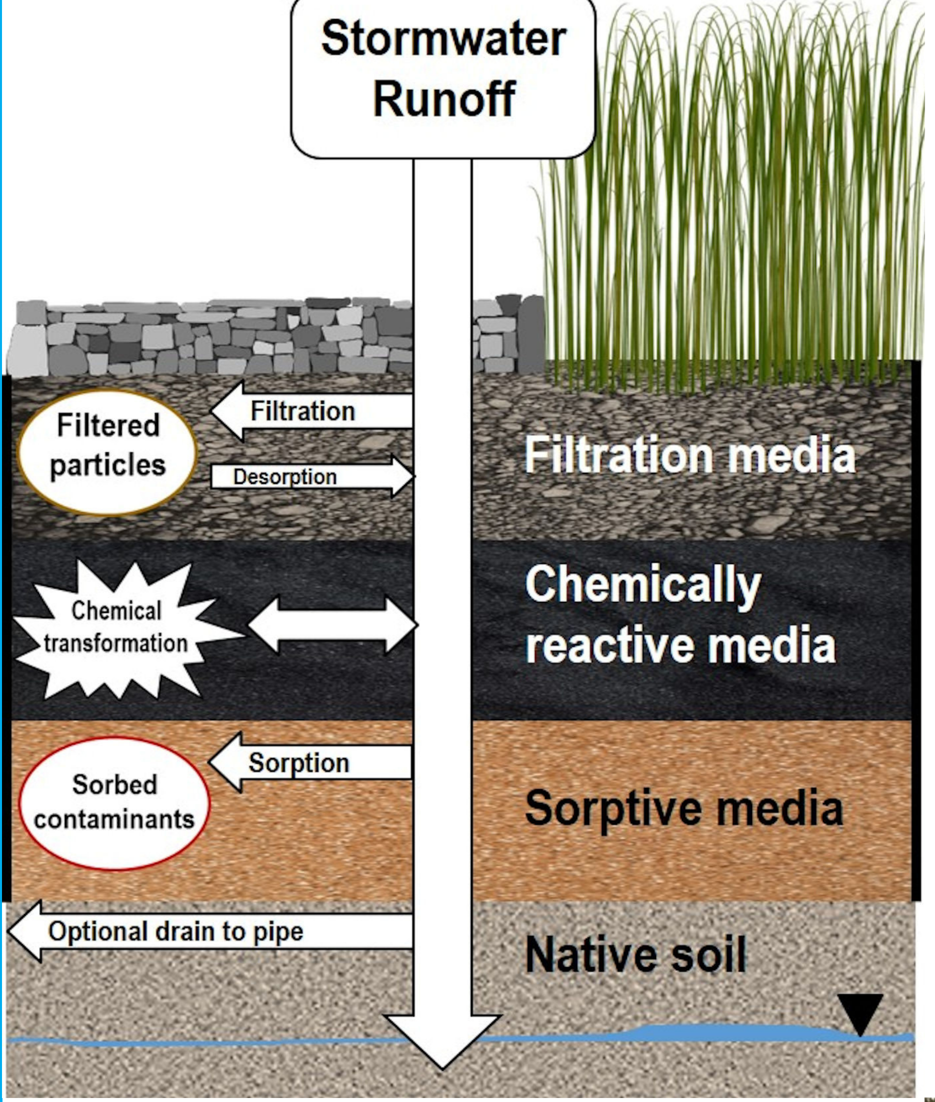

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Filtration Systems for Stormwater Quantity and Quality Management

Guideline for Finnish Implementation

Erika Holt | Harri Koivusalo | Juhani Korkealaakso |
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Preface

Worldwide, urban areas face challenges in urban water management related to changes in climate and demographics, stakeholder expectations, and future societal needs. Stormwater management in urban areas may be particularly challenging due to the division of responsibility among multiple organisations or units. There is increasing pressure to consider not only the volume of stormwater present but also its quality, and to elicit multiple benefits from stormwater management infrastructure. In addition, municipalities seek to incorporate stormwater management within urban planning and design to reduce the overall asset maintenance burden and whole-of-life costs. Drainage and stormwater management systems designed for both stormwater quantity and quality control can simultaneously reduce local flood risk as well as environmental performance.

The StormFilter (Engineered infiltration systems for urban stormwater quality and quantity) project investigated pollutant removal from stormwater surface runoff using individual filter materials and geotechnical filter modules, and quantitative models of stormwater surface runoff volume and quality. The objective was to validate tools and technologies appropriate for site-specific stormwater quantity and quality management, providing the basis for further development of new technologies and business using mineral- and bio-based materials for stormwater treatment. The StormFilter project (2015–2017) was funded by 17 partners, Tekes, VTT and Aalto University. Collaboration among project partners was central to planning research work to deliver economically feasible solutions suitable for the Nordic climate.

This document is intended to support the planning and implementation of stormwater management systems in urban areas by providing information about readily available stormwater management tools and technologies and their application to management schemes. Herein, we explore the outcomes and lessons learned from the StormFilter project, exploring possible innovations in infiltration system design for improved surface runoff quality management. Adoption of the approach outlined will assist in the development of an urban stormwater management network that is scalable, durable, functional, and sustainable, and capable of yielding a stormwater quantity and quality regime closely resembling pre-development conditions.

The information provided herein does not duplicate or replace that provided in other guidelines but provides references and supporting documentation as appropriate.

This document was co-produced by StormFilter project partners **VTT Technical Research Centre of Finland Ltd** and **Aalto University** in close collaboration with project partners (in alphabetical order):

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Ympäristörakennus Saarinen Oy
TEKES

Additional information about the StormFilter project and links to reports on project outcomes are available at http://www.vtt.fi/sites/stormfilter. We hope that this work inspires confidence in the use of modelling tools and innovative engineered filtration systems to manage urban stormwater surface runoff quantity and quality in Nordic environments.

Erika Holt, Juhani Korkealaakso and Laura Wendling, VTT, Espoo, 1.8.2018
Harri Koivusalo and Nora Sillanpää, Aalto University, Espoo, 1.8.2018

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Appendices

Terms and definitions

Absorption; FI: Absorptio

A physical or chemical phenomenon or a process in which atoms, molecules or ions enter some bulk phase – gas, liquid or solid material.

Adsorption; FI: Adsorptio

The adhesion/accumulation of atoms, ions, or molecules from stormwater (or a gas, liquid, or dissolved solid) on the surface of a material. This process creates a film of the adsorbate on the surface of the adsorbent.

Anion; FI: Anioni

An ion with more electrons than protons, giving it a net negative charge.

Best management practice (BMP); FI: Paras hallintakäytäntö

Methods or techniques identified as the most effective and practical means to achieve an objective (such as preventing or minimizing pollution) whilst making optimum use of available resources. For example, a range of measures designed to reduce the rate and quantity of surface runoff from developed areas and to improve surface runoff water quality.

Biochemical oxygen demand (BOD); FI: Biokemiallinen hapenkulutus

The measure of the concentration of biodegradable organic carbon compounds in a solution. A standardized test used as a water quality indicator.

Biofilter; FI: Biosuodatin, Biosuodin

A pollution control material/system including living components to capture and biologically degrade pollutants.

Bioretention; FI: Biosuodatus. Viittaa viivyttävään ja puhdistavaan luonnonmukaiseen hulevesien hallinnan rakenteeseen

A drainage practice that utilizes landscaping and soils to store and treat urban stormwater surface runoff.

Bioretention basin; FI: Ei vakiintunutta suomenkielistä termiä. Viittaa luonnonmukaiseen hulevesien hallinta-alueeseen

Landscaped depression or shallow detention basin, normally dry, used to slow and treat on-site stormwater surface runoff. Stormwater is directed to the basin and then percolates through the system where it is treated by a number of physical, chemical and biological processes.

Bioretention cell; FI: Ei vakiintunutta suomenkielistä termiä. Viittaa luonnonmukaiseen hulevesien tai jätevesien hallinta-alueen osaan tai pieneen maisemassa rajattuun em. rakenteeseen

An area making use of the chemical, biological, and physical properties of plants, microbes, and soils to remove pollutants from urban surface runoff or wastewater. Typically relatively small (usually treat catchment areas less than two hectares), identifiable as separate structures in the landscape.

Bioretention system; FI: Ei vakiintunutta suomenkielistä termiä. Viittaa luonnonukaiseen hulevesien hallintaan

A system using combined chemical, biological, and physical properties of plants, microbes, and soils to decrease the flow rate and volume of incoming surface runoff while simultaneously removing pollutants, reducing erosion, and recharging groundwater. Include bioretention cells, bioretention basins, and vegetated swales/bioswales.

Bioswale (bioretention swale); FI: Hulevesipainanne, viherpainanne

Refer to vegetated swales that convey and are able to retain and infiltrate stormwater to an extent defined by design through diverse vegetation, infiltrating soil layers, and check dams.

Catchment; FI: Valuma-alue

A defined area, often determined by topographic features or land use, from which rain will contribute to surface runoff to a particular point. Also known as a watershed.

Cation; FI: Kationi

An ion with fewer electrons than protons, giving it a positive charge.

Chemisorption; FI: Kemisorptio, kemiallinen adsorptio

Adsorption in which the adsorbed substance is retained by chemical bonds.

Clogging; FI: Tukkeutuminen

Decrease of water pervious porosity caused by fine material penetration and accumulation in the pores.

Computer model; FI: Tietokonemalli

A series of mathematical equations in a computer developed and used with the aim of replicating the behaviour of a system to enable prediction of the system performance for a range of conditions.

Constructed wetland; FI: Rakennettu kosteikko

A wetland designed and built for treating e.g. agricultural, municipal or industrial wastewater, or stormwater surface runoff.

Design rainfall; FI: Mitoitussade

The rainfall depth associated with a given average recurrence of Interval and duration, i.e. intensity–duration–frequency (IDF) rainfall data.

Detention; FI: Viivytys

A detention stormwater practice (‘dry bond’) is an area where stormwater is temporarily stored, or detained, and is eventually allowed to drain slowly when water levels recede in the receiving channel. Detention bonds are meant to slow down stormwater flow and keep it for a short period of time.

Filtration; FI: Suodatus

A common process in stormwater treatment that removes particulate matter by separating water from solid material usually by passing it through media such as sand, gravel or dense vegetation.

First flush; FI: Alkuhuuhtouma

The initial surface runoff of a rainstorm in which sediments and pollutants are of a higher concentration than average. Additionally: concentration-based first flush (CBFF) and mass-based first flush (MBFF).

Freundlich isotherm; FI: Freundlich´in isotermi

An adsorption isotherm by Herbert Freundlich (1909); an empirical relation between the concentration of a solute on the surface of an adsorbent to the concentration of the solute in the liquid with which it is in contact.

Geochemical modelling; FI: Geokemiallinen mallinnus

The practice of applying chemical thermodynamics, chemical kinetics, or both, to analyse the chemical reactions that affect geologic systems mineral-water interactions, commonly with the aid of a computer.

Green infrastructure; FI: Vihreä infrastruktuuri

A network of preserved or built landscapes providing the “ingredients” for solving urban and climatic challenges by building with nature.

Green roof; FI: Viherkatto

A roof with a set of constructed drainage and soil top layers with plants growing on its surface. The vegetated surface provides a degree of landscaping and microclimate values, retention of rainwater, and promotes evapotranspiration.

Groundwater; FI: Pohjavesi

The water present beneath Earth's surface in soil pore spaces and in the fractures of rock formations.

Habitat; FI: Elinympäristö

An environment of specific characteristics where an organism or ecological community normally lives or occurs.

Hydraulic conductivity; FI: Vedenläpäisevyys(kerroin), hydraulinen johtavuus, vedenjohtavuus

Describes the ease with which water can move through material pore spaces or fractures.

Indicator bacteria; FI: Indikaattoriorganismit

Types of bacteria used to detect and estimate the level of faecal contamination of water. They are not dangerous to human health but are used to indicate the presence of a health risk.

Infiltration; FI: imeytyminen

Process by which water on the surface of the ground enters the underlying soil.

Infiltration practices/stormwater infiltration practices; FI (huleveden) imeytysrakenne

Actions intended to promote stormwater infiltration into a site’s native soil, e.g. infiltration trench or infiltration pit. The engineered media of these systems are designed to act as a short-term reservoir for stormwater prior to deep infiltration.

Ion exchange; FI: Ioninvaihto

An exchange of ions between two electrolytes or between an electrolyte and a solid surface. Both absorption and adsoption can take place simultaneously.

Ion; FI: Ioni

An atom or a molecule in which the total number of electrons is not equal to the total number of protons, giving the atom or molecule a net positive or negative electrical charge.

Kinetics/Chemical kinetics; FI: Kinetiikka/kemiallinen kinetiikka

The study of rates of chemical processes. Chemical kinetics includes investigations of how different experimental conditions can influence the speed of a chemical reaction and yield information about the reaction's mechanism and transition states, as well as the construction of mathematical models that can describe the characteristics of a chemical reaction.

Langmuir isotherms; FI: Langmuir isotermi

The Langmuir isotherm was developed by Irving Langmuir in 1916 to describe the dependence of the surface coverage of an adsorbed gas on the pressure of the gas above the surface at a fixed temperature (Irving Langmuir 1916).

Low impact development (LID); FI: Ei vakiintunutta suomenkielistä termiä. Suora käännös: vähäisten vaikutusten kehitys/rakentaminen

A term used to describe a land planning and engineering design approach to manage stormwater surface runoff. Emphasizes conservation and use of on-site natural features to protect water quality. A LID area applies many BMPs (see also SuDS essentially referring to the same thing).

Master plan; FI: Yleiskaava

A general plan describing the principles of the desired development and future layout of a municipality or portion thereof. The master plan shows existing and proposed transport routes, open spaces, buildings, etc. and provides the necessary information for detailed planning, including construction and landscape design.

Mineral materials; FI: Mineraalinen materiaali

Naturally-occurring inorganic substances with characteristic chemical composition and physical properties.

Modelling, Numerical modelling; FI: mallinnus, numeerinen mallinnus

The use of computer models to replicate the behaviour of natural and manmade systems to assist in assessing their performance under a range of possible conditions.

Nutrients; FI: Ravinteet

A substance that provides food or nourishment, such as usable proteins, vitamins, minerals or carbohydrates. Phosphorus and nitrogen are the most common nutrients that contribute to eutrophication.

Pathogen; FI: Taudinaiheuttaja

Microorganisms that can cause disease in other organisms or in humans, animals, and plants (bacteria, viruses, or parasites).

Pervious pavement; FI: Vettä läpäisevä päällyste

A pavement with a permeable surface layer and porous base and subbase layers allowing stormwater infiltration and detention (also referred to as pervious concrete pavement, permeable interlocking concrete pavement, and porous asphalt pavement).

Pollutant; FI: Haitta-aine

A contaminant existing at a concentration high enough to endanger the environment or the public health or to be otherwise objectionable. Changes the natural quality of the environment by physical, chemical, or biological means.

Pond; FI: Lammikko, vesiallas

Depression of any size with a permanent pool of water, usually with ecological and landscape value.

Precipitation; FI: Saostuminen

The action or process of precipitating a substance from a solution.

Precipitation, total rainfall; FI: Sademäärä, sadanta

The amount of water falling in rain, snow, etc., within a given time and area (typically in 1, 6, 12 or 24 hours)

Priority Substances; FI Prioriteettiaineet

A selection of chemicals that present a significant risk to the aquatic environment or via the aquatic environment.

Rain garden; FI: Sadepuutarha

Refers to both bioretention cells and bioretention basins. The term ‘rain garden’ is commonly used in advertisement and public relations to promote stormwater management by vegetated landscapes.

Rainstorm; FI: Rankkasade

A storm characterized by substantial, heavy rainfall.

Reactive transport model; FI: Reaktiivisen kulkeutumisen malli

A computer model integrating chemical reactions with transport of fluids through a media. Predict the distribution in space and time of the chemical reactions that occur along flow paths.

Retention; FI: Säilytys, pidätys, pidättäminen

A practice of holding, or retaining, stormwater on a more permanent basis, with the exception of the water lost to evaporation and to infiltration into the underlying soil. Retention ponds are characterised by a permanent pool of water that rises and drops depending on the surface runoff coming from contributing areas.

Sedimentation; FI: Sedimentaatio

The tendency for particles in suspension to settle out of the fluid in which they are entrained and come to rest against a barrier.

Silt; FI: Siltti

The generic term for waterborne particles with a grain size of 2–63 µm, i.e. between clay and sand.

Soakaway; FI: Imeytyskaivo (vuotokuoppa)
A ´reverse well´ i.e. a ´hole-in-the-ground´ that loses water rather than collecting water.

Sorption isotherm; FI: Sorptioisotermi
Describes the equilibrium of the sorption of a material at a surface at constant temperature.

Sorption; FI: Sorptio
A physical and chemical process by which one substance becomes attached to another.

Stormwater treatment; FI: Hulevesien käsittely
Removal of the pollutants, based on understanding of the physical, chemical and biological properties of the pollutants and the control technologies.

Stormwater management; FI: Hulevesien hallinta
Refers to both stormwater volume and quality control.

Stormwater; FI: Hulevesi
Surface runoff that is generated on impervious (non-permeable) surfaces during precipitation events and snow/ice melt.

Surface infiltration rate; FI: Veden (pinta)imeytymisnopeus
The rate at which soil is able to absorb rainfall or irrigation.

Surface runoff; FI: Valunta, pintavalunta
The overland flow of water that occurs following surface deposition of precipitation, meltwater, or water from other sources in excess of the surface’s infiltration capacity, resulting in water flow over the ground surface.

Sustainable drainage systems (SuDS); FI: Luonnonmukaiset hulevesien hallintamenetelmät, luonnonmukaiset kuivatusratkaisut
A sequence of management practices and control structures designed to drain surface water in a more sustainable fashion than some conventional techniques. Also, sustainable urban drainage systems, SUDS, and sustainable rural drainage systems, SRDS. LID and BMP are similar concepts.

Treatment train; FI: Ketjutettu huleveden käsittely
A series of sustainable urban drainage system components, each designated to treat a different aspect of surface runoff that are implemented together to maximize their effectiveness.

Vegetated swale; FI: Viherpainanne, kasvallisuuspainanne
Bioretention systems, shallow ditches. Tend to be less complex in structure and plant diversity and relatively more linear in shape (serving conveyance) compared with other bioretention systems.

Water quality; FI: Veden laatu	
	The chemical and biological content of water, usually compared to defined standards, set by the national legislation or European Community Directives and enforced by regulatory authorities in member states.
Wetland; FI: Kosteikko	
	A land area that is saturated with water, either permanently or seasonally, such that it takes on the characteristics of a distinct ecosystem.

Abbreviations

AES	Atomic emission spectrometry
BOD	Biochemical oxygen demand
BMP	Best management practice
CAAC	Crushed autoclaved aerated concrete
CBFF	Concentration-based first flush
CEC	Cation exchange capacity
COD	Chemical oxygen demand
CW	Constructed wetland
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
E. coli	Escherichia coli
FF	First flush
FRP	Filterable reactive phosphorus
GAC	Granular activated carbon
HSY	Helsinki Region Environmental Services Authority
ICP	Inductively coupled plasma spectrophotometer
ICS	Iron-coated sand
IOCS	Iron oxide coated sand
LID	Low impact development
LWA	Light-weight aggregate
MBFF	Mass-based first flush
MCS	Manganese-coated sand
MCTT	Multi-chambered treatment train
MOCS	Manganese oxide-coated sand
MS	Mass spectrometry
MUSIC	Model for Urban Stormwater Improvement

NH3	Ammonia
NH4	Ammonium
NO2	Nitrite
NO3	Nitrate
NO_x	Nitrate/nitrite
NOM	Natural organic matter
OGS	Oil and grit separator
OM	Organic matter
PAC	Powdered activated carbon
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PO4	Phosphate/orthophosphate
PPS	Permeable pavement system
PRFS	Permeable reactive filter systems
SCM	Stormwater control measure
SDS/SuDS	Sustainable drainage system
SLAMM	Source loading and management model
SOC	Soil organic carbon
SOM	Soil organic matter
SRDS	Sustainable rural drainage system
SUDS	Sustainable urban drainage systems
SUSTAIN	System for urban stormwater treatment and analysis integration
SWMM	Stormwater management model
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSS	Total suspended solids
WQCV	Water quality control volume
WSUD	Water-sensitive urban design

1. Introduction

Urban development changes the landscape and has significant impacts on the hydrologic cycle. In particular, replacement of soil and vegetation with impervious surfaces decreases infiltration and increases surface runoff. Stormwater surface runoff is conventionally viewed as a flood hazard and is drained from the source as rapidly as possible to receiving waterbodies. In the absence of appropriate surface runoff quantity and quality management, diversion of surface runoff away from urban infrastructure as rapidly as possible can result in:

- increased downstream flood risk,
- increased erosion,
- reduced groundwater recharge and, in the long term, reduced groundwater resources,
- contamination of receiving waterbodies and environment,
- fluctuating flow conditions in streams and changes in stream morphology and habitats
- changes to urban ecosystems due to the changes in soil hydrology.

