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Current European approaches in highway runoff management: A review

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ABSTRACT

Highway runoff is one of the most significant non-point sources of pollution for the terrestrial and aquatic environment with biological, physical, and chemical effects. Considering local characteristics, treatment practices, and determining factors are essential for highway runoff management. The aim of this paper is to survey the review of highway runoff management in Europe with emphasis on runoff characterization, treatment, and modeling approaches and identifying possible knowledge gaps exists based on our review. The results showed that highway runoff has spatiotemporal variation, which is the main factor in the regional selection of the best management practice (BMP). Also, recent studies have poorly deemed characterization of highway runoff in different climatic scenarios, performance assessment of the current BMPs, and uncertainty analysis in modeling approaches. Furthermore, economic and risk analysis, along with decision-making methods, provide an optimum plan for the design and operation of BMPs.

1. Introduction

Roads are an integrated part of sustainable development and have a vital role in life quality (E.-E. Commission 2011, Meland, 2015). At the same time, road runoff is a pollution source for the aquatic environment (Angermeier et al., 2004). Highway construction and operation may reduce the quality of receiving waters by increasing the concentration of suspended solids (SS), metals and, hydrocarbons such as oil and Polycyclic aromatic hydrocarbons (PAHs). During operation, road runoff is a mix of exhaust and wear products from breaks, tires, and asphalt. Tunnels accumulate these products, and without any cleaning systems, highly contaminated tunnel wash water may impact receiving waters. De-icing salts and asphalt wear due to studded tires may increase the impact during wintertime (Meland, 2015, Meland, 2010). A vast spectrum of road runoff pollutants has been reported. In addition to the already mentioned (Helmreich et al., 2010, Lee et al., 2011, Brenčič et al., 2012, Kayhanian et al., 2012, Zhao et al., 2016), microplastics (such as 1,3-diphenyl guanidine (DPG) (Carr et al., 2016, Horton et al., 2017, Siegfried et al., 2017, Zhang et al., 2018, Li et al., 2018), nitrogen, carbon and sulfur oxides, nitrogen and phosphorus nutrients, oil and grease, hexa (methoxymethyl) melamine (HMMM) (Ma et al., 2021, Zuo et al., 2011, Monira et al., 2021, Wang et al., 2022, Campanale et al., 2020, Johannessen et al., 2021) may contribute (Helmreich et al., 2010, Kayhanian et al., 2012, Brezonik and Stadelmann, 2002, Lee et al., 2004, Chen et al., 2009). Road runoff adversely affects the aquatic environment (Meland, 2010, Hindar and Nordstrom, 2015).

Road runoff can be collected and treated before discharge to water bodies. As the most harmful substances are associated with particulate matter, the primary mechanism for removal is sedimentation. Sedimentation ponds may be efficient if constructed properly based on runoff volumes and particle characteristics and if maintained properly. Supplementary mechanisms for removal of contaminants are enhanced sedimentation by use of coagulants, filtration (smaller particles and colloidal contaminant), adsorption (dissolved contaminant), and microbial processes (degradation, reduction/oxidation) (Andersson et al., 2018).

Best management practices (BMPs) combine ecological and economic advantages and aims at keeping or restoring the chemical and ecological status of downstream water bodies (Poresky et al., 2011, Stagge et al., 2012). According to the above-mentioned removal mechanisms, the most common European BMPs for runoff treatment are: a) infiltration into road shoulders, road embankments and grassed side ditches (e.g., biofiltration systems and sand filters) (Davis, 2005, Hatt et al., 2009, A.A. Bloorchian et al., 2016), b) stormwater ponds and wetlands, c) sedimentation basins and centralized infiltration facilities (Chen et al., 2009, A.A. Bloorchian et al., 2016, Barbosa and Hvitved-Jacobsen, 2001, Hogan and Walbridge, 2007, Houser and Pruess, 2009), and d) combined sedimentation and infiltration facilities (Andersson et al., 2018). The assessments of BMPs typically focus on the

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quantitative and qualitative control of runoff (Bedan and Clausen, 2009, Leroy et al., 2015, A.A. Bloorchian et al., 2016).

Significant highway runoff is associated with precipitation events and, therefore, has considerable spatio-temporal variation (Thomson et al., 1997, Gan et al., 2008) controlled by a set of factors. Most important may be traffic characteristics (vehicle density and composition, speed, fuel type), the intensity of the event and the antecedent dry weather period (Helmreich et al., 2010, Crabtree et al., 2006, Huber et al., 2016, Horstmeyer et al., 2016). Also, data from measuring programs in downstream water bodies may also be affected by chemical and biological processes and the degree of contaminant dilution. Data from different sites may thus be highly variable even if, e.g., the traffic density is similar (Helmreich et al., 2010, Lee et al., 2004, Crabtree et al., 2006, Bulc and Sajn Slak, 2003).

To achieve the desired level of treatment, quantitative and qualitative information of the road runoff and its constituents is inevitable (Brenčič et al., 2012, Kayhanian et al., 2012, Barrett et al., 1998). Such information is particle size distribution, associated pollutants, and the fraction of pollution in the dissolved and bioavailable phase. Consequently, much research has been conducted to evaluate the association of metals and PAHs with particles (Kayhanian et al., 2004, Zhao et al., 2010), and appropriate cleaning systems.

Besides, for decision-making in sustainable highway management, there is a need to predict road runoff quality. This could be done by the use of models that include the most important regulating parameters (Barbosa, 2007, Barbosa and Fernandes, 2009, Chow et al., 2011, Barbosa et al., 2012). Data from monitoring during ordinary conditions and particularly throughout storm events should be the basis for such models (Munoz-Carpena and Parsons, 2004). The lack of detailed physical, chemical, and hydrological understanding of all processes involved has made the modeling approaches as an ideal solution for addressing the challenge of predicting runoff pollutant concentrations (Opher et al., 2009). Understanding through modeling approaches is an effective way to deal with this problem [50, 52]. Changes in the catchment or other input variables may affect the BMPs' effectiveness and runoff variations and may be better understood by running a calibrated model (Barbosa et al., 2012, German et al., 2005, Elliott and Trowsdale, 2007, Abrishamchi et al., 2010).

Considering all of those aspects, this review paper contributes to the understanding of highway runoff management through attending characterization and treatment of the runoff and considering the modeling approaches and current legislation adopted by different countries. Furthermore, this study points to future research challenges for environmentally sound management of highway runoff.

2. Highway runoff characterization

The highway runoff characterization must be performed at a local base because of site-specific and climatic characteristics that may affect the quantity and quality of highway runoff (Barbosa, 2007). Recently, much of the literature pay attention to characteristics of highway runoff (Lee et al., 2011, Kayhanian et al., 2012, Gan et al., 2008, Barrett et al., 1998, Mangani et al., 2005, Kayhanian et al., 2007, Nie et al., 2008, Lee, 2012, Hilliges et al., 2016, Winston and Hunt, 2016, Q. Wang et al., 2017). Proper characterization is dependent on sampling strategy and analytical methods. As road runoff is associated with precipitation events, the sampling should be during such events. Sampling at increasing flow, top flow, and end of event may give rise to event mean concentrations (EMC), and these may be averaged in order to get the site mean concentration (SMC). The SMC may, in turn, be multiplied with annual runoff to get the site-specific annual transport (SAT) of contaminants. By using this approach, it would be easier to compare between sites and also compare data from before and after the establishment of treatment facilities.

