Gemeente
Amsterdam

Causes, effects, and solutions for salinization of ground- and surface water in the Amsterdam region

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Contents

Abstract

Ground- and surface water in the Netherlands are threatened by salinization. Salinization can negatively impact drinking water provisioning, agriculture, industry and ecosystems. In the Netherlands in particular, the three most common ways of salinization are via groundwater, via estuaries and via sluice gates. This literature review examines the causes, consequences and solutions for salinization of ground- and surface waters in the Amsterdam region, as have not been elucidated yet. The findings indicate that ground- and surface water salinization in Amsterdam is already present. In addition, climate change will likely increase the salinity of the Amsterdam city waters. Increased city water salinity might increase groundwater salinity as well, through the permeability of quay walls. This might have consequences for the urban aquatic and terrestrial ecosystems; however, this should be evaluated further. Therefore, the review examines several nature-based mitigation strategies to salinization. The salinity of the surface waters likely increasing with climate change brings forth a decision that needs to be made. Climate change is expected to lead to lower river discharges and less freshwater availability, particularly during dry periods. This stresses the national water system and asks for rethinking of how we should manage our freshwater supplies. Therefore, the review ends by shedding light on two solution paths that focus on mitigation and adaptation to salinization of both ground- and surface waters.

Layman summary

In the Netherlands, ground and surface waters can become saltier, a process called salinization. Salinization can have detrimental effects to agriculture, drinking water, industry and nature. It is well-known that salinization in the Netherlands happens generally through groundwater, estuaries and sluice gates. How salinization happens in Amsterdam and what the effects are and what possible solutions exist, is, however, not yet studied. This literature study shows that the surface- and some groundwaters of Amsterdam are already experiencing salinization, which will be worsened by climate change. The saltier canal waters in Amsterdam might also make the groundwater more salty, possibly harming plants, trees and animals in the city, although more research is needed to fully understand these effects. To address the increased salt concentrations, the review also sheds light on some strategies to reduce salt concentrations in the city waters while simultaneously improving biodiversity. As it is predicted that climate change will cause lower river flows and less freshwater availability, especially during dry periods, we may need to rethink how we manage our freshwater supplies. The study concludes with two main solution paths: 1) finding ways to prevent salinization and 2) developing strategies to adapt to these changing conditions.

1. Introduction

1.1. Problem statement

A substantial part of the Netherlands consists of low-lying coastal areas, which are dependent on freshwater aquifers for their water demands (Seibert et al, 2024). However, ground- and surface water in these areas is often threatened by salinization (Seibert et al, 2024; Goswami & Clement, 2007; Eeman et al., 2011).

1.1.1. The most common causes of salinization in coastal areas globally

The most common causes for coastal groundwater salinization worldwide are seawater floodings and saltwater intrusion (Seibert et al., 2024). Floods can 'overwash' the land during storms, causing massive amounts of saltwater infiltration into the soil and groundwater aquifers (Cantelon et al., 2022). Saltwater intrusion on the other hand, is a non-visible and much slower process, which happens due to the so called 'hydraulic head gradient' that refers to the difference in water pressure and elevation between two points in a water body and an aquifer (Goswami & Clement, 2007; Michael, Russoniello & Byron, 2013). The hydraulic head gradient of the sea, e.g. saltwater intrusion into the coastal land, is dependent on local sea level rise, ground elevation, drainage, groundwater abstraction and groundwater recharge (Seibert et al., 2024).

1.1.2. Climate change and hydrodynamic processes driving salinization

Climate change can exacerbate saltwater intrusion in coastal areas by increasing hydraulic sea-to-land head pressure in a few ways (Seibert et al., 2024). First, mean sea level rise caused by climate change can increase hydraulic head pressure from the sea, increasing saltwater intrusion (Nicholls et al., 2021). Sea level rise might have a higher impact in areas with low hydraulic gradients, e.g. low-pressure differences between two water bodies, which increases the impact of an increased hydraulic pressure from sea level rise (Seibert et al., 2024). Secondly, groundwater abstraction and sediment compaction in coastal areas causes coastal ground subsidence, resulting in increased relative sea level rise in some of these areas, leading to an increased hydraulic sea-to-land head pressure (Nicholls et al., 2021). In some coastal areas, Seibert et al. (2024) explain, ground water abstraction seems to be the major driver of groundwater salinization, especially in areas with many water wells. Thirdly, climate change will cause a variation in groundwater recharge due to changes in precipitation patterns, changing freshwater availability in certain areas, which can also lead to increased hydraulic sea-to-land head pressure (Portmann et al., 2013; Seibert et al., 2024). Thus, the effects of climate change on saltwater intrusion in can be summarized as: sea level rise increases hydraulic head pressure on fresh groundwater aquifers, leading to increased saltwater intrusion, which is impacted by the pressure differences between the waterbodies that results from e.g. groundwater abstraction, sediment compaction and changes in groundwater recharge.

In non-coastal polder areas in the Netherlands, there is often a layer of fresh groundwater, called the freshwater lens, that is lying on top of often brackish or saline groundwater (Eeman et al., 2011). The thickness of this freshwater lens determines the hydraulic head pressure that the freshwater lens has against the underlying brackish or saline groundwater (Eeman et al., 2011; Michael, Russoniello & Byron, 2013). The thickness of the freshwater lens reduces with periods of drought, due to evaporation and evapotranspiration, and due to groundwater abstraction, which can cause the underlying brackish or saline groundwater to seep towards the surface, a process called seepage salinization (Maas, 2007; Oude Essink, 2001; Van Engelen, Oude Essink & Bierkens, 2022). Similarly, the freshwater lens is recharged with precipitation or artificial groundwater recharge, which provides resistance against seepage salinization (Maas, 2007; Oude Essink, 2001; Lal & Datta, 2018). As polders lie -4 to -7 meters beneath N.A.P., saline groundwater seepage is also pushed upwards from the hydraulic head pressure from the sea (Oude Essink et al., 2010). Sea level rise can lead to double the amount of salt load in polders due to increased water hydraulic pressure, leading to stronger seepage salinization, but only within 10 km of the coastline and main rivers (Oude Essink et al., 2010).

1.1.3. The most common causes of salinization in coastal areas in The Netherlands

In the Netherlands in particular, the three most important ways in which salinization happens are via groundwater, via estuaries and via sluice gates (sluizen) (Deltares, 2022). First, as previously mentioned, saltwater intrusion in coastal areas can happen due to a hydraulic head between coastal fresh groundwater and salty seawater (Goswami & Clement, 2007; Michael, Russoniello & Byron, 2013). This salt water will intrude into groundwater in the polders and polder ditches (Fig. 1A; Klimaateffectatlas, 2024). By adding fresh water to the polders and polder ditches, the created freshwater lens provides counter-pressure against the sea water (zoetwaterbel) (Eeman et al., 2011; Klimaateffectatlas, 2024). With sea level rise, a higher pressure from the sea asks for an increasing freshwater counter-pressure from the polder (Fig. 1B), which uses more freshwater resources (Klimaateffectatlas, 2024; Deltares, 2022).

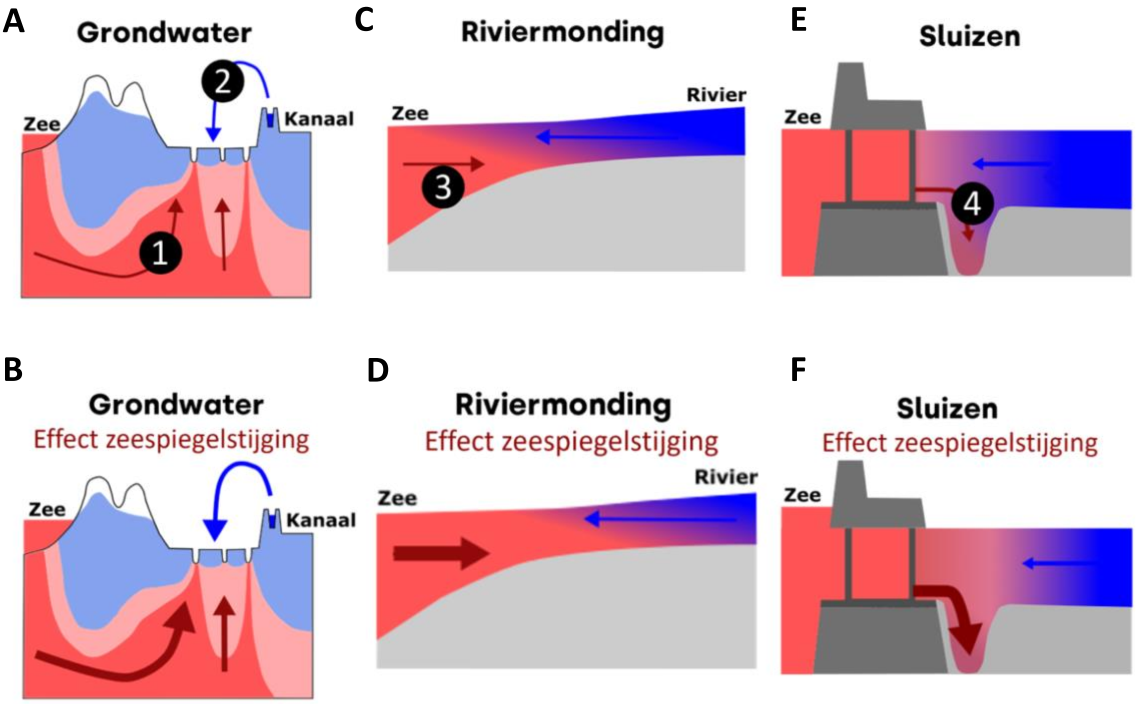

Figure 1. The effects of sea level rise on groundwater salinization (A-B), estuary salinization (C-D) and salinization of rivers via sluicegates (E-F). Adapted from information guide on the effects of climate change on salinization, Klimaateffectenatlas, 2024.

Secondly, in estuaries, seawater and freshwater counterbalance each other, which causes a brackish gradient in this surface water (Fig. 1C) (Telesh & Khlebovich, 2010). With sea level rise, this brackish gradient moves upstream, as a higher hydraulic pressure comes from the sea (Telesh & Khlebovich, 2010). Subsequently, due to climate change, increased periods of drought can occur and cause less freshwater flowthrough from the river downstream to the sea (Fig. 1D) (Telesh & Khlebovich, 2010; Klimaateffectatlas, 2024).

Thirdly, sluicegates can be a significant source of salinization of rivers (Fig. 1E). When boats and ships enter through the gates, saltwater mixes with some of the freshwater, which salinizes the freshwater river (Klimaateffectatlas, 2024). Similar to the effects of sea level rise on river salinization, sea level rise causes an increased pressure from the sea to freshwater bodies, which moves the brackish gradient more upstream with each sluice gate opening (Fig. 1F) (Nicholls et al., 2021; Klimaateffectatlas, 2024).