1.1 Background and Motivation

The overall objectives of urban stormwater management are appropriate drainage to minimise urban flood risk and erosion, and protection of groundwater and surface water quality. Urban areas experience substantially greater stormwater surface runoff volume and flow rates compared with undeveloped landscapes or rural areas. With increasing urban development, rainfall that previously infiltrated the soil is instead increasingly intercepted by impervious surfaces such as rooftops, streets, and parking lots. As landscape imperviousness increases, water infiltration decreases and more rainfall instead becomes surface runoff (Figure 1). In urban environments, even pervious areas often have decreased infiltration capacity due to compaction.

Increased surface runoff volume yields increased risk of pollutant transport to receiving waterbodies. As stormwater surface runoff flows over the surface of the landscape, it accumulates debris, chemicals, sediments or other pollutants that can adversely affect water quality if the surface runoff is discharged untreated. Stormwater discharge or infiltration without consideration of stormwater pollutants can pose a risk to the ecological status of urban ecosystems and water resources. In

Finland, there are at present no national-level environmental regulations for stormwater. Instead, stormwater treatment is often voluntary and based on local regulations. Environmental permits may detail specific obligations concerning stormwater discharge, particularly in groundwater recharge zones. Simultaneous management of urban stormwater surface runoff volume and quality on a catchment or sub-catchment scale is challenging, but necessary in order to effectively address the increasing extent of impervious surfaces, changing global climate, aging infrastructure and often undersized, centralised stormwater networks.

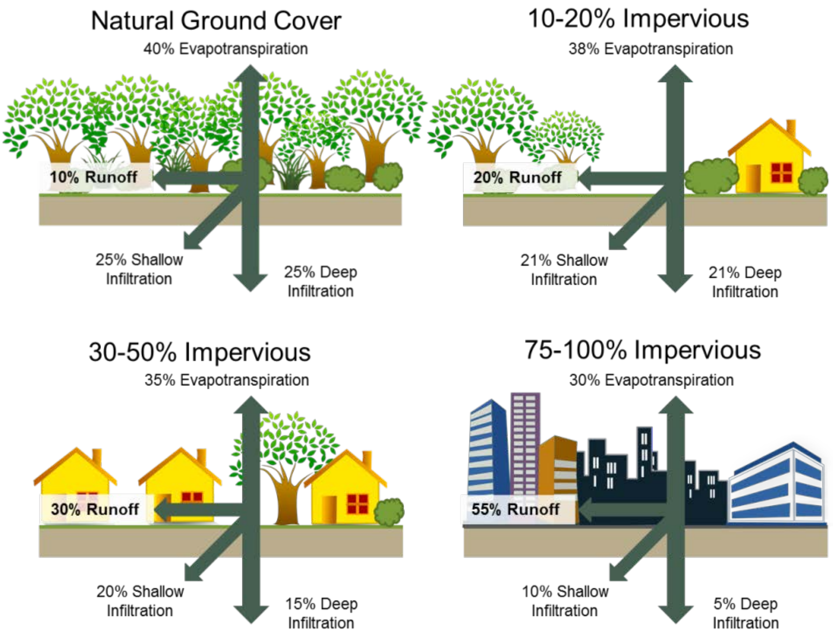

Figure 1. Effects of surface imperviousness on stormwater surface runoff and infiltration (adapted from EPA 1993).

Improved stormwater management aims to approach pre-development behaviour of the catchment and is based on retaining and detaining stormwater flows as well as improving stormwater quality. The main concept is to treat and reduce surface runoff naturally as near the source as possible whilst also considering aesthetic aspects and potential for multifunctionality of stormwater management infrastructure. Techniques that rely on these and similar principles are referred to as Low Impact Development (LID) systems in the USA, Sustainable Urban Drainage Systems (SUDS) in the UK, or Water Sensitive Urban Design (WSUD) systems in Australia.

Urban systems of green infrastructure such as rain gardens, green roofs, permeable pavements, swales, wetlands, and other designed to reduce stormwater surface runoff volume are identified in the EU Soil Sealing Guidelines (2012) as stormwater management solutions that enhance urban environments. In combination with blue infrastructure, or urban landscape elements linked to water (lakes, ponds, waterways, etc.), green systems for urban stormwater management have gained popularity due to their cost effectiveness as well as the multiple co-benefits yielded by blue-green stormwater management systems. Green infrastructure systems often utilise engineered infiltration or subsurface filtration media to optimise hydraulic conductivity/maximise water infiltration, filter particulate pollutants or provide growth media for plants and microbial communities.

1.2 Scope and Limitations of Guideline

In the Finnish StormFilter-project ("Engineered Infiltration Systems for Urban Stormwater Quality and Quantity", 2015–2017) the research target was to generate knowhow and to provide clean technologies in the form of engineered filtration materials and designs, i.e. enhanced stormwater filtration systems. These enhanced stormwater filtration systems improve stormwater management by both retaining surface runoff and by improving water quality. Stormwater was managed through removal of pollutants by reactive filter media, herein referred to as the 'grey' component of stormwater management systems. Stormwater pollutant removal and water retention by filter materials is affected by a number of complex and interactive physical, chemical, mineralogical, structural, hydrogeological and biological processes, which together slow the movement of stormwater surface runoff and remove physical and chemical pollutants. The target was to obtain quantitative values and models for the 'grey' and 'green' (vegetation) components of stormwater management solutions. This target complements Finnish strategies for green urban living by promoting increased stormwater infiltration, urban greening, and improved surface water and groundwater quality.

This Guideline is intended to help urban planners and designers develop effective, practical means for stormwater surface runoff volume and quality management. The concept of this document is not to limit any stormwater management and treatment solutions, but to provide new knowledge for enhanced urban stormwater pollution control. The inherent flexibility and scalability of the technologies and tools highlighted herein makes them suitable for both densified urban areas with only hard surfaces, as well as areas suitable for implementation of vegetated landscapes. This Guideline presents principles and methods for enhanced stormwater pollution control. Suggested stages of planning and decision-making are presented. Stormwater treatment options for various surface runoff source areas, site-specific pollution challenges and solution constraints are considered. Knowledge gaps remain which may limit to some extent the widespread application of innovative stormwater quantity and quality management systems. Both 'green' and 'grey' systems, and their combinations, should be suitable for implementation in Nordic environments and fit-for-purpose for specific stormwater applications.

1.3 Common Stormwater Contaminants

Stormwater surface runoff can be contaminated by road de-icing, vehicles, building materials, atmospheric deposition, chemicals used in homes and offices, erosion from construction sites, discharges from industrial plants, wastes from pets, wastes from processing and salvage facilities as well as chemical spills. The most significant substances are sediments or total suspended solids (TSS), nitrogen, phosphorus, chloride, copper, zinc, and oil hydrocarbons. In addition, lead, chromium, cadmium, nickel, sulphates and *E. coli* bacteria can be included. It must be noted that there are high variations in stormwater pollutant concentrations. This variation is caused by site-specific characteristics, and by seasonal and daily weather variations. Many pollutants are bound with fine solids. Filter material and system selection should be based on the properties of the surface runoff to be treated and the target water quality, as well as the water quality of the receiving waterbody.

1.4 Benefits and Challenges of Enhanced Stormwater Management

Desirable characteristics for all filter media are adequate permeability, low or no reactivity to substances in the water, high durability and resistance to compaction, free of impurities and insoluble in water. Additional considerations include material cost and availability, as well as specific handling requirements or safety considerations. This guideline presents general principles for the selection and application of filtration materials and designs, their suitability and limitations. Examples of common design options, tailored systems and engineered modules are presented. New materials and material combinations, as well as material further processing and modification options are presented. Both ‘grey’ and ‘green’ systems are included. Grey systems include engineered hard surfaces, with base and subbase materials, as well as added engineered filtration systems with one, mixed or layered media filtering. Green systems include bioretention and biofiltration systems or rain gardens, i.e. practices with the use of vegetation. Information on the availability and cost of different kind of filter materials and vegetation for bioretention is included. In addition, information on the available laboratory and field methods for material efficiency testing are included.

Existing design and dimensioning processes and tools for stormwater management are complemented with enhanced filtration materials and systems. For the Nordic environment applicable vegetation and engineered filter media, with specific porosity, permeability and pollutant removal capacity, is adapted to the existing design system. Existing water quality concerns and regulations are taken into account, as well as extreme precipitation events and stormwater surface runoff under ambient environmental conditions throughout the year. New geotechnical and landscape designs, new structures and engineered in situ infiltration structures and modules, are compared with conventional designs, taking into consideration also practical lifespan of the materials and vegetation.

Available modelling and simulation tools applicable to enhanced stormwater management are also presented. Processes in urban hydrology, and related models for practical design purposes, catchment or sub-catchment scale hydraulic modelling, are reviewed. In addition, enhanced simulation of stormwater pollutant load removal, including for instance physicochemical processes, is presented. The practical applicability of this kind of reactive transport modelling for the needs of stormwater management is presented.

This Guideline presents also basic steps in construction of infiltration systems for stormwater surface runoff treatment. The main variables to monitor during the lifespan of the systems are presented. Winter maintenance, needed cleaning and maintenance processes are also generally specified. Some case studies are also presented, and future research needs are identified.

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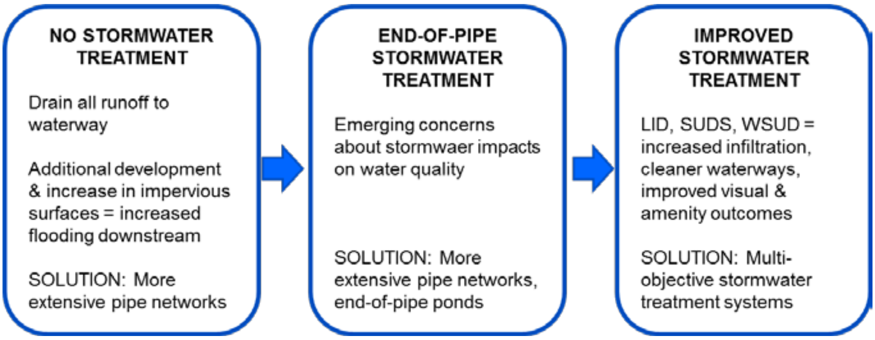
2. General principles for improved pollution control

Worldwide, the concept of urban drainage has evolved from draining all stormwater as rapidly as possible to a focus on meeting multiple objectives using a series of connected treatment units (Figure 2). This use of multiple connected stormwater treatment units within a single treatment system is sometimes referred to as a 'treatment train' and often includes both pollution source control and treatment practices. Techniques such as LID systems, SUDS and WSUD systems are all modern, multi-objective stormwater treatment systems.



NO STORMWATER TREATMENT

Drain all runoff to waterway

Additional development & increase in impervious surfaces = increased flooding downstream

SOLUTION: More extensive pipe networks

END-OF-PIPE STORMWATER TREATMENT

Emerging concerns about stormwaer impacts on water quality

SOLUTION: More extensive pipe networks, end-of-pipe ponds

IMPROVED STORMWATER TREATMENT

LID, SUDS, WSUD = increased infiltration, cleaner waterways, improved visual & amenity outcomes

SOLUTION: Multi-objective stormwater treatment systems

Figure 2. The evolution of modern urban stormwater drainage practices (modified from Roads and Maritime Services 2017).

2.1 Common designs

The selected stormwater treatment technology must appropriately address the site-specific pollutants. Stormwater treatment methods are founded on one or more of the following mechanisms: sedimentation, filtration, adsorption and ion exchange, biotransformation and bio-uptake, chemisorption and precipitation, heat transfer. Numerous treatment methods have been developed, including commonly encountered permeable pavement systems (PPS), biofiltration systems and flow-through cells.

Permeable pavement systems include a permeable top layer accompanied with a porous substructure for filtering, storing, retarding and curing of polluted stormwater. The top layer in PPS can be, e.g., a porous asphalt, permeable concrete or stone paver with permeable joints. Numerous filter materials can be used in the substructures/filter layers and some of them are discussed in the next chapter.

Biofiltration systems refer to the process of *filtration*, *infiltration*, *adsorption* and/or *biological uptake* of pollutants when stormwater runoff flows over and through vegetated areas and soils (Figure 3).

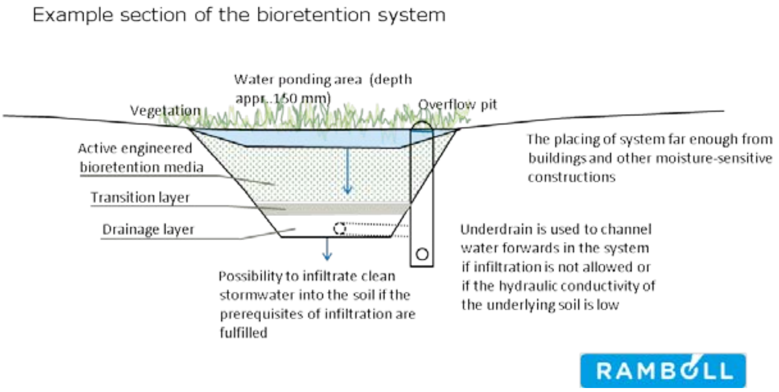


Figure 3. Basic principles of a bioretention system.

In contrast, flow-through cells are belowground filter systems. This term includes sedimentation chambers, horizontal and/or vertical flow filter systems, and hydrodynamic separators that remove suspended particles. Flow-through cells may contain specific filter media for removal of targeted dissolved pollutants. These and other solutions for stormwater treatment are briefly described in Table 1.

Table 1. Common types of stormwater treatment solutions.

Component	Description
Green roof	A planted soil layer on a roof of a building. Water is briefly stored in the soil layer before being taken up by vegetation. The stored water eventually returns to the atmosphere via evapotranspiration.
Infiltration system	Surface runoff is collected and stored, allowing the water to percolate into (*infiltrate*) the native soil. Vegetation and soil provide filtration of particulate pollutants.
Filter drain	Stormwater surface runoff is temporarily stored in a trench filled with stones or gravel providing flood attenuation, conveyance and water treatment.
Swale/bioswale	A vegetated channel that conveys and treats the surface runoff.
(Bio)retention basin	A shallow landscaped depression allowing surface runoff to pond temporarily before filtration through vegetation and/or underlying soils prior to collection or infiltration.
Permeable pavement system	Surface runoff soaks through permeable pavement (asphalt, concrete, and paver blocks). Water is stored in the sub-base and potentially allowed to infiltrate into the sub-surface. May contain reactive media as substrate to attenuate stormwater pollutants.
Ponds and surface wetlands	Permanent pools of water used to provide both flood attenuation and treatment of surface runoff. Outflows are controlled and water levels are allowed to increase following rainfall. They can support emergent and submerged vegetation, which enhances water treatment processes and biological diversity.
Flow-through cells/subsurface filter system	Belowground filter systems through which stormwater is conveyed. While passing through, suspended solids are separated from the stormwater. A specific filter material can be included to further treat dissolved pollutants in the stormwater during passage through the cell.

2.2 Planning assumptions

When planning a stormwater treatment system to any specific site one must have information about the climate, topography, hydrology and soil characteristics of the site. The aspects of stormwater quality must be estimated or known in order to choose the suitable treatment approach. It is also important to consider the location, condition, age and safe distances of technical systems, buildings and other site infrastructure in order to identify appropriate underground and aboveground spaces for stormwater systems.

2.3 Stages of planning and decision-making

The planning and construction of a stormwater treatment system includes many parties and requires efficient teamwork. Stages of planning include the following: Catchment area analysis, risk assessment, solutions for catchment area and master plans for future scheduled investments (over ~10 years). The development of city plans and prioritising actions is conducted in co-operation between various city departments. Whilst the parks and street department produces the detailed design of construction, a construction company (city owned or private) is responsible for execution of construction work, and the city supervises the completion of construction. Operation and maintenance are important after completion. Having the right team together from early on is important in order to get the stormwater treatment aspects considered collectively. All of the relevant authorities must be involved early enough in the process. The different aspects are considered in more detail in chapter 5.

2.4 Selection of materials

The selected stormwater treatment approach is highly dependent on land use and the receiving water system. Groundwater areas and industrial areas require special consideration. In general, catchment area categorisation or classification should be used when selecting a stormwater treatment approach. Special treatment needs might arise for certain pollutants depending on the stormwater quality. Seasonal variation of weather conditions needs to be accounted for. Individual materials and their properties are discussed in more detail in the following chapter. Ultimately, the economic aspect needs to be considered in order to maximise the benefits from a usually restricted budget.

2.5 The stormwater pollutants

Stormwater composition varies a great deal and is more or less unique in every catchment area. The pollution risk induced by a site depends on the sensitivity of the receiving environment, the pathway between the surface runoff source and the receiving waters, and the level of dilution available. The impacts can be acute (fast and short-term) and/or chronic (slow and long-term). The overall impact depends on the types of pollutants on the site, the peak concentrations of the pollutants and the total pollutant load build-up. Various stormwater pollutants and their adverse effects are presented herein. Total suspended solids is one of the most common stormwater parameters measured. It refers to the sediment or solid particles that are suspended in the stormwater solution. The suspended particles can reduce the sunlight penetration causing negative impacts on ecosystems. They also act as binding sites for heavy metals in stormwater. The dissolved pollutants can lead to reduced oxygen levels (eutrophication by phosphorus and nitrogen), toxic conditions (heavy metals, hydrocarbons) and the death of fish and other animals. Human health may also be at risk if exposed to significant levels of pathogens. In groundwater areas, the pollution is a risk that needs attention due to the irreversible and permanent nature of groundwater pollution.

Depending on the source (atmosphere, traffic, litter, de-icing activities etc.), the typical pollutant load in stormwater can be very different. Industrial activities and traffic exhaust fumes contribute to the atmospheric pollution that may contain, e.g., phosphorus, sulphur, heavy metals and hydrocarbons. In addition to exhaust fumes, traffic causes tyre abrasion, corrosion and oil leaks. Litter and animal faeces can pollute stormwater in the form of bacteria and viruses. De-icing chemicals contain chlorides that dissolve into the stormwater stream and end up to the receiving water bodies. Chlorides are not removed by any biological processes and their addition to waterbodies should therefore be avoided. Table 2 summarises the pollution sources and the associated pollutants in stormwater.

Table 2. Common sources of pollution in stormwater.

Source	Main pollutants	Details
Atmospheric deposition	Phosphorus, nitrogen, sulphur, metals, hydrocarbons, particulates	Industrial activities, traffic exhaust fumes, agricultural activities. Rain absorbs atmospheric pollutants which then end up in the stormwater surface runoff. Atmospheric pollutants can be deposited on roofing materials and discharged into roof runoff.
Traffic – exhaust fumes	Hydrocarbons, nitrogen, phosphorus, cadmium, platinum, palladium, rhodium	Emissions include polycyclic aromatic hydrocarbons, metals, particulates and other chemical components of incomplete fuel combustion.
Traffic – wear and corrosion	Particulates, metals, hydrocarbons	Abrasion of tyres, corrosion of vehicles and asphalt wear deposit pollutants on roads.
Animal faeces, sewer overflows and septic system leaks	Bacteria, viruses, phosphorus, nitrogen	Pollutants in uncollected animal waste wash off urban surfaces with runoff. Dead animals (e.g. road kill) and pet faeces release bacteria into the stormwater. Sewer overflows and septic system leaks release untreated wastewater and associated pollutants.

