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Reports

TURKU AMK
TURKU UNIVERSITY OF
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Emil Nyman (eds.)

Intelligent and Sustainable Stormwater Solutions

Results from the ISMO project 2022–2024

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MINISTRY OF
EDUCATION AND CULTURE
FINLAND

INTELLIGENT AND SUSTAINABLE STORMWATER MANAGEMENT
ISMO

TURKU AMK
TURKU UNIVERSITY OF
APPLIED SCIENCES

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Content

Acronyms and glossary

ARD	Artistic rainwater design
Digital twin	Virtual replica of a physical object or a process
CFD Models	Computational fluid dynamic models
NBS	Nature-based solution
UAV	Unmanned aerial vehicle
USM	Urban stormwater management
SWMM	Stormwater management model
US EPA	United States Environmental Protection Agency
Bioretention cell	A constructed, vegetated basin that collects stormwater runoff, partly infiltrates and evapotranspirates stormwater, and releases the remainder with some delay to a receiving water body or drainage system.
IoT	Internet of things: a network of wirelessly connect devices. Here a network of sensors that measure environmental parameters and transmit data to an online database.
LoRaWAN	Long Range Wide Area Network: a telecommunication protocol and system architecture, here used to transmit environmental monitoring data to an online database.

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The ISMO project has had ambitious goals, and without the computational resources of CSC – IT Center for Science (Rahti, Mahti and simulation services), the piloting of digital twin for stormwater management would have been impossible.

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Introduction

Globally, cities are growing. More areas are covered by sealed surfaces, such as roofs, roads and car parks. Rainwater that runs off from these surfaces is called stormwater. From sealed surfaces, up to 100% of rain turns into surface runoff, compared to 0–10% runoff from naturally covered surfaces, where most of the rain is retained by plants and either evaporated or infiltrated into the ground, forming groundwater or slowly discharged to receiving water bodies. These processes are crucial for maintaining the local hydrological balance.

Stormwater runoff is characterised by rapid and high peak flows that may cause flooding and elevated concentrations of various pollutants, such as nutrients, metals and microplastics. Due to climate change, the frequency of both extreme rain events and periods of drought is increasing in many regions, with a growing number of cities suffering from these phenomena.

The use of nature-based solutions (NBS) for stormwater management has been suggested as a solution for reducing the risks of floods and droughts, and for re-establishing regional water balance. The concept of mimicking natural systems and processes to manage urban water has evolved over the past 50 years, and various terms are being used to describe them. The most common are low-impact development (LID) and sustainable urban drainage systems (SUDS), but in the following, nature-based solution (NBS) is used. Here, it refers to engineered solutions that utilise natural elements such as soils, vegetation and water spaces in various combinations to manage urban stormwater runoff quantity and quality.

The NBS approach yields remarkably sustainable city development as it provides, in addition to stormwater management, several other benefits, such as noise reduction, improved biodiversity, mitigation of the urban heat island effect, recreation and carbon sequestration. Moreover, such solutions are widely acknowledged to increase cities' resilience to climate change, and to protect and restore habitats.

As a flat country with extensive water resources, Finland was not among the first countries to have serious problems with pluvial floods (caused by rain) or droughts. Here, stormwater was typically considered as something that should be conducted efficiently

through pipes from urban areas to the nearest waterbody. However, since the beginning of the new millennium, the occurrence of significant stormwater floods has increased due to the insufficient capacity of traditional stormwater pipes. Also, the load on pipes that convey both sewage water and stormwater has increased, leading to capacity problems and adverse effects on treatment efficiency in wastewater treatment plants. These combined effects raise concerns regarding pollution caused by stormwater and are acknowledged by HELCOM through the recent adoption of Recommendation 23/5 on the reduction of discharges from urban areas by the proper management of storm water systems.

Recently, the European Union also revised the Urban Wastewater Directive, to include holistic management of urban stormwaters. These concerns have led to a paradigm shift in Finnish urban planning practices, with cities increasingly requiring decentralised stormwater management using NBS.

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28 November 2024 in Turku, Finland

Section 1.

