Dagvatten från järnvägsinfrastruktur: kunskapssammanställning och miljöpåverkan

Drainage of railway transportation infrastructure: Status and environmental concerns

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www.ltu.se/vatten

2023

LULEÅ
TEKNISKA
UNIVERSITET

ISBN: 978-91-8048-288-2

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Sammanfattning

En litteraturstudie om påverkan av dagvatten från järnvägstransportinfrastruktur på recipienter har genomförts, med fokus på föroreningskällor och åtgärder under svenska förhållanden. Järnvägsanläggningar kan delas in i tre kategorier: järnvägsspår (med tillhörande strukturer), bangårdar och stationer. Avrinning från spåren rapporterades innehålla föroreningar som metaller, polycykliska aromatiska kolväten (PAH) och kemiska bekämpningsmedel (herbicider). Dessa kan släppas ut antingen genom att dagvatten sköljde av spåren eller genom slitage på spåren. Lakning orsakade en betydande belastning av Zn (upp till 98 % i löst fas) genom korrosion av galvaniserade metallkonstruktioner. Andra metaller som Fe, Cu, Mn och Cr frigjordes främst genom slitage av metalldelar. Granskningen av litteraturuppgifter om PAH:er och en generalisering av resultaten innebar stora osäkerheter. Detta orsakas ofta av platsspecifika förhållanden som t ex. omfattningen av användningen av diesel- eller ellok, vilket i allmänhet inte rapporterades i de analyserade referenserna. Den sista gruppen föroreningar var kemiska bekämpningsmedel, som har studerats i bl.a. Sverige under flera decennier. Huvudfrågan är användningen av glyfosat för vegetationskontroll längs spåren och risken att glyfosat når grundvattnet. Även om de svenska uppgifterna om effekterna av glyfosat inte är alarmerande, granskar både amerikanska och europeiska miljömyndigheter för närvarande användningen av glyfosat och dess miljöpåverkan, och det är mycket troligt att det kan komma att förbjudas. Därför är det viktigt att ta fram alternativa metoder. Föroreningen från järnvägsdagvatten är spridd över ett mycket långsmalt område (<50 m bredd som sträcker sig tusentals kilometer), och med undantag för herbicider i grundvattnet förekommer den i alla fall längs linjen utanför driftplatserna i låga koncentrationer som sällan ger upphov till oro.

Järnvägsbangårdar med många spår klassificeras däremot som industriområden med hög risk för förorening av aromatiska oljebaserade kolväten, metaller, organiska och oorganiska föreningar, sediment och klorid. I USA kontrolleras vattenkvaliteten för avrinning från sådana anläggningar enligt NPDES-tillståndssystemet (National Pollution Discharge Elimination System). Det är en viktig miljöfråga att undvika att obehandlat dagvatten från järnvägsbangårdar når grundvattnet.

Den sista kategorin är järnvägsstationer. Dessa bör uppgraderas så att deras dagvatten anslutas till de befintliga dagvattensystemen, utan att volym och kvalitet nedströms påverkas negativt.

Utformningen av dagvattensystemen måste alltså anpassas till respektive del av järnvägsinfrastrukturen, dvs. spår, bangårdar och stationer. Med tanke på den diffusa föroreningen från järnvägslinjen är de bästa åtgärderna minskning av föroreningskällor. Exempel på sådana åtgärder är eliminering av kreosotbehandlade slipers och användning av naturliga herbicider, magnetbromsar och miljövänliga smörjmedel (utan PAH och metaller) i rätt mängd. I motsats till järnvägsspåren är bangårdar och stationer betydande punktkällor för föroreningar. Valet av dagvattenåtgärder på dessa måste uppfylla lokala krav, i båda fall för att undvika förorening av grund- och/eller ytvattnet och i det andra fallet även för att undvika att kapaciteten i det befintliga dagvattensystemet överskrids. Slutligen bör man se över dräneringen av befintlig järnvägsinfrastruktur för att ta hänsyn till framtida förändringar i nederbörd till följd av klimatförändringarna.

Abstract

A literature study of water pollution potential of Railway Transportation Infrastructure (RTI) drainage has been undertaken, with emphasis on pollution sources and impact mitigation in Swedish conditions. RTI facilities can be divided into three categories: railway tracks (with associated structures), yards, and stations. Drainage effluents from tracks were reported as sources of such pollutants as metals, polycyclic aromatic hydrocarbons (PAHs), and chemical herbicides, which were released either by washoff of tracks by rainwater, or by attrition caused by rolling stock and subsequent transport of pollutants with runoff. Washoff produced a significant loading of Zn (up to 98% dissolved) by corrosion of galvanized metal structures. Other metals (Fe, Cu, Mn, and Cr) were predominantly released by attrition of metal parts. The review of PAHs literature data and its transposition to other locations suffered from high uncertainties, because such data depends on the extent of use of diesel locomotives, which was generally not reported in the references analyzed. The last group of pollutants were chemical herbicides, which have been studied in Sweden over several decades. The main issue is the use of glyphosate in track vegetation control and the risk of glyphosate ingression into groundwater. Even though the Swedish data on glyphosate impacts are not alarming, both US and EU environmental authorities are currently reviewing the glyphosate use and environmental impacts, and there is a high likelihood that it may be banned. Consequently, it is important to intensify search for alternative vegetation controls. The pollution of drainage effluent from railway tracks is diffused over a narrow band (<50 m) extending thousands of kilometers, and with the exception of herbicides in groundwater, occurs in low concentrations rarely causing concerns.

Railway yards, with numerous tracks and spurs, are classified as industrial sites with a high-risk of contamination by petroleum-derived aromatic hydrocarbons, metals, organic and inorganic compounds, sediments and chloride. In the US, water quality of drainage effluent from such sites is controlled under the NPDES (National Pollution Discharge Elimination System) permit system, and avoidance of penetration of untreated rail yard runoff into groundwater is a significant environmental concern. The last category are railway stations, which are subject to renovations and upgrading of drainage. The renovated stations and their drainage outfalls need to be connected to the existing storm or combined sewer systems, without detrimental changes in the quantity and quality of the site drainage effluent.

The conceptual design of stormwater management needs to match the characteristics of the RTI component serviced, i.e., tracks, yards, and stations. Considering the diffuse nature of railway track pollution, the best mitigation measures are source controls, including elimination of harmful substances. Examples of such measures are elimination of creosote-treated crossties, and using natural herbicides, magnetic brakes, and clean lubricants (without PAHs and metals) in right amounts. Contrarily to railway tracks, yards and stations are point sources of pollution. The choices of stormwater control measures in railway yards and stations need to meet local constraints; in the former case, to avoid groundwater contamination, and in the latter case, to avoid exceedance of the existing drainage system capacity. Finally, drainage of existing RTI should be reviewed for predicted changes of the rainfall regime, driven by climate change, and the drainage capacity upgraded as needed.

Utförlig sammanfattning och rekommendationer

Järnvägstransport är ett relevant och populärt transportslag i Sverige, vilket bl.a. framgår när det gäller svenska passagerarkilometer per capita (den femte högsta i världen), den stora årliga godslasten (> 21 000 miljoner ton/år) och det höga betyget som ett av de mest miljövänliga transportslagen när det gäller utsläpp av växthusgaser och föroreningar. Följaktligen borde järnvägens betydelse stärkas genom ytterligare tillväxt och utveckling av järnvägstransportsektorn och dess ledande ställning när det gäller miljömässig hållbarhet bör skyddas och stärkas. Som bidrag till detta syfte undersöktes i denna studie föroreningsutsläpp från avvattning av järnvägsinfrastrukturen. Denna har delats in i tre typer av anläggningar:

- järnvägslinjen (med tillhörande konstruktioner),
- bangårdar och
- stationer.

Järnvägsspår utgör diffusa föroreningskällor, medan bangårdar och stationer är punktkällor.

Järnvägslinjen

Ur föroreningsminimeringssynpunkt släpper själva spåret ut relativt låga nivåer av diffusa föroreningar som sprids över tusentals kilometer av spårets längd. När det gäller dagvattenavrinning släpps föroreningar ut genom att de sköljs av från infrastruktur, lok och vagnar och genom driften av järnvägen. De delar av infrastrukturen som släpper ut föroreningar är bl.a. följande:

- Räls: släpper ut försumbara mängder metaller,
- Slipers av olika material: kreosotbehandlade träslipers släpper ut polycykliska aromatiska kolväten (PAH). Ingen specifik information om utsläpp från betong- och kompositslipers har hittats i litteraturen,
- Ballast: kan avge föroreningar som härrör från atmosfäriskt nedfall, slitage av lok och vagnar och underhållsåtgärder (t.ex. smörjmedel och herbicider),
- Banvallar: kan vara känsliga för jorderosion och kan släppa ut suspenderade ämnen,
- Spårväxlar och korsningar: utgör 5 % av den totala spårlängden i Sverige (Hassankiadeh (2011) och kan släppa ut främst smörjmedel, och,
- Metallkonstruktioner i anslutning till spåren, inklusive skyltar, barriärer, korrosionsbeständiga metallstolpar, stöd för luftledningar och signalutrustning: Ofta är dessa konstruktioner konstruerade för att vara korrosionsbeständiga, med den vanligaste skyddsmetoden varmförzinkning (galvanisering) vilket kan frigöra Zn.

De ovan nämnda källorna släpper ut föroreningar vid regn. Utsläppen beror både på regnets egenskaper (mängd, varaktighet, intensitet och pH-värde) och på materialsammansättningen hos infrastrukturen. Resulterande utsläpp är spridda över tusentals kilometer och bör om möjligt minskas genom källkontroll.

Den andra gruppen av föroreningskällor från järnvägar utgörs av slitage av rörliga eller stationära metalldelar i järnvägssystemet. Deras omfattning varierar och beror t ex. på antal och typ av tåg (dvs. passagerar- eller godståg), typ av lokomotiv (diesel eller el), tågsvikt och -hastighet samt typer av bromsar. När det gäller utsläpp av partikulära metaller överstiger denna grupp betydligt utsläppen från urlakning av konstruktionsmaterial (Burkhardt et al., 2008).

Studier om utsläpp av föroreningar från järnvägsspår tyder på att slitage av bromsar, räls och hjul samt urlakning av zink från galvaniserade metallkonstruktioner är betydande källor som släpper ut relativt stora mängder Fe, Cu, Zn, Mn, Cr och Cd, dock i låga koncentrationer. Deras miljöeffekter är mycket diffusa och sannolikt mindre än de från andra källor (t.ex. vägtransporter). Större delen av metallerna frigörs i form av metallpartiklar, som i slutna utrymmen (t.ex. på järnvägsstationer) kan andas in av människor och orsaka hälsoproblem. Transporten av dessa partiklar med avrinning är inte väl känd eller dokumenterad.

Zink från galvaniserade ytor frigörs nästan uteslutande i löst form och kan därför vara biotillgängligt och transporteras lätt med avrinningen. Inga studier om toxiciteten hos sådan avrinning hittades i litteraturen. När det gäller föroreningsmängd är nästa viktiga föroreningsgrupp smörjmedel som regelbundet används vid drift av järnvägssystem, t ex. vid växlar, kopplingar mm. Effekterna av dessa kan minskas genom att inte använda mer än vad som behövs och använder miljövänliga smörjmedel utan metaller och PAH:er. En annan källa till PAH:er är dieselutsläpp vid dieseldrift. Den sista gruppen av föroreningar är kemiska bekämpningsmedel, dvs. herbicider, som ofta används för vegetationsbekämpning på och längs spåren. Herbicider, och särskilt glyfosat som används ofta, kan ge upphov till farhågor. Om de når grundvattnet kan de ha en direkt inverkan på människors hälsa.

Tidigare forskning om föroreningar från järnvägstransporter omfattar två typer av studier:

(i) Massflödesanalyser (mass flow analysis, MFA) (Burkhardt et al., 2008), som spårar kemikalier och material som används i branschen och beräknar utsläpp till miljön, och,

(ii) Studier som fokuserar på kemin i marken runt spåren, eftersom sådan mark ackumulerar tidigare föroreningstillförsel och hjälper till att identifiera (icke-nedbrytbara) föroreningar som släppts ut.

I allmänhet kan de rapporterade miljörelaterade föroreningarna delas in i tre grupper:

(i) Metaller (Fe, Cu, Zn, Mn, Cr och Cd), som främst produceras genom slitage av räls, hjul, bromsar och luftledningar (Burkhardt et al., 2008) samt urlakning från galvaniserade konstruktioner, och Hg-rester från konserveringsmedel som applicerats på slipers.

(ii) PAH:er från dieseldrift och äldre smörjmedel, och

(iii) herbicider som används för att bekämpa vegetation. De upptäckta nivåerna av dessa föroreningar låg i de allra flesta jordprover under de tillåtna nivåerna i respektive nationella bestämmelser.

Bland de anmärkningsvärda undantagen fanns följande:

- Höga Cd-halter i marken som överskred den tillåtna nivån på 1,5 mg/kg (Vaiskunaite och Jasiuniene, 2020),
- PAH16-koncentrationer upp till ~ 50 000–60 000 µg/kg (Wilkomirski et al., 2011), dvs. över de tillåtna nivåerna, som sannolikt orsakats av äldre smörjmedel och diesellok,
- Glyfosatkoncentrationer i grundvatten som i en svensk studie som överskrider EU:s kvalitetsstandard för grundvatten (EU:s grundvattendirektiv 2006/118/EG) på 0,1 µg glyfosat/L i 6 % av 645 prover (Cederlund, 2022).
- Även om koncentrationerna av enskilda föroreningar ligger under de tillåtna nivåerna kan toxicitetstester på jord- och vegetationsprover ge toxiska reaktioner på grund av den synergistiska effekten av en uppsättning kemikalier (Wierzbicka et al., 2015).

Bangårdar

Bangårdar är industrianläggningar med många källor till luft- och vattenföroreningar, som lämnar karakteristiska föroreningssignaturer i marken på och i närheten av bangårdsområdet. Jämförelser av bangårdens markkemi med oförorenade referensområden visar på stora förändringar i markkemin, med förhöjda koncentrationer av främst metaller och PAH:er. Medan metaller sannolikt orsakas av slitage av metalldelar, tillskrivs organiska föroreningar smörjmedel, kol, olja, gödningsmedel och herbicider (Biache et al., 2017; Wiłkomirski et al., 2011) som använts på bangårdsområdet. Bränslen, oljor och smörjmedel kommer in i miljön med läckage från tankar, tankstationer, utsläpp av föroreningar och drift av diesellok. Ytterligare föroreningar kommer från underhållsarbeten på bangårdarna, och inkluderar bl.a. klorerade och icke klorerade lösningsmedel, fenoler, frostskyddsmedel, rengöringsmedel, PAH:er, utsläpp av avlopp, mm. (Vo et al., 2015). Dessa föroreningar härrör från underhållsåtgärder som metallbearbetning, tankning, reparation av maskiner och batterier, underhåll av lok och vagnar samt rengöring av tåg.

Bangårdar utgör således en hög risk för förorening av dagvatten och följaktligen måste deras ägare och operatörer:

(i) följa bestämmelserna för dränering av industriområden med förhöjd risk för vattenförorening, och

(ii) undvika dagvattenhantering som kan förorena grundvattnet. Båda aspekterna diskuteras vidare i avsnittet om vattenrening på bangårdar.

Järnvägsstationer

Stora järnvägsstationer ligger oftast i centrala stadsområden med tät bebyggelse och stor andel hårdgjorda ytor. Stationerna innehåller vanligen ett stort antal spår, växlar och plattformar samt anläggningar för drift av station och passagerarnas behov. Med det ökade intresset för tågresor och åldrande stationsområden behöver många stationer renoveras, inklusive anläggningar för dagvattenrening och avvattning. Bristen på mark för att placera reningsanläggningar gör ofta att de måste placeras under jord. Renovering och uppgradering av dagvattenanläggningar vid befintliga järnvägsstationer är en stor utmaning. När stationens dagvatten ska avledas vidare till ett befintligt dagvattenledningsnät måste dess flödeskapacitet och kvalitetskrav beaktas. Dessutom kommer klimatförändringarna sannolikt att leda till kraftigare nederbörd, vilket kommer att öka den hydrauliska belastningen på ledningsnätet nedströms.