Source	Main pollutants	Details
Litter and debris	Gross pollutants	Clogging hazard for surface runoff collection systems. Sources include pedestrians and vehicles, waste collection systems, leaf litter from trees, lawn clippings, etc.
Building construction	Gross pollutants, particulates (sediment), hydrocarbons, metals	Site disturbance and heavy equipment use during building activities, together with vehicle traffic on site, results in high suspended solids content of stormwater surface runoff from building sites, along with hydrocarbons and metals, and may also contain gross pollutants.
Weathering of buildings and structures	Particulates	Variable in both extent and in the composition of particulates, physical and chemical weathering processes result in release of particulate solid materials from building surfaces.
Farming/landscape maintenance	Phosphorus, nitrogen, herbicides, insecticides	Herbicides and pesticides used for weed and pest control in landscaped areas. Nutrients used in farming cause eutrophication in receiving waterbodies.
De-icing activities	Chloride, particulates	Salts used for de-icing roads contain chlorides. Gritting (use of gravel or sand) increases the suspended solids content of stormwater surface runoff.
Cleaning activities	Particulates, phosphorus, nitrogen, surfactants, hydrocarbons	Pressure washing vehicles, widows, bins etc. leads to silt, organic matter, detergents and hydrocarbons entering the surface water drainage.

3. Materials for stormwater filtration

3.1 StormFilter project filter material testing

The StormFilter project examined a number of locally-available mineral- and bio-based filter materials with respect to their capacity for attenuation of the common stormwater pollutants, such as copper (Cu), lead (Pb), zinc (Zn), phosphorus (P), sulphate (SO_4^{2-}), and chloride (Cl^-). A synthetic stormwater was used in experimental work in order to have an influent stormwater with a known, constant chemical composition. Use of synthetic stormwater allowed standardisation of results among different experiments, and facilitated assessment of long-term performance through the use of higher concentrations than the reported average pollutant concentrations.

3.1.1 Mineral- and bio-based filter materials

Stormwater filter materials examined in detail included mineral aggregates, expanded clay products Leca® and Filtralite®, as well as peat and biochar products. Materials were first tested individually in batch tests to determine their sorption capacity for common stormwater pollutants (Wendling et al. 2017a). The composition of synthetic stormwater used in batch testing of filter materials is given in Table 3.

Table 3. Composition of synthetic stormwater used in the StormFilter filter material batch tests.

Stormwater contaminant	Nominal concentration (mg/L)
Copper (Cu)	0.5
Lead (Pb)	1.0
Phosphorus (P)	0.5
Zinc (Zn)	2.0
Chloride (Cl^-)	100
Sulphate (SO_4^{2-})	80
Organic carbon (OC)	10

Contaminant sorption capacities determined for solid filter materials using batch tests are concentration-dependent. The net removal of a given contaminant represents the maximum potential removal of that contaminant at the concentration tested and in a static system without constant replenishment of solution, where chemical equilibrium is achieved. Although not necessarily representative of real-world conditions, batch testing yields relevant information about the surface affinity of the tested material for a given pollutant.

In general, batch tests showed moderate to good metal and phosphorus removal from solution but low levels of chloride and sulphate removal. Stormwater contaminant removal capacities for tested filter materials at a 1:10 solid to liquid ratio are summarised in Table 4.

Table 4. Stormwater pollutant removal (%) by each filter material in laboratory batch tests. Negative values indicate net release of the respective ion.

	Proportion retained by filter material (%)					
	Cu	Pb	P	Zn	Cl	SO_4
KaM 0–5 mm crushed rock	29	0.0	2.3	52	-3.2	1.7
SSr 0–16 mm screened sand	36	14	37	70	-2.8	1.7
Leca® 2–4 mm round	41	53	27	75	-2.1	-2.4
Leca® 0–3 mm crushed	80	85	49	94	-7.2	-3.7
Leca® 3–8 mm crushed	45	53	25	71	2.3	-2.4
Filtralite® P 0.5–4 mm	56	65	56	75	9.9	-7.8
Peat 3–16 mm	90	98	88	91	-14	-6.0
Peat + 10% limestone	93	99	89	97	-20	-16
Birch biochar powder	98	>99	-208	>99	-20	-169
Spruce biochar chips	99	99	66	98	-7.9	-5.2

Because batch tests are concentration dependent, greater sorption of each contaminant, e.g. higher sorption capacities, would likely be observed for each of the materials tested if a more concentrated solution were used.

3.1.1.1 Individual filter materials

Flow-through testing of individual materials in a column configuration was used to assess material performance in a subsurface filter system or similar configuration. The composition of synthetic stormwater used in flow through testing of individual materials was initially the same as that used in batch tests (Table 3). Following several weeks' testing and the addition of 33.0 L of synthetic stormwater to each column, there was no indication of decreasing metal and phosphorus removal by any of the filter materials. The concentration of metals and phosphorus in the influent synthetic stormwater was subsequently increased 20-fold in an attempt to exhaust each filter material's capacity for contaminant removal in order to estimate longer-term filter material performance (Table 5).

Table 5. Composition of synthetic stormwater used in the StormFilter column tests of individual filter materials.

Stormwater contaminant	0–33 L concentration (mg/L)	30–40.5 L concentration (mg/L)
Copper (Cu)	0.5	10
Lead (Pb)	1.0	20
Phosphorus (P)	0.5	10
Zinc (Zn)	2.0	40
Chloride (Cl^-)	100	140
Sulphate (SO_4^{2-})	80	94
Organic carbon (OC)	10	10

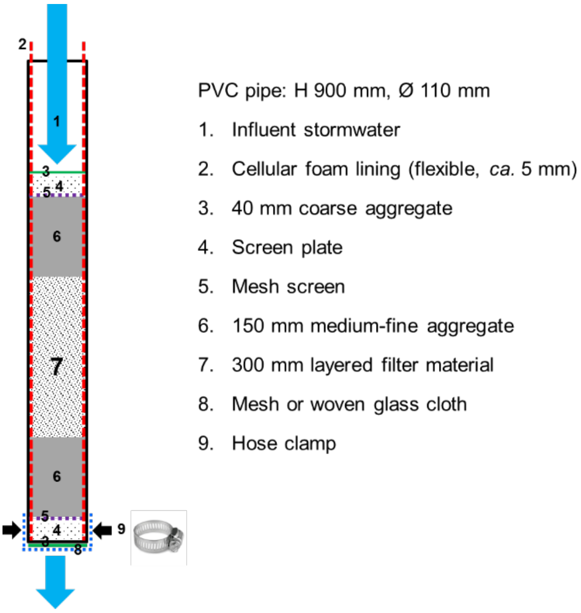


Figure 4. Configuration of laboratory columns for testing of individual filter materials in StormFilter project (reproduced with permission from Wendling et al. 2017a).

Nearly all individual filter materials demonstrated effective removal of copper, lead, zinc, and phosphorus from synthetic stormwater under controlled conditions. In contrast, none of the mineral- or bio-based filter materials showed substantial chloride or sulphate removal from the synthetic stormwater influent. Importantly, variable performance was noted among individual materials within a given class. For example, one biochar material initially released a small quantity of phosphorus into solution whereas the other biochar demonstrated a high rate of phosphorus attenuation. Although the variability of biochar materials and nutrient leachability is documented in the scientific literature (e.g. Chan & Xu 2009, Hollister et al. 2012, Mukherjee &

Zimmerman 2013, Uchimiya et al. 2010), the variability in biochar material characteristics and potential impacts on performance for specific applications may not be well-understood by practitioners.

A lack of substantial differentiation between pollutant removal by chemically "unreactive" filter materials and those known to possess high cation exchange capacity or specific surface reactivity towards particular contaminants was noted. This result suggests a primarily physical removal mechanism, i.e. contaminant precipitation followed by physical filtration of the solids, or a combination of physical and chemical metal and phosphorus retention such as flocculation, or complexation, or electrostatic retention. In this study, metal pollutants most likely precipitated due the presence of dissolved organic carbon in the form of humic acid and/or elements released from the filter materials, followed by physical filtration of the metal-containing particulates.

A general summary of filter material performance as determined in the StormFilter study is presented in Table 6. Where reported phosphorus concentrations in column effluents were less than the analytical limit of detection (i.e., <0.05 mg/L), a concentration equal to the limit of detection was assumed. Thus, the maximum phosphorus attenuation was 90% and the proportion of phosphorus removed by filter materials where phosphorus concentration in effluent was less than the limit of detection was ≥90%. Detailed results of column experiments are available in Wendling et al. (2017a), including evaluation of contaminant retention by each material with time.

Table 6. Stormwater contaminant removal (%) by individual filter materials in laboratory column tests. Negative values indicate net release of the respective contaminant (Wendling et al. 2017a).

	Proportion removed by filter material (%)					
	Cu	Pb	P[a]	Zn	Cl	SO_4
KaM 0–5 mm crushed rock	99	99	>90	99	5.6	-2.1
SSr 0–16 mm screened sand	>99	>99	>90	>99	3.8	-0.8
Leca® 2–4 mm round	99	99	>90	98	3.5	-2.1
Leca® 0–3 mm crushed	99	99	>90	98	3.7	-1.0
Leca® 3–8 mm crushed	86	85	76	80	6.0	-0.9
Filtralite® P 0.5–4 mm	99	>99	>90	99	4.4	-1.1
Peat 3–16 mm	92	93	88	90	4.1	0.7
Peat + 10% limestone	98	>99	>90	99	4.4	-0.4
Birch biochar powder	82	80	-70	73	8.0	-2.3
Spruce biochar chips	96	96	88	94	15	0.1

[a] The proportion of P removed by filter materials where P concentration in effluent was less than the limit of detection was ≥90%.

3.1.1.2 Mixtures of filter materials

Six different layered or homogeneously mixed filter systems were examined in laboratory column experiments:

1. 3–8 mm crushed Leca® + peat with 10 wt.% limestone + spruce biochar

2. 3–8 mm crushed Leca® + peat with 10 wt.% limestone + iron-treated spruce biochar
3. Iron-coated 3–8 mm crushed Leca® + peat with 10 wt.% limestone + spruce biochar
4. Homogeneous mixture of 10 wt.% spruce biochar and 90 wt.% 0–2 mm quartz sand
5. 3–8 mm crushed Leca® + peat with 10 wt.% limestone
6. 3–8 mm crushed Leca® + spruce biochar.

Each layered or mixed system was also comprised of layers of KaM 0–5 mm crushed rock aggregate above and below the filter materials shown above. In addition, the 3–8 mm crushed Leca® + peat with 10 wt.% limestone + spruce biochar layered filter system, also containing KaM 0–5 mm aggregate layers, was scaled up and further tested using a meso-scale stormwater filtration cell. The combinations of filter materials were selected based on each individual material's performance in flow-through column experiments. The concentration of metals and phosphorus in stormwater was increased 10X in the column trials using mixtures of filter materials, relative to the batch tests, to evaluate the impact of higher rates of pollutant loading on Cu, Pb, Zn and P removal by the layered filter systems (Table 7).

Table 7. Composition of synthetic stormwater used in the StormFilter mixed filter material column tests and meso-scale filtration study.

Stormwater contaminant	Nominal concentration (mg/L)
Copper (Cu)	5
Lead (Pb)	10
Phosphorus (P)	5
Zinc (Zn)	20

Investigation of the different combinations of layered materials demonstrated the potential for development of tailored filter products to address specific stormwater concerns (Table 8). The range of different filter materials available enables development of fit-for-purpose solutions to address a variety of site-specific conditions, such as existing soil characteristics, site conditions, anticipated or measured pollutant loads and expected rainfall.

Table 8. General summary of stormwater pollutant removal by systems containing multiple filter materials (Wendling et al. 2017b).

	Cu	Pb	Zn	P
Layered 3–8 mm crushed Leca® + peat with limestone + spruce biochar + aggregate *column*[a]	86%	88%	70%	43%
Layered 3–8 mm crushed Leca® + peat with limestone + spruce biochar + aggregate *filtration cell*[b]	97%	>99%	87%	81%
Layered 3–8 mm crushed Leca® + peat with limestone + Fe-spruce biochar + aggregate	97%	98%	96%	81%
Layered 3–8 mm crushed Fe-Leca® + peat with limestone + spruce biochar + aggregate	94%	95%	79%	61%
Mixed spruce biochar & sand + aggregate	95%	97%	80%	71%
Layered 3–8 mm crushed Leca® + peat with limestone + aggregate	88%	87%	71%	42%
Layered 3–8 mm crushed Leca® + spruce biochar + aggregate	81%	84%	50%	61%

[a] Leca® / Peat / Biochar + aggregate 1 stormwater loading rate = ca. 65 000 L/m^3 (laboratory-scale column.

[b] Leca® / Peat / Biochar + aggregate 1 stormwater loading rate = ca. 21 000 L/m^3 (meso-scale filtration cell).

In addition, when the same materials were used to test pollutant removal at two different scales (laboratory column and meso-scale infiltration cell), the relative decrease in stormwater loading rate in the larger system resulted in clearly increased pollutant removal efficiency. The up-scaled Leca® + peat with 10 wt.% limestone + spruce biochar layered system in the meso-scale filtration cell removed 87–99% of the copper, lead and zinc from influent stormwater, and >80% of the phosphorus. Detailed results, including analysis and discussion of pollutant removal mechanisms, are available in Wendling et al. (2017b).

The stormwater pollutant removal results of the StormFilter study were consistent with those of previous investigations and verify that the locally available mineral- and bio-based filter materials examined are suitable for treatment of urban stormwater surface runoff. Specifically, the rates of copper, lead and zinc removal (grams of pollutant per kilogram of filter material) obtained in the StormFilter study were superior to or comparable with metal adsorption capacities of modified natural materials reported in the literature (Barakat 2011, Ho and McKay 2000, McKenzie 1980).

Results of the StormFilter project showed that an important parameter affecting the behaviour of metals and phosphorus in filter systems was solution pH. This is consistent with existing knowledge of pollutant behaviour in the environment; pH affects both ion-solution chemistry and mineral surface chemistry. Metal adsorption to mineral surfaces is typically lowest at acid pH and increases as solution pH approaches 7. In general, most metals will be largely removed from solution at high pH by adsorption to mineral surfaces or precipitation reactions (Figure 5).

In the StormFilter study, analyses indicated that lead and some copper in influent stormwater were likely removed through both physical (trapping) and chemical (adsorption and/or precipitation) mechanisms. In contrast, zinc removal most likely occurred only through chemical reactions (surface adsorption and precipitation).

Specific adsorption of copper, lead and zinc to organic and hydrous oxides is known to occur in the preferential order: lead > copper > zinc (Alloway, 1995). The results of StormFilter work showed that the availability of iron, manganese, and aluminium oxide surface functional groups was particularly important with respect to zinc retention by filter media. The capacity for formation of strong chemical bonds between phosphate (PO_4^{3-}), the form of phosphorus used in these experiments, and iron oxide mineral surfaces is well known. In the StormFilter study, phosphorus was removed both by adsorption to oxide mineral surfaces and by the formation of calcium phosphate mineral precipitates. Thus, both the iron oxide mineral content as well as the content of available calcium in filter materials had significant impact on phosphorus removal from stormwater.

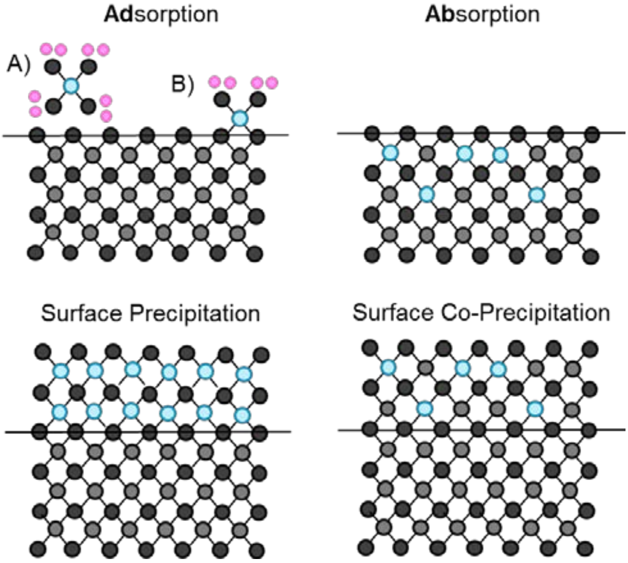


Figure 5. Metal sorption and precipitation processes on mineral surfaces. Adsorption can occur through electrostatic attraction or outer-sphere complexation (A, non-specific adsorption) or through the formation of chemical bonds/ inner sphere complexation (B, specific adsorption) to the mineral surface.

The StormFilter project demonstrated that engineered stormwater infiltration systems containing individual filter materials or select combinations of reactive filter media can significantly improve stormwater quality. Despite the application of high loading rates, none of the studied filter systems demonstrated a complete loss of capacity for copper, lead, zinc or phosphorus removal from influent stormwater. Pollutants in stormwater surface runoff are characteristically dilute, and therefore materials with a high capacity for pollutant removal can have a lengthy effective lifespan. In the absence of clogging by total suspended solids, filter media deployed within an appropriately dimensioned stormwater management structure could effectively remove copper, lead, zinc and phosphorus for 5–10+ years (Wendling et al. 2017a, 2017b).

3.2 Filter materials available in Finland

A number of different materials potentially appropriate for use in stormwater filtration systems are readily available in Finland (Table 9). The materials studied in StormFilter project and the companies producing these materials are highlighted in Table 9 by **red text**. Inclusion of materials other than those assessed during the StormFilter project does not indicate an endorsement of their use. With the exception of filter materials already tested during the StormFilter project, further examination of each filter material's fit-for-purpose use in stormwater treatment is necessary prior to implementation to ensure suitability. Additional information regarding filter materials and producers from Table 9 can is available from Loukkaanhuhta et al. (2016). Detailed information about individual materials' technical properties is available by request from the respective suppliers.

Table 9. Bio- and mineral based filter materials available in Finland.