1.2. Goal

The general effects, causes and solutions for salinization are relatively well-documented in the literature. However, how salinization affects the Amsterdam region specifically, what the causes are and what possible solutions are available for the Amsterdam region is still to be elucidated. The goal of this literature study is to i) find out how salinization of ground- and surface water will affect the City of Amsterdam specifically, ii) what the causes are for salinization of ground- and surface water, and iii) what possible mitigation and adaptation strategies are relevant for the City of Amsterdam.

1.3. Research questions

To get insights into salinization specific for the Amsterdam region, a research question was formulated:

1. How should Amsterdam manage the salinization of groundwater and surface water in the future?

Accompanying the main research question, four sub-questions were formulated to guide the research project in the right direction:

2. What is ground- and surface water salinization, how does it occur in Amsterdam specifically, and how do climate change and other factors contribute to its increase in Amsterdam?
3. What are the consequences of ground- and surface water salinization for drinking water provisioning, urban terrestrial and aquatic ecosystems, industry and agriculture?
4. What are the most effective solutions (such as Nature-Based Solutions, other technologies, or policy measures) to combat salinization in Amsterdam?
5. What (policy) changes are necessary to successfully implement these solutions in Amsterdam?

2. Methods

In this literature study, Google Scholar was used to find relevant research articles. To find relevant research articles terms such as salinization Netherlands, saltwater intrusion, coastal salinization were used. Title, abstracts and conclusions of the articles were first screened before deciding to analyze the methods, results and discussions. For information more specific to Amsterdam, a grey literature search was performed, searching through government reports and policy papers using the same keyword-based search strategy as described above. Further, the snowballing method was used as per the guidelines of Wohlin (2014) to find additional related studies by checking the references or related articles of highly relevant reports and papers. Finally, expert interviews were conducted to fill in knowledge gaps and identify relevant reports. Summaries with relevant information from these interviews can be found in the Appendix.

3. Ground- and surface water salinization in Amsterdam and the effects of climate change

3.1. Salinization of groundwater in Amsterdam

Deep saline groundwater is historically present all over the Netherlands, with its depth varying in each region (De Boer & Radersma, 2011). The depth of the saline groundwater in the coastal areas in the Netherlands is less than -50 meters in a strip of 25 – 75 km along the coast (De Boer & Radersma, 2011). These coastal areas are generally low-lying polders. In the eastern and southern parts of the country, the depth of saline groundwater ranges from -200 to -500 meters (De Boer & Radersma, 2011). As Amsterdam is a polder area as well, this historically present groundwater lies relatively close to the surface, which might pose risks for soil and terrestrial ecosystem health (Oude Essink et al., 2010; Herbert et al., 2015). In some polder areas, the freshwater lens can get relatively thin, causing the underlying saline groundwater to reach close to the surface, possibly negatively affecting vegetation when saline water reaches the root zone (Oude Essink et al., 2010; Herbert et al., 2015; Delsman et al., 2020). The depth of this border between saline and fresh groundwater seems relatively close to the surface in some areas in the Amsterdam region, especially near Weesp, Watergraafsmeer, Schiphol Airport, and the city center and north of Amsterdam (Fig. 2).

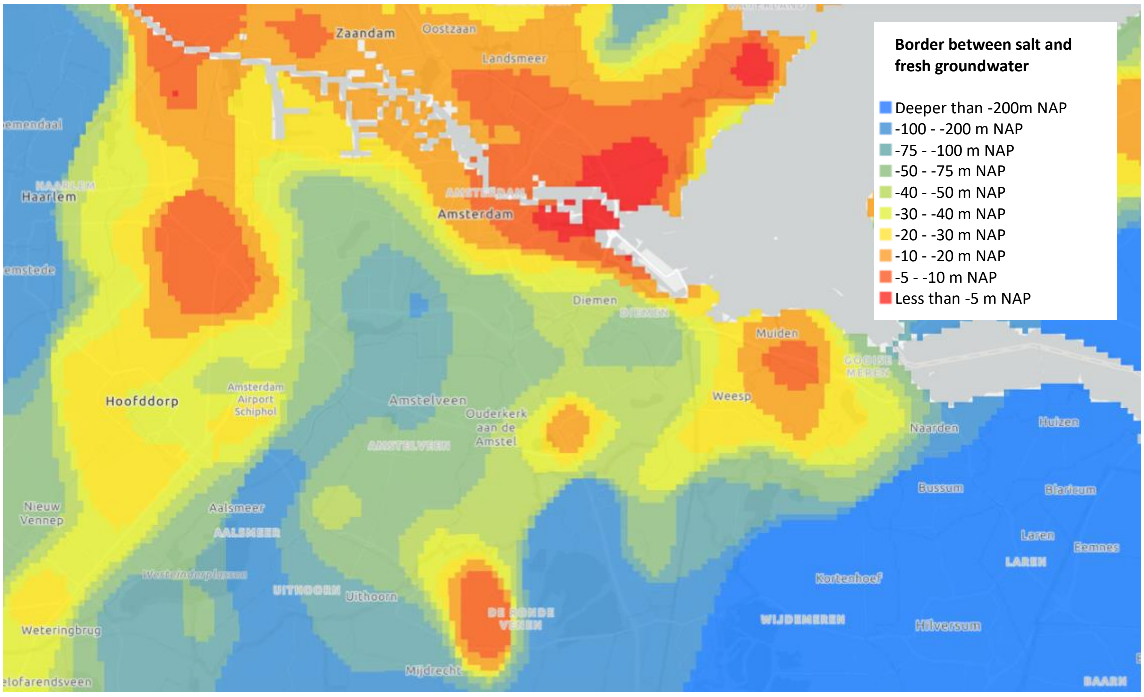

Figure 2. The depth of the border between fresh and saline groundwater (1000 mg/L chloride) in Amsterdam. Adapted from information guide on the effects of sea level rise on salinization, Klimaateffectatlas, 2024.

The influx of water from rivers and precipitation into the ground can stop the growing concentration of saline groundwater in polder regions (Delsman et al., 2020). However, in some areas of the Netherlands, like Zeeland, this influx of freshwater via rivers is not possible, leading to higher saline groundwater in summer periods (Delsman et al., 2020). Groundwater salinization happening in Amsterdam currently seems to be relatively minor for the largest part of Amsterdam, however models from Deltares (2022) show that in some parts of Amsterdam like Weesp, Watergraafsmeer, Schiphol Airport, Amsterdam Zuid-Oost and Buikslotermeer, saline groundwater can leach out of the ground (Fig. 3; Deltares, 2022).

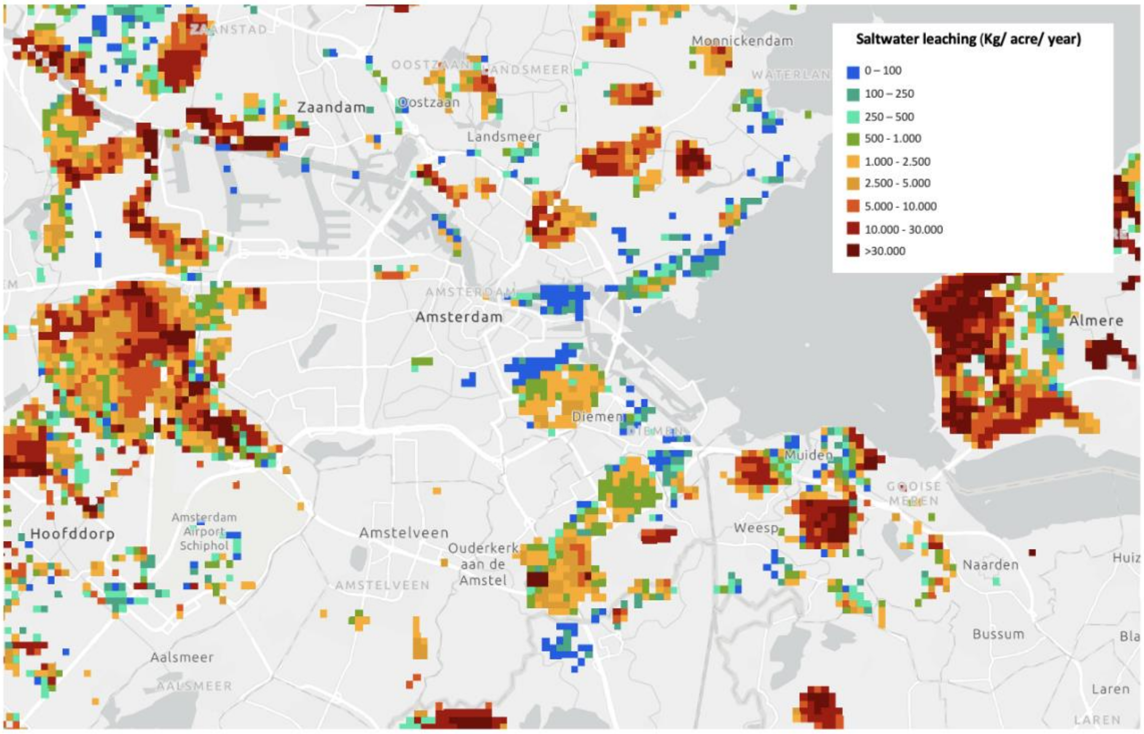

Figure 3. Amount of modeled saline groundwater that can leach out of the ground in the region of Amsterdam. Adapted from information guide on the effects of sea level rise on salinization, Klimaateffectenatlas, 2024.

In summary, in some areas in the Amsterdam region, the depth of the border between fresh and saline groundwater can reach between -10 meters and <-5 meters from the NAP. In addition, models show that saltwater leaching is possible in these areas where the border between fresh and saline groundwater is relatively close to the surface. The rooting zone depth in temperate climates, like the Amsterdam climate, is on average around 4 meters (Canadell et al., 1996). For urban vegetation, this could mean that saltwater in these areas might reach the rooting zones, possibly influencing vegetation health in these areas of high saline groundwater (Warrence, Bauder & Pearson, 2002; Munns & Tester, 2008).

3.2. The effects of climate change on groundwater salinization in Amsterdam

3.2.1. Effects of sea level rise on groundwater salinization

One of the main ways climate change affects salinization in the Amsterdam region is trough sea level rise (The Klimaateffectatlas, 2024; Deltares, 2022). We know the sea level will rise, but we don't know the exact effects that climate change will have on sea level rise, as this depends on how much greenhouse gasses will be emitted in the coming decennia. In some polder areas, saline groundwater can be pushed upwards due to sea level rise, leading to increased saltwater leaching to nearby surface waters (Deltares, 2022; Seibert et al., 2024). Models from Deltares (2022) show that saltwater leaching from groundwater in the Amsterdam region does not seem to change too much for up to 3 meters of sea level rise (Fig. 4; Deltares, 2022). Like the modeled current saltwater leaching in the Amsterdam region (Fig. 3), leaching occurs around Weesp, Watergraafsmeer, Schiphol, and Buikslotermeer (Fig. 4).

