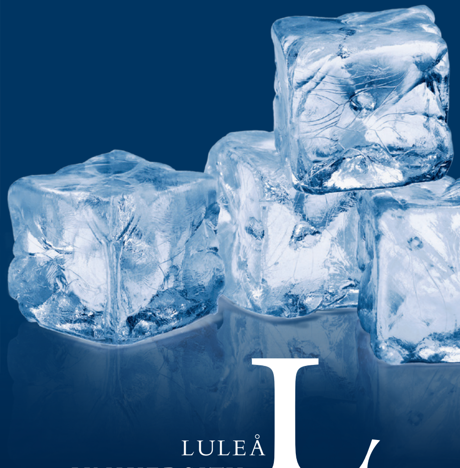
DRIZZLE
Centre for Stormwater Management

Synthesis of DRIZZLE research findings (2017-2022)



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Executive summary

Launched in late 2017, the DRIZZLE Centre of Excellence for Stormwater Management has worked closely with international researchers and practitioners to co-develop and implement a range of interlinked research programmes, developing new knowledge on the generation, behaviour and fate of stormwater from both water quality and quantity perspectives. The breadth and depth of its activities are evidenced through the 65 research articles reviewed in this report. DRIZZLE research has involved fieldwork, laboratory studies and desk based studies, with its competence in undertaking extensive fieldwork programmes (a particularly challenging endeavour given the unpredictable and dynamic nature of rainfall and snowmelt behaviours), a key strength.

To facilitate this review, DRIZZLE research articles are grouped into ten broad themes which between them encompass all stages of stormwater runoff management chain; from pollutant release, mobilisation and conveyance, to the mitigation of runoff quality and quantity, as well as contributing to policy development. In terms of pollutant sources, there is a strong DRIZZLE evidence base that many – if not all – urban materials and activities release substances which can be mobilised by rainfall and/or snowmelt runoff. Several studies have focussed on the occurrence and behaviour of pollutants in the sub-dissolved fractions i.e. colloidal and truly dissolved concentrations as well as the factors that influence their behaviour e.g. temperature, presence of salt. In terms of pollutant sources, the contribution from traffic-related activities, highway infrastructure and winter maintenance practices were identified as key sources. New data on the release of organic and inorganic substances from building materials has been generated, and the potential contribution of these results to enabling practitioners to select building materials in relation to reducing urban pollution footprints commenced. Novel work on the occurrence and behaviour of microplastics (MPs) in runoff has been undertaken, and new knowledge on the environmental behaviour of MP generated. In terms of the current urban pollutant evidence base, advances in clean manufacturing and pollution control technologies raise key questions on the relevance of historic stormwater pollution data to current stormwater management strategies. Further, whilst several international and European policies are pushing towards achieving a zero pollution environment, the number of substances and materials on the market continues to expand. Together, these changes in practice - and the implications of this in terms of substance use - highlights the need for the ongoing monitoring of stormwater sources, their pathways to receiving waters and fate as single substances and as components of the urban pollution cocktail.

In terms of stormwater quantity, DRIZZLE research has addressed key research questions in relation to evaluating factors underpinning model uncertainties together with the development of approaches for their reduction. Further studies have focussed on the use of established models to address new surface typologies (e.g. green areas, rain on snow events), at various scales and under differing climates. Stormwater quantity research has also involved field studies at system- and catchment-scales. Of particular note was the opportunity to develop extensive datasets associated with two adjacent commercial areas; one equipped with a blue green infrastructure (BGI) drainage strategy and the other a conventional piped system. A comparison of catchment performance indicated that the use of a BGI strategy reduced runoff volumes by 96%, peak flows by 99% and extended peak flow lags by 60%. A further entirely novel area of DRIZZLE research is the theoretical exploration of the use of sponge-like porous bodies (SPBs) to provide flood mitigation as a localised response to runoff events where permanent solutions are not an option. Initial modelling studies demonstrated that the use of porous media can be optimized in relation to storm event conditions associated with 60-min duration, 10 year return period events, confirming the potential of dynamic SPBs to provide a new approach to managing stormwater.

In relation to stormwater mitigation, DRIZZLE research has made a strong contribution to the international evidence base that promotes the use of BGI as a best management practice. Involving a combination of full-scale field systems and laboratory-based column experimental research, DRIZZLE has generated new knowledge on the treatment of conventional chemical pollutants (e.g. nitrates and phosphates), microbiological contaminants (*e.g. E. coli*) and contaminants of emerging concern (e.g. microplastics and polyfluoroalkyl substances) and the influence of e.g. plant species and variations in rainfall regimes on treatment performance. A further novel research concept is an extension of BGI into a multi-coloured concept in recognition of the fact that under non-temperate climates blue-green spaces may be white (i.e. covered by snow) or yellow/brown (i.e. exposed soil, dormant or dry vegetation). As an initial study, the implications of this in terms of ecosystem service delivery are mapped out using the application of BGI in a sub-arctic climate. The term blue-green-white infrastructure (BGWI) is introduced and the challenges and opportunities offered by the presence of snow as an abiotic ecosystem service provider are considered.

As with all drainage infrastructure systems, BGI systems require maintenance and DRIZZLE research has considered this from general operational and specific sediment management perspectives. For example, in a study of 26 biofiltration units, results indicated that sediment accumulation in BGI pre-treatment stages were a primary cause of the low hydraulic conductivity rates determined. Almost half of the studied facilities were identified to no longer provide sufficient capacity to retain design rainfalls, a finding of significant concern in terms of the efficacy of current operational and management practices. In terms of evaluating sediment management implications, a major DRIZZLE study involved the screening of sediments from 17 pond systems for 259 organic substances. Results indicated that 92 substances were detected in at least one sample, with a maximum of 52 substances detected in a single sample. Of particular note was the finding that, whilst pollutant concentrations varied greatly between ponds, 22 of the 32 samples exceeded threshold values derived from toxicity data. However, as well as BGI performance, DRIZZLE research has evaluated a range of approaches / technologies that may be adopted / retrofitted to current systems to enhance treatment performance. Innovative concepts include the evaluation of a bottom grid structure designed to be installed at the inlet to e.g. a detention pond to enhance sediment trapping and reduce resuspension. Laboratory-based experiments have also evaluated the use of a range of coagulants to reduce stormwater pollutant concentrations, with data indicating that the use of coagulants led to a > 90% removal efficiency for all pollutants investigated.

In terms of the wider dissemination of research findings and informing policy development at national, regional and international level, DRIZZLE researchers are active in several international networks (e.g. the International Water Association and Water Europe). Opportunities to share findings and support policy development provided by engagement with these networks have been seized with, for example, DRIZZLE researchers taking lead roles in the development of two white papers under the Water Europe umbrella on achieving zero pollution in the urban water cycle and opportunities associated with the use of green and grey stormwater infrastructure.

In conclusion, this synthesis report describes how the DRIZZLE Centre of Excellence for Stormwater Management has grasped the opportunity to implement a large number of novel research projects in the dynamic field of stormwater management. As a standalone body of work, DRIZZLE is an impressive data set underpinning development of a range of new insights and understandings of the sources and behaviour of stormwater runoff from quality and quantity perspectives, as well as options and opportunities for its mitigation. However, a real strength of DRIZZLE is that it is not a standalone body of work. DRIZZLE findings have been co-developed with practitioners and international researchers, and widely disseminated in research, practitioner and policy development arenas. As such, it not only provides a solid basis for future DRIZZLE studies but represents a major contribution to the stormwater research arena at an international level.

Acknowledgements We gratefully acknowledge the financial support provided by VINNOVA (Grant no. 2016–05176) and also recognise all DRIZZLE partners: Aarsleff Rörteknik AB, Stormwater&Sewers, Järven Ecotech AB, Luleå Municipality, Luleå University of Technology, NCC Infrastructure, Rent Dagvatten AB, City of Stockholm, The Environmental and Health Department, Stockholm Vatten & Avfall, StormTac AB and Tyréns for their financial support, scientific contributions and technical expertise.

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1. Introduction

A major effect of global warming is its impact on how water behaves within the hydrological cycle, increasing the risks of extreme weather events; from floods and droughts to heatwaves and fires (IPCC, 2022). For example, increases in the frequency and intensity of extreme rainfall events are predicted in many regions of the world, with major implications for urban areas due to a combination of their largely impermeable nature (generates stormwater runoff), limited green spaces (reduced opportunities for infiltration and evapotranspiration) and ageing drainage infrastructure (piped systems are expensive and disruptive to excavate). A further challenge is that rapid urbanisation over the course of the last 150 years means that many piped systems are already beyond their design capacity, further exacerbating the frequency of urban flooding events with associated (and increasing) social, environmental and economic damages. Within a national context, temperatures are predicted to increase in Sweden by 3-5oC by 2080 (SMHI, 2021), with more rainfall occurring in autumn, winter and spring. Likewise, warmer summers will increase rates of evaporation contributing to an increasing number of low flow days in rivers and drought events. Hence, globally, the same urban areas could face an annual increase in both flooding and drought events, raising a challenging but potential paradigm-shifting question: can the stormwater generated in wetter months provide an alternative water resource to mitigate summer droughts? Evaluating this hypothesis raises many questions, amongst which the potential to locally store and manage stormwater pollution are key.

In terms of managing stormwater (and its potential for reuse), particular attention needs to focus on stormwater quality. Stormwater runoff (whether derived from rainfall or snowmelt) can mobilise and transfer a wide range of organic and inorganic substances from a diversity of site-specific sources to receiving waters. Whilst the need to reduce the discharge of chemicals to the environment from point (e.g. industrial) sources has long been the focus of legislation, the need to also address diffuse sources of pollution (e.g. stormwater runoff) is gaining increasing policy attention. For example, UN Sustainable Development Goal (SDG) 3 (Good health and well-being), SDG 6 (Clean water and sanitation) and SDG 12 (Responsible consumption and production) refer to minimising the release of chemicals to the environment to protect human and environmental health (UN SDGs, 2015). At a European level, reducing human and environmental exposure to hazardous substances is a key component 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. 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 UWWTD, 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.

The traditional approach of managing stormwater runoff by directing it into piped systems is no longer considered best practice as its core function is to move – rather than manage - stormwater flows as well as offering little in the way of pollution treatment. Further (and as noted above), the combination of increasing numbers of extreme rainfall events in expanding urban areas means that many urban piped systems no longer offer the same level of protection, and are running at – or exceeding - system capacity on an increasingly frequent basis. This has increased interest in the use of blue green infrastructure (BGI) as alternative or complimentary approaches to the use of piped drainage systems. The term BGI refers to a range of systems types and sizes, from building- and street-scale biofiltration units to larger storage systems such as retention ponds and constructed wetlands. In contrast to pipe systems - which involve moving stormwater from one location to another as quickly as possible - BGI aim to infiltrate (or where not possible detain) stormwater runoff at source, offering the opportunity to manage stormwater from both water quantity and water quality perspectives. However, as well as contributing to stormwater management objectives, BGI can 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 promotion of BGI 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.

Established in 2017, the DRIZZLE Centre of Excellence for Stormwater Management is actively collaborating with international researchers and practitioners to respond to the urgent challenges identified above. This includes the co-development and implementation of a series of interlinked field, laboratory and modelling research studies and disseminating new knowledge on the management of stormwater quantity and quality from standalone and integrated perspectives. The aim of this report is to provide a concise overview of DRIZZLE research to-date, highlighting key findings and recommendations.

2. Methodology

All scientific articles which DRIZZLE researchers have led or contributed to were collated and allocated to one of four publishing categories:

- Publically available as a peer-review article on the journal database (e.g. Scopus)
- Articles under revision (i.e. accepted for publication in a peer-review journal subject to major or minor revisions)
- Articles under review
- Articles close to submission (i.e. draft manuscript sufficiently advanced that it can be shared for inclusion within this report)

Table 1 provides a summary of the number of papers in each category.

Table 1. *Overview of DRIZZLE research articles reviewed by publishing category*

Article categories	Number of papers
Peer-review article	52
Articles under revision	3
Articles under review	9
Articles close to submission	1
Total number of articles reviewed	**65**

In terms of numbers of articles published, there has been a clear increase over time as DRIZZLE has become established, attracted new research staff and research experiments commenced in 2017/18 have been completed and published (see Figure 1).

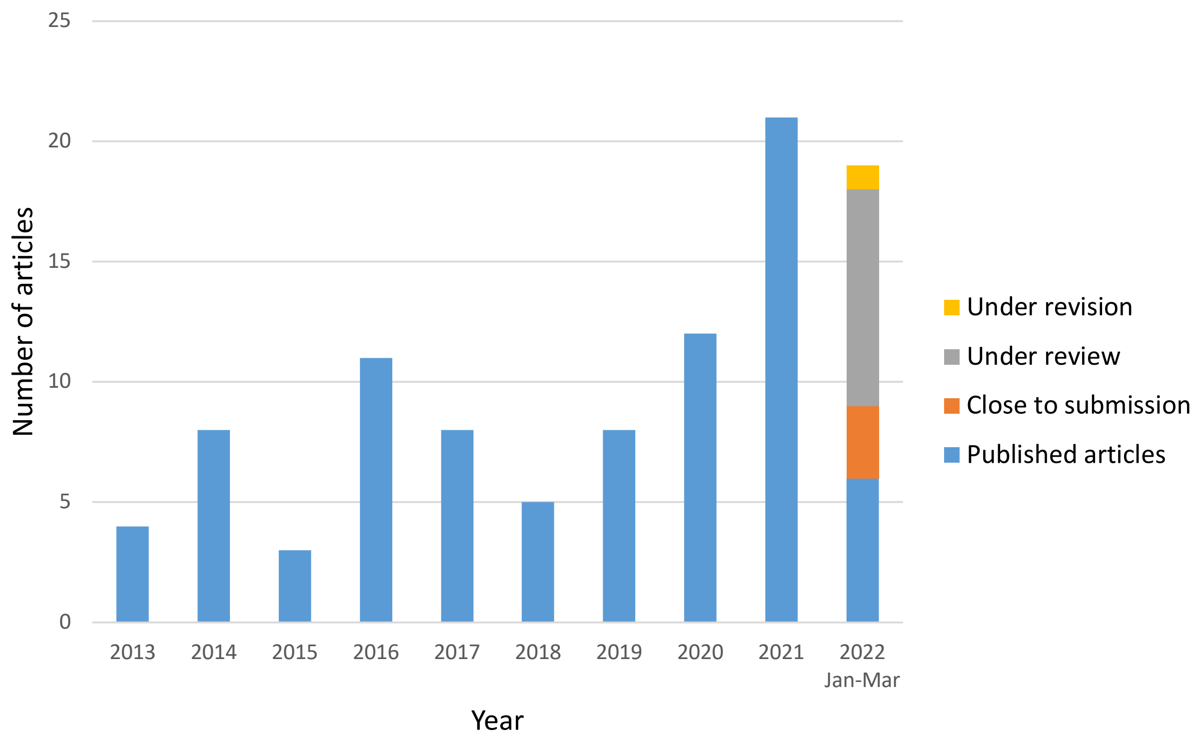

Figure 1. *Number of research articles per year by publication category (2013 - March 2022; DRIZZLE funding awarded 2017)*

The 65 articles were then grouped into nine broad topics (see Figure 2) to facilitate discussion and support 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 DRIZZLE research undertaken to-date.