Products type/Producer	Information
Sand and aggregates	
Sibelco	Quartz sand produced in Nilsiä; 0.7–1.2 mm, 1–2 mm, 3–5 mm
Viasveden Hiekka- ja Kuljetusliike Oy	Quartz sand produced in Pori; 0.8–1.2 mm, 1–2 mm
Seepsula	Sands and gravels
Processing Oy	Various filter materials in stock e.g. different kinds of sand
Finnsementti Oy	Crushed materials: limestone, granite, gabro, kyanite, dolomite, quartz
Rudus Oy	**SSr 0–16 mm**, sieved natural Finnish gravel; **KaM 0–5 mm**, crushed and sieved Finnish rock
Activated carbon	
KW-Filter Oy	Wide selection of activated carbon products

Products type/Producer	Information
Haarla Oy	Range of activated carbon products for e.g. water treatment
Akva Filter Oy	Importation of different kinds of water treatment materials e.g. activated carbon
Processing Oy	Various filter materials in stock e.g. activated carbon
Polynova (Finnish sales representative for the Jacobi Carbons AB)	Activated carbon designed for water treatment
Biochar	
Noireco Oy	**Biochar** for several purposes e.g. for soil amendment (biochar producing temperature over 350 °C)
Biolan Oy	Biochar for their gardening topsoil blends. Also studied as a greywater filter material (Basnet 2015)
Porous expanded aggregate	
Leca Finland Oy	**Leca® 0–3 mm and 3–8 mm crushed; 2–4 mm round** + other size fractions available
Leca Norge As	Different kinds of filter materials produced from expanded clay (**Filtralite®-P**)
Perlite	
Nordisk Perlite ApS, Denmark	Perlite for various purposes; produced in Denmark, importer Nutriforte Oy
Zeolite	
Processing Oy	Various filter materials in stock e.g. zeolite
Suomen Ympäristö-Pro Zeolit Ky	Product Zeolit-Ego TM (50% calcium carbonate, 50% zeolite)
Crushed Autoclaved Aerated Concrete (CAAC)	
Xella Finland	Ytong, CAAC 0.2–4 mm
Rudus Oy	Betoroc, contains CAAC but also bricks, mortar and concrete
Wollastonite	
Nordkalk	Micro-sized wollastonite for ceramics and plastic/rubber applications, from quarry in Lappeenranta
Slag	
Tapojärvi Oy	Rock material produced from the slag in the valorisation plant (Tornio)
Finnsementti Oy	KJ400, ground granulated blast-furnace slag
Peat	
Vapo Oy	Range of **peat based products**
Turveruukki Oy	Various peat products

Products type/Producer	Information
Oxide minerals	
Haldor Topsoe A/S (HQ)	Product CK-395 manganese oxide + alumina, spherical 3–5 mm diameter catalyst material
Kemwater ProChemie Ltd.	Aluminium-based products that are mainly used for water treatment and purification
GEH Wasserchemie GmbH&Co. KG	Range of granular iron hydroxide products
LANXESS Deautchland GmbH	Bayoxide® E33 ferric oxide water filtration media
Lime products	
Nordkalk Oy	Filtra A and Fostop. Filtra A for increasing alkalinity as a part of the water purification process. Fostop for reducing phosphorus leaching.
Biofiltration substrate/ biological soil	
Enregis GmbH Haveno Oy (importer in Finland)	Biocalith MR-F1; Biofiltration substrate
Other low cost materials	
	E.g. bark, sawdust, clay, moss; easy availability; the physical and chemical properties of the materials are not standardised for water treatment

3.3 Filter material cost

Decision-making regarding stormwater management solutions requires understanding of the associated costs and benefits. The benefits of improved quality of stormwater surface runoff are generally difficult to quantify (value of water quality). The costs, however, can be relatively straightforward. Costs based on the stormwater treatment system design and anticipated lifetime can be estimated for system installation, maintenance, and operation, annually or over the full lifetime of the filter. The monetary cost of alternative proposed stormwater treatment systems and their respective expected performance can be compared against one another to identify an optimal solution for a given scenario.

The total cost of a stormwater treatment system is comprised of several components, each of which contribute individually to the total cost of the system; the price of filter material is only one component of the total cost. Indicative prices for selected types of filter materials from Finnish suppliers are shown in Table 10. These prices are estimated assuming purchase of 30 m^3 of filter material, representing the estimated volume used in a biofilter system for a 200 m long green street design. No VAT or transportation costs are included in the indicative prices for each material.

Note that in practice some materials would typically be used in a mixture (for example, biochar with sand/gravel); indicative unit prices provided here are for one cubic meter comprised of 100% of the filter material in question.

Table 10. Indicative unit price (euros per cubic metre, €/m^3) of representative stormwater filter materials in 2017.

Material	Indicative price (€/m^3)[a]
Sand	7–10
Aggregate[b]	14–15
Crushed rock[c]	7–8
Crushed macadam	20
Biochar	200
Leca® products	40–75
Filtralite® P	115
Peat	50–60

[a] Costs shown in table assume purchase volume of 30 m^3, do not include VAT or delivery
[b] Aggregate similar to KaM 0/5 used in StormFilter investigation
[c] Crushed rock similar to SSr 0/16 used in StormFilter investigation.

3.4 Material testing and evaluation methods

The pH of a filter material is a key variable, which influences how pollutants behave in the environment and which is simple to measure. In fact, pH is commonly referred to as one of two ‘master variables’ intimately associated with chemical, biochemical and biological processes in the environment.

The second master variable is oxidative-reductive potential, or redox potential. Here, we assume that the stormwater filter systems are appropriately scaled to facilitate short hydraulic retention time, i.e. prevent long-term water saturation of filters. Where filter systems become flooded and influent stormwater remains ‘standing’ in the filter for a lengthy period of time it is possible that the system may become de-oxygenated or chemically reduced. This can have negative consequences on water quality, not the least of which is reduced oxygen content. Selection of appropriately permeable filter materials and sufficient scaling of stormwater filter systems to handle heavy precipitation events, thereby ensuring an appropriate hydraulic retention time, can prevent the onset of chemically reducing conditions.

Where chemically reducing conditions are desired as part of the water treatment process, for example to reduce nitrate nitrogen (NO_3-N) to nitrogen gas (N_2), intensive monitoring of redox potential, nitrogen species, and easily reducible carbon content or carbon to nitrogen ratio is required to ensure that release of intermediate products nitrite (NO_2^-), nitric oxide (NO) and nitrous oxide (N_2O) is limited. Nitrous oxide is a greenhouse gas with a global-warming potential approximately 320 times that of carbon dioxide (CO_2), largely due to the ca. 120-year atmospheric lifetime of nitrous oxide.

3.4.1 Filter material pH

The pH of a solid material is typically evaluated as the pH of the material in suspension. In aquatic ecosystems (Figure 6), harmful effects of pH may become noticeable at pH <5 or pH >9 (Svobodova et al. 1993). This range is approximate, however, as some species may be more or less tolerant to changes in pH. Indirect effects of pH change, such as increased aluminium availability or the presence of ammonia, can have detrimental impacts on aquatic ecosystem integrity (Connell & Miller 1984, Smith 1990). Solid filter material with pH less than 5 or greater than 9 may have no significant impact on the surrounding biota. The critical factor is the pH of effluent from the filter that is discharged to a receiving water body.

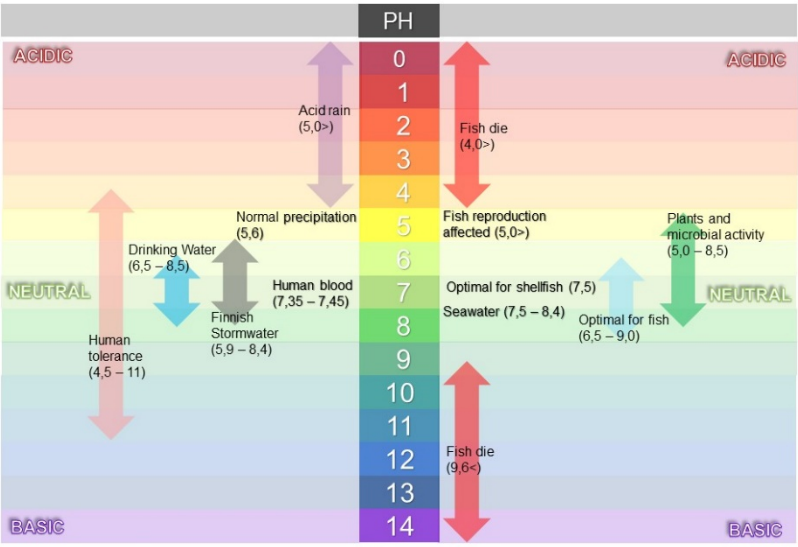


Figure 6. Water pH and the aquatic environment.

Fish begin to die when pH falls below 4.0 (EPA 2012). Any form of precipitation with a pH level less than 5.0 is considered acid rain. Natural, unpolluted rain or snow is expected to have pH levels near 5.6, assuming a standard atmospheric CO_2 concentration of 0.0355% (Dowdey 2017; Hakanson 2005). Harmful effects to aquatic biota become noticeable when the pH of water falls below 5.0 or rises above 9.6 (MDDNR n.d.). In general, fish reproduction is affected at pH levels below 5.0. Humans are able to consume water with pH ranging from 4–11 with minimal gastrointestinal irritation (Fink 2005). However, water with pH less than 6.5 or greater than 9.5 can damage and corrode pipes and other systems, further increasing heavy metal toxicity (Czuba et al. 2011). The pH of most raw water lies within the range 6.5–8.5. The optimum pH will vary in different supplies according to the composition of the water and the nature of the construction materials used in the distribution system, but is often in the range 6.5–9.5 (WHO 2003).

The solid-to-liquid ratio is a significant parameter in the material pH measurement because as the proportion of water changes relative to the solid phase, the pH is likely to also change. Therefore, it is important to use a consistent solid-to-solution ratio when measuring and comparing the pH of different solid materials.

In soils, the pH of the solid material may be measured in a 1:1 mixture, or ‘paste’, of ground, air-dry soil in deionised water (Thomas 1996). Another simple pH determination method specifies a 1:5 ratio of solid material in deionised water (Rayment & Higginson 1992). This method can also be used to simultaneously determine the electrical conductivity (EC), which provides an indication of the relative quantity of soluble salts associated with the solid material.

In general, pH 5.0–8.5 is considered acceptable for plant growth and microbial activity (McBride 1994). Note that a filter material exhibiting measured pH outside this “acceptable” 5.0–8.5 range can still be well-suited to use in environmental applications. The filter material may not be in contact with plants due to filter depth or design, the filter material may comprise only a proportion of the total filter bed, or it may be may mixed with other materials that can modify its impact on effluent pH. In addition, the residence time of stormwater within the filter may be substantially less than the time necessary for equilibration in pH measurement methods, and the relative volume of water treated per unit mass of filter material will likely be substantially greater than that used to measure solid material pH.

Material testing in a flow-through configuration such as a column should be undertaken prior to full-scale implementation if the material pH is less than 5.0 or greater than 8.5. This testing should evaluate the effect of hydraulic retention time and solution ionic strength on effluent pH.

3.4.2 Determination of pollutant capacity

Batch tests, wherein a solid material is placed in contact with an aqueous phase for a specified period of time, are a common means for determining the capacity of a material to adsorb a given contaminant. These tests represent a closed system in that after the initial addition of reactants, no further reactants are added and products are allowed to accumulate. A number of different techniques may be employed, with variations on the main parameters:

- Quantity and form of solid material
- Material-to-solution ratio
- Solution pH
- Solution composition
- Contact time
- Form of agitation
- Temperature.

When determining the values of the experimental parameters listed above it is important to consider the likely conditions of material application. For example, will the filter material be further processed prior to application or used “as received” from the manufacturer? What are the likely characteristics of the water that will be filtered? What is the maximum realistic contact time envisioned between the water and filter material in an application scenario?

For example: the batch technique used in the StormFilter project to estimate each filter material's capacity for sorption of copper, lead, zinc and phosphorus from stormwater employed a solid-to-solution ratio of 1:10 (Wendling et al. 2017a). The materials were used on an "as-received" basis with no further modification. The test solution contained all pollutants of interest as interaction among pollutants can increase or decrease apparent sorption by the solid filter material. Sealed containers with the solid filter material and stormwater solution were mixed end-over-end for 24 h. Thorough mixing is important to ensure unlimited contact between the solid material and the solution.

The contact time selected can vary considerably depending on the type of reactions of interest (Figure 7), and on the planned material application. Many ion exchange and sorption reactions can occur within minutes whilst other reactions may be considerably slower. The important consideration with respect to reaction time is that it is approximately the same order of magnitude as the anticipated duration of contact between filter materials and influent water in the deployed filter. A series of batch sorption tests in which the contact time between the solid and aqueous phase varies whilst all other variables are constant can be used to examine the rate of the reaction (reaction kinetics).

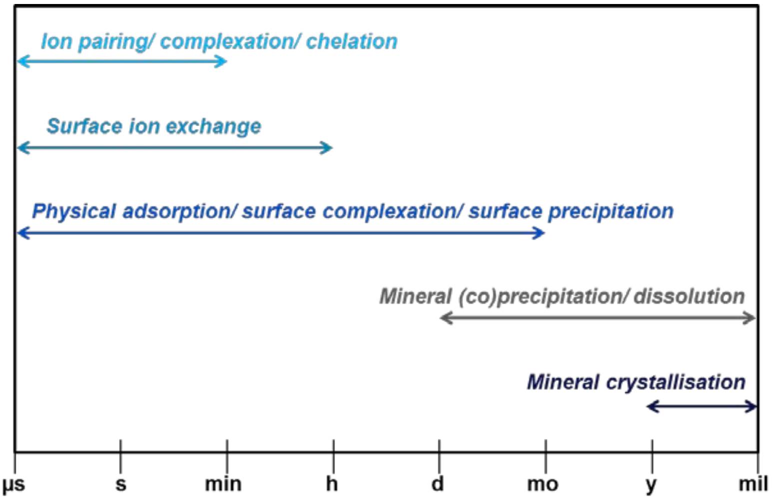


Figure 7. Approximate timeframe required to attain equilibrium by different types of mineral-solution reactions (adapted from Selim & Amacher 1996).

Batch testing is also useful to examine how a single variable, for example pollutant concentration, solution pH, or reaction temperature, affect interactions between the solid and solution phase.

3.4.3 Pre-installation material performance testing

Flow-through tests using fixed beds or columns are widely used to investigate reactive transport of pollutants, including sorption/ desorption, transformation, leachability, and similar parameters. These flow-through experimental systems are open systems, where solute (the influent solution) is continuously added and reaction products continuously removed in effluent. In comparison with batch tests, material examination using flow-through tests more realistically mimic field conditions, particularly with respect to solid to solution ratios.

Flow-through tests are particularly useful for the optimisation of filter components and configuration. Changes in operating parameters, for example the effect of flowrate or hydraulic retention time on pollutant removal, can be used to optimise filter design parameters.

Medium-scale, or meso-scale, testing under controlled conditions can be employed prior to “real world” deployment to further validate material performance and examine the scalability of filter system design. Pilot testing of filter design and performance under ambient environmental conditions will provide additional filter system performance validation. Testing of filter systems at the pilot scale is strongly recommended prior to full-scale implementation in order to identify potential issues and verify suitability of the filter system for the targeted application.

3.5 Filter material selection

Major considerations in the selection of filter materials for treatment of stormwater surface runoff include filter material porosity and permeability, as well as pollutant removal capacity. The physical character of the filter material used is significant because it determines a system’s stormwater pollutant trapping potential. Small particles have a large surface area relative to their volume. Therefore, the smaller the average size of the individual particles in a filter material, the larger the total surface area per unit volume. The total surface area available for reaction with pollutants is important because it determines the total maximum quantity of pollutant that can be adsorbed per unit volume of filter material. Particle size is also important because small particles have small pore spaces between adjacent particles and can trap particulate material more easily than large particles with large adjacent pore spaces.

Important structural characteristics of a material which strongly influence its suitability as a filter medium include porosity and permeability. A material’s *porosity* is the fraction of void space within the solid phase. For porous materials it is important to consider both internal and external porosity. Internal porosity is defined as the available pore volume in the filter aggregate, and external porosity is the volume (space) between the aggregates. *Permeability* is related to porosity, but represents the resistance of a material to water movement. The distribution of pore sizes and their relative connectivity strongly influences a material’s permeability.

Water will move more easily through solid media with relatively larger mean pore diameter. The dominance of larger pore spaces (i.e. macropores >80 µm) in coarse sand yields relatively low porosity but high permeability. In contrast, a clay may have relatively high total porosity but low permeability due to the large proportion of small pores (i.e. micropores and nanopores <80 µm). Water and air movement through micropores is restricted relative to larger pore spaces.

Table 11. Size classification of pore spaces and relevant functions (adapted from Brady & Weil, 2008).

Simple class	Pore class	Diameter (µm)	Characteristics
Macropores	Macropores	80–5000	Water drains by gravity; effectively transmit air; accommodate plant roots
Micropores	Mesopores	30–80	Retain water after drainage; transmit water by capillary action; accommodate root hairs
	Micropores	5–30	Found within aggregates or granules; retain water that plants can access
Nanopores	Ultramicropores	0.1–5	Found within clay-sized material; retain water unavailable to most plants; water movement through diffusion
	Cryptopores	<0.1	Exclude microorganisms & large molecules

When selecting filter media it is critical to achieve a balance between high treatment efficiency and high hydraulic loading capacity. As particle size in a solid material decreases, the specific surface area increases. As a result, an equal mass of small-sized particles will have more surface sites for pollutant adsorption compared with larger particles of the same solid material. The mean particle size of filter materials must be sufficient to avoid flooding due to low water permeability/ low hydraulic loading capacity.

Hydraulic retention time, or hydraulic residence time, is a function of material permeability and refers to the length of time that the influent water remains in contact with solid filter materials. Filter material selection, and system design and scaling seek to create optimal flow conditions through the filter that allow adequate time for pollutant interaction with solid filter materials without risk of flooding during intense rainfall events (e.g. cloudbursts).

The required minimum rate of water infiltration, or hydraulic loading rate, of a filter system will vary by location and application. Hydraulic modelling should be used to estimate hydraulic loading under a range of precipitation scenarios. Filter material selection and system design should then be based upon estimated filter capacity and hydraulic loading requirements to optimise surface runoff treatment and minimise risk of flooding.

Previous work has demonstrated that lead in urban surface runoff is largely particulate-associated, whereas copper is typically present in both dissolved and particulate form and zinc is usually dissolved (Prestes et al. 2006, Tuccillo 2006). For this reason, filter material pore size distribution and the relative tortuosity of the infiltration pathway are significant parameters with respect to the retention of lead and similar particulate-associated pollutants. In contrast, material surface reactivity (cation exchange capacity, CEC) and total surface area are more important parameters for treatment of zinc and other dissolved pollutants. It is also important to take into account the possible structural changes in the filter media due to e.g. drying, compaction or siltation. The structural changes and even clogging of the system may also occur because of the settling and sedimentation of coarse solids on the surface of the structure and trapping of finer particles in the filter media. Vegetation can help to maintain permeability of the system by penetrating the filter media with roots and mechanically stabilising filter media, and by providing pathways for water flow. Vegetation or a mulch layer above the filter media can also reduce long-term compaction of the system.

3.6 Practical service life of filter

The service life of a stormwater treatment filter depends upon the capacity of the filter material for pollutant retention, the mechanism(s) of interaction between the pollutants and the filter material, and the total pollutant load received. A simple, rough estimation of filter service life involves determination of the cation exchange capacity of the solid filter media. If approximate characteristics of the influent water and influent volume per unit mass of filter material per unit time can be estimated, it is possible to roughly calculate the length of time that the filter material will possess cation exchange sites available for pollutant cation sorption.

For example, consider a 30 m^3 filter strip which contains 90 vol.% clean quartz sand (CEC = 0) and 10 vol.% filter material, equivalent to 160 kg/m^3, with CEC of 100 mmol$_c$/kg. The total cation exchange capacity of the filter system can be estimated by multiplying the mass of reactive filter material by its CEC:

$$30\ m^3 \times \frac{160\ kg}{m^3} \times \frac{100\ mmol_c}{kg} = \frac{480000\ mmol_c}{filter\ system} \qquad \text{Eq. 1}$$

Further assume that the filter system is estimated to treat an average of 300 000 L per year of stormwater with mean pollutant concentrations of 0.5 mg/L Cu, 1.0 mg/L Pb, and 2.0 mg/L Zn. Metal cation concentration can be converted to unit of mmol$_c$ per unit volume, for example:

$$\left(\frac{0.5\ mg\ Cu}{L} \times \frac{1\ mmol\ Cu}{63.5\ mg\ Cu} \times \frac{2\ mmol_c}{mmol\ Cu}\right) + \left(\frac{1.0\ mg\ Pb}{L} \times \frac{1\ mmol\ Pb}{207\ mg\ Pb} \times \frac{2\ mmol_c}{mmol\ Pb}\right) + \left(\frac{2.0\ mg\ Zn}{L} \times \frac{1\ mmol\ Zn}{65.4\ mg\ Zn} \times \frac{2\ mmol_c}{mmol\ Zn}\right) = \frac{0.087\ mmol_c}{L} \qquad \text{Eq. 2}$$

This cation concentration in mmol_c per unit volume, 0.087 mmol_c/L, can then be multiplied by annual influent volume 300 000 L to obtain the estimated annual cation load to the filter:

$$\frac{0.087\, mmol_c}{L} \times \frac{300000\, L}{year} \cong \frac{26000\, mmol_c}{year} \qquad \text{Eq. 3}$$

Recall that the total CEC of the filter system was 480 000 mmol_c (Eq. 1). Dividing the estimated filter system capacity for metal adsorption (total CEC) by the estimated annual cation load to the filter yields a rough estimate of 18 years' filter service life:

$$480000\, mmol_c \times \frac{1\, year}{26000\, mmol_c\, load} \cong 18\, year\ filter\ lifespan \qquad \text{Eq. 4}$$

In reality, the quantity of pollutant adsorbed by filter materials is a function of both the material's spatial proximity to the influent (i.e. distance of the material from influent source) and time. It can be assumed that initially all the surface sorption sites on the filter material are available to adsorb pollutants. Influent stormwater carrying pollutants comes into contact with these surface sorption sites, which gradually become occupied by adsorbed pollutants. As the available sorption sites of filter materials near the entrance to the filter become saturated, pollutants move further into the filter before encountering an available sorption site and becoming adsorbed.