Monitoring of urban hydrology and nature-based stormwater solutions

The monitoring of urban hydrology is crucial for the planning, implementation and maintenance of resilient drainage infrastructure, including NBSs. Urban fabric is composed of heterogenous landcover and land use elements, such as roads, buildings, managed green areas, quasi-natural green spaces, different soil types, etc. Each element of urban fabric has different water detention and retention properties, which directly affect the formation of surface runoff, i.e. stormwater, during rain events and snow melt. The formation of stormwater and the retention or detention of stormwater is controlled by a variety of properties, such as the composition of soil and the resulting infiltration capacity. Further, general landscape surface roughness, the types and degree of cover of vegetation, and the rain interception and evapotranspiration characteristics of the vegetation, affect stormwater formation and conveyance in the landscape. At higher latitudes, in addition to soil, landcover, vegetation and landscape characteristics such as seasonal freezing and thawing cycles add complexity to stormwater management planning and practices.

To build robust numerical stormwater models for understanding current circumstances and the forecasting of precipitation impacts on urban hydrology, including flood and drought events, the hydrologic and hydraulic properties of the urban fabric must be known. While a lot of scientific and technical literature exists, information on local conditions is often scarce. The lack of local data has two important implications: 1) Building stormwater models and designing stormwater management solutions based on information obtained for different locations, often different climate zones, introduces uncertainties that are difficult to quantify. 2) The functionality and reliability of NBSs are often questioned, especially in regions with prolonged sub-zero temperatures and snowfall during winter. Showcasing examples, simulations and data from different regions is not an effective tool for demonstrating NBSs' potential for managing stormwater. To overcome these hurdles, ISMO collected an array of hydrologic and hydrometeorological observations to create a foundation for building robust numerical simulations and evaluating the functionality of NBSs in a Nordic climate.

The collected data constantly grows and is integrated with other projects. Providing open access to the data will enable the improvement of regional developments, including maintenance and management procedures. The data collected within ISMO comprises continuous, online accessible observations and repeated discrete sampling and measurements at multiple locations. Continuous observations include water level and discharge measurements, water temperature, precipitation and soil moisture measurements. Discrete measurement and sampling include infiltration and baseflow measurements and soil analyses. To reduce the initial investment and future operation costs of continuous in situ measurements, a sensor network was built during the project,

together with the Wireless Communication and Cybersecurity research group at Turku AMK, using an internet of things (IoT) approach. For data transmission, the national LoRaWAN network is used, which is developed and operated by Digita Oy[1]. To receive, store, quality check and visualise measurements, a new database backend and browser-based front end has been developed. The system is being further developed and refined during the currently ongoing Saaristomeren valuma-alueen ja rannikon ympäristöseurantajärjestelmä (SAVY) -project, funded by the Regional Council of Southwest Finland AKKE-programme.

The IoT sensor network consist currently of several temperature, acoustic distance or hydrostatic pressure (to measure water level), conductivity and turbidity sensors. Further, it includes three weather stations and an instrument measuring water flow using ultrasonic doppler techniques. The present version of the sensor network is made up of 39 sensors in coastal waters, lakes, open streams and stormwater network wells. More sensors are continuously being added to the network during other ongoing projects connected to the development and use of the system.

Data visualisation and database access solutions are being developed during the SAVY project, to include coherent visualisation of all measurement results, data base machine readable interfaces and an internet browser-based data download service. The status and future development of the system is shortly presented on a dedicated webpage[2].

Further, the potential of utilising weather radar data products for sub-catchment-scale precipitation estimates has been evaluated. The following sections briefly present the main procedures and findings of each monitoring activity.

Data management and sharing

All data collected during the project has been uploaded to the IT Center for Science's (CSC) Fairdata Service IDA with restricted access rights. Metadata descriptions, including a link to the IDA datasets, have been created with the CSC research data description tool QVAIN[3] and can be found through the CSC service Etsin[4].

[1] https://www.digita.fi/en/services/iot/

[2] https://vesijaymparisto.turkuamk.fi/en/real-time-monitoring/

[3] https://www.fairdata.fi/qvain/

[4] https://etsin.fairdata.fi/ (use search keyword string "ISMO Turku AMK")

Two types of data have been collected during the ISMO project: 1) continuous, online monitoring data, and 2) point measurements or sampling data. Type 1 data includes water level measurements in urban brooks and ditches, discharge measurements in a stormwater ditch, surface water temperature, inflow/outflow data of a bioretention cell, soil moisture measurements in a bioretention cell, and runoff measurements of a roof. Type 2 data includes repeated infiltration measurements at several sites, and repeated baseflow measurements in three urban brooks.