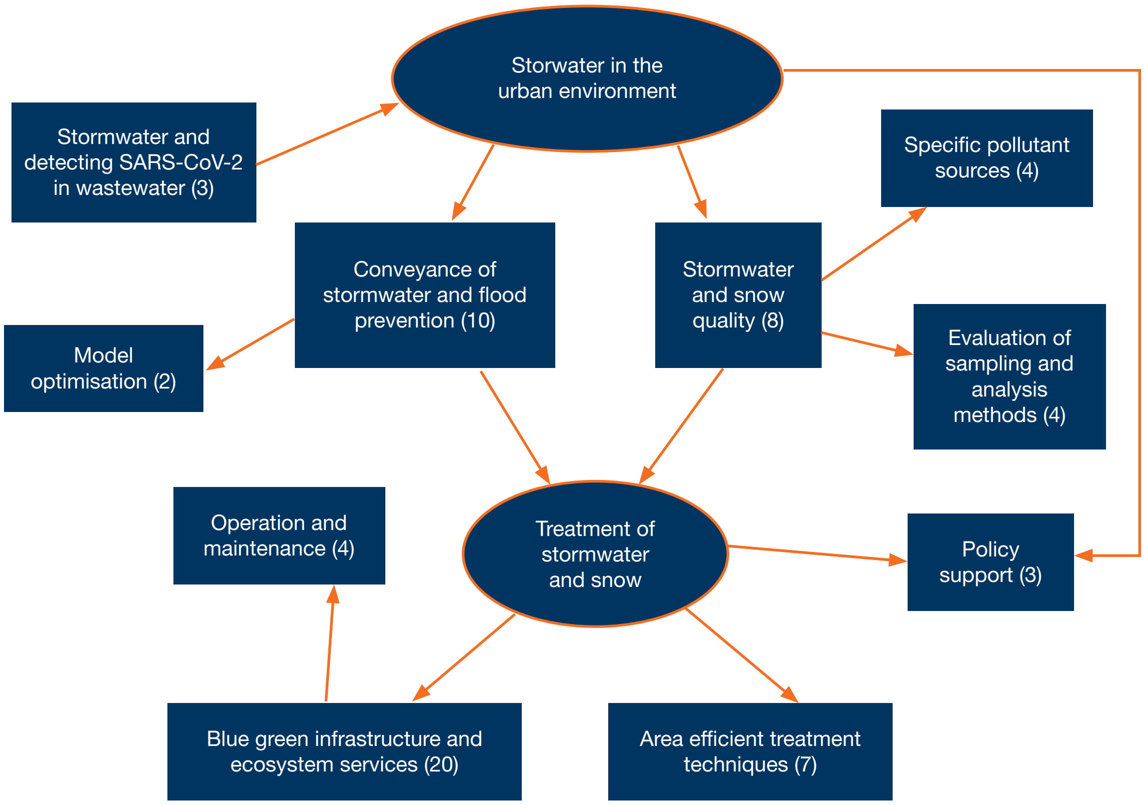

Figure 2. *Overview of DRIZZLE research articles grouped by research topic (boxed text) used to structure discussion (numbers in brackets refer to the number of articles per topic)*

3. Synthesis of DRIZZLE research findings

Since 1960, the urban population has increased four-fold to 4.3 billion (55% of the global population), a trend that is predicted to continue with over two-thirds of the population estimated to be living in urban areas by 2050 (Ritchie and Roser, 2018). Whilst the definition of an urban area remains contested (e.g. in Sweden urban areas are defined as localities with >2000 inhabitants, in Japan >50,000 inhabitants are required), the transition of humanity from predominantly rural living to urbanites has been rapid. By definition, urbanisation involves the construction of roads, pavements and building, effectively converting permeable to impermeable surfaces with associated impacts on the natural functioning of the water cycle. Under rainfall and snowmelt conditions, surface water runoff which would have largely infiltrated into the ground pre-urbanisation, recharging groundwaters and/or surface waters, accumulates on impermeable surfaces and are directed towards piped infrastructure to prevent localised flooding. However, this traditional approach has several limitations; rapid growth of urban areas have resulted in many piped systems being at - or over – capacity, leading to increased numbers of urban flood events. As runoff passes over impermeable surfaces - or 'less permeable' in the case of compacted soil/gravel roads, pathways and urban green spaces - it can mobilise pollutants deposited from multiple sources, including traffic, industrial land use and aerial deposition. Referred to as diffuse or non-point pollution, such sources can be a major source of pollutants entering receiving waters, either as direct discharges or components of combined sewer overflows. Large volumes of flow or melt water discharging from a single point can also cause erosion in receiving waters, of both native soils/substrates and the re-suspension of previously settled sediments. Urban stormwater runoff is often directly discharged to the closest receiving waters without treatment. 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 the multiple benefits provided BGI) objectives.

3.1 Stormwater and snow quality

A diversity of sources contribute a range of pollutants to urban stormwater runoff (Müller et al., 2020), urban snow and urban snowmelt (Vijayan et al., *under review*). The occurrence and relative contribution of sources vary on a catchment-by-catchment basis, and hence the types and magnitude of pollutants released also vary between catchments (see Figures 3 and 4 for an overview of sources and pathways for urban stormwater and snowmelt, respectively). Both systematic reviews identified the contribution from traffic-related activities as being a dominant source of diffuse pollution, with exhaust and non-exhaust vehicular activities, highway infrastructure and winter maintenance practices being key sources. The role of atmospheric deposition was also highlighted, in terms of both wet (transference from the atmosphere to the ground by raindrops and snowflakes) and dry (gravitational settling) deposition processes. The relative importance of each mechanism and the contribution of local vs long distance air pollution sources to pollutant loads mobilised by runoff at a catchment scale is highlighted as an area for further research. Of particular note was the observation by Müller et al., (2020) that the combination of advances in clean manufacturing and pollution control technologies together with the use of increasing numbers of new materials and chemicals draws into question the relevance of historic stormwater pollution data and underlines the need for ongoing monitoring of stormwater sources. The implications of the extended exposure times of urban snow, the opportunities this provides for pollution accumulation and how this snow is subsequently handled (i.e. melt *in situ* or hauled away for disposal outside of urban areas) was discussed by Vijayan et al., (*under review*) from the perspective of receiving water protection.

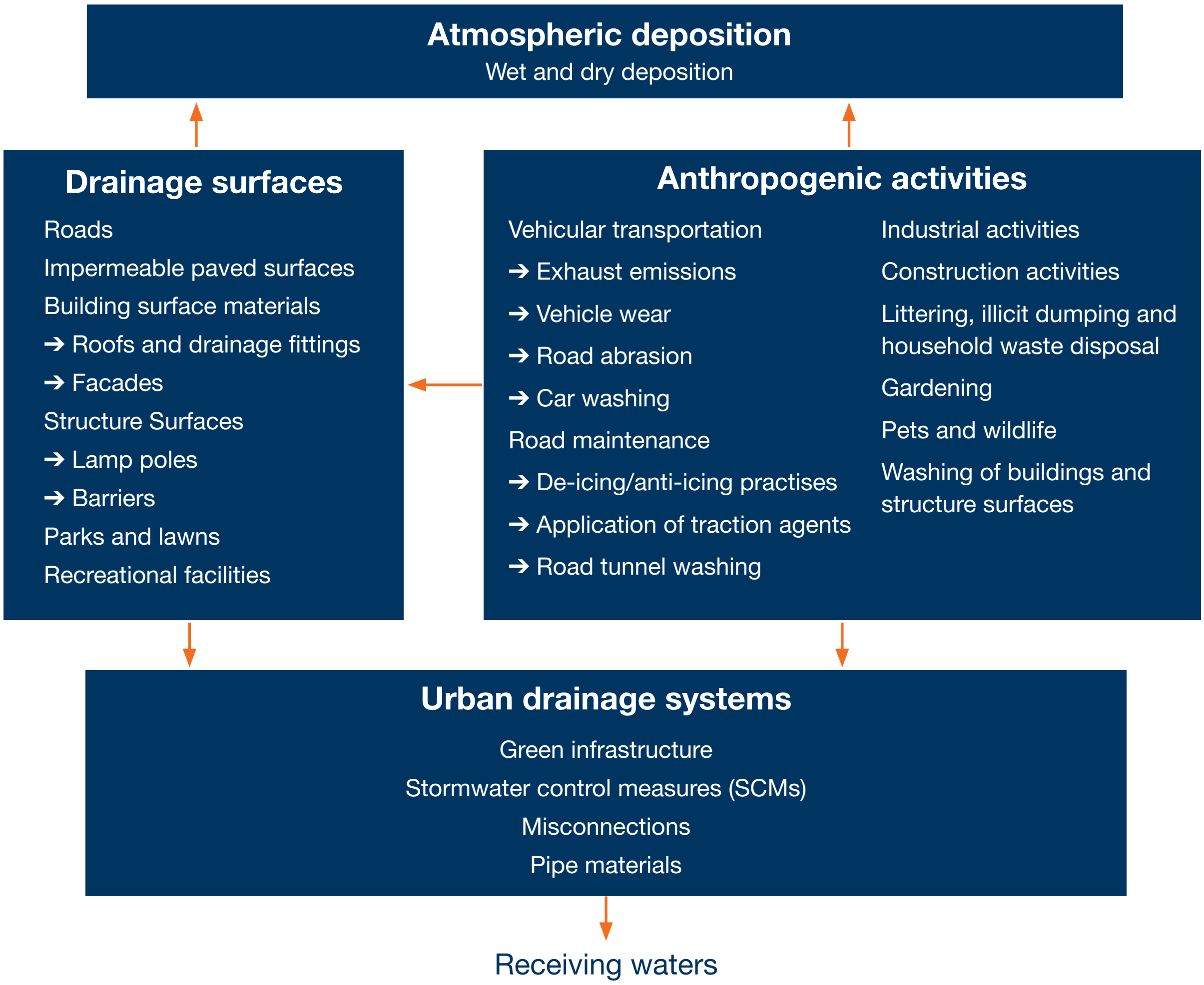

Figure 3. *Grouping of urban stormwater pollution sources and pollution transport pathways (modified from Müller at al., 2020)*

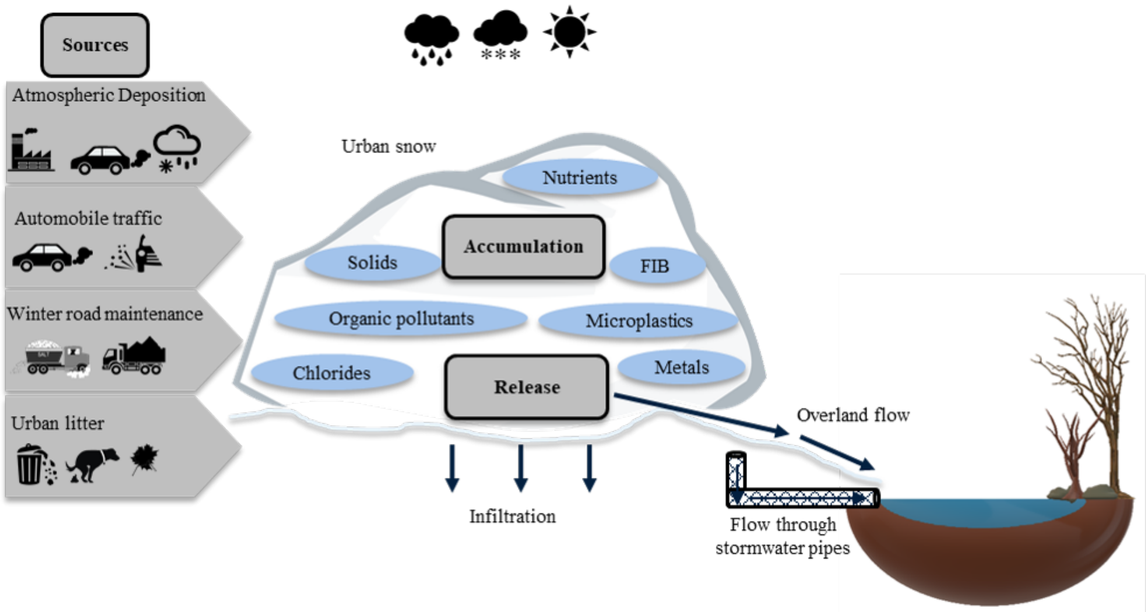

Figure 4. *Overview of urban snow pollution sources and pathways to receiving waters (Vijayan et al., under review)*

With increasing policy and practitioner attention on the behaviour and mitigation of the sub-dissolved metal fractions (e.g. development of environmental quality standards which target the bioavailable fraction), Lindfors et al., (2020) evaluated the size distribution of metals transported by runoff during 18 rainfall and snowmelt events derived from three trafficked areas using conventional and novel techniques. For all studied metals in all events and at all sites, the contribution of the truly dissolved fraction (defined using ultrafiltration) made a greater contribution to the total concentrations than the colloidal fraction. Truly dissolved Cd and Zn concentrations contributed (on average) 26% and 28% respectively, of the total event mean concentrations (EMCs) with truly dissolved Cu and Ni contributing (on average) 18%. In contrast, only 1% (V) and 3% (Cr) were identified in the truly dissolved fraction. Further analysis identified that truly dissolved and colloidal metal loads did not follow the patterns of particulate metal loads, indicating particulates are not the main source of sub-dissolved metals. A further study by Lindfors et al., (2021) compared measured dissolved and truly dissolved Cu, Ni, and Zn concentrations to the bioavailable metal fraction (as predicted using Bio-met, a simplified biotic ligand model) in runoff samples derived from the same three urban sub-catchments. Results showed that the Bio-met predicted bioavailable concentrations were significantly lower than truly dissolved concentrations for all metals indicating the terms cannot be used interchangeably and also that the bioavailable fractions originate from both colloidal and truly dissolved fractions. Similar results for metals were reported by Vijayan et al., (2019) in a laboratory-based evaluation of snowmelt quality derived from snow samples collected at two urban sites (see Figure 5).

