summers. Also, intrusion can be a result of high demand of groundwater for irrigation of crops especially during summer time. Frequent examples of such problems are the Mediterranean regions in Europe (Antonellini *et al.*, 2008; Calvache *et al.*, 2009), Australia (Werner and Gallagher, 2006) north-eastern Australia. A three-dimensional sea-water intrusion model has been developed using the MODHMS code to explore regional-scale processes and to aid assessment of management strategies for the system. A sea-water intrusion potential map, produced through analyses of the hydrochemistry, hydrology and hydrogeology, offsets model limitations by providing an alternative appraisal of susceptibility. Sea-water intrusion in the Pioneer Valley is not in equilibrium, and a potential exists for further landward shifts in the extent of saline groundwater. The model required consideration of tidal overheight (the additional hydraulic head at the coast produced by the action of tides or North America (Barlow and Reichard, 2010). Additional stressors of groundwater resources are the density of population since they require high amount of water in limited spatial extension. This can be applied in Denmark, where the population density is relatively high near the bigger cities. Considering this conceptual framework, it may be assumed that Denmark would have limited issues associated with saltwater intrusion, but a review of the documented cases shows that there are several situations showing well-documented salinization of coastal aquifers. Saltwater intrusion has generated problems for human supply and required advanced monitoring and modelling techniques to anticipate the consequences. The knowledge accumulated during the last decades open the door to know in what circumstances saltwater intrusion processes can be generated in Denmark. Especially considering that climate is far from arid, and the seasonality for water supply and groundwater recharge is not as extreme as in classic touristic destinations. At the same time groundwater management and monitoring is well developed allowing preventive measures.

The objective of this work is to present the different cases in which saltwater intrusion processes have been detected in Denmark and identify those situations that can generate saltwater intrusion issues under the climatic and geographic characteristics of this region. Current and future issues associated with saltwater intrusion will be also discussed.

2. Study area

Denmark has a soft topography dominated by hilly landscapes with low elevations where the maximum height is 170 meters above sea level. The country has a continental part, the peninsula of Jutland (29700 km^2), and more than 400 islands. The size of the islands ranges from the larger islands of Zealand (where Copenhagen is located) and Funen covering 7000 and 3100 km^2, respectively, to small uninhabited islands. To put into perspective, the full extension of the country is 43000 km^2. The climate of the region is coastal temperate with average monthly temperature ranging from -1 °C to 15 °C in winter and summer, respectively. Annual precipitation oscillates from 600 mm to 1000 mm with the highest in the West due to the proximity to the North Sea and a gradual decrease towards the East. The presence of relatively high elevations in the middle of the peninsula of Jutland plays also a role in the distribution of precipitation.

Geologically, most of the country is covered by Quaternary sediments associated with glacial processes taking place until 10000 years ago (Jørgensen and Stockmarr, 2009). This provides a variety of fluvioglacial sediments and tills that can be very permeable when they are dominated by sand and gravels or represent barriers to flow when they are composed of clay (Figure 1A). Below the top Quaternary cover, there is a variety of Cretaceous, Paleogene and Neogene geological materials that can represent aquifers, aquitards or be composed of limestone with or without karstic features (Figure 1B). The thickness of the overlying Quaternary layer is highly variable, from a few meters favoring the generation of karstic features like dolines, springs or karst lakes to more than 400 m (Nilsson and Gravesen, 2018). The regions in Denmark where chalk or limestone are identified below the Quaternary deposits are the North of Jutland, the North and South of the island of Zealand and almost the entire islands of Lolland, Falster and Møn (Fig. 1B).

The combination of climatic conditions and the geological settings generates multiple surface water bodies: 69 000 km of water courses, most of them of small dimensions (a few meters wide), 120 000 lakes larger than 100 m^2 and another 75 000 smaller than this size (Danish Environmental Protection Agency, 2020). Multiple studies have documented the interaction between groundwater and surface-water as the water table is usually very proximal to the topographic surface and the thickness of the unsaturated zone is often not exceeding a few meters.

The shape of the coast of Denmark has numerous inlets and outlets that enhance the generation of exchange areas between freshwater originated inland and the sea. They are locally named fjords because of their glacial origin even if they do not present such dramatic features as the fjords more frequently known in Norway. Along the coast of Denmark, 81 estuaries have been identified with a wide range in connectivity between the sea and salinity, water residence time and ecological status (Conley *et al.*, 2000). Most of these coastal water bodies have a high ecological value since they

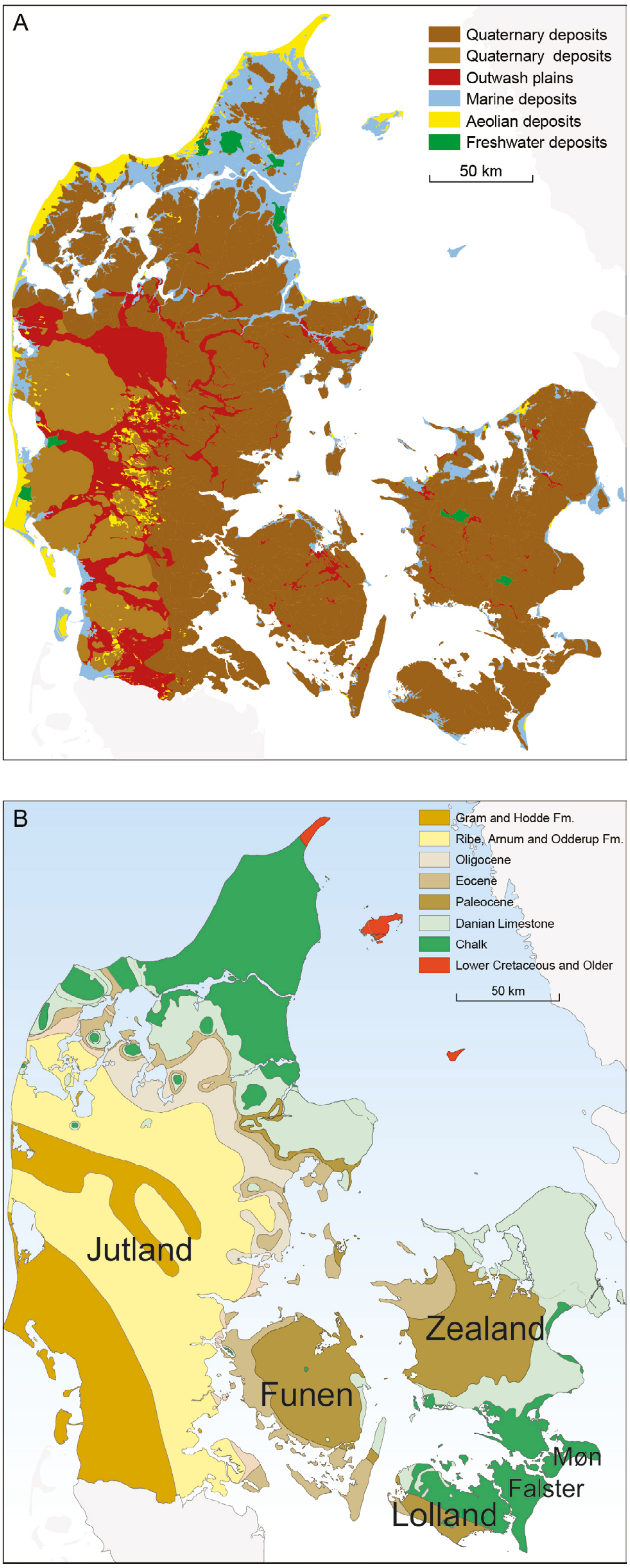

Figure 1. (A) Geological map of Denmark showing the cover of recent sediments and (B) the geology of the pre-Quaternary surface.

