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Systematic review of urban stormwater research in Sweden (2012-2021)

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Preface

This report presents the results of a systematic review of Swedish stormwater research during the period 2012–2021. The purpose of the review was to provide a comprehensive update of both the breadth and depth of Swedish stormwater research in a national and international context. A total of 149 articles were identified using defined search terms and criteria and reviewed. These articles were grouped based using a source-pathway-receptor approach, and were then placed in one of ten categories (based on the main focus of the article). The research articles linked to each category were then described to provide an overview of the current state of knowledge within a Swedish research context. The report concludes by identifying a number of knowledge gaps and makes recommendations for further research to enable cities' to manage their release of diffuse pollution to receiving waters and improve the sustainability of stormwater management in Sweden.

The report has been prepared on behalf of the Swedish Environmental Protection Agency. However, the authors are responsible for the content and design of the report.

Our hope is that this report will be useful for researchers, officials and practitioners in the stormwater area but also the entire community building sector.

Luleå in February 2022

Lian Lundy, Godecke Blecken, Heléne Österlund and Maria Viklander

Abstract

This report present the findings of a systematic review of Swedish stormwater research over the time period 2012-2021. Using defined search terms and inclusion and exclusion criteria, 149 papers were shortlisted for detailed review and discussion. The aim of the review was to provide a comprehensive update on the breadth and depth of Swedish stormwater research in a national and international context. Following an initial review, short-listed papers were initially grouped using a source pathway receptor approach, and then allocated to one of ten categories (based on the paper's main focus). The research papers associated with each topic are then described to provide an overview of the current state-of-knowledge within a Swedish research context together with identified research gaps. The report concludes with a series of recommendations for further research.

In terms of sources, the deleterious impact of urban stormwater runoff (a term which includes snowmelt) on receiving waterbody quality is well established in a Swedish context. The key sources of diffuse pollution (e.g. traffic, industrial activities) have been the subject of considerable attention with regard to classical urban pollutants (metals, hydrocarbons and particulate matter). However, much less is understood about their contribution to the occurrence of a wider range of substances e.g. microplastics and PFAS to the urban environment or of the processes contributing to pollutant release and how these vary over time in relation to e.g. ageing, corrosion and climate change. As the diversity of materials used within urban environments increases, developing an understanding of the identity of substances and their patterns of release overtime is an increasing priority in terms of mitigating current risks as well as informing (re) development practices to avoid contributing to future diffuse pollution loads. Pathways from the urban environment to receiving waters direct runoff, discharge after treatment or via combined sewer overflows. Dry deposition is a further pathway (e.g. wind dispersion and/or direct resuspension of previously settled particulate matter) but little is understood about its relative importance compared to wet deposition. There is an increasingly solid Swedish database pertaining to the quality of runoff derived from a variety of urban surfaces at sub-catchment scales. However, less is now about the ecotoxicological impact of these discharges on receiving water ecology. Further, whilst standard methods are available for the determination of many established pollutants, analytical methods for the assessment of e.g. microplastics are still in development meaning comparison between studies is challenging. With regard to predicting pollutant concentrations, several quantitative models have been extended to link flows with quality data. However, these typically struggle to reliably predict concentrations outside of their original site of development, indicating further research is required. In terms of stormwater quantity, the use of models to predict flow volumes is much more established with current research focussed on reducing uncertainties and how to predict volumes associated with climate change predictions.

There is now nationally, and increasingly internationally, recognition of the need to treat urban stormwater runoff before its discharge to receiving waters. As piped systems offer little – if anything – in terms of treatment, there is increasing interest in the use of the blue-green infrastructure (BGI) to manage both water quantity and quality objectives. The term BGI refers to a wide range of stormwater control measures – from rain gardens to constructed wetlands – which may also contribute to the delivery of a range of further ecosystem services e.g. local reductions in air pollution, temperature and noise. As such, their use is of potential interest to a wider range of stakeholders than those traditionally involved in urban planning and a key research theme is how to integrate the use of BGI within current institutional structures. This report concludes by identifying a series of knowledge gaps and makes recommendations for further research to both reduce the impact of urban diffuse pollution on receiving waters and enhancing the sustainability of stormwater management in Sweden.

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1. Introduction

1.1 Context

Sweden is undergoing rapid climate change, with temperatures predicted to increase by 3-5oC by 2080 under representative concentration pathway (RCP) 4.5 (SMHI, 2021). Amongst a range of impacts, changes in precipitation patterns (more rainfall occurring in autumn, winter and spring seasons leading to increased runoff rates and volumes) have implications for how we manage stormwater runoff quantity and quality. In terms of stormwater quantity, current trends and patterns of urbanisation in combination with an increased frequency of extreme short-term rainfall events will increase winter floods. Warmer summers will increase rates of evaporation contributing to an increasing number of low flow days in rivers and occurrences of drought across many parts of Sweden. Hence the same urban areas could face an annual increase in both flooding and drought events. How we manage stormwater runoff in urban areas can therefore have a year-round impact on the quality of life of urban residents; from the approaches used to manage this ‘wastewater’ in winter to its potential role as an alternative water resource to mitigate summer droughts, and the additional benefits alternative mitigation strategies generate.

With regard to stormwater quality, urban runoff (whether derived from rainfall or snowmelt) is an unintentional mix of chemicals derived from a diversity of site-specific sources which episodically discharge to the surface waters in response to climatic events. Recognition of the need to reduce the discharge of chemicals to the environment is gaining increasing policy attention. For example, UN Sustainable Development Goal (SDG) 3 (reduce the impacts of chemicals on human health and the environment, SDG 6 (minimise the release of chemicals to water bodies (SDG 6 and 12), air and soil (SDG12). At a European level, identifying opportunities to reduce the exposure of humans and the environment to hazardous substances is central to the EU’s Zero Pollution Ambition (a key commitment of the European Green Deal, 2019) and the EU Chemical Strategy for Sustainability (EU CSS, 2020). The EU CSS highlights the need to address combined exposure to multiple chemicals from different sources over time and draws attention to the issue of intentional versus unintentional chemical mixtures, and how this latter aspect is yet to be addressed in relation to either current or historic contamination (i.e. contaminated sediments). The EU Water Framework Directive (EU WFD, 2000) refers to the need to address diffuse sources of pollution within river basin management planning, and its contribution to surface water pollution is highlighted in the evaluation of the EU Urban Wastewater Treatment Directive (EU, 2019). Urban stormwater runoff – as a constituent of combined sewer overflows and via direct discharge - is identified as an important source of pollutant loads that are not properly addressed by the EU UWWTD in its current form and highlighted as a key source of pollution to surface waters that could be avoided.

As urban areas expand and seasonal storms increase their intensity, duration and frequency, traditional piped systems are increasingly overwhelmed, leading to localised flooding. As an approach that moves – rather than manages – stormwater flows and offers little in the way of pollution mitigation, there is increasing interest in the use of blue green infrastructure (BGI) and stormwater control measures (SCM) as alternative or complimentary approach to the use of piped systems. The term BGI refers to a range of systems types and sizes – from planters and rain gardens to large ponds and constructed wetlands - which look to infiltrate (or where not possible detain) stormwater volumes at source. However, as well as contributing to stormwater quantity targets, BGI systems can enhance water quality and also generate a range of other benefits including habitat provision, urban cooling, improved air quality and physical and mental health benefits. This has led to the use of BGI (also referred to as nature-based systems; NBS) being considered as best practice in managing stormwater. However, challenges remain in their implementation as a new approach which urban planners and municipalities require support to integrate into current institutional, operational and management strategies and approaches.

Within this policy development and implementation context, there is an urgent need to better understand:

- the sources of diffuse urban pollutants (i.e. which substances from which materials and their temporal patterns of release)
- processes affecting urban pollutant mobilisation and transportation by stormwater runoff (hydraulic and water quality modelling including in pipe transformations)
- opportunities to mitigate urban runoff discharging to receiving waters (performance, maintenance and implementation of stormwater blue green infrastructure and emerging approaches)
- opportunities to remediate contaminated sediments (management of gully pot and stormwater pond sediments)

1.2 Objective

As a contribution to addressing this need within a Swedish context, this report provides a systematic review of urban stormwater runoff research undertaken in Sweden over the time period 2012-2021, and the contribution of this research to the Scandinavian and wider international stormwater research literature.

With a focus on peer-reviewed scientific articles, this report uses a source-pathway-receptor approach to collate and synthesise the research undertaken by Swedish stormwater researchers, followed by a review of research related to the options for treatment of urban runoff prior to its discharge to receiving waters. The report is supported by a full list of references which provide links to the stormwater research articles published over the evaluated time frame and discussed in this report. The report concludes with a series of recommendations for further research within this dynamic and fast moving field.

2. Methodology

2.1 Selection of papers for review

The peer-review journal database Scopus (www.scopus.com) was searched in June 2021 to identify relevant research articles and review papers published over the time-period 2012-2021 in international scientific journals. The term ‘stormwater or runoff or snowmelt’ was used to search within article titles, keywords and abstracts (120,005 articles retrieved). This list was then searched using the term ‘urban’ (33,754 articles retrieved) and limited to the time-period 2012-2021 (20,507 articles retrieved) and then (excluding e.g. conference proceedings) to research article and reviews only (17,320 articles retrieved). This long list of articles formed the basis of the assessment of Swedish research within an international and Scandinavian context.

Of the 17,320 articles, 840 articles involved at least one Scandinavian author of which 370 articles included at least one Swedish author. A further search of the 370 articles identified for Sweden was undertaken using the key term ‘stormwater and urban runoff or snowmelt’ to identify articles that had these topics as their core focus (as opposed to brief mention). This identified a ‘short list’ of 176 articles which included at least one Swedish author.

This set of 176 papers were then reviewed manually using the following inclusion and exclusion criteria:

Papers by an all Swedish research team – included in report

- Papers by an international research team (including at least one Swedish researcher) and not involving a case study – included in report
- Papers by an international research team (including at least one Swedish researcher) and involving a Swedish case study – included in report
- Papers by an international research team (including at least one Swedish researcher) and involving a non-Swedish case study - not included in report

This manual review reduced the total number of papers assessed to 149 papers.

These papers were grouped into ten broad categories (see Figure 1) to facilitate readers to locate articles on topics of specific interest. Where an article related to more than one category, it is discussed within the category in which it predominantly fell. Each broad category of papers is then described to provide an overview of Swedish urban stormwater research undertaken in the area within the assessed time-period. Links to all reviewed papers are provided in Appendix A.

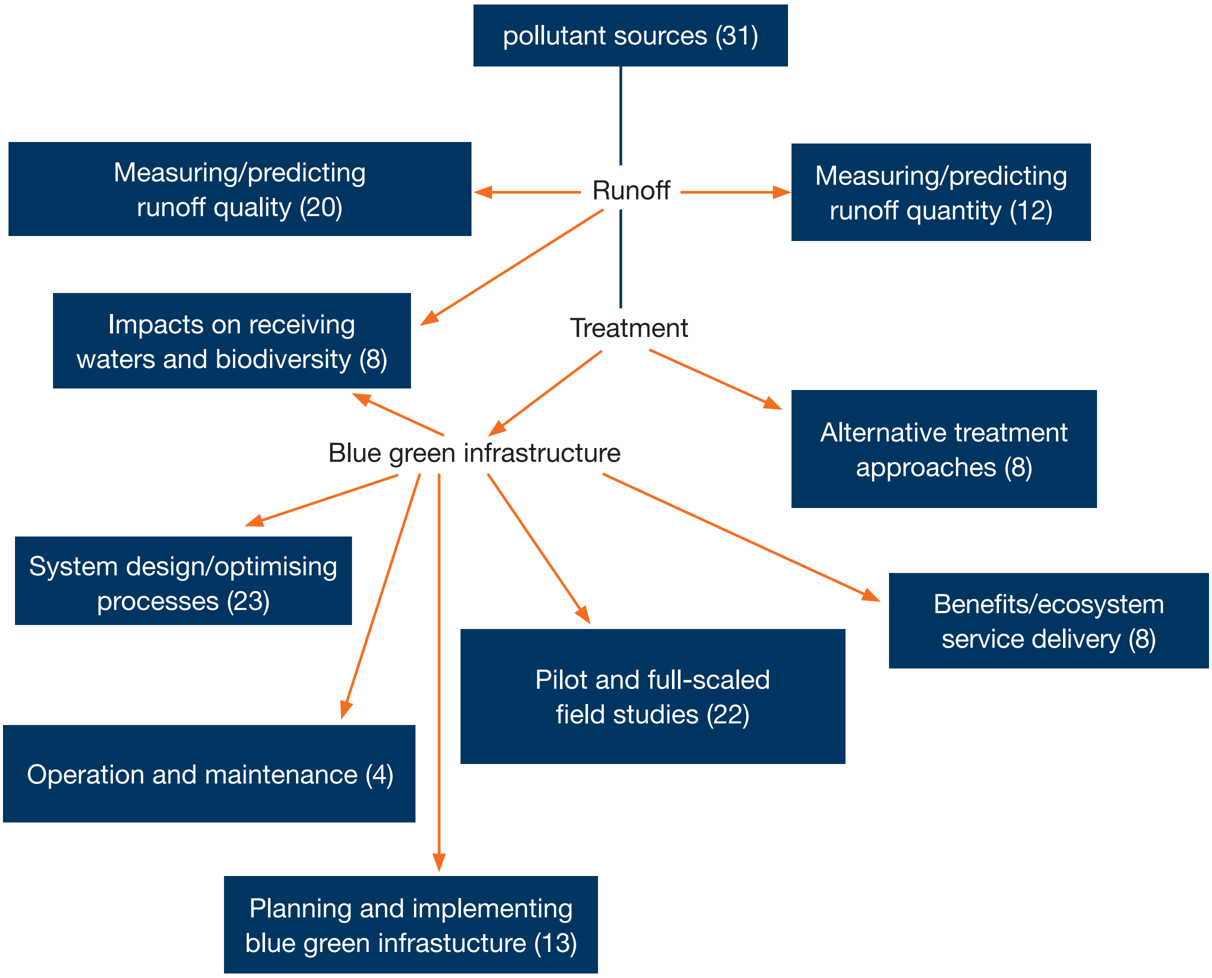

Figure 1. *Overview of key topics (boxed text) used to structure systematic review (numbers in brackets refer to the number of Swedish papers reviewed)*

2.2 Identification of sources of funding

Each paper published identifies the funder who financially supported the research. This information was used to develop a breakdown of the sources of funding of 340 Swedish research papers reviewed over the identified time period.