Contaminants may or may not be present in measurable concentrations depending on the analytical methods at hand. It could be that the methods produce numbers for heavy metals but not for PAHs due to high detection limits relative to the current concentrations. A pre-study at the site should therefore be performed in order to establish relevant analytical methods (Kayhanian et al., 2003).

Pollutants in highway runoff are known to appear both in particulate and dissolved form. The pollutant form is strongly influenced by the rainfall pH, the solids' characterization (i.e., size, solubility of all substances, and porosity), the surface type, site properties, and pavement residence (Meland, 2010, Andersson et al., 2018, Huber et al., 2016, Meland et al., 2010). Heavy metals like copper, nickel, zinc, and cadmium often can be found in the dissolved phase, while chromium and lead are mostly particle-bound (Huber et al., 2016, Gunawardana et al., 2015). Therefore, due to exchange reactions, cadmium and zinc have more mobility than chromium (Jayarathne et al., 2017). Key inorganic contaminants in road runoff include heavy metals, particularly zinc, copper, and lead (Wicke et al., 2012). While about 50% of the inorganic pollutants are adsorbed to particles with a diameter between 60–200 μm, a fraction of the nutrients is attached to fine particles. The concentration of heavy metals which is bound to the particles (mass of metal per mass of particulate matter) is almost the same in the particle size range of 63–250 μm. The main difference in this regard is related to the particle size distribution in the highway runoff, in which most of the suspended particles in the effluent are less than 63 μm (Baum et al., 2021). Moreover, the removal of fine particles (<63 μm), which is considered 30–40% of the total mass of sediment (<2 mm) is vital (Kayhanian et al., 2012).

The main concerns related to the entry of particulate matters from highway effluents into the environment include increasing water turbidity (Regier et al., 2020), habitat alteration (Gillis et al., 2021), esthetic and recreational problems, and the creation of the erosion banks (Beryani et al., 2021). On the other hand, dissolved pollutants change the surface and groundwater resources quality and make the problems such as algal bloom development (Smith et al., 2020), ammonia and nitrate toxicity, damage to plants, fish mortality, bioaccumulation in the food chain (Karlsson et al., 2010, Du et al., 2017, Luo et al., 2019), and esthetic problems. In addition, the design, operation, maintenance, and effectiveness of treatment approaches highly depend on the pollutant forms (Kayhanian et al., 2012, Huber et al., 2016, Hilliges et al., 2017). For example, the intervening effects of salt-containing effluents are very significant both in the environment and in the treatment process. About 60% of highway salts enter surface water sources and about 40% enter soil and groundwater sources (Perera et al., 2013, Schuler and Relyea, 2018, Green et al., 2008, Szklarek et al., 2021). The entry of salt-containing effluent into groundwater and soil causes the cationic exchange of Na^{+} ion with Ca^{+2} and Mg^{+2} ions (Robinson et al., 2017), thereby lowering the pH, and flushing heavy metals, nutrients, and organic matter, and reducing the retention of water in the soil (Schuler and Relyea, 2018, Green et al., 2008, Szklarek et al., 2021, Rommel et al., 2020). Therefore, the runoff containing road salt reduces the efficiency of biofilter systems in heavy metals treatment (Søberg et al., 2017). In surface water, it reduces the macrophyte biomass, decomposition of highway runoff by micro-organisms and detritivores, and specific denitrifying activity (Szklarek et al., 2021, Lancaster et al., 2016, Tyree et al., 2016, Stoler et al., 2018). Highway runoff characterization is different in diverse regions, mainly due to regional traffic load, site-specific characteristics, climatic factors, and maintenance practices (see Table 1).

The considerable variation in the parameter values is due to site-specific features but probably also to different sampling strategies and analytical methods, as already referred to. ADT, antecedent dry period, drainage area, maximum rain intensity, and land use may represent the most important regulating factors (Kayhanian et al., 2003).

Many of the measured parameters of road runoff correlate (Table 2). The most interesting correlations are those where harmful contaminants (e.g., heavy metals and PAHs) correlate with in-expensive and easily measurable parameters (e.g., turbidity, TSS, and DOC) that are suited for

Table 1
Concentration ranges and mean values of various highway runoff parameters for different vehicle densities.

Constituent	Range & (Mean) values for different ADT (vehicles/day)				
	(Robertson et al., 2019)	(Hilliges et al., 2016)	(Kayhanian et al., 2007)	(Han et al., 2006)	(Kayhanian et al., 2003)
	49,500	< 9690	2000–328,000	> 260,000	1800–259,000
pH (pH unit)		7.11–8.15 (7.83)	4.5–10.1 (7.1)		
Temp. (°C)			4.7–25.4 (12.5)		
Turbidity (NTU)			44–1400 (471)	11–171 (46.8)	
EC (μs/cm)		0.068–21.5 (-)	5–743 (96.1)		
Cl (mg/L)		0.93–7400 (-)	4.3–9000 (1260)		
Hardness (mg/L CaCO$_3$)					2–448 (49.5)
COD (mg/L)	148 ± 49			19–2283 (252.5)	2.4–480 (123.8)
DOC (mg/L)		2.1–21(6.87)	1.2–483 (18.7)	2.9–848.8 (66.9)	
O&G (mg/L)			1–20 (6.6)		
TDS (mg/L)			3.7–1800 (87.3)		
TOC (mg/L)			1.6–530 (21.8)		
TPH (mg/L)			0.12–13 (2.2)		
TSS (mg/L)			1–2988 (112.7)	8.8–466.4 (67.7)	
As* (μg/L)			0.5–20 (1.0)		
Cd* (μg/L)	0 ± 0		0.2–8.4 (0.24)	0.5–17.8 (1.4)	
Cr* (μg/L)	50 ± 37		1–23 (3.3)	0.5 19.3 (2.8)	
Cu* (μg/L)			1.1–130 (14.9)	5.2–735.3 (65.9)	
Fe* (μg/L)			32–3310 (378)		
Ni* (μg/L)	14 ± 7		1.1–40 (4.9)	0.8–229.2 (15.7)	
Pb* (μg/L)	80 ± 45		1–480 (7.6)	0.5–43.4 (4.9)	
Zn* (μg/L)	698 ± 399		3–1017 (68.8)	42.3–8150 (415)	
As** (μg/L)	6 ± 5		0.5–70 (2.7)		
Cd** (μg/L)		<0.1–14 (0.36)	0.2–30 (0.7)	0.4–20.2 (1.8)	
Cr** (μg/L)			1–94 (8.6)	2.3–40.1 (9.7)	
Cu** (μg/L)	143 ± 50	10–273 (67.1)	1.2–270 (33.5)	15.9–920.8 (92.9)	
Fe** (μg/L)			1400–104,000 (18,500)		
Ni** (μg/L)		1.0–67 (12.1)	1.1–130 (11.2)	2.4–253.7 (20)	
Pb** (μg/L)		<1.0–92 (21.4)	1–2600 (47.8)	4.6–151.6 (25.8)	
Zn** (μg/L)		49–1300 (311)	5.5–1680 (187.1)	83.3–8881 (506.3)	
NO3-N (mg/L)			0.01–4.8 (1.07)	0.3–34.7 (2.7)	
Ortho-P (mg/L)			0.01–2.4 (0.11)		
Total P (mg/L)	2.660 ± 2.295		0.03–4.69 (0.29)	0.1–8.2 (0.9)	
TKN (mg/L)			0.1–17.7 (2.06)	0.8–111.3 (9.6)	
Calcium (mg/L)					4.5–66.8 (12.7)
Magnesium(mg/L)					1–21.8 (3.2)
Sodium (mg/L)					1–56 (11)
Sulfate (mg/L)					0.23–57 (4.2)
Total coliform (MPN/100 mL)					2–900,000 (21,970)
Fecal coliform (MPN/100 mL)					2–205,000 (6083)
Oil and grease (mg/L)	144 ± 127			1.5–80.2 (14)	1–226 (10.6)

ADT (mean daily traffic on an annual basis),
* Metals (dissolved),
** Metals (total)

Table 2
Correlations between different road runoff parameters expressed by R^2.