Figura 1. (A) Mapa geológico de Dinamarca mostrando la cobertera de sedimentos recientes y (B) la geología de la superficie pre-Cuaternaria.

serve as breeding sites and home for relevant and protected species. The fjords are also highly valuable for society as they represent a significant proportion of the population living along their shores and they are an attraction point for tourism and leisure outdoors activities.

The water supply for the population in Denmark relies almost exclusively on groundwater. The abstracted groundwater is only treated by physical filtering with sand and active carbon filters, and by aeration to remove iron. There is no chemical treatment of the water, neither expectations of doing so in the future and therefore, high quality groundwater in the aquifers is required. This is partially in conflict with one of the major economic actors of the country, the agriculture. The use of fertilizers and pesticides can contaminate groundwater, jeopardizing not only water supply but also ecosystems in streams, lakes and coastal areas. For this reason, strong monitoring programs have been established in the country. In the so-called “particularly valuable groundwater abstraction areas” (Thomsen *et al.*, 2004) that cover approximately 35% of the country, a targeted mapping of vulnerability and protection of the present and future groundwater resources is taking place. Examples of potential measures to obtain the goal are restrictions on the use of pesticides on these areas. A look to the map of vulnerable groundwater abstraction areas (Figure 2) shows how extensive areas of the country are used for extraction of groundwater, generating a challenging task to keep both water quantity and quality in good terms. Additionally, it can be seen how many groundwater valuable resources are located in the proximity of the coastline where saltwater intrusion processes can menace the water quality.

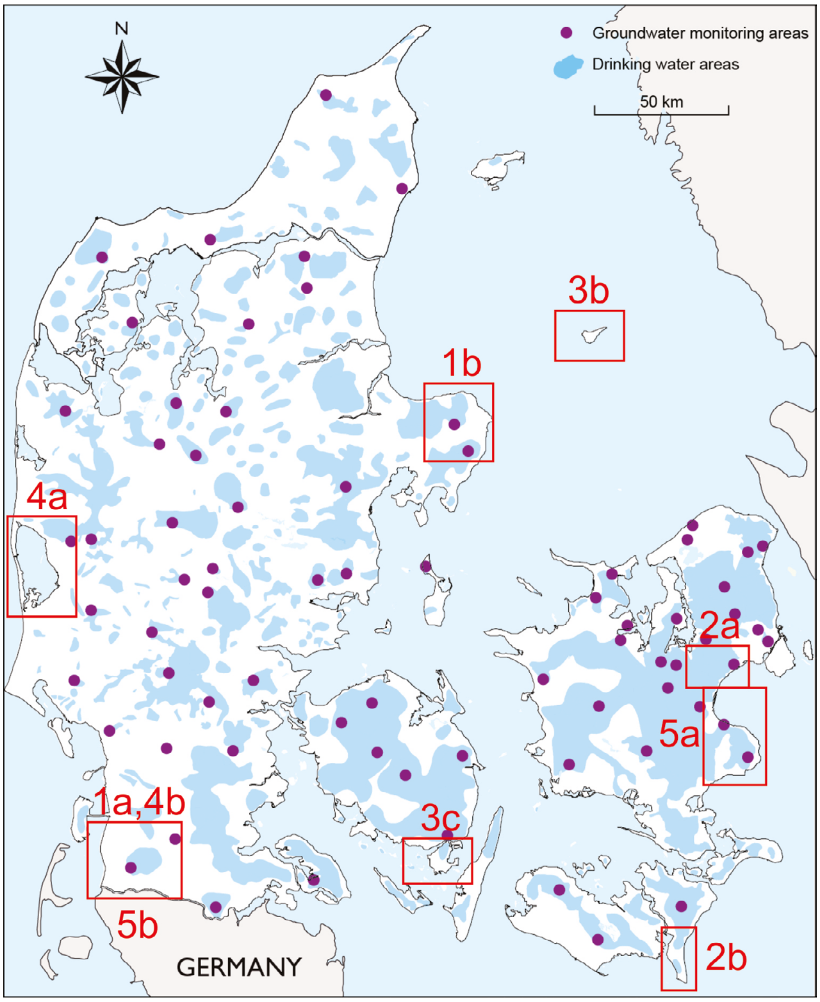

Figure 2. Drinking water areas, groundwater monitoring locations (modified from Jørgensen and Stockmarr, 2009) and locations of saltwater intrusion investigations of this review.

Figura 2. Áreas para uso de agua potable, puntos de control de agua subterránea (modificado de Jørgensen y Stockmarr, 2009) y localizaciones de las áreas que se han investigado en esta revisión sobre intrusión marina.

3. Methods and sources of information applied in studies about saltwater intrusion

3.1. Groundwater databases

Denmark established a national groundwater chemistry-monitoring program in the late 1980s (DGU, 1992) which was implemented in the period after 1989. It is based on 67 groundwater monitoring areas distributed equally across the country and supplemented by six areas from the land monitoring program. More than 1000 screens are sampled for the main constituents of the groundwater including chloride, while 864 are suitable for analysis of special parameters such as inorganic trace elements, pesticides and other organic micro-contaminants. The chemical analysis is carried out between one and four times a year depending on the substance type. Despite being functioning for decades, it is frequently updated to keep track of emerging challenges associated with groundwater (Jørgensen and Stockmarr, 2009). This information is often the starting point of any research relating to the salinity content of groundwater. The availability of this information and the length of the time series has allowed the study of trends and changes in different coastal aquifers.

In 2007 a national monitoring network with approximately 150 observation wells was established. The program was primarily based on existing wells with time series reaching back to the eighties for most wells while a few contain data from the fifties. Hydraulic head has traditionally been observed manually but in recent years loggers have been installed and the water level is now observed daily or more frequent. The evolution of the groundwater elevation relative to the sea level is another indicator that can be analyzed in these time series.

3.2. Airborne electromagnetic (AEM)

One of the main sources of information in Denmark about saltwater intrusion, is the data collected with electromagnetics surveys. Several systems have been developed (Sorensen and Auken (2004), and others) that allow the collection of high resolution information about resistivity of the underground but also covering extensive areas since the equipment is flown by helicopter. Most of the information is directly available after being used in a free accessible geophysical database (GERDA, 2020). As the presence of saltwater has a strong impact on the resistivity, the information provided by AEM has been an essential input to studies confronting saltwater intrusion.

3.3. Numerical modelling

The use of numerical models is one of the most common tools in the study of saltwater intrusion. Often it is required to forecast the consequences under different water management scenarios and to identify solutions to water conflicts between the requirements of society and the sustainability of the resources. Models can also be used to infer the distribution of saltwater as the information about coastal aquifers at high depths, where saline water is dominant, is frequently scarce due to the lack of practical use of saltwater. Numerical models with high density of geological information have been applied in Denmark with advanced calibration techniques implemented to deal with the amount of geological units and to estimate the uncertainty of hydraulic properties.