Dagvattenhantering för järnvägsinfrastruktur

Den konceptuella utformningen av dagvattenhanteringen måste anpassas till kraven hos respektive del av järnvägen som ska avvattnas/renas. Dvs olika metoder behöver användas dagvattenrening av järnvägsspår, bangårdar och stationer.

Den största utmaningen är dränering av spåren. Deras höga belastning kräver snabb avvattning. Detta krav är i motsats till den moderna strategin för urban dagvattenrening och avvattning, som bygger på att bromsa och fördröja avrinningen. Alla åtgärder som utformas för att fördröja eller infiltrera avrinningen måste därför placeras inom ett säkert avstånd från järnvägsspåret för att undvika störningar i spårets dränering.

När det gäller kvaliteten på dagvattnet från **spåren** är de bästa åtgärderna förebyggande källkontroll, inklusive

- utbyte av kreosotbehandlade (trä)slipers med miljövänliga material (t.ex. betong eller annat),
- alternativ vegetationsbekämpning som undviker kemiska bekämpningsmedel,
- användning av kompositbromsbelägg med minskat innehåll av koppar och
- användning av rätt mängd miljövänliga smörjmedel utan PAH:er och tungmetaller.

Efter källkontroll är nästa steg reningsanläggningar för dagvattnet. När det gäller järnvägsspår verkar det mest genomförbara vara en småskalig uppgradering av dräneringsdiken längs spåret till gräsbevuxna svackdiken med låg underhållsnivå.

På **bangårdarna** kan man tillämpa ett brett spektrum av åtgärder. Även här bör vikten ligga på förebyggande av föroreningsutsläpp och tekniska anläggningar eller anordningar för att fånga upp metaller, olja och fett samt förorenade sediment (t.ex. olje- och sandavskiljare, biofilter eller dagvattendammar, om utrymmet tillåter det). I allmänhet finns det god vägledning för utformning av sådana kontroller.

När det gäller **järnvägsstationer** är behöver dagvattensystemet uppgraderas vilket ofta endast r möjligt samtidigt med andra åtgärder. Även om konventionella dagvattenanläggningar lätt kan tillämpas måste de uppfylla de begränsningar som följer av kravet på anslutning till det befintliga ledningssystemet (avseende lutningar, flödeskapacitet och föreskriven vattenkvalitet). För att uppfylla dessa krav kan det krävas förbehandling och pumpning av dagvatten. Slutligen kan dräneringssystemen vid befintliga järnvägsstationer behöva ses över och uppgraderas för att ta hänsyn till ökningar av regnintensitet och regndjup till följd av klimatförändringarna.

Rekommendationer

De generella rekommendationerna utifrån denna studie och rapport omfattar två huvudpunkter:

(i) Det svenska järnvägstransportsystemets beredskap för ett förändrat klimat.

P g a. avvattningens betydelse för en säker och tillförlitlig drift av järnvägssystemet och samtidigt pågående klimatförändringar föreslås att avvattning av det svenska järnvägssystemet bör utvärderas avseende dessa hydrauliska belastning och resiliens.

Det rekommenderas att utveckla en plan för denna utvärdering och sedan strukturerat genomföra denna för att erhålla rekommendationer om de anpassningsåtgärder som behövs för att minska risken för översvämningar/översvämningsskador i systemet.

(b) Minska eller eliminera utsläpp av giftiga kemikalier i miljön.

En översikt över den nuvarande forskningen om järnvägsinfrastrukturens inverkan på miljön visar att det finns två prioriterade problemområden som innebär pågående och relevante utsläpp av giftiga ämnen i miljön:

- konservering av (befintliga) träslipers med kreosot, vilket leder till utsläpp av PAH:er, och
- användning av glyfosat som bekämpningsmedel.

Även om båda fallen sannolikt orsakar begränsade miljöskador, strider de mot målet att eliminera utsläpp av gifter till miljön. Det föreslås att man genomför en utredning för att undersöka om det är möjligt att avskaffa dessa två metoder och utarbeta en åtgärdsplan.

Utredningen bör innehålla möjligheten att avlägsna kreosot och giftiga kemiska herbicider från järnvägsnätet, med en redogörelse för nuläget, en bedömning av alternativa åtgärder (inklusive kostnader) och ett förslag till tidsplan för genomförandet av de rekommenderade åtgärderna.

Executive Summary with Recommendations

Rail transportation is popular in Sweden, as indicated by high ranking of Swedish passenger • km per capita (the 5th in the world), large annual freight load (> 21 000 million tons/yr), and high rating as one of the most environmentally responsible transportation sectors with respect to emission of greenhouse gases and pollutants. Consequently, further growth and development of the rail transportation sector can be expected and its leadership in terms of environmental sustainability should be protected and strengthened. Towards this end, pollution emissions by drainage of the rail transportation infrastructure (RTI) were examined for three types of facilities: railway tracks (with associated structures), yards, and stations. Railway tracks represent diffuse sources of pollution, whereas railway yards and stations are point sources.

Railway Tracks

From the pollution mitigation point of view, railway tracks generally release low levels of diffuse pollution spread over thousands of kilometers of the track length. With respect to drainage, the track and the rolling stock release pollution into the environment by washoff of pollutants from infrastructure and rolling stock surfaces by rainwater and stormwater, and by operation of the rolling stock.

RTI elements emitting pollution by washoff include:

- rails - emit negligible amounts of metals,
- railway crossties (sleepers), made of various materials - creosote-preserved wooden crossties emit polycyclic aromatic hydrocarbons (PAHs), but no information was found in the literature on emissions from concrete and composite crossties,
- ballast stones may emit pollutants originating in atmospheric deposition, rolling stock operations and track maintenance (e.g., lubricant and herbicide applications),
- rail track embankments are susceptible to soil erosion and may release suspended solids,
- track switches and crossings representing 5% of the total rail track length in Sweden (Hassankiadeh (2011); and,
- track associated metal structures including signage, barriers, corrosion resistant metal poles, supports of overhead lines, and signal equipment. Typically, these structures are designed corrosion resistant, with the most common method of protection being hot-zinc dipping (galvanization).

The pollutant sources in the above group are activated only in wet weather and their pollution releases depend on both rainfall characteristics (depth, duration, intensity, and pH), and the material composition of structures being washed off by rainwater. Discharges of the resulting water pollution are highly diffused over thousands of kilometers and where feasible, should be mitigated by source controls.

The second group of railway pollution sources represents mechanical attrition of moving or stationary metal parts of the railway system and their magnitude depends on rolling stock operations, including numbers and types of trains (i.e., passenger or freight trains), the type of locomotives (diesel or electric traction), gross train weights and speeds, and the types of brakes. In releases of particulate metals, this group significantly exceeds those by rainwater washoff (Burkhardt et al., 2008).

Studies of pollutant releases from railway tracks suggest that attrition of brakes, rails and wheels, and elution of zinc from associated galvanized metal structures are cumulatively significant sources of Fe, Cu, Zn, Mn, Cr and Cd, but their environmental effects are greatly diffused and likely smaller than those from other sources (e.g., road transport). Most of the metal load is released in the form of metal attrition particles, which in enclosed space (e.g., at railway stations) may be respired by humans and cause health concerns. Transport of these particles with runoff is not well understood or documented. Zinc from galvanized structures is almost exclusively released in a dissolved form and hence bioavailable and readily transported with runoff. No studies on toxicity of such runoff were found in the literature. In terms of mass loads, the next group of pollutants are lubricants regularly applied in operation of railway systems. Their effects can be mitigated by source controls consisting in limiting lubricant quantities only to those needed and using relatively clean lubricants without metals and PAHs. Another source of PAHs are diesel emissions, where diesel traction is used. The last group of released pollutants of concern are chemical herbicides, which are used regularly in annual vegetation control on tracks. Herbicides, and particularly frequently used glyphosate, cause concerns about their ingression into groundwater and contamination of sources of raw drinking water, with a direct impact on human health.

Past research of the pollution generated by railway transport comprises two types of studies:

(i) Mass Flow Analysis (MFA) (Burkhardt et al., 2008), which follows the environmental pathways and fate of the known mass of chemicals and materials used in the sector and estimated releases into the environment; and,

(ii) studies focused on the chemistry of soils in the vicinity of tracks, because such soils provide records of past pollution inputs caused by railway transportation and help identify conservative pollutants released.

In general, the reported pollutants of environmental relevance fall into three groups:

(i) metals (Fe, Cu, Zn, Mn, Cr and Cd; mostly produced by attrition of rails, wheels, brakes and overhead lines (Burkhardt et al., 2008); and, Hg residues originating from preservatives, applied to wooden crossties

(ii) PAHs (typically the 16 US EPA PAHs (polycyclic aromatic hydrocarbons), attributed to diesel traction operations and older lubricants), and

(iii) herbicides used in vegetation control. The detected levels of such pollutants were in a vast majority of soil samples below the permissible levels specified in the respective national regulations.

Noteworthy exceptions included the following:

- Cd in soils exceeded the permitted level of 1.5 mg/kg (Vaiskunaite and Jasiuniene, 2020),
- Sum of 16 US EPA PAHs concentrations up to ~ 50 000 – 60 000 μg/kg (Wilkomirski et al., 2011) – exceeding permitted levels and attributed to older lubricants and diesel locomotives,
- Glyphosate concentrations in groundwater exceeding in a Swedish study the EU Groundwater Quality Standard (GQS) (EU Groundwater Directive 2006/118/EC) of 0.1 μg glyphosate/L in 6% of 645 samples (Cederlund, 2022), and
- Even if individual pollutant concentrations are below the permitted levels, toxicity tests on soil and vegetation samples may produce toxic response, because of the synergistic effect of a set of chemicals (Wierzbicka et al., 2015).

Railway Yards

Railway yards are industrial facilities with numerous sources of air and water pollution, which leave characteristic pollutant signatures on soils at, and in the vicinity of, the yard property. Comparisons of the yard soil chemistry against unpolluted reference sites indicate large changes in the soil chemistry, with elevated concentrations of metals and PAHs. While metals were attributed to attrition of metal parts, organic contaminants in former yard soils were attributed to lubricating oils, coal, oil, fertilizers and herbicides (Biache et al., 2017; Wiłkomirski et al., 2011) used on yard property. Fuels, oils and lubricants enter the environment with leakage from storage tanks, filling stations, pollutant spills, and operation of diesel locomotives. Additional pollutants originate from maintenance operations in yards, including chlorinated and non-chlorinated solvents, phenols, antifreeze, detergents, PAHs, sewage waste, and related inorganics (Vo et al., 2015). These pollutants originate from such maintenance operations, as metal processing, fueling, repair of machines and batteries, maintenance of rolling stock, and train cleaning.

Thus, rail yards represent high risk of stormwater pollution and, consequently, their owners and operators are required to:

(i) comply with regulations for drainage of industrial areas with elevated risk of water pollution, and

(ii) avoid stormwater management measures that could contaminate groundwater. Both aspects are further discussed in the section on SWM in rail yards.

Drainage of railway stations

Large railway stations are located in central (downtown) urban areas with dense development and high imperviousness. Typically, such stations contain large number of railway tracks, switches, and platforms, plus the facilities supporting station operation and the needs of passengers. Currently, with increased interest in train travel, some stations have been scheduled to be renovated, including their drainage and SWM facilities. Shortage of land for siting SWM facilities necessitates their placement underground, or installation of green roofs. The green roof option was considered in recent renovations of the downtown Toronto Union Station (2010-2021), but the proposal was eventually abandoned because of technical challenges that would be caused by the green roof operation. Renovations of drainage at the existing railway stations are highly challenging, because these projects have to discharge stormwater to the existing sewer system and meet its capacity and the required quality of such influents. Furthermore, climate change is likely to produce more severe storm events, which will increase hydraulic loading on storm drainage infrastructure and the resilience of the existing facilities requires testing.

Stormwater management applied in drainage of the RTI infrastructure

Conceptual design of stormwater management needs to match the characteristics of the RTI components serviced, by taking different approaches to SWM of railway tracks, yards, and stations.

The most challenging is drainage of tracks, whose structural integrity and rail alignment require fast drainage limiting the contact between the track structure and water. Such requirements contradict the contemporary approach to urban SWM, which is based on slowing down and delaying runoff. Any measures designed to attenuate runoff flows, by infiltration or storage, have to be placed within a safe distance downgradient from the railway track to avoid interference with track drainage.

Concerning the track drainage effluent quality, the best mitigation measures are source controls, including substitution of crossties made of environmentally friendly materials (e.g., concrete or others) for creosote-treated wooden crossties, and alternative vegetation controls avoiding chemical herbicide applications (e.g., using natural herbicides, or native plant green carpets), use composite brake pads with a reduced content of Cu, and, applying only clean lubricants, without PAHs and heavy metals, in right amounts. After source controls, next stage are interventions along the stormwater transport route. In the case of railway tracks, the most feasible seem to be a small-scale upgrading of drainage ditches alongside the track to low-maintenance grassy swales, but only where needed and with a commitment to maintaining such swales.

In railway yards, a wide range of Best Management Practices (BMPs) can be applied, with emphasis on pollution prevention and technological facilities or devices intercepting metals, oil & grease, and contaminated sediment (e.g., oil and grit separators, bioretention, or stormwater ponds, where space allows). Generally, good guidance for design of such controls is available.

In the case of railway stations, a typical task would be station renovation, including the drainage system. While conventional urban BMPs or low impact development measures can be readily applied, they must meet constraints imposed by the requirement to connect to the existing drainage system, with respect to elevation, flow capacity, and prescribed water quality. Meeting such constraints may require drainage effluent pretreatment and pumping. Finally, drainage systems of existing railway stations may require a review and upgrading for increases in design rainfall intensities and depths due to climate change.

Recommendations

Broad recommendations of this study and report include two main points:

(a) Readiness of the Swedish Rail Transport System for Changing Climate

Recognizing the importance of drainage for safe and successful operation of railway systems and ongoing climate change, it is suggested that drainage of the Swedish rail system is subject to hydraulic stress and resilience testing by developing the procedure for this testing.

Project deliverable: A plan to undertake this study, plan of execution, and recommendations of adaptation measures needed to reduce the risk of flood/inundation damages in the entire system.

(b) Reducing or eliminating releases of toxic chemicals to the environment

Overview of the current research in RTI impacts on the environment indicates that there are at least two practices, which involve repeated releases of toxics into the environment: (i) preservation of wooden crossties by creosote, leading to releases of PAHs and (ii) vegetation controls by glyphosate.

Even though both cases likely cause limited environmental damages, they contradict the objective of eliminating toxics releases to the environment. It is suggested to undertake a planning study addressing the feasibility of eliminating these two practices and developing a plan of corrective action.

Project deliverable: A report on feasibility of eliminating creosote and toxic chemical herbicides from railway transport operation, addressing the current status, assessment of alternative measures (including the costs), and proposing a time plan of implementation of recommended measures.

1. Introduction

Affordable, safe, technologically advanced and environmentally friendly transportation is one of the basic needs of modern societies for both, the well-being of the population as well as the industrial development. During the past 30-40 years or so, the environmental requirements were defined as environmental sustainability and with respect to the immediate urgent goals, as a development approach minimizing emission of greenhouse gases and other pollutants and causing only low impacts on the living environment. Inevitably, all modes of large-scale transportation impact on human health and the environment, and railway transportation is no exception. A literature search revealed that the most frequently cited impacts of railroads on the living environment included those on human health (air and noise pollution, accidents), wildlife (habitat disturbance and fragmentation, noise, accidental kills) (Lucas et al., 2017), and impairment of the environment manifested by air, soil, water and vegetation pollution. Additional impacts are caused by construction of new railway tracks and facilities, and accidents involving hazardous cargo. The same review also indicated that compared to other competing transportation modes, roadway and air transportation, impacts of railways were among the lowest in the transportation sector.

For the purpose of this report, the Railway Transportation Infrastructure (RTI) was considered as a system of three types of components: (a) railway tracks and the associated corridors; (b) railway yards (often built-in conjunction with rail depots) defined as the facilities for handling rail freight and sorting, marshaling, loading, unloading and repairing railroad cars; and (c) railway stations (sometimes referred to as depots) serving passengers. All the three types of RTI components are exposed to precipitation and hence require drainage facilities, serving various operational needs and potentially impacting on the environment. Tracks and their drainage represent a diffuse source pollution spanning great lengths and varieties of surrounding environments; rail yards are industrial facilities, often built-in conjunction with stations, and are recognized as sources of industrial pollution; and (large) stations are generally located in downtown areas with shortage of sites for new stormwater management facilities and constrained connectivity to the existing drainage systems.

