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REVIEW

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Runoff water loaded with road de-icing salts: Occurrence, environmental impact and treatment processes

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Abstract

To ensure road safety during winter, it is necessary to use de-icing salts. However, the detrimental effects of these salts on aquatic ecosystems, vegetation, lakes, ground and surface water, and soils have become a major concern in recent years. This review aims to discuss the adverse environmental impact of using de-icing salts on the environment and explore current conventional methods used for managing and treating runoff water. Additionally, desalination techniques in terms of their effectiveness and energy requirements have been discussed. By comparing energy costs and considering the salinity levels of runoff water containing de-icing salts, electrodialysis as a potential technique is introduced to be combined with conventional approaches for removing and recovering salt from runoff water loaded from road de-icing salt.

KEYWORDS
de-icing salt, desalination techniques, environmental impact, management of road runoff water

1 | INTRODUCTION

Traditionally, the use of salt as a de-icing agent on roadways and sidewalks has been a commonly employed method used to lower the freezing point of ice and aid in melting. The utilization of de-icing salts on road surfaces can considerably enhance the safety of roadways and pavements by mitigating the potential for vehicular and pedestrian accidents resulting from reduced traction. The American Highway Users Alliance investigated the effect of applying de-icing salts to improve road surface traction, and the results showed that winter accidents reduced by more than 93% (Shi & O'Keefe, 2005). In the United States, approximately 20.3 million tonnes of salt were applied on roads in 2016 (Environment Canada, 2012). In a similar study, more than 6 million tonnes of de-icing salts were used for ice control and stabilization of Canadian roadways (Szklarek et al., 2022). The solubilization of road de-icing salts in rainwater and snowmelt can permeate into surface and groundwater, leading to a substantial increase in salinity (Dugan et al., 2020).

Table 1 summarizes the composition of melted water loaded with road de-icing salts in various countries (Canada, United States, Norway, Sweden and Germany), along with the US-EPA and WHO criteria for aquatic life. Notably, the composition of runoff water from road de-icing salts can vary owing to different parameters such as seasonal variations, precipitation level, traffic load and street sweeping (Huber et al., 2016). Regulating chloride concentrations is important for the protection of freshwater organisms and drinking water sources. As summarized in Table 1, the concentrations of chloride ions (Cl^-) in different countries exceed the limits set by the US-EPA and WHO. For instance, in Canada, Cl^- concentrations recorded in runoff water from road de-icing salts ranged from 50 to 600 mg/L. The Cl^- limit in Canada is 120 mg/L for chronic toxicity and 640 mg/L for acute toxicity (Canadian Council of Ministers of the Environment, 2011). Therefore, the direct discharge of such saline water into the environment adversely affects water quality, aquatic organisms and human health.

Sodium chloride (NaCl) is the most commonly used de-icing salt owing to its widespread availability and low cost. However, other

TABLE 1 Composition ranges of water loaded with de-icing salts recorded in different countries.

Parameters	Unit	Canada (Celis-Salgado et al., 2008; Fournier, 2021)		United States (Malina et al., 2005)	Norway (Kjensmo, 1997)	Sweden (Hallberg & Renman, 2008)	Germany (Hilliges et al., 2017)	US EPA criteria	WHO criteria
Location		Clément lake in Quebec City	Lakes in Muskoka, Ontario (Celis-Salgado et al., 2008)	The Austin Loop 360 site at Barton Creek and the Lubbock FM 289 site	The water masses of Lake Svinsjøen	A section of European motorway system E4 in the centre of Stockholm, Sweden	An arterial road (Derchinger Straße) in the city of Augsburg,		
pH		6.5–7.5	6.3–6.8			7–7.5	7.84	6.5–8.5	6.5–8.5
Conductivity	mS/cm	0.75–2.25			0.292	0.8–1.9	0.068–21.5		
Turbidity	NTU					6.1–19			
Total suspended solids	mg/L			30.8–119.2		5–14			
Total nitrogen	mg/L		0.06	1–3.4		2.3			
Phosphorus	mg/L		0.01	0.1–1.1		<0.1			
Chemical oxygen demand	mg/L	0.25–13.2		27.7–78.3		4.8–9.4			
Cl	mg/L	50–600		597–2604	14.4–17.5		0.93–7400	230–250	200
Na	mg/L	50–87	0.76		10.1–15				
Ca	mg/L	21–29	2.5		36–44	30.1–62.8			
Heavy Metal	mg/L								
-Cu				0.008–0.023		9–45	48	1.3	1
-Pb				0.002–0.018			17	0.21	0.05
-Zn				0.038–0.166		60–300	240	0.12	5
-Cd						0.1–0.3	<0.1	0.033	0.005
-Cr						5–15		0.57	
-Ni						0.7–15	7	0.47	

inorganic salts such as calcium chloride, magnesium chloride, potassium chloride, calcium magnesium acetate, potassium acetate and sodium acetate have been used as road de-icing agents. Overall, chloride-based de-icing agents are more efficient and cheaper than acetate-based ones. Salts are effective in melting ice at temperatures greater than their temperature thresholds. Figure 1 shows such values for various salts. According to the depicted figure, calcium chloride has the lowest temperature threshold compared to other salts. Despite sodium chloride having a higher temperature threshold than calcium chloride and magnesium chloride, it remains the preferred salt for road de-icing because of its affordability, abundance, ease of extraction, storage and distribution (Szklarek et al., 2022).

In addition to the anions and cations of salts, the presence of other compounds related to anti-caking agents is a concern in runoff water containing road de-icing salts. Anti-caking agents are used to prevent salt agglomeration when applied on roads (Mackiewicz & Mączka, 2021). In particular, a brine solution forms between salt crystals when the relative atmospheric humidity exceeds 70–75%. As relative humidity drops below 75%, water within the crystals evaporates, causing the brine solution to recrystallize and leading to salt agglomeration. Among various anti-caking agents, sodium ferrocyanide ($Na_4Fe[CN]_6$ $10H_2O$) is greatly recommended because it does not release free cyanide and is considered as a low-toxicity anti-caking agent (Kelting & Laxon, 2010).

Alternative techniques including utilizing ground source heat pipes, electric heating cables, infrared heat lamps, hot fluids, electrically conductive concrete and asphalt have been suggested as substitutes for de-icing salts. However, owing to their high operating costs and scalability challenges makes these approaches impractical (Zhao et al., 2011). Similarly, the use of renewable energy such as solar power is not feasible because it requires specific materials for road construction and pavements (Mirzanamadi et al., 2018). Another potential strategy for mitigating the adverse effects of road de-icing salts is to recover and recycle the salt. This can be achieved by installing drainage basins near road lanes to capture runoff water containing road de-icing salts (Craver et al., 2008).

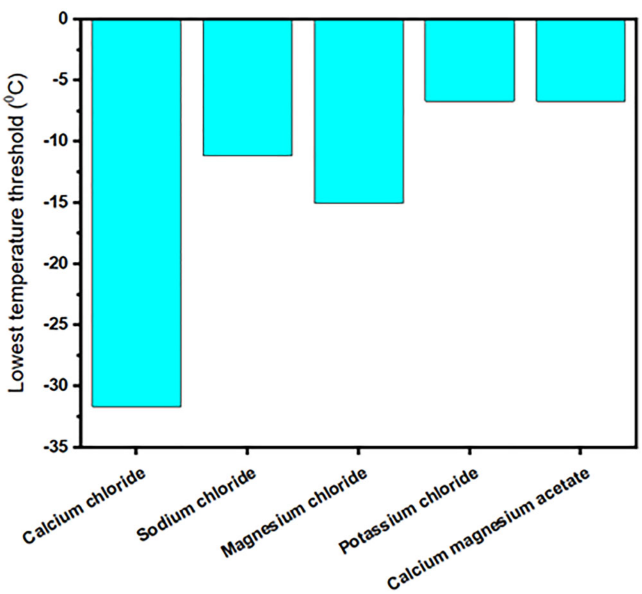

FIGURE 1 Thresholds temperature of the most common salts used for road de-icing purpose.