4. Results

Several documented cases of saltwater intrusion have been identified in scientific literature. Additionally, a few situations reported by local media due to the risk for water supply have been analyzed. Overall, they have been classified into five categories depending on the main reason attributed to the presence of saltwater along the coast of Denmark. These include: Lowlands and surface elevations below sea level, fractured (karstic) coastal aquifers, freshwater lenses on small islands, buried valleys as preferential flow paths for saltwater and salinity associated with ancient processes as eustatism and connate waters. Each of these categories have been explained and assessed based on previous studies.

4.1. Lowlands and elevations below sea level

Coastal areas occupied by marshes have been drained during the last centuries to gain agricultural land not only in Denmark but also in other regions. This required advanced engineering plans with construction of infrastructures like drain ditches, dikes and systems to evacuate water from low lying areas, even below sea level, to the sea. It was needed to drain the water but also to keep the water table below the land surface elevation allowing at least a thin unsaturated zone to facilitate the growth of crops. The benefits of these activities in Denmark were not only because of the development of new farmland but also because these areas often had a high content of organic matter resulting in high productivity. However, the proximity to the sea and the low water table maintained by human-made engineering can generate inverted hydraulic gradients resulting in sea water encroaching towards land. There are several examples of these practices in Denmark and the resulting seawater intrusion problems have been documented in at least two locations, in the South-West of Jutland sharing partially the issue with Germany (Figure 2, 1a) and in Kolindsund, in the East of Jutland, near to the city of Grenå (Figure 2, 1b).

4.1.1. South-West Denmark

This area (Figure 2, 1a) was converted into a drained marshland as a result of successive dike and drained system constructions in the last 500 years (Jacobsen, 1964). Around 300 km^2 were reclaimed to the land, and part of the area is below sea level. Currently, there are numerous pumping stations that lift the water from the drainage channels to the major river (Vidaa River) that routes the water to the North Sea (Jørgensen *et al.*, 2012). Based on extensive geophysical surveys with AEM and seismic profiles, it was possible to define the hydrogeological characteristics of the region and to identify saltwater at quite far distance from the sea border, up to 20 km (Jørgensen *et al.*, 2012). The effect of geology provokes an irregular distribution of salinity with depth showing complex patterns that requires the analysis of groundwater flow in the region. Contrary to the apparent geological homogeneity observed in the surface of the study area with only Quaternary sediments (Figure 1), there are quite a lot of heterogeneity at depth that plays an important role on the salinity distribution with faults, buried valleys and glaciotectonic complex with irregular distribution of materials.

Subsequent studies using advanced numerical modelling techniques combined with calibration of multiple parameters allowed a physical explanation of the regional flow system and the role of geological features for the advance of the salt water intrusion found in the region (Meyer *et al.*, 2018a, b). The authors concluded that the region is overall divided into two flow systems with depth, a shallow Pleistocene part and a deeper Miocene part separated by an aquitard. The two flow systems are connected by buried valleys with high hydraulic conductivity generating the mixing of waters circulating at different depths. The connection between the deep and the shallow systems allows the groundwater to flow to the surficial aquifer and from there it is captured by the drainage system, instead of emerging as fresh submarine discharge to the sea (Figure 3).

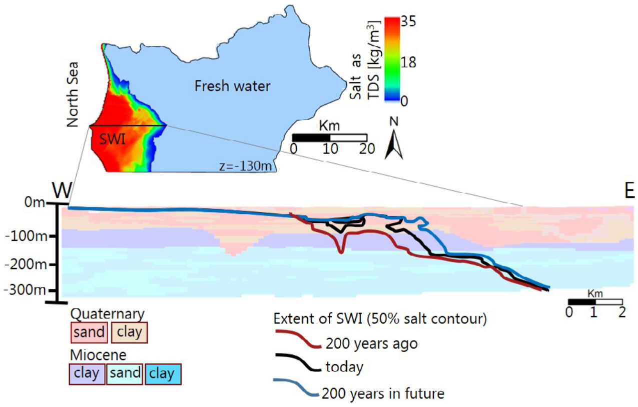

Figure 3. Saltwater intrusion in the South-West of Jutland. Top: Simulated horizontal extent of the salt water intrusion today at a depth of 130m (salt concentration as total dissolved solids). Bottom: Cross section with simplified geological information and simulated results of saltwater intrusion delineated at the 50% salt water contour for today and considering past and future climate changes.

Figura 3. Intrusión de agua salada en el Suroeste de Jutlandia. Arriba: Simulación de la extensión horizontal de la intrusión marina actual a una profundidad de 130 m (concentración de sal como total de sólidos disueltos). Abajo: Sección con información geológica simplificada y resultados simulados para intrusión marina (línea 50% de agua salada) para la actualidad, y considerando cambios climáticos pasados y futuros.

4.1.2. Kolindsund

Kolindsund was a narrow and elongated fjord and subsequently a lake close to the sea in the East of Jutland (Figure 2,1b). During the 19th century, a plan was designed and later executed after several decades of infrastructures construction for keeping the 26 km^2 area dry (Figure 4). The agricultural production in the new land has been very successful since then. Due to a combination of drainage and subsidence of the area, parts of its land surface are located up to five me-

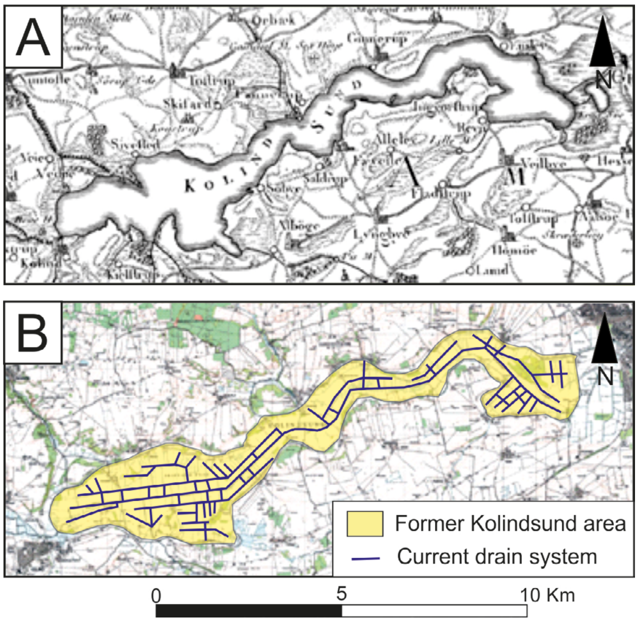

Figure 4. (A) Old map of Kolindsund, and (B) final cartography after implementation of the drainage system. The present coast line is situated approximately five kilometers to the east of Kolindsund. Modified from Hansen (2011).

Figura 4. (A) Mapa antiguo de Kolindsund y (B) Cartografía final después de la implementación del sistema de drenaje. La línea de costa actual está situada aproximadamente a 5 km al Este de Kolindsund. Modificada de Hansen (2011).