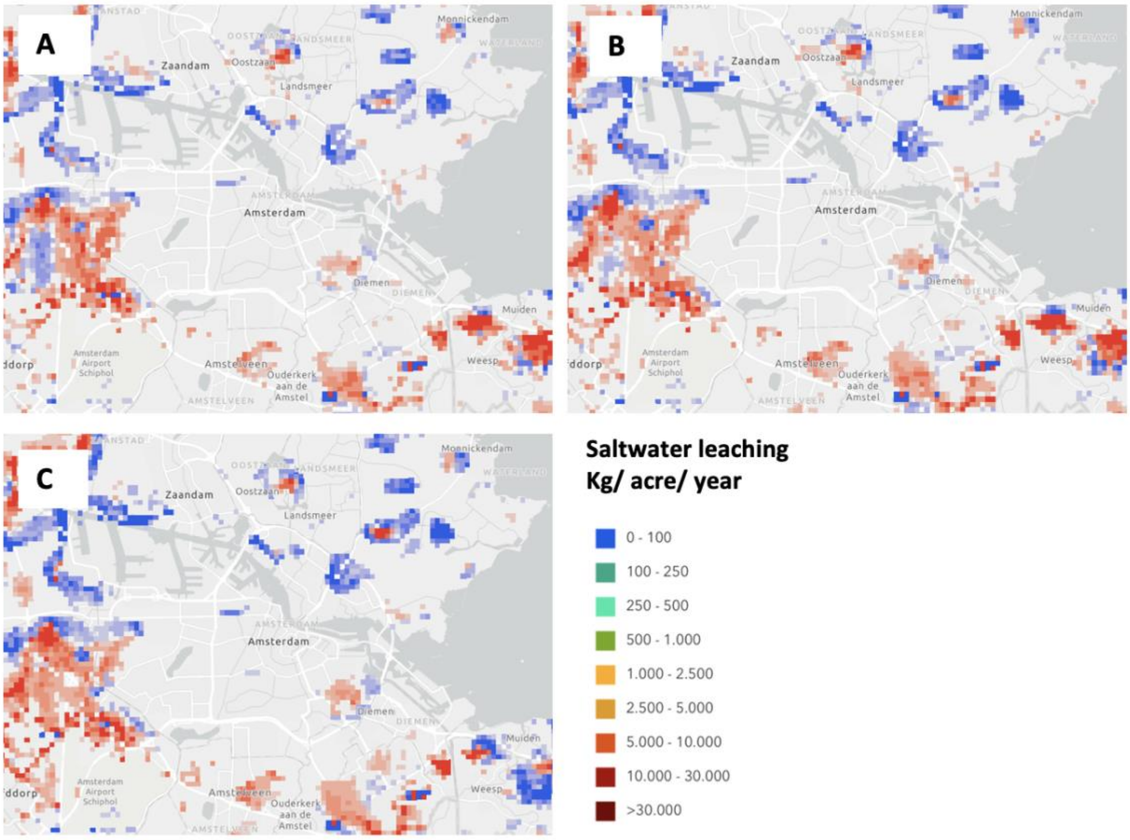

Figure 4. Amount of modeled saline groundwater that can leach to nearby waterbodies for different sea levels. For a sea level rise of 0.5 m (A) 1 m (B) and 3 m (C). Adapted from information guide on the effects of sea level rise on salinization, Klimaateffectenatlas, 2024.

However, the effects of sea level rise on saltwater leaching to nearby water bodies might not explain all the patterns that are seen in Figure 4. Other drivers, like land subsidence and autonomous processes (which refers to ongoing processes that were set in motion by historical events, such as land reclamation and changes in water management) might impact saltwater leaching more significantly (Deltares, 2022).

Sea level rise for up to 3 meters (Fig. 5A) will barely affect the Amsterdam area in terms of saline groundwater leaching. Land subsidence (Fig. 5B) can even make the groundwater in some areas fresher, as depicted with the blue patterns in Figure 5. Autonomous processes (Fig. 5C) appear to affect salinization the most. The areas that will be most affected by sea level rise alone are around Schiphol airport and Hoofddorp (Fig. 5A). In addition, land subsidence in Weesp might make salt leaching more prominent, but autonomous processes might blunt these effects with more freshwater provisioning (Fig. 5B). Thus, the effects of sea level rise on saline groundwater leaching due to a heightening of salty seepage in Amsterdam seems minor (Deltares, 2022; Klimaateffectenatlas, 2024).

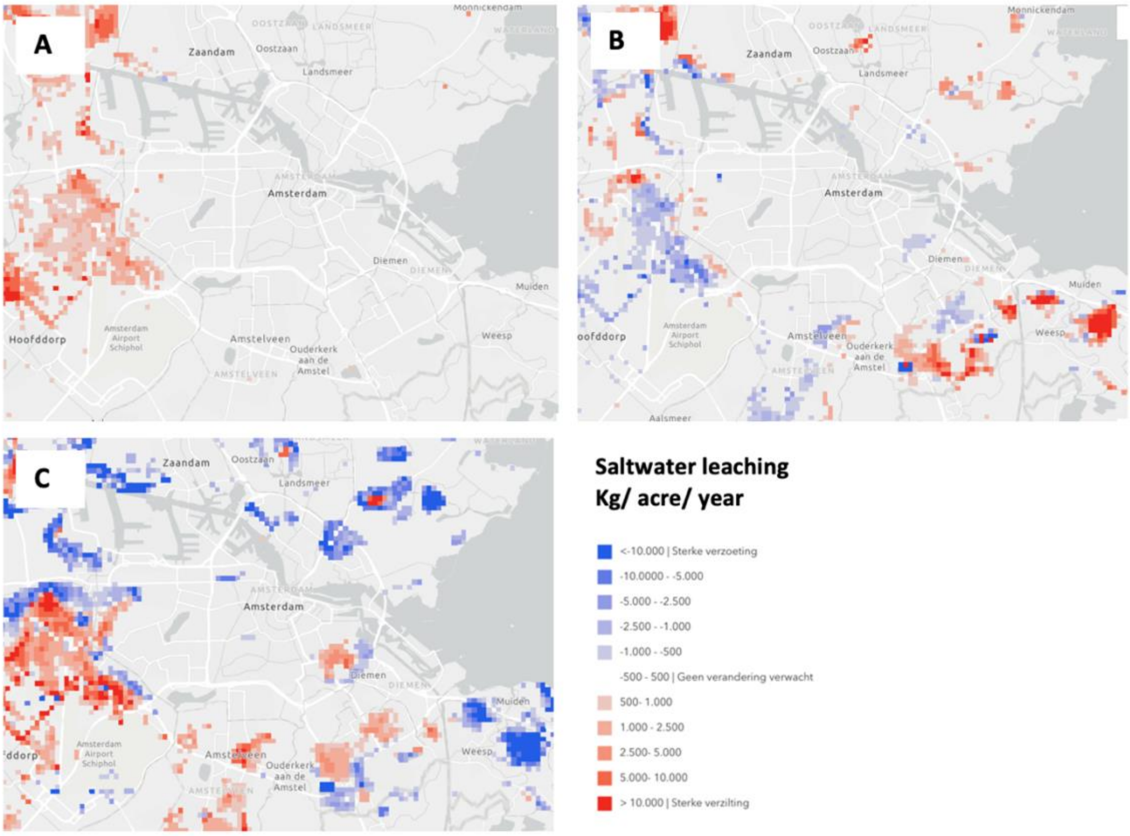

Figure 5. Modeled effects of either (A) three meters of sea level rise, (B) land subsidence, (C) or autonomous processes on leaching activities of saline groundwater to nearby waterbodies for 3 m sea level rise scenario. Adapted from information guide on the effects of sea level rise on salinization, Klimaateffectenatlas, 2024.

3.2.2. Effects of drought on groundwater salinization

During hotter and drier periods, groundwater in Amsterdam can get lowered due to increased evapotranspiration and evaporation from vegetation and soils respectively (Waternet, 2024; Berg & Sheffield, 2018). This can cause groundwater to lie lower than the surrounding surface water. In Amsterdam, groundwater can move through quay walls towards surface water via holes in the quay walls, but sometimes also through permeable columns (Waternet, 2024). Water can also flow the other way around, with surface water flowing towards groundwater (Waternet, 2024). Due to the difference in height of the groundwater and surface water, the surface water can permeate trough the quay walls, leading to surface water infiltration into the ground (Waternet, 2024). As we will explore later in this study, city surface water can get more saline in hotter and drier periods, due to lesser flowthrough from the ARK and the Amstel (Ministerie van Infrastructuur en Waterstaat, 2021a; Arcadis/Hydrologic, 2023). This might lead salinization of groundwater due to quay wall permeation.

In conclusion, the impacts of climate change on groundwater salinization in the Amsterdam region seems to be minor. Models show that sea level rise up to 3 meters will likely not affect groundwater salinization in Amsterdam significantly, except for Schiphol Airport. Land subsidence is likely the main cause of salinization in Weesp and Amsterdam-Zuidoost. Autonomous processes, the ongoing processes that were set in motion by historical events, such as land reclamation and changes in water management, are likely able to make groundwater salinization at Schiphol Airport worse and are likely the cause of groundwater salinization at Watergraafsmeer. In addition, in dry periods, saline surface water in Amsterdam might be able to permeate trough quay walls and cause groundwater salinization. However, whether this causes significantly more saline groundwater will need to be researched further with in-field testing.

3.3. Salinization of surface waters in Amsterdam

There are multiple waterbodies that can affect the Amsterdam water system (Fig. 6). These are the Amsterdam-Rijnkanaal (ARK) and the Noordzeekanaal (NZK), and to a lesser degree the IJsselmeer and Markermeer (Ministerie van Infrastructuur en Waterstaat, 2021a; Ministerie van Infrastructuur en Waterstaat, 2021b).

Figure 6. Map of the Amsterdam region with the major water bodies marked, plus the Lozingskanaal Zeeburg and the Oranjesluizen. Both the Noordzeekanaal (NZK) and the Amsterdam-Rijnkanaal flow towards each other and depending on the season, they meet approximately at the IJ. Water from the Markermeer / IJsselmeer can mix with the IJ water body via the Oranjesluizen in Schellingwoude (Gemeente Amsterdam, n.d.d). Water from the ARK via the Lozingskanaal at Zeeburg can provide water flowthrough to the Amstel (Arcadis/Hydrologic, 2023).