Railway tracks (RWT) represent a linear infrastructure typically encompassing thousands of kilometers of the track and the associated corridor. The Swedish rail transport system, ranked as the 22nd largest in the world (Wikipedia, visited on Nov. 2, 2022), comprises a network of about 15,000 km of track (Figure 1), of which 80% is electrified, and about one third is a double track (~4,900 km)(data from Wikipedia: https://en.wikipedia.org/wiki/Rail_transport_in_Sweden , visited on Jan. 19, 2023). Note however, that up to 95% of the total rail transport of passengers and freight in Sweden, is done under electric traction and Sweden is recognized as a leader in rail electrification technology. These statistics are important for environmental considerations, because electrical traction eliminates that part of pollution, which is caused by diesel engines, or in other parts of the world, coal driven engines.

Train travel is popular in Sweden, as evidenced by the Swedish passenger load being ranked number five in the world, in terms of passenger kilometers per capita, and number three in EU (Wikipedia, https://en.wikipedia.org/wiki/Rail_transport_in_Sweden , visited on Jan. 9, 2023). Rail freight transport is also well developed in Sweden, and during the most recent reported period (2019), it carried between 20 700 to 23 500 million tons of freight annually (https://www.statista.com/statistics/435305/sweden-tonne-kilometres-of-freight-transported-by-rail/, visited on Nov. 3, 2022). Recognizing that rail transport is considered as an environmentally friendly transport mode, which should play an important role in reducing greenhouse gases output in the transportation sector (Kamga et al., 2014; EEA, 2020), further growth and development of the rail transportation can be expected. Under such conditions, it would be prudent to sustain and solidify the leading environmental performance of the Swedish rail transport, for the benefit of the whole society.

Figure 1: Swedish railway network (source: modified after ACP Rail)

Objectives of the task assigned to the LTU Urban Water Group were to examine: (i) RTI drainage, (ii) environmental impacts caused by drainage of RTI (mainly railway tracks, corridors, yards, and stations), focusing on drainage water and polluted soils, and (iii) examining remedial measures serving to mitigate the impacts of rail transport. Towards this end, the authors prepared the report that follows and can be best described as an international literature review, focusing on refereed journal articles dealing with RTI drainage, including pollution sources and environmental impacts, and impact mitigation by stormwater management (SWM), and the related environmental policies.

The literature search identified three limitations of the analyzed references:

(a) Journal articles selected as relevant addressed mostly environmental science, while the original terms of references called also for examining practical (applied) planning and design aspects. Articles with such topics are usually not published by international scientific journals. Hence, the information on planning and design presented in the report is rather limited.

(b) Even the articles identified as "relevant" according to their topic had to be further scrutinized for information on study/survey areas and railway operations, and sometimes eliminated from our analysis. Modern rail transportation driven by electric traction on lines with concrete crossties causes much less pollution than rail systems with diesel (or even coal) traction and wooden crossties. Some details of these operational aspects may not be reported in the published papers.

(c) Finally, some topics important for the report (e.g., approval of glyphosate for vegetation control and alternative measures) are not in journal articles as yet, but can be found in newspaper articles and industry newsletters, and reflect the current developments in the rail industry. The acceptability of such sources and their information was scrutinized and those withstanding this process were included in the report. Hence, the report reflects not only the peer reviewed journal articles, but also some "gray" sources.

2. Drainage of railway tracks (effluent quantity and quality)

The railway track is a basic element of railway transportation infrastructure and as such, it must be well-designed, constructed, and maintained to retain its exact geometry prescribed by the structural and operational design. Changes in track geometry may result in a loss of alignment, with deterioration of the train ride and a potential risk of train derailment. Among the guided vehicle technologies, only the conventional system, comprising the steel wheel guided by a semi-flange on a steel rail, is considered here. A schematic picture of the railway track is shown in Figure 2 and further explained to the extent required by further discussion of track drainage addressed in this report. Current challenges placed on track structural integrity include climatic changes affecting design precipitation and rail temperatures, and ever-increasing lengths and loads of freight trains (Palin et al., 2021, Chinowski et al., 2019).

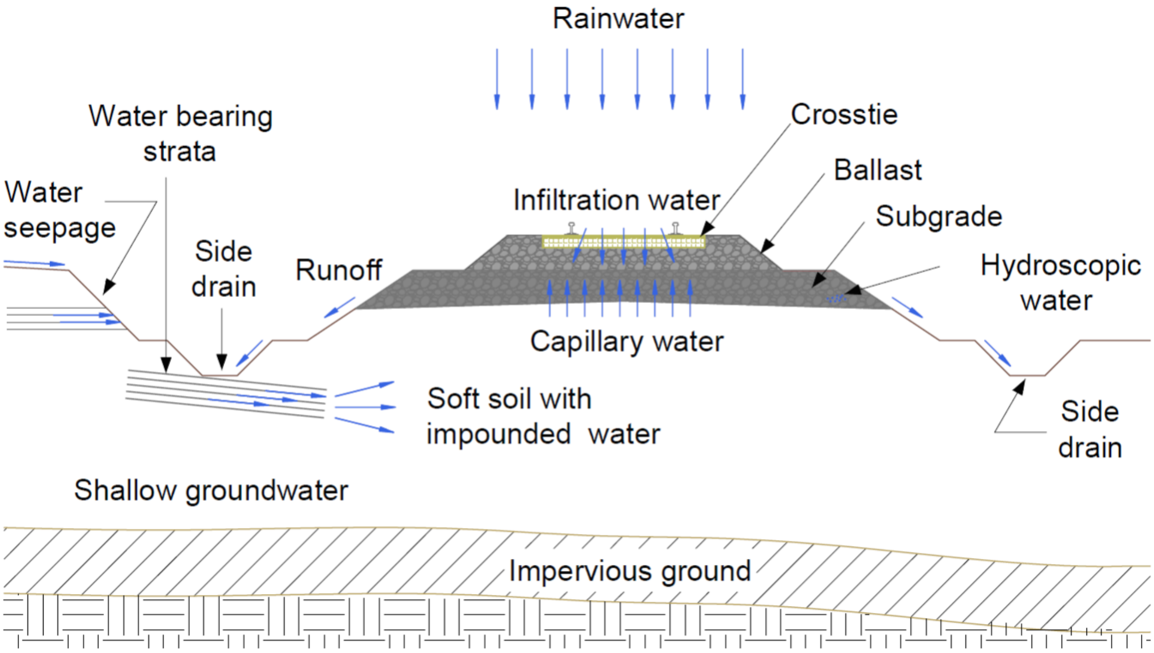

Figure 2. Railway track structure and drainage.

The railway tract having a quasi-trapezoidal shape consists of a number of elements, which fulfill specified structural (load bearing) and drainage functions. Starting on the bottom, the foundation of the track may be formed by bedrock, or a layer of native soil of a sufficient bearing strength, also called the formation, which has a cross-sectional camber facilitating lateral drainage of water. This layer then forms a foundation for subgrade (or sub-ballast), on top of which rests the ballast, supporting the rail crossties (also called sleepers) and the rails. Ballast comprises crushed stone and is designed to distribute the cyclic load exerted by moving trains and must meet a number of conditions, including the choice of hard stone (preferably granite or basalt), specific sizes (30-60 mm, or 10-70 mm), good internal drainage, and ability of stones "to lock" and form a load bearing structure.

Concerning track drainage, rainwater falling on the track enters the top layer of the ballast and percolates through into the sub-ballast, where it may be intercepted by the capillary water rising through the formation and sub-ballast. Water percolating downward may be retained in the ballast, if the ballast is contaminated by fine solids originating from the breakage of ballast stones or the pumping action upward caused by cyclic loading and forcing wet soils into the ballast layer. As seen in Figure 2incoming rainwater naturally drains laterally and runs down the side slopes of the track into drainage ditches running along the track. Rainwater entry and percolation through the structure is in contrast to other, commonly impervious, transport infrastructures like roads. Hence, any pollutants washed out from the track body (particularly the ballast) can be intercepted in the drains, which transport water towards natural streams, or allow it to infiltrate. From the pollution source point of view, the railway tracks are perfect examples of diffuse pollution sources, which are distributed along the whole railway network. It must be emphasized that Figure 2 and the descriptive text depict a simple version of the track and its drainage; many other variations are possible, depending on e.g., the track width (i.e., single or multiple tracks), lateral and longitudinal gradients of the terrain next to the track (i.e., whether it is above or aligned with the surrounding terrain, or placed in a cut), and whether it is a conventional or high-speed train track. In the latter case, different track structures are used, e.g., slab tracks, which are supported by concrete or asphalt slabs, with the former ones built as shallow-channel monolithic concrete structures supporting the crossties. Rail tracks in cuts may require additional drainage ditches intercepting surface runoff from the terrain sloping towards the track.

Drainage of surface and capillary waters from the track structure must function well, otherwise the retained water may contribute to structural track failure and costly repairs (Latvala et al., 2016; Sanudo et al., 2019). Hence, any stormwater management measures built next to the track in the rail corridor must avoid interference with positive track drainage. Furthermore, the rights of way along rail roads are granted by laws to rail operators and such protected lands form railroad corridors. With railway authority permission, the corridor space may be used for other than transportation activities and potentially could be used for placement of stormwater management facilities. This would be particularly important in urban areas, where the “greening” of railroad corridors is needed and has been proposed (Blair et al., 2017) as a means of improving visual appearance of the corridor, without interfering with its drainage.

2.1. Releases of pollutants into railway track drainage and pollutant environmental pathways

The railway track infrastructure and the rolling stock operation release pollutants into the ambient environment. Drawing analogy with the urban stormwater pollution (Muller et al., 2020), two types of wet-weather diffuse sources of pollutants can be distinguished in railway drainage: (i) washoff of rail infrastructure surfaces, and (ii) anthropogenic activities connected with operation of the rolling stock (trains).

The first category includes railway infrastructure components, such as rails; railway crossties (sleepers) made of various materials (Figure 4); ballast stones (containing pollutants emitted by train operations and track maintenance, e.g., herbicide applications); rail track embankments susceptible to soil erosion; track-switches; and, track signage and barriers, including corrosion resistant metal poles, signals and signs. These pollutant sources are activated only in wet weather and their pollution releases depend primarily on both rainfall characteristics (depth, duration, possibly intensity, and pH), and the material composition of structures being washed off by rainwater (Burkhardt et al., 2008).

Losses of metals by elution/corrosion are relatively small, compared to losses by attrition dicsussed later in the second category, with the exception of zinc-galvanized metallic structures like signals, signs, etc. (Burkhardt et al., 2008). Other pollutants in this category are lubricants applied to rail switches and herbicides used in vegetation control. Rails and their fasteners are likely to release some metals by washoff, but such amounts were considered here as negligible, when compared to the metal losses by attrition addressed elsewhere in this section.

In the second category, the sources are affected by rolling stock operations and mostly represent attritions of various metal surfaces, including rails, overhead lines, rolling stock wheels and brakes, and rail lubricants applied by spraying from a moving train to reduce excessive friction in railway turns (Abbasi et al., 2013; Burkhardt et al., 2008). Attrition releases occur in both wet and dry weather and are directed mostly into open air in the form of fine particulates, which typically settle on the track and its immediate vicinity, or inside rail tunnels and railway stations. This transport and fate of pollutants was confirmed by numerous studies of metal enrichment of soils along tracks (summarized below), indicating such enrichment in a band of about 20 m on both sides of the track. A thorough analysis of sources and releases of pollutants by railway transport was presented by Burkhardt et al. (2008), drawing on data and reports by

Swiss Federal Railways (SBB), and MFA (mass flow analysis). The rates of metal releases to the environment correlate with the particulates generated by attrition of metal parts, estimated for the (mostly electrified) Swiss rail system (total length of 5 200 km, or 1/3 of the Swedish rail system length) by Burkhardt et al. (2008) as follows: the rails (550 t/yr, 21% of the total load), rolling stock wheels (124 t/yr, 5%), brakes (1912 t/yr, 73%), and contact lines of electric locomotives (38 t/yr, 1%). Among the abrasion sources, the dominant ones were the brakes, contributing almost three quarters of the total metal releases. This load was estimated from MFA by considering the known weight of brake pads replaced during maintenance, minus the residual weight of pads returned after replacement. Besides total metal emissions from brakes, rails, wheels and contact lines, Burkhardt et al. (2008) also estimated individual metal loads (t/yr) released by attrition, in a descending order:

> Fe (2250) > Cu (46.7) > Mn (16.3) > Cr (7.7) > Ni > (0.4) > Mo (0.103) >
>
> > Ag (0.080) > Va (0.06) > Sn (0.03) > Bo (0.02) > Sb (0.003) > Pb (0.003)

Hence, an approximate estimate of metal attrition in the Swedish railway system could be readily produced and would likely significantly exceed that in the Swiss system, because of the greater length of the Swedish system and greater proportion of freight transport. On the other hand, the Swiss system may be characterized by higher usage of brakes, because of the greater population density leading to more frequent stops and steeper gradients of track layouts. Consequences of metal attrition were indicated by elevated concentrations of metals in track embankments and the adjacent corridor land (Bukowiecki, et al., 2007; Gustafsson et al., 2007; Chen et al., 2014). Erosion of such soil surfaces then contributes to metal and PAHs transport and their possible entry into receiving waters.

Depending on the rail transport traction, i.e., currently electric or diesel, the most common types of pollutants produced by both types of sources (i.e., surface washoff and attrition) include metals, diesel and other respirable particulates, PAHs, and lubricants (oil and grease) (Figure 3). In view of difficulties with monitoring dynamic releases of pollutants by railway transport operations, it is easier to monitor the impacts of all sources on the receiving environment, and in particular, soils in the track vicinity. There is a fair volume of the literature on soil pollutant enhancement by rail transport pollution, which reached soils either in the form of immediate air depositions, or via infiltration of runoff. A summary of findings on this topic follows and is intentionally focused on more recent references produced in railway systems with electric or diesel tractions.

Figure 3. Considerable leaching of diesel and oil from locomotive operation

Soil pollution studies were typically conducted within a band of 20 m along the railway track, and at depths ranging from 0 to 2 m, at sites mostly located at railway stations and yards. Studies focused mostly on metals, PAHs, oil and grease, and herbicides sampled at shallow depths (< 0.5 m) and are arranged chronologically.

Wilkomirski et al. (2011) studied PAHs and metals (Pb, Cd, Cu, Zn, Hg, Fe, Co, Cr, Mo) in soil and plant samples collected in different parts of a railway junction: a loading ramp, the main track within the platform area, a rolling stock cleaning bay and the railway siding (a low-speed track section distinct from the main line). The sampled soils were strongly contaminated with PAHs, particularly in the railway siding and the platform areas, with maximum concentrations of 59 510 and 49 670 µg kg^{-1}, respectively. On the loading ramp and in the cleaning bay, PAHs maximum concentrations were lower, but still high: 17 950 and 15 380 µg kg^{-1}, respectively, with all the samples exceeding the permissible levels. In all soil samples, four- and five-ring PAHs dominated. PAHs were also found in four dominating plant species occurring at the study sites, with the highest concentrations found in Taraxacum officinale (up to 22 490 µg kg^{-1}) growing in the cleaning bay. Heavy metal contamination was also widespread, with the highest concentrations of Pb, Zn, Hg and Cd found in the railway siding area, whereas Fe concentration was the highest in the platform area. Finally, it was noted that the process of pollutant accumulation is continuing; soil contamination has significantly increased since the previous sampling at the same sites in 1995, as indicated e.g., by a significant increase in mercury content in the cleaning bay area.

Wierzbicka et al. (2015) conducted a multidimensional evaluation of soil pollution near railway tracks. The assessment of soil chemistry generally did not exceed the permitted limits, but samples did show toxic effects at different trophic levels of the test organism. This was explained by the synergistic effect (sometimes called a chemical cocktail effect) of relatively intermediate concentrations of a number of pollutants, exerting larger combined impacts than individual substances.