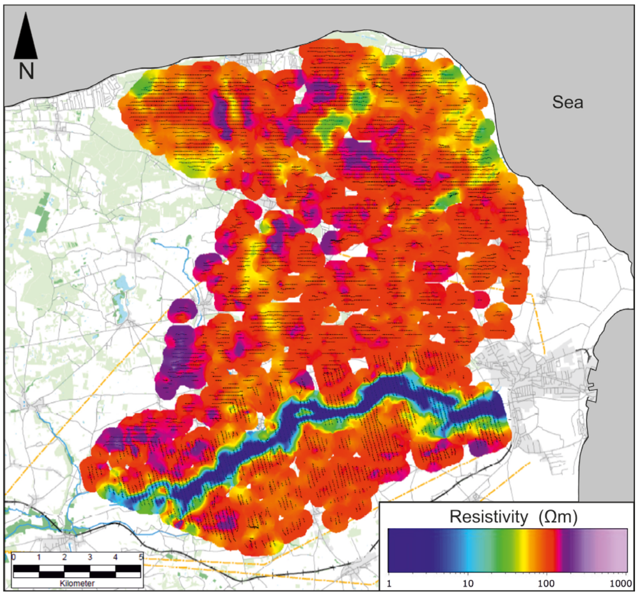

Figure 5. AEM survey results at 10 – 20 m below sea level. Blue colors indicate low resistivity that coincides with the area occupied by Kolindsund. Modified from Thomsen (2018).

Figura 5. Resultados de campañas con vuelos electromagnéticos a 10-20 m bajo el nivel del mar. Los colores azules indican baja resistividad que coincide con el área ocupada por Kolindsund. Modificada de Thomsen (2018).

ters below sea level. Because of the proximity of the coastline, this could generate saltwater encroaching from the sea. AEM surveys indicated that low resistivities were located in those zones of the aquifer below where the lake was located (Thomsen, 2018) that can be associated with the presence of saline water (Figure 5). Additionally, karstic features found in the limestone formations located beneath a thin Quaternary layer, connected deeper with more surficial sectors and showed increases in salinity.

4.2. Fractured aquifers

The existence of karstified aquifers in which preferential flow paths and conduits facilitate fast groundwater movement has been documented in Denmark (Nilsson and Gravesen, 2018). Specifically, karst features have been identified in those areas where the Quaternary cover is relatively thin resulting in an easier interaction between the surface and the groundwater in the carbonate aquifers. Many of the regions identified are in the proximity of the coastline and it is estimated that they provide about one third of the water supply in Denmark. In karstic systems, groundwater movement patterns can response faster to pumping and recharge conditions (Johansen *et al.*, 2014). Hence, this is another of the natural settings that can favor the generation of saltwater intrusion processes when combined depression of water table such as groundwater abstraction and the formation of drawdown cones. This problem has been reported in at least two study areas in Denmark: Greve, on the island of Zealand (Figure 2, 2a), and on the island of Falster in Southeast Denmark (Figure 2, 2b).

4.2.1. Greve

The study area is located South-West from Copenhagen (Figure 2, 2a) where groundwater is abstracted from chalk and limestone aquifers from the Late Cretaceous and Paleocene, respectively (Thorn, 2011). The pumping of groundwater started in the 1930's and increased continuously until the 60-70's when some wells started to present salinization problems. As a result, wells closer to the shore were replaced by other wells located more inland. In this area, the limestone and chalk aquifers are situated below a layer of 10-50 m of clayey till with lenses of sand and gravel. Groundwater is abstracted from the carbonate systems instead of the surficial geological layers that would not provide enough water. Most of the wells are located just a few kilometers from the sea. The pumping activity has generated depression cones in the water table during prolonged periods of time, often below the sea level. Historical data showed how the areas where these depression cones where located, coincided also with high chloride content. As the management of groundwater replaced the extraction wells affected by salinization, different depression cones were generated and their locations correlated well with the identification of high salinity in groundwater (Thorn, 2011).

In this area, an additional problem was identified as a source of salinity. Connate waters at high depths have high salinity and it has been suggested that diffusion can be the mechanism bringing saltwater to shallower layers (Bonnesen *et al.*, 2009). Thorn (2011) completed a geochemical analysis deciphering the main source of salt considering the effect of saltwater intrusion and the diffusion from deep layers assuming the different chemical processes that would be triggered in each case. In the area of Greve, Thorn (2011) concluded that based on geological reasons, the southern part is likely to be affected by seawater intrusion and therefore a more intense monitoring is recommended as this process can be relatively fast. Meanwhile in the northern section, the diffusion can be a more predominant factor. This study area is a good example of the different elements required to be considered when addressing saltwater intrusion processes. Geology plays an important role, but anthropogenic activity can generate faster changes and transient scenarios. While the source of salinity is usually associated with the sea in coastal areas, it is always required to check other potential sources of salt.

4.2.2. Falster

The study area is defined by a barrier island located in the southern part of the island of Falster (Figure 2, 2b). The geological configuration is similar to the one presented for the case of Greve, with a variable thickness (10-50 m) of Quaternary top layer composed of clay till with some non-continuous layers of sandy sediments and a lower continuous chalk aquifer, where the groundwater is abstracted for domestic use (Rasmussen *et al.*, 2013). This region presents a fast development in the last 100 years with the construction of summer houses and settlement of people living year around just in the last decades. This has increased the demand of high-quality groundwater. The region has also been modified by anthropogenic activity in the last 200 years including the construction of dikes to prevent the connection with the sea in the inland lagoon, the drainage of the lagoon and the construction of drain channels. Saltwater was located at both sides of the barrier island, and a cross section of the salinity distribution showed a thin lens of freshwater over saltwater as identified by AEM. Rasmussen *et al.* (2013) simulated the effects of climatic changes for the following 100 years together with the expected modifications in water supply to identify the areas with higher risk. They confirmed the pattern depicted with the electromagnetic methods, evaluated the equilibrium-transition status caused by land use changes and groundwater abstraction, and discussed the parameters sensitivity in the study area for future saltwater intrusion processes.

4.3. Small islands

On the islands of Denmark, groundwater is the only water resource for the supply of local communities and irrigation. As the islands are surrounded by saltwater, the infiltration of precipitation generates freshwater lenses floating above the saltwater. Because of the low surface elevation of the islands, the lenses have limited thickness and that links directly to the capacity to store freshwater. In the smaller islands of Denmark like Samsø (Figure 2, 3a), Anholt (Figure 2, 3b) and Drejø (Figure 2, 3c), saltwater intrusion is frequent during dry periods generating serious problems for the water supply (i.e. Alström and Nielsen, 2018; Kokkegård, 2018). These dry periods do not need to extend for years, an unusual dry summer, coinciding with the touristic high season associated with higher water demands, is often enough to challenge the management of the water supply. Therefore, these hydrogeological systems are highly dependent on the climatic regime and can be very sensitive to changes in the pumping procedure inducing saltwater intrusion.