Surrogate pairs	References	
	(Kayhanian et al., 2012)	(Han et al., 2006)
Fe & (Cu, Pb)	0.8	
TSS & (COD)	0.95	0.4
TSS & (DOC, TKN)		0.34, 0.4
COD & (TKN)		0.84
DOC & (TKN, COD, O&G)	0.8	0.92, 0.81, NA*
TOC & (DOC)	0.96	
TPH & (O&G)	0.86	
TSS & (Turbidity)	0.8	
Fe & (Total Pb, Cr, Cu, Zn, Pb)	0.8–0.9	
TDS & (EC, Cl)	0.8, 0.9	
DOC & (Total PAHs, pesticides)	0.8	
O&G & (COD, DOC)	0.8	
TSS & (Particulate metals, Total PAHs)	0.8	NA, 0.52–0.61
TSS & (Particulate Cu, Ni, Zn, Pb)	0.85	0.58–0.61

COD (chemical oxygen demand), DOC (dissolved organic carbon), O&G (oil and grease), TKN (total Kjeldahl nitrogen), TPH (total petroleum hydrocarbons), TDS (total dissolved solids), TOC (total organic carbon).

continuous measuring. After the correlation at a site is established this may be used to 1) reduce the analytical cost by measuring less expensive parameters than the actual target parameters (Kayhanian et al., 2012), and to 2) measure a suitable proxy parameter on a continuous basis to document variability and get a more robust basis for further calculations. Determining such correlations may also provide an improved basis for pollutant source identification as well as modeling efforts (Lee et al., 2004, Gan et al., 2008).

In this table, the value of the correlation between different constituents of road runoff is provided. For example, based on Han et al. (Han et al., 2006), the correlation between DOC and TKN, COD, and O&G are 0.92, 0.81, and not available (NA), respectively. While Kayhanian et al. (Kayhanian et al., 2012) give 0.8 as the correlation between DOC and each of the three parameters of TKN, COD, and O&G.

Three aggregate parameters (TSS, TDS, and TOC) along with iron (Fe) make the most reliable correlations with 13 other water quality parameters, including turbidity, DOC, O&G, TKN, TPH, EC, Cl, Cd, Ni, Cr, Cu, Zn, Pb. This shorter list as surrogate parameters consequently reduces the overall monitoring and analyzing cost (Kayhanian et al., 2012).

An essential but rarely described part of highway runoff is from tunnel washing. Tunnels are washed on a regular basis with detergents to clean walls for accumulated dirt. The wash water is highly polluted with contaminants, especially metals and PAH's (Meland, 2010, Vikan and Meland, 2013), from the exhaust, asphalt wear and tire wear, and demands adequate handling. This is not always the case, however, and the practice differs between countries (Meland et al., 2010). As with road runoff, the characteristics of tunnel wash water may vary significantly due to different tunnel use, traffic, and maintenance practices (Barbosa et al., 2007).

The consumption of road salt for traffic safety produces highly soluble and mobile chlorides, which may have an impact on the physical and biological status of water bodies. Road runoff with high salt concentrations may leach to lakes, accumulate in the bottom waters due to its weight, and cause meromixis. Meromixis means that the lake does not go through complete mixing in spring and autumn. Deicing salt is a growing environmental concern not only in the Nordic countries but also in other European countries (Meland, 2015).

3. Highway runoff treatment

Treatment approaches to reduce pollution loads have been assessed widely (Helmreich et al., 2010, Pontier et al., 2004, Starzec et al., 2005, Vollertsen et al., 2007, Stephansen et al., 2012, Hilliges et al., 2013, Leroy et al., 2016, Gang et al., 2016, Sun, 2017). Generally, the governing factor for the decision to treat runoff or not is traffic density defined as the mean daily traffic on an annual basis (AADT) (Horstmeyer et al., 2016). However, due to the weak correlation between ADT and pollution concentration, caused by several governing factors as already described, other approaches for decisions on treatment should be sought. The Highways Agency Water Risk Assessment Tool (HAWRAT), developed and used in the UK, can compensate for the weaknesses of ADT as a basis. The tool requires a comprehensive understanding of quantitative and qualitative characteristics, treatment level, and the local conditions available for the design of BMPs (Barbosa et al., 2012).

Treatment systems during construction and operation may differ depending on the anticipated pollutants. We, therefore, prefer to split the presentation according to this. European countries have somewhat different priorities when it comes to BMP's and treatment systems; see below

The current practice in European countries may illustrate the variation in both the basis for and the implementation of BMP's. In Austria, the NRA develops smaller and less space-demanding units, which focus on collecting and treating the first flush by sedimentation and filtration. This is in contrast to the situation in Switzerland, where the NRA develops larger treatment plants to receive runoff from larger areas. They claim that this is more cost-efficient than smaller treatment facilities (Meland, 2015). Our opinion is rather that the best technology should be selected site-specifically. Soil filters for retaining particles are currently the most common treatment in Austria (Andersson et al., 2018).

In tunnels, water from the surrounding rock is often separated from the polluted tunnel runoff for monitoring and pH adjustment (Meland, 2015). The clogging of soil filters is a common problem, and no electronic control systems are in use as far as we have seen. However, regular sampling of the inlet and outlet, as well as studies on the load and condition of the soil filter, are mandatory. In some countries, the result of the analysis is reported to the authorities to follow up and control.

In Switzerland, road runoff is handled depending on soil type, hydrogeological situation, ADT, and runoff flow rates (Andersson et al., 2018). Three solutions for treating road runoff are approved, including a) infiltration over the road edge, b) collection and transportation to infiltration/filtration facilities, and c) discharge into the municipal drainage/sewage network. The NRA has started to use new centralized treatment plants consisting of storing, sedimentation, and filtration. The current practice for tunnel wash water is to use sedimentation basins. Separation of leaked water from surrounding rock and polluted runoff is mandatory (Meland, 2015).

In Ireland, all new road projects have a drainage system that directs the runoff to the nearest wastewater treatment plant. Ireland has only three tunnels, in which the wash water is collected and transported/or directed to an approved wastewater treatment plant (WTP). In Italy, the NRA has established small tanks to retain first-flush runoff, comparable with the practice in Austria. Tunnel wash water used to be discharged untreated to the surroundings but is now collected and transported to an approved WTP. In Sweden, road runoff and drainage from road construction are commonly infiltrated via road shoulders, embankments, and open trenches. When infiltration is not possible, road runoff is collected via culverts and open trenches for treatment (Andersson et al., 2018). Since the 1990s, sedimentation ponds and wet infiltration ponds have been used frequently as treatment methods. The tunnel wash water is generally discharged untreated, but runoff from larger tunnels is directed to a sedimentation basin inside the tunnel combined with chemical treatment such as flocculation and/or pH adjustment (Meland, 2015). Modern treatment facilities for roads with high ADT are inspected and include sampling several times per year according to an approved control plan. In Germany, the treatment of road runoff in 90% of all roads in rural areas is local infiltration in the road shoulder and embankment. The most common treatment facilities consist of a concrete basin for the removal of coarse sediments along with an oil separation wall, followed by soil infiltration (Meland, 2015, Andersson et al., 2018). The frequency of inspections is not regulated in Germany, but the recommendations in H-KWES (control and maintenance of drainage systems on roads outside of closed local areas) are in widespread use (FGSV 2012). Control of sediment accumulation levels and sampling is often neglected, and the removal of accumulated sediments is infrequent. In Poland, the use of small sedimentation tanks, oil interceptors, and infiltration/wet ponds is growing (Meland, 2015).