Type 1 online monitoring data has been collected in three different online databases. Most of the water level measurements are stored in the database developed within the project. Some water level observations are stored in a proprietary database due to sensor requirements. Continuous soil moisture recordings have been stored in a proprietary database as well. All continuous and discrete monitoring raw data collected until 31 October 2024 was collated in Excel files and stored in CSC's Fairdata service.

Chapter 1.

Evaluating the usability of wireless soil moisture sensors for stormwater management applications

Joseph Perry

Understanding a soil's capacity to infiltrate, conduct and store water is important for assessing its ability to manage stormwater runoff and rain, particularly in urban and semi-urban areas (Johnson, Smith, & Thompson, 2018).

The need for accurate data on local soil infiltration-related parameters is clear when assessing the need for and design of engineered stormwater management solutions, especially those that utilise existing and constructed green infrastructure, e.g. nature-based solutions (NBS). This need will become increasingly acute as climate change drives more extreme weather conditions, including droughts and heavy rain. Low-cost online soil moisture sensors can improve our understanding of local soil-water dynamics and support the design, operation, and maintenance of NBSs. Soil moisture time-series data can be used as a proxy to assess water detention and retention in NBSs and provide valuable information for high-resolution stormwater models. Commercially available soil moisture sensors are based on physicochemical principles that do not directly measure soil moisture or soil water content. Instead, the sensor measures a parameter that is linked to the soil's water content.

More specifically, the method is based on measuring electric capacitance, which is linked to a known soil moisture in a specific type of soil. The relationship between the measured electrical capacitance and soil moisture for commercially available devices for different soil types is often pre-determined through calibration and stored in the devices as correction factors. The relationship is dependent on many factors, most notably soil

type, but also temperature and salinity of soil interstitial space water, soil density and compaction, non-water-filled void space and organic matter content. The internal sensor calibrations are usually not openly available, making the use of commercial soil moisture sensors for determining actual soil moisture content in varying environments challenging.

The ISMO project utilised a set of wireless soil moisture sensors to monitor the long-term soil moisture dynamics in a bioretention cell. Soil Scout[5] moisture sensors are wireless, soil-embedded devices designed to provide real-time data on soil moisture, temperature and salinity levels. Developed by Soil Scout, these sensors can be buried at varying depths to capture subsurface conditions without disturbing the soil structure. The selected sensors are the only true completely wireless sensors that are commercially available. Before deployment, the sensors are configured for a specific soil type based on a range of selectable soil types, which will determine the use of a predefined capacitance-soil moisture relationship that is typical for a specific category of soil type.

The maximum soil moisture or soil water content varies between soil types, as this is dependent on the void ratio of a soil type. Three laboratory tests were conducted to improve our understanding of the relationship between soil types, soil water content and temperature variations of the collected data, and to assess the sensors' precision and accuracy. The main aim was to verify the validity of sensor readings for selected soil types encountered in the study area by doing measurements with known volumetric water content, and to produce correction factors to convert sensor readings into actual volumetric water content of the specific tested soil types.

Methodology

The sensor readings were validated through laboratory tests designed to measure their performance under different soil and environmental conditions.

The laboratory validation involved testing the sensors in controlled environments to assess how accurately they measured soil moisture under different conditions. Each sensor was placed in various soil compositions and moisture levels, including:

- Buried 5.5 cm deep in dry soil
- Buried 5.5 cm deep in saturated soil
- Fully submerged in water
- Submerged in saturated soil and then frozen

[5] https://soilscout.com/

The reported soil saturation measured by the soil scouts was then compared to the known soil saturation in each condition.

A further validation test involved submerging the sensors in pure water and then periodically cycling through the different soil type settings, which could be changed through Soil Scout's online platform, to evaluate the effect of these settings (organic, clay, loam and sand) on reported soil saturation, to elucidate the devices' internal maximum soil moisture reporting limit for each setting.

A further test tracked the evaporation of a fully saturated soil sample for three different soil types, which were weighed twice daily as they dried. By tracking the water loss through evaporation, we could compare the changes in moisture content recorded by the sensors with the actual water loss, estimated by weighing the experimental units.

Results and discussion

The scatter plot in Figure 1.1 shows the estimated soil saturation against Soil Scout's reported soil saturation. As an example, this chart includes data from an evaporation test in which the sensors were buried in boxes of sand (grain sizes 1–4 mm), which were then fully saturated with water and allowed to evaporate at room temperature. Notably, this test shows variation in the soil moisture maximum readings, making it difficult to identify full saturation through the sensor data alone. During this evaporation test, maximum sensor readings in fully saturated conditions for the three sensors tested were 49.6%, 48.6% and 47.9% respectively. The smaller variation in data from sensors at full saturation compared to estimated soil saturation arrived at by weighing the experimental containers also suggested that the sensors struggled to show changes in water concentration at full (or potentially super-saturation) saturation. Evaporative losses of water content at full or super-saturation were not well tracked by the sensors.