Figure 5. *Image of a melting roadside snow sample in the laboratory showing presence of coarse sediments.*

Whilst metal concentrations were higher than those typically determined in runoff-derived samples from these sites (associated with a prolonged accumulation time period of five months) and the dissolved fraction contributed up to a maximum of 7% of dissolved concentrations, the truly dissolved concentrations again dominated the dissolved fraction in samples from both sites. This study also determined concentrations of the 16 US EPA polyaromatic hydrocarbons (PAHs) reporting that most occurred in the particulate-bound phase, with dissolved concentrations typically below reporting limits. In terms of developing a wider understanding of the occurrence of both established pollutants and contaminants of emerging concern, a study by Gasperi et al., (2022) involved the analysis of runoff from four urban sites for 128 pollutants using a combination of targeted and non-targeted analytical approaches. Whilst results indicated commonalities between sites with differing levels of traffic in terms of contamination profiles, concentrations increased with increasing traffic density confirming the role of traffic and traffic-related activities as a key source of urban diffuse pollution.

Research undertaken on modelling stormwater quality has focussed on the use of StormTac Web, a low-complexity conceptual model which combines annual precipitation data with land-use specific volumetric runoff coefficients and mean stormwater quality concentration data to predict stormwater quantity and quality (as concentrations and /or loads) discharging from a defined site (Wu et al., 2021; Larm et al., 2022). Initial research involved the application of StormTac Web to a small urban catchment in Stockholm (Sweden), using the Law of Propagation of Uncertainties and Morris screening methods to explore model uncertainties (Wu et al., 2021). Results indicate that levels of uncertainty associated with predicted annual runoff quality (~ 30%) were greater than that associated with annual runoff volumes (~24%), with the latter significantly contributing to runoff quality uncertainties. Further research explored the use of StormTac Web to predict stormwater loads of Cu, Zn, P and suspended solids entering and leaving stormwater control facilities located in two urban catchments (Larm et al., 2022). Comparison of model predictions with field data sets indicate that predicted concentrations were generally lower than field data for all parameters. Integration of an assessment of uncertainties associated with both flow and concentration data led to a reduction – but not elimination – of differences between field and predicted data sets, with variations discussed in terms of temporal changes, and trends in environmental practices and stormwater quality monitoring. In terms of mitigating the pollutant loads accumulated by snow and their subsequent release in melt water, research by Borris et al., (2021) supported development of a prototype snow management tool (PSMT). Available in MS Excel, the tool draws on catchment data to simulate the accumulation of snow and pollutants in an urban catchment, includes intermittent snowmelt episodes and a variety of snow management options including *in situ* melting, removal from the catchment, treatment of snowmelt by settling, and snow disposal in the receiving waters. The data is integrated to generate outputs in the form of a snow and selected pollutant mass balances and the prediction of the pollutant concentrations in snowmelt from individual snow deposits.

3.2 Specific pollutant sources

To inform the development of a more complete understanding of the emission of pollutants from specific sources and the factors which influence this, several studies have focused on the release and mobilisation of pollutants from specific sources including roofing and façade materials (Müller et al., 2019), gully pots (Wei et al., 2021; Wei et al. *under revision*) and litter (Öborn et al., *under revision*). Müller et al., (2019) investigated the release of metals, nonylphenols and phthalates from ten commonly used building surface materials and their mobilisation by rainfall runoff during six rain events. In terms of metals, the highest concentrations were derived from copper and zinc sheets (average concentrations of 3090 µg/L Cu and 7770 µg/L Zn respectively), while other metal materials e.g. weathering steel exhibited lower releases. Nonylphenols and phthalates were determined in runoff from PVC roofing (average concentrations of 26 µg/L and 455 µg/L for nonylphenols and diisononyl phthalate, respectively). Pollutant concentrations released varied between events, with variations in rainfall and antecedent dry conditions identified as contributing factors. The potential contribution of these results in supporting practitioners to identify and select building materials in relation to reducing urban pollution footprints is discussed.

With a focus on evaluating gully pots as both pollutant sources and sinks, research by Wei et al., (2021) identifies these systems as ubiquitous but poorly understood components of urban drainage infrastructure. Gully pots contribute to stormwater quantity (direct surface stormwater flows into underground piped systems) and quality (sediment trapping) objectives, and the ability of two basal sediment scour models (of differing levels of complexity) to predict scour behaviour under current and future rainfall conditions at sites for which they were not developed was systematically investigated (Wei et al., 2021). The output from Model One indicates that scour-induced total suspended solids in gully pot discharge can be kept well below a guideline value of 25 mg/l if the gully pot fullness level is maintained at < 60 %, with results from Model Two emphasising the relationship between gully pot design and particle characteristics. When applied to the same data set, effluent suspended solids concentrations predicted by the two models differed by up to two orders of magnitude, with further field studies required to identify which model has greater portability between sites. In terms of investigating the role of gully pots as pollutant sinks. Wei et al., (*under revision*) fully emptied eight gully pots in two catchment types (highway and housing) in Luleå, Sweden, and analysed their contents for total mass, particle size distribution and selected metal concentrations within six size fractions. The results of this sampling campaign were compared with the results of a 2005 study of the same gully pots to identify changes in the physiochemical properties of sediments over time and examine whether changes identified can be linked to changes in wider catchment management practices. Results highlight the potential impacts of winter road maintenance operations in terms of grit applications (increased solids loading rates) and the use of winter studded tyres (increased concentrations of Cu, Zn, Co, Cr and V in the < 63μm fraction). In contrast, concentrations of As and Pb in all size fractions decreased, with the adoption of unleaded fuels and strengthened industrial emission reduction measures identified as possible drivers.

Recently increasing attention has focused on identifying the sources of microplastics (MP) discharged into the sea, with several studies in the international literature focusing on tires and bitumen road materials as sources. However, less is known about the relative contribution of plastic litter to predicted / measured MP loads discharging to receiving waters. As a contribution to addressing this knowledge gap, Öborn et al., (*under revision*) established a laboratory-based system to simulate and evaluate the weathering of four polymers (low-density polyethylene (LD-PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET)) in a land-based environment using accelerated photodegradation with three exposure times. MPs were quantified with Fourier Transform Infrared Spectroscopy and identified using a spectra reference library. The results showed variations in both release patterns and numbers of particles generated. For example, whilst LD-PE did not show a clear pattern of UV-induced degradation, PS and PET showed similar UV-induced degradation behaviours over a 56 day exposure time period, whereby the number of particles released increased with exposure duration. In contrast, PP produced the largest number of particles after 28 days exposure with particle numbers decreasing by over 50% by day 56, potentially as particles continued to breakdown into pieces of an undetectable particle size (< 10 μm).

3.3 Evaluation of sampling and analysis methods

Both field and laboratory-based research is typically resource intensive in terms of direct costs (monitoring equipment, consumables and analytical techniques) and personnel hours. Further, whilst there is a considerable body of literature pertaining to stormwater and snow quality, standard protocols for sample collection, storage and analysis have yet to be developed. With a range of methodologies available, DRIZZLE research has included evaluations of sampling methodologies (McCarthy et al., 2018; Vijayan et al., 2021), comparison of approaches to screening building materials in relation to their contributions to stormwater quality (Müller et al., 2021) and an assessment of the impact of ageing on synthetic stormwater used to test the efficacy of filter materials (Milovanovic et al., 2022).

Research by McCarthy et al., (2018) involved intensive data collection programmes in seven catchments from which event mean and site mean concentrations were calculated for total suspend solids (TSS), total nitrogen (TN) and *Escherichia coli (E. coli*). The developed data sets were then interrogated using 17 different sampling strategies to estimate site mean concentrations (SMCs) and ratios of estimated/measured SMCs were further analysed to determine the most effective sampling strategies. Results indicated that optimal sampling strategies varied by pollutant type, from the use of random sampling strategies for estimation of SMCs for TSS and TN to a fixed sampling strategy for the estimation *E. coli.* Further analysis supported the development of recommendations on the number of events to be monitored to enable a catchment to be characterised which again varied on a per pollutant basis; from 27 events for TSS to 11 events for TN. Research by Vijayan et al., (2021) focused on identifying the most efficient way to estimate the pollutant loads in a snow pile. This involved the collection of 177 snow samples from nine snow piles during four sampling occasions with the analysis of samples for TSS, loss on ignition (LOI), pH, conductivity and a range of metals. Results indicated that pollutants are not uniformly distributed in the snow piles. A comparison between the load calculated using all samples collected for each pile (best estimate of mass load, BEML) and alternative sampling strategies (e.g. single snow column sample vs horizontal composite sampling etc.) indicated that the collection and volume-proportional mixing of subsamples from nine snow samples would enable pollutant loads to be estimated to within 50% of the calculated BEML (see Figure 6).

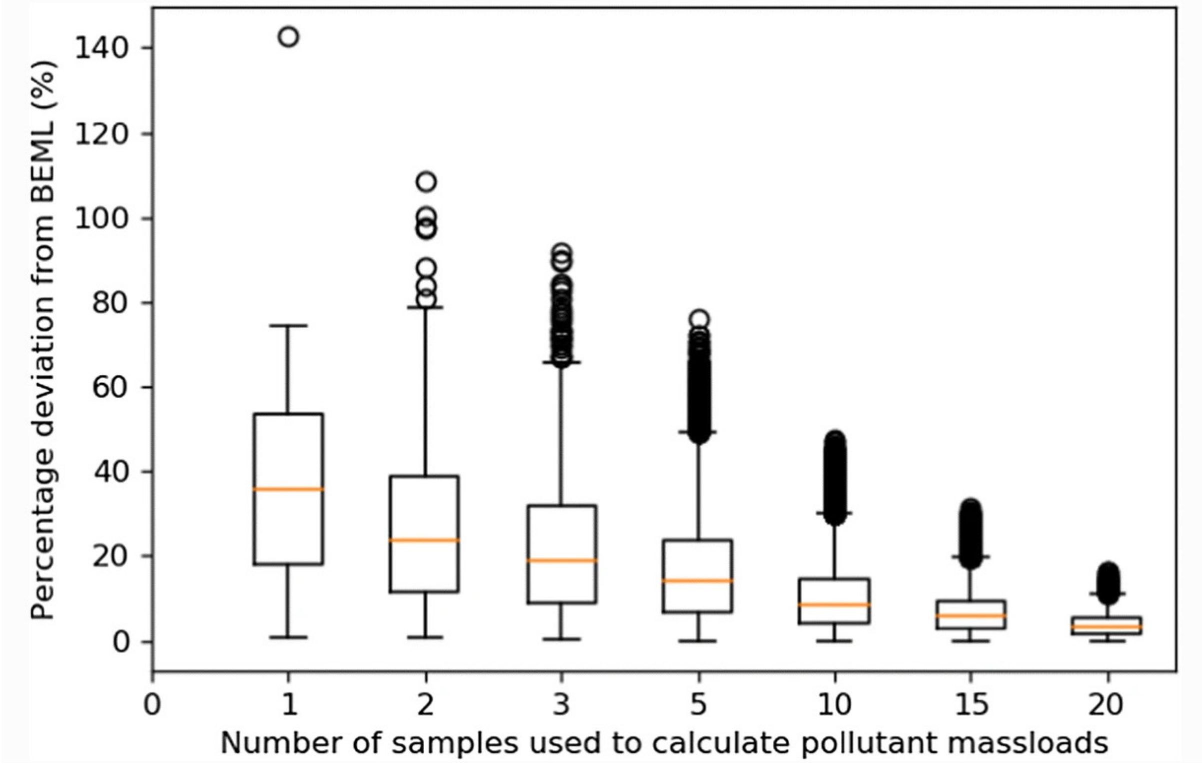

Figure 6. *Box and whisker plot of the percentage deviation of the calculated Zn mass loads in pile E from BEML, based on various numbers of point samples and all their combinations selected from the whole set of 20 samples.*

In terms of understanding the release of pollutants from building materials, Müller et al., 2021 evaluated the use of three alternative methods to identify and quantify the release of organic and inorganic pollutants from a range of building materials. Nine materials commonly used on building surfaces were tested using the following methods: direct analysis of material composition, laboratory leach tests using synthetic rainwater, and open-air pilot testing of material panels exposed to rainfall and runoff. Results showed that:

- direct screening of material composition was relatively quick and inexpensive, however, it may fail to identify minor sources of pollutants or - alternatively - could identify substances present in a material which would not be released in contact with water.
- laboratory leach tests can identify sources of substances present in surface runoff but were unsuitable for estimating the magnitude of actual concentrations in building runoff.
- open-air pilot studies of material samples (thought to provide ’real world data’) were resource intensive to establish and operate.

Thus, the choice of the method for pollutant identification should be based on study objectives, to enable the balance between resources and output to be optimised. A complimentary study by Milovanovic et al., (2022) included an evaluation of the impact of storage time on dissolved metal concentrations in synthetic stormwater. Experimental time periods ranged from 15 minutes post-preparation of synthetic stormwater to 11 days. Results indicated a rapid decrease in dissolved metal concentrations over of an initial time period of 240 minutes, whereby concentrations of Cu, Zn, and Cd decreased by 58%, 85% and 29%, respectively. A potential explanation for this decrease is the sorption of metal ions to the surface of the added sediments. After approximately three hours the dissolved metal concentrations stabilised with only minor further decreases reported. To address the impact of this on treatment performance data, correction coefficients for each metal were developed and applied, and their implications for future studies discussed.

Given the increasing awareness of microplastics (MP) pollution in the environment, the number of published studies on this topic have increased exponentially. As analytical methods for MP quantification are not standardised, the method used often varies between papers. Together with their study on MP occurrence in stormwater and its removal in treatment facilities (see Figure 7), Lange et al. (2021) provides a discussion on the suitability of different analytical technologies: visual analyses combined with tactile and melting tests, Fourier transform infrared (FTIR) spectroscopy, Raman and usage of markers. Compared to visual analyses with stereomicroscope, spectroscopic methods for particle analyses (FTIR and Raman) can provide additional information about the chemical composition of MP particles. However, also these methods have their limitations, e.g. when the objective is to analyze rubber and bitumen particles. Another important aspect is that the spectra of MP polymer structures isolated from field samples varies in relation to their level of degradation. Other methods for road related MP analysis such as the usage of markers (e.g., Zn signature) involve high levels of uncertainty due to multiple sources. Whilst uncertainties also apply to results based on visual analyses (e.g. as used by Lange et al., 2021) these are not necessarily higher than for the above-mentioned methods. Lange et al. (2021) argue that as long as the particles are in a size range allowing this method and the analyses are undertaken by experienced staff, combined visual and tactile identification is a reliable method, especially for rubber and bitumen particles present in road runoff.