Infiltration basins combined with a forebay (as a pre-sedimentation pond) are widely applied in Austria and Germany and should be interesting for other countries. They improve the quality of the discharged water by providing better retention than in ponds and are more cost-effective. Further testing in colder climates is, however, recommended (Andersson et al., 2018).

In Denmark and England, ponds are considered as the best practice. Due to vast agricultural activities, controlling the water quality at peak flows are prioritized as pollution control in Denmark (Meland, 2015).

In Norway, sedimentation ponds are the most frequently used treatment system, but also wetlands, infiltration ponds/ditches are utilized (Meland, 2015). Tunnel wash water from today's' tunnels is discharged to the surrounding terrain untreated. Mandatory treatment facilities for new tunnels have been recommended (Meland et al., 2010), and sedimentation basins have been implemented in many cases. Regular maintenance of stormwater facilities includes cleaning and mowing of grass, sediment removal, cutting vegetation two times a year, clearance, and maintenance of access roads to the facility and control of security (locks and fences). Monitoring programs to document the performance of treatment facilities are not generally used, but it is mandatory to build access roads for service vehicles to allow for proper maintenance. There is a general need in Norway to assess the performance of treatment systems (Meland, 2015, Andersson et al., 2018).

Pollutants of bridge runoff are like normal road runoff. Thus, for most of the European NRAs, bridge runoff has the same requirements as for normal road runoff. This may cause problems for streams and rivers receiving road runoff not only directly from the bridge through openings but also from the part of the road that drains to the bridge. This review shows that Switzerland, Germany, and Austria have a wide range of BMPs, while tunnel wash water is typically controlled using sedimentation basins/ponds (Meland, 2015).

In most cases, proper treatment system is determined based on site-specific parameters on one hand and cost-efficiency, national and

Table 3
Estimated removal efficiency (%) in various types of treatment systems.

Best Management Practice	Tot-P	Tot-N	Tot-Cu	Tot-Zn	SS	Oil	PAH-16	Reference
Grassed swale	7.5	5.3			49			(Luell et al., 2021)
	30	40	65	65	70	80	60	(Andersson et al., 2018)
	3–78	-62–86*			1–94			(Yu et al., 2013)
	29–99	14–61		68–93	30–97			(Ahiablame et al., 2012)
	20–40	10–35						(Troitsky et al., 2019)
	3–78	-62–86			1–94			(Yu et al., 2013)
	53	74	75	73	54	91		(Barrett et al., 1998)
Vegetated Filter Strip	40–50	40–50						(Troitsky et al., 2019)
	-19–75	-18–68			5–96			(Yu et al., 2013)
Bioretention systems	-3–99	32–99	43–99	62–97	47–99	83–97		(Ahiablame et al., 2012)
Pond	50	35	60	65	80	80	70	(Andersson et al., 2018)
	8.4	18.7			67.8			(Yazdi et al., 2021)
	50–75	30–40						(Troitsky et al., 2019)
					97			(Charters et al., 2015)
Wetland	50	35	60	65	85	90	70	(Andersson et al., 2018)
Constructed	50–75	25–55						(Troitsky et al., 2019)
Wetland	0–93	-40–48			5–97			(Yu et al., 2013)
Sedimentation Basin	55	15	60	65	75	65	60	(Andersson et al., 2018)
Centralized infiltration facilities (soil infiltration)	65	40	65	85	80	80	85	(Andersson et al., 2018)
Infiltration trenches	-29–74	-54–59			27–89			(Yu et al., 2013)
Sand Filter/Filtration Basin	50–65	30–45						(Troitsky et al., 2019)
Combined sedimentation and infiltration facilities	≥65	≥40	≥65	≥85	≥80	≥80	≥85	(Andersson et al., 2018)
permeable	10–78		20–99	73–99	58–94			(Ahiablame et al., 2012)
pavements	59–81	59–81						(Troitsky et al., 2019)
Media filters	-8–91	-59–99			3–100			(Yu et al., 2013)

* the minus sign (-) shows negative removal efficiency

international regulations, and recommendations from local authorities on the other hand.

Typical removal efficiencies for a set of contaminants in different treatment systems are summarized in Table 3. The most commonly applied BMPs are grassed swales, retention ponds, sedimentation basins, and wetland basins. While these approaches are of great potential to reduce runoff pollution, the literature reveals that BMPs show low removal efficiency for many pollutants (e.g., < 40% for total N, total P, and COD). Moreover, the lack of information about the ability of these systems to remove other contaminants such as organic compounds and the variety in the type and number of reported sites pose a challenge to fully understanding the performance of BMPs (Okaikue-Woodi et al., 2020). A part of the variation is probably due to inadequate sampling strategies and site-specific features (Tedoldi et al., 2016). Another issue related to BMPs is the nature of pollutants, seasonal variations, and the intervening effects of pollutants on each other (J. Wang et al., 2017). In winter, de-icing salt-containing effluents greatly reduce the removal efficiency of sedimentation systems due to density differences (Rommel and Helmreich, 2018). Also, biological treatment systems may have reduced performance in colder climatic conditions and should not be adopted without further considerations.

One of the key factors in the variation of results is the sampling protocol. The sampling process typically includes grab and composite methods depending on the rainfall patterns. Composite samples could be time or flow proportional. While a flow-weighted composite sample could be equated using a series of grab samples summed with flow reflecting weights, the programmable automatic flow weighted samplers are much better than grab sampling collections and provide more accurate results for EMCs and mass first flush ratios (Ma et al., 2009).

Variation in quantity and quality of contaminant loadings are significant issues in the design of BMPs. Average daily traffic, hydraulic and hydrological conditions, together with characteristics of the receiving water body, are essential factors (Li and Barrett, 2008, Sharma et al., 2016). Climate change effects, such as longer dry periods and increased intensity of heavy rainstorms are demanding (Field et al., 2012). With an increase of 1.5 °C and 2 °C due to global warming, the load of heavy metals increase by more than 90% and 50% on urban surfaces and stormwater runoff, respectively (B. Wijesiri et al., 2020). Longer dry weather periods increase the accumulation of pollutants. More intense precipitation events and retaining particles in treatment systems will necessitate further cleaning, which is already a demanding issue and will be an even larger challenge in the future (Sharma et al., 2016, Zhang et al., 2019). The climatic change effects on runoff quantity have been studied (Semadeni-Davies et al., 2008, Arnbjerg-Nielsen et al., 2013), but the impacts of climatic change on road runoff quality and treatment performance is less considered. A study by Sharma et al. (Sharma et al., 2016) in Denmark showed that under climate change scenarios, there is little change in retention pond performance for TSS removal. In contrast, its effect on the removal of soluble materials (such as Cu) and slowly biodegradable organic matters is significant. Therefore, it is necessary to investigate further the performance of existing BMPs in climate change scenarios and for the different forms of pollutants (particle-bound or dissolved). Another knowledge gap is related to changing pollutant behavior on impervious surfaces in rainfall and dry periods, particularly for the first flush phenomenon (B. Wijesiri et al., 2020).