The Amsterdam-Rijnkanaal (ARK) plays an important role in freshwater provisioning for Amsterdam and the rest of the West of the Netherlands, as comprehensively summarized by Ministerie van Infrastructuur en Waterstaat (2021a). They mention that the mouth of the ARK is in direct contact with the saline water of the Noordzeekanaal (NZK). Their ends meet most of the time around the IJ water body, depending on the passthrough (doorspoeling) from the ARK, which changes with the seasons. Water from the Markermeer and IJsselmeer can mix with the IJ via the Oranjesluizen in Schellingwoude (Fig. 6) (Ministerie van Infrastructuur en Waterstaat, 2021b).

Saltwater has a higher density and sinks to the bottom of the NZK (Ministerie van Infrastructuur en Waterstaat, 2021a). Thus, intrusion of saltwater into the ARK happens first at the bottom of the canal. The NZK is a deeper canal than the ARK (Fig. 7), which means that with more salinization of the NZK and saltwater intrusion happening higher in the water column, the saltwater can leach into the ARK (Ministerie van Infrastructuur en Waterstaat, 2021a).

If extra water is needed to support the passthrough in the ARK, this usually comes via the Pr. Irene Sluice gates near Wijk bij Duurstede (Ministerie van Infrastructuur en Waterstaat, 2021a). Further, if there is not enough water is available to support the passtrough, or the water from the IJsselmeer and Markermeer cannot be used for various reasons, the bubble screen (bellenscherm) near Weesp (Fig. 7) can get turned on (Ministerie van Infrastructuur en Waterstaat, 2021a). The bubblescreen causes salt water at the bottom of the canal to rise and be mixed more towards the top of the canal, so that the available freshwater from the ARK can give more counterpressure to the NZK saltwater (Oldeman et al., 2020; Ministerie van Infrastructuur en Waterstaat, 2021a). Saltwater intrusion from the sea into the NZK is modulated by the opening and closing of sluicegates at the Ijmuiden sluice gates and the sea level height, providing more saltwater pressure at the gates (Arcadis/Hydrologic, 2023).

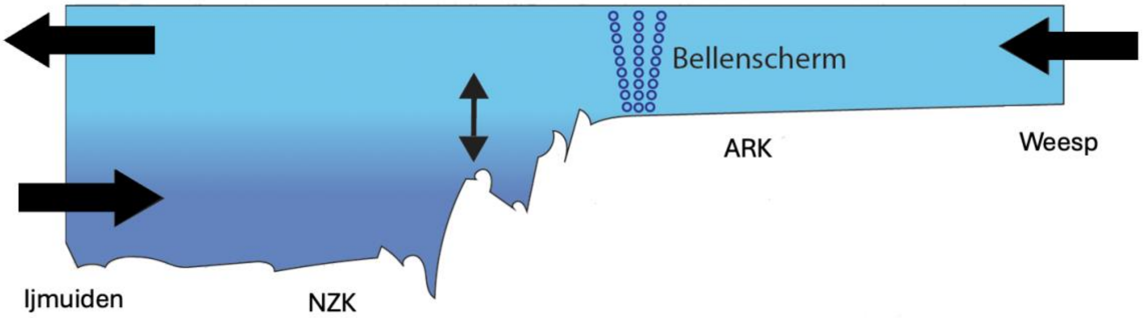

Figure 7. Visual representation of the height difference between the NZK, the ARK and lower-lying salt column (dark blue) in the NZK, the freshwater (light blue) and saline water flow directions and the bubble screen (bellenscherm) in the ARK. Adapted from Ministerie van Infrastructuur en Waterstaat, 2021a.

For the ARK, a freshwater passthrough of 25 m^3 / s as a 5-day average is approximately needed to keep this canal from getting more saline (Ministerie van Infrastructuur en Waterstaat (2021a). If the passthrough of the ARK is not enough to keep a counter-pressure on the saltwater from the NZK, there is a risk for the salinization of the bossom waters (boezemwateren) of the waters of Waterschap Amstel, Gooi and Vecht (AGV) (Ministerie van Infrastructuur en Waterstaat (2021a). In periods with more rainfall, the salt intrusion (zout tong) of the NZK-ARK canals might move up to 15 km back towards Ijmuiden, due to more freshwater flowthrough from the Amstelboezem and ARK (Ministerie van Infrastructuur en Waterstaat (2021a).

Freshwater from the Amstel flows from the Amstel bossom waters towards the NZK, however the amount of flowthrough depends on seasonal precipitation (Sikma & Lodewijk, 2008). The most important sources of freshwater for the Amsterdam city water are the Amstel and the ARK (Fig. 8). The most important source of saline water is the NZK (Fig. 8).

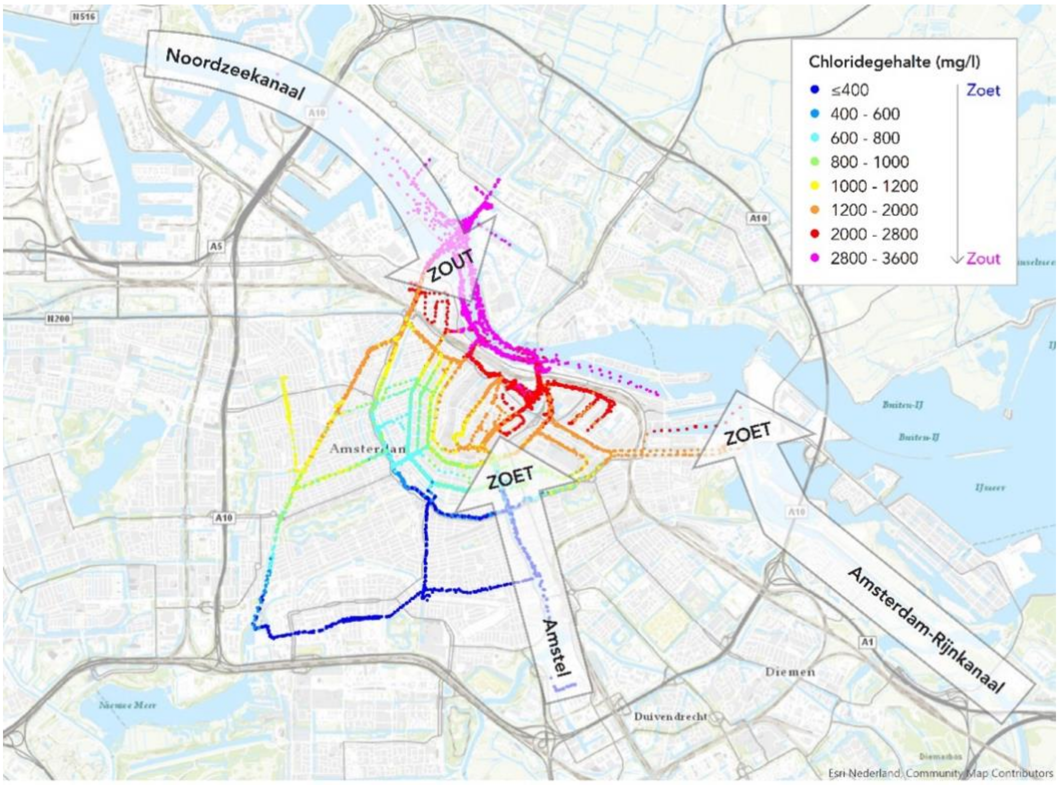

Figure 8. Map of Amsterdam the most important freshwater and saline water sources that influence the Amsterdam city water salinity. The freshwater sources are the ARK and the Amstel. The saline water source is the NZK. (Gemeente Amsterdam, 2023).

The IJsselmeer and Markermeer are important for freshwater provisioning for a significant part of the north, west and east parts of the Netherlands, but not for Amsterdam (Ministerie van Infrastructuur en Waterstaat, 2021b). Intake point for freshwater is at Andijk, and chloride levels average at 150 mg/L year-round in the Ijsselmeer, as explained in (Ministerie van Infrastructuur en Waterstaat, 2021b). Further, the major source of salt coming into the IJsselmeer and Markermeer is via the sluicegates at the Afsluitdijk, due to opening and closing of the gates, fish migration and minor leakages (Ministerie van Infrastructuur en Waterstaat, 2021b). Also, salinization in the lakes in controlled by spouting (spuien) of freshwater into the sea via the sluicegates (Ministerie van Infrastructuur en Waterstaat, 2021b). Usually, as channels (vaargeulen) and erosion pits (erosiekuilen) are deeper than the rest of the lake, saltwater gets trapped in these lower areas near the Afsluitdijk, due to sinking of saltwater from higher density. In periods of water shortage, spouting might be lessened, causing more salt intrusion into the lake. The Oranjesluizen at Schellingwoude prevent saline water from the NZK from coming into the freshwater of the Markermeer and IJsselmeer (Ministerie van Infrastructuur en Waterstaat, 2021a; Ministerie van Infrastructuur en Waterstaat, 2021b).

In summary, salinization in the system of the NZK-ARK is a function of saltwater intrusion into the NZK-ARK system from the sea at IJmuiden and freshwater counter-pressure from the ARK (Arcadis/Hydrologic, 2023). The NZK-ARK system heavily influences the salinity of the city waters in Amsterdam. In addition, the Amstel also provides freshwater to the Amsterdam city waters, with its intensity depending on the season. Saltwater intrusion from the sea into the NZK is modulated by the opening and closing of sluicegates at the Ijmuiden sluice gates and the sea level height. A freshwater passthrough of 25 m^3 / s as a 5-day average at the ARK is needed to mitigate saltwater intrusion from the NZK, otherwise risking salinization of the surface waters of the Amstelboezem. The bubble screen near Weesp can get turned on to increase the hydraulic head of the freshwater from the ARK against the NZK saline water.

3.4. The effects of climate change on surface water salinization in Amsterdam

3.4.1. Effects of sea level rise on surface water salinization

Arcadis and Hydrologic (2023) found that with 5 meters of sea level rise and a passthrough of 55 m^3 / s, brackish water (150 mg/L) could move up to 2 km downstream of the ARK. In addition, in summer periods 15 – 20 m^3 / s of extra passthrough of freshwater in the ARK would be needed to keep salinization from moving more downstream (Arcadis/Hydrologic, 2023). Saltwater intrusion into the NZK will increase linearly due to sea level rise up to 65% with 5 meters of sea level rise (Arcadis/Hydrologic, 2023).

3.4.2. Effects of sea level rise on salinization of Amsterdam city water

Arcadis and Hydrologic (2023) concluded in their report that the city waters of Amsterdam will keep on getting more saline if they stay in open connection to the NZK, especially in summer periods. According to Arcadis and Hydrologic (2023), Sea level rise can maximally increase the salinization of Amsterdam city surface waters with 30%, which is only marginally able to get mitigated with an increased freshwater passthrough in the ARK (Arcadis/Hydrologic, 2023). Freshwater from the ARK coming via the Lozingskanaal at Zeeburg (Fig. 6), will significantly make surface water in the Amstel at the height of the Berlagebrug less saline (Arcadis/Hydrologic, 2023). This can happen especially in dry periods when freshwater passthrough from the Amstel bossom waters is lessened (Sikma & Lodewijk, 2008). Salinization of the Amstel bossom waters (Amstelboezem) can for the most part get mitigated with increased passthrough of the ARK (Arcadis/Hydrologic, 2023). Key water connection points De Diemen, AGV (Amstel, Gooi, and Vecht) region exchange point, Driemond/Weesp, and Nigtevecht are sensitive to salinization, but this can be mitigated with enough freshwater flowthrough of the ARK (Arcadis/Hydrologic, 2023).