3. Swedish urban stormwater research in an international context

The results of the Scopus database search are presented in Table 1. Of the 17,320 research article identified, 16,603 were research articles and 717 identified as review articles. Of this total number, 5% are published by teams with at least one researcher located in Scandinavia. This 5% equates to 840 research articles and reviews of which 39% include Swedish researchers, 27% Danish researchers, with 18% and 16% including researchers based in Norway and Finland, respectively. As a region, Scandinavia would be ranked 7th in terms of number of stormwater peer-reviewed articles published (after USA, China, Australia, the UK, Canada and Germany), with Sweden ranked 15th in terms of a country-by-country comparison.

Table 1 *Overview of the number of peer-reviewed stormwater articles published 2012-2021 (identified using Scopus)*

Location	Number of papers*
Global	17,320
Scandinavia	840 (6.0%)
Sweden	370 (2.3%)
Denmark	255 (1.8%)
Norway	172 (1.0%)
Finland	146 (0.9%)

*Key: *number in brackets refers to the percentage of the total number of peer-reviewed papers published per region and country relative to the total number identified*

Table 2 lists the top ten most published authors in the field of stormwater research globally from 2012-2021, together with their affiliation and numbers of papers. This list is extended to include the names, affiliations and number of papers of all Scandinavian researchers with ≥15 published papers over the identified time period. One Scandinavian researcher is ranked within this international top ten: Viklander (Luleå University of Technology, Sweden). In terms of international citations, two Scandinavian researchers are co-authors of the most cited stormwater article over this time period; Steen Mikkelsen (Danish Technical University, Denmark) and Viklander (Luleå University of Technology (Sweden) (Fletcher et al., 2015; 581 citations).

Table 2. *International top ten most published authors in the field of stormwater research, together with Scandinavian authors with ≥ 15 papers*

Author	Institution	Number of publications
A Deletic	University of New South Wales (Australia)	95
WF Hunt	North Carolina State University (USA)	87
T Fletcher	University of Melbourne (Australia)	76
A Goonetilleke	Queensland University of Technology (Australia)	76
M Viklander	Luleå University of Technology (Sweden)	69
P Egdowatta	Queensland University of Technology (Australia)	59
DT McCarthy	Monash University (Australia)	56
J Li	Xi'an University of Technology (China)	52
A Liu	University of New South Wales (Australia) / Shenzen University (China)	51
LH Kim	Kongju National University (South Korea)	44

Researchers affiliated with Scandinavian universities ≥ 15 articles published		
J Marsalek	Luleå University of Technology (Sweden)	42
P S Mikkelsen	Danish Technical University (Denmark)	42
GT Blecken	Luleå University of Technology (Sweden)	25
MB Jensen	Copenhagen University (Denmark)	22
TM Muthanna	Norwegian University of Science and Technology (Norway) / Luleå University of Technology (Sweden)	21
N Sillanpää	Aalto University, Espoo (Finland)	20
J Vollertsen	Aalborg University (Denmark)	20
H Koivusalo	Aalto University, Espoo (Finland)	
H Österlund	Luleå University of Technology (Sweden)	16
K Arnbjerg Nielsen	Danish Technical University (Denmark)	17
MN Futter	Swedish University of Agricultural Sciences (Sweden)	15
L Vezzaro	Danish Technical University (Denmark)	15
CY Xu	University of Oslo (Norway)	15

Using the Scopus database and search terms (see Section 2.1), 176 articles were identified for manual review. Table 3 identifies the Swedish research groups responsible for publishing five or more articles in this short-list.

***Table 3**. Affiliations of Swedish researchers publishing stormwater articles by number of publications (2012-2012)*

Institution	Number of papers
Luleå University of Technology	72
Chalmers University of Technology	21
Swedish University of Agricultural Sciences	17
Lund University	14
KTH Royal Institute of Technology	11
Stockholm University	10
Linnaeus University	7
Uppsala University	5
IVL Svenska Miljöinstitutet	5
Swedish Meteorological and Hydrological Institute (SMHI)	5
Others	≤4

4. Review of Swedish research related to stormwater runoff

The process of urbanisation has a dramatic impact on the functioning of the natural water cycle, whereby the construction of roads, pavements and buildings effectively converts permeable to impermeable surfaces. Under rainfall and snowmelt conditions, surface water runoff which would have previously primarily infiltrated into the ground are directed towards piped infrastructure to prevent localised flooding. However this traditional approach has several limitations; rapid rates of urbanisation have resulted in many piped systems being at or over capacity, resulting in increased numbers of pluvial surface water flood events. As runoff passes over impermeable surfaces, it mobilises pollutants previously deposited (e.g. from traffic and industrial emissions), which are a major source of pollutant loads entering receiving waters, either as direct discharges or components of combined sewer overflows. Further, the discharge of a large volume of flow or melt water at a single point can cause erosion in receiving waters of both native soils and /or the re-suspension of previously settled sediments. Urban stormwater runoff is often directly discharged to the closest receiving waters. However, as awareness of its biological, chemical and physical impacts increases, the need for and benefits of treating urban surface runoff prior to its discharge is gaining increasing attention in both policy (meeting increasingly stringent environmental quality standards) and human health and wellbeing (protection of a finite resource and multiple benefits provide by urban blue-green spaces) objectives.

4.1 Pollutant sources

A diversity of sources contribute a range of pollutants to urban stormwater runoff (Müller et al., 2020). As the occurrence of sources vary on a catchment by catchment basis, the types and magnitude of pollutants released also vary between catchments (see Figure 2 for an overview of sources and pathways). Several studies have evaluated the quality of urban stormwater runoff (including flow generated from rainfall, snow melt and rain on snow events) as a source of diffuse pollution discharging to receiving waters. Identified catchment types include urban areas (Järlskog et al., 2021; Czemiel, 2014; Galfi et al., 2016 and 2017), industrial parks (Lindfors et al., 2020 and 2021), airports (Jia et al., 2019) and car parks (Lindfors et al., 2020 and 2021). Further studies have evaluated the pollutant loads generated by specific activities including traffic (Markiewicz et al., 2019), snow storage deposits (Vijayan et al., 2021; Vijayan et al., 2019; Lundberg et al., 2013), biomass fuel storage (Larsson et al., 2016) and log yards (Kaczala et al., 2012), wastewater intrusion into stormwater pipes (Panasiuk et al., 2015 and 2016; Hu et al., 2018) and landfill (Kalmykova et al., 2013). Monitoring the opening of the E18 highway (Sweden) provided an opportunity to investigate the environmental impacts of a range of pollutants originating from its operation (Earon et al., 2012). Results generated indicated the occurrence of year-round infiltration of runoff due to melting of the snowpack from road salt and the increased hydraulic conductivities of road construction materials relative to in situ soils. Metal concentrations within the snow pack were typically in excess of the Swedish Environmental Protection Agency's groundwater limits.

More recently researchers have begun to explore the release and mobilisation of pollutants from specific building materials including a range of roofing materials (Müller et al., 2019), building facades (Bollmann et al., 2014), Zn/Zn alloyed materials (Odnevall and Leygraf, 2017), Cu roofing / facades (Hedberg et al., 2014) and stormwater pipes (Borris et al., 2017) and urban components including road dust (Järlskog et al., 2020; Polukarova et al., 2020; Folens et al., 2018) and coarse road particles (Borris et al., 2016). Factors identified to influence pollutant release from sources include – for building materials - its inclination, orientation, and atmospheric exposure conditions (Hedberg et al., 2014) and rainfall characteristics (Odnevall and Leygraf, 2017). For street sediments, key factors influencing pollutant release include particle properties (e.g. organic matter content) and runoff pH, duration and energy input (Borris et al., 2016). In addition, the ongoing release of pollutants from historically contaminated areas (i.e. legacy issues) such as streams contaminated by pesticides (Rasmussen et al., 2015) and stormwater ponds (Flanagan et al., 2021) has also received attention.

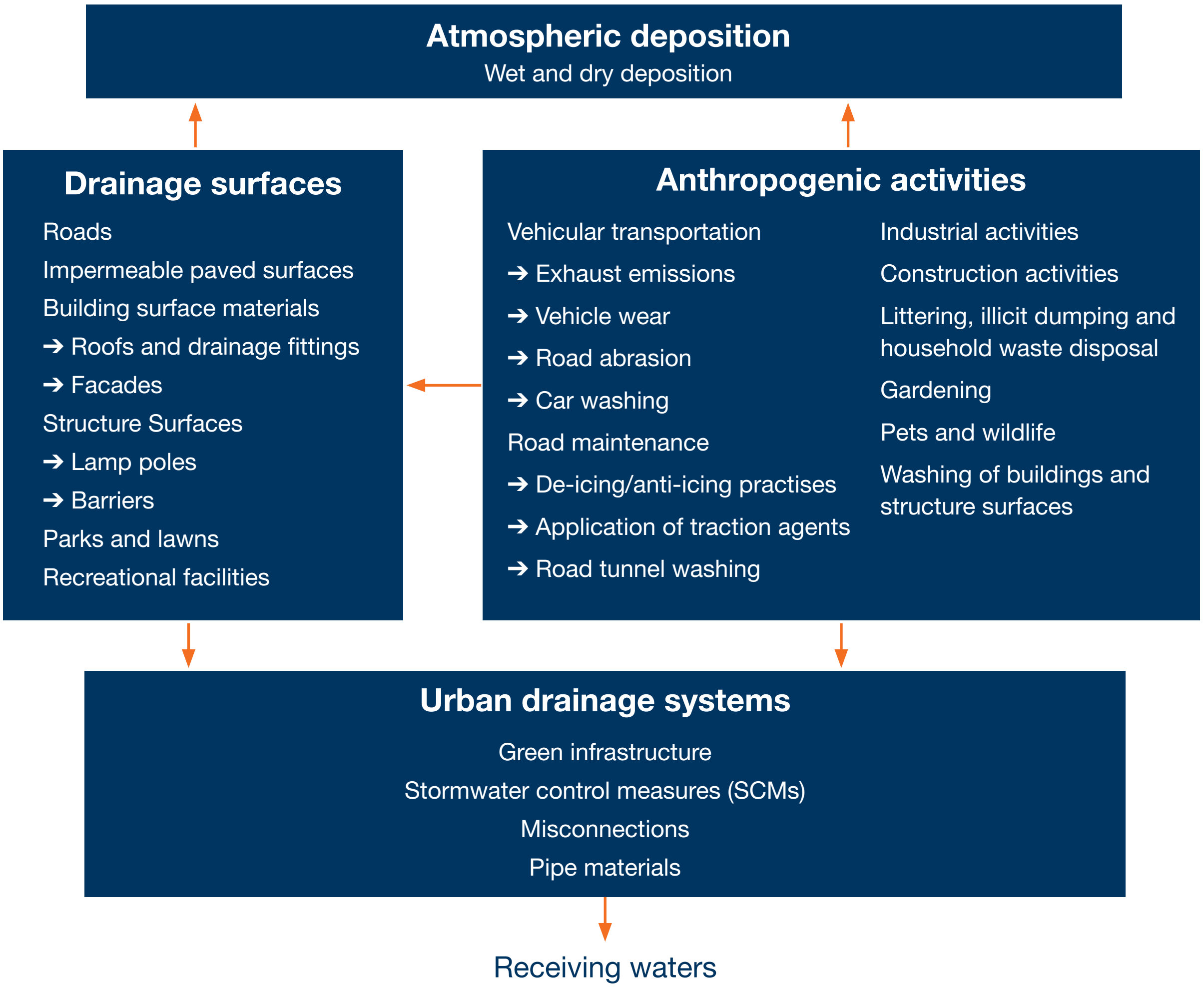

Figure 2. *Grouping of urban stormwater pollution sources and pollution transport pathways (modified from Müller at al., 2020)*

Key pollutants within urban runoff include metals of which Cu, Zn, Pb, Cd, Cr and Ni are frequently determined (Lindfors et al., 2020; Borris et al., 2016; Lundberg et al., 2013; Järlskog et al., 2021) as well as rare earth metals such as platinum (associated with the use of catalytic converters) (Folens et al., 2018). In terms of organic pollutants, aliphatic and aromatic petroleum hydrocarbons, alkylphenols, bisphenol A and polyaromatic hydrocarbons (PAHs) have been widely reported as occurring in urban runoff studies through a combination of field (e.g. Polukarova et al., 2020; Kalmykova et al., 2013; Järlskog et al., 2021) and literature review (Markiewicz et al., 2017) studies. More specifically nonylphenols and pthalates were detected in building material runoff (Müller et al., 2019), with a study by Bollman et al., (2014) also linking the detection of biocides in combined wastewater to their release from building facades and transfer to the drainage system by rainfall.