Appropriate technologies for runoff treatment are site-specific, governed by the recipients' vulnerability (Chen et al., 2009, Petersen et al., 2016), and should be part of highway planning (Stagge et al., 2012, Fassman, 2012). Efficient environmental protection is a united part of sustainable highways design and maintenance (Bulc and Sajn Slak, 2003).

4. Modeling approaches

The main goals of highway runoff quality modeling are to characterize the highway runoff (spatio-temporal variation of pollutants), provide input to receiving water analysis as well as the basis for decisions on cost-effective BMP's (Tsihrintzis and Hamid, 1997, Sutherland et al., 2006). The basic components of present-day water models are a) rainfall-runoff modeling and b) transport modeling. There is a need to establish a relationship between water chemistry parameters and runoff and how this relationship varies with regulating parameters. Hence, it is essential to have realistic hydraulic or hydrologic models, which have the appropriate spatial and temporal resolution required for the problem (Zoppou, 2001). Accordingly, site-specific hydraulic and hydrological datasets are utilized for calibration and verification of the model. Calibrated models may then be applied to assess different scenarios, such as the fate and transport of contaminants over time and for future conditions (Sutherland et al., 2006). Proper time-series for calibration/verification, as well as for estimating model uncertainty, are of great importance (Barbosa et al., 2012). A variety of modeling techniques capable of simulating water quality and quantity in urban catchments has been developed to assess the effectiveness of BMPs in highway runoff management. These may be categorized into two major groups, empirical and mechanistic models.

4.1. *Empirical methods*

The empirical methods based on direct observation and measurement applies past and present extensive data series to derive the probable outcomes of future events. Empirical models involve a practical relationship between a dependent variable and variables that are considered germane to the process, chosen from the knowledge of the physical processes and empirical measurements and reflect the current behavior of a catchment at a particular site. Regarding highway runoff modeling, empirical models focus on predicting the event mean concentration (EMC). Highway runoff quality models attempt to incorporate the buildup and wash-off process using an empirical exponential *wash-off* and the *buildup functions* (Zoppou, 2001).

Over the past few decades different empirical modeling approaches have been developed such as multiple regression (Barbosa, 2007, Kayhanian et al., 2007), artificial neural network (ANN) (Park and Stenstrom, 2006, MASOUDIEH and KEYHANIAN, 2008, Trenouth and Gharabaghi, 2016), data-driven models (Barrett et al., 1998, Opher et al., 2009, Ha and Stenstrom, 2008, MASOUDIEH and KEYHANIAN, 2008), optimization models (Pack et al., 2004, Lee et al., 2010, Ciou et al., 2012, Baek et al., 2015, Liu et al., 2016, Khatavkar and Mays, 2017), GIS-based models (A.A. Bloorchian et al., 2016, Ha and Stenstrom, 2008, Viavattene et al., 2010), and Bayesian Networks (Park and Stenstrom, 2006).

Statistical models for estimating flow and water quality loads are usually based on regression models, which are counted in the stochastic modeling approach. These may include climatic characteristics and catchment parameters. The most significant limitation of statistical models is their spatial arrangement, which means for any spatial patterns or processes, new data, and the statistical relationship must be developed (Zoppou, 2001). Notably, most statistical techniques, such as multiple regression, involve mathematical statements about the data generating process and are, therefore, also mechanistic. Regression models explain the relationships between road runoff quality (or water quality) variations and also through some mathematical equations illustrate the significant changes in the variables that control the process. The regression models for stormwater quality utilize concentrations or pollutant loads as variables dependent on traffic intensity, flow volume, interevent dry period, and adjacent land use (Barbosa, 2007). Regression models have been widely used to describe event mean concentrations EMC and total storm event load (Zoppou, 2001).

ANNs as the less input data-intensive assessment tool compared to either empirically- or physically-based modeling approaches are highly useful in the design process by finding the relationships between the input and output of environmental conditions (MASOUDIEH and KEYHANIAN, 2008). Furthermore, ANNs are useful for modeling highly complex, nonlinear environmental phenomena for which knowledge of input parameters and sensitive initial conditions remains poorly understood (Trenouth and Gharabaghi, 2016). Despite the success with which ANNs have been applied, there are some disadvantages, including the structure of the model itself, particularly their “black box” internal nature, as well as the input and output parameters and their selection method (e.g., trial and error approach, which require sensitivity analysis). The challenge is to select model input parameters that have a direct influence on the interested output parameter (Trenouth and Gharabaghi, 2016). Data-driven models are lately used in water and environmental research and have provided an effective, accurate, and easily calibrated predictive model for EMC of highway runoff pollutants (Opher et al., 2009). Also, other models, such as risk-based models (Lundy et al., 2012), were successfully developed in highway runoff management.

Given a large number of alternative management strategies and constraints that must be satisfied, some models include an optimization technique. Optimization is used to determine optimum values for a given set of decision variables that will maximize or minimize an objective function, usually cost. The coupling of a stormwater model with an optimization technique (linear, nonlinear, and dynamic programming) represents an influential tool for highway runoff management (Zoppou, 2001).

Besides, simulation models and optimization techniques as an integrating process has been explored to select (Lee et al., 2005, Reichold et al., 2009), locate (Perez-Pedini et al., 2005), design and analyze the treatment efficiencies (Lee et al., 2010, Zhen et al., 2004, Wong et al., 2006) of various types of BMPs. There is no comprehensive modeling system available in the public domain for systematically evaluating the location, type, and cost of stormwater BMPs (Lee et al., 2012).

Furthermore, the GIS-based models are intended to support a range of local authority/municipal, federal/state regulatory agencies, drainage engineers/consultants, and other interested stakeholders in the development and evaluation of stormwater drainage infrastructure contained within stormwater management plans (Viavattene et al., 2010).

Highway runoff management sometimes requires an intermediate process to overcome the monitoring and computational difficulty of the direct approach. For example, Park and Stenstrom (Park and Stenstrom, 2006) developed a model based on the Bayesian networks and an AI algorithm to predict stormwater pollutant loads through land-use data, which comes from satellite imagery. Despite numerous research projects in this field, there are still open questions regarding the identity and mutual influences of the many factors affecting pollutant concentrations in road runoff (Solomatine and Ostfeld, 2008, Opher and Friedler, 2009).

4.2. *Mechanistic models*

Mechanistic models are based on an understanding of the behavior of a system’s components. For example, a mathematical, mechanistic model that uses the laws of physics to predict tides. These models are applied to simulate the physical flow and transport processes, including advective-dispersive transport and mass exchange between the runoff and pavement surface (L.-H. Kim et al., 2005, L.-H. Kim et al., 2005, Kang et al., 2006, Massoudieh et al., 2008, Bentzen et al., 2009, Bentzen, 2010) and are mostly designed to predict the variation of concentration during a rain event (Abrishamchi et al., 2010). The overall idea of the mechanistic models is to develop physical/numerical models through historical time series of the pollutant discharges in which variation of pollutants removal by a BMP can be identified (Bentzen, 2010). Most models use buildup and wash-off equations for runoff, algorithms for solid transport in the sewers, proportional relationships between the suspended solids and their attached pollutants and pollutant decay or transformation equations (Barbosa et al., 2012). Mechanistic models were utilized for different purposes, including pollutographs prediction in highway runoff (Abrishamchi et al., 2010, Massoudieh et al., 2008), highway runoff modeling (German et al., 2005, Abrishamchi et al., 2010, Park and Stenstrom, 2006, Trenouth and Gharabaghi, 2016), and pollutant load estimation (Brezonik and Stadelmann, 2002, Opher et al., 2009, Massoudieh et al., 2008, Kim et al., 2006, Zhang et al., 2014). Furthermore, a wide range of such models was applied by researchers to evaluate the performance of BMPs under different site-specific circumstances. Table 4 presents a list of recent studies in detail.