Pollutant adsorption is thus a transient process, with the active region moving downstream from the inlet with time. This idealised pollutant breakthrough curve (Figure 8) represents ideal mass transfer of pollutant from the entrance of a filter to its outlet with continuing pollutant addition in influent water. The break point shown in Figure 8, C_b, indicates the point at which a specified concentration of unadsorbed pollutant is detected in filter effluent. The value of C_b is usually a small proportion of the influent concentration.

A filter is generally considered saturated when the influent pollutant concentration is nearly equal to the concentration of pollutant in filter effluent, i.e. C/C_0 = 0.95-0.99. At this point the filter has essentially zero remaining capacity for pollutant retention. The active adsorption zone is the physical portion of the filter where influent concentration is being reduced from C_0 to C_b. The nature of the pollutant breakthrough curve between break point and filter exhaustion (V_x-V_b), and the total mass quantity of effluent passing through the filter at the break point (V_b) provide important information for filter system designers.

The understanding of adsorption dynamics in filter systems explains why a rough estimate calculated in Eq. 4 cannot accurately predict filter service life. The break through point in Figure 6 is defined by the pollutant concentration that stakeholders are willing to accept in filter effluent. The time or influent volume prior to break through point will vary according to filter material and influent characteristics, the relative affinity of pollutants for filter material surfaces and the mechanism(s) of pollutant retention, material weathering, and other environmental parameters.

Differences in stormwater composition from one location to another, the complexity of pollutant retention mechanisms, physical and biochemical changes within the filter system with time, and the subsequent behaviour of pollutants within a filter system highlight the importance of thorough material and pilot-scale filter system testing prior to full-scale implementation. Increasing adoption of engineered filter systems for stormwater quality and quantity management will yield improved knowledge of filter system performance with time under a range of environmental conditions. This information will allow increasingly accurate estimation of filter system service life.

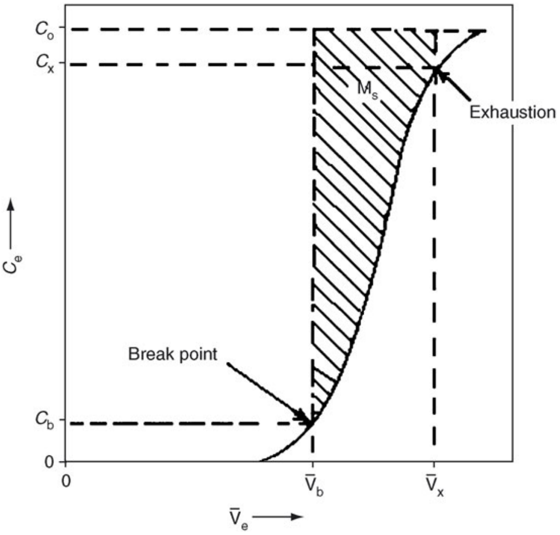


Figure 8. Idealised pollutant breakthrough curve, showing effluent pollutant concentration (C_e) as a function of total effluent volume (V_e). C_0=influent pollutant concentration; C_x=effluent concentration at filter exhaustion; C_b=effluent concentration at break point; M_a = active pollutant mass transfer zone; V = total mass quantity of effluent passing through filter per unit cross-sectional area at breakpoint (V_b) and point of filter exhaustion (V_x). Modified from Ali & Gupta 2006.

4. Modelling tools for enhanced stormwater management

4.1 Modelling concepts and available stormwater models

The key hydrologically relevant characteristics of urban areas with concentrated human activities are the large share of impervious surfaces and an efficient drainage network for conveying surface runoff out of the constructed areas. Computational assessment of stormwater quantity and quality needs to be able to deal with rapid flow volume changes and high levels of a range of different pollutants generated in areas of various human activities. From the modelling point of view, the key hydrological processes and constituent source areas are on the impervious surfaces, whereas the stormwater management is focusing on the control of surface permeability, retention and filtration of surface runoff, and exposing stormwater volumes with biogeochemical processes and water uptake by vegetation.

The modelling tools for stormwater management rest on widely available empirical and statistical models, as well as hydrological, hydraulic and solid/solute transport models designed for simulation of water quantity and quality at different spatial and temporal scales in an urban environment. The model selection and data requirements depend on the modelling objectives, which in practical design purposes typically include:

Catchment scale models

- Estimation of flood, concentration, and load magnitudes of a study area under design storm or during a series of rain storms.
- Sensitivity analysis of key factors controlling surface runoff and pollutant loads from urban areas at different times.
- Simulation how different setups low impact development tools (LID) alter stormwater flow and quality.
- Identification of suitable experimental design for stormwater monitoring based on model simulations.

Site models (e.g. individual LIDs)

- Simulation of water retention time and pollutant removal processes for determining design parameter values.
- Simulation of flow and concentration for short and long term periods.

- Simulation of scenarios for selection of LID alternatives.
- Identification of LID measurement designs.

The model complexity in stormwater models varies from simple lumped models to spatially distributed models. The lumped models are useful for producing initial estimates of catchment behaviour but they are not well suited for analysis of individual small scale LIDs and their impacts on flow and load dynamics. The description of distributed stormwater management systems (e.g. different LID tools) requires a spatial description of the studied area that is sufficiently detailed to host the locations of individual LID solutions (Krebs et al. 2014). Further model complexity is needed if the actual flow and solute behaviour needs to be described within an individual LID.

In the review by Zoppou (2001) the stormwater modelling approaches are classified. The basis for urban water resources planning is provided by continuous distributed models, which support simulation of multiple events in an area with mosaic of different impervious and pervious surfaces. The basic model components are (i) rainfall runoff modelling and (ii) transport modelling as illustrated in Figure 9. The modelling of water quality is strongly dependent on the water quantity, since the pollutant concentrations and loads are related to the flow volumes and dynamics.

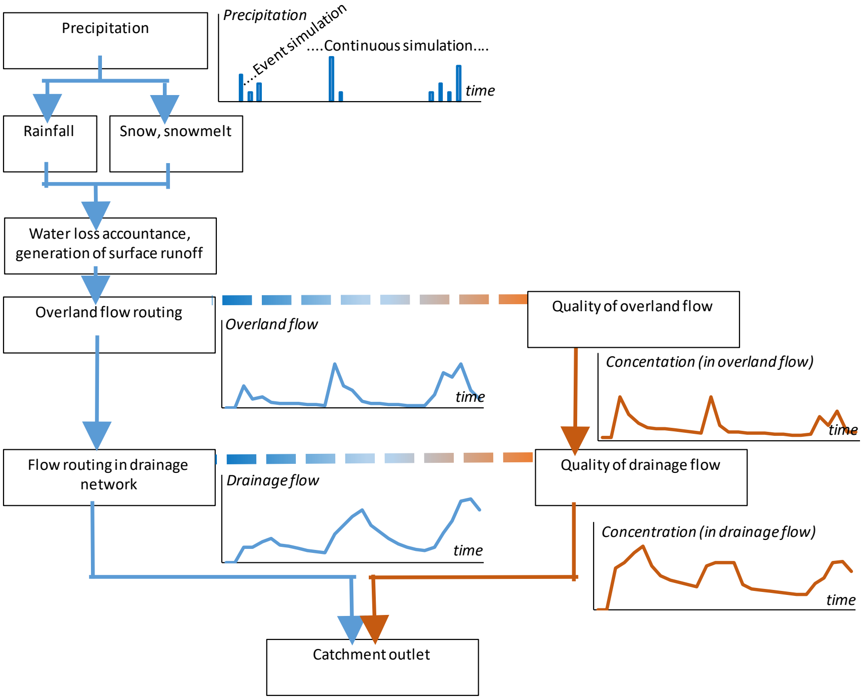


Figure 9. Processes in urban hydrological model (modified from Zoppou 2001).

The rainfall-runoff component simulates generation of runoff and infiltration after losses such as interception, evaporation, and depression storage are accounted for (Figure 9). Surface runoff entering the storm sewer network is conveyed to the catchment outlet and to receiving water bodies. The transport component simulates conveyance of water flow through the system of ditches, storm sewer systems, and ponds to the outlet of a studied catchment.

Optimisation and uncertainty analysis tools are an important aspect of urban water quantity and quality modelling. Available local stormwater quantity and quality data supports detailed calibration and validation of model against data and can secure reliable model behaviour in the studied conditions, as long as the model input data, especially precipitation, has sufficiently high quality (Niemi et al. 2017). From the water quality point of view the uncertainty analysis and a possibility to produce distributions and confidence limits of water quality variables using sampling techniques, such as the Monte Carlo analysis, provides methods to address the typical high variability of constituent concentrations and loads in stormwater (Table 12) (e.g. Suihko 2016, Leinonen 2017).

Table 12. Properties of selected models with respect to accessibility, time modelling scale, spatial description, and LID process description (modified from Zoppou 2001, Elliott and Trowsdale 2007, Ahiablame et al. 2012, Syme 2011, TUFLOW User Manual 2011).

Model (Code)	Accessibility		Time modelling scale		Spatial description		LID descriptions				
	Public domain	Commercial	Event	Continuous	Quasi-distributed	Lumped	Evaporation	Infiltration	Storage	Drainage	Pollutant removal
HSPF	✓		✓	✓	✓			✓	✓	✓	*^{9}
HYDRUS 2D/3D							✓	✓	✓	✓	
L-THIA-LID	✓		✓	✓				*^{2}			
MIKE_SWMM		✓	✓	✓	✓		✓	✓	✓	✓	*^{4}, *^{5}, *^{6}
MOUSE		✓	✓	✓	✓		✓	✓	✓	✓	*^{6}, *^{8}, *^{9}
MUSIC		*^{1}	✓	✓	✓	✓		✓	✓		*^{6}, *^{9}, *^{14}
SLAMM		*^{1}	✓	✓		✓		✓	✓		*^{9}
STORM	✓		✓	✓	✓						
SUSTAIN	✓		✓	✓	✓		✓	✓	✓	✓	*^{4}, *^{5}, *^{6}, *^{9}
SWMM	✓		✓	✓	✓		✓	✓	✓	✓	*^{4}, *^{5}, *^{6}, *^{9}
TUFLOW							✓	✓	✓	✓	
UVQ	✓		✓	✓	✓						*^{9}, *^{10}, *^{11}
WBM	✓		✓	✓		✓			✓		

*^{1} small fee, *^{2} CN method, *^{3}, conceptual, *^{4} linear relationship rainfall minus interception, *^{5} user pecified formulation, *^{6} first-order decay, *^{7} not directly in the LID but in the outlet node, *^{8} advection-dispersion, *^{9} soil loss, *^{10} removal fraction, *^{11} output concentration, *^{12} input hydrograph, *^{13} transport with a time lag or dispersion based on Muskingham-Cunge routing, *^{14} second-order decay

The hydrologic processes are driven by precipitation. Sufficiently detailed information about precipitation is necessary to aim at usable simulation of urban hydrological processes. The modelling of local stormwater flows, and especially estimation of LID impacts on local flows requires accurate precipitation records near the study site with measurement frequency in the order of few minutes. The urban hydrological models need to capture the flashy response of urban catchments to rainfall events. Hourly and daily data support merely crude larger scale estimations of water balance and pollutant loads.

Modelling is beneficial in the identification of the best stormwater management strategy. The target is to secure uncompromised hydraulic behaviour of stormwater system, while reaching the water quality objectives and obtaining low-cost solutions at the same time. Although economic analyses are rarely included in stormwater modelling, Zoppou (2001) points out how different alternatives of economic analyses in conjunction with stormwater modelling extend assessment of stormwater management. The aim is to recognise and quantify different costs such as design, construction and life cycle costs, including maintenance, capital, operating, replacement, disposal and land acquisition costs. Another dimension comes from the inclusion of externalities, which do not have clearly defined monetary value (e.g. nature, security). Decision making benefits from information about both monetary and external factors over the lifetime of the management solutions.

4.2 Building a model for an urban catchment

This section presents a compilation of practical information related to urban hydrological modelling based on recent studies in Finnish climatic conditions (Figure 10). The focus is on distributed models with detailed subcatchment discretization based on land cover types, because these models are needed for modelling decentralised LID systems and diffuse pollution sources. In addition, the free availability of the model and data is emphasised. For this reason, the studies cited here all have been carried out with EPA SWMM (Rossman 2015), which is one of the most widely used urban surface runoff modelling tool for both practice and research. The purpose is not to give detailed instructions for using e.g. SWMM, because practical guidance for its use is easily available from its user manual and supporting reference manuals (Rossman 2015, Rossman & Huber 2016a, 2016b, Rossman, 2017). However, the purpose is to summarise sources of data needed for model building and established parameter values obtained in recent studies for Finnish conditions (Figure 10).

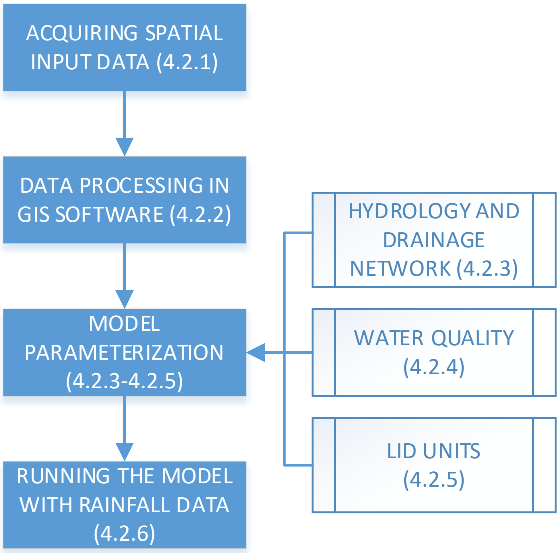


Figure 10. Phases of model development and application. Each phase is further described in the following sections 4.2.1–4.2.6.

According to Rossman and Huber (2016b) subcatchment discretization is defined as the process of dividing a study area into subcatchments that characterise the spatial variability in overland flow routes, surface properties and connections into drainage system. One approach to subcatchment discretization is to divide the catchment area into subcatchments based e.g. on catchment topography and the locations of the inlets to the storm sewer system. This supports simulation of large subcatchment areas with heterogeneous land use types and land cover. The high-resolution models discussed in this section differ from these models so that each subcatchment represents single land cover type (Figure 11). At the same time, the number of subcatchments increases and their surface area decreases in comparison to the traditional approach. In addition, the flow paths within the model become more complex – instead of the direct connection to the sewer system from all subcatchments, most subcatchments are first linked to each other before surface runoff can enter sewer inlet node from its closest subcatchments.

Although the detailed subcatchment discretization requires higher effort compared with the traditional catchment delineation it enables the modelling of decentralised LID systems and the evaluation of source-specific pollutant contributions. This type of subcatchment delineation enables accurate flow routing e.g. around buildings and, hence, it simplifies the modelling of decentralised small surface runoff treatment units, i.e. LID units, and the modelling of pollutant sources and the transport of surface runoff and pollutants through subcatchment areas. An additional important advantage is that detailed discretization of land cover types seems to improve the performance of uncalibrated models (Petrucci and Bonhomme 2014, Warsta et al. 2017). Krebs (2016) proposed such detailed discretisation to be a plausible method of model regionalisation to ungauged catchments without calibration against monitoring data.

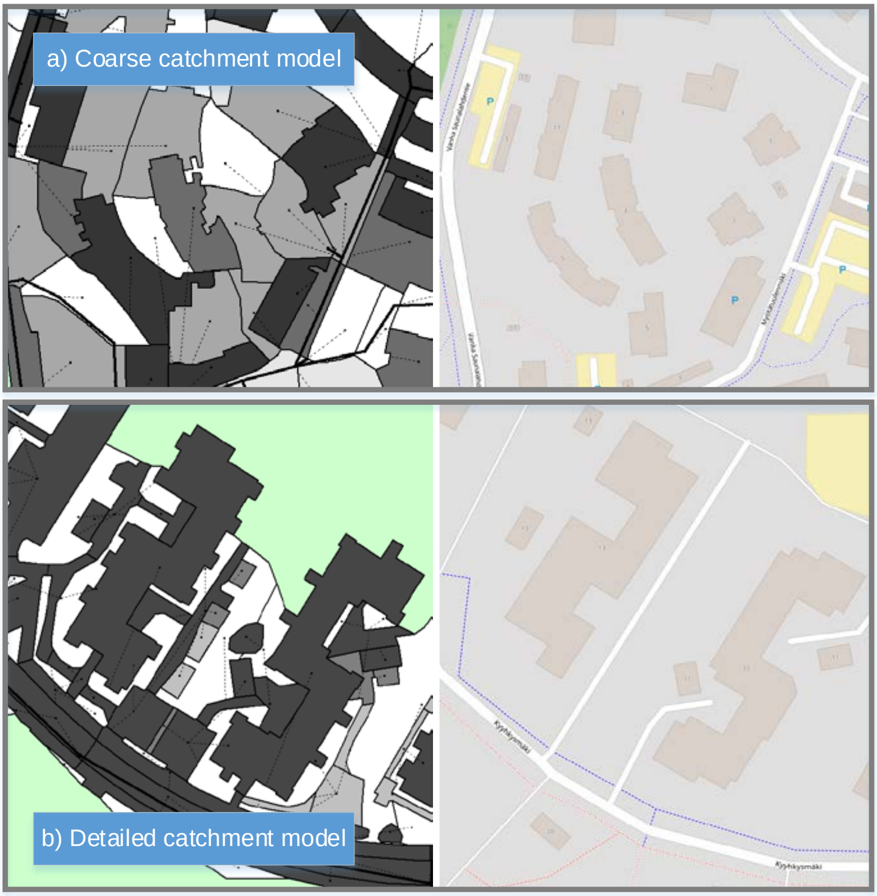


Figure 11. Examples of coarse (a) and detailed (b) catchment discretisations with corresponding map views on the right (provided by OpenStreetMap, www.openstreetmap.org). The catchment layouts were extracted from the EPA SWMM's graphical user interface. Subcatchment areas are colour coded from white (100% pervious) to dark grey (>80% impervious). Green areas in figure b) are outside the catchment border.

4.2.1 Spatial input data

For a high-resolution urban surface runoff model, it is convenient to create model input files using external GIS software and various spatial data sets. The following spatial data sources are mostly freely available and fulfil the basic needs of distributed stormwater modelling:

- Terrain elevation data: digital elevation models, the file service of open data by National Land Survey of Finland (NLS), http://www.maanmittauslaitos.fi/en/e-services/open-data-file-download-service.
- Existing drainage/storm sewer networks: local water utility or municipality
- Bed rock and soil types: digital soil and bed rock maps, digital map service by Geological Survey of Finland, GTK), http://en.gtk.fi/information-services/map_services/.
- Land cover data: online municipal map services, ortophotos (the NLS file service of open data, municipalities), satellite images in online services such as Google Maps (https://maps.google.fi) and Open Street Map (https://www.openstreetmap.org/). Within the Helsinki Region, the HSY land cover dataset is freely available from the HSY website (https://www.hsy.fi/fi/asiantuntijalle/avoindata/Sivut/AvoinData.aspx?dataID=38). Also for larger city areas, a pan-European land use and land cover data set Urban Atlas provided by the European Environment Agency is available (http://www.eea.europa.eu/data-and-maps/data/urban-atlas).