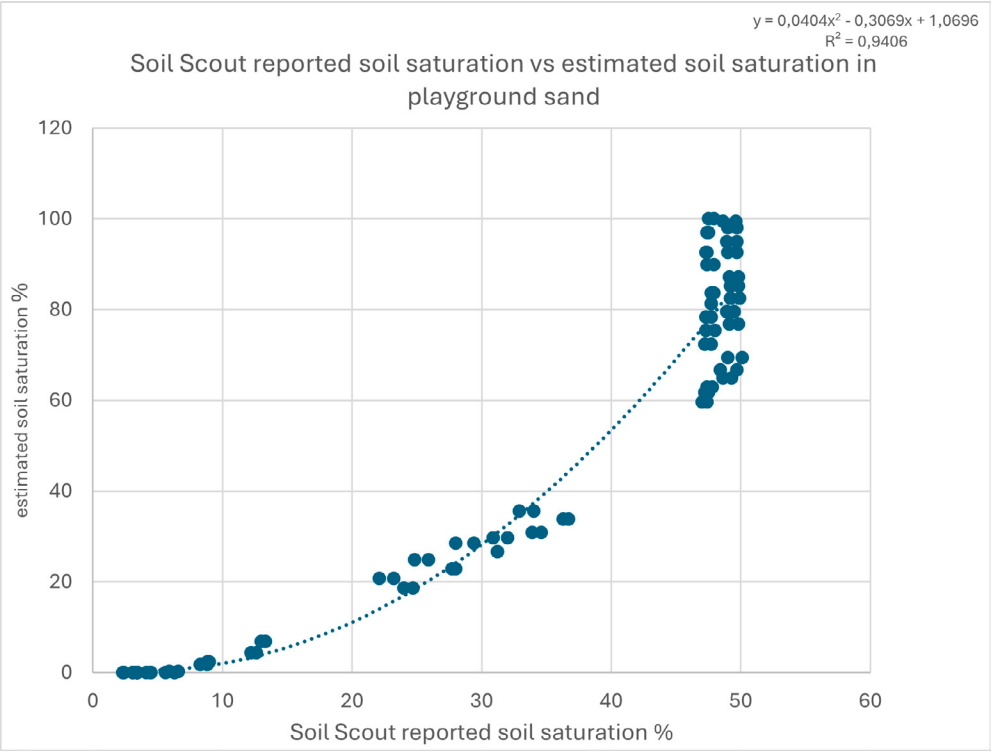

Figure 1.1. Sensor reported soil saturation vs estimated soil saturation in playground sand. The sand was fully saturated at the beginning of each test, and evaporation was measured by weighing experimental containers twice daily. Gaps in data are due to weekends with no measurements.

The minimum and maximum reported moisture content for a sensor when submerged in pure water varied between approximately 40% and 69% (Fig. 1.2), depending on the sensors' selected soil type setting. The settings significantly impacted reported soil saturation, reflecting the devices' internal field capacity settings. If used without validation experiments, it is important to ensure that the settings accurately reflect the real conditions in which they are installed. However, since pre-determined settings rarely accurately reflect real-world soil characteristics, it is advisable to conduct validation experiments to relate the relative soil moisture readings the sensors provide to actual soil water content.