Table 4
Mechanistic models used in highway runoff research.

Model	Application in highway runoff	Features	Reference
CREAMS[1]	Investigate the effectiveness of grass strips for various geometrical scenarios	It considers land use (agricultural, forest/natural, chemical application), hydrology (surface runoff, subsurface runoff), water quality (sediments, nutrients, pesticides/toxics), and time frame (event load, continuous simulation) (Tsihrintzis and Hamid, 1997).	(Williams and Nicks, 1988)
WEPP[2]	Predicting the movement of sediment in grass strips	It does not track backwater, has a non-symmetric behavior for fine and medium particles (under-predict and over-predict, respectively), which may cause uncertainties given the associated pollutants (Akram et al., 2015).	(Flanagan and Nearing, 2000)
PHREEQC-2	Simulating pollution transport processes and chemical reactions	Excellent for mixing, speciation, mineral equilibration, surface complexation, ion-exchange, and reaction modeling	(Bäckström et al., 2003)
RPM[3]	Predicting the sediment trapping efficiency in riparian buffers	Simple conceptualization and accurate surface runoff estimation. However, the detachment process, as well as size distribution for inflow sediment, are not considered. So, the prediction of water pollution is not applicable (Akram et al., 2015).	(Newham et al., 2005)
VFSMOD [4], VFSMOD-W	Studying the hydrology, sediment, and associated pollutant transport through VFS[5].	Applies finite element solution, Green-Ampt infiltration method, and contaminant transport component to provide water and sediment balance, sediment graph and deposition pattern within the filter, and filter efficiency. It could not accurately predict the amount and size of sediment in the outflow, especially when sediment is highly distributed (Akram et al., 2015).	(Munoz-Carpena and Parsons, 2004, Munoz-Carpena et al., 1999, Han et al., 2005, Dosskey et al., 2008, White and Arnold, 2009)
TRAVA[6]	Field performance of grass filters (strip and swale) in TSS removal	A mathematical model uses a series of empirical equations and able to simulate the outflow particle size distribution. TRAVA's performance is limited to experimental conditions (Akram et al., 2015).	(Deletic, 1999, Deletic, 2000, Deletic and Fletcher, 2006)
SIMPTM[7]	Simulate the runoff volume and Pollutant loading/concentration and pollutant buildup and washoff during each storm event	Explicitly simulates the physical processes and can simulate the pollution Reduction benefits for different cleaning operations. SIMPTM model includes a rainfall analyzer called RAINEV to evaluate the characteristics of a historical rainfall record.	(Sutherland et al., 2006)
k-C* [8]	Assessing BMPs performance by storage-release models for pollutant removal		(Wong et al., 2006, Rousseau et al., 2004, Lin et al., 2005, Pack et al., 2005, Park and Roesner, 2012)
Mathematical model	Prediction of highway runoff pollutographs during storm events	Time and cost-effective model.	(Massoudieh et al., 2008)
BMPDSS [9]	Supporting analysis and decision-making processes for planning and design of BMPs		(Cheng et al., 2009)
STUMP [10]	Simulation of micropollutants transport to the surrounding environment	Flexible and dynamic fate model given the inherent properties of substance's, to partition between the particle-bound phase and the dissolved phase (Vezzaro et al., 2012).	(Vezzaro et al., 2012)
Monte-Carlo simulation	Assessing the effect of BMP design on pollutant removal efficiency and uncertainty analysis		(Abrishamchi et al., 2010, Park and Roesner, 2012)
SEWSYS	Simulation of runoff quality based on sources of pollution		(Lindblom et al., 2011)
STORM [11]	Quantitative and qualitative simulation of runoff, bypass flow, and flow through BMPs, given watershed land use.	STORM considers land use (urban), hydrology (surface runoff, subsurface runoff, snowmelt), water quality (sediments, nutrients), and time frame (continuous simulation) (Tsihrintzis and Hamid, 1997).	(Pack et al., 2004, Viavattene et al., 2010, Park and Roesner, 2012)
SWMM [12]	Simulation of runoff quantity and quality, modeling the contaminant build-up and wash-off behavior, has a different variation (e.g., PCSWMM[13] to assess the effectiveness of BMPs for retaining the first inch of highways runoff and functionality in plan and design)	2D hydrodynamic model, which has pollutant predictive method (empirical, buildup and washoff, soil loss), pollution transport (completely mixed reactor), and mathematically describes the contaminant's build-up and wash-off (Zoppou, 2001). SWMM applies diverse methods in estimation of runoff (Green Ampt, Horton, CN, Manning) and water quality constituents (continuously stirred tank reactor or CSTR, power function, saturation function, rating curve, EMC, first-order decay) (Ahiablame et al., 2013). Considers land use (urban), hydrology (surface runoff, subsurface runoff, snowmelt), water quality (sediments, nutrients), and time frame (single event load, continuous simulation) (Tsihrintzis and Hamid, 1997). Limited in pond hydraulics and pond nutrient treatment (Troitsky et al., 2019).	(A.A. Bloorchian et al., 2016, Wicke et al., 2012, Baek et al., 2015, Flanagan et al., 2016, Moore et al., 2017, Osouli et al., 2017, Sañudo-Fontaneda et al., 2018, Lin et al., 2018)
SUSTAIN [14]	A decision-support system for both watershed and BMP by evaluating the optimal location, type, cost, planning, and design of BMPs.	It enables the analysis of multiple alternatives for water quality management considering different objectives such as location, scale, and cost (Lee et al., 2012). Have single event time frame (Gao et al., 2015), which uses a wide range of stormwater quantity (Green Ampt, Holtan-Lopez, CN, Manning) and quality (CSTR, power function, saturation function, rating curve, emc, storage routing, first-order decay)simulation algorithms. SUSTAIN currently covers a variety of BMPs, including bioretention, cistern, constructed wetland, dry/wet pond, grassed swale, green roof, infiltration basin/trench, porous pavement, rain barrel, sand filter, and VFS (Ahiablame et al., 2013)	(Lee et al., 2012, Gao et al., 2015)

(*continued on next page*)

Table 4 (*continued*)

Model	Application in highway runoff	Features	Reference
L-THIA-LID [15]	Evaluates the benefits of BMPs; measure the impact of land use on hydrology and water quality.	Evaluates runoff volume using the Curve Number method (Miller et al., 1986) and estimates pollutant loads by runoff volume and EMC of specific land use. It has both a single event and a continuous time frame.	(Liu et al., 2016, Ahiablame et al., 2013, Lindström and Håkanson, 2001, Shirmohammadi et al., 2006, Engel et al., 2007, Park et al., 2010, Granato, 2014, Granato and Jones, 2014, Y. Liu et al., 2015, Y. Liu et al., 2015, Beck et al., 2017, Granato and Jones, 2019, Weaver et al., 2019)
SELDOM [16]	Provides risk-based information for decision-makers about streams and lakes that receive runoff from highways.	Uses Monte Carlo methods to generate a mass balance model for a receiving stream (Granato and Jones, 2019). Also, it applies the trapezoidal distribution and the rank correlation with the highway-runoff variables to model volume reduction, hydrograph extension, and water-quality treatment (Granato, 2014).	(Granato and Jones, 2019, Weaver et al., 2019)
WASP [17]	3D hydrodynamic and water quality model.	Flexible to be coupled with other 3D models include uncertainty analysis tools, water quality sub-model that has sediment oxygen demand and nutrient fluxes. Limited in mixing/complex hydraulics zones and settling /floating particles.	(Troitsky et al., 2019)
GUEST [18]	Simulates the water and sediment transport for grass buffer strips	Considers the deposition and erosion of sediment in single-runoff events	(Akram et al., 2015)
TELR [19]	Quantify runoff reduction	Lower input data and user expertise. Responsive to management actions, such as the installation of structural BMPs	(Beck et al., 2017)
GSSHA [20]	A physical model to model the fate and transport of sediment and constituent in streams and channels	1-D infiltration and streamflow, 2-D overland flow and groundwater, and considers the interaction of streams, shallow soils, groundwater, and overland flow. Useful for shallow soils and overland flow.	(Moore et al., 2017)
FullSWOF-ZG [21]	Evaluate the road-bioretention stripes' performance	Simulation of the incompressible Navier–Stokes flow occurring in the water body. This model can consider spatialized rainfall, infiltration, and friction determination as well as a new 2D-1D drainage inlet submodule. Modeling impervious and pervious surfaces simultaneously in one domain.	(Li et al., 2021)