This review focuses on examining the extensive impacts of road salts on soil, groundwater, surface water and vegetation, while also exploring existing management practices and potential techniques for treating runoff water containing road de-icing salts. The paper is divided into three distinct sections, each addressing crucial aspects of the above-mentioned topics. In Section 2, the environmental effects of road de-icing salts are extensively discussed with the aim of providing a deeper understanding of the potential consequences associated with the use of road de-icing salts. Section 3 is dedicated to exploring the current management strategies and treatment techniques employed for mitigating the impact of runoff water loaded from road de-icing salt to assess their effectiveness and identify areas for improvement or further research. Finally, in Section 4, potential technologies for desalination are discussed with special attention to efficiency and energy costs.

2 | EFFECTS OF ROAD DE-ICING SALTS ON THE ENVIRONMENT

The main contaminant found in road de-icing salts is Cl^-. These ions possess high mobility and solubility in water, allowing them to easily permeate and affect nearby soil, surfaces and groundwater. The detrimental impact of elevated Cl^- concentrations on surrounding ecosystems, including soil, groundwater, surface water and vegetation, will be explored in this section.

2.1 | Impact on soil

Soil salination is one of the most challenging environmental concerns. The introduction of large salt ions into soil disrupts the cohesive forces that bind soil particles together, resulting in the expansion, swelling and dispersion of soil particles (Warrence et al., 2002). Moreover, the presence of NaCl causes a change in the structure and pH of soil through the substitution of Ca, Mg and K with Na ions. This shift in pH triggers the leaching of ammonium and dissolved organic matter from the soil, along with a decrease in organic N mineralization and nitrification (Garakani et al., 2018). Soil microorganisms play a crucial role in maintaining a soil structure that is sensitive to salt concentrations. The presence of salt can adversely impact the metabolism of soil organisms, thereby reducing soil fertility and promoting water resistance in the deeper layers (Shrivastava & Kumar, 2015).

Na ions deteriorate the soil structure because these ions decrease water circulation through the soil, which in turn reduces water infiltration (Bäckström et al., 2004). Additionally, elevated concentrations of Na may induce chemical reactions among organic and inorganic elements, thus disrupting the random distribution of the organic and inorganic elements. This can result in the displacement of natural cations, such as Zn, Cu, K and Mn, as well as dispersed soil colloids because of high concentrations of Na^+, ultimately leading to decreased soil permeability, reduced aeration and increased rates of surface runoff and erosion (Cunningham et al., 2008). Furthermore, the presence of Na^+ and Cl^- can hinder the growth of soil-dwelling microorganisms. In fact, Na^+ and Cl^- enhance the mobility of nutrients and heavy metals within the soil matrix, which is essential to fertilize soil microorganisms (Cunningham et al., 2008).

2.2 | Impact on vegetation

The impact of salt on roadside vegetation arises from its accumulation on the surface of foliage and branches, typically caused by splashing and spraying. This undesired consequence manifests in the form of drought, stunted growth, browning and shedding of leaves or needles and a decline of limbs (Li et al., 2014). Dissolved salts in runoff water also affect plants. As mentioned earlier, elevated concentrations of dissolved Na and Cl ions disrupt the balance of other mineral nutrients in the soil. Therefore, plants absorb chloride and sodium instead of essential plant nutrients such as potassium and phosphorus, leading to nutrient deficiencies. Cl^- can also reach leaves, where they interfere with photosynthesis and chlorophyll formation, resulting in leaf burn and die-back. Several factors, such as soil characteristics, plant species and age, plant tolerance, the availability and volume of nearby fresh water, runoff flow and salt type, play crucial roles in determining the extent of damage inflicted on vegetation (Czerniawska-Kusza et al., 2004). Considering the type of salts, it has been reported that non-chloride based salts have less of an effect on vegetation (Akbar et al., 2006).

2.3 | Impact on groundwater and surface water

Over time, runoff water has the potential to elevate the salt concentration of groundwater through penetration of excessive salt ions into the soil surface above the water source. The quantity and duration of precipitation, soil structure and condition, watershed topography and soil composition can contribute to determine the amount of salts and dissolved contaminants that make their way into groundwater. An increase in the sodium content can cause a decrease in the concentrations of calcium and magnesium in water, hence reducing water hardness (Lax & Peterson, 2009).

Runoff water finds its way into surface water through two ways: directly through overland flow and streams within the watershed and indirectly through soil and groundwater. The introduction of excess salt into surface water poses a major issue, notably leading to pronounced stratification (Marsalek, 2003). Taking a lake as an example of a surface water source, lake stratification can diminish the amount of dissolved oxygen in water, resulting in a greater depletion of oxygen over time (Bhateria & Jain, 2016). This oxygen shortage and inadequate nutrient distribution at affected depths jeopardizes the well-being of fish and other species (Wegner & Yaggi, 2001). Moreover, reduced oxygen levels trigger the release of phosphorus from the sediment at the lake bottom, which poses a threat to aquatic species (Hupfer & Lewandowski, 2008). The salinity of surface water also escalates when it receives runoff loaded with road de-icing salts, which severely affects aquatic species and freshwater organisms. Szklarek et al. (2022) reported a decline in the number of aquatic species as salinity increased from 1000 to 3000 ppm.

3 | MANAGEMENT AND TREATMENT OF RUNOFF WATER LOADED WITH ROAD DE-ICING SALTS

In many countries, runoff water is typically directed by conventional unit sewer systems and subsequently treated in municipal treatment plants. However, these traditional urban drainage approaches have adverse ecological effects. Therefore, it is necessary to identify more efficient practices for pollutant removal. Implementing management practices that preserve or restore the chemical and biological characteristics of water bodies can offer ecological and economic advantages. These practices can be classified into three categories: (a) drainage into combined sewer systems (CSSs) and treatment in purification plants, (b) treatment through sedimentation for separate sewer networks and (c) implementing structural management practices (Davis et al., 2022).

3.1 | Drainage into sewer systems and treatment in purification plants

There are two main types of sewerage systems: CSS and separate sewerage system (SSS). In a CSS, road runoff water, rainwater, domestic sewage and industrial wastewater are collected in one main pipe, while separate pipelines are used for SSSs. The benefits of SSSs include fewer health risks, no issues related to industrial wastewater discharge and improved efficiency during wet conditions. After undergoing simplified treatment, the outlet of an SSS can be reused for purposes such as irrigation. In a CSS, sewage is typically transported to a wastewater treatment plant (Webber et al., 2022). Moreover, CSSs have several advantages, such as (1) easier sewer cleaning owing to its larger size, (2) low maintenance costs and (3) self-cleaning properties owing to its high velocity. In contrast, SSSs have higher maintenance costs and often require effective anti-odour measurements (Abbas, 2019). Sewerage systems carry various types of pollutants including toxic materials and debris, which can impact the physicochemical and biological characteristics of the receiving water bodies. For instance, the discharge of sewage from a CSS without treatment can result in (a) oxygen depletion because of high organic matter loads, (b) increased turbidity that reduces photosynthesis and (c) elevated concentrations of pathogenic, faecal organisms, heavy metals and micropollutants in surface water (Passerat et al., 2011).