A good example of this is the study carried out on the island of Drejø by Sorensen *et al.* (2001). They combined electromagnetic methods with information collected *in situ* about lithology and hy-

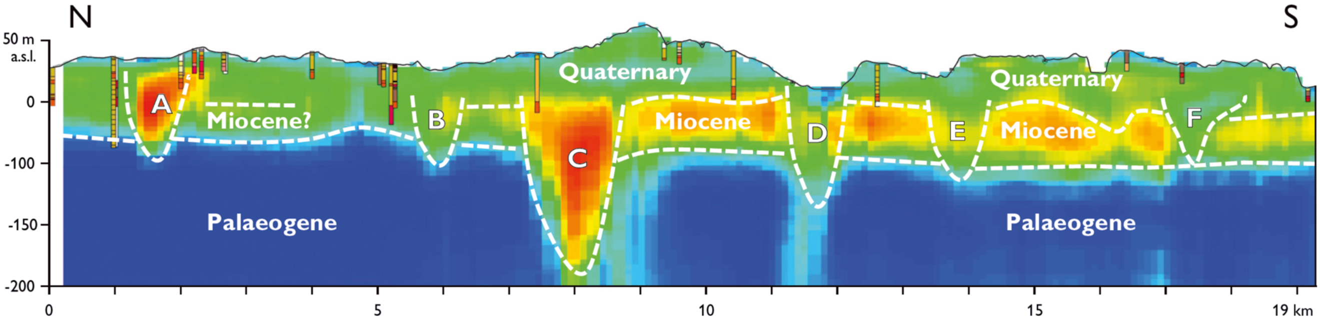

Figure 6. Geological cross section where several buried valleys can be identified (A to F) in contrast to the surrounding geology based on AEM data. From Sandersen and Jørgensen (2017).

Figura 6. Perfil geológico en el que varios paleovalles enterrados pueden ser identificados (A hasta F) por el contraste con la geología que los rodea basado en datos aeromagnéticos. Figura de Sandersen and Jørgensen (2017).

drochemistry to identify the different aquifer units, evaluate the connectivity with the sea and determine the degree of contamination in the different aquifer layers. This study was carried out as a response by the authorities to the decrease in the water quality supply detected early in the 90's, with the aim to improve the management strategies. The island has an extension of 2.5 km^2 and is inhabited by 80 people in winter and up to 300 during summer and commonly presents other groundwater problems associated with intensive agriculture (Sørensen *et al.*, 2001).

4.4. Buried valleys

Buried or incised valleys are very common geological structures in the subsurface of Denmark (Sandersen and Jørgensen, 2017). They have elongated shapes and are differentiated by the surrounding geology because of different and younger sediments carried by meltwater under ice sheets (Sandersen and Jørgensen, 2017). Their dimensions are frequently ranging between 500 to 1500 m in width while they can reach 25-30 km in length. The depth is variable but they have been identified up to 400 m below the land surface. Buried valleys are very frequent, 5600 km have already been located (Jørgensen and Sandersen, 2006) but it is expected that up to 13000 km could be identified if its study continues (Sandersen and Jørgensen, 2017).

The connection between saltwater intrusion and buried valleys roots on the different hydraulic properties of these channels compared to the surrounding geological materials (Figure 6). The younger infill sediments represent preferential flow paths that can work either for freshwater discharge at equilibrium between the freshwater elevation and the sea, either for the encroachment of seawater when there is an imbalance between freshwater and saltwater heads.

The effect of buried valleys could be present in any study area in Denmark, but as a result of their dimensions and sedimentary infill, they can be better identified in studies covering extensive areas supported by AEM data. Two examples of saltwater intrusion enhanced by buried valleys have been identified: Ringkøbing Fjord (Figure 2, 4a) and the South-West of Jutland (Figure 2, 4b).

4.4.1. Ringkøbing Fjord

Kirkegaard *et al.* (2011) especially considering that the amount of available information is often very sparse relative to the size of the area and the complexity of the problem. We used geophysical transient electromagnetic (TEM focused on the detection of fresh-groundwater discharge to a coastal lagoon as part of the study of the water balance in the catchment of the river Skjern (Jensen and Illangasekare, 2011). The lagoon has an extension of 300 km^2 and therefore, methods covering large areas were needed. In this case, the authors used 350 km of AEM lines. The results showed differences when moving downwards in the aquifer systems below the lagoon. In the shallowest layers, the highest resistivity is located in the inland part while in the area covered by the lagoon, the resistivity is low (Figure 7). This was logically interpreted as freshwater inland and saltwater offshore in the lagoon. Interestingly, at deeper locations, 60-70 m below the sea level, additional high resistive features were identified in the proximity of the lagoon shore (Figure 7) due to a different geological filling of a buried channel and/or the flow of freshwater

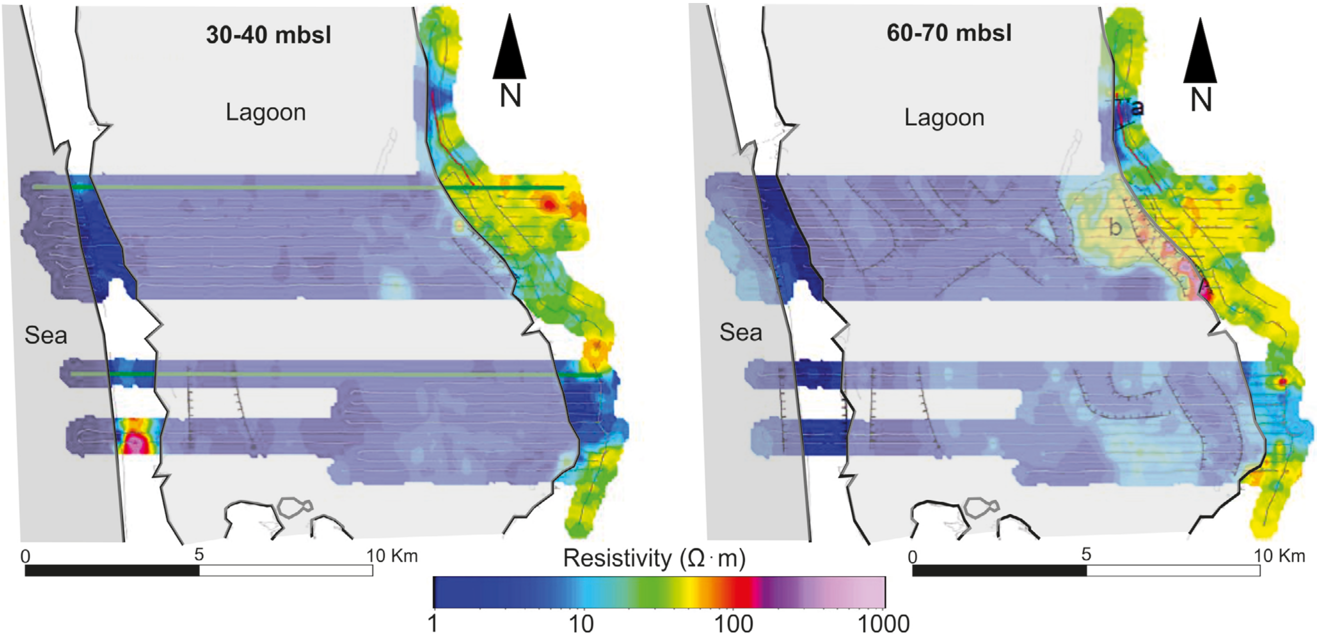

Figure 7. AEM results for different depths in Ringkøbing Fjord. Blue areas indicate low resistivity that can be produced by the presence of saltwater while yellow and green colors represent high resistivity that could be due to freshwater presence. Modified from Kirkegaard *et al.* (2011).