[1] CREAMS (chemicals runoff and erosion from agricultural management systems),
[2] WEPP (water erosion prediction project),
[3] RPM (riparian particulate model),
[4] VFSMOD (vegetative filter strips modeling system),
[5] VFS (vegetative filter strips),
[6] TRAVA (a deterministic model based on the Aberdeen Equation),
[7] SIMPTM (the SIMplified Particulate Transport Model),
[8] k-C* (a first-order kinetic model, where k is the first-order decay rate and C*is the equilibrium concentration),
[9] BMPDSS (best management practice decision support system),
[10] STUMP (the stormwater treatment unit model for micropollutants),
[11] STORM (the storage treatment overflow and runoff model),
[12] SWMM (the US EPA's stormwater management model),
[13] PCSWMM (the personal computer stormwater management model),
[14] SUSTAIN (the system for urban stormwater treatment and analysis integration),
[15] L-THIA-LID (the long-term hydrologic impact assessment-low impact development),
[16] SELDM (the stochastic empirical loading and dilution model),
[17] WASP (water quality analysis simulation program),
[18] GUEST (Griffith University soil erosion and deposition-vegetative buffer strips 2),
[19] TELR (the stormwater tool to estimate load reductions),
[20] GSSHA (gridded surface/subsurface hydrologic analysis).

Simulation accuracy is more likely dependent on the skill of the modeler, parameterization, and model formulation than model type (Moore et al., 2017). Model selection for a project is generally driven by the problem that needs to be solved, and the project goal (Engel et al., 2007). The complexity of a model has consequences on the reliability of the results produced by the model. Reliability places confidence limits on the outputs of the model due to the uncertainties and should be an integral part of the decision-making process. Furthermore, risk analysis that considers the probability of system failure (depends on the climate, hydrology, and/or management strategies) is another useful approach for the decision-making process (Abu-Zreig et al., 2001) in highway runoff management (Zoppou, 2001). Given the model uncertainty, it is notable that the uncertainty sources can be divided into model parameters, conceptual model (model structure), and observation data (measurement) uncertainties. In addition, the uncertainty stemmed from boundary conditions is sometimes referred to as scenario uncertainty (Lindblom et al., 2011). This is particularly important to the stormwater runoff quality, where the dynamics exceed those of most other environmental systems (Lindblom et al., 2011). Uncertainty analysis attempts to quantify the effect of uncertain parameters of the model on the models' response. Uncertainty analysis can be performed by analytic, approximation, and numerical methods. The derived-distribution method (DDM) is the most classical approach in analytical uncertainty analysis (Park et al., 2010). The numerical methods include sensitivity analysis (Baek et al., 2015, Vezzaro et al., 2012, Lindblom et al., 2011), the first-order second-moment (FOSM) method (Park and Roesner, 2012, Shirmohammadi et al., 2006, Park et al., 2010), Monte Carlo simulation (MCS) (Park and Roesner, 2012, Shirmohammadi et al., 2006, Daebel and Gujer, 2005), and Mellin transform. Other approaches such as Latin hypercube sampling (LHS), which is a modified stratified sampling of MCS, (Shirmohammadi et al., 2006, Park et al., 2010), and the generalized likelihood uncertainty estimation (GLUE) technique

Table 5
United States legislation about highway drainage, water quality and environmental protection (Malamataris, 2014).

Legislation	Year	Aims and scope
Federal-Aid Highway Act (Public Law 81–769)	1950	Hold public hearings for projects bypassing cities or towns.
National Environmental Policy Act (NEPA)	1970	Declaring and promoting the appropriate national policies, goals, and measures for environmental protection.
Federal Water Pollution Control Act of (Clean Water Act)	2011	Principal federal law in the United States regulating subjects about water pollution and ensuring that surface waters would meet the standards for water consumption. The discharge regulation has been applied to all communities with a population of 10,000 or more (US-EPA 2011).
The Federal-Aid Highway Act of 1973 (Public Law 93–87)	1973	Highway safety improvement and the funding provision for urban and rural primary and secondary roads.
The Safe Drinking Water Act of 1974 (SDWA)	1974	Standards for protecting the water sources: lakes, rivers, reservoirs etc. and drinking water quality in order to protect public health.
Surface Transportation Assistance Act of 1982 (Public Law 97–424)	1982	Extensive policy act to deal with problems about the surface transportation infrastructure.
The intermodal Surface Transportation Efficiency Act of 1991 (Public Law 102–240)	1991	Regulation in the post-interstate highway system era.
Moving Ahead for Progress in the 21st Century Act of (Public Law 112–141)	2012	Funding bill to govern federal surface transportation spending (Delaware Department of Transportation 2008)

Table 6
EU legislation about highway drainage, water quality, and environmental protection.

Aims and scope	Legislation
Possibility of pollution of water resources by highway effluent	(Directive2000/60/EC 2020)
Investigation of surface and groundwater status of highway effluent receiving environment	(Directive2011/92/EU 2011) (Directive2013/39/EU 2013) (Directive2010/75/EU 2010)
Effluent discharge standards to drinking water sources or areas with groundwater wellhead protection program	(Directive2000/60/EC 2020)
Effluent discharge legislations to water sources of economically significant aquatic species	(Directive2000/60/EC 2020)
Effluent discharge legislations to the sensitive area defined by the UWWD criteria	(Directive91/271/EEC 1991)
Effluent discharge legislations to a water body within an area defined as Natura 2000 habitat or ecosystem area	(Directive92/43/EEC 1992)

(Vezzaro et al., 2012) have also been utilized to assess uncertainty in BMP performance.

5. Legislations

According to the authors' knowledge, there are no specific directives or regulations in the EU in the field of drainage and highway stormwater management. Existing frameworks are mostly based on the type of water consumption and different characteristics of receiving water bodies. Tables 5 and 6 provide a set of legislations and guidelines for highway effluent management in the United States and the EU based on their discharge points. In general, the main legislation instruments in the EU to restrict the discharge of highway runoff into water resources include the EU WFD assessment guidelines (Directive2000/60/EC 2020), EU Groundwater Directive (European Union 2006), EU Habitats Directive (Directive92/43/EEC 1992), surface and groundwater (drinking water) protection zones, Natura 2000 areas (areas designated for the protection of habitats or species), and non-legislative initiatives on the management of receiving water bodies influenced by traffic-related activities. The mentioned set of legislations can be used with each other to evaluate highway runoff risks based on legal environmental/water constraints (Martins et al., 2020).