According to the Water Framework Directive 2000/60/EC in 2000 and the Clean Water Act of 1972 in the United States (WEF, 1997), most European cities, including Rome, Paris and London, as well as cities in the United States utilize CSSs for draining runoff water. Although SSSs have been implemented in most new metropolitan areas, CSSs still dominate in many older cities worldwide. For instance, CSSs account for 54% of sewer systems in Germany and 82% in Tokyo, Japan and 31% in China. However, converting CSSs to SSSs presents major challenges and carries high costs. Nevertheless, there is a noticeable global trend towards adopting SSSs, especially in industrialized countries (US Environmental Protection Agency Office of Water, 2004).

3.2 | Treatment through sedimentation for SSSs

Sedimentation is the main technique employed to eliminate suspended solids and pollutants associated with particles. The effectiveness of sedimentation as a treatment method relies on various factors, including the flow rate of the basin and its structural properties (Bruijn & Clark, 2003). Overall, sedimentation can be categorized into settlement ponds and tanks, sedimentation basins and grassed surface water channels.

Filter strips and grass swales are commonly used as pre-treatment for sedimentation (Silva et al., 2022). Grass swales are shallow, wide channels that are lined with vegetation and designed to direct water towards infiltration areas or watercourses. They trap contaminants through the filtering effects of vegetation (Scholz, 2014). Swale sedimentation primarily separates sand from coarser particles. This method allows for the effective removal of suspended particles, heavy metals, organic compounds, oils and greases (Shammaa & Zhu, 2001). Within this technique, the removal efficiency of suspended solids has been reported to exceed 50% (Bäckström, 2003). While the removal of nutrients is technically feasible, its efficiency is limited because of nutrient uptake by plants (Boger et al., 2018). However, a study conducted in Switzerland demonstrated that swale sedimentation was able to remove approximately 20–25% and 20% of total suspended particles and metals, respectively (Bäckström, 2002). Therefore, it should be noted that swales alone cannot be considered as comprehensive treatment systems for runoff water but can be valuable at pre-treatment stages before utilizing ponds or other infiltration facilities (Blecken, 2016). A grassed surface-water channel is a shallow, triangular or trapezoidal channel that is lined with grass. At specific points along the channel, water is directed into a separate pipe (Escarameia et al., 2006). The presence of grass in the channel is used to trap sediment, which slows down the flow of water. Consequently, suspended sediments and heavy metal pollutants such as Pb, Cu, Zn and Cd are expected to be captured by the grass leaves (Bäckström, 2003).

Settlement ponds and tanks are open permanent water reservoirs or underground tanks that store water for long periods. Accordingly, they allow particles to settle and undergo biological treatment prior to release into the receiving watercourse (Karlsson et al., 2010). Although settlement tanks with baffle tanks are less commonly used because of their higher cost compared to ponds and other alternatives, they offer efficient removal of heavy metals and suspended particles. However, the effectiveness of oil and grease removal through settling, adsorption and biodegradation is only moderate, while the removal of nutrients can vary from poor to moderate (Arantes et al., 2017).

The primary purpose of basin sedimentation is to retain runoff water and facilitate the settling of sediments, allowing a considerable portion of the sediment to accumulate in the basin. Sedimentation basins have shown removal efficiencies ranging from 30% to 65% for total metals and approximately 50% for phosphorus. In addition, sedimentation plays a role in removing oils and volatile pollutants that are bound to particles (Andersson et al., 2018). Compact or underground sedimentation (retention) basins can be employed when the structural requirements for building runoff water ponds are not met on the surface (Raspati et al., 2017).

3.3 | Structural management practices

Structural management practices can be categorized into four main subcategories based on their specific functions, as follows (Andersson et al., 2018):

- Collected in storage facilities (retention ponds, lagoons and wetlands)
- Infiltration systems (catchment wells, infiltration trenches and infiltration basins)
- Filter bed and landscaped ditch installations
- Alternative road structures (porous pavement and asphalt)

3.3.1 | Storage facility (reservoir) retention

Storage facilities (reservoirs) such as ponds and wetlands are used for retaining runoff water. Wet ponds are among the most common centralized runoff water treatment systems. Moreover, ponds are frequently supplied with a separate area known as a forebay, which is dedicated to the sedimentation of larger fractions (Blecken, 2016). Ponds are frequently combined with ditches and channels (Watson et al., 2017). According to Blecken (2016), ponds have demonstrated a removal efficiency of suspended particles ranging from 65% to 90%.

Constructed wetlands are another conventional runoff water treatment system (Zhou et al., 2009). This treatment system benefits from the roots of plants and microorganisms already present in the environment to degrade certain pollutants before discharging runoff water into surface water bodies (Mthembu et al., 2013). Constructed wetlands are often utilized to treat suspended solids, organic matter, faecal coliforms, nitrogen, phosphorus and toxic metals. Notably, they also exhibit some capability to treat partially de-icing salts present in runoff water (Roy, 2016). Wetlands and ponds with plant zones are generally effective in removing phosphorus (30–65%) and metals (approximately 60%) (Blecken, 2016). In comparison with ponds, wetlands have a higher capacity to separate dissolved pollutants (Kadlec et al., 2000). In a laboratory study conducted by Morteau et al. (2014), halophyte plants were used as phytodesalinators, and the results demonstrated a chloride removal rate of up to 97%, depending on the halophyte species. As for road de-icing salts, a study was conducted on Lake St-Augustin (Quebec, Canada), and the result indicated that wetlands are also effective for removing de-icing salts, particularly during dry weather periods, although the overall recovery amounts were not notable (Roy, 2016).

3.3.2 | Infiltration systems

Infiltration systems include catchment wells, trenches, basins, grassland-side ditches, road shoulders and road embankments (swales) (Eriksson et al., 2007). The natural removal of pollutants in these systems occurs through a combination of physical processes such as filtration, chemical reactions such as sulphide oxidation, and biological degradation under aerobic or anaerobic conditions (Kjeldsen et al., 2002). Infiltration systems can be implemented using two structures: soakaways and infiltration trenches. A soakaway is a structure filled with a specific media that facilitates hydraulic discharge into groundwater (Roldin et al., 2013). In contrast, infiltration trenches consist of rock-filled pits or large tank structures that allow percolation of runoff water into groundwater (Doyle et al., 2003). Road runoff treatment commonly involves local infiltration into road shoulders and embankments, while the use of grassed-side ditches in conjunction with grassed swales is also prevalent (Trocmé Maillard et al., 2013). These practices help to reduce the presence of coarse particles in runoff before they are directed to drains or allowed to percolate into the ground (Shokri et al., 2021).

Infiltration systems are anticipated to effectively remove suspended solids and the associated heavy metals through filtration and settlement (Siriwardene et al., 2007). Additionally, the removal of oils and greases can be achieved through filtering, adsorption, settlement and natural biodegradation (Maniquiz-Redillas & Kim, 2016). It is worth mentioning that the efficiency of pollutant removal depends on various factors including soil characteristics and the depth of the unsaturated zone beneath infiltration systems and groundwater (Clark & Pitt, 2007). Given that even a small amount of suspended solids can clog an infiltration basin, pre-treatment is crucial for the efficient use of infiltration systems (Hatt et al., 2007). However, one drawback of this system is the possibility of groundwater contamination, which is why infiltration systems require upstream pollution control (Mikkelsen et al., 1996).