Recently – and partly as a result of a review of data undertaken by the Sweden Environmental Protection Agency (Magnusson et al., 2016) – increasing attention has focused on identifying the sources of microplastics (MP) discharged into the sea. This review drew attention to the mass of MP predicted to be released from tires and bitumen road materials, and thus available for wash off and discharge to receiving waters. Whilst methods for the analysis of microplastics is still in development i.e. standard methods for the analysis or reporting of MP have yet to be agreed, initial studies have reported the presence of a range of MP in stormwater runoff and street dust (Järlskog et al., 2020 and 2021) together with the co-occurrence of a range of metals and organic pollutants, supporting the hypothesis that traffic is an important source of MP to the environment. This is complimented by a desk-based study by Schernewski et al., 2020 which developed MP specific emission scenarios as input for 3D-model simulations, enabling the transport, behaviour, and deposition of various MPs within the Baltic Sea to be estimated. However, whilst an increasing number of field studies (both nationally and internationally) report the widespread occurrence of MP across a diversity of environmental compartments, both the type and level of impact of MPs on human and/or ecological health remains a heavily debated issue (Rahman et al., 2021).

Whilst urban runoff pollution studies typically focus on metals and/or organic micropollutants (including MP), these are not the only diffuse pollutants reported to occur in urban runoff. For example, Wu et al., (2015) and Wu and Malmström (2015) evaluated diffuse nutrient sources and pathways within urban catchments where key sources were identified as atmospheric deposition and traffic. In terms of biological parameters, the contribution of urban catchments to diffuse pollutant loads of several indicator bacteria (including *Escherichia coli,* enterococci and *Clostridium perfringens*) was evaluated by Galfi et al., (2016). Involving the collection of grab samples, data indicated that the indicator groups were one to two orders of magnitude higher in snow melt and rainfall runoff, respectively, in comparison to dry weather base flow data. Method comparison research also reported stormwater as source of microbial pathogens (Hu et al., 2018) and viruses (Rusiñol et al., 2019), where key sources to stormwater are thought to include misconnections and pets.

In reducing the discharge of urban stormwater pollution to receiving waters, a first step is to characterise each pollutant source within the targeted catchment area to develop a clear understanding of its relative importance. Establishing an inventory of catchment pollution sources is a key initial step within, for example, the development of river basin management plans (EU WFD, 2000) to inform the development of targeted emission reduction schemes (Lützhøft et al., 2012). With a view to supporting this aim within an urban environment, Lützhøft et al., (2012) developed a source classification framework which enable users to extract data from two European pollution inventories: the Statistical Classification of Economic Activities in the European Community (NACE) (Eurostat 2008) which identifies the economic activity responsible for a pollutant release and EU harmonised Nomenclature for Sources of Emissions (NOSE-P) (Eurostat 1998) that specifies the process resulting in pollutant release. Extracted data is then linked to a series of attributes including the urban structure / environmental compartment the pollutant is released to, and data on emission factors and release profiles.

4.2 Measuring and predicting urban runoff quality and behaviour

As reported in Section 4.1, several studies have reported the pollutants and ranges of concentrations associated with a variety of urban catchment types, activities and specific materials / components. However, it is now recognised that – dependent on the type of pollutant - total concentrations of individual pollutants are not the most appropriate indicator of environmental impact. For example, given the exponential increase of new substances appearing on the market and the fact that urban runoff is essentially an unintended mixture of chemicals – or a pollution cocktail – in which substances may act both synergistically or antagonistically, there is growing attention in the international research literature and within policy for news ways to identify, assess and regulate the impact of urban stormwater discharges. Two approaches to addressing this challenge are gaining traction: firstly the use of ecotoxicity testing and biodiversity assessments (see Section 4.7) and, secondly, evaluation of the behaviour of metals and organic pollutants in the sub-dissolved fractions as an approach to better inform the design and selection of treatment techniques. The latter approach is also recognised in policy, where a review of the 2008 EU Environmental Quality Standards (EQS) Directive in 2011 led to the establishment of revised annual average environmental quality standards for Ni and Pb which relate to the bioavailable concentration of each metal (EU, 2013) (Lindfors et al., 2021). This move was followed by the development of national bioavailable EQS by several Members States, including for Cu in Sweden (Hoppe et al., 2015).

With a focus on metal partitioning, Lindfors et al., 2020 evaluated the distribution of metals in 18 events (covering rainfall, snow melt and rain on snow conditions). Analysis indicated that in all samples the truly dissolved fraction was greater than the colloidal fraction though the contribution varied on a metal by metal basis. Likewise, in a laboratory-based snow melt experiment, Vijayan et al., (2019) reported that the majority of dissolved metals occurred in the truly dissolved fraction. An alternative approach is the use of passive samplers which enable time-averaged dissolved metal concentrations to be derived. Knutsson et al., (2014) evaluated the use of passive samplers to determine metal speciation in urban runoff in comparison to samples collected using pooled spot samples and to model predictions derived using visualMINTEQ. Results indicate that passive samplers are useful for monitoring metal speciation under chemodynamic conditions and that model predictions partly describe the metal speciation in non-equilibrium systems. With regard to organic pollutants, Nielsen et al., (2015) investigated the partitioning of PAHs between various fractions including total, particulate, colloidal and dissolved fractions in field and synthetic stormwater samples. The PAHs identified in stormwater in the particulate fractions and dissolved fractions followed their hydrophobic properties (i.e. over 50% of the high molecular weight (MW) PAHs were found in the particulate fractions, while the low MW and medium MW PAHs were found to a higher extent in the colloidal and dissolved fractions indicating the importance of developing technologies that both can manage particulate matter and effectively remove PAHs present in the colloidal and dissolved fractions. An alternative approach to understanding variability of pollutant concentrations relates to exploring the representativeness and impact of using alternative sample collection approaches (e.g. grab vs composite samples; Galfi et al., 2014; McCarthy et al., 2018) and sampling strategies (Jia et al., 2018) both between and within events (Galfi et al., 2016). With a focus on investigating the pollutant load associated with snow piles, Vijayan et al., (2021) compared the use of different snow sampling strategies to identify the most efficient approach to estimating snow pile pollutant loads. Aligned with this, several studies have explored the impact of analytical method itself on results generated including total suspended solids (Nordqvist et al., 2014), microbial indicators (Hu et al., 2018; Rusiñol et al., 2014), and the use of turbidity and conductivity probes as surrogates for TSS and phosphorous as determined in grab and flow-proportional samples (Villa et al., 2019).

Partly as a function of the time required to collect runoff samples which - by definition – are event driven and also the high costs of sample analysis (particularly for organic pollutants), several studies have developed models to predict runoff quality under both current and future climatic conditions (Vezzaro et al., 2015; Borris et al., 2013, 2014 and 2016; Andersson et al., 2020). These studies covered a range of pollutants including Cu, Zn and fluoranthene (Vezzaro et al., 2015), total suspended solids, Cu, Zn and Pb (Borris et al., 2013, 2014 and 2016) and MP (Fältström and Anderberg, 2021; Bondelind et al., 2020). More specifically, Vezzaro et al., (2015) used a dynamic modelling approach to assess the impact of alternative emission control strategies to reduce the discharge of targeted pollutants to achieve receiving water EQS. The results indicated that all strategies reduced loads discharging to receiving waters, with the use of source control measures predicted to perform the best. However, none of the strategies evaluated were predicted to result in achievement of EQS in receiving waters. While environmental occurrence MP data sets are growing, the current data sets are insufficient to undertake substance flow analysis (SFA). As an alternative approach to inform current MP mitigation measures, Fältström and Anderberg (2020) systematically compared SFA data sets for a range of better characterised pollutants to identify opportunities in the source-pathway-receptor chain for MP mitigation, with conclusions supporting the value of taking a holistic approach to targeting compartments for protection. A further study by Bondelind et al., (2020) used MP literature data as input for a hydrodynamic model (MIKE 3 FM) to predict the fate tyre wear particles in road runoff in the Göta River (Gothenburg, Sweden). Results identified preferential zones for deposition, and the influence of the vertical water density gradient (caused by saline water from the Kattegat strait) on the potential for smaller MP to reach marine waters.

In terms of assessing model performance, Wu et al., (2021) undertook an assessment of the uncertainties associated with the low-complexity conceptual model StormTac in simulating annual urban runoff quantity and quality. Results indicate that the uncertainty of the modelled annual runoff quality (~ 30%) is greater than that of annual runoff volumes (~ 24%), with the most sensitive factors identified as land-use specific parameters. In addition to approaches to predict total pollutant concentrations, a variety of full and simplified biotic ligand models are available which integrate local water quality parameters with data on dissolved metal concentrations to predict the fraction of metal likely to be available in a bioavailable form. Lindfors et al (2021) explored the use of the simplified BLM Bio-met on runoff generated from three sites and compared results with analytically determined concentrations, concluding that predicted bioavailable concentrations were significantly lower than truly dissolved concentrations for all metals.

Looking forward, and as an approach to inform urban climate change adaptation planning measures, several studies have look to evaluate how alternative climate change predictions impact on both urban runoff quantity (see Section 4.3) and quality. For example, research by Borris et al. (2013 and 2016) used the WinSLAMM and the US EPA SWMM to generate data on changes in pollutant concentrations under changed rainfall patterns predicted for the North of Sweden. These analyses indicated that – depending on the scenario evaluated – increase of 10-70% for TSS (with the higher values associated with the use of winter maintenance practices). The type and speed of land use change were identified as key influencing factors pollutant concentrations generated (Borris et al., 2013) with rainfall depth and intensity (as opposed to the number of antecedent dry days) also identified as influential (Borris et al., 2014 a and b). A key conclusion of these studies was that the smaller storm events (which carry a high percentage of the annual pollutant load) were most sensitive to predicted climate changes, and that the use of green infrastructure to reduce directly connected impervious spaces were effective in reducing both runoff quantity and pollutant load.

4.3 Predicting runoff quantity

Nationally and internationally mathematical stormwater models have a long history of use in the planning and assessment of urban drainage systems for stormwater management. Hence recent research has focussed on methodological studies, primarily looking to identify types and levels of uncertainty and how these may be addressed. For example, Sharafati et al., (2020) undertook an assessment of uncertainty in flood hydrograph features (e.g., peak discharge and flood volume) due to variability in the rainfall-runoff model HEC-HMS. Using simulated data, uncertainties due to rainfall and model parameters on generated flood hydrographs were evaluated using the relative coefficient of variation, identifying that rainfall depth is the main source of uncertainty of flood peak and volume predictions. Talei et al., (2013) investigated the use of a local learning for a rainfall-runoff modelling application. Applied to three catchments of different sizes, results of the local learning model were comparable or better than results obtained from physically-based models such as the Kinematic Wave Model (KWM) and Storm Water Management Model (SWMM). Reynolds et al., (2018) evaluated the impact of using differing definitions of climatological and discharge day on a tipping-bucket hydrological model, reporting that the definition of the climatological day (and its impact on how water was assigned to one or two daily rainfall values) was a key driving factor in the magnitude of model performance uncertainties. Further studies have explored the use of models developed to predict the response of impermeable surfaces to also predict the response of permeable surfaces - such as green spaces (Broeckhuizen et al., 2019 and 2020) and snow pack (Moghadas et al., 2016 and 2018) – to rainfall events. For example, Broeckhuizen et al., (2019) explored the impact using of models with differing underlying mathematical structures (i.e. SWMM, MOUSE and Mike SHE) to predict a range of outputs including the number of events that generated runoff and the initial conditions for rainfall events. Encompassing the analysis of eleven different soil types and six different soil depths over a study time period of 26 years, results, outputs varied between the three models indicating that choice of model will impact overall study results. This study was complimented by a further study which explored the impact of different approaches to model calibration (Broeckhuizen et al., 2020). Focusing on the model SWMM, the study concluded that both single stage and two stage calibrations were successful. However, the two-stage strategies reproduced more validation events poorly (Nash-Sutcliffe efficiency < 0) than the single-stage strategies, but they also reproduced more events well (NSE> 0:5) indicating that various strategies for selecting calibration events may lead in some cases to different results in the validation phase.