Figura 7. Resultados aeromagnéticos para diferentes profundidades in Ringkøbing Fjord. Las zonas azules indican baja resistividad que podría ser generada por la presencia de agua salada mientras que colores amarillos y verdes representan resistividades altas que podrían deberse a la presencia de agua dulce. Modificado de Kirkegaard *et al.* (2011).

through them. It is possible to correlate the presence of buried valleys saturated with saltwater, as they would have lower resistivity than the surrounding materials. The buried valleys can therefore act as preferential flow paths for fresh or for saline water simultaneously. Deeper in the system (100-160 m below sea level), it is possible to identify higher resistivities, probably associated to freshwater flow below higher salinity layers (Figure 7). The changes of resistivity are not gradual with sharp lateral changes that can be also indicative of the effect of heterogeneous hydraulic properties when buried valleys are present. This was the first study, where such high depths were reached with AEM, in a situation with the additional difficulty of the saltwater presence of the lagoon in the surface, and required several technical innovations in the data acquisition and processing.

Haider *et al.* (2015) used these geophysical results to verify and test different hydrogeological hypotheses by using a variable density groundwater model. The presence of confining layers at variable depths, and the discontinuity of some of them, was considered the main conditioner for the salinity distribution identified with geophysical methods.

4.4.2. South-West Jutland

Jørgensen *et al.* (2012) studied an area of 730 km^2 based on an airborne electromagnetic survey combined with other information such as lithological columns, seismic surveys and hydrochemical sampling. In this case, the buried valleys were potentially filled up with either sandy sediments or clay till producing clear differences in the resistivity detected with the airborne methods (Figure 8). To identify the saltwater, it should be verified that the valley was filled up with sandy sediments to associate the decrease in resistivity with the presence of saline water. This study shows how the geological heterogeneity, specially associated with the buried valleys, determines the way that the saltwater intrusion takes place and also the methods and approaches interpreting the geophysical results. These geological and geophysical investigations were later used as input and validation data for the density driven groundwater flow study by Meyer *et al.* (2019) highlighting the importance of buried valleys both for freshwater discharge either to the sea or the drainage area and preferential flow paths for seawater intruding the fresh groundwater resources from the ocean boundary.

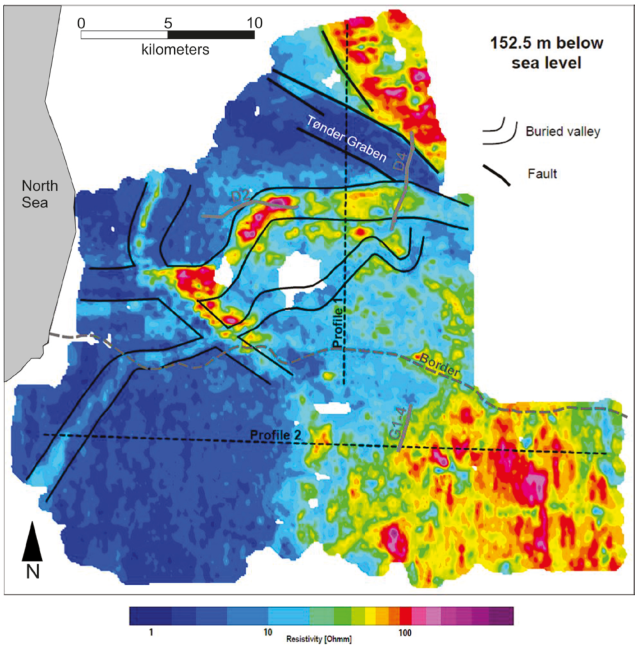

Figure 8. AEM resistivity measurements at 32.5 m below sea level and distribution of buried valleys. Modified from Jorgensen *et al.* (2012).

Figura 8. Medidas de resistividad aeromagnéticas a 32.5 m bajo el nivel del mar y distribución de paleovalles enterrados. Modificada de Jorgensen *et al.* (2012).

4.5. Connate waters and saltwater intrusion associated with eustatic changes

In the study of saltwater intrusion in Denmark, there is an additional sourc e of salinity that has to be often considered, especially when working in deep aquifer systems. Several studies detecting saltwater at larger depths, hypothesize about the possibility that saline water was not belonging to current seawater intrusion processes but from previous climatic stages or as connate water that has not been flushed yet.

4.5.1. East-Zealand

Bonnesen *et al.* (2009) studied regional chalk aquifers in North-West Europe focusing on the high salinity that is measured in these aquifers. Using the information collected at deep boreholes and a numerical 1D diffusion model, the mechanism and the velocity of the processes that explain the salinity distribution pattern was explored in East Zealand (Figure 2, 5a). The use of a simple 1D model was considered because the flow was so small that diffusive transport was the dominating mechanism. This approach is well suited for situations where dense saltwater is located at low permeable formation below a high permeable aquifer where saltwater is flushed. The investigation was supported by simulations using the two-dimensional flow and transport model FRACTRAN (Larsen *et al.*, 2004).

4.5.2. South-West Jutland

Meyer *et al.* (2019) developed a numerical model with variable density to simulate the processes that took place in the South-West area of Jutland that is heavily salinized (Figure 2, 5b). Continuous eustatic and land use changes make difficult to establish the initial conditions for salinity distribution. For that reason, a model covering the last 4200 years was developed. The changes involved the transgression of the North Sea associated with an interglacial period, the modification of the recharge as a result of climatic changes and several anthropogenic modifications of the surficial water system that have been described above. The simulation matched the saltwater intrusion extent (to depths of 200 m-330 m at almost 20 km inland, Figure 3) observed by AEM and were consequently used to predict the saltwater intrusion development in the future 200 years using climate change scenarios considering eustatic changes (sea level rise by 85 cm over 200 years) and changes in recharge. The results showed the intensification of the salinization of the groundwater resources in the area (Meyer *et al.*, 2019) (Figure 3). The authors concluded that the salinity distribution did not reach an equilibrium during the 4200 years simulation and that the present saltwater could be still a remnant from postglacial sea level rise a few thousand years ago. This is also supported by low ^{14}C content indicating old groundwater ages (Meyer *et al.*, 2018b).

5. Discussion

The potential relevance of the knowledge on saltwater intrusion processes in Denmark is justified based on its physiography and the high dependence on groundwater resources for human supply. Many of the areas where groundwater is abstracted are located in the proximity of the coast (Figure 2) where the depression of the water table can induce the encroachment of saltwater. However, there are other reasons that should be considered in this analysis. The low surface elevation and the presence of former wetlands and near-coast lakes that were drained in the last centuries have generated extensive areas with groundwater levels below sea level where salinization can be detected. One question that has been locally addressed in South-West Jutland by Meyer *et al.* (2019) is if the effect of the drainage activity is already at equilibrium, that means, is it in its maximum extension, or if there is a possibility that the saline front is still continuously moving inland. The human intervention in coastal region have been taking place in a relatively short period (~100 years) while the movement of groundwater is a slow process that might not reach an equilibrium until longer period of times. This problem of developing groundwater models in areas where saline groundwater likely has not reached an equilibrium, has been also presented in previous studies in other regions like the Netherlands (Delsman *et al.*, 2014) and Spain (Duque *et al.*, 2019c). These studies also provide an idea of the long-term changes that are often overlooked when changing natural systems. The study conducted by Meyer *et al.* (2019) in the South-West of Jutland shows that the system is still in a transient condition and therefore, the position of the saltwater-freshwater interface will still keep moving in the following decades even if no additional changes take place in the study area.