Seda et al. (2016) studied Cu, Na and Hg in soils along railways and highways, where Cu was a pollution indicator, Na served to track salt applications on highways, and Hg was a tracer of an antifungal preservative in wooden crossties. The highest concentrations were Cu=52.7, Na = 770, and 0.180 and 0.145 mg/kg for wooden and concrete crossties, respectively. Hence, wooden crossties can be sources of Cu and Hg. The level of Cu depended on the distance from the rails, and the distance of 10 m was sufficient to bring Cu concentrations down to acceptable levels for agricultural land.

Figure 4.: Railway with wooden sleepers (source Wikipedia)

Strelkov et al. (2016) suggested that the railway transport pollutants in soils reflect those in track runoff. Analyses of iron and petroleum products in soils and runoff yielded concentrations of Fe up to 10 000 mg/kg in soils and 8.3 mg/L in runoff. Petroleum product concentrations ranged from 600-800 mg/kg and 20-72 mg/L in soils and runoff, respectively. Discharges of runoff with the above peak concentrations would require environmental permits.

Winiarek and Kruk (2017) studied pesticide residue in soils, at depths up to 2 m, along two railway lines, one modernized and one older. The substances studied included 2,4 D (2,4-Dichlorophenoxyacetic acid), MCPA, carbofuran, atrazine, phenol, DDT/DDE/DDD, aldrin, dieldrin, and endrin. Concentrations of residues were below the permitted values, and lower than those found in agricultural areas. There were no differences in results between both lines, no changes along the lines, and vegetation control by chemical herbicides did not affect the adjacent areas.

Jiasheng et al. (2020) studied environmental problems caused by railway transportation in China and identified heavy metal pollution along the railway lines as the main problem. Among the remedies, they recommended pollution prevention and planting non-edible crops along the lines.

Samarska et al. (2020) sampled ballast rocks in the track for analysis of heavy metals and herbicide contents in the rocks, at a station with high traffic. Ballast stones did not contain enough Cd, Co, Mo, Pb, Sn and W to be detected, but contained other detectable metals arranged in the following descending order: Fe>Mn>Cu>Cr>Zn>Pb>As. Fe strongly correlated with Ni, Cr and Mn, which are all components of the "railway" steel. Abrasion of wheels and rails was identified as the source of these metals. All the herbicide mixtures studied contained glyphosate and Cd, Cr, Co, Cu, Fe, Mn, Ni, Pb and Zn at negligible levels.

Vaiskunaite and Jasiuniene (2020) studied Pb, Cd and Zn at three major railway stations and reported the following findings: (i) Pb peaked at 5 m from the track and never exceeded the permitted level of 80 mg/kg, (ii) Zn reached the highest concentration of 130 mg/kg below the permitted value of < 300 mg/kg, but Cd exceeded the permitted limit of 1.5 mg/kg, (iii) The highest pollution levels were at stations with high traffic, (iv) the most concerning contamination was that by Cd, and (v) most pollutants were attributed to combustion engines of the rolling stock.

Finally, recent research findings on pollution of runoff and soils, attributed to railway transportation, can be summarized as follows: Soils near railway tracks provide records of past pollution caused by railway transportation, and are helpful for identification of conservative pollutants released by the railway transport. In general, the reported pollutants fit into three groups: (i) metals (mostly produced by attrition of rails, wheels, brakes and overhead lines; Hg residues originated from wood preservatives), (ii) PAHs (attributed to diesel traction operations and older lubricants), and (iii) pesticides used in vegetation control. The detected levels of such pollutants were, with the exception of Cd in one study, below the permissible levels, though in one study the point was made that soils studied produced toxic responses in bioassays. However, this finding may be affected by the chosen toxicity tests and sample preparation and processing for these tests. The only group of constituents causing serious concerns are herbicides, which may be transported with runoff and infiltration flow into high-quality groundwater serving for raw drinking water supplies, and thereby affect human health. This point is discussed in more detail in next Section 3.2 of this report and further details are shown in Table 1 below.

Table 1. Main pollutants washed-off from surfaces of railway transport infrastructure (RTI)

Railway transport infrastructure elements	Main pollutant groups washed off from RTI		
	Metals	Oil & Grease (Lubricants)	Trace organics
Rails	Mostly Fe, some Cr, Mn;	Rail lubricants	
Railway ties: Wood	Possibly Hg from wood preservatives		Creosote (mostly PAHs)
Steel	Mostly Fe		
Concrete	Calcium[1]		
Composite	No data found	No data found	No data found
Ballast stones	Metals transported with percolating water	Rail lubricants transported with percolating water	Herbicides transported with rainwater
Track associated metal structures (supports of overhead lines and signage) and barriers	Zn from galvanisation, Cd (traces)	Lubricants	
Track switches	Some Fe, Cr, Mn, Ni	Lubricants	

[1] considered harmless, but may reduce elution of metals from component surfaces

Discharges from the ballast enter side drains, which in the case of sufficiently large flows could convey runoff with pollutants to the receiving waters. Where such drains carry significant flows, they could be modified to follow the specs for grass swales providing some level of treatment, particularly when conveying low flows ensuring a good contact between the polluted flow and the grass swale surface (Bäckström, 2003; Stagge et al., 2012; Gavric et al., 2019; Ekka et al., 2021).

Railway crossties are made of several materials, including wood, concrete, steel and composite materials. The choice of crosstie materials depends on a number of factors, including economic efficiency, climate, material availability, and environmental protection and legislation. Wooden crossties are particularly popular in the US, because of their economic attractiveness and ability to withstand and attenuate dynamic loading caused by heavy freight cars. In fact, in 2008, about 90% of the 17 million of new crossties were wooden (AREMA, 2008). Crosstie materials were compared in two Life Cycle Analysis studies performed in two different climates and about 10 years apart. While Bolin et al. (2013) rated the wooden crossties the best in the US (Mid West) conditions, the most recent Australian study (Thompson et al., 2022) rated the composite crossties as the best. In the US study (Bolin et al., 2013), wood was the best in environmental impacts (including those caused by the production of crossties) and the least costs, and concrete was the second, followed by composite materials (Ferdous et al., 2015). The environmental rating did not seem to reflect the concerns reported in the literature that freshly installed wooden crossties preserved with creosote released PAHs (85% of total trace organics releases) in hot weather, as referenced below. The Australian study (Thompson et al., 2022), conditionally rated the short-fibre composite crossties the best with respect to low costs and environmental emissions, pending the condition that the industry develops and reuses “at least some of material.” Furthermore, there was a great need for more of actual field performance data of composite crossties. Concrete crossties were rated the second (a widespread use, currently the least costly, and having low environmental emissions), and wood (referred to by the authors as “timber”) was the third, mostly because of shorter life expectancy, which increases its life-cycle costs, and the highest environmental releases among the tested materials.

The diversity of LCA results was to be expected for a number of reasons, including: a conditional state of one of the ratings, time lapsed between both studies (~10 years), uncertainties in LCA results caused by a number of assumptions made in the analysis, reflecting different climates, resources, and economic conditions (Bolin et al., 2013; Thompson et al., 2022). Hence, the user of the published data is advised to treat them with precaution.

In Sweden, according to Borg and Rane (2014), 40% of the railway system was equipped with wooden crossties, mainly on less trafficked lines and in railway yards. The authors reported that during the period leading to 2014, 150 000 new wooden sleepers were installed each year. However, this number has likely decreased since then given that wooden sleepers are usually replaced by concrete sleepers when renovating railway lines. Even though there is pressure on rail operators to eliminate wooden ties (to prevent releases of toxic substances – creosote – into the environment), wooden sleepers will be present in the Swedish rail system for a long time to come.

While it is indisputable that creosote crossties release PAHs, as confirmed mostly by lab studies (Kohler et al., 2000; Becker et al., 2001; Moret et al., 2007; Gallego et al., 2008; Thierfelder et al., 2008; Yang et al., 2013; Cargouët et al., 2018; Jurys et al., 2018), it is important to examine these releases along the ultimate fate path and in appropriate time scales (Kang, et al., 2005). Brooks (2004) studied the migration of PAHs from creosote treated railway ties and described the migration process in detail for a realistic physical setting of a railway track next to a wetland. The study was carried out in Romeoville (Illinois, 41.65° N, 88.09° W), with the climate similar to that of southern Sweden. PAHs migrated out of newly treated ties in hot weather, but only during the first summer after the crosstie installation, with phenanthrene and fluoranthene dominating the migrating PAH mixture during the initial period of 2 to 3 years. Such PAHs entered the track ballast and their distribution changed in time, with LMW (low molecular weight) PAHs degrading or evaporating and consequently, the proportion of HMW (high molecular weight) PAHs increasing. PAHs in general, and particularly the HMW compounds, are hydrophobic, adhere to dry surfaces, and thereby become immobilized. Brooks (2004) further hypothesized that the most likely process of PAH degradation was photo- and chemical oxidation (weathering) on railway ballast, with only a small portion of PAHs moving up to 60 cm downward in the ballast layer. Small amounts of PAHs migrated from the ballast into adjacent wetlands, but even for the highest PAH levels observed in wetland sediment samples, no adverse biological effects could be predicted. It was also concluded that atmospheric deposition (including that attributed to railway sources) contributed a significant portion of the observed PAHs, and that creosote treated crossties would at most contribute an additional 0.3 µg of TPAH/g dry sediment within half a meter of the toe of the ballast. It can also be assumed that stormwater runoff would carry only less toxic LMW, because of their higher solubility. Nevertheless, an improvement of environmental practices was recommended with respect to disposal of derelict railway crossties, safe temporary storage of new creosote treated crossties while awaiting installation, and in production of new wooden crossties, precaution should be taken to avoid over-application of creosote and the risk of its release into sensitive environments. Besides PAHs, wooden crossties may contain low levels of Hg originating from an antifungal preservative used, e.g., on Czech railways (Seda et al., 2016).

Regarding the two other crosstie materials discussed, concrete and composites, no suggestions of pollution releases from such materials were found in the literature, and both LCA studies addressed concrete and composites as relatively non-polluting materials.

Track-associated metal structures. Railway infrastructure includes a large number of metal structures, serving various purposes, including support of overhead lines, signage, signal poles, and safety barriers (Figure 5). Typically, these structures are designed corrosion resistant, with the most common method of protection being hot-zinc dipping (galvanization). Washoff of galvanized structures (roofs, corrugated storm sewer pipes) by rainwater/stormwater was reported in the literature by a number of authors, including Wicke et al. (2014), Borris et al., (2017) and Müller et al. (2019). Wicke et al. (2014) and Müller et al. (2019) investigated galvanized roofing materials and Borris et al. (2017) investigated galvanized steel sewer pipes. Roof runoff studies concluded that depending on the material in contact with water, there were high concentrations of Cu and Zn in roof runoff over prolonged time periods. For example, Wicke et al. (2014) observed Zn concentrations in runoff from a galvanized roof, after the first flush, between 200 and 450 µg/L (98% in the dissolved fraction) for the whole event duration. Laboratory experiments with metal roof sheets showed a high influence of rainwater pH on metal concentrations in runoff. Dissolved metal concentrations further increased with decreasing pH, which was varied in lab experiments in the pH range of 4-8. Older, weathered metal materials showed 10-40% higher Cu and Zn concentrations. Peak concentrations from galvanized metal roofs, with Cu guttering and downpipes, were as high as 13 800 and 7 900 µg/L for Cu and Zn, respectively. It is hypothesized here that metal concentrations in washoff from rail track structures are smaller, because of much shorter contact times between the rainwater/stormwater and the exposed envelopes of metal structures, positioned on steep angles.

Figure 5. Metal structures and other building material along a railway track

Burkhardt et al. (2008) estimated the annual washoff of galvanized poles along the railway tracks at 140 g of Zn/pole/yr (equivalent to Zn volume of 20 cm^3). Recognizing high numbers of these structures in the rail system, they may release significant quantities of metals into the environment. For example, the total number of metal "poles" in the Swiss railway system (i.e., a system with 7 200 km of rails, compared to 15 000 km in Sweden) was reported by Burkhardt et al. (2008) as 144 000 (hence about 20 poles/1 track km). Under the Swiss conditions, the cited authors estimated the annual releases of Zn at 140 g/yr/pole, and the Cd release at 14 mg/yr/pole, yielding for the entire Swiss rail system 20 tons of Zn and 2 kg of Cd annually. Zn loads appear to be rather high and may require further scrutiny.

The last source in this group of pollution sources subject to pollutant washoff are railroad track switches, which guide trains from one track to another. Switches are of various complexity and their operation is generally motorized. According to Hassankiadeh (2011), in 2011, there were 12,000 units of track switches and crossings in the Swedish railway network and represented 5% of the total track length but required 13% of the total track maintenance costs. So, track switches and crossings are an important part of the rail infrastructure and require proper maintenance to operate well and ensure safe operation of the rail transport system. Applications of lubricants lead to their releases into the environment. Estimates of lubricant releases can be produced from the annual use of lubricants and MFA. Burkhardt et al. (2008) reported the annual use of lubricants in the Swiss rail transportation network as 580,000 L/y; this estimate combines lubricant uses on mechanisms (engines, gearing, buffer, bearings) and wheel flanges in sharp bends. Considering the density of lubricants ranging from 0.7 to 0.95 g/cm^3, the mass of lubricants used would be 390 – 520 t/y, for the Swiss system. A rough estimate of the annual load of lubricants used in Swedish track switches and crossings could be obtained by using the average of Swiss lubricant loads per km (= 0.5(390+520)/5000) multiplied by the total track length of the Swedish system (15 000), yielding about 1 400 t/y. This estimate includes both lubricants washed off from track switches and crossings as well as those applied to wheels in sharp bends; the second component depends also on rolling stock operations.

There is an important caveat concerning the above estimates of annual lubricant use: (i) not all the lubricants used are released into environment (Burkhardt et al., 2008), (ii) the lubricants currently used are carefully selected to match the actual lubrication needs (Waara, 2006) and to protect the environment, no undesirable heavy metals, PAHs or halogens are allowed in the lubricants used (Burkhardt et al., 2008), and (iii) in terms of fate, significant quantities of released lubricants will be immobilized in track ballast. The above facts document the ongoing efforts to mitigate environmental impacts of lubricants usage in railway operations.

The second group of pollution sources depends on train operations, including numbers and types of trains (i.e., passenger or freight trains), the type of locomotives (diesel or electric traction), gross train weight and speed, and the types of brakes (Figure 6). Since these characteristics vary between countries and change over time (e.g., increased use of disc brakes instead of shoe brakes or the use of frictionless magnetic track brakes on high-speed trains), uncertainty remains when comparing studies and data from different countries and time periods.

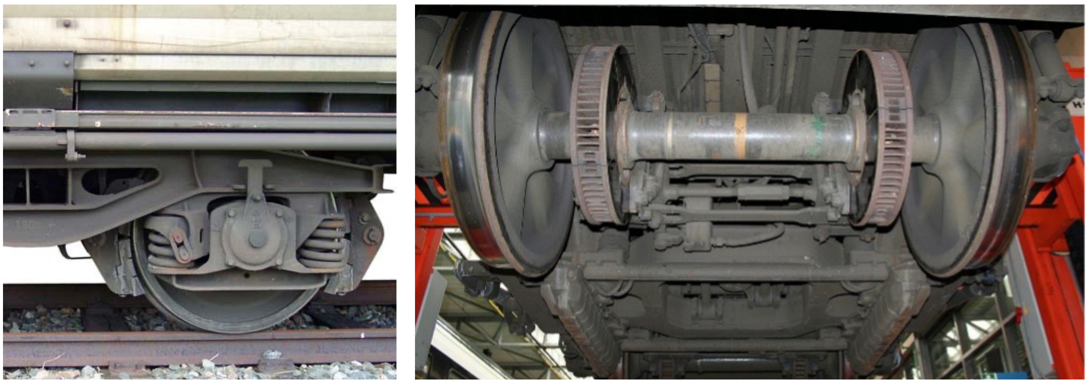

Figure 6. Different brakes on rolling stock: left shoe brakes, right: disk brakes (source: Wikipedia)

The rates of metal releases to the environment correlate with the particulates generated by attrition of metal parts, estimated for the (mostly electrified) Swiss rail system by Burkhardt et al. (2008) as follows: the rails (550 t/yr, 21% of total), rolling stock wheels (124 t/y, 5%), brakes (1912 t/y, 73%), and contact lines of electric locomotives (38 t/y, 1%). Among the abrasion sources, the dominant ones are the brakes, contributing almost three quarters of the total metal releases. This load was estimated from MFA by considering the known weight of brake pads replaced during maintenance, minus the residual weight of pads returned after replacement. Besides total metal emissions from brakes, rails, wheels and contact lines, Burkhardt et al. (2008) also estimated specific metals emitted and their yearly loads, listed below in (t/yr) and descending order:

Fe (2250) > Cu (46.7) > Mn (16.3) > Cr (7.7) > Ni > (0.4) > Mo (0.103) >
> Ag (0.080) > Va (0.06) > Sn (0.03) > Bo (0.02) > Sb (0.003) > Pb (0.003)

Hence, an approximate estimate of metal attrition in the Swedish railway system could be readily produced and would likely significantly exceed that in the Swiss system, because of the greater length of the Swedish system (3 x) and greater proportion of freight transport. On the other hand, the Swiss system may be characterized by higher usage of brakes, because of the greater population density contributing to more frequent stops and steeper gradients of track layouts. Consequences of metal attrition were indicated by elevated concentrations of metals in the air and on track embankments and the corridor land (Bukowiecki et al., 2007; Gustafsson et al., 2007). Erosion of such soil surfaces then contributes to metal and PAHs transport and possible entry into receiving waters.