In terms of modelling rain-on-snow events, a study by Moghadas et al., (2018) evaluated the use of SWMM to predict runoff volumes generated during rain-on-snow events under current and future climates. A key finding was the impact of snow cover characteristics, in particularly snow depth which influences the volume of rainwater and/or snowmelt retained in or released from the snowpack. Also with a focus on the impact of snow cover, Järvi et al., (2018) integrated field data and modelling to evaluate the energy and water exchanges of four cities exposed to wintertime snow. Results suggest that the presence of snow critically changes the impact that city design has on local-scale hydrology and climate. After snow melt, the cities return to being strongly controlled by the proportion of built and vegetated surfaces, and the authors show how inter-year variability of wintertime temperatures may modify the current partitioning between runoff and evapotranspiration with implications for wintertime runoff rates.

In terms of planning for climate change, Arnbjerg-Nielsen et al., (2013) undertook a review of methods for assessing future changes in urban rainfall extremes and their effects on urban drainage systems. Reinforcing the key role of climate change as the key driver in changing urban drainage paradigms, it identifies that there are still many limitations in our understanding of how to describe precipitation patterns in a changing climate in order to optimally design and operate urban drainage infrastructure. A key conclusion is that the design and optimization of urban drainage infrastructure considering climate change impacts and co-optimizing these with other objectives will become ever more important to keep our cities habitable into the future. Also with a focus on assessing the impacts of climate change on the hydraulic capacity of urban drainage systems, Berggren et al., (2014) evaluated the impact of using alternative types of design rainfalls: Block Rainfalls (BR) and the Chicago Design Storm (CDS) together with two methods for considering future climates (use of a constant factor and a Delta Change (DC) factors that depend on rainfall intensity). Outputs across the approaches were not consistent, with use of CDS generating the maximum hydraulic response but BR giving a better insight of critical durations in the system. An overall conclusion was that differences between the two methods indicate a high dependence related to the maximum factors applied on the rainfalls.

More broadly, Sørup et al (2018) explored the use of four different weather generator (WGs) products in relation to both current and future conditions on two different catchments. Under current conditions, all WG products result in realistic catchment responses (e.g. number of full flowing pipes and the number and volume of combined sewer overflows). Under future conditions, the WGs differ in terms of their output. However, all results indicate that catchments will have to handle more events that utilise full drainage system capacity. Working at larger scale, Tanouchi et al., (2019) compared the use of the high-resolution polygonal land cover data of EEA Urban Atlas with the less detailed EEA CORINE for land-use characterization in the dynamic multi-basin hydrological model HYPE. Established for a basin including the town Svedala (Southern Sweden), the simulated flow rate was evaluated against river flow time series, statistical indicators and flow duration curves. Data indicated that the use of Urban Atlas data generally agreed better with observations of summer storm events, especially when the daily rainfall amount was 10 mm/day or more.

4.4 Blue-green infrastructure (BGI) and stormwater control measures (SCM): measuring and modelling performance

Recognition of the need for measures which address urban runoff quality as well as quantity has increased significantly over the last 25 years. The traditional approach of direct surface flow via piped systems to receiving waters evolved when stormwater runoff was considered an essentially clean water. However, as a function of an increasingly strong evidence base (see Sections 4.1 and 4.2), the need for and benefits of reducing the pollutant loads associated with urban stormwater runoff is gaining traction in practitioner and policy development fields (see Section 1). Whilst pipes are efficient in moving (if not managing) surface runoff, they offer limited – if any – opportunity for pollutant removal. An alternative approach to piped systems is the use of blue-green infrastructure (BGI) i.e. keeping surface runoff above ground and managing flow using a range of blue and green system to infiltrate and/or detain flow for subsequent release. As interest in the approach grew nationally and internationally, terminology associated with the use of BGI has grown increasingly complex, with the use of differing terms for the same system and the same name for differing systems causing confusion and miscommunication. This led to researchers from several countries collaborating to develop and share a common understanding of the relationship between key terms and concepts in relation to their primary focus and specificity.

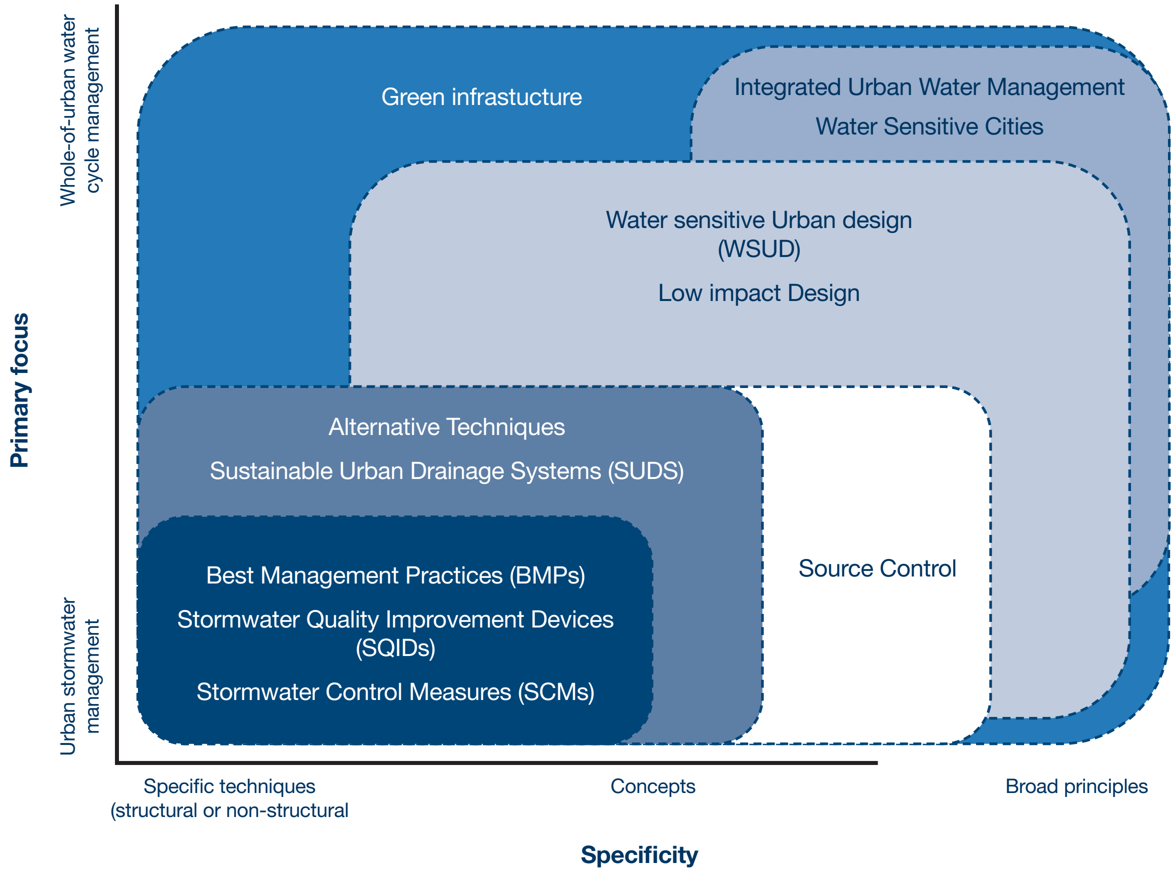

Figure 3. *Classification of urban drainage terminology in relation to their specificity and focus (Fletcher et al., 2015)*

4.4.1 Field measurements

In terms of the performance of BGI, several studies have evaluated the impact of a range of types of BGI in terms of their impact on water quality, water quantity, biodiversity (see Section 4.7) and the delivery of a wider range of ecosystem services (see Section 4.10). For example, Gavrićet al., (2019) reviewed the use of grass swales and filter strips (GS&GFS) in stormwater management. This reported that, whilst understanding of the hydrology of stormwater control measures is adequate for current needs, studies on the behaviour and fate of pollutants have focused on a limited number of pollutants which are themselves not reported systematically, making comparisons between studies challenging.

Al-Rubaei et al., (2017a) surveyed the operational status of 25 municipal stormwater ponds (aged between 3 and 26 years) through an assessment of hydraulic loading and efficiency, vegetation health and characteristics of bottom sediments. This found that estimated hydraulic efficiencies correlated well with the pond length-to-width ratios and the ratio of the pond surface area to the impervious area of the runoff contributing catchment. Sediment quality was found to be impacted by anthropogenic (traffic) activities, but not to a level warranting special disposal requirements. The inspection survey revealed relatively few minor issues that could be corrected easily demonstrating the importance of relatively simple regular inspections serving to detect minor problems at an early stage before they would seriously impact pond functioning.

In terms of constructed wetland performance, Herrmann (2012) monitored a 1 ha system receiving water from residential and road areas over a four year period. Whilst yearly average reduction of nitrogen (173kgha -1y -1) and phosphorous (12.1kgha -1y -1) were reported, comparison of outlet concentrations with Swedish Environmental Quality Criteria (EQC), typically identified total nitrogen levels as moderate or high and total phosphorous levels as very high or extremely high. Metal (Cd, Cr, Cu, Pb and Zn) concentrations were low or moderate in terms of EQC. This study also reported that vegetation was well established after one year. In terms of faunal assessment, results indicated that while invertebrate colonisation was initially dominated by chironomids and corixids, later prominent increases were noticed for the isopod *Asellus aquaticus,* the snail *Physa fontinalis,* and the mayfly nymph *Cloeon dipterum* indicating that biodiversity and nutrient reduction objectives may be achieved simultaneously in stormwater wetlands.

With a view to evaluating performance of older systems, Al-Rubaei et al., (2017b and c) evaluated the stormwater runoff quantity and quality treatment performance of a 6.8 ha 19-year old combined pond-wetland system, located in south Sweden. Mean volume reductions for 53 storm events for the pond and wetland were 40% and 28%, respectively, while the mean flow reductions were 60% and 76%, respectively. Despite highly variable influent concentrations, the pond-wetland system removed an average of 91%, 80%, 94%, 91%, 83% and 92% of TSS, TP, particulate Cd, Cu, Pb, and Zn, respectively, whereas the removal of particulate and dissolved Ni was highly variable with an average of 67% ± 62% and –5% ± 41%, respectively, indicating that relatively old systems can also provide efficient treatment.

Several studies have focused on the behaviour and fate of nutrients in stormwater systems. For example, Land et al., (2017) undertook a systematic review of the performance of constructed wetlands to reduce the input of nutrients to receiving waters. Quantitative analysis of the data from over 200 wetland systems situated in Europe and North America found that the removal rate of both total nitrogen (TN) and total phosphorus (TP) is highly dependent on the loading rate, with median removal rates of TN and TP of 93 and 1.2 g m^2 year^1, respectively. With a focus on the impact of nutrient status on pollutant removal processes, Svensson et al., (2015) investigated whether a wetland treatment system treating stormwater from a wood industrial site faced nutrient deficiency or lacked efficient microbes, and whether addressing these possible problems through the addition of nutrients and microbes contained in paper mill sludge) enhanced the degradation of organic matter. Results indicated that whilst nutrient additions had a positive effect on the treatability of the stormwater, the addition of paper mill activated sludge led to resulting stormwater exerting a toxic effect.

Across the range of BGI systems available, a key pollutant removal process is the retardation of flow to facilitate the sedimentation of particulate matter and associated pollutants. Over time, sediments accumulate requiring periodic removal to maintain BGI hydraulic and treatment capacity. It is hence important to develop a detailed understanding of quality of accumulated sediments from both operational (see Section 4.8) and sediment disposal perspectives. As a contribution to addressing this need, Flanagan et al., (2021) analysed sediments from 17 stormwater sedimentation facilities for 259 organic substances likely to be found in an urban environment. The study reports that 92 substances were detected in at least one sample, with a maximum of 52 substances detected in a single sample. This comprehensive screening study enabled a typical profile of urban organic contamination to be developed, which includes polychlorinated biphenyls, polycyclic aromatic hydrocarbons, organotins, aliphatic hydrocarbons, phthalates, aldehydes, polybrominated diphenyl ethers, perfluorinated substances, and alkylphenols. Whilst pollutant concentrations were reported to vary greatly between ponds, 22 of the 32 samples exceeded the regulatory threshold values derived from toxicity data for at least one substance. In relation to swales, Gavrić et al., (2021) investigated the metal enrichment of soils in three roadside swales which are snow covered for the part of the year (and therefore subject to additional pollutant loads from the use of road salt and grit, studded tires and the storage and melting of snow cleared from trafficked areas. The swale receiving runoff from highest trafficked area exhibited the highest mean concentrations of most of the metals studied (Pb, Cu, Zn, Cr, Cd, Ni, Co, V, Ti, and W). A key finding was that metal concentrations did not decline with distance from the trafficked surfaces, suggested that stored snow was an important source of metals partly balancing spatial distribution of metals in swale soils.