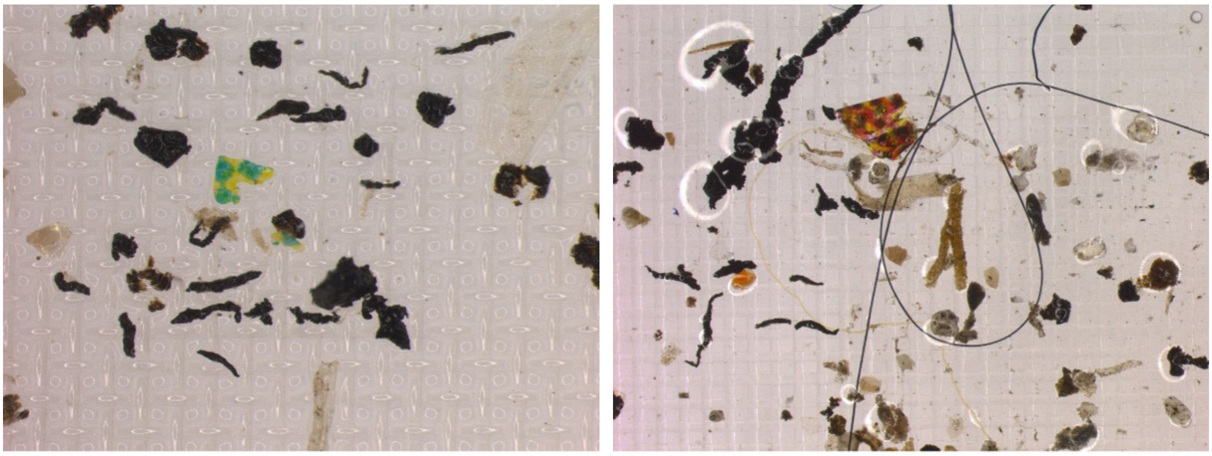

Figure 7. *Images of MP-particles from road runoff under a stereomicroscope*

3.4 Stormwater and detecting SARS-CoV-2 in wastewater

The presence of SARS-CoV-2 RNA in wastewater was first reported in the Netherlands in March 2020, with viral RNA material detected in wastewater treatment influent samples in seven Dutch cities (Medema et al., 2020). This landmark study included data on the detection of viral fragments in wastewater in one city prior to the detection of any clinical cases, raising the prospect that it may provide public health teams with an early warning of the presence of the virus within a community. Over the subsequent months, the potential for wastewater surveillance to contribute to COVID-19 mitigation programmes has been the focus of intense national and international research activities, gaining the attention of policy makers and the public. However, whilst wastewater surveillance has a history of use in polio eradication programmes in Israel, Egypt and India, its use to detect SARS-CoV-2 in wastewater is an emerging application and many open challenges exist within this research area and use of data by public health teams (Lundy et al., 2021). For example, there is limited understanding of the fate of viral particles within combined and separate piped systems which vary significantly in design and flow dynamics and – from a stormwater perspective – how to account for changes in flow associated with stormwater and snowmelt events.

To support development of a common understanding of how, when and where the outputs of this non-invasive community-level approach can deliver actionable outcomes for public health authorities, DRIZZLE researchers co-led development of the NORMAN SCORE SARS-CoV-2 in Wastewater initiative which included:

- sharing of a common sampling and analytical protocols
- buddy scheme to link wastewater researchers who wanted to participate but had not worked with viral detection (and vice-versa)
- establishment of a platform for the rapid, open access data sharing of data on sampling weather conditions, wastewater treatment plant characteristics, basic wastewater parameters, viral concentration data and clinical case numbers database (https://www.norman-network.com/nds/sars_cov_2/)

To-date, almost 1000 data sets from 10 countries have been uploaded. Through offering direct access to underpinning meta-data sets, the NORMAN SCORE database is a resource for researchers to explore the relationships between parameters and how this may vary spatially, temporally and in relation to catchment characteristics and rainfall conditions (Lundy et al., 2021).

As a contribution to understanding the relationship between wastewater data and clinical case numbers, Isaksson et al., (2022) collected samples at two wastewater treatment plants (WWTPs) in Luleå (Sweden) and explored the use of alternative normalization approaches in data interpretation. Normalisation factors explored include the use of WWTP flow (to account for episodic stormwater and snowmelt inputs), population size estimates (derived from nutrient data and census data) and the use of pepper mild mottle virus as a human-specific biomarker. Results indicated that the strength of correlation between normalization approaches and clinical cases differed between WWTPs (indicating that the use of wastewater as an epidemiological tool is context dependent), with time-shifted analysis suggesting that wastewater SARS-CoV-2 RNA predated a rise in clinical cases by 0-2 and 5-8 days, for the lager and smaller WWTP, respectively. As part of a wider study in Belgrade, Serbia, Kolarević et al., (2021) investigated if raw wastewater and stormwater discharges lead to the detection of SARS-CoV-2 RNA material in the Danube River. Grab and composite samples were collected at discharge point to the Danube, with grab samples collected upstream and downstream of a major entry point. SARS-CoV-2 RNA (5.97×10^3 to 1.32×10^4 copies/ L) was detected only in samples collected at the site strongly impacted by the wastewater. Determined concentrations correspond to those reported in wastewater influents sampled at treatment plants indicating an epidemiological indicator function of this approach in rivers with high pollution loads.

3.5 Conveyance of stormwater and flood prevention

Building on the long history of using stormwater quantity models in the planning of urban drainage systems, DRIZZLE research in this field has focussed on methodological issues; from evaluating model performance under various conditions/scenarios to extending the use of current models to address emerging needs. For example, Broeckhuizen et al., (2019) explored the impact of using models with differing underlying mathematical structures (SWMM, MOUSE and Mike SHE) on predicted runoff characteristics, including the generation of runoff from urban greens paces. Involving the analysis of eleven soil types and six soil depths over a study time period of 26 years, results varied between models, indicating that choice of model impacts study results and that the generation of runoff from green spaces should not be ignored in urban drainage modelling studies. Research 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 total of 177 simulations were run covering four scenario categories: eight rain events, three climates, three soil infiltration rates, and five snow water equivalent values. Results identified differences between runoff generated by rain-on-snow and summer rainfall events, with snow depth identified as playing a key role in influencing the volume of rainwater and/or snowmelt retained in or released from the snowpack.

With a focus on modelling the performance of green roofs, Broeckhuizen et al., (2021) evaluated the use of four models (Urbis, SWMM, Hydrus-1D and Mike SHE) to evaluate the performance of full-size green roof systems located under two climates (Lyon, France, and Umeå, Sweden) with two calibration periods per site. Results indicate that the uncertainty and accuracy of model predictions were dependent on the selected calibration site and period. The performance of each model is discussed, with each model offering strengths and weaknesses in relation to the parameter considered. For example, whilst predictions from SWMM and Mike SHE were jointly best in terms of raw percentage observations, levels of uncertainty SWMM predictions were lower, with a general conclusion being that calibration periods where rainfall retention was highly variable between events were more informative for parameter values in all models.

In a study on modelling the performance of swales, Rujner et al., (2018) explored the use of Mike SHE (typically utilised at a catchment scale) to simulate the hydrological response of a grass swale to artificially introduced runoff inflows. Data generated from 12 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 supports the use of Mike SHE for process-oriented small-scale modelling of grass swale flow hydrographs.

In an aligned field study, Rujner et al., (2018) evaluated the effect of soil water content (SWC) on the formation of run-off in two 30m long, trapezoidal grass swales. This study involved the irrigation of both swales with two flow rates reproducing run-off associated with two-month and three-year events with initial SWC (SWCini) ranging from 0.18 to 0.43m^3/m^3. Under low SWCini, run-off volumes were reduced by up to 82% falling to 15% as SWCini increased. Similar trends were reported for run-off flow peak reductions (4% to 55%) and outflow hydrograph lag times (from 5 to 15 minutes). The implications of results for swale planning and design are discussed. A further study investigated the added value of including soil water content (SWC) observations within Mike SHE through its inclusion within the likelihood function used to quantify model performance and – as an alternate approach - using SWC observations when setting initial model conditions (Broeckhuizen et al., *under revision*). Results show that using SWC observations to set initial model conditions improves model performance and affects the degree to which soil hydraulic parameters are identifiable and supports the use of SWC observations as a complement to outflow observations in the modelling of urban swales. In further work, Rujner et al., (*under revision*) undertook a paired-catchment study of the hydrological performance two adjacent commercial areas; one with a blue green infrastructure (BGI) drainage strategy and the other with a conventional storm sewer system approach. The main feature of the GI catchment was the avoidance of directly connected impervious areas achieved by diverting runoff from an asphalt parking lot to a cascade of three infiltration features, a gravel/fractured rock strip, draining onto a sloping infiltration area, which in turn was draining into a runoff collecting swale. Both catchments were monitored for rainfall, runoff, soil water content and groundwater level over a four year period, generating a set of 60 rainfall/runoff paired events. A comparison of catchment performance indicated that the median BGI effectiveness in reducing runoff volumes and peak flows and extending peak flow lags was 96, 99 and 60%, respectively. Further BGI benefits identified included avoiding the cost of installing a conventional storm sewer system in the BGI area, reducing/eliminating polluted discharges of stormwater to the receiving waters and avoiding the disturbance of the environment during drainage construction.

With a view to considering variations in climatic conditions on blue green infrastructure (BGI) design, Mantilla et al., (*close to submission*) used SWMM to predict and evaluate variabilities in the hydrological performance of two types of BGI (biofilter cells and green roofs) in relation to a 23 year meteorological time-series available for eleven sites located throughout Sweden. Results show that runoff volume reduction levels were lower in winter, suggesting the need to adapt BGI design in relation to regional climatic conditions, with the use of e.g. conservative estimates of infiltration rates and coarse engineered soils to facilitate low water content in facilities at the onset of freezing weather.

With regard to innovation in managing stormwater quantity, an entirely novel research concept is the theoretical exploration of use of sponge-like porous bodies (SPBs) to provide flood mitigation as a local response to relieving pressure on piped systems where permanent and / or space-demanding solutions are not an option (Larsson, et al., 2018; Lundström et al., 2020; Åkerstedt et al., 2021). Figure 8 gives an overview of the three SPB designs currently under assessment: a top down approach, a supported bottom-up approach and a freestanding bottom up approach.

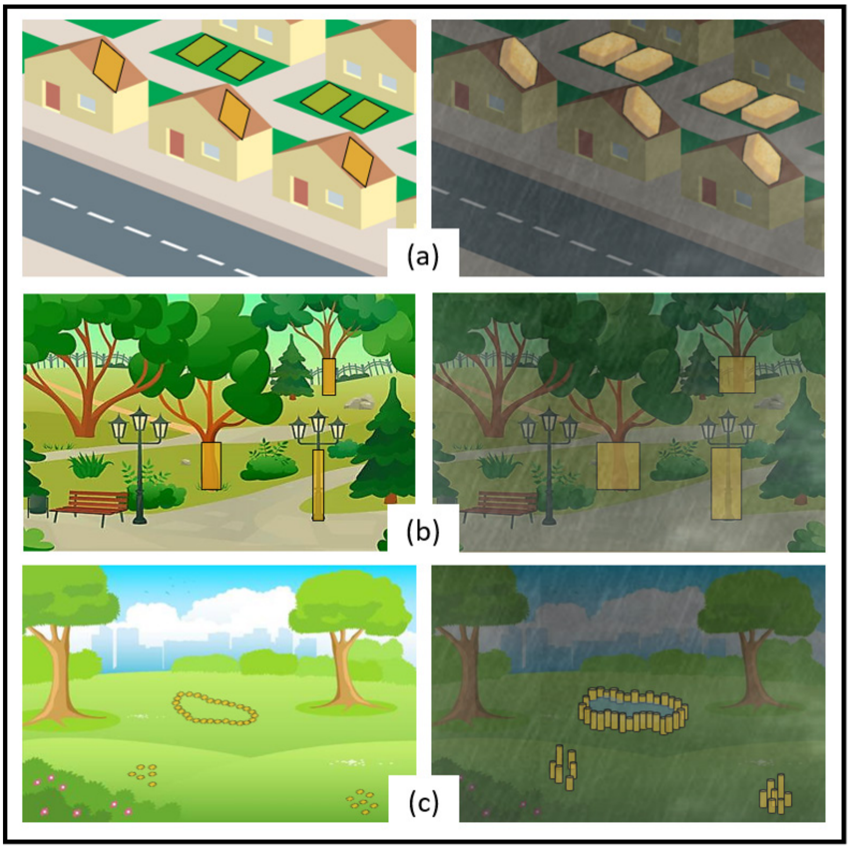

Figure 8. Schematics of three sponge approaches being evaluated under dry and wet weather conditions (a: rooftop system; b: wrap around structure; c: pop-up structure)

Initial modelling studies focused on exploring the potential of geometrically well-defined porous materials for stormwater management, demonstrating the use of tomographic three-dimensional, three-component particle image velocimetry (3D3C PIV) to provide a detailed description of the flow field within an ordered thin porous media (Larsson et al., 2018). Further modelling research demonstrated that the use of absorbing and/or porous media on several scales can be optimised in relation to storm event conditions, maximum storage capacities and inflow rates (Lundström et al., 2020). Analysis of data indicated that the rates of inflow and storage filling match - or exceed - the rates of rainwater inflow and volume accumulation associated with 60-min duration, 10 year return period events (see Figure 9), confirming the potential of dynamic SPBs to control stormwater runoff and serve as one of numerous elements contributing to restoration of pre-urban hydrology in urban catchments.