3.4.3. Effects of drought on surface water salinization

Changes in precipitation patterns can significantly impact surface water salinization. Low levels of precipitation cause lower levels of river flow. This causes less counter-pressure from rivers to the sea, which moves the saline-freshwater gradient (zouttong) more land inlands (Klimaateffectenatlas, 2024). In dry periods, less river water flow also coincides with more water demand from the Dutch water system to meet increased water needs for e.g. agriculture (Klimaateffectenatlas, 2024). The higher water demand lowers the amount of water available for river flow even more, driving the saline-freshwater gradient more land inwards. In addition, longer periods of drought will then cause increased salinization level for longer, which causes more salinization related damage (Klimaateffectenatlas, 2024).

In summary, with climate change, sea levels rise, which increases water demand for keeping the ARK fresh, while climate change also increases demand for freshwater resources due to increased evaporation, evapotranspiration and water use in general due to droughts and higher temperatures. Especially in summer periods, keeping the ARK from getting saline might stress the national water system the most. Due to the open connection with the NZK, surface waters in Amsterdam can increase in salinity by up to 30%, which is expected to be only minimally mitigated with increased freshwater flowthrough from the ARK.

4. The effects of salinization on nature and different sectors in Amsterdam

4.1. Freshwater provisioning and salinization risks

Drinking water provisioning in Amsterdam is provided by Waternet, which gets their freshwater for one third from the Loenderveense plassen and for two thirds from the Lekkanaal near Nieuwegein (Drinkwaterplatform, 2021). The water from the Loenderveense plassen gets naturally filtered in the Waterleidingplas and gets further processed in Weesperkarspel (Fig. 9). Freshwater from the Lekkanaal gets further processed in the Waterleidingduinen south of Zandvoort (Fig. 9) (Drinkwaterplatform, 2021).

Figure 9. Freshwater provisioning locations from Waternet. Two thirds of the freshwater supply from Amsterdam comes from the Lekkanaal, after which it is processed in the Waterleidingduinen, and one third comes from the Loenderveense plas, with processing in the Waterleidingplas and Weesperkarspel.

4.1.1. Salinization Lekkanaal and Waterleidingduinen Salinization Lekkanaal and Waterleidingduinen

As the Waterleidingduinen are relatively close to sea water, salinization of this freshwater source might be a risk due to sea level rise. However, Waternet (2024) recently reported that salinization of the surface waters of the Amsterdamse Waterleidingduinen is not present. Waternet (2024) mentions that in the Waterleidingduinen, saltwater seepage (zoute kwel) beneath the fresh groundwater is increasingly lowering due the growth of the amount of fresh groundwater (zoetwaterbel) beneath the surface waters. In addition, the fresh surface water abstraction in the Waterleidingduinen is equal to the addition of surface water, which negates risks for groundwater salinization (Mol-Posthumus, 2024). As per water provisioning for the Waterleidingduinen, the Lekkanaal is a downstream canal from the river Rhine (Rijn), thus the water availability in this canal depends on water passthrough of the river Rhine, and salinization of this freshwater source is generally not applicable (Arnold et al., 2009).

4.1.2. Salinization Loenderveense plas and Waterleidingplas

At the Loenderveense plas and Waterleidingplas, there is saline groundwater under the fresh surface and groundwater (Provincie Utrecht, 2019). During periods of drought, salinization of surface water can happen and might ask for a halt in drinking water provisioning of this source until water availability is sufficient again (Provincie Utrecht, 2019). However, in in drought periods, freshwater from the ARK at the Nieuwersluis (next to the Loenderveense plassen), 22 km from the ARK river mouth, can also get used to add more water to the Loenderveense plas and Waterleidingplas to mitigate salinization of the Loenderveense plassen and Waterleidingplas (Waternet, 2021; Deltares 2017). In theory, salinization of the ARK at the height of the Nieuwersluis should only be possible if enough freshwater flowthrough in the ARK is not possible (Deltares, 2017).

In summary, drinking water provisioning in Amsterdam is highly dependent on freshwater from the ARK. Drinking water collection points are, however, far away enough from the point where the ARK meets the NZK to not get saline. Deltares (2017) reported that salinization of these points can get mitigated with enough water flowthrough of the ARK.

4.2. Effects of salinization on industry

Freshwater is important in facilitating many industry processes. Salinization has impacts on industry as process water with a chloride concentration of higher than 150 mg/L can corrode internal structures of the used machinery (Stowa, 2020). This can lead to higher costs due to maintenance and for extra processing costs of the water to desalinize the water (Stowa. (2020).

4.3. Effects of salinization on the urban ecosystem

In the Omgevingsvisie Amsterdam 2050 report, the municipality of Amsterdam states that the goal for 2050 in terms of city-nature is to make the public space as green as possible. This means more city parks, more nature along routes, more green corridors, investing in nature development and protection of existing nature. Around 10.000 different species of plants and animals live in the urban green spaces of Amsterdam (Gemeente Amsterdam, 2020). These urban green spaces (Fig. 10) in Amsterdam provide numerous ecosystem services for human and ecological thriving, such as biodiversity and pest control, climate adaptation, carbon sequestration, soil health, emotional wellbeing and recreation (Breuste et al., 2013; Gemeente Amsterdam, 2020).

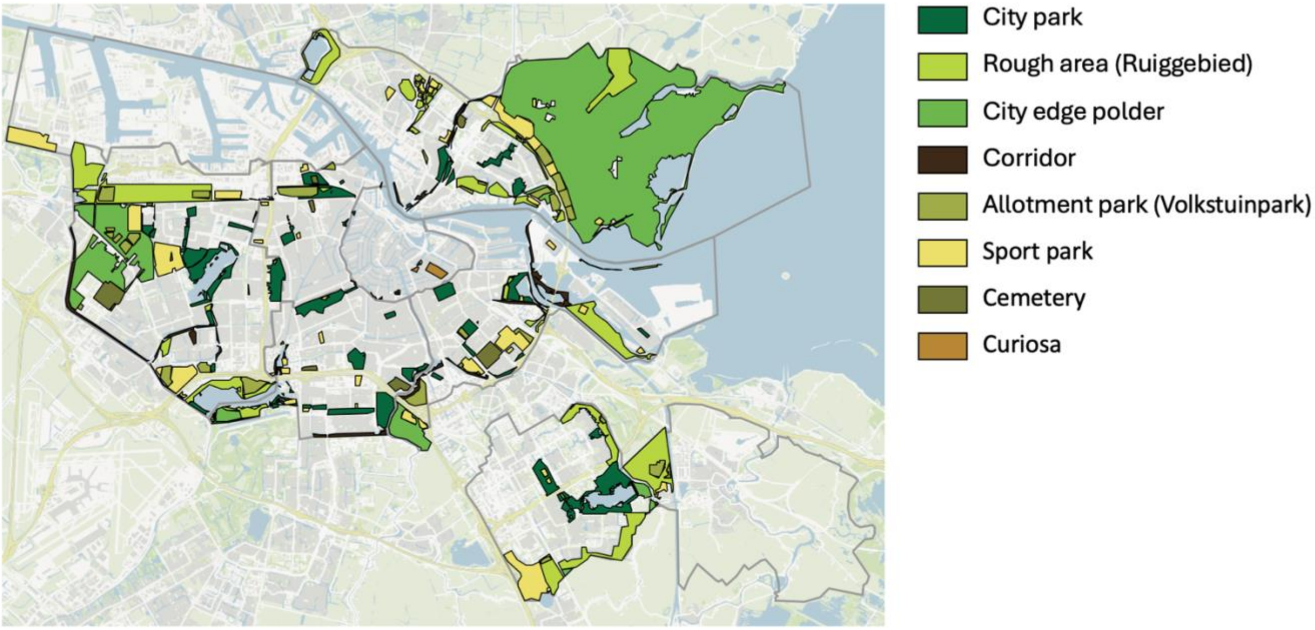

Figure 10. Map of the Hoofdgroenstructuur of Amsterdam, which are the main urban nature areas in the Amsterdam region. General urban nature, like trees or small vegetation patches are not visualized in this map. Adapted from Gemeente Amsterdam, n.d.c.

4.3.1. Effects of salinization on the urban aquatic ecosystem

Amsterdam has both urban freshwater aquatic ecosystems and aboveground urban ecosystems (Kees Dekker, 2024). Salinization of freshwater can have detrimental effects on freshwater organisms and ecosystems, as these organisms only can survive up to certain levels of water salinity (Cañedo-Argüelles et al., 2013). Freshwater organisms maintain a certain osmotic pressure in their bodies, keeping their internal salt concentrations higher than external salt concentrations. However, in cases of higher external salt concentrations, the freshwater organism must use more energy to maintain their internal salinity levels, or they must live with higher internal salt levels, both of which causing more physiological stress in the organism (Cañedo-Argüelles et al., 2013). Therefore, salinization of freshwater generally reduces aquatic biodiversity and has negative impacts on the provisioning of ecosystem services from aquatic ecosystems (Cañedo-Argüelles et al., 2013). Salt tolerance differs between species, thus increasing salinity levels in the Amsterdam city waters might not affect each aquatic species equally (Bal et al., 2021).

Thus, the current aquatic ecosystem could get more stressed in more saline conditions. However, the aquatic ecosystem can change and adapt to increases in salinity (Kees Dekker, 2024; Wersebe & Weider, 2023). The city waters of Amsterdam with an increase in salinization can be seen as a big urban estuary, with a large zone of brackish water in the canals (Kees Dekker, 2024). Estuarine ecosystems are amount the most rare and productive ecosystems on the world and house large amounts of unique and rare biodiversity (Davidson, 1990). Thus, in this way, the city water of Amsterdam could form a bigger habitat for unique aquatic species that need brackish water.

4.3.2. Effects of salinization on the urban terrestrial ecosystem

Salinization of soils via saline groundwater can degrade both the belowground soil ecosystem and aboveground ecosystem. For the soil ecosystem, salinization can decrease water infiltration and aeration, cause soil crusting and degrade the soil structure, which are soil properties that are all crucial for both soil life and soil vegetation (Warrence, Bauder & Pearson, 2002; Creamer et al., 2020). In addition, plants suffer from soil salinization due to osmotic stress in root tissues and ionic stress due increased internal salt concentrations, both of which cause stunted plant growth (Munns & Tester, 2008). However, there are plant species that are tolerant to increased salinity in the soil (Flowers & Colmer, 2015). Thus, more saline soils might call for more salt tolerant species to be planted throughout the city. Summarized, salinization of surface waters might lead to a decrease in current aquatic biodiversity in Amsterdam, followed by inhabitation of new aquatic species that thrive in more saline conditions. This brings forth an interesting opportunity for the city waters to become a unique and valuable estuarine ecosystem. Salinization of the soil also could lead to inhabitance of new vegetation types that are more salt tolerant. The consequences these changes in species composition with salinization on ecosystem services provisioning needs to be researched further.