In terms of direct measurements of the long-term hydraulic function of BGI, Al-Rubaei et al., (2015) monitored the hydraulic performance of twelve stormwater infiltration systems including permeable asphalts, vegetated and unvegetated concrete grid pavers, unvegetated interlocking concrete pavers and grassed swales through a combination of field and laboratory experiments. Initial data indicated that, due to a range of issues including a lack of regular maintenance, use of an inappropriate joint filling material and severe compaction of swale soils, most systems showed a reduced infiltration capacity. Despite this, older vegetated systems were still found to be capable of infiltrating intense design rainfalls. However, relationships between a range of factors (e.g. type and age of the system, the type of joint filling material and distance from the pavement) and the long-term infiltration behaviour of systems was also identified, with conclusions emphasising the need for full implementation of construction and regular control and maintenance by the inspecting authority has to be ensured.

4.4.2 Modelled performance

As noted in Section 4.1, generating field data is expensive and time consuming. Data on the removal of many pollutants by the range of BGI is limited, particularly for many contaminants of emerging concern such as microplastics and per- and polyfluoroalkyl substances (PFAS). To support the development of stormwater management plans in the absence of full data sets, several studies have looked to develop and validate models to predict the removal of a range of diffuse urban pollutants by a range of BGI. However, the high levels of uncertainty commonly affecting stormwater runoff quality modelling (see Section 4.3) also influences the performance of stormwater treatment models (Vezzaro et al., 2012). To better understand sources of uncertainty, Vezzaro et al., 2012 evaluated the use of a conceptual dynamic model for the removal of Cu and Zn in a retention pond and a biofilter (BGI systems which differ in their main removal processes). The most sensitive model factors were identified using Global Sensitivity Analysis (GSA) and model prediction bounds were estimated using the Generalized Likelihood Uncertainty Estimation (GLUE) technique. Key factors influencing performance (i.e. the most sensitive) related to the physical characteristics of the simulated systems (flow and water losses) and to the fate processes related to TSS, whereas GLUE highlighted model structural uncertainties. However, despite the uncertainties identified, the use of conceptual dynamic fate models based on substance-inherent properties in combination with field data to estimate pollutant removal in different stormwater treatment systems was supported. In terms of modelling pollutant accumulation by sediments, Gavrićet al (2019) evaluated the use of the proprietary StormTac Web model to predict the accumulation of Cu, Pb and Zn in the soils of three swales through comparison with the results of a detailed field sampling campaign. Comparisons of measured (MBm) and simulated (MBs) metal burdens retained by the swales indicated that whilst, measured values typically exceed simulated results, results support the feasibility of assessing swale performance.

In terms of modelling the water quantity impact of BGI, most models are developed and utilised to support decision-making at a catchment scale. For example, Haghighatafshar et al (2018a) coupled one-dimensional (1D) sewer and two-dimensional (2D) overland flow hydrodynamic models to evaluate the flood mitigation efficiency of the Augustenborg BGI development (Malmö, Sweden). Simulation results showed that the blue-green stormwater systems were effective in controlling local surface flooding in inner-city catchments, having reduced the total flooded surfaces by about 70%, with BGI retrofits reducing peak flows by approximately 80%. In aligned research, Haghighatafshar et al (2018b and 2019b) drew on observed rainfall-runoff responses from two catchments with SuDS and a pipe-bound catchment to inform development of a conceptual model of mesoscale Sustainable Drainage Systems (SuDS) performance. The model indicated that, in contrast to pipe systems, SuDS disaggregates the catchment into a group of discrete mini catchments that have no instant connection to the outlet. These mini catchments start to connect to each other (and potentially the outlet) as the rainfall depth increases. Results indicate that the order of stormwater control measures utilised affects the system's overall performance concluding the approach can support the design and implementation of mesoscale SuDS retrofits which include several types of BGI systems with different retention and detention capacities. In a further development of the meso-scale SuDs modelling, Haghighatafshar et al (2019b) extended the approach to include a conventional urban sewer network. This hybrid model integrates the retention/detention effects of mesoscale blue-green stormwater systems with the hydraulic dynamics of the sewer network. The model was further developed through the integration of a cost-oriented multi-objective optimization algorithm with the aim of minimizing the total costs through optimal placement of mesoscale blue-green systems of optimal size. While yet to be fully validated, the approach is put forward as a useful methodology for sustainable management of the existing sewer networks in cities from a hydro-economic perspective

At a local scale, Rodin et al., (2012) coupled a soakaway model to a physically distributed urban drainage model to investigate the impact of soakaways on urban drainage networks. A comparison of model predictions with field data suggested that the behaviour of individual soakaway could be modelled efficiently using this approach. This study also included the analysis of alternative approaches to aggregating data for individual soakaways, with results suggesting the use of a weighted geometric mean hydraulic conductivity of individual allotments was optimal when comparing total outflow volume and peak flow rate. In a further aligned study, Rodin et al., (2013) describe the use of a simplified modelling concept for soakaway infiltration in the presence of a shallow groundwater table which includes a representation of the local groundwater mound and its effects on the infiltration rate. The outputs of this model were compared to the output from a two-dimensional (2D) unsaturated/saturated flow model based on Richard's equation. The comparison shows that soakaway emptying times calculated by the new model are on average 13% higher than the emptying times of the 2D model, leading to the conclusion that this new approach is a useful tool for simulating small-scale stormwater infiltration in the presence of a shallow groundwater table with distributed models on larger scales.

With a focus on swales, Rujner et al., (2018) evaluated the use of the hydrological model Mike SHE (typically utilised at a catchment scale) to simulate the hydrological response of a grass swale to runoff inflows. Data generated from 12 irrigation events was used as model input, and goodness of fit statistically assessed for observed and simulated peak flows, hydrograph volumes, Nash-Sutcliffe model efficiencies (NSE), and soil water content (SWC) in swale soil layers. The best fit (NSE > 0.8) was obtained for high inflows and wet antecedent moisture conditions (AMC); the least fit was noted for low inflows and dry AMC, when the primary swale function is flow attenuation. Results indicate the importance of correct modelling of the soil infiltration and, whilst the effects of spatial variation of SWC on the swale discharge hydrograph could not be confirmed from simulation results, high topographical accuracy was beneficial for reproducing well the locations of the observed water ponding.

In addition to evaluations of the stormwater quality and quantity performance of BGI, a variety of other approaches for assessing the impacts of such systems have also been considered. For example, Sörensen and Emilsson (2019) explored the use of insurance data to evaluate the level of flood risk reduction associated with the use of BGI in Augustenborg (Malmö, Sweden) in comparison with neighbouring areas that rely on conventional drainage systems. Analysis focused on the impact of the 2014 extreme precipitation event (return period of 50-200 years) and indicated that less flood damage occurred in areas retrofitted with BGI. Research by van Bergen et al (2019) took a different perspective again, evaluating the daily and seasonal emissions of greenhouse gases by a small urban pond over an 11 month period. Results showed that over the course of a year the pond was a net emitter of greenhouse gas emissions, and suggests both that carbon emissions be considered when constructing ponds and that such emissions may be reduced by pond management which focus on reduction of nutrient and organic matter input. For further approaches to assessing BGI performance see Sections 4.10

4.5 BGI system design

Whilst a series of national and international guidelines (e.g. CIRIA, 2015; ISO 24536, 2019) are available to inform BGI design and implementation strategies, research to develop a more complete understanding of pollutant processes occurring within BGI and their relationship with various design components is ongoing. For example, in a review of swale design, Ekka et al., (2021) identified that current design guidelines focus primarily on hydraulic conveyance. To address this gap, existing literature data was used to develop science-based swale design guidance for treating targeted pollutants in stormwater runoff, with the use of check dams or infiltration swales recommended as the best options for both runoff volume reduction and removal of sediment and heavy metals. Research by Sami Al-Janabi et al., (2020) also supports the use of check dams in swales but notes that their design (e.g. height and spacing) has a significant influence on the flow regime in grassed stormwater channels and thus channel infiltration capacity. For example, their empirical study found that that an increase of check dam height from 10 to 20 cm increased channel infiltration from 12% to 20%.

In terms of green roofs, a review by Kotze et al., (2020) focused on the terminology used to describe and report the design and performance of these systems. Finding that common terms such as intensive and extensive roof – as well as green roof itself - were defined and used in multiple ways, they propose a new classification system based on the roof's primary function(s) and vegetation. For example, categories such as stormwater meadow roof, and biodiversity forest roof are proposed as an approach to avoid confusion, allow for generalizations and facilitate communication in this rapidly-expanding field. With a view to understanding how green roof vegetation abundance and community composition (factors which influence their role in stormwater retention) change over time in cold climates, Lönnqvist et al., (2021) investigated vascular plant covers and species compositions on 41 roof sections located in Northern Sweden. Results show that whilst unintended species accounted for approximately 70% of species found, they formed sparse cover (~7%) and therefore made less contributions to green roofs' potential functionalities than the intended vegetation (~93% cover). Key conclusion relate to both the importance of substrate depth for plant abundance and species diversity and show that even in a cold climate, colonizing unintended species can strongly contribute to green roofs' species richness. Moving to green walls, Lausen et al., (2020) report that a relatively narrow range of species – primarily selected for ornamental reasons – are used in current designs. To enhance knowledge in this area and inform the selection of plants of in relation to their response to periodic drought, the growth responses of eight native, herbaceous perennials to water shortages ranging from one to six weeks were evaluated under controlled greenhouse conditions. The study found that species with a degree of succulence of root, shoot, or leaves dealt best with drought conditions and that the trait relevant for absolute volume of water transpiration is plant biomass. With a focus on enhancing constructed wetland performance, Svensson et al., (2015) investigated the effects of aeration and/or vegetation in series of experimental constructed wetlands on the removal of polyphenols (PP), chemical oxygen demand (COD) and water colour (key parameters in stormwater contaminated with oak wood leachate). Results showed that aeration increased the effect of both COD and PP removal, and that vegetation alone had a small but significant effect on removal of COD. The study concluded that wetlands can be used to treat stormwater contaminated by oak wood leachate, the importance of including open-water habitat within treatment systems and that the hydraulic retention time is more important for removal than aeration and vegetation related processes.

As an alternative to designing stormwater treatment systems based on volume and/or area related correlations alone, Larm and Alm (2014) updated a wider range of existing design criteria using new field data sets e.g. inlet concentration, detention time, shape and temperature. The results of this review were implemented into the proprietorial stormwater water design StormTac (used to inform the design of stormwater ponds and wetlands and predict pollutant removal performance). Their study includes an assessment of climate effects parameters such as design flow and inlet concentration, with the models predictive capacity evaluated in relation to field data. Results indicated that integration of site specific data on the wider range of criteria identified, led to a better predictive capability than use of area and volume relationships alone.

In addition to field studies, several researchers have undertaken laboratory-based column experiments, exploiting the opportunity to control experimental conditions as a mechanism to interrogate both removal processes and the factors which influence their occurrence. For example, Søberg et al., (2014) undertook a series of column experiments to evaluate the impact of Swedish winter conditions (i.e. low temperature and elevated salt concentrations) on the retention of metals by stormwater biofilters. Both factors (separately and in combination) led to increased metal concentrations in column outflow. However, despite this, outflow concentrations for total metals met the class 4 threshold value defined in the Swedish freshwater quality guidelines. A further study additionally assessed the impact of including a submerged zone with an embedded carbon source (SZC) within the experimental design (Søberg et al., 2017). Results indicated that inclusion of a SZC had an overall positive effect and supported previous findings that bioretention provides a functioning stormwater treatment option in areas experiencing winter conditions (road salt, low temperatures) or coastal regions (salt-laden stormwater). The same experimental design was then used to investigate the impact of temperature, salt and a SZC on the removal of nitrogen, phosphorus and TSS by biofilters (Søberg et al., 2020). Results showed that overall, phosphorus and TSS removal percentages were high across all treatments. As with metals, the presence of salt deteriorated total phosphorus removal, however, dissolved phosphorus removal was not affected with the presence of the SZC statistically significant for both phosphorous and TSS removal. In earlier studies, Zinger et al., (2013) used laboratory-based mesocosms to establish if retrofitting a saturated zone to stormwater biofilters enhanced total nitrogen and total phosphorus removal. Established with different plant species, retrofitting a saturated zone significantly increased overall N removal in all columns but total phosphorous removal decreased. A recent study by Søberg et al., (2021) reports that also in cold temperatures, nitrogen removal was supported by a submerged zone. The impact of drying episodes and temperature on the removal of bacteria by stormwater biofilters with and without a submerged zone was evaluated through the establishment of 16 bioretention columns under an experimental design which supported the analysis of possible interactions between these factors (Søberg et al., 2019). Results showed that outflow concentrations were independent of inflow concentrations indicating the importance of internal processes. The effect of temperature varied between bacterial species and sample types; whereby first outflow samples reported lower concentrations that event based samples indicating remaining/surviving bacteria in the bioretention cells have little effect on initial peak outflow concentrations. Whilst the presence of submerged zones significantly reduced bacteria outflow concentrations, sudden temperature increases generated significantly higher bacteria outflow concentrations in columns with submerged zones indicating this design may be a poor choice for managing stormwater runoff in areas experiencing winter conditions.