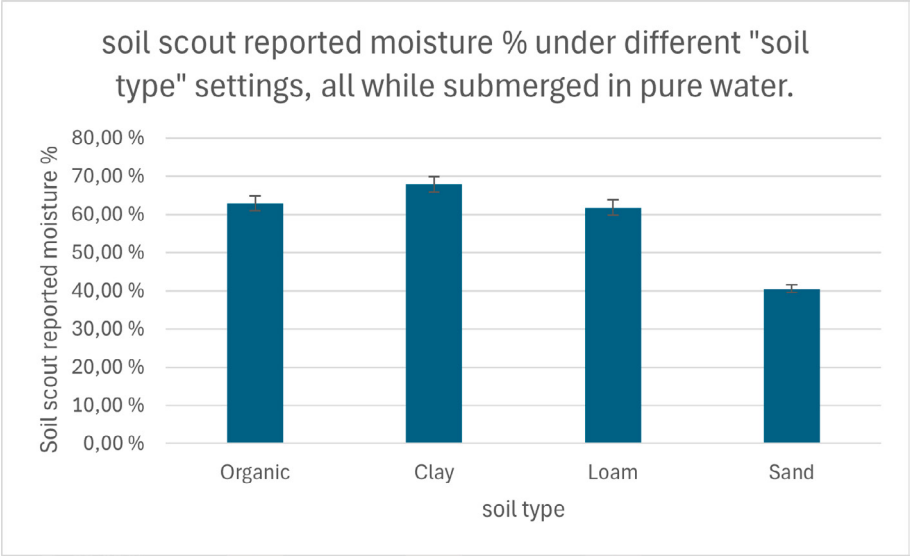

Figure 1.2. Soil Scout reported soil moisture content under different soil type settings while submerged in pure water only.

The sensor validation tests demonstrated that while these sensors can provide useful relative estimates of moisture levels, validation is critical for ensuring accuracy. One of the key findings was the significant variation in reported soil saturation between different devices, even when placed in seemingly identical conditions, highlighting the need to replicate measurements at any single site due to small-scale variation in soil characteristics and variation in the results caused by soil disturbance during installation and subsequent consolidation of soils at the installation sites. To mitigate this issue, it is recommended to establish correction factors for each sensor prior to installation with soil from the installation site and to ensure enough replicates. This approach will help ensure that the reported moisture content data more accurately reflects actual soil moisture conditions.

Another important observation was the impact of soil type settings on the sensors' readings. These settings tests involved submerging the sensors in pure water and altering the soil type settings, which resulted in differences in maximum moisture content readings. This reflects the choice of internal settings of the devices by the manufacturer, to report maximum moisture content relative to soil type field capacity.

The evaporation tests revealed that while the sensors could track moisture loss over time relatively well, their capacity to track water content changes close to maximum moisture readings was less accurate. Therefore, this makes the data less reliable when the soil is either super-saturated, fully saturated or near-fully saturated.

These inconsistencies suggest that while the sensors can provide general trends, they may lose data granularity in saturated conditions. In practice, this means that while the sensors are valuable for long-term monitoring, they should be used in conjunction with more precise measurement tools when capturing short-term, high-precision data.

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Chapter 2.

Long-term infiltration rate measurements for different urban fabric types

Joseph Perry

The capacity of soil to take up water and conduct it is an important parameter in the design of NBS-based stormwater management, stormwater modelling, and land cover-based assessment of pluvial flood risk. Infiltration varies based on soil composition, compaction and vegetation, for example. Local infiltration measurements have been conducted to create a database of infiltration rates for surface types typically found in urban areas. The data allows for a better understanding of the local hydrology and supports appropriate stormwater planning. The data is applicable in places with similar climatic and geologic conditions.

Infiltration describes the process of water moving in a gravity-driven way through pores and cracks ("pore space") in the soil. *Unsaturated* infiltration occurs when pore spaces are air-filled, or partly water-filled, while *saturated* flow occurs when all pore space is filled with water. Saturated flow, or the soil's *saturated hydraulic conductivity*, can be highly variable due to macropore ("cracks") flow. In contrast, unsaturated hydraulic conductivity depends on the soil's water potential and content and is less variable as it focuses on the soil matrix. In the ISMO project, the unsaturated hydraulic conductivity was measured for various permeable surface types commonly found in urban environments.

Methodology

Infiltration measurements were collected repeatedly at 13 locations with varying soil type and land use characteristics. Sites were chosen to represent a gradient in infiltration capacity in an urban landscape. To ease regular data collection, all sample sites are in a large urban (sports) park that provides a heterogeneous fabric with differing land uses (Kupittaanpuisto, Fig. 1.3).