3.3.3 | Filter bed and landscaped ditch installations

Different materials, including bio and absorptive compounds, have been investigated as reactive media in filter beds to treat runoff water. The principle of a filter bed is based on the use of a granular-type filtering material or a bed that is colonized by purifying biomass. Notably, biofilters have shown the capability of reducing suspended solids, carbon, total organic matter, BOD5, ammoniacal nitrogen and nitrates (Basu et al., 2016). In a study conducted by de Santiago-Martín et al. (2016), different materials such as anthracite coal, dolomite, limestone and pozzolan were assessed as reactive media for filter beds. According to their results, dolomite was introduced as an appropriate candidate for filter bed construction and maintenance owing to its physical properties such as fragmentation resistance and porosity. Moreover, the removal of NaCl was studied in batches with various concentrations ranging from 150 to 5000 mg/L Cl^-. The findings revealed that the removal efficiency varied depending on the element (Cl^- or Na^+). For instance, anthracite and dolomite exhibited higher Cl^- removal rates (48% and 59%, respectively), while limestone and pozzolan showed Na^+ removal rates of 54% and 67%, respectively.

3.3.4 | Alternative road structures (porous pavement and porous asphalt)

Alternative road structure practices aim to address runoff water through on-site treatment methods rather than traditional approaches. Porous pavements have the potential to remediate water runoff through infiltration (Boving et al., 2008). Porous asphalt pavements are made of deep-base, large-sized crushed stone and a relatively thin layer of an open-graded asphalt mix (Yong et al., 2013). The crushed stone base helps to retain runoff water and provides more time to penetrate the subbase and drain laterally. Other types of porous pavements include concrete lattice blocks and porous concrete mixtures. Compared to traditional asphalt, porous pavements contain lower concentrations of heavy metals, mineral oil, polynuclear aromatic hydrocarbons and suspended solids (Jiang et al., 2015). However, there are certain limitations to their use, such as their shorter lifespan, the potential clogging of voids, higher salt usage during winter and high construction costs (Scholz & Grabowiecki, 2007). Table 2 compares the typical removal efficiencies for a range of pollutants using different conventional treatment techniques.

4 | DESALINATION TECHNOLOGIES

Although several studies on runoff water treatment aim to remove heavy metals, polycyclic aromatic hydrocarbons, nitrogen and phosphorus, there is a lack of studies on practical treatment techniques to deal with the elimination of salts loaded in runoff water. Considering the failure of conventional practices in this regard, alternative desalination techniques could be adapted to remove salts from runoff water. Desalination is a process commonly used to remove total dissolved salts from salty water sources such as seawater and brackish water. Although the applicability of the techniques discussed

TABLE 2 Removal efficiency (per cent) of pollutants using conventional processes while treating road runoff water.

Best management practice	Phosphor	Nitrogen	Total heavy metals	Suspended solids	Oil	Polycyclic aromatic hydrocarbons	References
Vegetated filter strip	19–75	18–68		5–96			Ciou et al. (2012); Troitsky et al. (2019)
Constructed wetland	50	35	60	85	90	70	Andersson et al. (2018)
Grassed swale	20–78	10–86	65–93	54–94	80	60	Ciou et al. (2012); Luell et al. (2021); Troitsky et al. (2019)
Sedimentation basin	55	15	65	75	65	60	Andersson et al. (2018)
Infiltration trench	74	59		30–90			Yu et al. (2013)
Combined sedimentation and infiltration facilities	More than 65	More than 40	More than 80	More than 80	More than 80	More than 85	Troitsky et al. (2019)
Pavement	10–78		20–99	73–99	58–94		Troitsky et al. (2019)
Media filters	91	99		3–100			Yu et al. (2013)

below for removing salt loaded in runoff water may be limited, this section aims to review current desalination techniques and evaluate their potential for reducing salt content in runoff water. Several techniques allow for the elimination of dissolved salts in water, among which thermal distillation and membrane methods (reverse osmosis [RO], nanofiltration [NF] and electrodialysis [ED]) have gained considerable attention in practical applications (Mezher et al., 2011).

4.1 | Thermal technologies

Thermal desalination technologies are based on heating water to its boiling point and collecting the vapour phase through a condensate drum. There are three large-scale thermal methods: multistage flash distillation (MSF), multi-effect distillation (MED) and vapour compression distillation (VCD) (Gude, 2015). Suitable temperature in relation to ambient pressure, sufficient energy for vaporization to achieve optimal conditions and scale formation control are all crucial considerations for thermal technologies (Islam et al., 2018).

In MSF, saline water is preheated to a working temperature (typically 90–110°C) by steam. The heated saline water is subsequently transferred to the first stage. At this stage, the pressure is maintained below the heated saline water equilibrium pressure, resulting in partial evaporation of the saline water. Because each stage has a lower pressure than the previous one, a portion of the feed continues to flash at each stage. The vapour produced by flashing is then cooled down using a heat exchanger; thus, fresh water is obtained as the product. MED involves several evaporators, which evaporate saline water through a low-pressure chamber. To improve its efficiency, each stage of the process is run at a lower pressure compared to that of the preceding stage. Unlike MSF and MED, the VCD approach does not rely on an external source of heat (Saidur et al., 2011). The heat required for water evaporation is supplied through compression of the vapour.

4.2 | Membrane technologies

Membrane technology offers separation of particles, molecules, colloids and ions from aqueous solutions. The driving force for membrane processes is typically provided by pressure or electricity. RO and NF can be introduced as pressure-driven membrane processes, whereas ED is an example of an electrically driven membrane process (Duranceau, 2001). RO is highly effective in removing inorganic pollutants, dissolved salts and chemical components from water (Díez & Rosal, 2020). In particular, RO operates based on the osmotic pressure difference between salty and pure water. The principle of NF is similar to that of RO (Mohammad et al., 2015). In comparison with RO, membranes with larger pore sizes (less than 1 nm) are used in NF, which results in a lower pressure demand relative to that of RO (Yang et al., 2019). ED achieves the separation of ionic species from an aqueous solution by utilizing charged membranes and an electric potential difference (Gurreri et al., 2020). Hence, ED can remove salts from aqueous solutions by passing them through an ion-exchange membrane placed between two electrodes serving as the cathode and anode. Accordingly, cations and anions pass through cationic and anionic exchange membranes, respectively, thereby preventing the passage of contrary ions. This results in the dilution of salts in one compartment and the simultaneous concentration of salts in the adjacent compartment, as illustrated in Figure 2.