Another type of pollutants depending on railway rolling stock operations are oil and grease lubricants, applied to engines, gearboxes, bearings, couplings, and rails in track sections with excessive friction between the wheel (semi-flange) and the rail. The release of these materials was discussed in one of the preceding sections.

In summary, attrition of brakes, rails and wheels, and elution of zinc from railway galvanized metal structures are cumulatively significant sources of Fe, Cu, Zn, Mn, and Cr, but their environmental effects are significantly diffused and likely smaller than those from other sources (e.g., highway transportation). Most of the metal load is released in the form of metal attrition particles, which in enclosed space (e.g., railway stations) may be respired by humans and cause health concerns. Transport of these particles with runoff is not well understood or documented. Zinc from galvanized structures is almost exclusively in a dissolved form and hence readily transported with runoff. No studies on toxicity of such runoff were found in the literature. In terms of loads, the next group of pollutants are lubricants regularly applied in operation of railway systems. Their effects can be mitigated by source controls consisting in limiting lubricant quantities to those needed and using relatively clean lubricants without metals and PAHs.

2.2. Vegetation controls on railway tracks by chemical herbicides: Swedish practice

Railway companies are generally required to clear the railway tracks and their right-of-way from any uncontrolled vegetation (Figure 7) that may pose safety hazards, including vegetation fires, poor visibility at road crossings, damage to structural integrity of the track bed, and impairment of infrastructure inspections (CN Canada; available on line, https://www.cn.ca/en/delivering-responsibly/environment/biodiversity-and-land-management/vegetation-management/, visited on Oct. 13, 2021). To meet this requirement, tracks have to be regularly inspected and the vegetation growth controlled, usually once a year. There are numerous techniques of vegetation control available, including manual or mechanical weed removal, application of steam & hot water, installation of plastic barriers stopping plant growth, and chemical controls of weeds by herbicides, and others are currently tested.

Figure 7. Weeds colonizing the railway track

Among the vegetation controls, annual applications of herbicides to ballast stones are widely adopted as the controls of choice serving to protect tracks against contamination by weeds and maintain their functionality (Cederlund, 2022). When applied on a system-wide scale, these applications represent releases of large quantities of potentially toxic chemicals into, and contamination of the environment. Concerns about such practices, and particularly the ingress of herbicides into groundwater, were expressed more than two decades ago by Schweinsberg et al., (1999). The first estimate of such system-wide releases was reported by Burkhardt et al. (2008) who identified glyphosate (also known by the commercial name Round-up) as the non-selective herbicide of choice in maintenance of the Swiss railway system by the operator, SBB. MFA of this herbicide indicated the usage in Switzerland at 3.9 t annually (reported in 2008).

Currently (2022), broad-scale applications of herbicides, and particularly of glyphosate, are being scrutinized by governments, international authorities, and railway system operators, and great changes can be expected in next several years. This scrutiny is conducted at various levels, ranging from scientific discussion concerning the permission to use glyphosate by the European Union expiring at the end of 2022 (Agathokleous, 2022), to a review of the glyphosate approval by the US EPA. In the last cited case, on June 20, 2022, the U.S. Federal Appeals Court ordered the US EPA to take a fresh look at whether glyphosate, the active ingredient of round-up, poses the alleged "unreasonable risks" to humans and the environment. This action was initiated by the court's assertion that the EPA did not properly justify its findings that glyphosate did not threaten human health, and the court stated that some aspects of the agency's approval process were faulty.

In anticipation of the findings and decisions by the regulatory bodies, some large operators of rail transport are planning to eliminate the use of herbicides and also intensified search for alternative methods that would be applied either singularly or in groups. Among those planning to eliminate glyphosate, one can name Swiss SBB, which set a deadline by 2025 (Swissinfo (2019); https://www.swissinfo.ch/eng/society/herbicide_swiss-railways-to-phase-out-use-of-glyphosate-by-2025-/45063178, visited Jan. 22, 2023). In the meantime, SBB concentrates on developing alternative methods, including hot water spraying (from special cars sensing the plant presence and then applying hot water); antifouling materials including structural measures reducing plant growth; land cover by vegetation green carpets preventing the growth of harmful weeds; the use of weeding robots; and, applications of bioherbicides, which are ecologically less harmful than chemical herbicides (https://www.railjournal.com/infrastructure/weeds-in-hot-water-as-sbb-trials-herbicide-alternatives/ ; visited Jan. 22, 2023). Other railway companies are also looking for alternatives to non-selective herbicides. Examples of such efforts are German Deutsche Bahn's ongoing investigations of the use of hot water, electric shocks, and UV lights for killing weeds on tracks, or the Belgian rail infrastructure manager Infrabel who is considering weed control by manual maintenance, or weed growth barriers made of geotextile, or asphalt.

For safe usage of herbicides in the environment, their toxicological characteristics, for specified application rates, and fate in the environment are important. Chemical, physical and toxicological properties of herbicides approved for use by the railway operators (including the Swedish Rail Transport) are relatively well known, but the environmental fate needs to be determined for local conditions. In a soil environment, which the chemical herbicides enter with infiltrating runoff, they are mainly absorbed to clay and organic matter. The presence of such materials in small quantities implies low absorptive capacity of soils and an increased risk of transport out of the target area. A low content of organic matter also implies low microbiological activity. Since the activity of microorganisms is the main factor controlling decomposition of herbicides in soils, low microbiological activities result in slow rates of transformation and consequently long persistence times, possibly contributing to herbicide accumulations. Hence, when a herbicide is to be chosen for use on a railway track, it is not enough to be well informed about its effects on weeds colonizing the track embankment, but it is also necessary to know the binding, mobility and decomposition of the herbicide substance in the embankment material to ascertain that there will be no significant risks to the surrounding environment. After this introduction, the remaining parts of this section deal with Swedish experience with using herbicides in rail track vegetation control.

Historical perspective. Swedish experience with using chemical herbicides for control of vegetation on railway tracks spans more than 90 years (Torstensson, 2001). Focusing on the last 30 years, in the early 1990s, the diuron herbicide was used on Swedish railway tracks, but since 2003 (Torstensson et al. 2002), it has been replaced by glyphosate (dosage ≤ 3L/ha) in combination with Arsenal 250 containing imazapyr. In 2003, imazappyr was banned, to prevent groundwater pollution, and the glyphosate dosage was adjusted to 1800 g/ha (equivalent to about 1.1 L/ha, applied once a year. Herbicides used in non-agricultural soils may follow different environmental fate than those used on agricultural soils and have longer half-times (Fogliatto et al., 2020). In general, ballast comprising coarse material is rather sensitive to herbicide loadings (Cederlund et al., 2007) and exhibits effective herbicide transport with water percolating to deeper layers, including those holding groundwater. Consequently, protection of groundwater aquifers and other sensitive areas was facilitated by introducing "no-spray" zones, where no herbicides were applied. In 2006, a monitoring program of glyphosate on Swedish rail tracks was introduced with two objectives: (1) increase information on herbicides in the environment, and (2) assure municipalities that herbicides used on railway tracks were monitored (and controlled) at the national level. Thus, herbicide monitoring was done to comply with the Swedish environmental regulation requiring that parties applying herbicides on railway tracks must inform local municipalities (Cederlund et al., 2007). Consequently, every year, the Transportation Administration sends letters to about 180 municipalities advising them where and in what manner herbicides will be applied. Municipalities have a legal right to specify the application conditions and impacts, e.g., requesting that the administration monitors herbicides wind drift, leaching and potential entry into groundwater aquifers (Cederlund, 2022).

The monitoring program sponsored by the Transportation Administration had to be somewhat simplified to be manageable, by focusing on possible accumulation of glyphosate and its first metabolite, AMPA (aminomethylphosphonic acid) in the environment over time. Results of such monitoring efforts were published (Cederlund et al., 2007; Cederlund, 2022) and served to evaluate the findings from two sampling periods, by providing statistics on likelihood of groundwater contamination by glyphosate in the vicinity of railway tracks and drawing general conclusion on mobility and persistence of glyphosate applied on Swedish tracks.

Herbicide transport was described by Torstensson (2001) for specific substances: in principle, all of them moved downward in the ballast, with percolating water, but reached various depths of penetration. The main mass slug of glyphosate stayed in the top 20 cm, and only small amounts penetrated up to 50-60 cm deep, but the main mass of imazapyr was found in the upper 30 cm (traces were at the depths of up to 60-80 cm), and diuron was fairly mobile. Considering the track material (macadam, gravel), herbicides were likely transported in both fractions, the dissolved and particulate, by infiltrating rainwater. Herbicide draining out of the track body, into the side drains, may be bound by soils, depending on soil characteristics and climatic conditions. Various herbicides varied in their persistence after applications; diuron was detected almost 10 years after the last application (not used on railway tracks in Sweden after 1993), and glyphosate and imazapyr have not been detected in groundwater above the detection limit of 0.1 µg/L, 1-2 years after their application in the recommended amounts (Torstensson, 2001). Among the common pesticides used in Swedish practice, only diuron penetrated all the way down to the groundwater.

Experience with herbicides on Swedish tracks indicates that they can be highly effective (Torstensson et al., 2005) and, in terms of labour and material costs, inexpensive in controlling vegetation, but they may cause environmental effects. Changes in applied herbicides have been motivated by science documenting toxicity of the currently or earlier used herbicides, and public concerns. During the past 15 years or so, the herbicide of choice was glyphosate, whose use on Swedish rail tracks has been studied for almost 20 years (since 2003). The most recent study (Cederlund, 2022) dealt with monitoring glyphosate and AMPA during two periods: 2007-2010 and 2015-2019. Both substances were analysed in 603 groundwater and 645 soil samples collected at 12 sites. Glyphosate and AMPA were detected in 16 and 14% of samples, respectively, with reporting limits for both substances RL= 0.1 µg/L initially but lowered to 0.05 µg/L in 2009-2010. The observed concentrations in groundwater were as high as 7 µg glyphosate/L and 1.1 µg AMPA/L, respectively, and the former values exceeded the EU Groundwater Quality Standard (GQS), in the EU Groundwater Directive 2006/118/EC, of 0.1 µg glyphosate/L in 6% and 4% of all cases, respectively. There was little horizontal spread, with only 1-3% of samples detected outside of the track footprint. In 2018, higher concentrations were detected beneath 3 out of 5 active sites; a hot summer may have limited the chemical degradation. No accumulation of glyphosate in ballast was observed. The risk posed to valuable groundwater resources was characterized in a peer-reviewed article as “probably not that large” (Cederlund, 2022).

Furthermore, when examining exceedances of GQS, one needs to understand the purpose of GQS - to initiate further investigations, where such exceedance occurs at more than several points of the groundwater body (Annex III of the GW Directive). Such investigations may then lead to further remedial actions, including avoidance of herbicide use in the sensitive locations of concern. Observed glyphosate data were used to address the environmental concerns of municipalities, on whose territories glyphosate applications took place (Cederlund, 2022). In view of the earlier mentioned concerns about the use of glyphosate and the risk that such use may be banned by EU (the current permit expires at the end of 2022), Railway Traffic Authority (RTA) would be well advised to keep abreast of the developments in this field, and be prepared to implement alternative methods, should glyphosate become banned.

In summary, in spite of economic efficiency of using herbicide glyphosate for vegetation control on Swedish rail tracks, there is too much uncertainty surrounding the continuation of this practice and RTA needs to address expediently alternative measures for vegetation controls. Main concerns arise from the risk of glyphosate penetration into groundwater and contamination of sources of raw drinking water. Furthermore, the most recent article on glyphosate effects on human health reported in an agricultural health study (Chang et al., 2023) that people exposed to glyphosate exhibited oxidative stress biomarkers (a key characteristic of carcinogens) in their urine.

2.3. Railway drainage pollutant pathways and environmental impacts

Sources of pollutant releases by washoff of RTI were listed in Table 1, and the discussion in this section follows the same order: rails, railway crossties, ballast stones, track-associated metal structures and switches.

Rails and their fasteners are likely to release some metals by washoff, but this amount was considered here negligible, compared to the metal losses by mechanical attrition addressed later in this section. On the other hand, crossties may release pollutants, as demonstrated for wooden crossties treated with creosote. Very few studies of railway pollution attempted to describe the associated pollutant pathways in the environment. One of those studies is Brooks (2004) dealing with creosote treated ties. The study demonstrated that while it was relatively easy to apply MFA and determine potential release of trace organics from wooden crossties (consisting of up to 85% of PAHs), determination of their transport in the environment was a challenging task, requiring the following considerations:

(i) potential release of organics from crossties (i.e., movement from the wooden structure to the crosstie surface) can be measured, but occurs mostly in the case of freshly treated crossties and at high (summer) temperatures,

(ii) transport from the tie surface into the ambient environment depends on ambient conditions, and may involve either the dripping of creosote into the ballast, or hydraulic transport as a rainwater/creosote emulsion entering the ballast, followed by hydraulic transport with rainwater,

(iii) The PAHs mixture exuding from wood changes its composition. While the early process is dominated by LMW PAHs, which may be relatively soluble and volatile, the later phases are dominated by HMW PAHs, which are hydrophobic. Thus, during the early phase of runoff, there is a higher likelihood of PAH transport in the dissolved phase, the later phases will be dominated by the hydrophobicity of HMW PAHs and considering the slow percolation of water through the ballast, the transported load will mostly end up adsorbed to ballast stone surfaces, without reaching the receiving aquatic environments (Brooks, 2004). Under such circumstances, the best management measures are source controls, including substitution of harmless materials for crossties, e.g., concrete, where dealing with sensitive receiving environments.

Ballast stones – the ballast and sub-ballast layers represent coarse filters (stone sizes 10-70 mm), which only partly improve the quality of water passing through. This enhancement excludes mechanical filtration of solids in size categories up to the sand size but may provide adsorption surfaces for hydrophobic substances (e.g., HMW PAHs) (Brooks 2004) percolating through the layers. Both ballast layers may become “tighter” to percolating water if contaminated with fine particles. However, such cases should be corrected by maintenance, to keep the ballast layers well-drained and fully functional with respect to their load bearing capacity. The contaminated ballast needs to be either cleaned or replaced with new stones. Among cleaning processes, Anderson et al. (2002) tested three solvents for cleaning ballast and noted that while all solvents removed >90% of contaminants, there were some chemical residues, which required additional removal by rinsing.

Discharges from the ballast enter side drains, which in the case of sufficiently large flows could convey runoff waters with pollutants to the receiving waters. Where such drains carry significant flows, they could be modified to follow the specs for grass swales providing some level of treatment, particularly when conveying low flows ensuring a good contact between the polluted flow and the grass swale surface (Bäckström, 2003; Gavric et al., 2019; Ekka et al., 2021).

Environmental impacts and concerns. The pollutants released from the RTI sources are spreading in the environment in the form of the diffuse pollution. Field studies (e.g., Wilkomirski et al., 2011; Wierzbicka et al., 2015; Strelkov et al., 2016; Winiarek and Kruk, 2017) confirm the rail transport pollutant distribution in soils, which are characterized by pollutant deposition in a relatively narrow band overlapping the track layout. After deposition, further transport may be mediated by surface runoff and infiltration flows. Recognizing the predominance of electric traction in Swedish rail transport (up to 95% of the total load transported is accomplished by the electric traction), the discussion of rail impacts on the environment focuses on that particular traction. For completeness of the discussion, brief references are made to the diesel traction, or the impacts unrelated to track drainage, where deemed appropriate and documented by the literature.