Additional sources of uncertainty are the different origin of saltwater in Denmark. It has been demonstrated that at depths beyond a few hundred meters in chalk aquifers, there is saline water associated with the origin of the water and old geological processes (Bonnesen *et al.*, 2009). Other sources of salt in groundwater are the presence of diapirs in North Jutland (Sørensen, 2012) or the salting of roads to avoid icing during winter (Kristiansen, 2012). These alternative sources of salt have to be considered when developing new studies on saltwater intrusion.

In a geological sense, for the study of saltwater intrusion along the coast of Denmark, the two major conditioners are the heterogeneity generated by buried valleys in detrital sedimentary aquifers and the fractures and karstic features developed in carbonate aquifers. Both function in similar ways, as preferential flow paths either for fresh or salty water. These preferential channels represent structures where saltwater would encroach more easily if the hydrological conditions favored the movement of seawater inland. Due to their hydraulic properties, these areas are often preferentially selected for groundwater abstraction. Hence, the combination of these two factors can be a threat for waterworks located in the proximity of the coastline. The common geological heterogeneity at variable scales implicates that even local studies would need to take regional aspects into consideration when studying salinization of coastal aquifers as shown by previous researches (Kirkegaard *et al.*, 2011; Meyer *et al.*, 2018a; Thorn, 2011). The differences in how far inland seawater is detected can change up to kilometers considering lateral changes of hydrogeological facies.

The geological history of Denmark plays a big role for the presence of saline water in coastal aquifers. The majority of pre-Quaternary deposits in Denmark are of marine origin. The sequence of Cretaceous, Paleogene and Neogene sediments has subsequently been tilted and eroded such that Chalk deposits from Cretaceous are found just below a relatively thin Pleistocene cover in the eastern part of Denmark. As we move towards west, clayey deposits from Paleogene are found on top of the Chalk formations and subsequently, sedimentary deposits (sand, clay) from Miocene are found above. The thickness of the mainly clayey deposits increases towards west and reaches up to several hundred meters. The Miocene sediments are to a certain degree of terrestrial origin (Scharling *et al.*, 2009), as the coastline moved across Denmark several times during the Miocene, resulting in brackish conditions. However, connate saltwater has to a large degree been flushed after deposition during periods with relative low sea level. Most Quaternary sediments are of terrestrial origin and some have subsequently been flooded with seawater because of eustatic sea level rise. During several glaciations the sea level was significantly lower than presently (approx. 100 m or even lower), and the land surface was overpressured by the weight of the glaciers. However, as the ice melts away a rebound is observed (also referred to as the Glacial Isostatic Adjustment) since the weight of the glacier is removed.

High saltwater concentrations may be a result of modern seawater intrusion taking place during periods where eustatic sea level rise exceeds isostatic uplift (e.g., Elliot *et al.*, 2001). It may also consist of older seawater that has entered the aquifer during transgressions taking place after the connate seawater was flushed (Crampon *et al.*, 1993) or it may be a result of residual connate seawater trapped in the pore space during deposition.

Finally, brine waters may migrate from deeper formations or salt diapirs (Schönfeld, 1990) but this subject is not discussed in the present work.

Hence, connate waters with high saltwater contents are primarily found in the Chalk formations and the clay deposits from Paleogene. Connate waters in the Miocene formations are expected to be flushed by freshwater but may contain saltwater originating from subsequent periods.

In the case of Danish islands, there is quite a limited amount of published research about saltwater intrusion, and the interest about it would be based on the population density and the amount of freshwater required. However, since the fresh groundwater resource is in direct connection with the precipitation regime and patterns, climatic changes can have a big impact in the long term on the size of the freshwater lens. These factors have been frequently studied in the islands of the Pacific (White and Falkland, 2010) but there is almost no research on this topic for Denmark. Another expected consequence of climate change is the sea level rise. As this would change the size of the island, the amount of freshwater that can be stored would be also modified. Nevertheless, these effects would have to be considered from a long-time perspective (>100 years) when significant changes on the precipitation patterns and sea level rise can be comparable to the existing uncertainties in hydraulic properties and hydrogeological functioning. For short-term effects, droughts and dry periods during summer can have a strong impact on the availability of water for the inhabitants supply and the freshwater ecosystems.

In this study, we have reviewed the research done so far on saltwater intrusion in Denmark. Still, other coastal aquifers in Denmark different from the ones presented here could currently be encroached by saltwater but with unnoticed effect. In order to identify potential precursors of saltwater intrusion, all the wells in the Jupiter database where the chloride content exceeded 250 mg/l, the WHO/EU limit drinking water standard, were identified. This information is part of the national water quality monitoring program and covers several thousand wells sampled every 3-5 years. The spatial distribution shows wells all over the country exceeding the limit of drinkable quality (Figure 9). Some of them are located at a distance far enough from the coastline to be initially discarded from the current connection with seawater. They might be caused to the presence of old groundwater salinized as a result of previous eustatic changes. A significant number of wells at the coastline can be identified. Also, it can be observed that areas with higher density of population are also prone to relative higher number of wells with high salinity. This map (Figure 9) is an indicator of the extension and amount of early warnings that can be detected along the coast of Denmark. The good news is that the problem is already identified and the authorities are already aware that groundwater is not suitable for drinking at these locations. On the other hand, since there are many cases, some of them can be early indicators of a slowly growing problem for future decades.

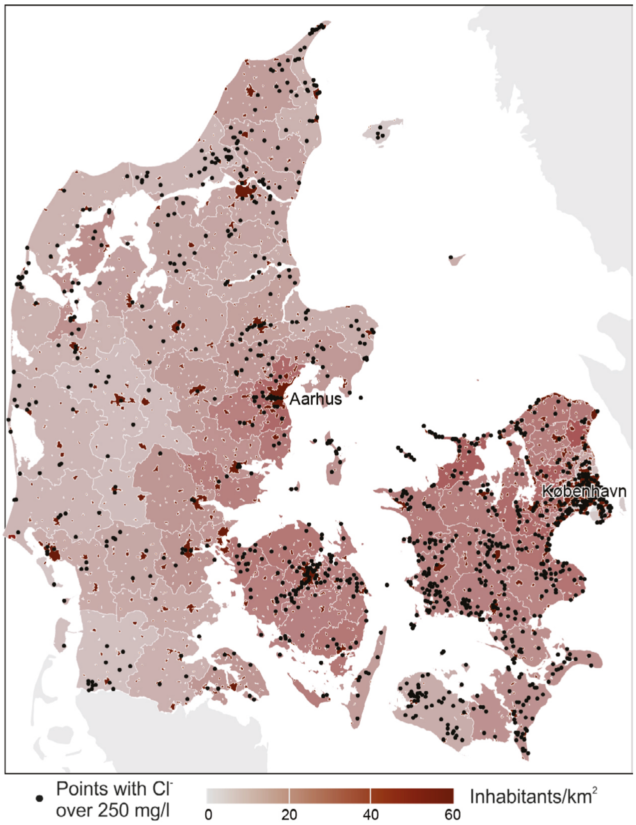

Figure 9. Identification of wells in the Jupiter database in which the chloride content exceeds 250 mg/l (all available measurements) over the map with population density (1st January 2020, data from www.statistisbanken.dk).

Figura 9. Identificación de sondeos en la base de datos Jupiter en los que el contenido en cloruro sobrepasó los 250 mg/l (todas las medidas disponibles) sobre el mapa de densidad de población (1 de Enero de 2020, datos de www.statistisbanken.dk).