For a specified project, the relevant authorities may be able to provide more accurate data relating to land use, technical systems, constructions, soils, terrain elevation and land cover than the sources mentioned above.

The amount of freely available spatial data is increasing rapidly, especially after the establishment of the INSPIRE Directive by EU commission in 2007. Updated information about the availability of spatial data, their sources, and providers in Finland can be found e.g. in Paikkatietoikkuna service maintained by National Land Survey of Finland (https://www.paikkatietoikkuna.fi/) or in Avoindata.fi that is a centralised repository for Open Data released by Finnish entities.

4.2.2 Processing of spatial data and catchment delineation

Practical guidance for how to use GIS tools to create urban catchment models for SWMM with the spatial data sets listed in Section 4.2.1 are available from the following references:

- Raudaskoski (2016) presents step-by-step guidance on the processing of spatial data using QGIS software. QGIS is a free open source geographic information system (QGIS User Guide, 2017), available for download at http://www.qgis.org/en/site/. The spatial data used for creating a SWMM model file for an 11 ha residential area included a 2 m digital elevation model (from the file service of open data by NLS), and an AutoCAD file of the existing storm sewer network (provided by the local municipal body). Additionally, ortophotos, city maps, Google Maps service and field visits provided necessary information for the detailed determination of the land cover.
- After processing information in a GIS software, spatial information about the subcatchments and the sewer system is converted into a format of SWMM

input file. For example a free software inp.PINS (available at: https://sites.google.com/site/inppins/home) creates SWMM model input files from GIS files.
- When addressing large city areas, the manual pre-processing of sewer data and catchment delineation is a slow and laborious task. Warsta et al. (2017) created the GisToSWMM5 tool for automatic subcatchment discretization and flow routing between subcatchments and storm sewer network. The tool can be downloaded from https://github.com/AaltoUrbanWater/GisToSWMM5.
- Another documentation of the model building process for larger city area can be found in Tikkanen (2013). Tikkanen (2013) created a large-scale SWMM model by processing spatial data including local DEM and storm sewer data with ArcGIS.

It is worth considering all the possible uses for the model already during the processing of spatial data, because the classification of land cover types will form the basis for the model parameterisation. For runoff modelling, impervious and pervious land cover types are separated and in addition, roofs are distinguished from other impervious surfaces due to the different parameter values for surface roughness and depression storage. From the water quality point of view, it is useful to divide impervious areas into land cover types based on differences in their water quality, which leads to separation of roofs, parking lots, walkways and roads. For any model use, it is advisable to separate semi-impervious and pervious land cover types such as pavers, sand/gravel, and vegetated areas.

It is noteworthy that spatial data available in digital form is always incomplete and, therefore, field visits are vital for crosschecking and correcting e.g. missing information about pipe sewer networks, the locations and types of manholes, and the details of land cover information. Nevertheless, even a high-resolution catchment model is always an incomplete description of the reality. Often drainage pipes on private plots are not included in the digital sewer network and runoff from roofs and yards are connected to the nearest node of the public storm sewer network or to a neighbouring subcatchment. Also depending on the spatial scale of the modelling project, storm sewer pipes with a diameter below a certain threshold can be ignored (e.g. Krebs et al. 2014).

4.2.3 Model parameterisation: hydrology and hydraulics

After creating the model files using spatial data, user faces the difficult task of assigning values for various parameters that cannot be directly measured or determined by GIS software. In real life planning and design situations, monitoring data for model calibration seldom exist. Hence, the designers solely rely on values given in user manuals or values well tried in practice. In Finland, several studies have recently been published where on-site monitoring data has been used to calibrate SWMM. Table 13 provides a summary of these calibrated land cover specific parameter values. Additionally, a range and a recommended initial value is given to key parameters, which can be used if no local data is available for model calibration. Detailed descriptions of different model parameters can be found e.g. in Rossman (2015).

The benefit of detailed land cover discretization in model parameterisation is that subcatchments do not need inconsistent parameter sets for impervious and pervious areas. Even land cover types characterised as semi-impervious such as pavers or sand/gravel surfaces, as shown in Table 13, can have consistent parameter values for surface roughness and depression storage for both impervious and pervious parts of the subcatchment. The only difference from the completely impervious/pervious catchments is that the amount of infiltration occurring from these surfaces is restricted by the imperviousness assigned for these land cover types. When the subcatchment discretization is based on homogeneous land cover types, the consistency of the parameter values between the land cover types can be maintained by assuring that the surface roughness and the depression storage usually increase when moving from roofs to other impervious surfaces and from paved areas to gravel and vegetation surfaces.

Some of the most difficult SWMM parameters to define are the soil parameter values. The Green-Ampt method has been a popular choice for infiltration modelling in Finnish urban rainfall-runoff studies. The parameters used to define soil physical and chemical characteristics dictate the extent of infiltration occurring on pervious or semi-impervious land cover types and/or the rate of percolation from unlined LID units into the soil below. Difficulties arise because recommendations of suitable parameter values cannot be found in the user manuals for some typical Finnish soils, such as different types of glacial till. Furthermore, the calibration of soil parameters against onsite monitoring data requires flow data for infrequent, large rainfall events, which usually do not exist owing to the short duration of flow monitoring campaigns. For Finnish urban catchments, some examples of locally calibrated soil parameter values can be found. For a high-density residential area in Espoo, Guan et al. (2015) attained the calibrated SWMM soil parameter values of hydraulic conductivity (mm/h) = 4.21, suction head (mm) = 88.9, and initial soil moisture deficit (-) = 0.217. For a medium-density residential area in Helsinki, Niemi et al. (2018) attained the following calibrated values: hydraulic conductivity (mm/h) = 24.965, suction head (mm) = 55.832, and initial soil moisture deficit (-) = 0.350.

Table 13. Land use/land cover specific parameter values for rainfall-runoff modelling based on studies conducted at small urban catchments in Finland.

		Catchment specific calibrated parameter values					Recommended parameter range		
Parameter	**Land use/land cover type**	*City centre residential, Lahti(1*	*High-density residential, Lahti(2*	*Low-density residential, Lahti(2*	*High-density residential, Espoo(3*	*High-density residential, Espoo(4*	**Min**	**Max**	**Initial estimate**
Manning's roughness n *Catchment properties*	Impervious area						0.011	0.016	0.014
	Asphalt		0.011	0.013		0.016			
	Asphalt/concrete				0.014				
	Gravel		0.03	0.024		0.01	0.01	0.03	0.02
	Stone paver		0.02	0.02		0.019			0.02
	Roofs					0.0084	0.001	0.014	0.01
	Roofs (metal sheeting)		0.001						
	Roofs (sheeting)			0.012					
	Roofs (tiles/sheeting)			0.014					
	Open rock					0.05			
	Lawn		0.168	0.2					
	Lawn/vegetation		0.238	0.3					
	Vegetation/lawn		0.326	0.399					
	Vegetation		0.667	0.79		0.5	0.1	0.8	0.4
	Tree (stand-alone)		0.21						
	Forest			0.668					
	Lawn/forest				0.3				
Manning's roughness n *Sewer/drainage network*	Pipes					0.015			
	Concrete		0.015	0.015			0.011	0.015	0.015
	PVC		0.011				0.011	0.015	0.011
	Open channel			0.049					
	Concrete/PVC	0.011			0.012				
Depression storage (mm)	Impervious area				0.7				
	Asphalt	0.39	0.42	0.62		0.826	0.35	0.85	0.5
	Gravel	2.54	2.49	2.54		0.4	0.4	2.5	1.5
	Stone paver	1.01	0.39	1.09		0.3	0.3	1.1	0.7
	Roofs					0.28	0.1	2.54	
	Roofs (metal sheeting)	0.18	0.1						
	Roofs (sheeting)			0.87					
	Roofs (tiles/sheeting)			2.54					
	Open rock					3.16			
	Lawn	4.98	4.82	5.07					
	Lawn/vegetation		4.22	5.07					
	Vegetation/lawn		3.59	2.54					

		Catchment specific calibrated parameter values					**Recommended parameter range**		
Parameter	**Land use/land cover type**	*City centre residential, Lahti(1*	*High-density residential, Lahti(2*	*Low-density residential, Lahti(2*	*High-density residential, Espoo(3*	*High-density residential, Espoo(4*	**Min**	**Max**	**Initial estimate**
	Vegetation	4.18	4.13	7.53		2.45	2.45	7.6	4.6
	Tree (stand-alone)		3						
	Forest			7.39					
	Lawn/forest				6				
Imperviousness (%)	Asphalt		89	100		94.1	85	100	
	Gravel		33	70		33	30	70	
	Stone paver		87	100		84.9	80	100	

1) Krebs et al. (2013) Urban Water Journal, 10(6): 394–410.

2) Krebs et al. (2014) Journal of Hydrology, 512: 482–497.

3) Guan et al. (2015) Hydrological Processes, 29: 2880–2894.

4) Raudaskoski (2016) Hulevesien hallintavaihtoehtojen mallinnus tiiviissä taajamassa. MSc thesis, Aalto University.

Recommendations for suitable soil parameter values are usually given as per soil types although soil surfaces in urban areas are often compacted and not representative of the properties of native soils. Previous urban catchment studies in Espoo and Lahti have adopted soil parameter values corresponding to the hydraulic conductivity and suction head of silt loam (Krebs et al. 2014) or smaller (Guan et al. 2015). Tuomela (2017), for instance, used values corresponding silty clay loam in LID simulations in order to avoid too optimistic results related to the infiltration capacity of the local soil type, sandy till. To evaluate the uncertainties related to the choice of soil parameter values, it is recommended to produce a range of model simulation results with different soil parameterisations. Raudaskoski (2016), for instance, used two different soil parameter combinations according to the SWMM user manual (Rossman 2015) to evaluate the impact of soil permeability on the performance of different LID techniques for controlling surface runoff quantity. Although in high-density urban catchments such as city centres the soil parameters do not have much importance in stormwater runoff simulations owing to the high catchment imperviousness (Krebs et al. 2013), pervious areas may contribute large amounts of surface runoff during exceptional rainfall events in typical urban catchments. The importance of the correct soil parameters on the surface runoff response has been shown by Guan et al. (2016): during a 60-mm storm in a medium-density residential area in Espoo, the soil parameters corresponding to silty clay loam nearly doubled the amount of surface runoff compared with sandy loam.

4.2.4 Model parameterisation: water quality

The simplest method for estimating pollutant loads from urban areas is the use of representative concentrations, typically an event mean concentration (EMC). In SWMM, the user-defined EMCs can be assigned for different land use types to model pollutant wash-off together with runoff simulation. Detailed subcatchment discretization according to land cover types enables the user to estimate the impact of source area on stormwater quality. Usually local data for EMCs are not available, and hence, literature data is needed. In Finland, Tuomela (2017) investigated the suitability of literature based EMCs for the modelling of source area contributions of different pollutants for a 10 ha high-density residential area in Vallikallio, Espoo. The simulation results were compared with hydrological and water quality monitoring data from the catchment outlet. In Table 14, pollutant concentrations producing the most reliable results compared with the catchment outlet monitoring and other Finnish stormwater studies are presented (Tuomela 2017). These data can be used for estimating the impact of different source areas on catchment scale diffuse pollution. However, as pointed out by Tuomela (2017), simulations conducted with different literature EMCs produce highly variable results reflecting large uncertainties. For this reason, a range of EMC values should be used in modelling.

It is noteworthy that SWMM in its basic form does not take into account the processes affecting the pollutant transport and concentrations along the path from the source areas through a system of connected subcatchments and sewer networks. Tuomela (2017) concluded that the use of constant EMCs tended to overestimate pollutant loads particularly during very rainy periods, when the pollutant concentrations were likely diluted.

Table 14. Event mean concentrations (EMCs) for modelling source area contributions based on literature values (Tuomela, 2017).

		Recommended EMCs(*	**Other combinations from literature references**			
Total suspended solids (mg/l)	Parking areas	**150(a**	1660(c	440(c	173(e	44(g
	Paved walkways	**7.4(a**	20(c	20(c	58(e	46(g
	Roads	**163(a**	242(c	232(f	662(e	64(g
	Roofs	**43(a**	13(c	41(f	27(e	20(g
	Stone/tile pavers	**15.8(b**	20	20	15.8(b	15.8(b
	Sand, gravel	**33.7(b**	810(c	810(c	33.7(b	33.7(b
	Vegetation, lawns	**12(a**	11(c	71(f	397(e	75(g
Total phosphorus (mg/l)	Parking areas	**0.36(c**	0.244(b	0.244(b	0.62(d	1.16(e
	Paved walkways	**0.8(c**	0.8(c	0.8(c	0.8(d	0.8(d
	Roads	**0.62(c**	0.31(c	0.24(f	0.49(d	1.31(e
	Roofs	**0.03(c**	0.1(c	0.14(f	0.04(d	0.15(e
	Stone/tile pavers	**0.36**	0.162(b	0.162(b	0.62	1.16
	Sand, gravel	**0.2(c**	0.155(b	0.155(b	0.2	0.2
	Vegetation, lawns	**0.05(c**	0.05(c	0.07(f	0.2(d	2.67(e
Total nitrogen (mg/l)	Parking areas	**2.2(d**	3.1(c	8(b	2.88(a	
	Paved walkways	**1.1(d**	1.1(c	1.1(c	2.34	
	Roads	**1.6(d**	2.4(c	2.2(f	5.9(a	
	Roofs	**0.8(d**	1.1(c	0.71(c	6.17(a	
	Stone/tile pavers	**1.1**	1.1	0.7(b	2.34	
	Sand, gravel	**1.3(d**	1.3(c	1.6(b	2.34	
	Vegetation, lawns	**1.3(d**	0.94(c	0.95(f	2.34(a	

		Recommended EMCs(*	**Other combinations from literature references**	
Lead	Parking areas	**22(e**	250(c	137(a
(µg/l)	Paved walkways	**17(e**	80(c	107(a
	Roads	**55(e**	180(c	170(a
	Roofs	**21(e**	30(c	69(a
	Stone/tile pavers	**17**	80	107(a
	Sand, gravel	**17**	30(c	107
	Vegetation, lawns	**17**	0(c	9(a
Copper	Parking areas	**15(e**	100(c	80(a
(µg/l)	Paved walkways	**15**	20(c	23(a
	Roads	**56(e**	40(c	97(a
	Roofs	**15(e**	100(c	153(a
	Stone/tile pavers	**15**	20	23
	Sand, gravel	**15**	20(c	23(a
	Vegetation, lawns	**13(e**	0(c	11(a
Zinc	Parking areas	**450(d**	520(c	400(a
(µg/l)	Paved walkways	**60(d**	60(c	585(a
	Roads	**160(d**	180(c	407(a
	Roofs	**310(d**	320(c	370(a
	Stone/tile pavers	**40**	60	585
	Sand, gravel	**40(d**	40(c	585(a
	Vegetation, lawns	**40(d**	0(c	80(a

a) Göbel et al. (2007), b) Gilbert & Clausen (2006), c) Heaney et al. (1999), d) Pitt & McLean (1986), e) Bannerman et al. (1993), f) Duncan (1999), g) Wascbusch et al. (1999)

4.2.5 Model parameterisation: LID units

As in the case of water quality, a detailed catchment discretization into small homogenous subcatchments of specific land cover types allows the user to assign stormwater treatment units within the catchment. For example in SWMM, the LID units such as permeable pavements or green roofs are easily parameterised when LID covers the whole subcatchment area. In the case of bioretention (also called biofiltration system or raingarden), the surface area of the structure can be adjusted as a certain percentage of the subcatchment area, e.g. 5% of the subcatchment. Table 15 provides examples of parameter values for permeable pavements, biofiltration systems (bioretention cells, raingardens) and green roofs based on recent Finnish studies.

SWMM can be applied to simulate the water balance of a LID unit, but SWMM does not take into account pollutant processes within LID units. Since SWMM produces water balance output for all LID units individually, the computation of pollutant retention within LID units can be accomplished in other programs outside of SWMM. To take into account pollutant reduction within the LID units, Tuomela (2017) calculated pollution reductions externally to SWMM based on literature values of load reductions for different LID types. Suihko (2016) and Leinonen (2017) used firstly

SWMM to produce water balance of a small catchment draining into road area filtration system as a single LID unit, and secondly estimated LID pollutant mass balance in spreadsheet outside of SWMM to estimate impact of water mixing on LID pollutant concentrations. They used the simulation results to determine a target level for pollutant removal efficiency.

Table 15. Parameterisations for selected LID units in previous Finnish studies (Krebs et al. 2016, Raudaskoski 2016, Tuomela 2017).

LID Layers	Parameter	Bioretention cell	Permeable pavement	Permeable pavement	Green roof	Additional information
		Tuomela 2017(a	Tuomela 2017(a	Raudaskoski 2016(b	Krebs et al. 2016(c	See detailed descriptions of the parameter values in the source materials.
Surface layer	Berm Height (mm)	200	0	0	30	
	Vegetation Volume Fraction	0.15	0	0	0.1	
	Surface Roughness (Manning's n)	0.6	0.2	0.02	0.168	
	Surface Slope (%)	0.5	*equal to sub-catchment slope*	1.5	8	
Pavement layer	Thickness (mm)		75	50		
	Void Ratio (Voids/Solids)		0.24	0.24		
	Impervious Surface Fraction		0	0		
	Permeability (mm/h)		360 (h	72 (h		Based on the design value ($0.02 \cdot 10^{-3}$ m/s) and the recommended permeability ($>10^{4}$ m/s) for permeable asphalt in Kling et al. (2015)(h
Soil layer	Thickness (mm)	700	400	0	100	
	Porosity (volume fraction)	0.52 (d	0.463 (f		0.41	
	Field Capacity (volume fraction)	0.15 (d	0.094 (f		0.29	
	Wilting Point (volume fraction)	0.08 (d	0.05 (f		0.02	
	Conductivity (mm/h)	119.4 (d	114.0 (f		37.9	
	Conductivity Slope	39.3 (d	48 (f		40	
	Suction Head (mm)	48.26 (d	49.53 (f		61.3	
Drainage mat	Thickness (mm)				3.8	
	Manning's roughness (-)				0.01	
	Void fraction (-)				0.41	
Climatology	Potential evaporation coefficient (-)				0.48	An additional factor for scaling the daily PET rates.
Storage layer	Thickness (mm)	300	300	100		
	Void ratio (Voids/Solids)	0.5	0.43 (f	0.43		
	Seepage Rate (mm/h)	1.016 (e	1.016 (e	10.92/1.02		Equal to the hydraulic conductivity of the surrounding soil.
	Clogging factor	0	0	0		
Drain	Flow Coefficient (mm/h)	5.4(g	25(g	1/5.9(g		Drain parameters are unique depending on the geometry of the LID unit and the desired emptying time.
	Flow Exponent	0.5(g	0.5(g	0.5(g		
	Offset Height (mm)	150	150	0		

a) Tuomela (2017), b) Raudaskoski (2016), c) Krebs et al. (2016), d) Rossman & Huber (2016a), e) Guan et al. (2016), f) Rossman & Huber (2016b), g) Rossman (2015), h) Kling et al. (2015)

4.2.6 Running the model with rainfall data

The basic approach in designing urban drainage networks is to simulate the flow rates during short-term design storms of given duration and frequency. While this approach is necessary and valid as single event analysis, the design of drainage units relying on storage capacity and appropriate emptying times benefit from simulations with varying storm depths and the use of long-term time series with multiple events. The long-term simulations enable the assessment of chronic pollutant loads, the frequency of flooding or overflows from LID units, and the estimation of long-term hydrological performance of LID systems.