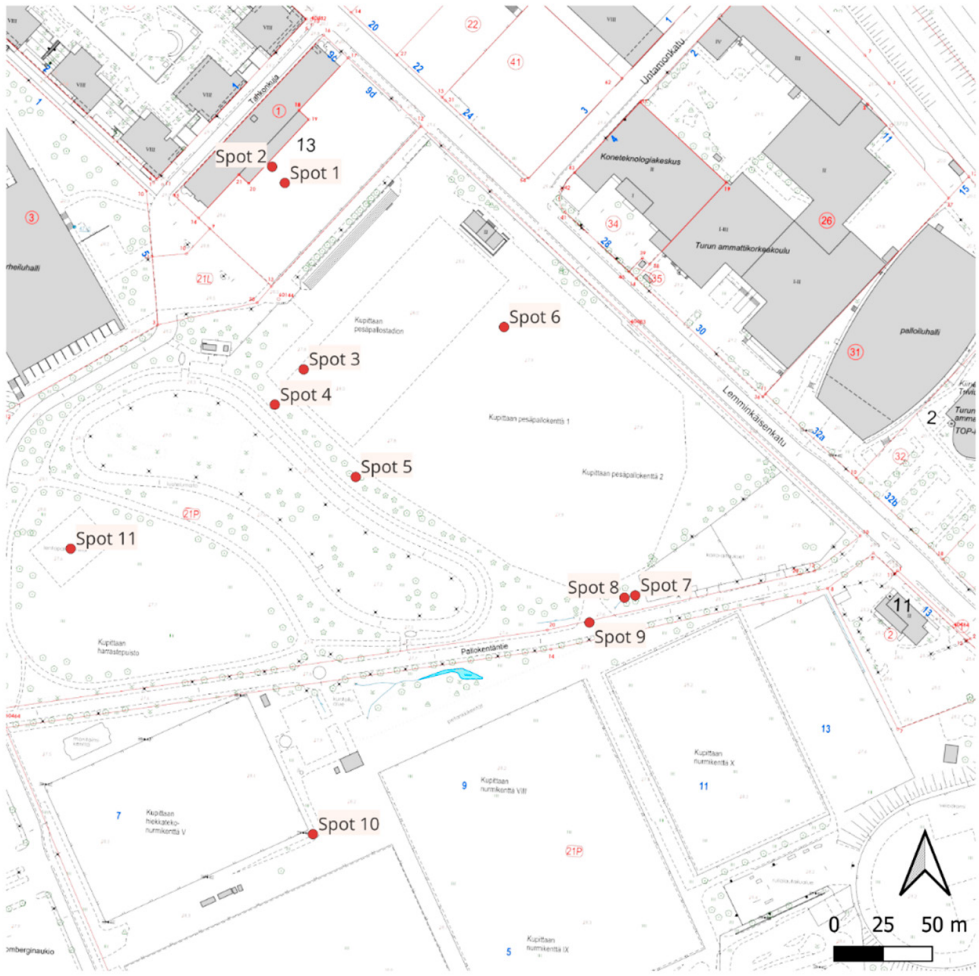

Figure 1.3. Kupittaanpuisto urban park and location of infiltration monitoring sites.

Infiltration at each monitoring site was measured weekly in triplicate during the frost-free period over the course of one year to capture possible seasonal variations. During periods when the ground was frozen, it was assumed that infiltration rates would be close to zero. The unsaturated infiltration was determined with a METER GROUP *Mini Disk Infiltrometer*[6].

[6] https://metergroup.com/products/mini-disk-infiltrometer/

The sites selected for the infiltration rate measurements included:

1. Two car parks with compacted sand, representative of similar areas, e.g. sand/gravel roads, storage areas
2. A baseball pitch with a cover of artificial lawn, representative of sports fields and playgrounds
3. Four types of grassy areas, with higher vegetation such as trees and areas without higher vegetation, including areas that are used for recreational purposes and more natural areas less affected by human activity
4. Gravel area
5. A bioretention cell
6. A vegetated swale connected to 5
7. A beach volleyball court representative of sandy areas, like playgrounds, beaches, etc.
8. A sports field with rubber crumbs and artificial grass, representative of similar sports facilities
9. Asphalt-covered area

A surface soil sample has been taken, where possible, to determine the grain size distribution and organic matter content of the sites.

Results and discussion

The infiltration rate (k-value) varied between sites and throughout the year-long monitoring period. Site 11 (sand field) showed the highest infiltration rates, with values regularly above 0.02cm/s. This site also displayed the largest range of k-values during the monitoring period, with values ranging between 0.008 cm/s to 0.031cm/s. Infiltration rates at Site 3 (baseball pitch) also had a wide range, with measured k-values between 0.0019cm/s and 0.021cm/s. Infiltration rates were lower and displayed a smaller absolute range at Sites 1, 2, 6, 7, 8, 12 and 13. Site 1, for example, demonstrated k-values consistently below 0.0004cm/s.