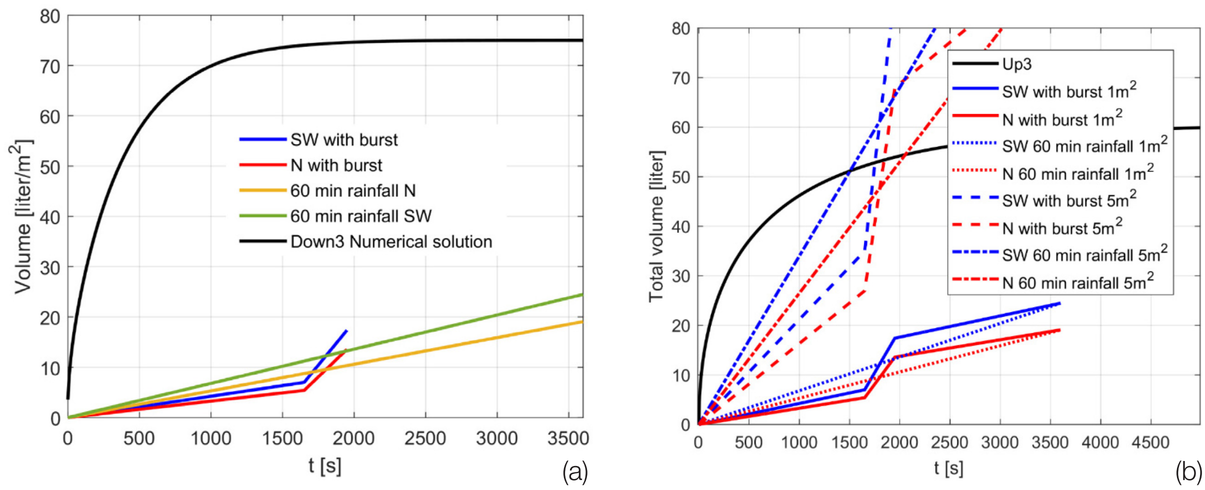

Figure 9. Comparison between the cumulative rainfall volume (blue, red, green and yellow lines) and the SPB storage filling (black solid lines) (a) down-flow approach and (b) up-flow approach.

Building on these initial studies, the impact of the swelling effect of SPB material on predicted volumes of stored water was evaluated through a comparison of the theoretically determined total amount of absorbed water (based on the effect of diffusion) with that determined when the effect of material swelling was also included (Åkerstedt et al., 2021). Results indicate that geometrical variables influence both the maximum possible absorbed volume and the time to reach that volume, and in all the cases considered, the swelling in general increases the maximum possible absorbed water volume by an amount of 14% (see Figure 10).

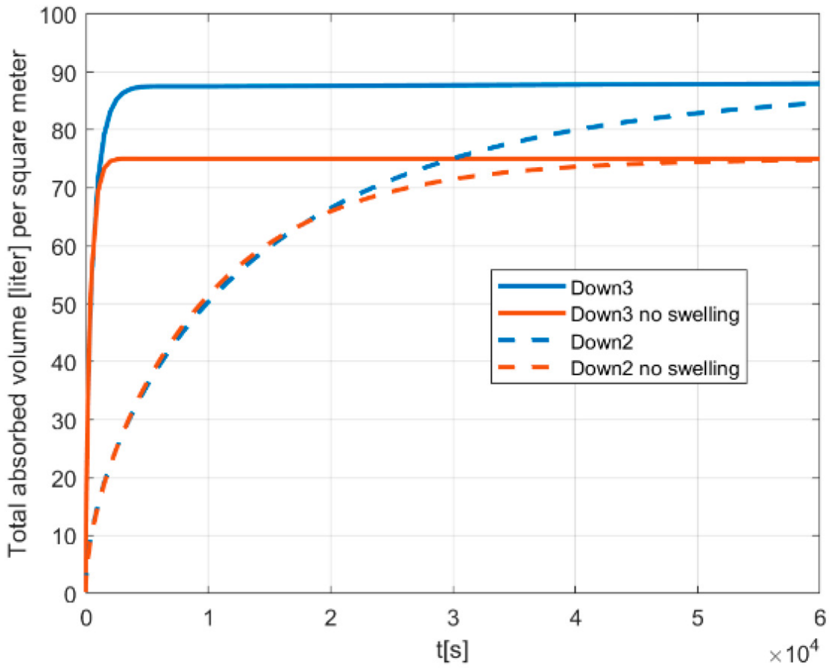

Figure 10. *Total volume in litres/m² absorbed in the Down-flow approach, comparison between cases with and without swelling. Down2 and Down3 have different geometrical variables.*

3.6 Model optimisation

The calibration of urban drainage models typically involves utilisation of a limited number of observed rainfall-runoff events selected from a larger dataset. With a view to optimising model performance, Broeckhuizen et al., (2020) explored the impact of using different approaches to selecting events through testing fourteen single- and two stage strategies for selecting calibration events. Focusing on the model SWMM, the study found that both single stage and two stage calibrations were successful, with the various calibration strategies satisfactorily predicting 7 to 13 out of 19 validation events. However, whilst the two-stage strategies reproduced more validation events poorly (Nash-Sutcliffe efficiency < 0) than the single-stage strategies, they also reproduced more events well (NSE> 0:5) and performed better than the single-stage strategies in terms of predicting total runoff volume and peak flow rates. Findings suggest that the strategies used for selecting calibration events may lead - in some cases - to different results in the validation phase and that calibrating impervious and green-area parameters in two separate steps in two-stage strategies may increase the effectiveness of model calibration and validation.

A further key aspect in calibrating rainfall runoff models is the timing of the simulated hydrograph in comparison to the observed event. The objective functions used in model calibration typically compare the simulated and observed values for the same point in time, and so, if a model reproduces the observations quite well, but with a shift in time, it will receive a poor score from such an objective function. However, recognising that the exact timing of a simulated hydrograph is not always the most important aspect to consider, research to evaluate the use of an alternative objective function that explicitly takes into account timing errors and allows the modeller to specify how severely timing errors should be penalised was undertaken (Broeckhuizen et al., 2021). Results show that this alternative approach was just as reliable as the use of traditional objective functions but with more precision (i.e. smaller estimated uncertainty of model predictions), with the study concluding that the use of objective functions based on the hydrograph matching algorithm can be useful to reduce uncertainties in urban drainage modelling.

3.7 Blue green infrastructure and ecosystem services

Whilst piped systems are efficient in moving surface runoff, they offer limited – if any – potential for either its local detention or opportunities for pollutant removal. An alternative approach to piped systems is the use of blue-green infrastructure (BGI; also referred to as nature-based solutions) 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. Such systems can be used as standalone devices, in combination (a treatment train) or in combination with conventional piped systems where their installation can effectively free up in pipe capacity by providing an alternative pathway and/or receptor for stormwater flows. Several DRIZZLE studies have focused on evaluating BGI treatment performance from a variety of perspectives, and are summarised below.

In terms of microplastics (MP) removal, Lange et al., (2021 and 2022) evaluated the performance of two treatment trains (a gross pollutant trap (GPT) followed by either a vegetated bioretention cell or non-vegetated sand filter) in terms of their potential to remove MPs. Lange et al., (2021) focussed on rubber, bitumen and other microplastics (including fibres, fragments, and paint particles) from highway runoff. Involving the monitoring of nine rainfall events, identified inlet MP particles were mainly represented by the 100–300 µm fraction and included high ratios of rubber (30%) and bitumen (60%). Whilst overall, both treatment trains efficiently removed MP particles, the filter cells accounted for the major share of this removal. GPT did not reduce MP particle concentrations, and this is associated with the fact that the MP particles have a density close to the density of water and thus their removal by sedimentation is limited (see Figure 11). The implications of this MP behaviour in the environment are discussed. An associated study at the same field site investigated the occurrence and composition of MP particles in the 20 - 100 µm) size range was evaluated, as well as their potential to be removed by the treatment trains monitored in Lange et al., (2022). MP analyses were carried out using µFTIR and FTIR-AT (enabling the detection particles containing carbon black). Results show that MP particles in the 20-100 µm size range are abundant in highway runoff, with a median of concentration of 230 particles/L (ranging from 42 - 8577 particles/L). The dominant polymer types identified were polypropylene, ethylene propylene diene, rubber and ethylene-vinyl acetate. In contrast to the similar level of removal of larger MP particles by vegetated and non-vegetated systems reported by Lange et al., 2021, the vegetated filter removed significantly more of the finer MP particles than the non-vegetated filter.

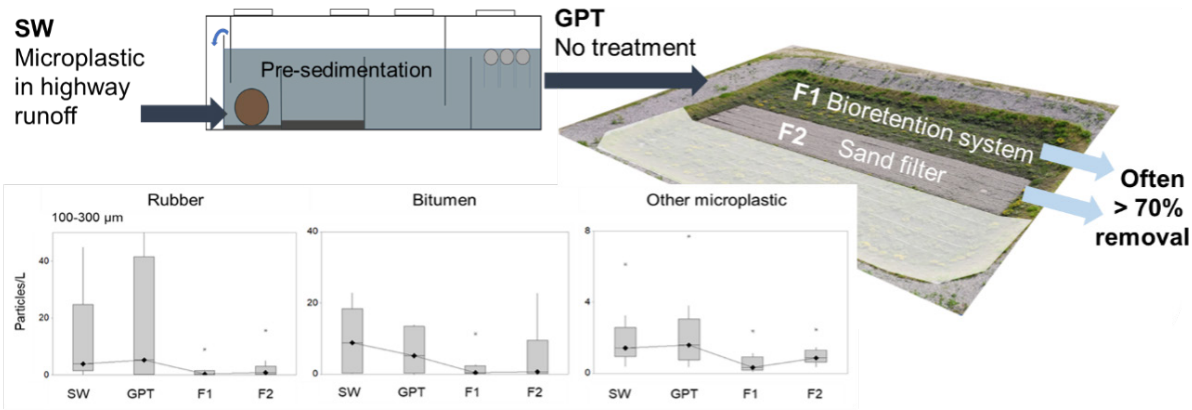

Figure 11. *Illustration of treatment train and MP removal (Lange et al, 2021)*

A further study at the same field site focused on evaluating intra-events variations of total, dissolved and truly dissolved concentrations of Zn, Cu, Cd and Pb in highway runoff, and how they were affected on movement through the same treatment trains described above (Lange et al., 2022). Whist results demonstrated the occurrence of intra-event variations in concentrations in highway runoff, neither the effluent from the GPT or the effluent from the bioretention system demonstrated a 'first flush' effect. Further, while total metal concentrations were on average, significantly reduced by the bioretention system (ranging from 76% -94%), the removal of dissolved metals was lower with only limited (if any) removal of truly dissolved metals reported (see Figure 12). An exception to this was for truly dissolved Zn, with a reported removal rate of 65%. The impact of this is that metal speciation in the bioretention effluent shifted towards greater a percentage of fractions in the colloidal and truly dissolved phases, and the implications of this are discussed in relation to environmental thresholds.

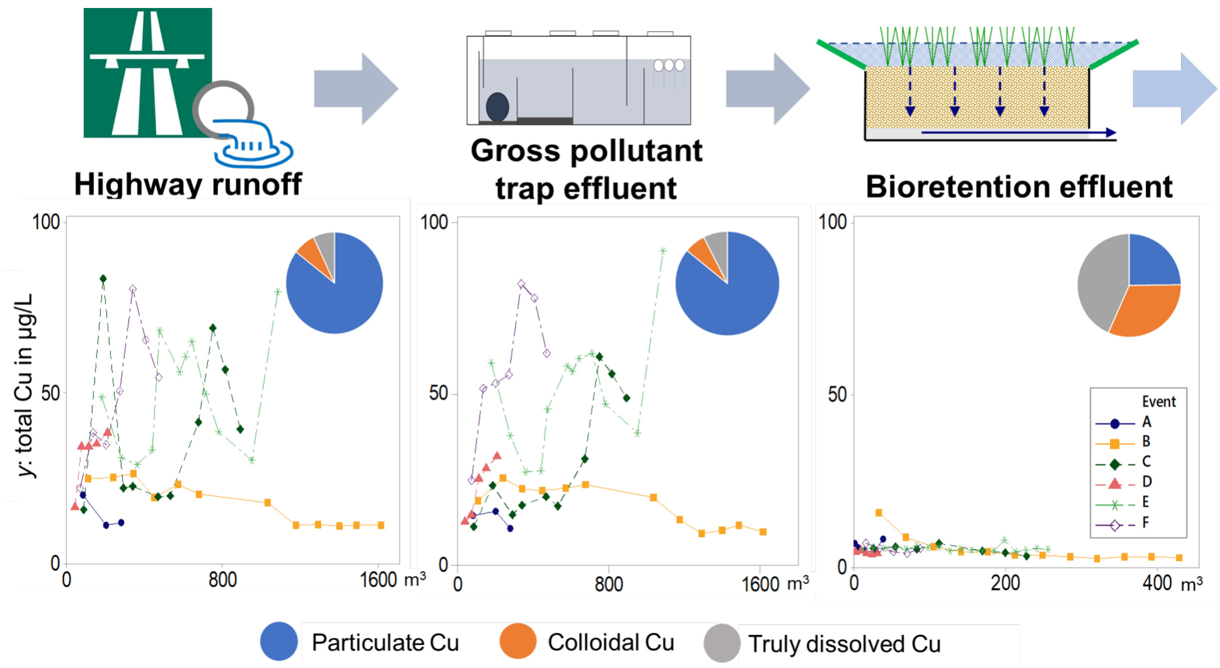

Figure 12. *Overview of treatment train, variations of metal concentrations during each rain and metal fractionation (Lange et al. 2022).*

In addition to full-scale stormwater treatment BGI field monitoring programmes, several studies have focused on the use of laboratory-based column experiments as an opportunity to develop new knowledge on pollutant removal processes and the factors which influence their occurrence. With a focus on metals, Søberg et al., (2019) explored the sorption of dissolved single and multi-metal solutions by ten different filter materials utilised in bioretention facilities using laboratory-scale batch tests (see Figure 13). Results demonstrated that all ten tested materials adsorbed metals, with 90% of adsorption occurring within a 1 hour time period. In general, results indicated that filter materials classified as sand (naturally high pH, relatively low organic matter (OM) content and large specific surface area) performed the best. The addition of biochar did not significantly improve metal retention and may therefore be unwanted as its degradation over time is likely to contribute an extra source of OM. Regardless of filter material type, metals primarily adsorbed in an exchangeable form indicating that metal adsorption from solution might not be permanent.