Useful, up-to-date rainfall data for urban drainage simulations and their sources are listed below:

- Intensity, duration and frequency of design storms: https://ilmasto-opas.fi/en/ilmastonmuutos/videot-ja-visualisoinnit/-/artikkeli/b4df9633-7e1f-4389-9dd0-a0539588f211/visualisoinnit.html#rankkasateiden-toistuvuus
    - Common design storms of constant rainfall intensity for dimensioning sewer pipes and other structures providing conveyance of peak flow rates in urban drainage systems. The most common design storm in sewer design in Finland is a 10-minute storm of a recurrence interval of 2 to 5 years. It is noteworthy that the duration of the design storm should be equal to the time of concentration of the catchment. Hence, 10 minutes should not be used without estimating the actual time of concentration of the catchment in question.
- Design storms shapes for different return periods based on weather radar observations: https://ilmasto-opas.fi/fi/datat/mitoitussateiden-muotokirjasto
    - Design storms with actual shapes to provide more realistic runoff response for design purposes.
- Long-term continuous rainfall: rainfall data for various locations in Finland can be obtained from the open data service by the Finnish Meteorological Institute FMI (https://ilmatieteenlaitos.fi/avoin-data). This data can be acquired from http://en.ilmatieteenlaitos.fi/download-observations#!/ or using external software, e.g. the FetchFMIOpen tool developed by Aalto University (available at https://github.com/AaltoUrbanWater/FetchFMIOpen).
- Storm depths for 24 h precipitation events with return periods of 10, 20, 50, 100 or 500 years for various parts of Finland: https://ilmasto-opas.fi/en/datat/sateiden-toistuvuustasot
    - These data enable the modelling of exceptional storms of longer duration than the short-term design storms. It is reasonable to assume that these storms produce runoff from total catchment area and not only from the directly connected impervious subcatchments, hence creating an important design event e.g. for storage units.

5. Design for enhanced (Nordic) stormwater management

Filter system design and dimensioning depends on a number of factors, such as:

- the pollutants present in surface runoff
- the size and landscape characteristics of the catchment area
- catchment hydrology and infiltration rates of the native soil
- the presence of groundwater recharge zones or contaminated soils
- location and safe distances of technical systems, buildings and other constructions in the site.

Large detention ponds, infiltration basins and wetlands are typically most appropriate for large sites, e.g. greater than ca. 5 ha. Infiltration trenches, swales, filter strips, rain gardens, and porous pavements and similar designs are suitable for sites of any size, and all can easily incorporate engineered filtration systems such as those investigated in the StormFilter project. Several different types of stormwater management system may be employed within a single catchment area for effective stormwater quantity and quality management.

5.1 Operational environment and aspects of the planning process

In designing of the stormwater management practices, a number of different aspects such as hydrological, technical, economic, functional, organisational and socio-cultural must be taken into account. Close cooperation between designers, various administrative sectors and stakeholders is therefore needed to reconcile different aspects and to deliver a holistic sustainable solution. It is also very important to ensure the continuity of the entire planning process from start to final use by passing on the visions of stormwater management ideas throughout the planning process. In the following checklist the different aspects are considered and in Figure 12 the operational environment of the planning process is described.

In the planning process the full life-cycle of the structure must be considered, and durability and the maintenance needs of the design solutions assessed. The helpful document for the future would be a maintenance plan created during the design process in cooperation of the designers and the responsible maintenance administrative. That would help on the one hand to relay the rationale of the selection of the design solutions to maintenance and on the other hand to ensure that the maintenance of the designed structure is possible to match efficiently with other maintenance practices. In the life-cycle assessment also the lifetime of the structure needs to be estimated based on e.g. the stormwater quality.

The construction phase is critical for the function and durability of the structure. In the planning documents precise instructions for the critical construction phases must be given and particularly the deviations from the normal practices must be pointed out. In the construction phase the role of supervising is emphasised and more guidance than normally is needed. The careful documentation of the construction phase helps to assess the reasons for the possible deviant functioning of the structure afterwards.

When designing stormwater management practices, it would be beneficial to perform extensive and cross-disciplinary cost-benefit assessments on different alternatives (including a life-cycle analysis on current state and future state) in order to find the most holistically sustainable solution.

Checklist of different aspects for designing the stormwater management practices:

Hydrological /functional:

- catchment properties (e.g. size, runoff coefficient) and location of the site in the catchment
- possibilities and needs of stormwater management in the catchment scale (e.g. rain event frequency and volume)
- possibilities to support natural water cycle in the catchment (e.g. infiltration, use of vegetation for evapotranspiration)
- soil and bedrock properties in the site (e.g. soil type, soil depth, bedrock type and bedrock topography)
- groundwater (e.g. water table, significance of the aquifer)
- stormwater quality amounts and types of site-related impurities)
- underground and aboveground space requirements of different stormwater management practices
- possibilities for multipurpose structures
- possibilities for vegetation-covered structures -varying conditions must be taken into account (e.g. soil moisture conditions, micro-climate conditions)
- city plan and plan regulations related to stormwater management
- Winter-time functionality.

Technical:

- location, condition and age of technical systems in the site (e.g. sewer systems, pipes and cables)
- location / spatial pattern of constructions and buildings in the site
- safety distances of technical systems, other constructions and buildings – effective free underground and aboveground space for stormwater systems.

Economic:

- life-cycle of different management practices and the overall economy of the structures
- maintenance needs
- cost-benefit assessments.

Organisational:

- organisational culture of the administrative sectors (e.g. types of cooperation and cooperation network, transparency of the decision-making in the organisation)
- the objectives of the different sectors and stakeholders
- possibilities to organise workshops – improving co-operation, taking all concerns and opinions into consideration and relaying information during the planning process (vision – general plan – detailed plan including aspects related to construction and maintenance)

Socio-cultural:

- perceptions and attitudes of different sectors and stakeholders towards the stormwater management practices (Figure 12).

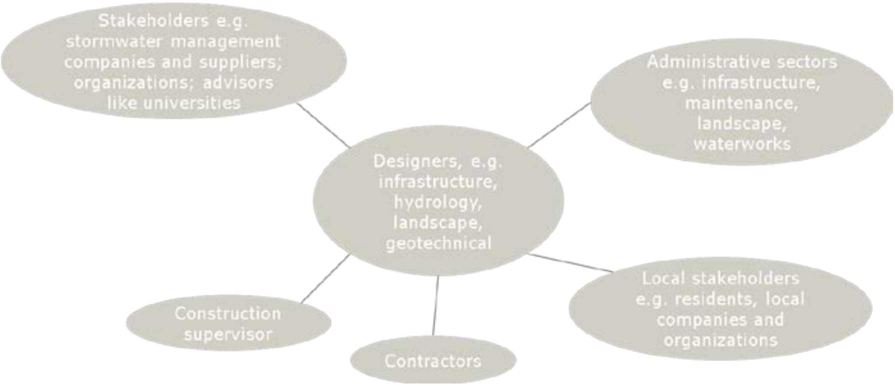


Figure 12. Schematic representation of co-operation among actors in blue-green infrastructure projects.

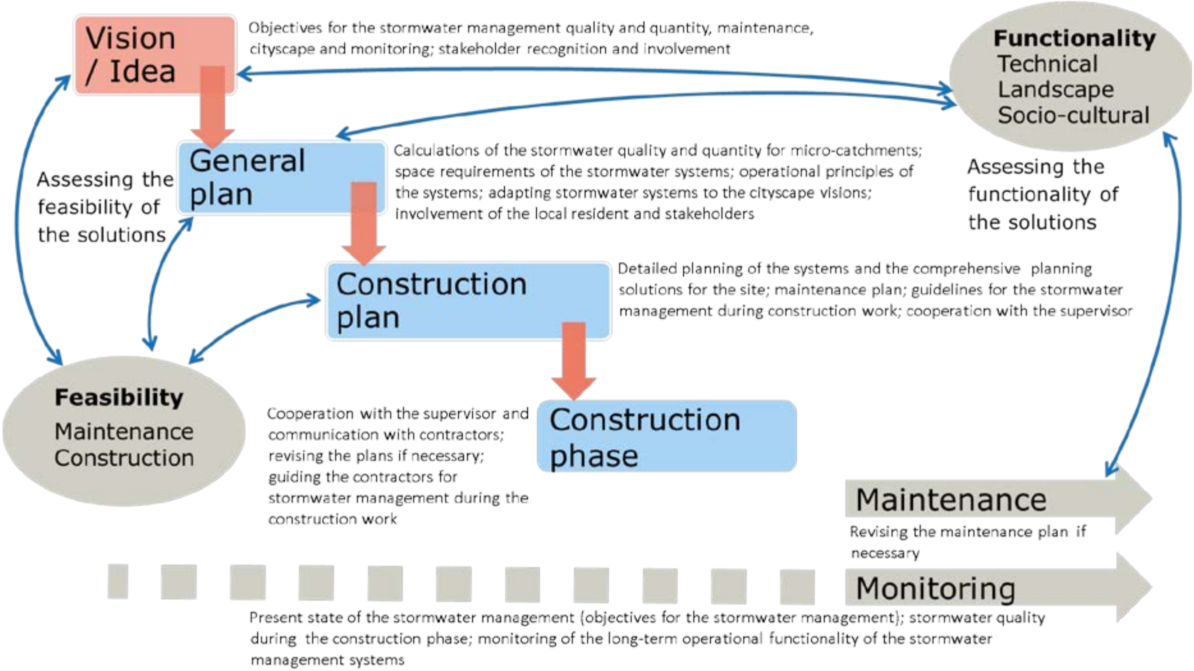


Figure 13. Continuous information chain throughout the planning process, and feasibility and functionality assessment of the stormwater management solutions in all phases are important to achieve holistic, sustainable solutions.

6. System monitoring & maintenance

Infiltration of water through engineered filter systems may deteriorate over time due to clogging of pore spaces. The greatest risk of clogging occurs during the construction phase. Thus, protection of the filter structure is important during its construction. Where stormwater filtration systems are installed as part of a new development, the filter structures should be finalised only after the catchment area has been stabilised after the construction of major infrastructure. Systems that rely on infiltration or filtration cannot cope with the excess loads of suspended solids generated during large-scale construction activities. The rate of infiltration should be routinely measured to assess the need for filter system maintenance or adoption of measures to mitigate clogging.

System maintenance arrangements should be considered during early design phases, as the maintenance requirements are likely to strongly influence stormwater filter system design. The need for heavy machinery in landscape and filter system maintenance should also be carefully planned depending on the type and location of the stormwater treatment system. The use of heavy machinery for filter system maintenance can limit system applicability as a result of more expensive designs and/or larger spatial requirements.

6.1 Monitoring performance

A monitoring programme to evaluate the performance of a stormwater filter system should take into consideration some or all of the following:

- What pollutant removal efficiency is desired or necessary to meet stormwater surface runoff quality objectives?
- How does pollutant removal efficiency vary from one pollutant to another?
- How does pollutant removal efficiency vary with the size of rain event?
- How does pollutant removal efficiency vary with rainfall intensity?
- How does pollutant removal efficiency vary with different maintenance approaches?
- Does pollutant removal efficiency improve, remain the same, or decrease with time?
- How does the pollutant removal efficiency of the filter system compare with other, similar filter systems?

Stormwater management system monitoring can address numerous management, regulatory or programmatic goals. Some performance indicators can be monitored solely through water quality monitoring to provide an indication of system function whilst others may require additional monitoring to obtain meaningful results (Table 16).

Table 16. Objectives of stormwater management and ability of water quality monitoring to provide useful information (adapted from EPA 2002).

Category	Project objectives	Performance evaluation
Hydraulics	- Improve upstream/ downstream flow characteristics	N[1]
Hydrology	- Flood mitigation	Y
Water Quality	- Reduce pollutant load; achieve desired pollutant concentration in outflow	Y
Regulatory	- Compliance with applicable regulatory guidelines	P
Cost	- Capital, operation & maintenance costs	N
Aesthetic	- Improve site appearance	N
Maintenance	- Operate within planned maintenance & repair schedule - Ability of system to be retrofit, modified or expanded	N N
Longevity	- Long-term functionality	Y
Services	- Erosion control - Provision of habitat - Multiple use functionality	N N N
Safety, Risk	- Function without significant risk or liability	N
Public perception	- Improve public understanding of stormwater surface runoff management	Y

[1] **Y** = can be evaluated using water quality monitoring as primary information source; **P** = can be evaluated using water quality monitoring as primary information source with a secondary source of comparative data; **N** = cannot be directly evaluated using water quality monitoring, but may be supported by work associated with water quality monitoring data.

6.1.1 Infiltration capacity

Infiltration rate is a key stormwater surface runoff filter system design and performance parameter, and as such should be regularly checked to ensure the system is operating within design parameters. Infiltration rate is, simply, the speed at which water enters the filter system, typically measured as depth per unit time. A measured infiltration rate of 10 mm/h means that in one hour, a water layer of 10 mm depth on the surface of the filter will enter the filter zone. Kling et al. (2015) recommend that a critical value for infiltration capacity for permeable pavements is 7×10^{-5} m/s (252 mm/h), with lesser infiltration values indicating need for cleaning.

The most common technique for measuring infiltration rate is using a cylinder of ring infiltrometer.

Regular monitoring of the infiltration rate will provide warning if the filter is becoming clogged by particulates and time to take remedial action.

6.1.2 Pollutant removal performance

Water quality monitoring of stormwater surface runoff filter effluent should focus on known pollutant species. Automatic monitoring of water quality parameters such as pH and EC can provide an indication of changes to effluent quality and the need for additional analyses of specific analytes. In addition, regular monitoring of effluent dissolved oxygen (DO) content will provide advance warning of potential deoxygenation of stormwater, e.g. due to system clogging and substantially increased residence time of stormwater within the filter. An example performance monitoring scheme is presented in Appendix A: Performance monitoring of an individual stormwater treatment practice, with further detail available from Assmuth (2017).

Of the metals investigated in the StormFilter project, zinc exhibited the least specific sorption to material surfaces. Thus, the retention of zinc on filter materials was the least ‘stable’ in the longer term. Displacement of retained zinc from filter materials by elements with greater specificity for surface sorption sites would be an indication that the filter’s capacity for stormwater purification has been exceeded and needs to be renewed. Prior to zinc displacement, however, declining rates of zinc retention would indicate that the filter materials were approaching the end of their functional lifespan.

6.2 Filter system maintenance

For filter systems underlying pervious pavements, clogging of the systems can be prevented by proper maintenance action such as cleaning of pavement surfaces if the infiltration rate falls below a desired minimum. For permeable pavements (asphalt, concrete, paver blocks), the cleaning methods include for example sweeping machine, pressure cleaning, and suction. During winter months, sanding of surfaces might cause clogging of the permeable pavements. The particle size of the gritting material should be taken into account to minimise clogging of the pavement or underlying filter system. Typically, this means that gritting materials should be sieved to eliminate the fine fraction from the sanding material.

The longevity of filter systems will be enhanced by the incorporation of a vegetated strip adjacent to the filter inlet to pre-filter particulates in stormwater surface runoff. It is also possible to use a ‘settling threshold’ to pre-filter runoff, e.g. in the streetscape filtration systems. These coarse-paved areas, with the shallow threshold in front of the filter inlet, should be designed to be easy to clean e.g. with street sweeping machines. A gully or sump pit may also be appropriate depending on the filter inlet design and catchment characteristics. A gully can effectively remove larger debris such as leaves via screening, and is most effective for use with a filter that has a single pipe-type entrance to a subsurface filtration bed. Sump pits can similarly be used to capture and screen stormwater surface runoff prior to discharge to a subsurface filter bed. Both the gully and sump pit provide additional opportunity to screen debris from stormwater surface runoff prior to entry to the filter, and can be readily cleaned as part of a regular maintenance regime.

7. Research needs

Engineered stormwater filtration modules yield numerous opportunities for continued improvement in the handling of urban stormwater. Diversity and redundancy within urban stormwater management systems will improve the resilience of urban areas to extreme weather events resulting from global climate change. Decentralised stormwater infrastructure solutions that incorporate engineered filter modules for management of both stormwater quantity and quality can play a significant role in slowing variables and feedbacks related to the urban hydrologic cycle and mass transfer of pollutants. Further, the integration of engineered stormwater filter modules within multipurpose green infrastructure and/or nature-based solutions in urban areas can substantially improve urban hydrologic cycle connectivity, specifically that between surface waters and groundwater.

Additional research in the following core areas will provide essential knowledge to ensure that stormwater management technologies employed are cost effective in the long term, appropriately aligned with water management objectives, and can be tailored to address emerging water quality concerns as needed:

- **Intensive monitoring and characterisation of urban stormwater surface runoff in Nordic cities as a function of land use and land cover**
  - Nutrients, metals and metalloids, trace organic compounds, specific priority pollutants, and contaminants of emerging concern (including microplastics)
  - Exploitation of new sensor and digital data acquisition, retrieval and processing technologies

- **Temperature, moisture and salt effects on stormwater filter media - long-term filter performance in pilot scale studies**
  - Resilience of filter systems to pulses of salts
  - Effects of repeated wetting-drying cycles on pollutant retention and filter performance

- **Optimisation of engineered filter maintenance and monitoring programmes**

- **Quantification of catchment-scale source reduction and pollution prevention as a result of engineered filter system deployment, and identification of priority management zones by land use and catchment characteristics**
    - Integration of spatially distributed stormwater models and process-based biogeochemical models
    - Simulation of urban water quantity and quality using the latest high-resolution climate change projections for urban areas

- **Filter system service life and cost/benefit analysis**
- **The suitability of Finnish native or adapted plant species for various types of engineered filter designs for urban environments**
    - Vegetation growth as affected by road salt and stormwater pollutant content
    - Pollutant uptake by vegetation and fate in the ecosystem
    - Optimal placement of various plant species within or in close proximity to filter media for vigorous plant growth and long-term filter performance
    - Role of vegetation in maintaining good hydrological and hydraulic performance of filtration systems during varying seasonal conditions
    - Examination of the root systems of different species of plants and their effects on hydraulic, hydrologic and biochemical processes in the filter media
    - Optimal filter media for different treatment goals, including long-term plant growth, water retention, and water quality

- **Implementation of stormwater treatment systems during construction works**
    - Suitable stormwater management practices at construction sites
    - Treatment performance of stormwater management practices considering the unique water quality during construction activities, e.g. high solids and nitrogen loads
    - Implementation of stormwater treatment systems during the construction works aimed at providing surface runoff treatment for post-development conditions

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Appendix A: Performance monitoring of an individual stormwater treatment practice

Case: Sand and sand-biochar filtration systems for road runoff in Vantaa

Eero Assmuth, Nora Sillanpää, Antti Auvinen, Harri Koivusalo

Objectives

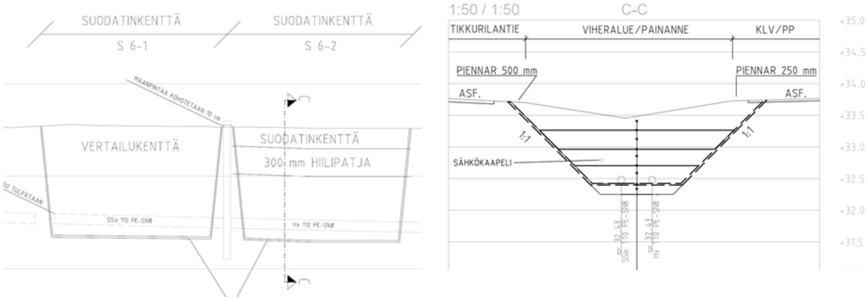
The aim was to demonstrate how an individual stormwater management structure can be designed and instrumented to provide field evidence about the performance of the structure from both water quantity and quality viewpoints. A practical example is presented to outline how the design of two different structures were implemented to support their comparison. The example is the road stormwater filter structures implemented in the city of Vantaa (Assmuth 2017).

Site description

The studied site is located at Tikkurilantie road area in Vantaa, Finland (60°18'52" N; 24°52'52" E). The road was built and paved with asphalt in 2013. Its annual average daily traffic (AADT) is 7610 vehicles per day (2016). The site has two pilot stormwater filters constructed in January 2017 (Figure A1): a sand filter and a sand filter amended with a layer of birch biochar. Both filters are 10 m long and 3.4 m wide, thus having a filter area of 34 m^2. The catchment areas of the filters consist of asphalt road and walkway with total area of ca. 100 m^2 per each filter.