At a local scale, several studies have been published on saltwater intrusion in the proximity of the surface and the coastline. Andersen *et al.* (2005, 2007) monitored the changes in salinity based on geophysical methods and numerical modelling. They also studied geochemical processes affecting fresh submarine groundwater discharge with nitrate. This process has been identified in many regions of the world and can have severe impacts on coastal ecosystems (Duque *et al.*, 2019b). Jørgensen *et al.* (2008) completed an experiment in which they induced saltwater intrusion by pumping to test the use of different isotopic tracers and understand the sources of water and the mixing processes. Poulsen *et al.* (2010) used vertical multielectrode profiling to monitor the freshwater-saltwater interface between different seasons. The combined study of the saltwater intrusion and the fresh submarine groundwater discharge has been also researched by estimating fluxes with seepage meters and measuring salinity in groundwater at shallow depths (Duque *et al.*, 2018), analyzing the nutrient discharge pattern to a lagoon (Duque *et al.*, 2019a) or using stable isotopes together with electrical conductivity of water as a dual tracer of saltwater intrusion (Müller *et al.*, 2018) a coastal lagoon at the west coast of Denmark Study focus: A dual tracer approach based on salinity and δ 18 O is used to assess seasonal dynamics at the saltwater-freshwater interface of a coastal lagoon. At the site, salinity is prone to vary on a sub-seasonal or daily frequency due to riverine freshwater inputs to the lagoon. In contrast, δ 18 O compositions of end-members only vary seasonally. New hydrological insights: The dual tracer approach shows to be valuable in coastal settings where end-member concentrations vary substantially over the seasons and hence, an unambiguous end-member definiti on does not exist. Calculated mixing fractions using only salinity, deviated from the dual tracer approach on average by 18%, but were as high as 97%. Although, these differences decrease to 6% on average when using only δ 18 O, our study strongly suggests their simultaneous application. Moreover, we found that seawater intrusion occurs during the summer when salinity in the lagoon is high and fresh submarine groundwater discharge (SGD. The application of other methods more frequent in groundwater surface water interaction, as temperature, has been also tested in coastal areas in Denmark (Duque *et al.*, 2016; Tirado-Conde *et al.*, 2019). The study of shallow processes in the coastal areas has the advantage of the accessibility for the collection of samples and data regarding groundwater providing insights of deeper processes. These areas are also prone to the salinization as a result of flooding by storms that can be an additional source of uncertainty as salinity content in the aquifer can have different origins.

6. Future perspectives and risks

It is predicted that climate change during the next decades will cause sea level rise in Denmark (0.27-0.47 m for 50 years and 0.39-0.89 m for 100 years according to Colgan *et al.*, 2019) and increasing variations in the precipitation regime (i.e. more frequent droughts) (DMI, 2014; IPCC, 2014) while societal changes will rise the demand for pumping of fresh groundwater (Klee, 2013). Additionally, a population increase of 15-25% by 2100 (European Environment Agency, 2017) is expected in Denmark, resulting in an equivalent rise in water demands. As in many other regions of the world, all these changes together will increase the risk of saltwater intrusion (Post and Werner, 2017; Werner *et al.*, 2013) and will require wise management strategies (Oude Essink, 2001) based on adequate knowledge. Saltwater intrusion is a global problem for all coastal regions, requiring new tools for its study (Michael *et al.*, 2017), but in the case of Denmark it is a key issue both because of the 100% dependency on groundwater resources but also because of the presence of lowlands along most of the coastline. Michael *et al.* (2013), using 2D synthetic models simulating saltwater intrusion demonstrated that topography limited coastline is actually more vulnerable than recharge-limited coastlines. In Denmark, many examples of topography limited areas can be found, where the water table elevation in the coastline cannot be increased much more than the current status because of the low land surface elevation, even if climate projections indicate that recharge by precipitation will be increased (DMI, 2014). Denmark is a wealthy country, well positioned to confront technologically and economically sea level rise challenges compared with other lower income countries, however, the impacts would be significant both in the long run (lowlands can be easily inundated permanently) and in a shorter perspective with occasional storm events (Yu *et al.*, 2016). Seawater intrusion should be considered when constructing barriers as they would prevent the flooding but would not stop the encroachment of the saline wedge in aquifers.

There are significant differences between the climatic characteristics of Denmark and other dryer regions as South of Europe and the Mediterranean. Additionally, the stresses over water resources are different, for example, irrigation requires relative high amounts of water in South Europe while in Denmark irrigation is limited to some areas and the summers are less dry (the average precipitation for July, August and September are over 70 mm). One reason for the limitations in the irrigations is the characteristics of soils. Areas with higher clay content (Figure 1A) can store soil moisture better than sandy soils, and therefore plants can cope with the mild temperature summer conditions fairly well without irrigation. However, this can change with different climate conditions prompting additional extraction of groundwater for irrigation as it is frequent at southern latitudes. Even if climatic change forecasts for Denmark indicate an increase in annual precipitation that can compensate increasing pumping, the effect of saltwater intrusion cannot be analyzed in terms of average resources because pumping has local effects. The intensification of pumping can often trigger saltwater intrusion even in cases where there is high net recharge. Also, droughts are relatively frequent in Denmark (Hisdal and Tallaksen, 2003) and even if they might have less severe impact compared with southern regions, they are an added risk for the development of saltwater intrusion.

7. Conclusions

The main factors to be considered in the study of saltwater intrusion in Denmark have been identified and analyzed based on the current published knowledge. The key features to be considered are: (1) Drained lowlands with water table below the sea level, (2) the high connectivity of the sea in fractured and karstified coastal aquifers, (3) the small dimensions of the freshwater lens in small islands, (4) the abundance of buried valleys as preferential flow paths for saltwater intrusion and (5) the presence old saltwater associated with previous saltwater intrusion processes due to eustatic changes or connate waters.

In most of the cases, the use of geophysical systems to identify the presence of saltwater in coastal aquifer has been essential to obtain knowledge about the spatial distribution and links to geology. Especially the use of AEM has provided high-density data covering extensive areas and multiple depths, an advantage in comparison to studies using more traditional methods. Combined with data measured in wells, as part of the national monitoring program like water table elevation, hydrochemical properties and lithological columns also provided reliable results beyond the uncertainties in the interpretation of geophysical results. Other studies focusing on more surficial processes have also demonstrated the utility of the research on shallow aquifers, also to study fresh-submarine groundwater discharge.

Only a limited number of cases have been studied in detail along the coast of Denmark, however, samples from several hundreds of wells with chloride content exceeding the limits for consumption have been identified. Many of them can be associated with seawater intrusion in an early stage that can be managed with simple modifications of the water works functioning. However, in other cases they can be early warnings about more challenging problems that might require remediation measures in the following decades. Serious groundwater salinization issues have been reported in several locations in Denmark. In most of them, the coalescence of several risk factors has triggered the problem (i.e. changes of land uses by human, water abstraction for supply, ancient sea level oscillations and heterogeneous geology).

The physiography of Denmark, with many kilometers of coastland, and the low land surface elevation combined with the potential changes brought by climatic changes in the coming decades can be a threat for the groundwater resources that are in the proximity to the coastline. Careful water management would be essential to keep the balance between saltwater and freshwater, but also studies considering long-term effects and prevention measures would be important to keep and protect fresh groundwater along the coast.

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