4.4. Effects of salinization on agriculture in Amsterdam

Amsterdam only has limited space for agriculture, and mostly so-called community supported agriculture (CSA) is present in the metropolitan area (Gemeente Amsterdam, n.d.a). There are, however, a few small-scale production farms scattered throughout the outskirts, present in the west, north and southeast of Amsterdam (Gemeente Amsterdam, n.d.b). Agriculture depends on healthy soils for its primary productivity. As previously discussed, soil and plant health will degrade under saline conditions, thus also impacting yield for agriculture (Warrence, Bauder & Pearson, 2002; Munns & Tester, 2008). However, the weight of this problem in Amsterdam might be minimal, as the agricultural lands in Amsterdam are relatively small in number. In other parts of the Netherlands, however, salinization poses more significant risks for agriculture (Klimaateffectenatlas, 2024).

4.5. Causal loop diagram of salinization in Amsterdam

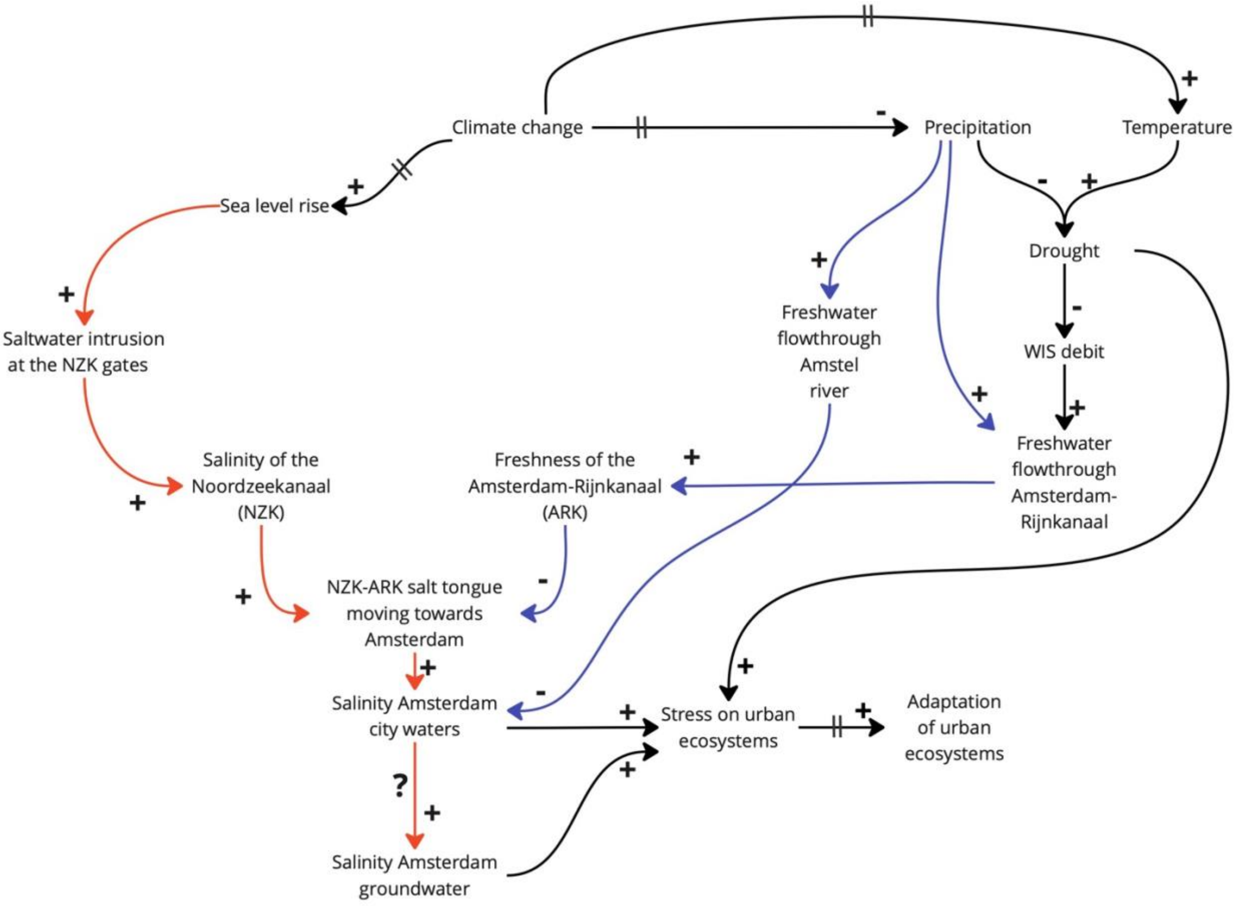

Figure 11. Visualization of the causes and effects of salinization in Amsterdam with a causal loop diagram. Red arrows represent sources of saline water, blue arrows sources of freshwater and black arrows represent neither. Arrows with (-)'s represent negative relationships, and arrows with (+)'s represent positive relationships. Two lines (||) intercepting an arrow represents a relationship that is delayed in some fashion.

To visualize the information discussed in previous about the causes and consequences of salinization in the Amsterdam region, a causal loop diagram was made (Fig. 11). Salinity of the Amsterdam city waters can be influenced by climate change via two different routes. First, climate change can cause a rise in sea levels, increasing saltwater intrusion at the NZK gates, which increases salinity of the NZK. Secondly, climate change can cause increased periods of drought, increasing pressure on the water network of the Netherlands, leading to less freshwater flowthrough at the ARK and the Amstel. How much the saline water of the NZK influences the city waters depends on the amount of freshwater counter pressure from the ARK and the Amstel. Climate change likely won't worsen groundwater salinization in Amsterdam directly. Indirectly, groundwater might be able to get more saline from increased salinity in the surface waters. However, the impact of increased salinity of surface waters on groundwater in Amsterdam is unknown and needs to be researched further. Increased salinity of the city waters might stress urban ecosystems, possibly leading to a decrease in urban ecosystem services.

5. Solutions against salinization in Amsterdam

This chapter is about strategies for mitigating salinization of the Amsterdam ground- and surface waters with solutions that might within the sphere of influence of the City of Amsterdam. The chapter is specifically about desalinization strategies that seem promising. Desalinization of water can be performed trough technological processes, such as reverse osmosis, forward osmosis, electrodialysis desalination or membrane distillation, however all these processes require relatively large amounts of energy and have high water costs (Sayed et al., 2020; Behnam, Faegh & Khiadani, 2022). Nature-based solutions (NBS) aim to protect, sustainably manage and restore ecosystems and simultaneously provide benefits to humans and biodiversity (IUCN, 2016). NBS are promising due to their multifunctionality in addressing problems, simultaneously addressing biodiversity loss and climate change, while providing effective solutions to societal challenges (IUCN, 2016). As the technological processes are relatively well known, this chapter focusses on exploring which Nature-Based Solutions might be able to be used for desalinization in Amsterdam.

5.1. Salt marshes

Salt marshes might be a promising biobased solution to mitigate salinization, especially in colder environments and places where salt marshes were historically present, e.g. the Netherlands (Tarolli et al., 2024). In salt marshes, saline water is desalinized by halophile bacteria and marsh plants (Shukla et al., 2011). These halophiles and marsh plants filter saline water by absorbing salt during their growth (Redondo-Gómez et al., 2007; Kargi & Dinçer, 2000). Shukla et al. (2011) showed in a modeling study salt concentration in saline water can be significantly reduced if densities of halophile bacteria and marsh plants are high enough. The exact desalination rates of halophiles and marsh plants in salt marshes, however, hasn't been elucidated further since the study of Shukla et al. (2011), highlighting the need for further research. As wetlands, salt marshes can also be a possible nature-based solution against saltwater intrusion. Coastal wetlands, including salt marshes, are considered as one of the most ecologically valuable and productive ecosystems on the planet, while being under treat due to urban coastal reclamation (Mitsch, Bernal & Hernandez, 2015; Billah et al., 2022). Tarolli et al. (2024) explain that salt marshes can filter and store freshwater, which leads to a recharge of fresh groundwater aquifers. This freshwater storage can prevent saline groundwater intrusion by providing a counter pressure to saline surface water (Tarolli et al., 2024). In addition to recharging groundwater aquifers, salt marshes can deliver multiple Ecosystem Services, such as cleaning water pollution, supporting a unique variety of flora and fauna, improving ecosystem resilience, mitigating floods, and they provide a variety of cultural and provisioning services (Mitsch, Bernal & Hernandez, 2015; Billah et al., 2022). Thus, due to the multitude of Ecosystem Services that salt marshes can provide, these wetlands seem to be promising avenue to research further for desalinization of the Amsterdam surface water. However, desalinization rates of salt marshes have not been determined, therefore further research on the desalinization efficiency of these wetlands is needed. Salt marsh-like habitats might be possible to include in the city landscape along canals or water bodies.

5.2. Natural buffer zones

Tarolli et al. (2024) discuss the possibility of natural buffer zones along canals and ditches as a possible saltwater intrusion mitigation strategy. These natural buffers represent a natural barrier between saltwater bodies and fresh groundwater (Das, 2023). In these natural buffer zones, native salt-tolerant plants are placed and therefore these species need to be site specific and adapted to the local climate (Tarolli et al., 2024). These salt-tolerant plants improve the structural integrity of the soil and absorb saline water, and thereby decrease hydraulic pressure of the saltwater body, which should minimize saltwater intrusion into nearby fresh groundwater (Das, 2023). Similar to salt marshes, these natural buffer zones provide habitat for rich biodiversity, improving ecosystem resilience (Tarolli et al., 2024). Thus, natural buffer zones, like salt marshes, might be interesting for mitigating saltwater intrusion and simultaneously increasing biodiversity in the city. However, the effectiveness of natural buffer zones in mitigating saltwater intrusion has not been assessed yet.