5 | COMPARISON BETWEEN DESALINATION TECHNOLOGIES

Further research and development of desalination techniques for treating runoff water loaded with road de-icing salts should be prioritized. As discussed in Section 4, thermal and membrane technologies are the main technologies used to efficiently remove salt from saline water. Selection of the desalination process depends on a variety of factors, including location, feed water salinity and quality, plant

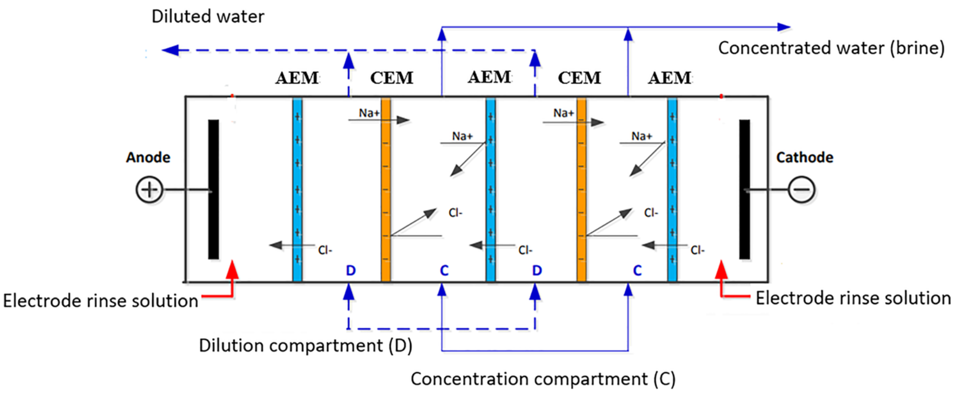

FIGURE 2 Schematic of the electrodialysis process consisted of three anionic-exchange membranes (AEMs) and two cationic-exchange membranes (CEMs). Electrode rinse solution is recirculated between compartments with electrodes, where diluted and concentrated water are discharged from dilution and concentration compartments, respectively.

capacity, energy and labour costs, and energy consumption, which is the most crucial factor when selecting a technology (Ghaffour et al., 2013; Reddy & Ghaffour, 2007). Specific energy consumption (kWh/m^3) is defined as amount of energy required to desalinate 1 m^3 of saline water. Owing to the lack of available data on energy consumption specifically for desalinating runoff water loaded with road de-icing salts, the above techniques were compared between salty and fresh water. Therefore, a comparison was made between these techniques using data from Mezher et al. (2011) and Al-Karaghouli and Kazmerski (2013). According to these studies, MED requires an energy consumption ranging from 14.45 to 21.35 kWh/m^3. Similarly, MSF and VCD consume energy in the range of 19.58–27.25 and 7–12 kWh/m^3, respectively. In contrast, the energy consumption for RO and ED has been reported to be approximately 0.7–5.5 kWh/m^3 (Okampo & Nwulu, 2020). As expected, thermal-based processes have higher energy requirements and capital costs because they produce a considerable amount of waste heat compared to membrane-based plants. By comparing energy costs, the selection of membrane-based techniques may arguably be a suitable option to combine with conventional techniques for the treatment of brackish and runoff water, given their lower energy consumption.

RO is the dominant membrane method used for brackish water desalination (Alghoul et al., 2009), accounting for 60 to 90% of the market share (Campione et al., 2018). However, ED accounts for only 4% of the total installed capacity of brackish water desalination plants, and there are several advantages of considering ED as a viable option for desalination of runoff water loaded with road de-icing salt. In particular, ED offers a higher water recovery rate and is less sensitive to changes in feed water quality compared to RO. It also has a lower specific energy consumption, making it more energy efficient (Al-Amshawee et al., 2020). Additionally, ED provides greater flexibility in adjusting treated water quality compared to other desalination techniques. The amount of salt removed by ED can be directly controlled by varying the applied voltage between the anode and cathode (Karimi et al., 2018).

Most studies comparing the energy requirements of ED and RO have consistently shown ED can operate more efficiently at lower feed salinities (Patel et al., 2021; Walha et al., 2007). In a study by Patel et al. (2021), the energy consumption of the ED and RO processes as a function of salt removal and water recovery was investigated. The results revealed that for feed water with a salinity of 3 g/L, ED had lower energy consumption than RO for a salt removal and water recovery of 90% and 80%, respectively. Conversely, similar salt removal rates at higher salinity concentrations (i.e., 5 g/L) showed that ED required more energy than RO. Similar results regarding the dependency of energy consumption on the initial salinity concentration (2600 and 5300 ppm) were obtained by Walha et al. (2007).

To benefit from advanced techniques, the authors implemented ED to desalinate runoff water loaded with road de-icing salts discharge to Lac Clément, located approximately 18 km north of Quebec City, Canada. Lac Clément receives several streams that drain percolated water from various roads upstream (Laurentian Highway, Talbot Boulevard and Yellow River Avenue). A study conducted by the Association for the Protection of the Environment of Lake Saint-Charles and Lake Clément (APEL) documented maximum conductivity and chloride concentrations of 3.7 mS/cm and 1000 mg/L, respectively (APEL, 2011). In a field study conducted by the authors, different samples were collected over 1 year from a sampling point located 140 m from the lake, and the results were in agreement with those obtained by APEL, ranging from 1.9 to 2.9 mS/cm for conductivity and 100 to 810 ppm for Cl ion concentration, depending on the sampling time. Considering the harsh and extreme cold experienced during Quebec's cold seasons, a considerable amount of salt is required for road safety purposes. Therefore, it may be inferred that the salinity of runoff water loaded with road de-icing salts does not exceed the above values, at least locally. Interestingly, this concentration range falls within the efficient operating range of ED. Accordingly, the relatively low operating cost and high efficiency of ED, within this salinity range, make it an economically viable option for desalinating runoff water loaded with road de-icing salts.

6 | CONCLUSION

While road de-icing salts are essential to ensure road safety, their usage has negative impacts on soil, ground/surface water and vegetation, making it crucial to develop new approaches to minimize the adverse impacts of their use on the environment. Conventional management and treatment techniques for runoff water mainly remove heavy metals, polycyclic aromatic hydrocarbons, nitrogen and phosphorus but are not effective in removing road de-icing salts. In contrast, the high energy consumption and operational cost associated with thermal desalination techniques and RO make them economically impractical for this purpose. Meanwhile, the salinity of road runoff water resulting from de-icing salt usage is not expected to exceed 2000 ppm. Notably, ED has demonstrated capability at a low cost and with high efficiency at salinities not exceeding this value. Therefore, combining ED with other conventional techniques could be a useful hybrid system for the treatment of runoff water loaded with road de-icing salts.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper.

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REFERENCES

Abbas, A.H. (2019) *An innovative design for a separate sewer system*. United Kingdom: Liverpool John Moores University.

Akbar, K.F., Headley, A., Hale, W.H. & Athar, M. (2006) A comparative study of de-icing salts (sodium chloride and calcium magnesium acetate) on the growth of some roadside plants of England. *Journal of Applied Sciences and Environmental Management*, 10(1), 67–71. Available from: https://doi.org/10.4314/jasem.v10i1.17307

Al-Amshawee, S., Yunus, M.Y.B.M., Azoddein, A.A.M., Hassell, D.G., Dakhil, I.H. & Hasan, H.A. (2020) Electrodialysis desalination for water and wastewater: a review. *Chemical Engineering Journal*, 380, 122231. Available from: https://doi.org/10.1016/j.cej.2019.122231

Alghoul, M.A., Poovanaesvaran, P., Sopian, K. & Sulaiman, M.Y. (2009) Review of brackish water reverse osmosis (BWRO) system designs. *Renewable and Sustainable Energy Reviews*, 13(9), 2661–2667. Available from: https://doi.org/10.1016/j.rser.2009.03.013

Al-Karaghouli, A. & Kazmerski, L.L. (2013) Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, 24, 343–356. Available from: https://doi.org/10.1016/j.rser.2012.12.064

Andersson, J., Mácsik, J., van der Nat, D., Norström, A., Albinsson, M., Åkerman, S., Hernefeldt, P.C. & Jönsson, R. (2018) Sustainable design and maintenance of stormwater treatment facilities: reducing highway runoff pollution.