Lange et al., (2020a) undertook a series of column experiments to evaluate the impact of plant species selection on the removal of total and particulate metal fractions from artificial stormwater which was applied either regularly or in intervals to represent the effect of a long dry period (e.g. five weeks without watering). Results showed that effluent concentrations of both total and dissolved metals significantly differed between different plants, with differences in dissolved metal concentrations particularly noticeable after the dry period. Plant specific variations on the behaviour of the dissolved concentrations of Cd, Zn and Cu were observed, with all metals exceeding Swedish reference values on occasion. In an extension of this study, Lange et al., (2020b) investigated the behaviour of particulate, colloidal and truly dissolved Cd, Zn and Cu under varying vegetation and salt levels. Results indicate that while total metal removal was often >95%, removal of the dissolved and truly dissolved fractions was significantly lower. Whilst the presence of vegetation generally had little effect on metal removal and fractionation, the presence of salt increased the concentrations of Cd and Zn in the truly dissolved fraction. With regard to organic pollutants, Markiewicz et al., (2020) used columns granulated activated carbon, Sphagnum peat or *Pinus sylvestris* bark with sane pre-filters to explore the retention of colloidal and truly dissolved HOCs. All filters showed efficient reduction of aliphatic diesel hydrocarbons C16–C35, benzene, and the PAHs phenanthrene, fluoranthene, and pyrene during the majority of the 18 month experimental run.

Further studies have examined the performance of a range of components of stormwater biofilters, with a particular focus on the performance of alternative filter materials to adsorb specific pollutants (and the factors that influence such processes) with a view to enhancing biofilter design. For example, Björklund and Li (2015) assessed the potential of five low-cost sorbent materials (two minerals, two pine barks and a sawdust) to remove dissolved and colloidal phases of selected hydrophobic organic compounds (HOCs) within a series of batch studies. While the mineral sorbents exhibited insignificant removal of the organic contaminants, the wood-based materials retained >80% of the initial HOC concentration. Further analysis suggested that removal was a function of chemisorption of HOCs onto a monolayer on the wood-based media, and that this could lead to early saturation of the materials. A second study investigated the HOC-sorption of four further potential sorbents (cellulose, chitosan, chitosan-covered bark and polypropylene/polyethylene fibres; PP/PE fibres) plus pine bark (Björklund and Li, 2018). Results show that cellulose and chitosan offer very low sorption capacity for HOCs, whereas >70% removal was achieved using PP/PE fibres and >80% with pine bark and chitosan-covered bark. Further research by Björklund and Li (2016) investigated whether the presence of dissolved organic matter (DOM) had a negative effect on the adsorption of HOCs onto sludge-based activated carbon (SBAC) in batch adsorption tests. Involving the use of two types of DOM (soil organic matter and humic acid; HA) results indicated that both types of DOM did not have a significant negative effect on the adsorption of HOCs under tested experimental conditions (except for a highly hydrophobic compound). Kinetic studies of adsorption indicate that bulk adsorption of HOCs occurred within 10 min, adsorption capacity generally negatively correlated to the compounds' hydrophobicity (log Kow) and positively associated with decreasing molecule size (Björklund and Li, 2017a). However, in repeated adsorption tests, where competition between HOCs was more likely to occur, adsorbed pollutant loads exhibited strong positive correlation with log Kow. Later research by the same team evaluated the impact of amending a stormwater bioretention medium with SBAC with regard to HOC removal (Björklund and Li, 2017b). The experiment involved the addition of SBAC (0.5% w/w) to two of three soils columns to which artificial stormwater was applied over a 28 day period. Results indicated that the amended soil was the most efficient for removing HOCs with a log Kow 4.0–4.4, concluding that the addition of SBAC may extend bioretention medium lifetime by approximately 10–20 years.

In a similar approach, Genç-Fuhrman et al., (2016) investigated the effects of contact time, solution pH, and the presence of humic acid (HA) on the combined removal of Sb, Cd, Cr, Cu, Ni and Zn by three types of sorbent (alumina, granulated activated carbon (GAC), and bauxsol coated sand (BCS). Whilst some differences in behaviour between metals was reported, key recommendations emerging were that pH-value of stormwater must be in the range of 6-7 in order to achieve removal of the full spectrum of metals, and that natural organic matter may severely influence the removal efficiency. Also with a focus on metals, Søberg et al., (2019) explored the accumulation of dissolved metals (as single and multi-metal solutions) by ten different filter materials recommended and/or implemented in bioretention facilities. Results demonstrated that all tested materials adsorbed metals with 90% of adsorption occurring within 1 h. In general, results indicated that filter materials classified as sand (naturally high pH, relatively low OM content and large specific surface area) performed. The addition of biochar did not significantly improve metal retention and may therefore be an unwanted (due to degradation over time) extra source of OM. Regardless of filter material type, metals primarily adsorbed to the exchangeable form which indicates that metal adsorption might not be permanent, but rather substantially reversible in some cases, with more research required to investigate this further.

In contrast to studies focusing on metal removal by sorption to a filter material, research by Schück and Greger (2020) assessed the role of 34 floating wetland plant species to remove Cd, Cu, Pb and Zn from the water column. Results show that the most important plant traits for metal removal from water are transpiration and high total biomass, especially large amounts of fine roots and leaves (with stronger correlations found after a five day – as opposed to 30 minute – exposure time). The utility of these results to enhance metal removal by floating wetlands is described.

4.6 Conventional and emerging stormwater management approaches

In terms of research linked to conventional approaches, the ubiquitous gully pot is an excellent example of a widely used – but incompletely understood - urban drainage feature. Recent research by Wei et al., (2021) evaluated the ability of two basal sediment scour deterministic models (of differing levels of complexity) to predict behaviour at sites other than those for which they were established was assessed under both current and future rainfall conditions. Two models (developed using differing parameters) were applied to the same study site and the predicted effluent TSS concentrations were not consistent. However, useful information was derived. For example, the use of model one indicates that scour-induced total suspended solids in gully pot discharges can be kept well below 25 mg/L (guideline value for surface waters) if the gully pot fullness level is maintained at < 60%. Results from Model Two identify that fine sediments are particularly susceptible to in-pot scour with, for example, sediment with a specific gravity of 1.1 and diameter of >63 µm predicted to account for 50% of scour-induced total suspended solids in gully pot discharge.

With respect to enhancing treatment processes within in stormwater retention facilities, Nyström et al., (2019) investigated the use of two commercial coagulants to promote coagulation and flocculation of urban runoff pollutants as a pre-cursor to their removal by sedimentation. Results of this laboratory-based experiment indicated that the use of the coagulation products resulted in particle and total metal reduction of > 90% compared to 40% for only sedimentation (i.e. no coagulant added). Up to 40% reduction of dissolved Cr, Cu and Pb was also observed compared to 0% for sedimentation alone, suggesting that coagulation may be a useful process for stormwater treatment systems. Building on this successful pilot study, Nyström et al., (2020) screened the use of twelve coagulants and flocculant aids to identify chemicals that efficiently reduced turbidity and suspended solids within a stormwater matrix. Five coagulants were short-listed for further research within a laboratory based system (jar tests). Treatment efficiencies of >90 % for both turbidity and suspended solids was achieved by all coagulants, with charge neutralization identified as the process driving coagulation. A further study investigated the ability of selected coagulants to remove a wider range of pollutants from a semi-synthetic stormwater, including particle content, organic carbon, total and dissolved metals, hydrocarbon oil index, and polycyclic aromatic hydrocarbons (PAHs) (Nyström et al., 2020). Results indicated that the performance of all coagulants was > 90% removal on average for all pollutants. In terms *in situ* field trials, Hallberg et al., (2014) evaluated the use of flocculants to enhance sedimentation processes within tunnel wash waters. Results indicated that use of a sedimentation time of < 24 hours together with a chemical flocculent significantly reduced TSS, metals and PAH concentrations, as well as acute toxicity. An alternative novel approach to enhancing the removal of stormwater sediments entering ponds and also reduce sediment resuspension is the use of a bottom grid structure (BGS). Designed to be installed at the inlet to e.g., a detention pond, a BGS is an artificial mesh structure which promotes sediment of and then traps suspended materials (Milovanović et al., 2020). This initial study explored the BGS concept in a hydraulic scale model to develop a better understanding of the effects of BGS geometry on stormwater sediment trapping, with results suggesting larger cells (footprint 10 × 10 cm) were more effective than the smaller cells (5 × 5 cm) in sediment trapping, cell depth exerted little influence on performance and cells with inclined cross-walls proved more effective in sediment trapping.

In terms of emerging approaches for managing stormwater quantity, Lundström et al. (2020) have explored the potential of dynamic stormwater storage in sponge-like porous bodies (SPBs). A completely novel concept (see Figure 4), the approach has been modelled using first principles, for down-flow and up-flow variants of SPBs. Theoretical analysis showed that the rate of inflow is driven by absorption and/or capillary action into porous material structures as a function of time and critically dependent on the type of structure and the porous material used. Using case study data, the rates of inflow and storage filling were modelled for various conditions and found to match, (or exceed) the rates of rainwater inflow and volume associated with two types of Swedish rainfalls (60-minute duration; return period of 10 years). Initial data hence confirm the potential of dynamic SPB storage to control stormwater runoff. Building on this initial analysis, further theoretical analysis involved comparing how the theoretical total amount of absorbed water by SPB was modified by the inclusion of swelling. The results can be summarized in terms of the geometrical dimensions of the storage device and the magnitude of the diffusion coefficient D. Key conclusions were that in all the cases considered, the swelling in general increased the maximum absorbed water volume by 14%.

4.7 Impacts on receiving water ecology

Whilst the majority of studies have focused on physico-chemical changes associated stormwater and its treatment, several studies have explored the impact of urban water on receiving water quality and its ecology. For example, Rentz and Öhlander (2012) investigated the impact of urban stormwater discharges on urban water bodies in Luleå (northern Sweden). Their study identified elevated levels of PAHs, and that water and sediment quality depended on catchment area characteristics. However, they also reported that an absence of urban runoff discharges (together with low water levels and ice cover) contributes to the development of anoxic conditions in the water column and sediments. In an aligned study, Blecken et al, (2012) collected surface sediment samples from in front of three storm sewer outlets as well connecting ditches and receiving waters, as well as from a control site that did not receive stormwater. Data indicated that stormwater discharges affected contaminant concentrations in the bottom sediments, with analysis of seasonal differences suggesting that relatively high amounts of contaminants are discharged during snowmelt. With a wider perspective of assessing the levels of risks posed to human health from stormwater discharges, Björklund et al., (2018) used hydrodynamic modelling to investigate the influence of urban stormwater discharges and CSOs on the Göta River (Sweden). The study focussed on the transport of Cu and benzo[a]pyrene (BaP) during two storm events, with results indicating that water quality guidelines for Cu would be exceeded at several sites. Data suggested that stormwater discharges generally give rise to higher Cu and BaP concentrations than CSOs, and were within an order of magnitude of field data suggesting that hydrodynamic modelling is a useful tool for identifying suitable sites for mitigation measures.

In terms of impact of stormwater runoff on receiving water ecology, results are not conclusive. For example, Søberg et al., (2016) evaluated bioaccumulation of metals by natural and caged fauna in two wet retention ponds and a reference lake, and their relationship to sediment metal concentrations. Results indicated that metal concentrations in fauna were higher in the ponds than in a reference lake, with positive correlations reported for some metals in fauna and sediment only. Research by Pohl et al., (2015) explored the impact of stormwater quality on embryo development of the amphibian *Xenopus (Silurana) tropicalis,* with a view to assessing the habitat quality of stormwater ponds. Whilst analysis of water quality suggested that most of the studied ponds had water of sufficient quality for amphibian embryo development, laboratory tests identified that – at some sites – water caused premature hatching and/or reduced heart rate in *X. tropicalis* embryos. Amphibian larvae were not detected in the majority of ponds, with sub-lethal effects detected in laboratory studies identified as potential causative factor. To explore the potential of stormwater ponds to combine their primary function of pollution and peak flow control with the promotion of biodiversity, Meland et al., (2020) assessed the environmental conditions and biodiversity of macroinvertebrate communities in twelve highway stormwater ponds and nineteen natural ponds (located within or in the vicinity of cultivated landscape). Results indicated that highway stormwater ponds had much higher conductivity and were larger (almost twice the surface area of natural ponds). Results of the biodiversity assessment found that the community composition was very different between the two types of ponds, with the number of taxa being slightly higher in the highway stormwater ponds. Together with conductivity and surface area, the number of ponds within 1 km radius was also identified as key predictive variable, with overall conclusions supporting the potential of highway ponds to provide a valuable highway habitat.