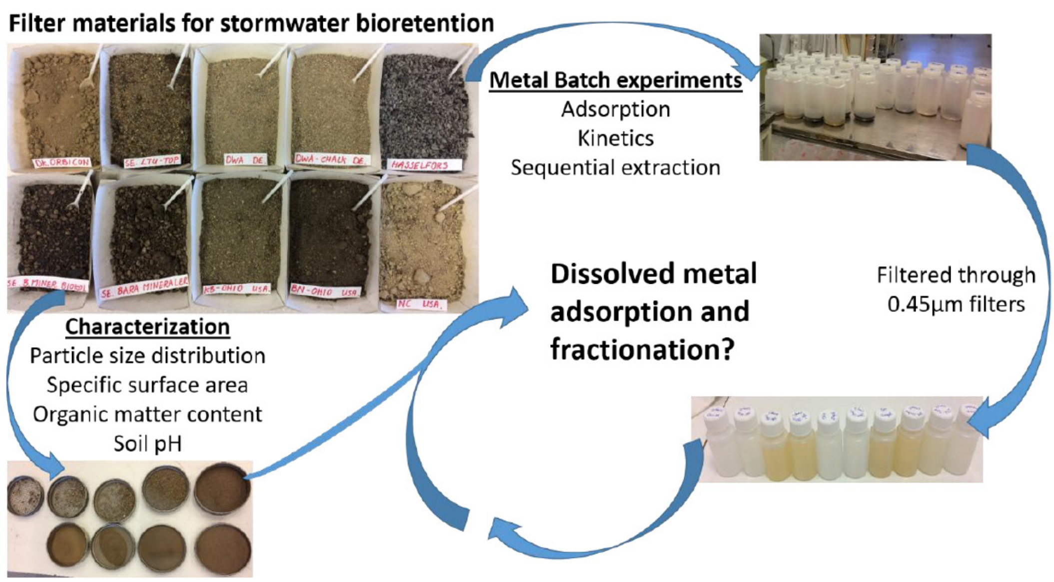

Figure 13. *Overview of the experimental setup of batch tests by Søberg et al., (2019)*

In further laboratory column experiments, Lange et al., (2020a) evaluated the impact of plant species selection on the removal of total and particulate Cd, Zn and Cu fractions from synthetic stormwater applied either regularly or at intervals to represent the effect of a 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 a prolonged dry period. 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 indicated that while total metal removal was generally >95%, removal of the dissolved and truly dissolved fractions was significantly lower (see Figure 14). The presence of vegetation generally had little effect on metal removal and fractionation. In contrast, the presence of salt increased the concentrations of Cd and Zn in the truly dissolved fraction in inlet samples but had no impact on ether Cu or Pb fractions. This study included an evaluation of the truly dissolved metal fraction for the first time in bioretention research.

With a focus on evaluating factors contributing to the removal of nitrogen and phosphorus species, Søberg et al., 2020 and 2021 evaluated the impact of temperature, salt and a submerged zone with carbon (SZC) on the removal of phosphorous and the effects of drying, temperature and an submerged zone on the removal of nitrogen species, respectively. Results showed that overall, phosphorus removal percentages were high across all treatments. However, whilst the presence of salt reduced total phosphorous removal, it did not affect the removal of dissolved phosphorous, whilst the presence of an SZC did enhanced its removal. In terms of nitrogen removal, Søberg et al., (2021) reported that in cold temperatures, nitrogen removal was enhanced in the presence of a submerged zone. In terms of temperature, both studies indicated that the removal rates of phosphorous and nitrogen increased with decreasing temperatures (Søberg et al., 2020 and 2021).

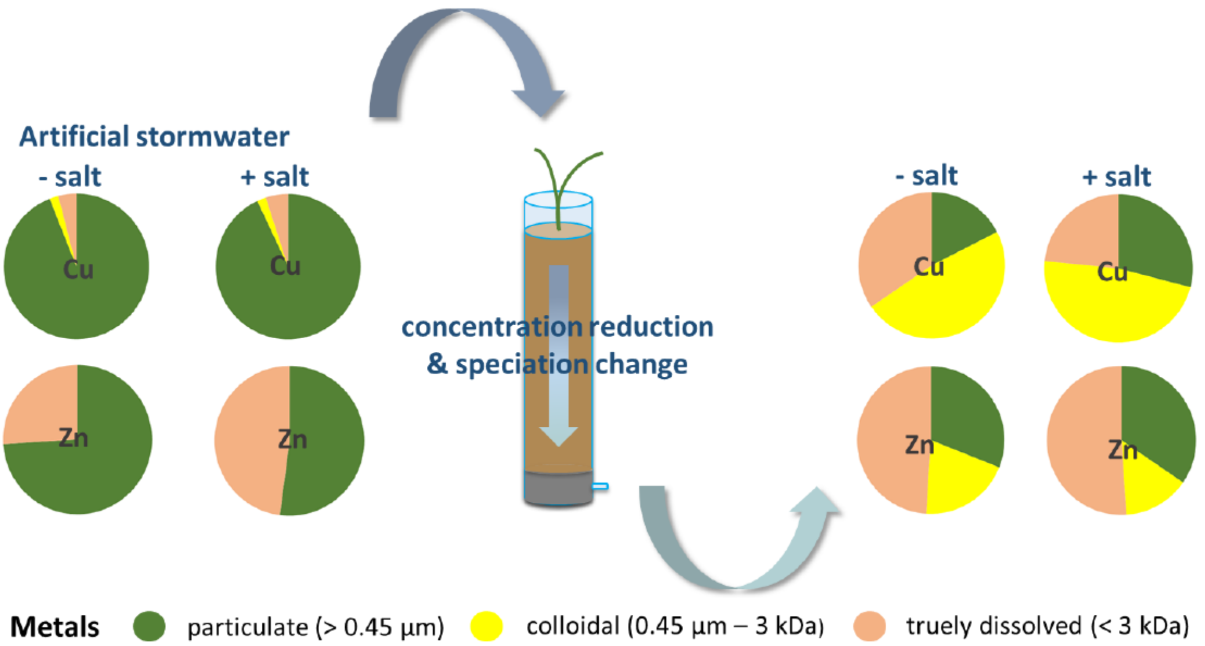

Figure 14. *Metal speciation change during passage through the biofilter: despite lower concentrations in the effluent, metals are to larger extent present in the more environmental relevant truly dissolved fraction.*

A further study evaluated the impact of drying episodes and temperature on the removal of three species of bacteria (*Escherichia coli, Enterococcus faecalis* and *Pseudomonas aeruginosa*) by biofilters columns with and without a submerged zone (Søberg et al., 2019; see Figure 15). Results indicated that outflow bacterial concentrations were independent of inflow concentrations indicating the importance of internal processes. The effect of temperature varied between bacterial species and sampling collection methodology. However, 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.

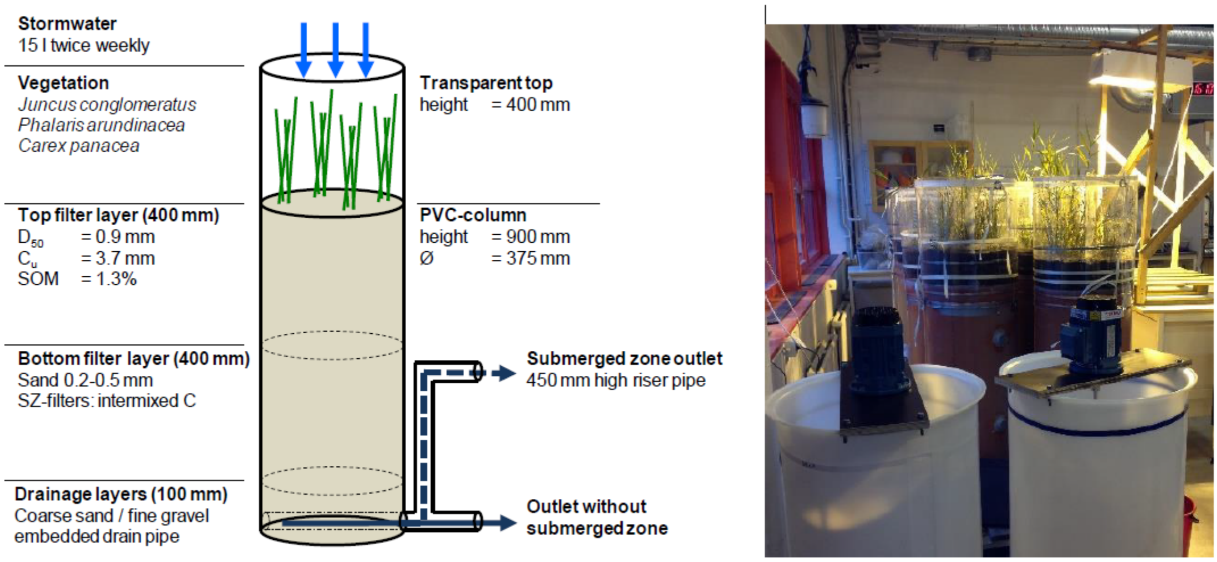

***Figure 15**. Overview of the laboratory column set-up used by Søberg et al. 2019*

With a focus on developing a better understanding of the treatment performance of grass swales and filter strips (GS&FS), a review by Gavrić et al., (2019) reported that most field studies to-date have focused on the removal of a relatively limited range of pollutants, with few studies addressing nutrients, hydrocarbons, oxygen demanding substances, chlorides or faecal indicator bacteria. Further, performance results are typically generated in relation to the monitoring of steady flow irrigation events (as opposed to episodic rainfall events) with the use of differing system designs and evaluation methodologies making results hard to compare. Little if any field data is available on the specific relationships between unit operating treatment processes (such as adsorption/desorption, plant uptake and microbial degradation) and flow quality, with the need for better knowledge of stormwater quality processes in GS&GFS facilities identified as a prerequisite for modelling studies. In a complimentary review of swale design guidance, Ekka et al., (2021) look to address the current design guideline focus on hydraulic conveyance by using available literature data to develop recommendations to supports users to design systems which target the removal of specific stormwater pollutants. DRIZZLE supported especially the design criteria recommendations for cold regions, e.g. Scandinavia. Whilst proposed recommendations are evidence-based, further research to support the identification of optimal design parameters for all swale types is recommended. In terms of swale treatment performance in the field, Gavrić et al., (2021) explored soil metal concentrations in three roadside swales. All three swales are snow covered for the part of the year, and therefore subject to additional pollutant loads from seasonal road activities (e.g. use of road salt and grit and studded tires) as well used to store and melt 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). The study concluded that metal concentrations did not decline with distance from the trafficked surfaces, indicating that the process of using swales to store snow influences the spatial distribution of metals in swale soils. In terms of modelling pollutant accumulation in swales, Gavrić et al (2019) evaluated the use of the StormTac Web model to predict the accumulation of selected metals in the soils of three swales through a comparison with the results of an intensive field sampling campaign. Comparisons of measured (MBm) and simulated (MBs) metal burdens retained by all three swales indicated that whilst measured values typically exceed model predictions (see Figure 16), results do support the feasibility of assessing swale performance with a recommendation to supplement modelled results with soil chemistry samples for older swale facilities.

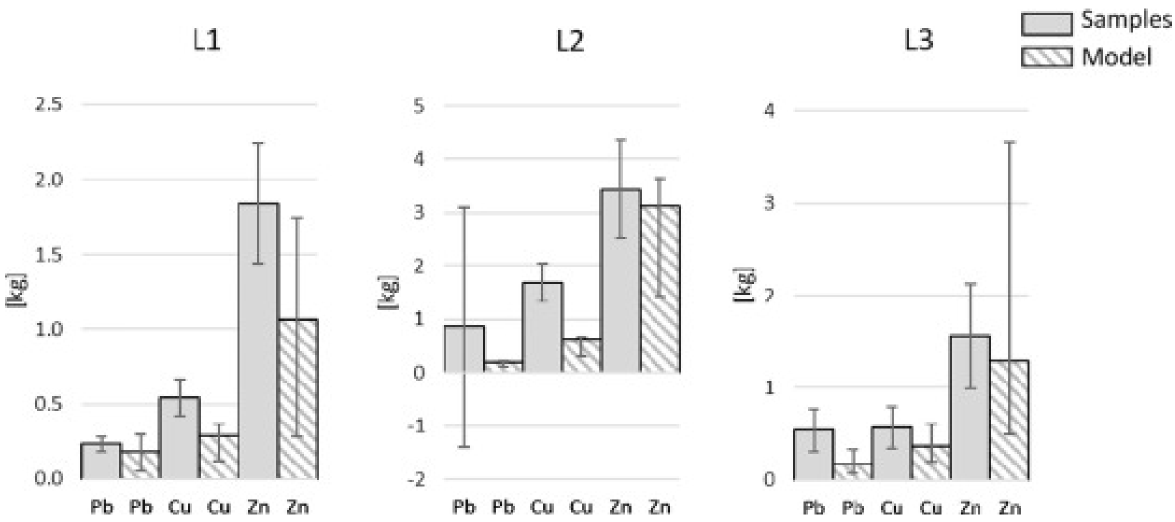

Figure 16. *Metal mass without the native soil burden, and metal mass calculated from the model output. Uncertainty bands for metal burdens calculated for soil samples represent ± standard deviation. Uncertainty bands for the modelled burden display the burdens calculated for the two extreme scenarios.*

In terms of green roofs, research by Lönnqvist et al., (2021a and b) has focused on developing a better understanding of how green roof vegetation abundance and community composition change over time in cold climates (see Figure 17). For example, in Lönnqvist et al., (2021a) levels of vascular plant cover and species compositions were monitored on 41 roof sections located at three sites in Northern Sweden. Results showed 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 conclusions 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.

Figure 17*. Green roofs with different angles and high and low vegetation coverage illustrating the need for site/climate-specific choice of vegetation.*

In a related study Lönnqvist et al., (2021b) investigated the survival of planted and unintended vegetation on green roofs at nine temperate, cold, and/or wet locations in Norway and Sweden in relation to a range of climatic conditions over a two year period. Results indicated a significant decline in intended species cover at all sites, with both the survival rate and level of cover positively related to the mean annual temperature. Whilst intended vegetation cover was negatively related to mean annual precipitation, unintended vegetation was favoured by high mean annual precipitation and low mean annual temperature, with a possible explanation being its ability to colonise bare patches and outcompete the intended vegetation. Results also highlight the need for further research on species traits and factors driving extinctions/colonisations to improve vegetation survivability and coverage throughout the successional stages of a green roof.

In addition to mitigating stormwater quantity and quality, BGI can offer a wider range of benefits (referred to as ecosystem services; ES) from habitat and carbon sequestration to mitigation of the urban heat island effect, air and noise pollution. Several studies have looked to quantify the wider benefits offered by BGI, using alternative methodologies such as life cycle and ecosystem services assessment. For example, research by Hamann et al., (2020) compared the use of two ES costing tools (B£ST and TEEB) to BGI sites located in Luleå, Sweden, under both current (baseline) conditions and potential future development scenarios. Whilst direct comparisons of the categories used in each tool were not possible (categories and monetisation methodologies varied), 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 to land use changes reducing the levels of carbon sequestration and biodiversity (see Figure 18).