APEL. (2011) Suivi du lac Clément: evaluation de la contamination par les sels de voirie. Consulté le 8 janvier 2022a. https://agiro.org/wpcontent/uploads/Suivi_du_lac_Clement_Evaluation_de_la_contamination_par_les_sels_de_voirie_APEL_2011_web.pdf

Arantes, R., Schveitzer, R., Magnotti, C., Lapa, K.R. & Vinatea, L. (2017) A comparison between water exchange and settling tank as a method for suspended solids management in intensive biofloc technology systems: effects on shrimp (litopenaeus vannamei) performance, water quality and water use. *Aquaculture Research*, 48(4), 1478–1490. Available from: https://doi.org/10.1111/are.12984

Bäckström, M. (2002) Grassed swales for urban storm drainage. Luleå Tekniska Universitet.

Bäckström, M. (2003) Grassed swales for stormwater pollution control during rain and snowmelt. *Water Science and Technology*, 48(9), 123–132. Available from: https://doi.org/10.2166/wst.2003.0508

Bäckström, M., Karlsson, S., Bäckman, L., Folkeson, L. & Lind, B. (2004) Mobilisation of heavy metals by deicing salts in a roadside environment. *Water Research*, 38(3), 720–732. Available from: https://doi.org/10.1016/j.watres.2003.11.006

Basu, O.D., Dhawan, S. & Black, K. (2016) Applications of biofiltration in drinking water treatment—a review. *Journal of Chemical Technology and Biotechnology*, 91(3), 585–595. Available from: https://doi.org/10.1002/jctb.4860

Bhateria, R. & Jain, D. (2016) Water quality assessment of lake water: a review. *Sustainable Water Resources Management*, 2(2), 161–173. Available from: https://doi.org/10.1007/s40899-015-0014-7

Blecken, G. (2016) Literature review Stormwater control measures for quality treatment. Tech. rep. 2016-05. Bromma: Svenskt Vatten Utveckling.

Boger, A.R., Ahiablame, L., Mosase, E. & Beck, D. (2018) Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: a tutorial review. *Environmental Science: Water Research & Technology*, 4(4), 478–486. Available from: https://doi.org/10.1039/C7EW00230K

Boving, T.B., Stolt, M.H., Augenstern, J. & Brosnan, B. (2008) Potential for localized groundwater contamination in a porous pavement parking lot setting in Rhode Island. *Environmental Geology*, 55(3), 571–582.

Bruijn, H.D & Clark, S.E. (2003) Research and development of effective suspended solids removal from stormwater runoff in collection systems using in-line lamella plate separators. Terrehill Concrete Products.

Campione, A., Gurreri, L., Ciofalo, M., Micale, G., Tamburini, A. & Cipollina, A. (2018) Electrodialysis for water desalination: a critical assessment of recent developments on process fundamentals, models and applications. *Desalination*, 434, 121–160. Available from: https://doi.org/10.1016/j.desal.2017.12.044

Canadian Council of Ministers of the Environment. (2011) Canadian water quality guidelines: chloride ion scientific criteria document. Canadian Council of Ministers of the Environment, Winnipeg, Canada.

Celis-Salgado, M.P., Cairns, A., Kim, N. & Yan, N.D. (2008) The FLAMES medium: a new, soft-water culture and bioassay medium for Cladocera. *Internationale Vereinigung für Theoretische Und Angewandte Limnologie: Verhandlungen*, 30(2), 265–271. Available from: https://doi.org/10.1080/03680770.2008.11902123

Ciou, S.-K., Kuo, J.-T., Hsieh, P.-H. & Yu, G.-H. (2012) Optimization model for BMP placement in a reservoir watershed. *Journal of Irrigation and Drainage Engineering*, 138(8), 736–747. Available from: https://doi.org/10.1061/(ASCE)IR.1943-4774.0000458

Clark, S.E. & Pitt, R. (2007) Influencing factors and a proposed evaluation methodology for predicting groundwater contamination potential from stormwater infiltration activities. *Water Environment Research*, 79(1), 29–36. Available from: https://doi.org/10.2175/106143006X143173

Craver, V.O., Fitch, G.M. & Smith, J.A. (2008) Recycling of salt-contaminated storm water runoff for brine production at Virginia department of transportation road-salt storage facilities. *Transportation Research Record*, 2055(1), 99–105. Available from: https://doi.org/10.3141/2055-12

Cunningham, M.A., Snyder, E., Yonkin, D., Ross, M. & Elsen, T. (2008) Accumulation of deicing salts in soils in an urban environment. *Urban Ecosystem*, 11(1), 17–31. Available from: https://doi.org/10.1007/s11252-007-0031-x

Czerniawska-Kusza, I., Kusza, G. & Dużyński, M. (2004) Effect of deicing salts on urban soils and health status of roadside trees in the Opole region. *Environmental Toxicology*, 19(4), 296–301. Available from: https://doi.org/10.1002/tox.20037

Davis, A.P., Hunt, W.F. & Traver, R.G. (2022) *Green stormwater infrastructure fundamentals and design*. Hoboken, New Jersey: John Wiley & Sons.

de Santiago-Martín, A., Michaux, A., Guesdon, G., Constantin, B., Despréaux, M. & Galvez-Cloutier, R. (2016) Potential of anthracite, dolomite, limestone and pozzolan as reactive media for de-icing salt removal from road runoff. *International journal of Environmental Science and Technology*, 13(10), 2313–2324. Available from: https://doi.org/10.1007/s13762-016-1085-1

Díez, B. & Rosal, R. (2020) A critical review of membrane modification techniques for fouling and biofouling control in pressure-driven membrane processes. *Nanotechnology for Environmental Engineering*, 5(2), 1, 15–21. Available from: https://doi.org/10.1007/s41204-020-00077-x

Doyle, P., Hennelly, B. & McEntee, D. (2003) SUDS in the greater Dublin area. In Proceeding of the UNESCO International Hydrological Programme, National Hydrology Seminar. OPW, Ireland, 77–82.

Dugan, H.A., Skaff, N.K., Doubek, J.P., Bartlett, S.L., Burke, S.M., Krivak-Tetley, F.E., et al. (2020) Lakes at risk of chloride contamination. *Environmental Science and Technology*, 54(11), 6639–6650. Available from: https://doi.org/10.1021/acs.est.9b07718

Duranceau, S. (2001) Reverse osmosis and nanofiltration technology: inorganic. Softening and Organic Control.

Environment Canada. (2012) Five-year review of progress: code of practice for the environmental management of road salts. Environment Canada, Ottawa.

Eriksson, E., Baun, A., Scholes, L., Ledin, A., Ahlman, S., Revitt, M., et al. (2007) Selected stormwater priority pollutants—a European perspective. *Science of the Total Environment*, 383(1–3), 41–51. Available from: https://doi.org/10.1016/j.scitotenv.2007.05.028

Escarameia, M., Todd, A. & Watts, G. (2006) Pollutant removal ability of grassed surface water channels and swales: literature review and identification of potential monitoring sites. TRL Limited.

Fournier, I. (2021) Salinisation des écosystèmes lacustres par les sels de voirie: perturbations chimiques et réponses des communautés microbiennes. Université Laval.

Garakani, A.A., Haeri, S.M., Cherati, D.Y., Givi, F.A., Tadi, M.K., Hashemi, A.H., et al. (2018) Effect of road salts on the hydro-mechanical behavior of unsaturated collapsible soils. *Transportation Geotechnics*, 17, 77–90. Available from: https://doi.org/10.1016/j.trgeo.2018.09.005

Ghaffour, N., Missimer, T.M. & Amy, G.L. (2013) Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination*, 309, 197–207. Available from: https://doi.org/10.1016/j.desal.2012.10.015

Gude, V.G. (2015) Energy storage for desalination processes powered by renewable energy and waste heat sources. *Applied Energy*, 137, 877–898. Isah, A. S.; Takaijudin, H.; Singh, B.; Singh, M. Principles and modes of distillation in desalination process, 2022. Available from: https://doi.org/10.1016/j.apenergy.2014.06.061

Gurreri, L., Tamburini, A., Cipollina, A. & Micale, G. (2020) Electrodialysis applications in wastewater treatment for environmental protection and resources recovery: a systematic review on progress and perspectives. *Membranes*, 10(7), 146. Available from: https://doi.org/10.3390/membranes10070146

Hallberg, M. & Renman, G. (2008) Removal of heavy metals from road runoff by filtration in granular slag columns. In Proceedings of the 11th international conference on urban drainage. Edinburgh, Scotland, UK.