- The possibility of highway effluent contamination can be assessed by WFD (Directive2000/60/EC 2020), Groundwater (European Union 2006), EIA (Directive2011/92/EU 2011), Priority substances (Directive2013/39/EU 2013), and IPPC (Directive2010/75/EU 2010) legislative frameworks.
- If the effluent acceptor environment is drinking water or in the area with the program of groundwater wellhead protection zone, the effluent risk assessment can be evaluated using WFD (Art. 7 Drinking water) framework (Directive2000/60/EC 2020).
- If the effluent discharge site has economically significant aquatic species, the instructions of WFD guideline (Art. 6 Protected areas) (Directive2000/60/EC 2020) can be used to assess highway effluent risk.
- If the water body receiving the highway effluent is a protected area, the Natura 2000 guidelines can be used to assess the risk.

Management practices for handling highway runoff vary between the various European national road administrations (NRAs), as already documented. We concluded that the NRAs have different planning, construction, and operation system for runoff treatment facilities, see also Andersson et al. (Andersson et al., 2018). The Water Framework Directive (WFD) (Directive2000/60/EC 2020) in Europe and related directives set Environmental Quality Standards (EQS) for water bodies and demand measures to improve the water quality if the standards are not met. But there is also a wide variety of national guidelines, recommendations, and requirements that regulate road runoff management. In Sweden and Norway, policy documents are qualitative and focus mainly on water quality, retention capacity, aesthetics, and ecology. Germany, Austria, and Switzerland focus on particle transport and TSS as the major pollution.

In Norway, there are four main guidelines for road runoff handling, indicated in Table 7.

In some countries, ADT is considered as a first parameter in determining the status of runoff and management action plans. Table 8 presents the classification of runoff quality based on ADT in Germany, Norway, and Austria. In Germany and Austria, roads with a traffic load of more than 15,000 (vehicles/day) need to be treated, while in Norway, roads with a traffic load of more than 30,000 (vehicles/day) need to be treated. In Germany, in addition to ADT, the expected annual load of TSS smaller than 63 μm (AFS_{63}) is also used to classify highway effluents. For example, the AFS_{63} loads above 530 kg/ha per year indicate high pollutant loads that require treatment (DWA-A102-2/BWK-A3-2 2020).

There are also different legislations for road runoff outside of settlements, road construction in sensitive areas, and maintenance of stormwater treatment facilities (Andersson et al., 2018). In Sweden, the Swedish Environmental Law and WFD regulate stormwater management. Despite the nine documents outlining recommendations and requirements for handling road runoff in Sweden, there is no prescribed

Table 7
Norwegian guidelines for road run-off management.

Name & Number	Reference
N200 (Handbook N200 for building roads)	(Y. NPRA 2014)
R760 (Handbook R760 Control of road-building projects)	(Y. NPRA 2014)
Nr. 597 (Water reservoirs vulnerability to road runoff during building and operational phase)	(Y. NPRA 2016)
Nr. 212 (State of the stormwater facilities in Norway)	(NPRA 2013)
Nr. 650 (Inventories of facilities in the Southern region)	(Y. NPRA 2016)

Table 8
Guidelines of Germany, Norway, and Austria to the classification of runoff quality based on ADT.

Pollutant load	ADT (vehicles/day)			Action
	Germany	Norway	Austria	
Low	<2000	<3000		Released to surface or groundwater without treatment (Infiltration in the road shoulder)
Moderate	2000–15,000	3000–30,000		Treatment is generally required prior to discharge
Highly polluted	>15,000	>300,000	>15,000	Highway runoff is considered highly polluted, and treatment is required before release

decision-making process to determine when a treatment facility is required. The current Swedish Transport Administration (STA) document to determine the need for stormwater treatment is STA (Andersson et al., 2018). STA also operates a spatial database of the Swedish roads and railways network to identify runoff risks close to existing infrastructure and to plan maintenance and construction work of existing BMPs. In Austria, the OEWAV regulation, Regelblatt 25, stipulates the guidelines and technical instructions for planners (Binner, 2002). The minimum requirements for purification are mechanical treatment (sedimentation) and filtration. In Switzerland, permitting procedures follow the national road law. Permitting procedures include the rebuilding of national roads (construction), structural modification of an existing national road (expansion), and maintenance practices. Based on Andersson et al. (Andersson et al., 2018), the current Norwegian and German guidelines and regulations regarding the handling of stormwater sediments are synchronized and up to date. Sweden's guidelines are, however, outdated, and present challenges that may lead to technical issues.

6. Knowledge gaps and potential research directions

According to the EU WFD, all countries should achieve 'good status' for their water bodies by 2015 or finally by 2027. But in 2015, 47 % of the EU's surface waters did not achieve the standards (Meland, 2015). Although not documented, runoff from roads probably contributes significantly to this gap. Studies on highway runoff characteristics and suited treatment technologies should, therefore, be encouraged. Stormwater management is a complex matter and comparing the results of various studies necessitates collecting and analysis of proper, consistent, and scientifically valid data for each specific case and considering their site-specific parameters (e.g., geographic and climatic issues). Notably, some significant topics, including monitoring network and measurement technology, frequency of data collection, sampling method, and data analysis should be considered in highway runoff management. Also, the particle size distribution and the associated pollutants will have a strong influence on runoff toxicity, BMP design, and removal efficiency. We propose here potential research directions for future studies.

1. There is a notable lack of documentation on the operation and the need for maintenance of BMPs. If run without such documentation and control, poor performance or breakdown may cause undesired environmental effects in downstream water bodies. For instance, many of the existing wet ponds in Norway are in poor condition with accordingly limited performance, partly because of low construction quality and partly due to insufficient operation and maintenance. The development of models that can be run to identify shortcomings should be initiated.
2. Due to the variety of regulating factors and their complicated interactions, there is a need for models that handle the most important variables for the resulting road runoff chemistry during different scenarios. Models may be used to calculate the uncertainties and effects of a set of treatment technologies.
3. Different decision scenarios can be defined based on economic or technical constraints. Advanced and high-tech alternatives do not necessarily result in large and adequate improvements if the use of simple techniques meets the standards set. Hence, the selection of the best alternative depends on adequate information on the road runoff itself, the efficiency of treatment systems based on site-specific parameters, and water regulations. Economic analysis (e.g., life cycle cost and cost-benefit analysis) can provide a powerful tool to assess different alternatives.
4. Limited knowledge exists on the buildup/washout of pollutants and mobilization of inorganic and organic compounds by stormwater in the present and future climate. This probably results in a non-optimal design of BMPs and how they should be adapted for future conditions. This issue is of great importance in the climate change framework.
5. Future research should aim to optimize BMPs in terms of smaller and more cost-effective BMPs with low-maintenance and high removal efficiency. Developing multi-objective optimization models that consider the objectives of different involved stakeholders can facilitate the selection of BMPs.
6. A comprehensive study is required to develop a guideline for the choice of treatment based on site-specific conditions, expected pollutant load, and environmental impact. The guideline should give advice on when treatment is necessary.
7. The performance of existing BMPs under climate change scenarios and for the different forms of pollutants (particle-bound or dissolved) should be investigated. Another knowledge gap is related to changing pollutant behavior on impervious surfaces over dry and wet periods, particularly under the first flush effect.
8. More relevant parameters than ADT should be developed. Systematic monitoring with a recommended sampling strategy at sites with different ADT could, however, reveal that the relation between ADT and contaminant runoff is adequate for decision-making.
9. Risk analysis and uncertainty analysis are not adequately addressed in modeling. There is a challenge for modelers to include these issues in the development of user-friendly decision support tools.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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