Two types of rail transport impacts, which are significant and often listed in the literature, are noise and interference with wildlife, both mentioned in the Introduction, but outside of the scope of this report. Next item on the list is air pollution, generated by rail transport and reported in two forms: (i) respirable particulate matter (generally particles smaller than 4 µm, in the US, often defined as smaller than 2.5 µm) (Brown et al., 2013; Jaffe et al., 2014) and (ii) diesel particles from diesel-powered locomotives. The respirable particles were reported in the air in somewhat confined spaces at railway stations, as reviewed by Loxham and Nieuwenhuijsen (2019), and often represent metal particles released by attrition of metal surface during rail transport. Such particles are recognized for their detrimental impacts on human health. The second source are emissions of diesel exhausts from diesel locomotives in shunting yards (Abbasi et al., 2013). The older diesel-electric locomotives produce diesel exhausts, particularly during idling, and such exhausts are harmful to human health. Studies show that the presence of diesel exhausts is not limited just to the railway yards but may be found in yard neighbourhoods (Hricko et al., 2014; Jaffe et al., 2014), or at rehabilitated sites of former rail yards (Hagmann et al., 2019). No studies were found which would examine whether such exhausts deposit on nearby impervious areas and could be picked up by surface runoff and transported to receiving waters.

As mentioned earlier, fine particles produced by attrition of metallic surfaces deposit on soil surface and contribute to elevated concentrations of metals in such soils (Vaskunaite and Jasiuniene, 2020). These elevated concentrations may be also observed at some depths below the soil surface, perhaps due to transport of such particles with water seeping into the soil. Generally, the metal concentrations found in soils adjacent to rail tracks were relatively low and did not cause serious concerns with respect to human health. The last contaminants mentioned are chemical herbicides used in vegetation control, which represent a major environmental concern. Further aspects of herbicides control are discussed in section 4.

3. Drainage of railway yards and stations

Drainage of railway yards and stations is a point source of pollution and, consequently, both source components are discussed in the same section.

3.1. Railway yards

Railway yards are often built-in conjunction with other rail transport facilities along the main rail lines and represent industrial facilities with numerous sources of air and water pollution. Historically, as the main lines and rail transport changed, the importance of, and need for, specific yard facilities changed as well, and some of them were no longer needed. This resulted in yard properties sales for restoration and redevelopment. While there are numerous cases of restorations of former railway yard properties described on the internet, relatively few cases were reported at the level of scientific studies. Investigations of former rail yard properties reveal traces of the past activities in railway yards, including the adverse effects of industrial activities on soil contamination and ecological health. Hagmann et al., (2019) undertook a forensic environmental study of a former rail yard site in New York City and noted that yard activities changed the soil chemistry, compared to an unpolluted reference site, by elevation of heavy metals and PAHs. Other authors attributed organic contaminants in former yard soils to released lubricating oils, coal, oil, fertilizers and herbicides (Biache et al., 2017; Wiłkomirski et al., 2011).

Fuels, oils and lubricants enter the environment with leakage from storage tanks, filling stations, locomotives and pollutant spills. Risks of such leakage reflect the use of diesel locomotives (also called switchers) in the railway yards (Vo et al., 2015). Diesel locomotives and their extensive idling also significantly contribute to air pollution in yards and adjacent areas (Hricko et al., 2014), with impacts on human health (Spencer-Hwang et al., 2015). Oil and grease are commonly dispensed and used for lubricating gears (e.g., for the numerous switches in a railway yard), and engines, and older data also indicated leakage of transformers (Gustafsson et al., 2007). Additional pollutants originate from maintenance operations in yards, including oil and grease, chlorinated and non-chlorinated solvents, phenols, antifreeze, detergents, PAHs, sewage waste, and some inorganics (Vo et al., 2015). These pollutants originate from such maintenance operations, as metal processing, fueling, repair of machines and batteries, maintenance of rolling stock, and train cleaning. The only reference found on the quality of rail yard runoff was Gill (2012), a B.Eng. thesis.

Thus, rail yards represent operations with high risk of stormwater pollution, and this resulted in two environmental controls imposed on yards drainage and SWM: (i) full compliance with regulations for drainage of industrial areas with elevated risk of water pollution, and (ii) avoidance of SWM measures that could contaminate groundwater. Both aspects are further discussed in the section on SWM in rail yards.

3.2. Railway stations

Large railway stations are typically located in central (downtown) urban areas with dense development and high imperviousness, which can be lowered only by acquiring additional land and turning it into a green area (e.g., a park). For example, an expansion of the Boston South Station (2013) was made possible by acquiring an adjacent property and lowering the site imperviousness from 99% to 94%. Generally, the railway station sites in downtown areas are highly impervious and essentially do not differ much from similar highly developed urban sites in the city centre. Typically, such stations contain large number of railway tracks and switches, and platforms, plus the facilities supporting station operation and the needs of passengers. Currently, with increased interest in, and promotion of, train travel, it is unlikely that station footprints could be reduced to create space for surface stormwater management measures, but there are opportunities to manage rainwater falling on the station roof by installing green roofs or placing treatment technology devices underground and pumping the treated effluent into the existing storm sewers. The green roof option was considered in recent renovations of the downtown Toronto Union Station, but the proposal was eventually abandoned because of technical challenges that would be caused by the roof presence.

In terms of drainage design, the commonly used approach is based on underground drainage, which has to drain into the existing storm sewer system, ensuring this connectivity may require stormwater pumping. The literature search produced just one reference on train station drainage design in Boston, the US (see above). An example of the railway station drainage and stormwater management design is presented in next section.

4. Stormwater management of RTI facilities

Advanced stormwater management (SWM)was introduced into urban drainage practice about 60 years ago and defined in various way, as discussed, e.g., by Fletcher et al. (2015) with respect to urban settings and management evolution. In legal language, the abundance of definitions found in contemporary technical and legal documents was noted in the Law Insider Dictionary, which lists more than 270 definitions of SWM (available on line: https://www.lawinsider.com/dictionary/stormwater-management-system , visited Jan. 22, 2023) and one of those is copied below to document the complexity of contemporary SWM process dealing with various aspects of rainwater/snowmelt drainage from anthropogenically impacted catchments: "Stormwater management system means the entire set of non-structural site design features (*also called green drainage infrastructure*) and structural BMPs for collection, conveyance, storage, infiltration, treatment, and disposal of stormwater runoff in a manner designed to prevent increased flood damage, streambank channel erosion, habitat degradation and water quality degradation, and to enhance and promote the public health, safety and general welfare."

In practice, the application of the above SWM definition depends on the size and complexity of the drainage project and its impact on the environment. Not surprisingly, as noted by the authors of a relatively recent review paper on SWM in rail transportation (Vo et al. 2015), stormwater management of RTI tracks focuses on drainage issues, but water quality, respectively the rail transportation pollution, is largely neglected. Even though the railway track generated pollutants are acknowledged, the resulting water pollution and transport of RTI pollutants by water is ignored (Vo et al., 2015). This finding reflects the reality of roles that the water quantity and quality play in railway transportation. Quantitative aspects of RTI drainage (flow rates, volumes) are of utmost importance for system design and operation, because effective drainage of railway tracks is a prerequisite for structural integrity and safety of tracks and their embankments (Latvala et al., 2016). On the other hand, the pollution generated by RTI and rolling stock operation is diffused over a great length (in Sweden, > 15 000 km), the associated pollutant concentrations are mostly relatively low, and except for railway yards with concentration of polluting activities, fall below the harmful levels listed in various guidelines and regulations. At the same time, railway transportation is a large-scale operation moving large numbers of people and freight over great distances and the total releases of pollutants into the environment represent significant quantities (Burkhardt et al., 2008). Hence, the applied SWM system must reflect these realities and focus on management measures tailored to diffuse pollution – pollution prevention. Recognizing that different elements of RTI may require different SWM approaches, SWM is discussed here separately for three classes of RTI elements – railway tracks, yards and stations.

4.1. Railway Tracks

Besides pollution prevention, source controls, the opportunities for applying SWM directly to railway tracks are rather limited, recognizing that the most common processes listed in the earlier presented definition of SWM include stormwater infiltration, storage and soil/vegetation filtration, which imply extended contact of the track structure with rainwater, while the safe design of track drainage requires quick water removal. Thus, it is not surprising that documents on track drainage (e.g., U.S. Army Corps of Engineers 2004), do not address drainage quality at all. In conventional track structures, rainwater passes quickly through the highly porous ballast layer, unless the ballast is contaminated by fine particles and requires restoration by particle removal. Water percolating through the ballast should exit laterally on the sides and drain into side drains, which then convey drainage water into receiving water bodies. Impairment/blockage of this drainage water path, combined with cycling variations of dynamic loads on the track by rolling stock, may lead to clay pumping from the subgrade to the ballast and eventually to the impairment of the track structural integrity (Rushton and Ghataora, 2009). While the ballasted tracks are used most frequently, alternative designs forcing water out of, and strengthening the track (by inserting an asphalt or concrete layer), or preventing clay pumping by using geotextile barriers, are also used (Esveld, 1997; Teixeira et al. 2009). For high-speed trains, modern rail tracks can be supported by a concrete slab.

Source controls have been applied to railway tracks for quite some time and further extension of this approach appears to be feasible. Among advantages of such measures, one could name:

- Avoiding toxic preservatives of wooden ties (creosote, pentachlorophenol, mercury) by using less-toxic preservatives, or by using concrete or composite crossties
- Avoiding or reducing the use of chemical herbicides on rail tracks, and
- Using relatively clean grade of oils and lubricants without trace metals and PAHs.

Applications of stormwater treatment along railway tracks are rather challenging. The drainage area to be serviced by a treatment facility is long and narrow and the footprint of the treatment facility would need to reflect this shape, and there needs to be positive drainage away from the track body. These restrictions could be met by a series of small facilities (e.g., grassy swales) designed to ensure that surface runoff is conveyed to the facility, rather than allowed to infiltrate into the ground.

Focusing on ballasted tracks, the side drains, also called drainage ditches, are usually cut in the native material, without further improvements of stormwater transport and quality, which could be achieved by upgrading them to vegetated swales. Swales are a robust, cost-efficient stormwater control measure which can provide simple water quality treatment. In most cases they should be sufficient for treatment of railway drainage. In case further treatment is required (e.g., due to specifically sensitive receiving water bodies), other treatment facilities as e.g., bioretention/biofilters could be implemented. However, these systems need considerably more maintenance and are more costly. Thus, their widespread use along railway lines is in most cases not needed and not recommended. Swales have been extensively studied in Swedish conditions and found effective in managing drainage flow quantity and quality by infiltration and filtration through vegetation (Bäckström, 2003; Gavric et al., 2019; Ekka et al., 2021).

However, before deciding on ditch upgrading to grassy swales, two considerations need to be made: (i) confirming the need for such an upgrading (e.g., it would be helpful in retaining some pollutants, including herbicides), and (ii) making a commitment to maintaining the upgraded facility so it does not impair drainage of the track (possibly including vegetation control) and the swale does not become a pollution “hot spot” by accumulating pollutants (metals, PAHs, oil and grease), which would harm wildlife.

4.2. SWM in railway yards

Railway yards are often built-in conjunction with other rail transport facilities. Storm drainage in yards should follow the recommendations (i.e., best management practices) for drainage of industrial areas, and in jurisdictions with regulations of stormwater quality, it would have to comply with such laws. For example, in the US, drainage discharges from railway yards have to comply with the earlier introduced NPDES regulations (US EPA, 2021). A specific environmental concern is the contamination of groundwater by infiltrating stormwater (Aquafor Beech, 2020). Railway yards, tracks and spurs are classified as high-risk sites with potential for high levels of contamination by hydrocarbons, metals, organic and inorganic compounds, sediments and chloride. In such areas, pollution prevention practices in the form of non-structural and structural controls should be applied. Among Low Impact Development (LID) techniques, those primarily based on (bio)filtration, evapotranspiration or stormwater re-use may be acceptable, and only relatively clean rainwater or stormwater can be infiltrated without further treatment (Aquafor, 2020).

Among pollution source controls, some are common with those applied to railway tracks, including substitutes for wooden railroad ties or their toxic preservatives, eliminating chemical herbicides, and developing and implementing spill and dust controls for freight handling areas. Where liquids are handled, in bulk or in containers, drips between the rails and spill-control loading docks with shutoff valves are recommended (Best Management Practices for Storm Water Management, The City of Sacramento, undated). Besides the quality of railway yard effluents, another concern is about the generated air pollution. Some studies have examined rail yards as sources of air pollutants and have found that diesel fuel combustion was a primary source of PM2.5 (i.e., particulate matter < 2.5 μ) at such facilities and could exceed the national air quality standards. Jaffe et al. (2014) pointed out the risk of such non-compliance for their study conducted in the US. Primary sources of diesel particulate are exhausts of diesel-powered locomotives used in shunting yards serving for rearrangement of freight cars.

Besides source control BMPs for industrial activities, there are structural measures serving for interception and immobilization of pollutants. Such measures include spill and pollution protection by special designs of loading docks, fueling sites, and on-site stormwater management by flow diverters to sanitary sewers, throttling of stormwater flows, and stormwater quality improvement focusing on oil and grit separation by proprietary devices marketed by various companies. In general, larger scale BMPs would be also applicable (ponds, bioswales, bioretention, wetlands), but such facilities require larger areas. When railway yards are abolished, their sites require thorough rehabilitation (Hagmann et al. 2019).

4.3. Railway Station SWM: A case study

In countries with stormwater quality legislation, the drainage design and monitoring must meet the relevant regulations. That was the case in the USA, South Boston Station (MDT, 2014), which was subject to the NPDES controls (i.e., National Pollution Discharge Elimination System). This program, established under the U.S. Clean Water Act, prohibits anybody from discharging “pollutants” through a point source (e.g., a storm drain outfall) into the waters of the United States, without a NPDES permit. The permit specifies limits on what can be discharged, monitoring and reporting requirements, and other provisions to ensure that the permitted discharge does not hurt water quality or people’s health. In essence, the permit translates general requirements of the Clean Water Act into specific provisions tailored to the operations of each entity discharging pollutants. A point source is defined as a discernible, confined and discrete conveyance, such as a pipe, ditch, channel and similar. Details of the expansion project follow.

The report on stormwater management for the South (Boston) Station Expansion evaluated the impacts of this project on downstream water resources, by examining two alternatives: (i) Build Alternative (BA) and No Build Alternative (NBA). Because the BA included additional land acquisition and progressive SWM, it produces smaller impacts on water resources than NBA, mostly because of reduced site imperviousness from 99 to 94%, resulting in smaller runoff volumes and peaks. Consequently, the BA drainage can be connected to the existing drainage without any needs for capacity expansion. Furthermore, the proposed BMPs will improve stormwater quality and will not increase CSOs (frequency and volumes) of the affected combined sewers. The proposed construction/development complies with all the NPDES, state and federal stormwater standards.

The general mitigation principles and measures included in the station expansion project followed these objectives (MDT, 2014):

- Minimize impervious cover (where possible),
- Prevent disturbance of existing site vegetation,
- Retain existing stormwater management infrastructure as much as possible to eliminate the need for additional outfalls to surface waters,
- Implement pollutant source controls through good housekeeping measures,
- Minimize potential soil erosion by avoiding exposed soils and steep slopes in landscaping,
- Avoid stormwater infiltration into soils, which are, or may be, contaminated, and
- Meet the 10 Massachusetts Stormwater Standards (MSS) to the maximum extent practicable.

The MSS standards encompass the following guiding principles for stormwater management (Massachusetts Government, 2008, available on line: https://www.mass.gov/guides/massachusetts-stormwater-handbook-and-stormwater-standards ; visited Jan. 22, 2023):

1. No New Untreated Discharges,
2. Peak Rate Attenuation,
3. Stormwater Recharge,
4. Water Quality (protection),
5. Land Uses with Higher Potential Pollutant Loads,
6. Critical Areas,
7. Redevelopments and Other Projects (need to follow the Standards only to the Maximum Extent Practicable),
8. Construction Period Pollution Prevention and Erosion and Sedimentation Controls,
9. Operation and Maintenance Plan, and
10. Prohibition of Illicit Discharges.