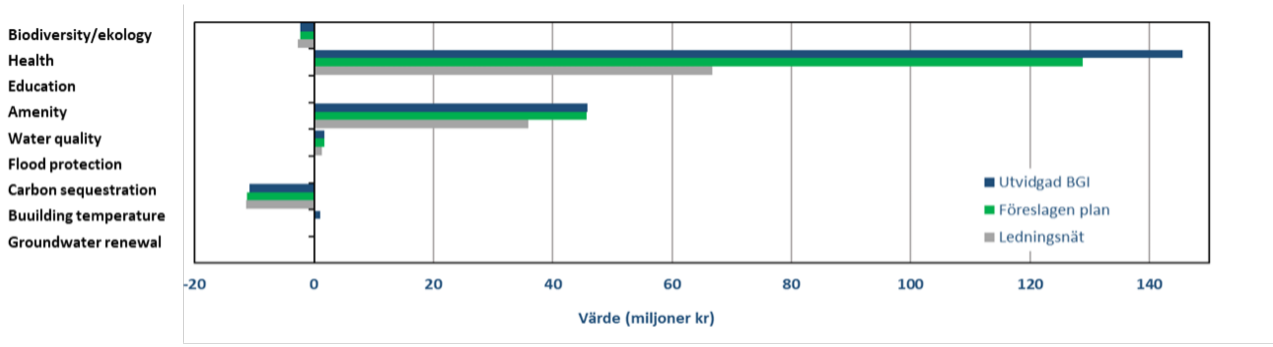

Figure 18. *Net present value of different benefit categories generated by BGI over a 30-year perspective: results for three scenarios for a case study in Luleå (Hamann et al, 2020)*

Recent research by Sagrelius et al., (*under review*) took a life cycle assessment approach to assessing the environmental impacts related to the production, transportation, and installation phases (i.e. before operation) of bioretention systems with various design and construction components. Results show that various construction components and filter media mixtures incur differing levels of environmental impact and that, for example, filter media mixtures involving long transportation distances were associated with the highest environmental impacts.

The potential for green roofs to provide a wider range of ecosystem services in urban settings that lack vegetation and open space was investigated by Schrieke et al., (2021). Findings show that, as implementation of green roofs is limited by high construction and maintenance costs, the installation of green roofs may disproportionately benefit wealthy communities and marginalise disadvantaged communities by further increasing property values and housing costs. Results also show that whilst colonisation by spontaneous species (e.g. Lönnqvist et al., 2021a and b) can be perceived by some as green roof failure (i.e. 'weediness'), dense vegetative coverage can still deliver a range of ES such as stormwater mitigation, habitat provision, and climate regulation. Further, as spontaneous species can establish on green roofs without irrigation and fertiliser, reduced input costs could help facilitate adoption particularly in markets without an established green roof industry. Thus, the installation of green roofs with spontaneous vegetation coverage may apply less pressure to property values and housing costs than conventionally planted green roofs, increasing the resilience of urban communities while limiting gentrification (see Figure 19).

In terms of the BGI approach as a whole, research by Sagrelius et al., (*under review*) discusses how the approach was developed in a temperate climate and introduces the novel notion that its use in non-temperate climates introduces the need for broader ‘multi-coloured’ thinking. This is in recognition of the fact that for large parts of the year blue-green spaces may be white (i.e. covered by snow) or yellow/brown (i.e. exposed soil, dormant or dry vegetation). In recognising that in many climates the occurrence of blue and green is a seasonal feature of BGI, this research focuses on the application of BGI in a sub-arctic climate, introducing the concept of blue-green-white infrastructure (BGWI) and considers the challenges and opportunities offered by the presence of snow as an abiotic ES provider (see Figures 19 and 20).

Spontaneous green roof vegetation traits	Social function	Ecological function	Trade-off
Prolonged flowering continuity[a]	Cue to care[e], ecological beauty[f], high preference[g]	Support butterfly biodiversity[a], floral resource for pollinators[h]	No clear trade-off
High biodiversity[b]	Biodiverse vegetation preferred[d], acceptance increases when residents informed of ecological function[i]	Habitat for rare insects and spiders[j], increased GR functionality[k–m]	Perceived messiness of naturalistic plantings[i]
Fast growth/ annual lifecycle[c]	Accumulation of organic matter when plants senesce perceived as ‘messy’[i]	High transpiration[c] may increase stormwater mitigation	Accumulation of organic matter when annual plants senesce provides arthropod habitat[n]
Gaps in vegetation[d]	Significant negative impact on green roof aesthetic[d]	Gaps provide safe sites for plant colonisation[o]	Loss of transpiration and canopy cooling when vegetation senesces[p]
Low maintenance	Reduction to green roof costs, a significant deterrent to adoption[d]	No fertiliser, herbicide, or pesticide application	No clear trade-off

Colours represent perceived beneficial (green) and unfavourable (red) outcomes.
[a]Wang et al. (2017), [b]Madre et al. (2014), [c]Schrieke and Farrell (2021), [d]Vanstockem et al. (2019), [e]Nassauer et al. (2009), [f]Sutton (2014), [g]Lee et al. (2014), [h]Bretagnolle and Gaba (2015), [i]Southon et al. (2017), [j]Kadas (2006), [k]Dunnett et al. (2008), [l]Farrell et al. (2012), [m]Kemp et al. (2019), [n]Kyrö et al. (2020), [o]Harper et al. (1961), and [p]Speak et al. (2013).

Figure 19. *Potential trade-offs between spontaneous green roof vegetation traits and their social and ecological function (Schrieke et al, 2021).*

		Imortance during annual cycle											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Dec
		Winter			Spring snow melt		Summer		Autum			Winter	
White Structure	Compact snow layer in winter: green infrastructure is used for snow storage, snow can be used for skiing, snow mobiles etc.	+++	+++	+++	++	+				+	+	++	+++
Blue Structure	Part of green-blue infrastructure, stormwater management, synergies with white structure during snow melt			++	+++	+++	++	++	++	++	+		
Green Structure	Green structure in snow-free season: parks and recreation, synergies with blue structure					+	++	+++	+++	++	+		

Figure 20. *Importance of the blue, green and white component during the annual cycle.*

Figure 21. *Example of a simple utilisation of snow to deliver recreational ES. Left: a swale used for snow storage only. Right: a swale is used as skiing track during winter. Both pictures taken in April in Luleå, northern Sweden.*

3.8 Operation and maintenance

To maintain performance delivery over time, all drainage infrastructure system require maintenance and, in this regard, BGI is no different. Whilst BGI systems come in a range of designs and sizes, from household-scale biofilter units to large storage pond systems, a key common pollutant removal process is the sedimentation of particulate matter and associated pollutants. Overtime, deposited sediments accumulate requiring periodic removal to maintain BGI hydraulic and treatment capacity. The development of a detailed understanding of sediment behaviour and quality is therefore a research priority from both operational 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 (see Figure 22).

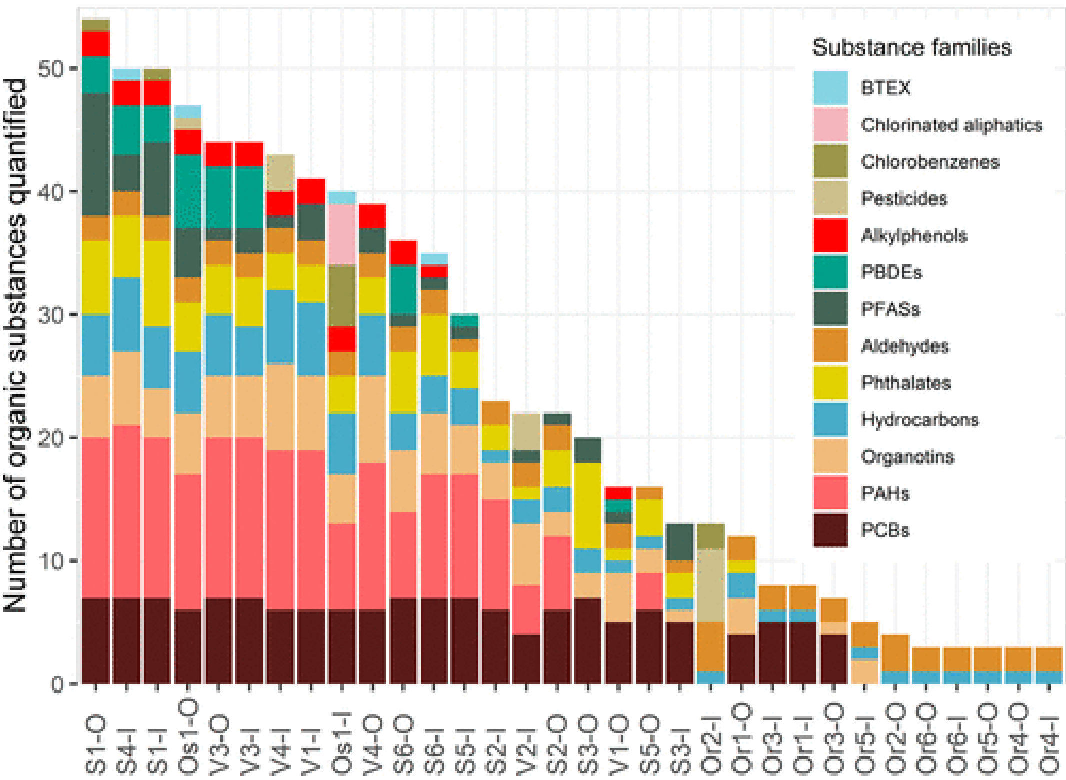

Figure 22. *Total number of quantified organic substances per sample (nquant) according to the substance family. Sample names refer to samples taken from ponds in Stockholm (S), Östersund (Os), Växjö(V), and Örebro (Or) at inlet(I) and outlet (O).*

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, and implications for sediment management are discussed. A further study Gavrić et al., (*under review*), analysed samples from the same 17 stormwater sedimentation facilities for selected metals using a range of analytical techniques including total extraction, sequential extraction, diffusive gradients in thin films (DGT) and pore water extraction. As is typical for stormwater ponds, large variations in metal occurrence and speciation were observed between ponds. No clear relationship was found between analyses that have the potential to measure similar metal fractions (e.g. DGT and adsorbed or exchangeable metals and carbonates or pore water concentrations). Whilst loss on ignition (LOI) had a significant positive correlation with an indicator for environmental risk developed in this paper, results indicate LOI cannot be used as a surrogate for metal contamination risk. Rather, LOI is an important sediment parameter that can aid understanding of sources of accumulated particles and metal behaviour.

To inform understanding the long-term performance of the use of bioretention facilities and the management implications of the periodic need to remove and dispose of biofiltration media/accumulated sediments at end-of-life, Furén et al., (*under revision*) evaluated 12 bioretention facilities to determine the occurrence and accumulation of 16 polycyclic aromatic hydrocarbons, 7 polychlorinated biphenyls, 13 phthalates, and two alkylphenols. Results show that these pollutant groupings appear to behave similarly, with both higher levels of occurrence and concentrations in upper media layers which rapidly decrease with increasing depth (see Figure 23). As could be anticipated for stormwater treatment systems, determined concentrations for all parameters vary between sites, most likely as function of catchment activities influencing pollutant sources. However, a range of pollutant physico-chemical characteristics such as molecular structure and solubility may also contribute to contamination patterns identified and results are discussed in this context.

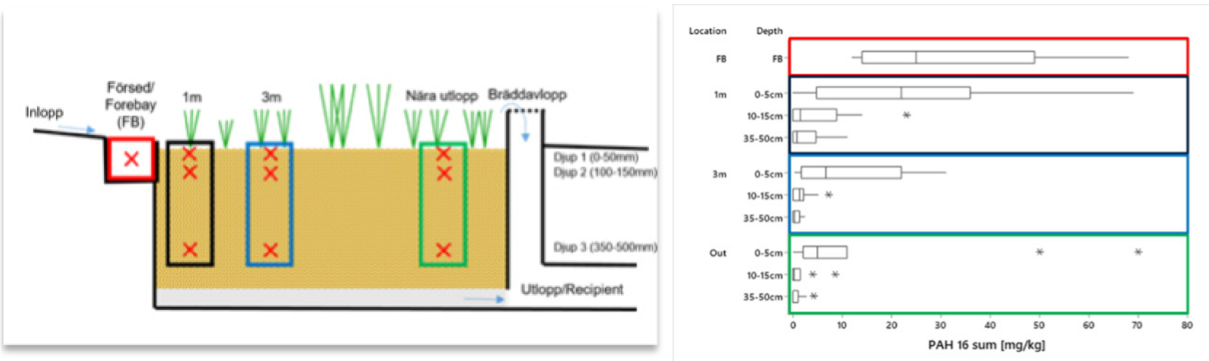

Figure 23. *Sampling points in bioretention filter material and box plot of the sum of 16 PAHs*

With a view to developing a wider understanding of field performance and the level of implementation of operation and maintenance schedules in the field, Beryani et al., (2021) evaluated the operational status of twenty-six biofilter facilities located in nine cities in Sweden. Each site was evaluated in relation to a range of indicators including functional design criteria, engineered design features (filter media composition, hydraulic conductivity, and drawdown time) as well as a visual inspection of the biofilter components (pre-treatment, in/outlet structures, filter media, and vegetation) to evaluate the performance level of each system in relation to achieving stated operational design objectives. Results indicate that the soil media used was consistent with design recommendations. However, field-tested hydraulic conductivity levels ranged from 30 to 962 mm/h, with this range – together with levels of sediment accumulation observed within the biofilter - indicating that not all the sites were operating optimally (see Figure 24).