Hatt, B.E., Fletcher, T.D. & Deletic, A. (2007) Treatment performance of gravel filter media: implications for design and application of stormwater infiltration systems. *Water Research*, 41(12), 2513–2524. Available from: https://doi.org/10.1016/j.watres.2007.03.014

Hilliges, R., Endres, M., Tiffert, A., Brenner, E. & Marks, T. (2017) Characterization of road runoff with regard to seasonal variations, particle size distribution and the correlation of fine particles and pollutants. *Water Science and Technology*, 75(5–6), 1169–1176. Available from: https://doi.org/10.2166/wst.2016.576

Huber, M., Welker, A. & Helmreich, B. (2016) Critical review of heavy metal pollution of traffic area runoff: occurrence, influencing factors, and partitioning. *Science of the Total Environment*, 541, 895–919. Available from: https://doi.org/10.1016/j.scitotenv.2015.09.033

Hupfer, M. & Lewandowski, J. (2008) Oxygen controls the phosphorus release from Lake sediments–a long-lasting paradigm in limnology. *International Review of Hydrobiology*, 93(4–5), 415–432. Available from: https://doi.org/10.1002/iroh.200711054

Islam, M.S., Sultana, A., Saadat, A.H.M., Shammi, M. & Uddin, M.K. (2018) Desalination technologies for developing countries: a review. *Journal of Scientific Research*, 10(1), 77–97. Available from: https://doi.org/10.3329/jsr.v10i1.33179

Jiang, W., Sha, A., Xiao, J., Li, Y. & Huang, Y. (2015) Experimental study on filtration effect and mechanism of pavement runoff in permeable asphalt pavement. *Construction and Building Materials*, 100, 102–110. Available from: https://doi.org/10.1016/j.conbuildmat.2015.09.055

Kadlec, R., Knight, R., Vymazal, J., Brix, H., Cooper, P. & Haberl, R. (2000) *Constructed wetlands for pollution control: processes, performance, design and operation*. London, England, UK: IWA Publishing.

Karimi, L., Ghassemi, A. & Zamani Sabzi, H.Z. (2018) Quantitative studies of electrodialysis performance. *Desalination*, 445, 159–169. Available from: https://doi.org/10.1016/j.desal.2018.07.034

Karlsson, K., Viklander, M., Scholes, L. & Revitt, M. (2010) Heavy metal concentrations and toxicity in water and sediment from stormwater ponds and sedimentation tanks. *Journal of Hazardous Materials*, 178(1–3), 612–618. Available from: https://doi.org/10.1016/j.jhazmat.2010.01.129

Kelting, D.L. & Laxon, C.L. (2010) Review of effects and costs of road de-icing with recommendations for winter road management in the Adirondack Park. Adirondack Watershed Institute.

Kjeldsen, P., Barlaz, M.A., Rooker, A.P., Baun, A., Ledin, A. & Christensen, T.H. (2002) Present and long-term composition of MSW landfill leachate: a review. *Critical Reviews in Environmental Science and Technology*, 32(4), 297–336. Available from: https://doi.org/10.1080/10643380290813462

Kjensmo, J. (1997) The influence of road salts on the salinity and the meromictic stability of Lake Svinsjøen, southeastern Norway. *Hydrobiologia*, 347(1–3), 151–159. Available from: https://doi.org/10.1023/A:1003035705729

Lax, S. & Peterson, E.W. (2009) Characterization of chloride transport in the unsaturated zone near salted road. *Environmental Geology*, 58(5), 1041–1049. Available from: https://doi.org/10.1007/s00254-008-1584-6

Li, Z., Liang, Y., Zhou, J. & Sun, X. (2014) Impacts of de-icing salt pollution on urban road greenspace: a case study of Beijing. *Frontiers of Environmental Science & Engineering*, 8(5), 747–756. Available from: https://doi.org/10.1007/s11783-014-0644-2

Luell, S.K., Winston, R.J. & Hunt, W.F. (2021) Monitoring the water quality benefits of a triangular swale treating a highway runoff. *Journal of Sustainable Water in the Built Environment*, 7(1), 05020004. Available from: https://doi.org/10.1061/JSWBAY.0000929

Mackiewicz, P. & Mączka, E. (2021) The impact of water and road salt with anti-caking agent on the stiffness of select mixes used for the road surface. *Materials*, 14(6), 1345. Available from: https://doi.org/10.3390/ma14061345

Malina, J.F., Barrett, M.E., Jackson, A. & Kramer, T. (2005) Characterization of stormwater runoff from a bridge deck and approach highway: effects on receiving water quality.

Maniquiz-Redillas, M.C. & Kim, L.-H. (2016) Evaluation of the capability of low-impact development practices for the removal of heavy metal from urban stormwater runoff. *Environmental Technology*, 37(18), 2265–2272. Available from: https://doi.org/10.1080/09593330.2016.1147610

Marsalek, J. (2003) Road salts in urban stormwater: an emerging issue in stormwater management in cold climates. *Water Science and Technology*, 48(9), 61–70. Available from: https://doi.org/10.2166/wst.2003.0493

Mezher, T., Fath, H., Abbas, Z. & Khaled, A. (2011) Techno-economic assessment and environmental impacts of desalination technologies. *Desalination*, 266(1–3), 263–273. Available from: https://doi.org/10.1016/j.desal.2010.08.035

Mikkelsen, P.S., Jacobson, P. & Fujita, S. (1996) Infiltration practice for control of urban storm water. *Journal of Hydraulic Research*, 34(6), 827–840. Available from: https://doi.org/10.1080/00221686.1996.10525034

Mirzanamadi, R., Hagentoft, C.-E., Johansson, P. & Johnsson, J. (2018) Anti-icing of road surfaces using hydronic heating pavement with low temperature. *Cold Regions Science and Technology*, 145, 106–118. Available from: https://doi.org/10.1016/j.coldregions.2017.10.006

Mohammad, A.W., Teow, Y.H., Ang, W.L., Chung, Y.T., Oatley-Radcliffe, D.L. & Hilal, N. (2015) Nanofiltration membranes review: recent advances and future prospects. *Desalination*, 356, 226–254. Available from: https://doi.org/10.1016/j.desal.2014.10.043

Morteau, B., Galvez-Cloutier, R. & Leroueil, S. (2014) Développement d'un système de traitement des eaux de ruissellement routier par marais épurateur adapté et lit filtrant réactif. Université Laval.