Figure A1. a) Upper part of the filters, highlighted in red. The manholes in front are connected to underdrains that convey water under the walkway to the left. b) Two drain outlets from the sand filter (left) and biochar filter (right) discharging into the ditch next to the road. (Images by Eero Assmuth)

The filters (Figure A1a and A2a) are separated with bentonite mat to prevent water leakage from one filter to another. In addition, bentonite lining prevents percolation from the filters to the groundwater, allowing water infiltration only to subsurface drains (Figure A2b) and further conveyance to an open ditch (Figure A1b) for discharge monitoring and water sampling. This enables precise investigation of the treatment performance of the filters.



a) b)

Figure A2. a) Sectional view of the sand filter (left) and biochar filter (right). Bentonite lining separates the filters from each other and from surrounding ground. b) Cross-section of the biochar filter (Section C-C in Figure A2a). 300 mm biochar layer is the second layer from the top. Subsurface drains are installed at the bottom of the filter, and bentonite lining covers the sides of the filter. Structure of the sand filter is similar but has no biochar layer. (Images by City of Vantaa/Pöyry)

The sand-biochar filter has 300 mm thick biochar layer (Figures A2 and A3b), which is buried deep enough to keep the material fixed at the filtration bed. Biochar has smaller density than stormwater, which causes a risk of biochar being washed away from the surface of the filter. This is prevented with a 200 mm surface layer of sand on top of the filter. In addition, the biochar layer is separated from sand layers with filter fabric to prevent biochar being washed with soil water flow.

Filter dimensioning is based on the design rainfall intensities used by the city of Vantaa, which correspond to 150 L/s/ha for base calculation and 167 L/s/ha for flood calculation. Theoretical catchment area of the filters used for the dimensioning is 15 m x 10 m = 150 m^2 per filtration unit, which forms maximum 2.25 L/s base flow and 2.51 L/s flood flow. As a result, the filtration units with an area of 34 m^2 should have the minimum hydraulic conductivity of 6.6 x 10^{-5} m/s (base) and 7.4 x 10^{-5} m/s (flood). Laboratory tests in July 2016 by VTT confirmed that biochar can be used as a filter material, as the hydraulic conductivity was sufficiently high. The hydraulic conductivity of the tested birch biochar was on average 2.11 x 10^{-4} m/s with standard deviation of 1.8 x 10^{-6} m/s.

The Tikkurilantie experiment was designed as a paired study of the biochar addition in stormwater filters. The two filters were constructed to be as identical as possible, except the biochar layer, and receive surface runoff from the same road area, feeding the filters with a similar influent. For further information on the study site, see Assmuth (2017).

Monitoring of the Tikkurilantie stormwater filtration system

This section describes the monitoring campaign planned for the Tikkurilantie stormwater filtration site. The main aim of the monitoring was to create a cost-effective monitoring program that would be easy to conduct without extensive resources yet maintaining the reliability of the gathered data. In addition to the general performance monitoring of a treatment practice, a specific aim was to compare the performance of two types of filters, sand and sand/biochar filter (see additional details in Assmuth 2017). Further guidance on stormwater monitoring for practical purposes can be found e.g. in Law et al. (2008). The Tikkurilantie filters were supplied with instrumentation and water sampling design to record the quantity and quality of filter inflow and outflow. The monitoring design aimed to fulfil the following requirements:

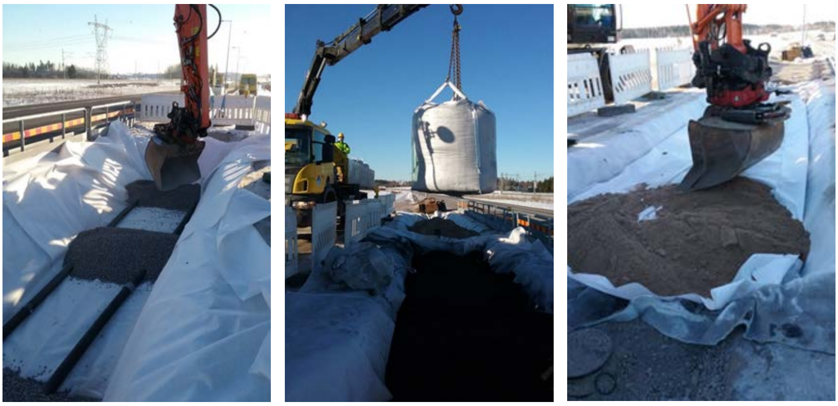
- **The measurements of inflow and outflow volumes should be made with sufficiently high temporal frequency.**
- **The sampling should be representative of the water quality changes throughout the runoff event both in inflow and outflow.**
- **The sampling points (inlet/outlet) should be chosen so that the samples represent the inflow and outflow without mixing with surface runoff from other sources or e.g. backwater from downstream network connections or water bodies.**
- **Water samples should be analysed for water quality parameters important for local management needs.**

Concentrations of the pollutants are highly variable during rain events both in the untreated stormwater (influent) and in the outflowing filtered water (effluent), depending on the rain and flow rate. Therefore, a single water sample from a runoff event is not adequate and is misleading as it describes the runoff and water quality characteristics at one specific time. Instead, several samples should be taken in relatively short intervals during a rainfall-runoff event.

The costs of performance monitoring may restrict the amount of analysed pollutants and number of samples. To overcome this challenge, one solution is to establish long-term programs that focus on sampling of a few storms annually, hence, resulting in several sampled storms over a period of several years. The required number of sampled storms depends on the type of pollutant in question and can be defined based on the methods described in Law et al. (2008) or Järveläinen (2014) and Järveläinen et al. (2017). In general, more sampled events are needed for pollutants that exhibit large temporal concentration variations.

The filters at Tikkurilantie site were studied in high detail during three rain events in summer of 2017. The analysed water quality parameters included:

- pH
- Alkalinity
- Electrical conductivity
- Turbidity
- Suspended solids
- UV-absorbance
- Redox potential
- Total organic carbon (TOC)
- Dissolved organic carbon (DOC)
- Ammonium (NH_4)
- Nitrite & Nitrate (NO_2+NO_3)
- Total Nitrogen
- Phosphate (PO_4)
- Total Phosphorus
- Cadmium (Cd)
- Copper (Cu)
- Lead (Pb)
- Manganese (Mn)
- Nickel (Ni)
- Aluminium (Al)
- Calcium (Ca)
- Chloride (Cl)
- Iron (Fe)
- Magnesium (Mg)
- Potassium (K)
- Silicon (Si)
- Sodium (Na)
- Sulphate (SO_4)
- Zinc (Zn)



a) b) c)

Figure A3. Construction of the filters in January 2017. a) Underdrains and subsurface drainage gravel at the bottom of the filter. b) Addition of the biochar layer. c) Addition of the surface sand layer. (Images by the City of Vantaa)

The number of analysed water quality parameters was high in this study. For monitoring of such filters in practice, the studied parameters should be chosen based on the local management needs and available resources. Monitoring of suspended solids, total nitrogen and phosphorous, bacteria and selected metals – such as copper, lead and zinc – may be sufficient for typical purposes of performance evaluation.

1) Influent sampling

To assess the treatment performance of the filters at Tikkurilantie, the untreated stormwater (influent for the filters) was sampled and local rainfall was recorded (Figure A4b). Because stormwater sampling from the road surface is difficult, substitutive inflow quality samples, following the recommendation of Inha et al. (2013), were taken from a downspout of a nearby bridge (Figure A4a). During intensive rain peaks, the samples were taken in 3–10 minute intervals. About 10 samples were taken per each rain event. Flow rate for the inflow water was estimated using the precipitation measurements and the catchment areas of the filters.

a) b)

Figure A4. a) The bridge downspout used for untreated stormwater sampling. The actual test site is ca. 250 m away. b) Rain gauges at the site used for continuous precipitation monitoring. (Images by Eero Assmuth)

2) Effluent sampling

Flow rates of the effluent from the filters were determined with manual measurements. This is the simplest and most inexpensive method (from the instrumentation point of view), as it requires only a measuring glass and a stopwatch. The flow rate can be measured simultaneously while gathering the water quality samples (Figure A5). Flow rate is calculated as:

$$Q = \frac{V}{t} = \frac{measured\ volume}{measured\ time}$$

Figure A5. Data gathering in progress in June 8, 2017. 3-litre cans were used for quality sample gathering, and 1000-ml measuring glasses for manual flow rate measurements. (Images by Eero Assmuth)

Concentrations of both the untreated stormwater and the effluent from the filters varied drastically between the studied rain events, but also within each event. This is exemplified in Figure A6 showing the rapid changes in the concentrations of suspended solids and in flow rates. The lag between the rain impulse and the effluent flow rate peak depends on the filter and catchment area characteristics.

Figure A6 shows that the influent (stormwater) should be sampled during intensive rain event in short intervals, whereas the effluent from the filters has less rapid changes and the elevated concentrations last longer, and thus require longer monitoring. The effluents were mostly sampled in 15–60 minute intervals.

3) Event mean concentrations

Flow rate at the filter outlet is as important as the concentrations, since together they determine the total load of the pollutants. Even low concentrations with high flow rate lead to considerable loading, and vice versa. Average concentration weighted by the flow rate, known as *event mean concentration* (EMC), is more representative value than simple concentration average. EMCs for each pollutant for each rain event were determined with the following equation:

$$EMC = \frac{\sum_{t=1}^{T} Q_t C_t}{\sum_{t=1}^{T} Q_t}$$

where Q_t is the flow rate and C_t is the concentration at time t (Kaczala et al. 2012; Davis & McCuen 2005). EMCs of the effluents can be compared to the influent and to threshold values (Figure A7).

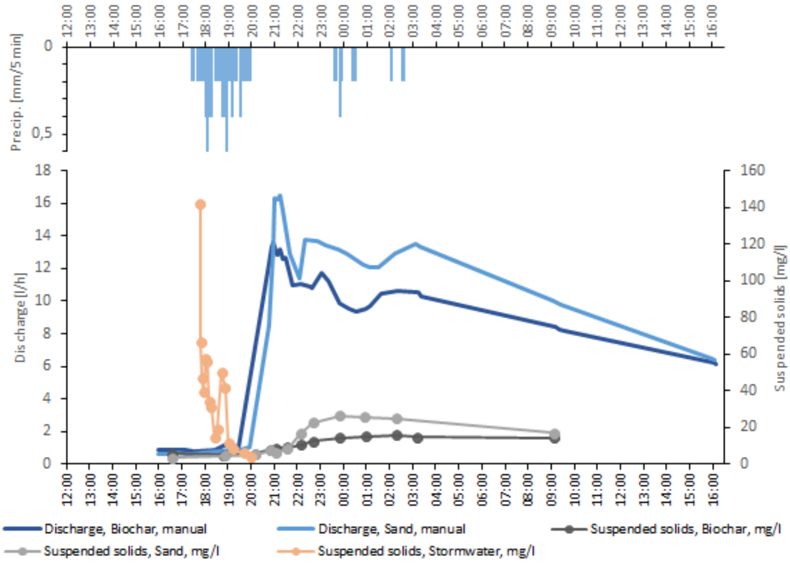


Figure A6. An example of changing concentrations during rain event. Concentration of suspended solids in July 11, 2017. Note the rapid changes in both concentrations and flow rates. (Modified from Assmuth 2017)

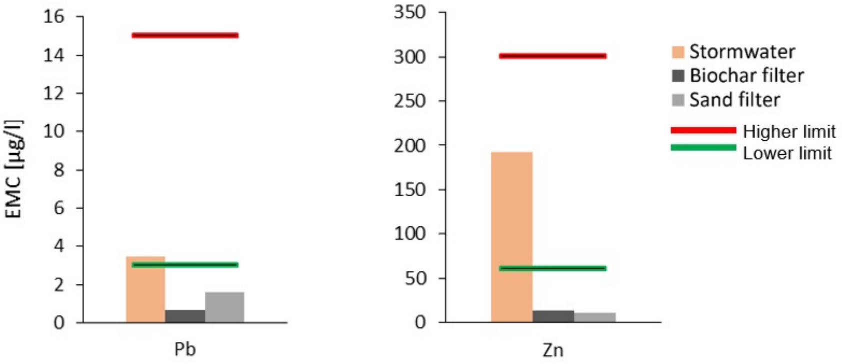


Figure A7. An example of EMC values for influent and effluents. EMCs of lead (Pb) and zinc (Zn) in June 20, 2017. Threshold values by Stockholm Vatten AB (2001) shown with red and green lines. (Modified from Assmuth 2017)

4) Removal efficiencies

Filter performance can be described with different effectiveness measures, *EMC Efficiency* and *Mass Efficiency* being the most common ones (Law et al. 2008).

EMC Efficiency is the ratio of the EMC reduction and the influent EMC (EMC_{in}) (Law et al. 2008):

$$EMC\ Efficiency = \frac{EMC_{in} - EMC_{out}}{EMC_{in}} * 100\ \%$$

When the filter reduces water volume (due to deep percolation and evapotranspiration), it also reduces pollutant loads, even though the concentrations of effluent may increase due to decreasing water volume. In these cases *Mass Efficiency* is a more representative value than *EMC Efficiency*, as it takes into account the water losses in the filter. It is determined as:

$$Mass\ Efficiency = \frac{Load_{in} - Load_{out}}{Load_{in}} * 100\ \%$$

where *Load* refers to EMC multiplied with event water volume. (Law et al. 2008)

Removal efficiencies should not be reported with only one value. For example, reporting just the average efficiency of several events may hide the fact that the treatment performance is not only filter specific but also event specific. This means that efficiency values estimated from sparse events should be interpret with doubt. (Law et al. 2008)

Notes

- The opportunities to organize monitoring and sampling should be considered in the planning and construction phases of the filter systems. To accurately assess the treatment performance of the system, it is necessary to be able to sample water both from the inflow and outflow at locations upstream and downstream of the filter i.e. from the influent and effluent. For example, small part of a larger filter system can be planned so that its monitoring in selected locations is possible.
- Monitoring both water quantity and quality (both influent and effluent) is essential to estimate load reduction caused by the filter.
- The effluent flow rate could be measured automatically using e.g. ultrasonic water meter, but it may not be as reliable method as manual measurements due to high variability in outflow rates from filter systems, and the low outflow rates during low intensity rainfall periods. See Assmuth (2017) for details. There is also a need to gather manual measurements to secure the operation of the automated gauge.
- If the monitored filter is small and/or the size of the filter is large compared to its contributing catchment area, the effluent flow rates are low for most events due to small rainfall depths and the relatively long detention of runoff within the treatment unit. This means that if the required sample volumes are large (e.g. 3 litres per sample) due to high number of analysed parameters, the collection of each sample consumes time and thus the samples are not instantaneous but more of composite samples representing longer time period.
- In case rain gauges are not available, the rain data by the Finnish Meteorological Institute (FMI) can be used. However, it is noteworthy that the summer storms occur quite locally and short term precipitation vary considerable with distances of few kilometres.
- As on-site rain is unpredictable, planning of the sampling is difficult, and typically the timing and intervals of the sampling need to be decided on site during the event. For precise information, the entire rainfall-runoff event (both influent and effluent) should be covered, which may require sampling during a prolonged period (Figure A6).

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VTT Technology 338

Title	**Filtration Systems for Stormwater Quantity and Quality Management** Guideline for Finnish Implementation
Author(s)	Erika Holt, Harri Koivusalo, Juhani Korkealaakso, Nora Sillanpää & Laura Wendling
Abstract	The overall objectives of urban stormwater management are appropriate drainage to minimize urban flood risk and erosion, and protection of groundwater and surface water quality. Urban systems of green infrastructure such as rain gardens, green roofs, permeable pavements, swales, wetlands, and other designed to reduce stormwater surface runoff volume have gained popularity due to their cost effectiveness as well as their multiple co-benefits. Systems of green infrastructure often utilise engineered infiltration or subsurface filtration media to optimise hydraulic conductivity/maximise water infiltration, filter particulate pollutants or provide growth media for plants and microbes. The use of chemically reactive geo- or bio-based filter media can enhance pollutant removal. The wide range of different filter materials available enables development of fit-for-purpose solutions to address a variety of site-specific conditions, such as existing soil characteristics, site conditions, anticipated or measured pollutant loads and expected rainfall. Modelling of stormwater quantity and quality, whether at catchment or site scale, provides essential information for planning and design of effective stormwater management systems. Detailed site examination of key hydrological processes and stormwater constituent source areas allows optimization of stormwater treatment system design and informs decision-making. A multi-disciplinary approach that effectively integrates robust engineering and design principles with novel material technologies and innovative blue-green solutions can manage stormwater surface runoff quantity and quality to enhance the resilience of urban areas to climate change.
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Julkaisun sarja ja numero

VTT Technology 338

Nimeke	**Suodatusjärjestelmät huleveden määrän ja laadun hallinnassa** Soveltaminen Suomen olosuhteissa
Tekijä(t)	Erika Holt, Harri Koivusalo, Juhani Korkealaakso, Nora Sillanpää & Laura Wendling
Tiivistelmä	Hulevesien hallinnan yleisenä tavoitteena on toteuttaa alueen kuivatus siten, että hulevesitulvia ja eroosiota voidaan ehkäistä ja pohja- ja pintavesien hyvä laatu voidaan turvata. Kaupunkialueiden viherpintojen, kuten sadepuutarhojen, viherkattojen, läpäisevien päällysteiden, kosteikkojen ja muiden viherrakenteiden käyttö hulevesien määrän vähentämisessä on lisääntymässä menetelmien kustannustehokkuuden ja moninaisten hyötyjen ansiosta. Viherrakenteet perustuvat usein hulevesien imeyttämisen tai suodatuksen teknisiin ratkaisuihin, joiden avulla optimoidaan pintojen hydraulista johtavuutta, maksimoidaan imeytyviä vesimääriä, suodatetaan partikkelimuotoisia haitta-aineita ja luodaan kasvualustoja kasveille ja mikrobeille. Kemiallisesti reaktiiviset mineraali- tai orgaaniset ainekset voivat suodatinmateriaaleina edistää haitta-aineiden poistamista hulevedestä. Erilaisten suodatinmateriaalien laaja saatavuus mahdollistaa räätälöityjen hallintaratkaisujen kehittämisen yksittäisiin kohteisiin, joissa on poikkeavat maaperäolosuhteet, pintojen ominaisuudet, hulevesien määrä ja laatu tai sääolosuhteet. Huleveden määrän ja laadun mallintaminen valuma-alueen tai pienalueen mittakaavassa tarjoaa käyttökelpoista tietoa tehokkaiden hallintaratkaisujen suunnitteluun. Hydrologisten prosessien ja huleveden haitta-aineiden tarkka havainnointi hulevesikuormituksen lähdealueilla mahdollistaa huleveden käsittelyratkaisujen optimoinnin toimivimpien ratkaisujen valitsemiseksi. Monitieteinen lähestymistapa hulevesien määrän ja laadun hallintaan kytkee tekniset ja kaupunkisuunnittelulliset periaatteet uusien suodatusmateriaalien ja innovatiivisten viherratkaisujen käyttöön ja edistää kaupunkialueiden resilienssiä muuttuvassa ilmastossa.
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Filtration Systems for Stormwater Quantity and Quality Management
Guideline for Finnish Implementation

Urban areas experience substantially greater stormwater surface runoff volume compared with undeveloped landscapes or rural areas. With increasing urban development, rainfall that previously infiltrated the soil is instead increasingly intercepted by impervious surfaces such as rooftops, streets, and parking lots. As stormwater surface runoff flows over the surface of the landscape, it accumulates debris, chemicals, sediments or other pollutants that can adversely affect water quality if the surface runoff is discharged untreated. Simultaneous management of urban stormwater surface runoff volume and quality on a catchment or sub-catchment scale is challenging, but essential to effectively address the increasing extent of impervious surfaces, changing global climate, aging infrastructure and often undersized, centralized stormwater networks.

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