5.3. Soil health

Soils with healthy ecosystems generally show faster water infiltration, better soil structure, more organic matter and therefore absorb and store more groundwater (Creamer et al., 2022). A relatively simple and cost-effective way of improving the soil ecosystem is mulching. Mulching consists of covering the soil with mulches containing organic matter that can feed the soil organisms, such as bark, straw, leaves, stems, woodchips (Ngosong, Okolle & Tening, 2019). Mulch can be added on top of the soil, which can increase the amount of soil organic matter, improving soil structure and water holding capacity (Creamer et al., 2022; Liu et al., 2017). Additionally, mulch can increase the amount of groundwater in the soil by regulating temperature and therefore reducing groundwater evaporation (Ngosong, Okolle & Tening, 2019). The increased amount of stored groundwater reduces the soluble salt concentration in the soil and simultaneously increases the fresh groundwater counterpressure to more saline groundwater, decreasing soil salinization and saltwater intrusion respectively (Amini et al., 2016). Additionally, increased water infiltration into the soil (groundwater recharge), seen in healthier soils (Creamer et al., 2022), can help decrease soil salinization in the root zone by leaching soluble salts into deeper ground layers (Michael, Russoniello & Byron, 2013; Lal & Datta, 2018). Thus, increasing the water holding capacity of the soil by increasing soil health in the city can be a strategy to mitigate groundwater salinization.

5.4. Filtering with halophilic algae

Halophilic algae absorb NaCl or other salts during their growth (Brock, 1976), which makes them interesting candidates for desalination of saline water (Gautam & Kapoor, 2022). The species *Pheridia tenuis* desalinizes water by absorbing salts in their vacuoles and can make saline water completely salt-free (Yensen, 2006). Further, Abomohra, El-Sheekh & Hanelt (2017), showed that *Scenedesmus sp*. and *Chlorella vulgaris* can effectively desalinize sea water and brackish water in bioreactors. In addition to desalinizing water, algae have the potential to contribute to the provisioning of biofuels and food supplements, such as omega-3 fatty acids and beta-carotene (Gautam & Kapoor, 2022). Biodesalinization with halophilic algae is still in its infancy but appears to be a promising method of industrially desalinizing water with minimum costs and high efficiency (Gautam & Kapoor, 2022).

5.5. Groundwater recharge and extraction

As previously discussed, groundwater salinization can happen trough seepage salinization (zoute kwel) and trough saltwater intrusion from nearby saline or brackish water bodies. Important in these mechanisms of salinization is the hydraulic head of the fresh groundwater source, which in simpler terms is the counter-pressure that the freshwater can provide against the saline waterbody to stop saltwater intrusion (Michael, Russoniello & Byron, 2013). Thus, the thickness of this fresh groundwater lying on top of often brackish or saline groundwater, called the freshwater lens, is vital for countering salinization (Eeman et al., 2011). The thickness of the freshwater lens reduces with periods of drought, due to evaporation and evapotranspiration, and due to groundwater abstraction, which can increase saltwater intrusion and seepage salinization (Maas, 2007; Oude Essink, 2001; Van Engelen, Oude Essink & Bierkens, 2022). Similarly, the freshwater lens is recharged with precipitation or artificial groundwater recharge, which provides resistance against seepage salinization and saltwater intrusion (Maas, 2007; Oude Essink, 2001; Lal & Datta, 2018). Thus, improving fresh groundwater recharge artificially or with rainwater, and reducing groundwater evaporation and abstraction, can lead to more resilience against groundwater salinization from seepage salinization and saltwater intrusion.

One of the ways groundwater recharge can be improved, and groundwater evaporation can be reduced is improving soil health with methods like mulching, as previously discussed.

6. Discussion

This literature study aimed to explore causes, consequences and solutions for salinization of ground- and surface waters in the Amsterdam region. First of all, models show that groundwater salinization is already happening in Weesp, Watergraafsmeer, Schiphol Airport, Amsterdam Zuid-Oost and Buikslotermeer. Land subsidence is likely the main cause of groundwater salinization in Weesp and Amsterdam-Zuidoost. Autonomous processes are likely the cause of groundwater salinization in Watergraafsmeer and at Schiphol Airport. For urban vegetation, groundwater salinization could mean that saline groundwater in these areas might reach the rooting zones, having possible detrimental effects on the health of the soil ecosystem and terrestrial vegetation. However, since these results are based on models, potential inaccuracies in predicting salinity levels can be present. This points to the need for empirical validation of salinity level of groundwater throughout the city with field studies. Further, the surface waters of Amsterdam already have a gradient of salinity, with areas closer to the IJ being more saline. The NZK-ARK system heavily influences the salinity of the city waters in Amsterdam. In addition, the Amstel also provides freshwater to the Amsterdam city waters, with its flowthrough intensity depending on the season. Salinization in the system of the NZK-ARK depends on the amount of saltwater coming in from the NZK and the amount of freshwater from the ARK providing counter-pressure to this saltwater.

Models show that the salinity of the Amsterdam surface waters can increase by up to 30% because of rising sea levels, due to the open connection of the Amsterdam city waters to the NZK. Studies show that this can only marginally get mitigated by increasing ARK flowthrough. This also raises the question of whether the open connection of the Amsterdam city waters with the NZK should remain. However, this depends on the consequences of salinization of the surface waters, whether salinization is acceptable for all the stakeholders around the Amsterdam city waters and whether other mitigation strategies are possible. Further, the impacts of climate change on groundwater salinization in the Amsterdam region seem to be minor. Models show that sea level rise up to 3 meters will likely not affect groundwater salinization in Amsterdam trough salty seepage significantly, except for Schiphol Airport. However, sea level rise can increase salinity of the city waters especially in dry periods, which consequently might cause groundwater salinization because of permeable quay walls. But, whether permeation of saline surface water trough quay walls can significantly increase groundwater salinization in Amsterdam needs to be researched further.

From an ecological perspective, salinization of surface waters might lead to a decrease in current aquatic biodiversity in Amsterdam, followed by inhabitation of new aquatic species that thrive in more saline conditions. Salinization of the city waters thus brings forth an interesting opportunity for the city to become a unique and valuable estuarine ecosystem. Similarly, salinization of groundwater might lead to a decrease in terrestrial biodiversity, which can be followed by inhabitance of new vegetation types that are more salt tolerant. However, the consequences of changes in species composition of both the urban terrestrial and aquatic ecosystems on urban Ecosystem Services provisioning needs to be further assessed. Further, salinization of agricultural lands in Amsterdam might lead to decreased yields. However, the weight of this problem in Amsterdam might be minimal, as the agricultural lands in Amsterdam are relatively small in number. In addition, drinking water provisioning in Amsterdam is highly dependent on freshwater from the ARK and does not seem threatened by salinization. This is because drinking water collection points are far away enough from the point where the ARK meets the NZK to not get saline, and salinization of these points can get mitigated with enough water flowthrough of the ARK.

Saltwater intrusion from the sea into the NZK is modulated by the sea level heigh and by the opening and closing of sluicegates at the IJmuiden. Rijkswaterstaat has implemented a mechanism of 'selective withdrawal' or 'selectieve onttrekking' at the NZK sluice gates at IJmuiden to minimize saltwater intrusion with each opening of the gates for ship traffic (Rijkswaterstaat, 2022). However, this mechanism doesn't stop saltwater from intruding completely (Rijkswaterstaat, 2022). Thus, to minimize salinization of the NZK-ARK system, lessening the ship traffic at Ijmuiden should also reduce salinization of the NZK. However, with an added monetary value of €7.2 billion that the Port of Amsterdam brings to the North Sea Canal Area (Port of Amsterdam, 2018), lessening the frequency of sluice gate openings comes at a significant cost. Freshwater passthrough from the ARK (25 m^3 / s as a 5-day average) can mitigate saltwater intrusion from the NZK. Sea level rise will increase the amount of freshwater flowthrough that is needed to mitigate salinization from the NZK, with dry periods demanding even more extra flowthrough. Mitigation of salinization of the ARK also protects the salinization of the surface waters of the Amstelboezem. The bubble screen near Weesp can get turned on to increase effectiveness of the freshwater counter-pressure of the ARK in scenarios where not enough water is available for flowthrough of the ARK. Further, possible promising desalination strategies in the future might be salt marshes and biodesalinization with halophilic algae. Due to the multitude of Ecosystem Services that salt marshes can provide, including increasing biodiversity, these wetlands seem to be promising avenue to research further for desalinization of the Amsterdam surface water. However, desalinization rates of salt marshes have not been determined, therefore further research on the desalinization efficiency of these wetlands is needed. The wetland ecosystems might be able to fit in the aquatic ecosystem of Amsterdam, but this should be ecologically evaluated further. Biodesalinization with halophilic algae is still in its infancy but appears to be a promising method of industrially desalinizing water with minimum costs and high efficiency. In the scenario that mitigation of groundwater salinization is desired, improving urban soil health, constructing natural buffer zones along canals and increasing groundwater recharge could be interesting solutions for the City of Amsterdam to mitigate groundwater salinization.

7. Conclusions and recommendations

In conclusion, climate change will likely increase the salinity of the Amsterdam city waters. Increasing the flowthrough rate of the ARK can only marginally decrease the city water salinity. Increased city water salinity might increase groundwater salinity as well, through the permeability of quay walls. However, this should be verified with field tests. Ground- and surface water salinization might be detrimental to the urban aquatic and terrestrial ecosystem. Similarly, however, the ecological consequences of salinization on the terrestrial and aquatic ecosystems of Amsterdam need to be assessed further. Nonetheless, the salinity of the surface waters likely increasing with climate change brings forth a decision that needs to be made. Climate change is expected to lead to lower river discharges and less freshwater availability, particularly during dry periods. This stresses the national water system and asks for rethinking of how we should manage our freshwater supplies. At a high level, two solution paths can be identified:

- Mitigating city water salinization. A higher flowthrough rate of the Amsterdam-Rijnkanaal can decrease surface water salinization, but a large part of the salt load remains with projected sea level rise. Using nature-based desalination techniques, the city can reduce the salinity of its surface waters while providing a multitude of Ecosystem Services. Also, technological desalination techniques can be used, although coming at a higher cost. Further, reducing the opening frequency of the sluice gates at the NZK sluice gates can reduce salinity of the NZK, however, this comes at a significant economic cost. In addition, Rijkswaterstaat is responsible for the flowthrough rate of the ARK and sluice gate operation at the NZK, possible rendering these mitigation avenues outside of the zone of influence of the City of Amsterdam. The opening between the Amsterdam city waters and the IJ remains one of the main ways in which salinization of the canals in the city can happen. Therefore, reducing water flow between the IJ and the Amsterdam city waters might also effectively reduce city water salinization. This might also be an interesting avenue for further exploration.

- Accepting salinization and adapting to more saline ground- and surface water. An increased salinity in the surface waters of Amsterdam can increase the amount of brackish water in the city. This can be interesting from an ecological perspective, since large brackish ecosystems are relatively uncommon in the Netherlands due to the introduction of sluice gates between sea and rivers. Certain species like the eel, young mullet, three-spined stickleback, brackish water sturgeon shrimp, bait shrimp, trumpet lime tube worms, perch, and others thrive in brackish water. However, salinization of the surface water of Amsterdam might also lead to salinization of groundwater via permeable quay walls. Consequently, this might have negative effects on the terrestrial urban ecosystem. Therefore, the consequences of changes in species composition of both the urban terrestrial and aquatic ecosystems on urban Ecosystem Services provisioning needs to be further assessed. In addition, the effect of the permeability of quay walls on groundwater salinization needs to be studied.