The new station drainage would be designed with a specific goal of minimizing drainage impacts on local water resources. Towards this end, both non-structural and structural best practices will be used, following the commentary described below.

- Non-structural practices. Emphasis was placed on source controls to be implemented in the railway station catchment, including pavement sweeping, catch basin cleaning, waste handling, and control of dumpsters and loading areas. This would include spill prevention. Salt would be applied in snow management and snow manipulation would avoid placing snow on ballast stone or adjacent to it.
- Structural practices. A broad range of structural measures is contemplated, including catch basins with sump and hood (keeping floatables in the basin), drip pans in areas where locomotives would be parked, oil/grit separators (as a form of pre-treatment upstream of other BMPs), infiltration basins (where local hydrogeology permits), gravel wetlands, vegetated swales, infiltration basins, bioretention/rain gardens, permeable pavement, tree box filters (supporting trees and promoting infiltration), wet ponds, underground filtration systems/proprietary separators, and underground infiltration/detention systems

4.4. Conclusions on RTI Stormwater Management

The literature on stormwater management for RTI was rather limited but allowed to synthesize the published information below.

Conceptual design of stormwater management needs to match the characteristics of the RTI serviced, by taking different approaches to SWMI in drainage of railway tracks, yards, and stations.

- The best opportunities for source controls include substituting environmentally friendly materials for creosote wooden ties (where needed, e.g., with concrete or other materials), select alternative vegetation controls to avoid chemical herbicide applications (e.g., natural herbicides, or native plant green carpets), use composite brake pads with a reduced content of Cu, and apply only clean lubricants without PAHs and heavy metals.
- After source controls, next stage are interventions along the stormwater transport route. In the case of RW tracks, the most feasible suggestion seems to be a small-scale upgrading of drainage ditches alongside the track with grassy swales, only where needed to protect a sensitive environment and with a commitment to maintain such swales.
- For RW yards, a wide range of BMPs can be applied, with emphasis on best practices in pollution prevention and devices intercepting metals, oil & grease, and contaminated sediment (e.g., oil and grit separators, bioretention, or stormwater ponds, where space allows).
- For RW stations, conventional urban BMPs or LIDs can be applied, recognizing potential restrictions imposed by other applicable regulations or bylaws. Physical restriction on these facilities include space (locations in central city parts have limited space for placement and footprint of facilities; they may have to go underground), and drainage outflow needs to be connected to, and meet the capacity of, the existing local drainage network. This may require pumping the effluent from the retrofitted facilities.

The nature of RWI drainage pollution is such that source controls are probably the best and most effective approach. In the case of tracks, the potential runoff contributing area is rather narrow and elongated (constrained by the size of the railway corridor, or natural drainage) and among the current environmental priorities, the main efforts should be directed towards: (i) reducing or eliminating applications of chemical herbicides, which are practically impossible to recapture once they enter soils, and (ii) searching for substitutes to creosote in protection of wooden crossties, to reduce or eliminate inputs of PAHs to the environment.

5. Commentary on hydrological/hydraulic design of railway drainage

The earlier sections of this report focused on water quality aspects of railway drainage. However, operators of railways also encounter drainage capacity problems caused by extreme rainfalls and floods, which are likely to get worse with progressing climate change. As emphasized in the report Introduction, severe rainfalls may cause numerous problems in drainage of railways, which can be related to soils (e.g., unequal settling of subgrade), and others are related to the track structure material itself (Sañudo et al., 2019). Besides common flood damages, the main risk of inadequate track drainage is the loss of geometric track quality. Typical causes were listed earlier and include such processes and events as erosion of track embankments by surface water, frost heave of soils, contamination of ballast by capillary water rise and pumping of clay by cyclical rail loading, and accelerated wear of ballast material. It is noteworthy that Robinet (2008) reported that 92% of problems on French railways were caused by inadequate drainage of foundations. Many drainage problems, like failing drainage and flooding, manifest themselves by operational costs faced by the operators of railway transportation, who then request financial compensation from infrastructure owners.

Modern railway transportation and its demands on railway infrastructure require improvements in geometric tolerances of rail settings, track resilience, and service life. While traditional track with ballast can still provide good service, a competing system, referred to as a slab track (Sañudo et al., 2019), was developed more than 50 years ago. This system uses a binder, concrete or bituminous agglomerate, to replace the ballast structure. While the slab track is more costly to build than the ballast track, it is cheaper to maintain. Note also that both tracks have different drainage patterns; in the ballast track, water easily percolates through a clean ballast layer at velocities up to 0.15 m/h and drains laterally by the sloping subgrade (3-5%). Hence, attention must be paid to water transport in the lower layers. Track designs with concrete slabs utilize either porous concrete, or more often cambered concrete shape to drain laterally water from the track top. It is generally acknowledged that ballast tracks have many more maintenance issues that the slab tracts.

In search for better track drainage, researchers have analyzed the reasons for poor drainage performance attributable to various elements of the track and identified five types of infrastructure damages: (i) infrastructure damage, (ii) superstructure damage, (iii) operations and circulations risks, (iv) drainage network damages, and (v) third party damages (further away from the track). Details follow.

Risk and damages to railway track body infrastructure are caused by water remaining in the substructure for long periods of time and causing increased slope instabilities, surficial erosion, clay pumping, and problems with frost heave cycles caused by poor drainage (Latvala et al., 2016). Subgrade deformations can form pockets in ballast that may need to be drained by cross drains. Top of the track has low permeability; hence, more runoff is generated and must be directed away from the track to the receiving waters.

Risk and damages to railway top superstructure may be caused by impacts of impounded water on rails, through higher corrosion and high friction in expansion joints, and impacts on rail fasteners, which corrode during extended periods of wetness of rails, and such conditions may have to be remedied by using welded rails.

Risk of damage to crossties depends on their material; it is advisable not to mix crossties made of different materials and avoid steel crossties in wet conditions to reduce the risk of corrosion. Metallic structures are generally subject to corrosion and to reduce this risk, it is advisable to drain water away rapidly and ensure that the conveyance system has sufficient capacity all the way to the receiving waters.

In a traditional track system, ballast provides load bearing capacity and drainage. Where ballast rests on clayish soils, there is a risk of clay pumping by cyclic loading by passing trains. In tunnels, excessive water may contaminate ballast by various materials. There are two major causes of ballast fouling: degradation of the material itself by cyclic loading and infiltration or inclusion of fine particles from the exterior. Dynamic loading also causes ballast breakage – 70-76% of ballast fines come from the ballast itself (Sañudo et al., 2019). Contaminated ballast has poor drainage and needs to be cleaned using one of several methods, like vacuuming and wash with chemical solvents. For fully clean ballast, the rain saturation rate was reported as 15.24 cm/h (Sañudo et al., 2019). In general, ballast particle sizes vary between 10 and 63 mm, and their hydraulic conductivity can be as high as 30 cm/s. Partly contaminated ballast is acceptable if its hydraulic conductivity is greater than C> 360 cm/h (note this rate refers to the ballast only, discharging into the atmosphere); if it is less, the ballast needs to be cleaned.

Concrete slabs are made of reinforced or bituminous concrete. Cracks are dangerous, because they may further develop and cause problems. Generally, humidity combined with frost causes problems with concrete slabs. Traffic, operations and circulation risk – metallic material and electrolyte contact needs to be established for corrosion to take place. Damage to drainage system commonly occurs by scouring, erosion and clogging. Inadequate drainage performance can damage infrastructure (e.g., undermine rails). Damage to third parties can be caused by anything that happens downstream of the track, including stray currents.

5.1.Design of linear drainage systems

For designing linear infrastructure, the designer needs to know the flow of water through the track (Ghataora and Rushton, 2012), as exemplified in Figure 2. Distinction is made among the following sources of water: precipitation input, surface runoff, and groundwater. Precipitation statistics serve to quantify the direct inflow. Ground slope and drainage pattern will determine the direction of runoff, either towards to, or away from, the track. Capillary head, which is important for determining whether there can be entry of groundwater into the track body, depends on many factors including particle size, void ratio, density of soil particles, interconnectivity of void spaces, and grain shape and roughness. Ballast capillarity raise and head typically vary from 6-20 cm, for coarse and fine gravel, respectively. Drainage water may flow longitudinally (i.e., along the track) or laterally, and either diffuse on flat faces of infrastructure, or in porous media, or concentrate in drainage ditches.

In classification of drainage systems of railways, it is common to distinguish between external and internal drainage. Ballast track has high permeability; hence the bottom interface needs to have camber and the lower layer should be waterproof. For concrete slab tracks, the top surface of concrete must slope laterally away from the track to facilitate quick drainage and avoid water ponding. Porous surface on the top of track is generally discouraged to prevent water from getting into the track body. Furthermore, external drainage should be designed to direct water (runoff) away from the track.

5.2.Drainage design using simplified calculations

Computations of the design flow start with assembling input data: the design return period, and precipitation and soil characteristics. Those are used to calculate rain-generated flow, which forms the basis for calculating longitudinal and lateral flows. Precipitation data is available in Sweden in two formats – either as historical data available for various return periods, durations and intensities from SMHI (Swedish Meteorological and Hydrological Institute), or as intensity data calculated from an empirical equation developed by Dahlström (2010) for Swedish conditions. Choices of computational methods depend on national regulations, which may specify, e.g., return periods for various parts of the infrastructure, and acceptable hydrological methods (e.g., empirical formulas, or hydrological models). According to Sanudo et al. (2019), design flows for sizing small drainage elements are calculated most often by the empirical Rational Method (RM) in the following form:

$$Q = k\,C\,I\,A$$

Where Q is the flow rate [m^3/s], k is the unit conversion coefficient, C is the dimensionless runoff coefficient, i is the rainfall intensity [mm/h] for selected time of concentration, and A is the runoff contributing area [ha].

Even though there is a loss of information (i.e., the calculation yields just a peak flow), RM is used widely, particularly for small runoff contributing areas. According to Sañudo et al. (2019), this loss becomes more significant when dealing with catchments of several hectares or larger. The RM use is further supported in jurisdictions, where a block rainfall is recommended as a design hyetograph (that is the case in Sweden). An alternative method may be a hydrological model, which employs a more sophisticated (comprehensive) analysis of hydrological conditions and may be required for assessing the final design. An obvious disadvantage of hydrological models is that they require considerably more input data, than the RM.

The design return period (T) is usually specified by a national authority and depends on: (a) damage cost by design failure, and (b) characteristics of the drainage element. In Spain (Sañudo et al., 2019), T varies from 100 to 500 yr, for sizing lateral rail drainage network, depending on local conditions. Modelling methods must be employed to check the propagation of changed hydraulics upstream and downstream of the site under design. For longitudinal drainage, T=50 -100 yr applies (the high value in specific cases). High Speed Rail Authority in California (HSRAC, 2012) distinguishes between railways in urban and rural areas, longer Ts are used in urban areas, because of higher risk of loss of human life and damages. T = 10-50 yr are used for longitudinal drainage and between 100 and 500 yr for lateral drainage.

The sizing of drainage elements is usually done by using Manning equation and selecting the element roughness n (e.g., for concrete) and then selecting the pipe size and slope that can match the calculated capacity (pipes come in fixed nominal sizes). Calculations with granular material (e.g., French drains) are done by Darcy equation. In ballast tracks, each layer affects the track drainage. Ghataora and Rushton (2012) derived an equation for calculation of flow through the ballast. Lateral drainage elements generally require inflow controls. Geotechnical methods, like flow nets, are recommended to use, but fall outside of this report scope.

The final activity is construction, with typical drainage works having objectives to collect and evacuate runoff on the cut slopes, collect and evacuate water from the top of track itself, and control the phreatic water surface, if it is too close to the track top. Surrounding soils have to be known and the topography of the area well understood. External drainage is also known as interception drainage, since it must intercept and divert all water from underground sources and channels. Drainage ditches can be built as infiltration trenches with an interception drain.

Summary – even though the drainage systems are important for railway infrastructure, a review of return periods applied in drainage design shows that they are sometimes not long enough, and consequently, higher flowrates should be used in new design calculations, and existing drainage systems should be reviewed if they are resilient enough to cope with increases in design rainfall due to changing climate. Climate change makes drainage problems more frequent because of obsolete design. Also, due diligence is needed in inspections, maintenance and repairs of drainage works to prevent drainage and infrastructure failures.

6. Conclusions

Rail transport is very important for Swedish population, industry and economy, and is expected to further grow and expand. While it belongs to most environmentally responsible sectors, in terms of CO2 and other pollutant releases, there are opportunities for further improvements in operation of railway tracks, yards and stations. Tracks release diffuse pollution, including metals, PAHs and chemical herbicides, over a relatively narrow band (20-50 m) of great length (> 1 000 km). The highest priority of remediation should be ascribed to chemical herbicides, and particularly glyphosate, which is currently under review by both US and EU authorities and may be banned from regular applications on railway tracks. The Swedish data indicate that glyphosate may penetrate into groundwater, though it was found at low concentrations in a small fraction (~5%) of samples. This data would be most helpful for developing remedial action plans, including the delineation of areas, in which chemical herbicides should not be applied, and other alternative methods should be used. The second group of concern are PAHs, which are released by diesel locomotives, older types of lubricants, and creosote used for wooden crossties preservation. In all these applications, PAHs releases can be reduced or virtually eliminated by material substitutions (e.g., using harmless preservatives (linseed oil), crossties made of non-wooden materials, electric traction locomotives, and applying clean lubricants without PAHs, in right amounts). Finally, in terms of mass, the highest track emissions are those of metals produced by attrition of metal parts. In the contemporary literature, there is no strong evidence of impacts of metal releases on the environment. Drainage of railway yards and stations represents point sources of water pollution, which can be controlled by the existing technology. Yards are industrial sites requiring applications of best management practices in running switchers (locomotives), spill prevention, and interception of oils and contaminated sediment. Where on-site stormwater infiltration is contemplated, the risk of groundwater contamination has to be addressed and minimized. Finally, rail station drainage needs to be addressed in renovation projects. The main issue is implementing a mix of BMP measures meeting the constraints imposed on drainage effluent discharges, and their quality, into the existing drainage system. A brief overview of design of railway drainage indicated the need for ensuring that the design procedures are up to date with respect to design rainfalls adjusted for climate change.

6.1. Recommendations

Readiness of the Swedish Rail Transport System for Changing Climate

Ongoing research on climate change in Sweden predicts general changes in the precipitation regime, with likelihood of increasing rainfall depths and intensities, and frequency of significant or extreme events. In this connection, various professional associations offer to their members guidance to navigation of adaptation measures (e.g., Swedish Water Association Svenskt Vatten, advising municipalities). Recognizing the importance of drainage for safe and successful operation of railway systems, it is suggested that drainage of the Swedish rail system is subject to hydraulic stress and resilience testing by developing the procedure for this testing (e.g., planning horizons, design parameters of the precipitation/rainfall regime, a catalogue of adaptation measures, etc.) and conducting the testing in a prioritized manner. Priorities would be established by examining the costs of failures and examining the current conditions in the railway system. Deliverable: A plan to undertake this study, plan execution, and recommendations of adaptation measures needed to reduce the risk of flood/inundation damages in the entire system.

Reducing or eliminating releases of toxic chemicals to the environment

One of the contemporary objectives of Swedish environmental research (see e.g., FORMAS) is elimination of releases of toxics into the environment. Overview of the current research in RTI impacts on the environment indicates that there are at least two practices, which involve repeated releases of toxics into the environment: (i) preservation of wooden crossties by creosote, leading to releases of PAHs and (ii) vegetation controls by glyphosate. Even though both cases likely cause limited environmental damages, they contradict the objective of eliminating toxics releases. It is suggested to undertake a planning study addressing the feasibility of eliminating these two practices and developing a plan of action. Deliverable: A report on feasibility of eliminating creosote and toxic chemical herbicides from railway transport operation, addressing the current status, assessment of alternative measures (including the costs), and proposing a time plan of implementation of recommended measures.