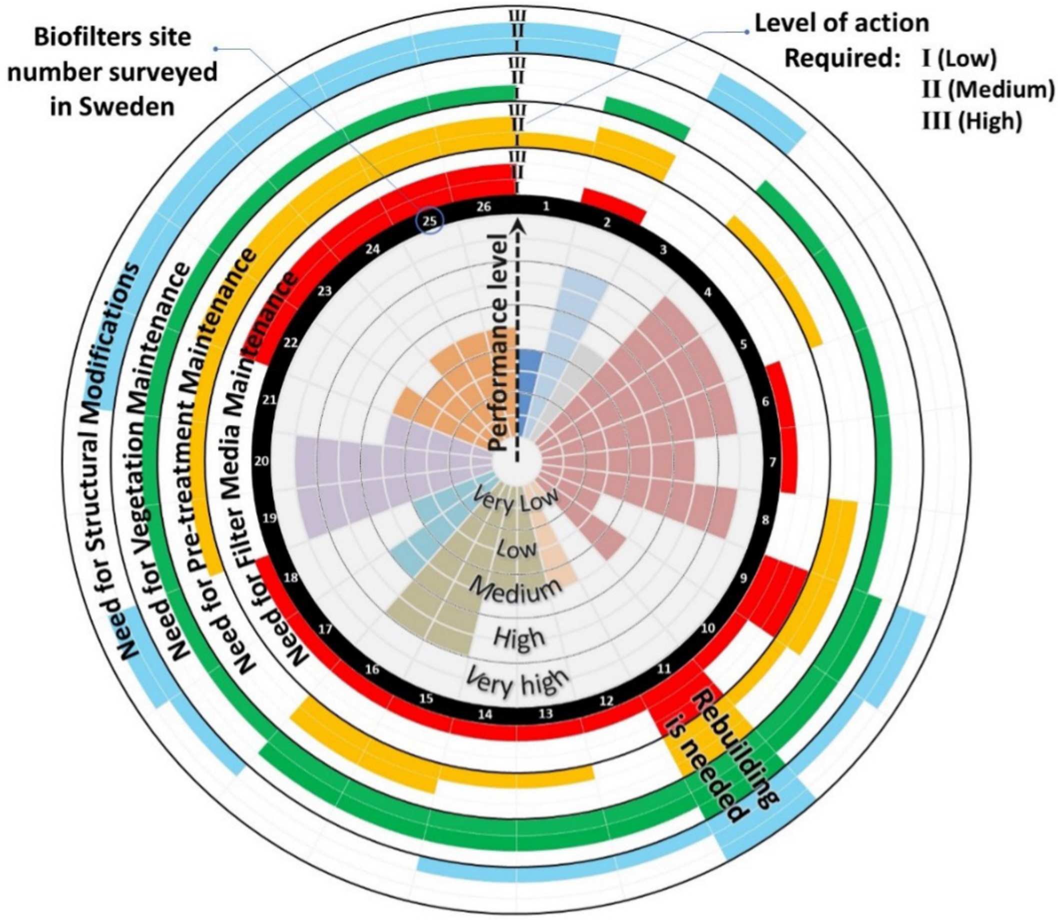

Figure 24. Performance level and need for maintenance of 26 evaluated Swedish bioretention facilities: a large percentage perform insufficiently and require modifications and/or maintenance.

In particular, the accumulation of sediment and litter in pre-treatment stages were identified as primary causes for and indicators of low hydraulic conductivity rates, with pond volume calculations indicating that 40 % of facilities evaluated had insufficient capacity to retain daily and/or design rainfall due to design and/or construction flaws. These results are of considerable concerns indicating that design objectives of e.g. water retention and flood protection identified are not being met. Recommendations to address these challenges are described.

3.9 Area efficient treatment techniques

Space in urban areas is often both limited and expensive. Therefore, in addition to the BGI research described above, a range of other approaches to enhancing stormwater quality – both as standalone systems and as an approach to enhance treatment efficiencies within existing conventional and/or BGI systems - have been evaluated. For example, Milovanović et al., (2022) investigated the treatment efficiency of a zeolite filter system to mitigate Cu roof runoff under field conditions during seven rainfall events. Results indicate that the filter reduced total and dissolved Cu by 52 – 82% and 48 – 85%, respectively. However, although the average treatment efficiency was initially high, a considerable decline in filter efficiency was noticed over the sampling period, indicating the filter medium may have reached saturation. Further, outlet Cu concentrations ranged from 350–600 µg/l, a value significantly higher than the local environmental threshold values and results are discussed in this context. With a focus on enhancing the removal of suspended sediments entering ponds and also reducing levels of sediment resuspension Milovanović et al., (2020) explored the use of a bottom grid structure (BGS) designed to be installed at the inlet to e.g. a detention pond. Initial research explored the BGS concept in a hydraulic scale model to develop a better understanding of the effects of BGS geometry on stormwater sediment trapping. Results suggesting larger cells (footprint 10 × 10 cm) were more effective than the smaller cells (5 × 5 cm), whereas cell depth exerted little influence on performance.

As an alternative approach to enhancing treatment processes within in stormwater retention facilities, Nyström et al., (2019) explored the use of two commercially-available coagulants to promote coagulation and flocculation as a pre-cursor to pollutant removal by sedimentation. Laboratory-based studies indicated that the use of the coagulation products resulted in particle and total metal reduction of > 90% compared to 40% in the absence of coagulant addition. A similar trend was observed for dissolved metal concentrations, where levels fell by 40% in the presence of a coagulant but did not change in its absence. Building on this successful pilot study, Nyström et al., (2020a) assessed the use of twelve coagulants and flocculant aids to identify substances that efficiently reduced turbidity and suspended solids within a stormwater matrix. Based on the results of an initial screening process, five coagulants were short-listed for further research. Treatment efficiencies of >90 % for both turbidity and suspended solids were achieved by all coagulants, with charge neutralization identified as a key 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., 2020b). Results indicated that the performance of all coagulants led to a > 90% removal on average for all pollutants investigated (see Figure 24).

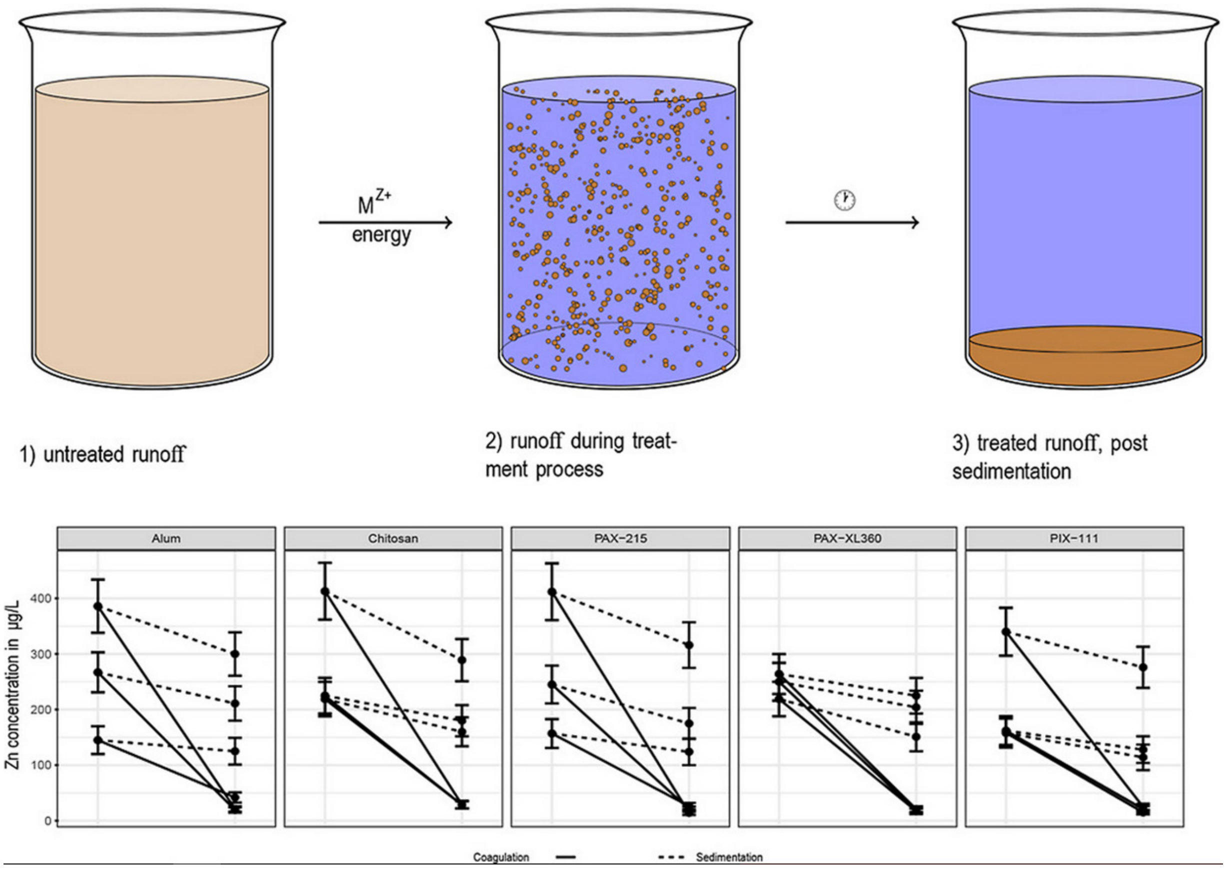

Figure 24. *Graphical schematic of laboratory set up and change in Zn concentrations on exposure to selected coagulants*

In terms of snowmelt treatment, Kaykhaii et al., (*under review*) evaluated the use of a hydrophilic polyether sulfone/polyvinyl-pyrrolidone (PES/PVP) ultrafiltration membrane. Snowmelt was pre-treated using sieving and sedimentation, with forward wash used in constant intervals to postpone reversible fouling. Results showed that the ultrafiltration membrane completely removed suspended solids, oil and turbidity from melted snow samples under both pulsatile and steady flow conditions. TOC content was reduced by at least 70% with dissolved metal concentrations reduced as follows: As 16%, Cd 13%, Cr 24%, Cu 12%, Ni 21%, P 73 % and Pb 44%. In terms of flow, increasing pulse frequency increased both permeate volume (from 2.2 to 15.2 L) and experimental run times (from 6.6 to 55 minutes), indicating that pulsatile flow postponed fouling in polymeric ultrafiltration membrane. Results are discussed in relation to the EU minimum water quality criteria for water reuse.

3.10 Policy support

In addition to undertaking high impact stormwater research and supporting its translation into practice, DRIZZLE researchers as active in several international networks including the International Water Association, Joint Committee on Urban Drainage, Water Europe and the NORMAN network. These platforms provide further opportunities and mechanisms to both share research findings and support policy development in a range of fields and sectors related to the management of stormwater quality and quantity as key action contributing to achievement of a non-toxic environment. For example, DRIZZLE research contributed to the NORMAN proposal to collaborate with the EU joint research and innovation programme to strengthen the scientific basis for chemical risk assessment in the Partnership for Chemicals Risk Assessment (PARC) initiative (Dulio et al., 2020). Specific activities include provision of expertise in the sources, behaviour, fate and mitigation of diffuse urban pollutants (including contaminants of emerging concern) mobilised by stormwater and snowmelt runoff, as well as support in scoping the use of stormwater as an alternative water source to meet non-potable needs. Under the Water Europe umbrella, DRIZZLE research has also contributed to the development of two white papers:

- Opportunities for hybrid green and grey infrastructure in water management: challenges and ways forward (Van de ven, *under revision*)
- Towards a zero pollution strategy for contaminants of emerging concern in the urban water cycle (Lundy et al., *under review*)

Written in an accessible style, the target audience for both white papers are policy developers at local to international levels. Both papers provide a concise synthesis of the current state-of-the-art in their respective fields, using this evidence-base to make a series of clear recommendations for policy development.

4. Conclusions

This report presents a synthesis of the 65 articles produced to-date by the DRIZZLE Centre of Excellence for Stormwater Management independently and in partnership with international researchers and practitioners. Since its launch in 2017, the number of articles produced per year has increased significantly as the DRIZZLE centre has attracted new staff and research planned in 2017/2018 reached completion and was reported. To facilitate their review, the 65 DRIZZLE research articles are grouped into ten broad themes which between them encompass the entire scope of the stormwater runoff management chain; from pollutant source materials to mobilisation and the mitigation of runoff quality and quantity using a range of approaches.

In terms of pollutant sources, there is a strong DRIZZLE evidence base that many – if not all – urban materials and activities release substances which can be mobilised by rainfall and/or snowmelt runoff. Several studies have focussed on developing a deeper understanding of the occurrence and behaviour of pollutants in the colloidal and truly dissolved concentrations, as the fraction most relevant for environmental management. New data on the release of organic and inorganic substances from building materials has been generated, including novel work on the occurrence and behaviour of microplastics (MPs) in runoff. From a stormwater quantity perspective, DRIZZLE research has informed a more complete understanding of processes and factors contributing to model uncertainties and developed approaches for their reduction. Further studies have focussed on the use of established models to address new surface typologies (e.g. green areas, rain on snow events), at various scales and under differing climates.

In relation to managing stormwater quality and quantity, DRIZZLE research has made a strong contribution to the international evidence base supporting the use of blue-green infrastructure (BGI) as a best management practice. Involving research over a variety of scales and time-frames - from laboratory batch tests to full-scale field systems and monitoring time periods of minutes to years depending on the experimental focus - DRIZZLE research has generated new knowledge on the treatment of conventional pollutants (e.g. nitrates and phosphates), microbiological contaminants (e.g. E. coli) and contaminants of emerging concern (e.g. polyfluoroalkyl substances) and enhanced understanding of the processes and factors which influence treatment performance. A further novel research concept is an extension of BGI into a multi-coloured concept in recognition of the fact that under non-temperate climates blue-green spaces may be white (i.e. covered by snow) or yellow/brown (i.e. exposed soil, dormant or dry vegetation). An initial study explores the implications of this in a cold climate through the opportunities offered by the presence of snow as an abiotic ecosystem service provider.

As with all drainage infrastructure systems, BGI requires periodic maintenance. To better understand maintenance needs and current practices, DRIZZLE research included an evaluation of the operational status of 26 biofiltration units. Results indicated that sediment accumulation in BGI pre-treatment stages was a primary factor in the finding that almost half of the studied facilities no longer had sufficient capacity to retain design rainfalls. With a focus on managing sediments, a major DRIZZLE research study involved the screening of sediments from 17 pond systems for 259 organic substances. Results indicated that 92 substances were detected in at least one sample, with a maximum of 52 substances detected in a single sample and concentrations in 22 of the 32 samples exceeding toxicity threshold values. However, as well as BGI performance, DRIZZLE research has evaluated a range of approaches that may be adopted or retrofitted to current systems to enhance treatment performance. Innovative concepts investigated include the evaluation of a bottom grid structure designed to be installed at the inlet to e.g. a detention pond to enhance sediment trapping and reduce resuspension and the use of a range of coagulants to reduce stormwater pollutant concentrations.

DRIZZLE researchers are also active in several international networks and have taken lead roles in the development of two white papers under the Water Europe umbrella (Towards a zero pollution strategy for contaminants of emerging concern in the urban water cycle and Opportunities associated with the use of green and grey stormwater infrastructure) providing a pathway and mechanism for DRIZZLE research to inform policy development at a European level.

This synthesis report describes the large number of co-developed novel research projects undertaken by the DRIZZLE Centre of Excellence for Stormwater Management, and clearly evidences the Centre's research depth, breadth and scope. This collection of articles represents an impressive data set which has underpinned development of a range of new insights and understandings of the sources and behaviour of stormwater runoff from quality and quantity perspectives, as well as options and opportunities for its mitigation. As such, it not only provides a solid basis for future DRIZZLE studies but represents a major contribution to the stormwater research arena at an international level.

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