A study by Johansson et al., (2019) involved sampling 18 stormwater ponds in Uppsala (Sweden) to explore the relationship between dragonfly beta diversity and a range of environmental factors (e.g. local and land use variables). A total of 31 species of Odonata were recorded (61% of all Odonata species reported to occur in the Uppland provine), indicating the value of stormwater ponds in contributing to urban biodiversity. Further analysis indicated that species richness was primarily related to pond area and total vegetation cover and that the management of different types of vegetation is key to maximizing the potential of these systems in contributing to regional biodiversity levels. In a further study, Johansson et al., (2020) compared dragonfly abundance data collected by citizen scientists (volunteers) with dragonfly abundance data in from stormwater ponds collected using scientific, standardized design. Results showed that the citizen science datasets differed significantly from datasets, with particular regard to the under-reporting of common dragonfly species. A key conclusion was that if citizen science data is to be used for estimating or predicting biodiversity, a methodology to correcting for the under-reporting of common species in citizen science is required.

4.8 Operation, maintenance and management of BGI and SCMs

To ensure a sufficient performance over time, all infrastructure system require maintenance, and in this regard urban drainage infrastructure / BGI is no different.

With regard to operation and maintenance aspects associated with a wide range of BGI systems, Blecken et al., (2017) reviewed the key maintenance needs for wet ponds, constructed stormwater wetlands, bioretention, infiltration practices, permeable pavement, swales and rainwater harvesting systems. Common maintenance themes identified across systems include the cleaning of pre-treatment areas and the preservation of infiltration surfaces, leading to enhanced performance levels. Reasons identified for a lack of maintenance include insufficient communication, unclear responsibilities (partly as a function of the use of decentralised measures), lack of knowledge and financial barriers. A key recommendation of the study was that future designs should specifically identify the need for and facilitate system access to undertake required maintenance.

For example, permeable paving requires regular maintenance to maintain the pavement surface infiltration rate (IR). Whilst IR testing is commonly used to determine maintenance needs/frequencies, conventional tests require specialist equipment and can be time consuming. To address this need, Winston et al., (2016a) tested the use of a simplified infiltration test (SIT) and the conventional test at several sites in Sweden and the USA (total of 873 test). Results showed that both tests predicted approximately the same IR up to 250 mm/min, with the SIT taking one-quarter the time to run, offering potential savings in costs and personnel time. In an aligned study, Winston et al., (2016b) evaluated the use of eight different small-scale and full-scale maintenance techniques used to recover pavement permeability at ten different permeable pavement sites in Sweden and the USA. Al-Rubaei et al (2012) investigated methods for recovery of the permeability of porous asphalt pavements in northern Sweden. The methods used by these two studies included manual removal of the upper 2 cm of fill material, mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high pressure washing, and milling of porous asphalt on three different paving materials. Results indicated that the efficacy of the various techniques varied in relation to paving material type with for example, industrial hand-held vacuum cleaning, pressure washing, and milling identified increasingly successful at recovering the IR of porous asphalt.

With regard to identifying the management needs for stormwater treatment facility sediments, Karlsson et al., (2016) evaluated the mobility of metals in sediments accumulated in sedimentation tanks, gully pots and stormwater ponds. Employing the use of sequential extraction, the study reported that the majority of metals were weakly associated with sediments and may therefore be released if physico-chemical conditions change (e.g. during maintenance processes such as sediment removal).

4.9 Planning, implementation and practice

Taking a reflective approach to understanding how changes occur in Swedish stormwater management, Cettner et al., (2012) reviewed the drivers and processes associated with the establishment of the Swedish urban water system over the nineteenth and twentieth centuries. Their analysis identifies that current approaches are a combined function of human desires and the expansive growth of system-supporting public initiatives, and that – as a socially constructed system – can be transformed. However, a key finding of their study is that such transforming efforts require a determined break away, both physically and mentally, from the traditional pipe-bound system and systems culture. Moving forward, several studies have conceptually explored current and possible future stormwater management approaches. For example, in recognising that traditional engineering approaches increase the long-term flood risk and harm the riverine ecosystems, Sörensen et al. (2016) propose an alternative concept which emphasizes resiliency and achieved synergy between an increased capacity to handle stormwater runoff and improved experiential and functional quality of the urban environments, identifying a series of areas where contemporary challenges call for improved collaborative urban flood management. These include flexibility of stormwater systems, energy use reduction, priority of transport and socioeconomic nexus and resolving questions regarding responsibilities. Cettner et al., (2014) proposed a framework to support the systematic assessment of the role and impact of context on individual and organisational receptivity to change. The validity of the framework was evaluated using the findings of discussions (questionnaires and interviews) with Swedish stormwater professionals. Results indicated that whilst respondents were professionally prepared for change (action) they were not practically prepared due to inadequate supportive contexts. Use of the developed framework was found to provide new insights on the influence of receptive contexts for a change in water management, which can be used by policy makers to the translation of sustainable stormwater research into practice. In contrast, Ward et al., (2020) argues that – as two extremes of the same cycle – analysis of hydrological risks should focus on assessments of both flood and drought risks as these phenomena are closely linked. Drawing on a series of examples of where flood or drought (or their mitigation measures) have impacted on the risk of the opposite hazard, they identify key challenges for moving towards a more holistic risk management approach.

Recognising the need for change in stormwater management (many piped systems flood during storms with expected future increases in short-term rainfall intensities as a result of climate change), Olsson et al., (2013) modelled the flows associated with current and projected storm events using the town of Arvika, Sweden, as a case study site. Using MOUSE and a detailed coupled surface-sewer model setup (TSR), the study predicts an increase by 10-30 % of today's short-term rainfall extremes by the end of the century, and that upgrading systems to achieve a satisfactory performance for the future design storm would cost approximately twice as much as an upgrade based on today's design storm. As limitations to the current piped approaches to managing stormwater runoff both now (no treatment) and in the future (need for greater storage capacity) are recognised, interest in alternative approaches such is blue-green infrastructure (BGI) is increasing. With a view to exploring the use of BGI approaches in practice, Zischg et al., (2017) developed a methodology compare the use of different planning alternatives for stormwater handling. Using the Info-Gap robustness pathway method, three planning alternatives involving defined combinations of blue-green and grey infrastructure were evaluated to identify critical performance levels at different stages over time. Applied in Kiruna (Sweden), results indicate that including green infrastructures Pbs to more robust solutions with respect to future uncertainties, compared to traditional network design alone. Exploring the use of a broader, system thinking approach, Pan et al., (2018) coupled regional land use, economy, and water system interactions to identify the drivers and system feedbacks with implications for urban water systems. Results indicate that physical availability of land for economic activities (forecasted via a bottom-up land use change model) and their locations differ sharply from top-down sectoral-based economic forecasts. Indicating that both human systems (economic and land use planning) and natural systems (land use limitations and associated water implications) need to be considered, the paper argues that modelling social and natural processes using a systems approach provides a more comprehensive understanding of coupled causal mechanisms, impacts, and feedbacks in applications of integrated water resource management.

Urban planning processes are widely advocated as a key way to encourage the uptake of BGI in practice. In this context, Cettner et al (2013) explored opportunities Swedish water professionals have to influence urban stormwater planning processes, and barriers that limit their participation in the planning processes. Involving completion of in-depth semi-structured interviews with urban water professionals from nine Swedish municipalities, the research identified there is a perception of legal requirements related to the provision of drainage services and that this inhibits the utilisation of non-piped solutions. Further, a lack of clarity over 'ownership' was also apparent i.e. is stormwater an issue for the planning department or for the water department? A key conclusion was that water professionals have unique opportunities to integrate stormwater management approaches within wider urban planning practice and should be supported to do so. In an aligned study, Cettner et al., (2014) evaluated awareness and use of sustainability indicators (SI) in decision-making by Swedish water professionals. Finding current interest in SI is low, they describe how reframing the current stormwater management discourse in in terms of possible future sustainable stormwater systems which embrace green infrastructure opportunities and benefits may facilitate change. With a specific focus on better understanding the slow rate of implementation of sustainable stormwater managment, Qiao et al., (2018) undertook a systematic review of stormwater studies to identify limiting factors from a governance perspective as well as suggested solutions. Challenges identified included unclear leadership and responsibilities and a lack of funding, cost data, uniform guidelines and stakeholder participation. Potential solutions include researchers acting as knowledge brokers, the involvement of social capital among local stakeholders and increasing market incentives to engage stakeholders. While an open co-governance arrangement (in contrast to closed or hierarchical approaches) was suggested as a useful governance structure, further research on social-economical aspects was recommended to better characterise processes. In a follow-on study, Qiao et al., (2019) examined how specific governance factors influenced local stormwater management decisions implementation in four case cities in Sweden and China. Through undertaking a series of semi-structured interviews, researchers were able to identify frequently mentioned governance factors and cross-compare between cities and countries. Results indicate that the role of national policy in setting local leaders' priorities, the strong organizational set-up, and planning instruments are significant factors in the Chinese cities. In the two Swedish case cities, public awareness, local government politicians' priorities, and trust in sustainable stormwater systems performance key for their implementation. A common challenge identified was acquiring funding for long-term maintenance of systems.

In a further study of barriers and drivers, Wihlborg et al., (2019) applied a transition theory approach to understanding factors influencing successful BGI implementation in a Swedish context. Through undertaking semi-structured interviews of municipal stormwater practitioners, the increased need for recreation, protection of biodiversity and climate change were identified as factors driving the use of BGI. Internal (i.e. within the municipal stormwater management structure itself) and external (e.g. lack of knowledge among politicians, officials, exploiters and civilians) barriers to implementation were also identified. A key finding of the study was that transition to a new approach cannot be induced by pilot projects alone. Changes in legal structures and altered financing models for blue-green solutions are required, with the ongoing, but slow, change to more sustainable stormwater management approaches evidence of an evolutionary transition (where new approaches are combined with traditional, pipe-bound solutions). Bohman et al., (2020) also identify that the shift towards inclusive forms of planning required to implement sustainable stormwater management approaches is slow, and look to evaluate how formal and informal institutional change could contribute to enhancing sustainability in the sector. Drawing on the findings form workshops, interviews and surveys, a series of recommendations for integrating stormwater concerns into planning processes are proposed including stormwater risk assessment at a catchment level to be mandatory and centralised leadership to facilitate progress towards common goals.

4.10 Ecosystem services and benefits

With the need to fulfil an ever-growing range of national and international commitments to support delivery of sustainable cities (e.g. UN SDG 11, Swedish Environmental objectives related to the built and water environments), interest in the use of multiple benefit systems is growing in many sectors including stormwater management. Increasingly seen as best practice, the use of BGI are an alternative (or complimentary approach) to piped drainage systems which can offer a range of benefits (referred to as ecosystem services; ES) from water quality enhancement to mitigation of heat, air and noise pollution. For example, in a systematic review of the provision of ES by BGI in a range of Nordic countries, Amorim et al., (2021) concluded that BGI can deliver a wide range of ES which make crucial contributions to the quality of life in cities. However, they also note the potential for BGI to generate a range of disservices (e.g. pollen emission and property damage) and that these should also be considered in planning and design. In relation to a specific Nordic context, the authors identify the need for climate sensitive planning practices to ensure that seasonal climate variability is accounted for, together with better engagement and communication with stakeholders.

Several studies have looked to quantify the benefits offered by BGI, using alternative methodologies such as life cycle assessment (Byrne et al., 2017) and ecosystem services assessment (Goldenberg et al., 2017). In terms of LCA, Byrne et al., (2017) undertook a systematic review of LCA studies related to a range of urban water infrastructure components including stormwater systems (both conventional and NBS). Their review identified a range of preferences in how LCA was undertaken as well the opportunities the approach offers with regard to integrating a wider range of objectives e.g. public health, economic and social assessments into decision-making. Using the language of ecosystem services, Goldenberg et al (2017) explored the dependence of ecosystem service delivery on air and/or water flow processes which can carry services from supply to demand areas. Distinguishing between potential and realised services, flow dependencies are quantified for a specific landscape (the Stockholm region, Sweden). The flow processes linking the provision of local climate regulation and storm water regulation to locations where these services are in demand are mapped with key conclusions referring to the need to better understand the flow process linking service providers to service users.