Suggestions of research studies addressing selected knowledge gaps:

- Elution of creosote from wooden crossties in the northern climate
- Washoff of Zn from railway track associated structures exposed to rainfall
- Laboratory study of transport of toxics through the ballast
- Effectiveness of selected stormwater management measures in immobilizing toxicants related to operation of railway transport
- Continuation of the existing herbicide monitoring program (see ref. Cederlund, 2022)

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Appendix 1:
Railway Infrastructure Drainage Study

Aim based on proposal to *Trafikverket*

The project will be carried out as a literature study / knowledge compilation. As there is probably a lack of Swedish literature / data, the study will have an international focus. In this study, mainly international scientific literature, as well as reports, regulations and requirements for drainage of railway infrastructure (unless these are available in English) will be compiled and discussed. A short search on the internet shows that there are some recommendations from German-speaking countries (mainly Switzerland). These will also be taken into account.

The literature study shall contribute to (as far as possible) providing answers to the following questions:

Q1. What knowledge about hydrology / water transport in different types of railway facilities is available?

Q2. What types of rain events have the greatest potential to cause transport of pollutants to the surroundings of the railway facility?

Q3. How do different parts of the railway facility differ in generating pollutants that can be transported by water?

Q4. What other factors affect the spread of pollution from railway installations?

Q5. When must water from railway facilities be taken care of in treatment plants and how should they be dimensioned and designed, and which technology should be chosen?

Q6. How is water handled from railway facilities in (English-language) regulations from comparable organizations in other countries

Q7. How must flow measurements and sampling be designed in order to obtain representative results?

As there are probably relatively few studies on stormwater in the railway context, not all of these questions can probably be answered. A focus will therefore be on identifying and compiling these knowledge gaps. Therefore, the following issue will be given special consideration:

Q8. What knowledge is lacking and what should further research and development target?

Appendix 2:
Railway Infrastructure Drainage: Responses to Eight Questions presented in Appendix 1

One of the objectives of the Railway Infrastructure Drainage Study (RIDS) was defined by the study sponsor as follows: *"The literature study shall contribute to (as far as possible) providing answers to the following questions"* listed in the Appendix 1. As stated in the main report (MR), the international literature analysed in the report predominantly dealt with applied science issues discussed at a general level, rather than specific technical issues addressed in infrastructure management. Hence, besides the main report, the technical issues are addressed in this Appendix 2 with the objective of providing technical guidance on dealing with specific drainage concerns. The narrative that follows is largely based on the literature review presented in the main report (MR), expanded for technical information gathered from other sources.

Q1. What knowledge about hydrology / water transport in different types of railway facilities is available?

In the main report, the railway infrastructure was divided into three categories: railway tracks, yards, and stations (depots). In all the three cases, one needs to follow the path of water and quantify drainage flows and their pathways. Such flows are driven by rainfall and snowmelt runoff. Rainfall events are characterized by the total depth and duration, variation of intensities during the event, described for individual events by hyetographs, and a return period. In drainage design, the design events need to be selected or synthesized from historical data available for Sweden in Dahlstrom (2010) – see the reference in the main report. For small catchments, or runoff generation areas, peak flows are calculated for the selected design return period and the time of concentration from Dahlstrom's equation, or comparable sources of rainfall data generally available from the SMHI (Swedish Meteorological Hydrological Institute). Similar calculations are done for snowmelt events, in which generation of surface runoff is driven by air temperatures. Compared to design rainfall runoff, snowmelt events are generally characterized by much lower flow rates, but relatively high runoff volumes. Runoff flows produced by both types of events are conveyed by open drainage channels (swales), or drainage pipes. Computational methods for design of open channels and storm pipes are available in hydraulics handbooks. Hence, besides describing the drainage flows correctly and characterizing them by properly chosen empirical coefficients (e.g., runoff coefficient, Manning roughness coefficient, etc.), the designer can calculate flow rates (if storage is involved, also the volumes of runoff events) corresponding to the design events, and size the conveyance elements (drainage ditches, pipes) ensuring good drainage of the track. These calculations can be accomplished by commercial drainage models.

The main knowledge gap in this design process is accounting for climate change, as listed in MR on p.5 in Recommendations. The historical rainfall data need to be scaled up to account for changing climate. Thus, there is a need for a policy decision on what level of protection, described by the design event return period, is needed for various types of railway infrastructure facilities to reduce the frequency of flood damages. This process involves deciding on the return frequency of the design events and the level of magnification of rainfall data. For example, in the municipal sector, the Swedish Water Association recommends increasing the older design rainfall intensities by 25%.

Drainage of railway yards and stations is simpler than that of tracks, because both types of facilities have relatively small footprints. In both cases, drainage flows can be calculated using the above-described procedures and accounting for the changing climate.

Q2. What types of rain events have the greatest potential to cause transport of pollutants to the surroundings of the railway facility?

In general, transport of pollutants to adjacent properties of railway facilities requires two precursors: (a) Availability (presence) of pollutants of concern (i.e., those that impact on the living environment in various ways including the impacts on human health and toxicity, and (b) generation of runoff flows with a sufficient transport capacity. The former point can be mitigated by source controls. For the railway sector, the occurrence of pollutants is described in Table 1 of the main report and includes the following groups of pollutants: (a) metals (Fe, Cr, Mn, Zn, Cd), (b) lubricants and oils, and (c) trace organics (creosote, PAHs and chemical herbicides).

Several observations are noteworthy: (i) 97% of the total mass of the 12 metals listed by Burkhardt et al. (2008) (see the main report Section 2.1) is contributed by Fe, which was not identified in the literature as causing environmental problems. (ii) Environmental issues with lubricants can be mitigated by using lubricants without metals and PAHs, in "as needed" quantities. (iii) The main sources of PAHs are diesel locomotives and creosote-preserved wooden crossties, both sources can be controlled: in the former case, by switching to electrical traction locomotives, and in the latter case, by using crossties not requiring creosote preservation. (iv) Finally, elimination of chemical herbicides is much more challenging, as the alternative methods (e.g., hot water, mechanical weeding, etc.) may not have the effectiveness and economic efficiency of the currently used herbicides but avoid chemical impacts (see section 2.2 in the main report).

The second part of Q2 concerns generation of wet-weather flows providing sufficient hydraulic capacity to transport pollutants. This is a very general question to which the answer depends not only on the rainfall characteristics, but on the catchment characteristics as well. In highly impervious catchments, or catchments with low evapotranspiration (northern, wet climate) high fraction of rainfall/snowmelt is converted to runoff and streamflow and contributes to pollutant transport. Higher flows and potential transport of pollutants may be caused by increased runoff, e.g., due to increased precipitation caused by climate change, or due to changes in land use contributing to higher runoff and streamflow. Thus, the greatest potential to transport pollutants is associated with severe rainfall/runoff events occurring over highly impervious or wetted catchments.

Q3. How do different parts of the railway facility differ in generating pollutants that can be transported by water?

When classifying railway facilities as: railway tracks, yards and stations, the first difference is in nature of the generated pollution, tracks generate diffuse pollution spread over thousands of kilometres, but yards and stations produce a "point source" pollution. Identification of wet-weather pollution sources, contributing to pollutant washoff, is shown in Table 1 in the main report. The second group of pollution generation processes is mechanical attrition of metallic parts, which dominates the generation of metal particles (see the last page of section 2.1). In this case, attrition produces pollutants, but the actual pollution loads, while proportional to the mass of attrition, is always smaller – because not all pollutants on the railway property surface get washed away (analogous to stormwater pollution in urban catchments – the current models produce estimates of solids and pollutant deposition on the surface, but the actual transported mass depends on the effectiveness of washoff.

Q4. What other factors affect the spread of pollution from railway installations?

Air transport of pollutants and the resulting air pollution generated by operation of the rolling stock is highly influential with respect to the transport and distribution of railway transportation pollutants in the environment. Air transport can be generated by wind, or by airflow driven by the moving stock. This has been demonstrated in studies in the vicinity of rail yards, characterized by operation of diesel switchers (i.e., locomotives) including long periods of idling. General impacts concern human health, particularly in the case of diesel traction switchers or train locomotives. Other impacts are caused by respiration of metal particles in underground railway systems (Loxham & Nieuwenhuijsen, 2019). For further detail, see the following references cited in the main report: Hricko et al., 2014; Jaffe et al., 2014; Spencer-Hwang et al., 2015.

Q5. When must water from railway facilities be taken care of in treatment plants and how should they be dimensioned and designed, and which technology should be chosen?

The answer is provided in the form of a table listing the facility/source, trigger for action ("when must"), general approach, sizing and technology chosen. Further details follow the table.

Facility/Source of polluted stormwater	Procedural steps			
	Action trigger	General approach	Quantity sizing	Technology
Railway tracks	Municipal request, or compliance with effluent guidelines	Apply best management practices (BMPs), including source controls (e.g., no spray/ application areas, product substitutions)	Apply these measures opportunistically only in locations with a high risk of contamination of valuable groundwater	Apply simple, inexpensive facilities even in hard to access places – e.g., grassy swales, make provisions for maintenance
Railway yards	Municipal stormwater policy & guidelines (where available, for industrial areas)	Apply BMPs for industrial areas, including source controls and product substitutions	Source controls, intercept and treat high percentage of stormwater (90%)	Focus on filtration & (bio)filtration, and trapping floatables – e.g., commercial oil&grit separators, to intercept and remove small particles
Railway stations	Municipal stormwater policy & guidelines, and any existing sewer influent criteria	Apply best management practices (BMPs), including source controls; match quantity and quality of stormwater in the receiving sewer system	Source controls, intercept and treat high percentage of stormwater (90%)	This case will most likely deal with renovations of exist-ing facilities; select a treatment train to match the available space. Likely candidates: stormwater filters & biofilters, oil & grit separators

Railway tracks – action may be triggered by the request from the municipality, on whose territory the railway track is located. In that case, the drainage planning and operation may have to comply with municipal guidelines for stormwater management. In the case of herbicides and groundwater, the municipality may have the right to request how the herbicide will be applied (including specifying no-spray areas). The main purpose of railway drainage right-of-way is to ensure structural integrity and safety of the railway track structure. Concerning the quality of infiltrated stormwater, emphasis would be on source controls (i.e., pollution prevention) by eliminating certain chemical herbicides or creosote preserved crossties and applying alternative measures or products, which may include no herbicide spraying at locations characterized by risk of contamination of groundwater with herbicides. Exceptionally, there may be situations warranting the limited use of simple stormwater management measures, like grassy swales, or biofiltration, assuming that it is feasible to maintain such facilities. Pollutant characteristics – fine particles transporting metals, lubricants, PAHs, or herbicides. Among these, herbicides and washed off Zn may have significant dissolved loads.

Railway yards – their drainage must meet regulations for drainage of industrial areas. Where effluent criteria are not available, it should be possible to use those which were developed for municipalities of Gothenburg and Stockholm, depending on the receiving environments. A general approach would be to develop a stormwater management plan meeting the industrial area drainage regulations, with stormwater quality improvements by removals of fine metal-laden sediment particles and oily floatables. Commonly used technologies – source controls, stormwater ponds with pre-treatment, (bio)filtration, oil & grit separators, and reactive filters.

Railway stations – action would be triggered by renovation of the existing station. Such a construction activity would be subject to environmental assessment and approval, including the approval of a stormwater drainage report. One of the constraints imposed on railway station would be maintaining or improving the existing drainage flows and their quality, because the drainage effluent would be discharged into an existing sewer system. The renovated system would have to be designed to account for design rainfall changes resulting from climate change considerations. Where feasible, additional land may have to be acquired for placement of stormwater management measures, or they may have to be placed underground. In terms of technologies, emphasis is placed on stormwater treatment measures (filtration, oil and grit separation), or consideration of green roofs.

Fourteen key references on management of stormwater quantity and quality in RTI are listed in the main report, including: Aquafor (2020); Bäckström (2003); Blair et al., 2017; Clark and Pitt (2012); Ekka et al., (2021); Gavric et al., (2019); Jurys et al., (2017); Lim et al., (2015). MDEP (2008); Sacramento Stormwater Management Program (undated); Sañudo et al., (2019); Stagge et al., (2012); USEPA (2021); and Vo et al., (2015).

Q6. How is water handled from railway facilities in (English-language) regulations from comparable organizations in other countries

No publication dealing exclusively with regulations of drainage of railway transportation infrastructure was found in the literature, but several references cited the U.S. NPDES (National Pollutant Discharge Elimination System), which requires that parties intending to discharge pollutants to surface waters of the US must first obtain a permit to do so. Permit applications are tailored to specific conditions (e.g., a railway facility) and may have to include field measurements of stormwater quality. Eventually, the permits are generalized by the granting agency and adopted for certain classes of discharges, e.g., stormwater from residential areas, industrial areas, transportation facilities, etc. The main report referred to some specific application of the NPDES, e.g., to the South Station in Boston, US, (see section 4.3 in the main report), and drainage of industrial areas with direct applicability to railway yards (Sacramento Stormwater Management Program (undated): Best Management Practices for industrial stormwater pollution control). Both documents are available on-line, as referenced in the main report.

Q7. How must flow measurements and sampling be designed in order to obtain representative results?

The literature on measurements and sampling of drainage flows is fairly voluminous, as partly documented by reference citations below, and the fact that practically all research papers (globally counted in tens of thousands) provide descriptions of valid measurement techniques. It should be also added that detailed specifications of such measurements depend on the purpose of data collection and use. Examples of such purposes include: (i) research on runoff/snowmelt formation, with respect to both flow quantity and quality, (ii) characterization of stormwater quantity and quality for planning runoff flow and pollution controls, (iii) compliance monitoring (providing a proof that the stormwater facility operates as required; e.g., certain pollutant concentrations are kept below the permissible values), and so on. Hence, the discussion herein is kept at a general level and focuses on most common situations.

Stormwater studies essentially focus on environmental fluxes of water, sediment and various chemicals; hence one needs to measure flow rates and the associated flow quality described by material and chemical concentrations. For flow measurements, the following factors are commonly of interest and considered in a data acquisition system design: a range of flows, type of flow (subcritical or supercritical, steady or unsteady, open channel or pressurized flow, presence of sediments, stratified or non-stratified flows), required flow measurement accuracy, primary flow sensors, secondary sensors (i.e., e.g., sensing water levels), and recorders. For quality measurements, there are three approaches – (a) using continuous water quality sensors (e.g., a conductivity probe), or (b) collecting and analyzing liquid samples, or (iii) conducting toxicity measurements reflecting water quality. Among these three methods, the choices of parameters which can be measured by continuous sensors are still rather limited, toxicity measurements and their interpretations can be too complex, and consequently, flow sampling and analysis represents the prevailing approach.

Considering that chemical flux is a product of the flow rate and the substance concentration, Q(t) x C(t), uncertainties are introduced into the flux estimation by measuring flow continuously, but withdrawing samples discretely at certain time intervals (Δt, measured in minutes, or tens of minutes), which can be constant, or variable during the event. Effectively, the pollutograph (i.e., a graph of concentrations in time) is approximated by a stepwise function, in which the sampled concentration is assumed to be constant over the step width equal to the sampling interval (Δt). The shorter the sampling interval, the better the accuracy of the fitted stepwise function. In modern instrumentation, the flow meters and the samplers are operated by the same controller, and sampling intervals are short (5-10 minutes) to improve the accuracy of pollutograph approximation. For estimating loads of a substance passing through the monitoring station, good accuracy can be achieved by flow proportional sampling, in which flow samples are withdrawn after a certain constant flow volume passed through the station.

Further guidance on flow measurement and sampling can be found in these references:

Harmel, R.D., Slade, R.M., Haney, R.L. Impact of Sampling Techniques on Measured Stormwater Quality Data for Small Streams. Journal of Environmental Quality, Vol. 39, 1734-42, 2010. Available on-line: https://pubag.nal.usda.gov/download/59154/pdf . (visited Jan. 30, 2023).

Leecaster, M., Schiff, K., Liesl, Tiefenthaler, L.L. 2002. Assessment of efficient sampling designs for urban stormwater monitoring. Water Research 36 (2002) 1556–1564.

Langeveld, J.G., Liefting, H.J., Boogaard, F.C. 2012. Uncertainties of stormwater characteristics and removal rates of stormwater treatment facilities: Implications for stormwater handling. Water Research, 15, 1-13.

U.S. EPA. Industrial Stormwater Monitoring and Sampling Guide. Report EPA-832-B-09-003. Available online: _ (visited Jan. 30, 2023).

Q8. What knowledge is lacking and what should further research and development target?

Suggestions of further research were presented in the main report, Section 6, Conclusions and recommendations.

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