An in-depth cost-benefit analysis between (a) the costs of accepting salinization of surface waters in Amsterdam for all the related stakeholders and (b) the costs of mitigating salinization in Amsterdam might shed more light on whether mitigation or adaptation is the best choice.

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Appendix

1. Informatie uit het gesprek met Erik Spronk, Programma Coördinator Grondwater, Waternet

Beweging van zout stadswater naar de stadsbodem

De kademuren in de stad zijn permeabel: grondwater kan door deze constructies heen stromen. In Amsterdam worden momenteel veel oude kademuren vervangen. Daarbij geldt als eis dat de nieuwe kademuur ook weer grondwater doorlatend moet worden aangelegd. Meestal wordt dit gedaan door gaten in damwanden, maar soms ook door permeabele kolommen. De permeabiliteit van de kademuren is belangrijk voor het grondwater: anders ontstaat er een soort grote badkuip. De kademuren (zowel de nieuwe als de oude) faciliteren de stroom van grondwater door naar de grachten wanneer de grondwaterstand hoger is dan de waterstand in de grachten. Dit kan bijvoorbeeld gebeuren in de winter, in periodes van veel neerslag. Water kan ook andersom stromen, van stadswater naar grondwater. Dit gebeurt wanneer het oppervlaktewater hoger staat dan het grondwater. Dit kan in droge periodes gebeuren, wanneer bomen en andere vegetatie veel water uit de bodem transpireren. In de zomer kan tegelijkertijd het oppervlaktewater in Amsterdam zouter zijn. Dit heeft te maken met de hoeveelheid water dat door het boezemsysteem stroomt. In de zomer is deze geringer vanwege meer druk op het Nederlandse watersysteem door droogte. Wanneer het boezemsysteem onder druk staat door deze droogte en er maar weinig water richting de Noordzee stroomt, dringt de zouttong van het Noordzeekanaal verder inlands richting het boezemsysteem. In zomers kan de zouttong al ter hoogte van de Berlagebrug komen. De waterafvoer van Amstel, Amsterdam-Rijnkanaal richting het Noordzeekanaal en de zee is dan dus niet genoeg om zoutintrusie tegen te gaan. Het zoutere stadswater kan dan dus vanwege een lage grondwaterstand de bodem intrekken, met potentiële gevolgen voor de gezondheid van de bodem en voor de vegetatie. Omdat van waterintrusie van oppervlaktewater richting de bodem vrij traag verloopt, wordt de kans op schade voor groen hierdoor nu klein geacht.

IJsselmeer, Markermeer en IJmeer: bron van zoetwater

Het IJsselmeer, Markermeer en IJmeer zijn in principe grote zoetwaterreservoirs. Deze grote regenton wordt hoofdzakelijk gevoed door de rivieren die er op uitkomen. Het zoeter maken van Amsterdams stadswater met water van het IJsselmeer, Markermeer en IJmeer wordt niet gedaan, omdat het zoete water van deze meren ook wordt gebruikt voor bijvoorbeeld drinkwaterproductie en de landbouw voor heel Noord-Nederland.

Verzilting van stads- en boezemwater (grondwater)

Waternet maakt zich voor Amsterdam weinig zorgen om verzilting van grondwater door zoute kwel, omdat dit eerder in diepe polders gebeurt. Verzilting van het oppervlaktewater via het Noordzeekanaal is het meeste aan de orde. Het zouter worden van het Noordzeekanaal gebeurt voornamelijk door het schutten van de Noordzeesluizen. In periodes van droogte kan Rijkswaterstaat een schutbeperking opleggen, zodat zoutintrusie wordt beperkt. Dit kan echter een grote economische impact hebben vanwege verminderde scheepvaart naar Amsterdam. Aan de andere kant heeft Rijkswaterstaat een verplichting om onherstelbare schade aan natuurgebieden (o.a. Natura 2000) die indirect in verbinding staan met het Noordzeekanaal en Amsterdam-Rijnkanaal te voorkomen. Dat betreft de boezenwateren van het Amstel, Gooi en Vecht gebied.

Het rotten van houten paalfunderingen

Houten paalfunderingen, die veel woningen in Amsterdam hebben, moeten nat blijven, anders gaan ze rotten en kan het de integriteit van het huis beïnvloeden. In droge periodes kan grondwater lager komen, waardoor deze funderingen kunnen gaan rotten. Er kan met een DIT-systeem oppervlaktewater naar de bodem worden getransporteerd. Wanneer het stadswater zouter is, kan de bodem hierdoor ook zouter worden. Hoe snel dat gaat is echter nog niet goed onderzocht. Als dit op veel verschillende plekken in Amsterdam wordt toegepast, kan dit ook een grote last worden voor het oppervlaktewatersysteem wat in tijden van droogte toch al onder druk staat. Hoe groot die last is, en of het watersysteem dit aan kan wordt nog onderzocht.

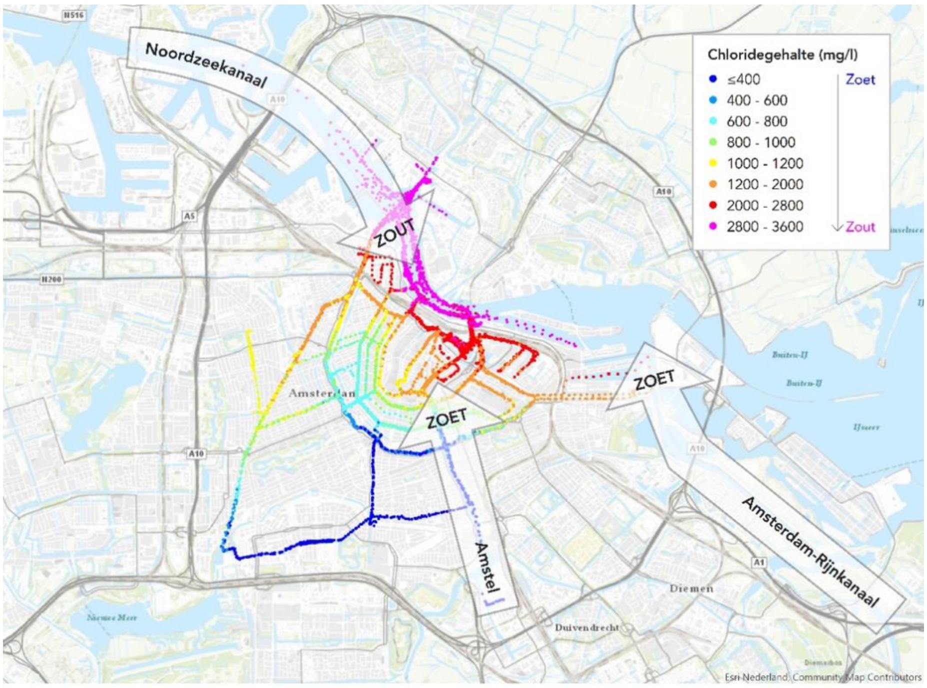
Grondwaterzorgplicht: kwantiteit, niet zozeer kwaliteit

Alle gemeenten in Nederland hebben een grondwaterzorgplicht. Die plicht houdt in dat gemeenten hun best moeten doen om in het openbaar terrein structurele nadelige gevolgen van de grondwaterstand zo veel mogelijk tegen te gaan, voor zover dit doelmatig is. Waternet voert voor de gemeente Amsterdam de grondwaterzorgplicht uit. Deze zorgplicht gaat dus in de basis over de kwantiteit van het grondwater, maar niet zozeer de kwaliteit van het grondwater. Verzilting van grondwater valt dus niet onder de verplichtingen van Waternet, maar kan wel rekening mee gehouden worden. Tegengaan van verzilting van de bodem zou waarschijnlijk wel in het takenpakket van de afdeling Bodem van de Gemeente Amsterdam zitten.

2. Informatie uit het gesprek met Kees Dekker, stadsecoloog Ingenieursbureau Gemeente Amsterdam

Huidige zoutwater gradiënt in de stad

Het stadswater is op dit moment al zouter, omdat het in connectie staat met het Noordzeekanaal. Waternet heeft een goede kaart van de verschillen in zout concentratie in het hele waternetwerk van Amsterdam, zie figuur hieronder. Er bestaat al een bepaalde gradiënt van zoutconcentratie in de stadswateren, waarbij de zoutconcentratie toeneemt naarmate het stadskanaal dichter bij het Noordzeekanaal is. De zouttong loopt tot ongeveer de Berlagebrug.



Afbeelding zoet-zout Amsterdam (Gemeente Amsterdam, 2023).

Amsterdam als estuarium

Vanuit een ecologisch perspectief op de stadswateren is het zouter/brakker worden van de stadswateren juist heel interessant. Zo kan je het brakkere watersysteem van Amsterdam juist zien als een urbaan estuarium. En omdat estuaria juist niet zo veel voorkomen en er veel verschillende unieke soorten worden gevonden, is het interessant om het water brakker te laten worden. Sommige aquatische soorten brengen delen van hun leven in de zee door, en andere delen van hun leven in brak water, maar juist niet in zoet water. Voor deze soorten is het vergroten brakke habitat juist voordelig. Door het tegenhouden van zeewater met sluizen zijn brakwater gebieden tegenwoordig minder groot, wat dit habitat voor unieke soorten verkleint. Hierdoor zijn estuaria tegenwoordig een zeldzaam type habitat. Het brakker worden van de Amsterdamse wateren kan wel zorgen voor een verandering in de huidige soortensamenstelling, maar in principe is dat niet erg omdat de natuur zich wel aanpast aan de nieuwe omstandigheden. Een voorbeeld van hoe een andere stad omgaat met brak water is het Rotterdam getijdenpark.

Zout tolerante vegetatie

Door het zouter worden van het oppervlaktewater kan de bodem ook verzilten (vanwege poreuze kademuren). Er zijn een aantal soorten die wel tegen een zoutere bodem kunnen, zoals de schietwilg. Het stadse terrestrische ecosysteem zou dan ook zich moeten aanpassen aan een zoutere omgeving. Wat dit betekent voor de stadse Ecosysteemdiensten zou dan verder onderzocht moeten worden.

Zorgen voor de juiste omstandigheden

Planten en waterorganismen hoef je in principe niet te plaatsen op plekken waar je wilt dat ze leven in de stad. Waar je voor moet zorgen is de juiste omstandigheden, zodat de soorten die graag in die omstandigheden leven daar vanzelf op af komen. Hetzelfde geldt voor brakwater soorten, die komen op de brakwater omstandigheden af zonder dat je ze daar hoeft te plaatsen.