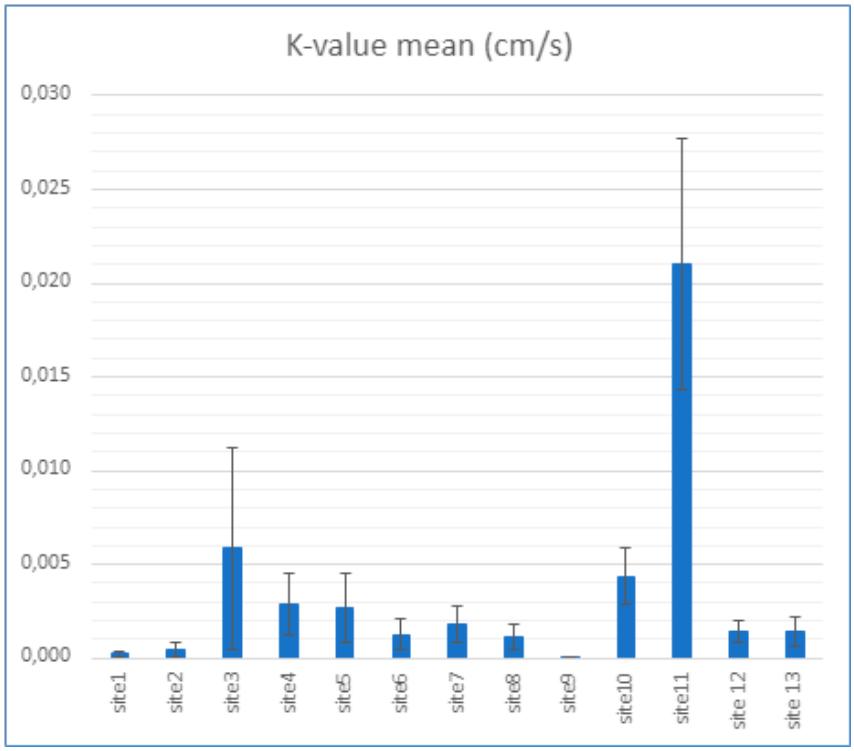

Figure 1.4. K-value triplicate means (cm/s) and standard deviations for all monitoring locations.

K-value (infiltration rate) means and standard deviations of all measurements per site are presented in Figure 1.4. The sites can broadly be separated into four groups of sites with: 1) low or no infiltration (sites 1, 2 and 9); 2) moderate infiltration (sites 6, 7, 8, 12 and 13); 3) high infiltration (sites 3, 4, 5 and 10); and 4) very high infiltration (site 11). The coefficient of variation for each site allows for a further approach to grouping, whereby sites 10 and 11 are considered to demonstrate low variability (< 40%); sites 1, 4, 6, 7, 8, 12 and 13 demonstrate moderate variability (< 60%), and sites 2, 3 and 5 demonstrate high variability (> 60%). Variability of infiltration rates varied across all classes of infiltration rate, without any apparent pattern. However, moderate infiltration rates most often coincided with moderate variability, and discounting site 9 (asphalt covered), sites with high infiltration rates displayed low variability in results, even though the k-values ranged over an order of magnitude, e.g. for the sand-covered volleyball court site (site 11).

The infiltration monitoring over an entire frost-free period of one year confirmed marked variation in infiltration rates between different surface types. Reflecting the variation in infiltration rates found for different land cover types in an urban setting, but also possible inconsistencies in the data collection and methodological issues with the used measurement device. Even though triplicate measurements were taken at each site during each measurement occasion, the surface area of the device is small, subjecting the results to inconsistencies caused by within-site small-scale variation of compactness of soil, including the potential presence of macropores not detected during measurement, for example.

The data shows a slight seasonal pattern, with the warmer summer months tending to display higher infiltration rates. One possible explanation for this is that the ground could still be occasionally frozen in sub-surface layers in early spring and late autumn, resulting in lower infiltration rates in natural and semi-natural soils. Further, vegetation is likely to affect the infiltration during the warmer months. The variation in infiltration within individual artificial surfaces (sites 2, car park; and 3, baseball pitch, both showing high CV% values) may be due to maintenance of the surfaces, or small-scale heterogeneity of the surfaces, for instance.