Mthembu, M., Odinga, C., Swalaha, F.M. & Bux, F. (2013) Constructed wetlands: a future alternative wastewater treatment technology. *African Journal of Biotechnology*, 12(29), 4542–4553. Available from: https://doi.org/10.5897/AJB2013.12978

Okampo, E.J. & Nwulu, N.I. (2020) Optimal energy mix for a reverse osmosis desalination unit considering demand response. *Journal of Engineering, Design and Technology*, 18(5), 1287–1303. Available from: https://doi.org/10.1108/JEDT-01-2020-0025

Passerat, J., Ouattara, N.K., Mouchel, J.M., Rocher, V. & Servais, P. (2011) Impact of an intense combined sewer overflow event on the microbiological water quality of the Seine River. *Water Research*, 45(2), 893–903. Available from: https://doi.org/10.1016/j.watres.2010.09.024

Patel, S.K., Biesheuvel, P.M. & Elimelech, M. (2021) Energy consumption of brackish water desalination: identifying the sweet spots for electrodialysis and reverse osmosis. *ACS ES&T Engineering*, 1(5), 851–864. Available from: https://doi.org/10.1021/acsestengg.0c00192

Raspati, G.S., Azrague, K. & Jotte, L. (2017). Review of stormwater management practices. Klima. 2050 report.

Reddy, K.V. & Ghaffour, N. (2007) Overview of the cost of desalinated water and costing methodologies. *Desalination*, 205(1–3), 340–353. Available from: https://doi.org/10.1016/j.desal.2006.03.558

Roldin, M., Locatelli, L., Mark, O., Mikkelsen, P.S. & Binning, P.J. (2013) A simplified model of soakaway infiltration interaction with a shallow groundwater table. *Journal of Hydrology*, 497, 165–175. Available from: https://doi.org/10.1016/j.jhydrol.2013.06.005

Roy, S. (2016) Traitement du ruissellement routier chargé en sels de déglaçage et en métaux lourds par un marais épurateur construit et adapté.

Saidur, R., Elcevvadi, E.T., Mekhilef, S., Safari, A. & Mohammed, H.A. (2011) An overview of different distillation methods for small scale applications. *Renewable and Sustainable Energy Reviews*, 15(9), 4756–4764. Available from: https://doi.org/10.1016/j.rser.2011.07.077

Scholz, M. (2014) Rapid assessment system based on ecosystem services for retrofitting of sustainable drainage systems. *Environmental Technology*, 35(9–12), 1286–1295. Available from: https://doi.org/10.1080/09593330.2013.866170

Scholz, M. & Grabowiecki, P. (2007) Review of permeable pavement systems. *Building and Environment*, 42(11), 3830–3836. Available from: https://doi.org/10.1016/j.buildenv.2006.11.016

Shammaa, Y. & Zhu, D.Z. (2001) Techniques for controlling total suspended solids in stormwater runoff. *Canadian Water Resources Journal*, 26(3), 359–375. Available from: https://doi.org/10.4296/cwrj2603359

Shi, X. & O'Keefe, K. (2005) Synthesis of information on anti-icing and pre-wetting for winter highway maintenance practices in North America. Pacific Northwest Snowfighters in Collaboration with the Washington State Department of Transportation.

Shokri, M., Kibler, K.M., Hagglund, C., Corrado, A., Wang, D., Beazley, M., et al. (2021) Hydraulic and nutrient removal performance of vegetated filter strips with engineered infiltration media for treatment of roadway runoff. *Journal of Environmental Management*, 300, 113747. Available from: https://doi.org/10.1016/j.jenvman.2021.113747

Shrivastava, P. & Kumar, R. (2015) Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences*, 22(2), 123–131. Available from: https://doi.org/10.1016/j.sjbs.2014.12.001

Silva, T.F.G., Beltrán, D., de Oliveira Nascimento, N., Rodríguez, J.P. & Mancipe-Muñoz, N. (2022) Assessing major drivers of runoff water quality using principal component analysis: a case study from a Colombian and a Brazilian catchments. *Urban Water Journal*, 1–13. Available from: https://doi.org/10.1080/1573062X.2022.2029913

Siriwardene, N.R., Deletic, A. & Fletcher, T.D. (2007) Clogging of stormwater gravel infiltration systems and filters: insights from a laboratory study. *Water Research*, 41(7), 1433–1440. Available from: https://doi.org/10.1016/j.watres.2006.12.040

Szklarek, S., Górecka, A. & Wojtal-Frankiewicz, A. (2022) The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution—a review. *Science of the Total Environment*, 805, 150289. Available from: https://doi.org/10.1016/j.scitotenv.2021.150289

Trocmé Maillard, M., Brodmann, R., Gutmann, M., Boivin, P. & Kaufmann, P. (2013) Strassenabwasserbehandlung an Nationalstrassen–Richtlinie.

Troitsky, B., Zhu, D.Z., Loewen, M., van Duin, B. & Mahmood, K. (2019) Nutrient processes and modeling in urban stormwater ponds and constructed wetlands. *Canadian Water Resources Journal/Revue Canadienne des Ressources Hydriques*, 44(3), 230–247. Available from: https://doi.org/10.1080/07011784.2019.1594390

US Environmental Protection Agency Office of Water. Report to congress: impacts and control of CSOs and SSOs. Office of Water, 2004.

Walha, K., Amar, R.B., Firdaous, L., Quéméneur, F. & Jaouen, P. (2007) Brackish groundwater treatment by nanofiltration, reverse osmosis and electrodialysis in Tunisia: performance and cost comparison. *Desalination*, 207(1–3), 95–106. Available from: https://doi.org/10.1016/j.desal.2006.03.583

Warrence, N.J., Bauder, J.W. & Pearson, K.E. (2002) Basics of salinity and sodicity effects on soil physical properties, 129. Department of Land Resources and Environmental Sciences, Montana State University–Bozeman, MT, 1-29.

Watson, E.B., Wigand, C., Davey, E.W., Andrews, H.M., Bishop, J. & Raposa, K.B. (2017) Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for southern New England. *Estuaries and Coasts*, 40(3), 662–681. Available from: https://doi.org/10.1007/s12237-016-0069-1

Webber, J.L., Fletcher, T., Farmani, R., Butler, D. & Melville-Shreeve, P. (2022) Moving to a future of smart stormwater management: a review and framework for terminology, research, and future perspectives. *Water Research*, 218, 118409. Available from: https://doi.org/10.1016/j.watres.2022.118409

Wegner, W. & Yaggi, M. (2001) Environmental impacts of road salt and alternatives in the New York City watershed. *Stormwater*, 2(5), 24–31.

Yang, Z., Zhou, Y., Feng, Z., Rui, X., Zhang, T. & Zhang, Z. (2019) A review on reverse osmosis and nanofiltration membranes for water purification. *Polymers*, 11(8), 1252. Available from: https://doi.org/10.3390/polym11081252

Yong, C.F., McCarthy, D.T. & Deletic, A. (2013) Predicting physical clogging of porous and permeable pavements. *Journal of Hydrology*, 481, 48–55. Available from: https://doi.org/10.1016/j.jhydrol.2012.12.009

Yu, J., Yu, H. & Xu, L. (2013) Performance evaluation of various stormwater best management practices. *Environmental Science and Pollution Research International*, 20(9), 6160–6171. Available from: https://doi.org/10.1007/s11356-013-1655-4

Zhao, H., Wu, Z., Wang, S., Zheng, J. & Che, G. (2011) Concrete pavement deicing with carbon fiber heating wires. *Cold Regions Science and Technology*, 65(3), 413–420. Available from: https://doi.org/10.1016/j.coldregions.2010.10.010

Zhou, J.B., Jiang, M.M., Chen, B. & Chen, G.Q. (2009) Emergy evaluations for constructed wetland and conventional wastewater treatments. *Communications in Nonlinear Science and Numerical Simulation*, 14(4), 1781–1789. Available from: https://doi.org/10.1016/j.cnsns.2007.08.010

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