Whilst the benefits derived from BGI can be quantified in a number of ways, the development and implementation of methodologies to derive economic valuations (as the unit of measure most widely understood) have been the focus of considerable attention in Sweden and internationally. For example, Zalejska-Jonsson et al., (2020) explored the theory and practice of the use of ”willingness to pay” (WTP) for BGI and its consequences for residential development. Again identifying a wide range of benefits generated by BGI in urban areas, the authors look to identify if, when and to what extent residents are willing to pay for BGI as a mechanism to enable sellers or policy makers to influence the amounts of BGI in developments. Results suggest that while there is evidence that purchasers pay more for residential property with high levels of BGI, but they do so without any understanding of the possible decision processes leading to those premiums concluding there is a need for a more comprehensive understanding of drivers for BGI in residential developments. In a separate study, Hamann et al., (2020) compared the use of two ES costing tools (B£ST and TEEB) which were applied to site located in Luleå, Sweden, under both current (baseline) conditions and to alternative proposals for its development (future scenarios). Whilst direct comparisons of each category used in each tool was not possible (categories and the way in which the monetized values were determined differ), both tools identified economic benefits related to amenities, home values, health, and social cohesion under the baseline and future development scenarios. However, comparison between baseline and future scenarios also identified negative economic benefits (i.e. costs) due land use changes reducing the levels of carbon sequestration and biodiversity. Whilst B£ST generated higher negative impacts than TEEB, a key conclusion was the need for calculations and data to be adapted to local Swedish circumstances.

With a focus on quantifying the delivery of the ES carbon sequestration, Merriman et al., (2017) investigated carbon (C) accumulation in four different climate zones (including two in Sweden) representing a range of annual mean temperatures, growing season lengths and rainfall depths. Results show that stormwater wet retention ponds can sequester C across different climate zones with annual rainfall and lengths of growing season being important general factors for C accumulation. In a broader study focussed on the use of ecological restoration to mitigate inland floods, Nilsson et al., (2018) evaluated a range of restoration measures aimed at facilitating communities to 'live with floods', identifying the need for researchers to better understand the relative importance of alternative approaches in managing floods, as well as their indirect effects on the flood cycle. With a focus on enhancing sustainability of landscapes at a catchment scale, Keesstra et al., (2018) reviewed the role of BGI to enhance soil and landscape functions. Drawing on a range of international examples (including wetland construction in Sweden), their results support the use of BGI are cost-effective long-term solution for hydrological risks and land degradation and contribute to the achievement of the UN Sustainable Development Goals.

5. Sources of research funding

Table 4 provides an overview of funding sponsors as identified in the acknowledgment section of the longlist of Swedish research papers (370 articles).

Table 4. *List of funding sponsors of five or more papers (as identified in article acknowledgements) over the identified time period*

Funder	Number of Swedish research papers (370)
Svenska Forskningsrådet Formas	72
Europeiska kommissionen	36
VINNOVA	33
Vetenskapsrådet	16
UK Research and Innovation	17
Svenskt Vatten	12
National Natural Science Foundation of China	11
Natural Environment Research Council	11
China Scholarship Council	9
Seventh Framework Programme	9
Fundação para a Ciência e a Tecnologia	8
Ministario da Educaao e Ciancia	8
Engineering and Physical Sciences Research Council	7
Australian Research Council	6
Department of Education and Training	6
Government of Canada	6
Horizon 2020 Framework Programme	6
Ministry of Science and Technology of the People's Republic of China	6
Natural Sciences and Engineering Research Council of Canada	6
Styrelsen för Internationellt Utvecklingssamarbete	6
European Regional Development Fund	5
European Research Council	5
Naturvårdsverket	5
Norges Forskningsråd	5

The Swedish Research Council Formas and VINNOVA dominate the list of Swedish research funding sponsors, between them funding almost 30% of Swedish stormwater research papers. In total, 24 organisations have contributed to funding five or more articles. Of note is that this list includes 19 non-Swedish funders demonstrating that Swedish stormwater research is recognised and valued not only nationally but also internationally. For example, under the five differing EU streams identified, EU funding contributed to the publication of 61 articles (16% of papers) with national funding sponsors located in six countries outside of Sweden (representing four continents) contributing to publications involving Swedish researchers. This is a clear and strong endorsement that Swedish stormwater research is valued, Swedish research skills are in demand and that Swedish researchers make a strong contribution to the discipline at an international level.

6. Conclusions and recommendations for further research

6.1 Conclusions and knowledge gaps

Sweden has a long history of stormwater research. The first stormwater runoff paper identified by Scopus was published in 1982, with Swedish research contributing to the international shift in understanding that managing stormwater runoff was a quality as well as quantity issue (e.g. Morrison et al., 1984; Malmqvist, 1986). The number of Swedish stormwater research articles published per year continued to increase over the next two decades, but it was not until the early 2000s that the number of papers published per year regularly exceeded ten. Over the last decade, and in tandem with increased awareness of the need to mitigate diffuse urban pollution numbers to meet regulatory requirements and sustainability objectives, the number of articles published have continued to increase with almost 60 Swedish stormwater papers published in 2020.

In terms of stormwater sources, there is a strong Swedish evidence base that many – if not all – materials and activities in the urban environment may release substances which can be mobilised under wet weather and hence discharge to receiving waters. It is therefore essential that more attention is given to the materials used within our urban environments and how they perform / degrade over time. With global chemicals production anticipated to double by 2030 (EU Chemicals Policy, 2019), the number of substances and combinations of substances that may occur within urban environments is likely to increase exponentially. Further research on processes associated with substances release e.g. relative importance of leaching vs ageing vs weather-driven erosion/corrosion processes (and how these change over time) is urgently required to inform pollution mitigation strategies for both current and emerging materials. Likewise, whilst the pathways by which pollutants mobilised by stormwater reach receiving waters are characterised at a 'gross' level (i.e. direct discharge of treated or untreated stormwater and indirect discharge within combined sewer overflows), a key area requiring further research is the subject of pollutant 'in pipe transformations' and the implications of this for stormwater quality and its treatment. Once within a piped system and depending on piped system dynamics, pollutants associated with particulate matter may repeatedly be deposited and resuspended as storm events 'pulse' through the system. In addition, dissolved pollutants may repeatedly sorb and desorb to particulate matter and biofilms as in pipe conditions change, organic materials degrade etc. As a result, the stormwater discharging from piped system can be of a very different physico-chemical and biological composition from that which entered the system, making identification of sources a significant undertaking.

The influence of catchment activities and rainfall events on stormwater runoff is well evidenced within the Swedish literature. While the most is known about the classical urban diffuse pollutant (suspended solids, metals and polyaromatic hydrocarbons), relatively few studies have focussed on the wider range of contaminants of emerging concern (a generic term referring to pollutants which are not regulated but for which concern exists e.g. microplastics and perfluoroalkyl chemicals; PFAS). Further, in terms of achieving 'good ecological status' (as identified under the EU Water Framework Directive 2000), chemical water quality is only one aspect to be considered. Whilst still the primary means of demonstrating regulatory compliance, the limitations of water quality standards applied on a pollutant-by-pollutant basis are increasingly apparent. The need to address mixture effects is recognised at a policy level (see Section 1) with recommendations made on the need to develop a mixture effects factor for use within risk assessment with the EU CSS (2020). An alternative - though complimentary - approach to generating mixture effect data is the use of ecotoxicity testing where by a battery of species from differing trophic levels are challenged with stormwater samples. To date little research has been undertaken on this topic within a Swedish context. While field data on environmental concentrations remains 'gold standard' in terms of understanding occurrence and effect of urban diffuse pollutants, the need to make decisions now in the absence of complete data sets has driven interest in stormwater quality models. Several predictive models have been used within Swedish case studies (typically extensions of stormwater quantity models). However, their calibration and subsequent application often requires site-specific data that is not always readily available.

In contrast, the knowledge base and associated application of stormwater quantity models is much better understood. Several models are routinely used with Swedish research and practice, with current studies focused on reducing levels of identified uncertainties to optimise their use further and at increasingly localised scales. The current major challenge with regard to stormwater quantity modelling is their use in urban water management planning in the face of a rapidly changing climate. Key climate change predictions for Sweden are increased intensity, frequency and duration of winter rainfall, and events used in current design (e.g. provide sufficient capacity for the 1 in 30 year storm) may now only provide capacity for the 1 in 10 year event, with implications for current system performance as well as future systems and management measures.

In terms of stormwater mitigation approaches, Swedish stormwater research has made a strong contribution to the international evidence base that stormwater requires treatment and that municipal wastewater treatment plants are not optimal for this purpose. The use of blue green infrastructure (BGI; also referred to as nature based solutions, sustainable drainage systems and stormwater best management practices) is a promising approach that can address both water quantity and quality objectives as well as offering a range of additional benefits. However, whilst many studies have focussed on evaluating single BGI systems, the evaluation of the contribution of multiple BGI to achieving stormwater management objectives at a catchment scale has yet to be fully evaluated.

Also referred to as ecosystem services, differing types of BGI can deliver valuable services (which generate ecosystem benefits) in an urban environment such as thermal cooling, air quality enhancement, noise mitigation and habitat provision. Identifying these benefits as arising from 'services' opens the concept of ecosystem assessment to the use of economic costing tools, enabling an economic value to be place on services provided by nature within cost benefit analysis. As multi-benefit systems, their inclusion within urban planning can be of interest to a wider range of stakeholders than are typically involved in urban water management, and further efforts are required to engage with this wider audience. Hence, the delivery of ecosystem services by BGI is a 'hot topic' both nationally and internationally. Current key areas of research in the field include:

- Developing a better understanding of BGI processes (often involves laboratory based studies) and using this knowledge in full-scale field trials
- Developing decision support tools to enable practitioners to select the most appropriate system in a specific location
- Assessing the short- and long-term operation and assessment management requirements of alternative BGI systems
- Identifying opportunities for the integration of multi-benefit urban water management systems into institutional structures that typical operate with sectoral or departmental 'siloes'.

6.2 Recommendations for further research

Based on the findings of this systematic review of Swedish stormwater research over the last decade, this section identifies a series of topics for further research with the twin aims of reducing the impact of urban diffuse pollution on receiving waters and enhancing the sustainability of stormwater management in Sweden.

Stormwater pollution: sources, occurrence and transport

- Improved and mass flow analyses to facilitate the identification and prioritisation of diffuse pollution sources. Output: improved understanding of pollutant sources and their prioritisation for substance release dynamics studies (e.g. better understanding of the factors governing emission and their interactions)
- Investigation of in pipe pollutant interactions and transformations. Output: support in pollutant source tracking

- Evaluate the relative contributions and significance of dry vs wet aerial deposition processes to overall runoff pollutant concentrations. Output: new knowledge to inform predictive water quality models
- Development of standard methods for reliably determining contaminants of emerging concern (e.g. microplastics) concentrations in stormwater runoff and the relative contributions of various urban sources. Output: development of a predicted environmental concentrations (PEC) database
- Systematic assessment of stormwater runoff from differing catchment types in using a battery of ecotoxicity tests. Output: development of a predicted no-effects concentrations (PNEC) database

Stormwater quantity: retention, infiltration and transport

- Investigate the impact of the widespread use of localised infiltration BGI systems on groundwater levels. Output: new knowledge on interactions between stormwater surface flows and groundwater bodies
- Investigate the impact of the widespread use of BGI systems on flood risks. Output: new knowledge on climate change adaptation of cities

Receiving water impact

- Environmental risk assessment (PEC:PNEC). Output: new understanding of the receiving water risks posed by stormwater runoff

Stormwater control measures/Blue Green Infrastructure

- Systematic performance monitoring of BGI systems based on their unit operating processes and inherent pollutant characteristics. Output: evidence base to select / design BGI based on their potential to remove pollutants with identified physico-chemical behaviour
- Investigating the performance of stormwater treatment facilities for pollutants of emerging concern. Output: evidence base for the election of BGI for a wider range of parameters.
- Performance monitoring of compact treatment systems (including commercial solutions). Output: evidence base for implementation of such devices.
- Evaluate how local communities and stakeholders involved in the delivery of BGI perceive their role in an urban environment, including the benefits/dis-benefits they provide. Output: new data on public and municipal understandings of BGI to support the development of decision-support tools
- Identify and explore ways in which local communities can support decentralised stormwater management approaches e.g. as citizen scientists Output: understanding of the activities and types of data collection that local communities can undertake and its role in supporting BGI operation and maintenance
- Recognising that BGI are essentially white for a large part of the year in Northern climates, systematically explore the concept of blue-green-white infrastructure (BGWI), and its role in ecosystem service delivery. Output: the development a more nuanced understanding of the role of BGI in cold climates and their contributions to wider sustainability objectives
- Systematic assessment of current approaches to operating and maintaining stormwater systems including BGI systems to identify blockers and enablers in undertaking routine activities. Output: new knowledge to inform development and implementation of BGI operation and maintenance regimes

Storage and access to stormwater data

- Development of a harmonised approach to facilitate collection and open-access storage of compatible and comparable stormwater data sets. Output: comparable data sets and support for modelling approaches

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