The ISMO monitoring project's findings align with those of Salvadore et al. (2015), reiterating the significant impact of soil type and urban surface permeability on infiltration rates. The observations included in this study – of reduced infiltration on impervious surfaces, such as asphalt, and compacted clay-sand areas and increased rates in sandy and vegetated areas – support the conclusions of Salvadore et al. (2015) regarding urban hydrology. Furthermore, the specific infiltration rates observed by ISMO correspond with those described by Kahlon et al. (2012), particularly concerning the influence of soil organic content and grain size on infiltration. These results also fall within the standards of the USDA's Natural Resources Conservation Service and the European Commission's Joint Research Centre, which are widely accepted standards for soil infiltration (European Commission, 2016 & USDA NRCS, 2022).

The main factor controlling the infiltration rate is the grain size distribution. Sites with a higher proportion of small grains, such as clay (e.g. sites 1 and 2), had lower infiltration rates than sites with a higher proportion of larger grains, such as sand (site 11). This is explained by the smaller pore spaces of soils with a larger proportion of small grains. Further, a general correlation exists between the organic content of soils and their associated infiltration rates. Of all sites with a mixed grain size distribution and/or some vegetation, sites with higher organic content, such as sites 4 (18.2% organic content) and 5 (12.9% organic content), had higher infiltration rates. Still, site 11, which is almost

entirely composed of quartz sand, had the highest infiltration rate underscoring the complex interplay between soil composition, texture and infiltration capacity.

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Chapter 3.

Assessing seasonal baseflow variation in urban streams

Joseph Perry

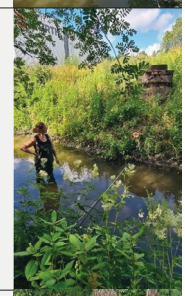
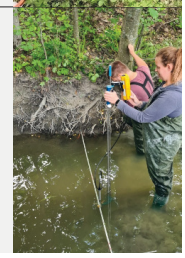
Baseflow describes a stream's dry weather flow sustained largely by weather-independent processes such as groundwater seepage or inflow from springs. Long-term monitoring of baseflow in urban streams can help to separate the effect of stormwater runoff and precipitation-independent flow on a stream's hydrology. This can support the development of stormwater models and planning of stormwater management solutions that aim to reduce runoff generation and peak flow.

In the ISMO project a handheld acoustic flow meter was used to establish seasonal baseflow estimates for three urban streams in Turku, Southwest Finland. The main findings are presented in the following section.

Study area and methodology

The study was conducted in the Kuninkoja stream and two of its smaller tributaries. The Kuninkoja stream is a small urban watercourse with several tributaries. The river flows through residential and commercial areas, passing under and along several large roads before discharging into the coastal area west of the city of Turku's main harbour. The Kuninkoja is predominately narrow and experiences seasonal variation in flow conditions in line with regional weather patterns. Land use around this river is predominately peri-urban. Residential and commercial areas run along much of the watercourse, with green spaces, fields, meadows and roads intermingled. Characteristics of the four monitoring sites selected for this study are presented in Table 1.1.

Table 1.1. Description of characteristics and sampling procedures of the monitoring sites.

Site name	Site description	
Kuninkoja Lumenkaatopaikka	• Measurement taken directly in front of a road culvert. • Measurement taken on top of a strip of concrete which runs along the stream bed, protruding beyond the bottom lip of the culvert (see site picture). • Nearby land use is industrial, with several factories nearby which receive regular heavy goods vehicles. • There is significant vegetation on both banks of the stream. The banks are very steep.	
Saukonoja Pitkämäki	• Stream section runs between scrubland/industrial land and a busy dual carriageway. • The adjacent scrubland is not regularly used, although there are stores and warehouses on either side of the scrubland. • The dual carriageway is 35m from the river, with a grassy bank, trees and a footpath separating them. • Significant vegetation on both banks.	
Kovasoja Ruohonpää	• The stream section runs through a lightly wooded area alongside a walking path that links residential areas. • One side of the stream is heavily vegetated and not regularly used for human activity. The other side has managed grassy areas and a stony walking path. • Banks are short, with a vertical drop-off as you enter the stream.	
Kuninkoja Länsikeskus	• Stream section with fields on one side and a busy crossroads on the other. A bioretention cell is installed on the same bank as the crossroads. • Both sides of the stream have a thin line of trees planted and a mixture of low vegetation and grasses.	

Flow measurements were made using a Sontek Flowtracker 2 acoustic doppler velocimeter[7]. Total discharge was calculated based on several measurements with the device along a cross-section of the stream, which was marked in the field to ensure consistency of measurements. Measurements were not made directly after rain events, to avoid including stormwater-related flow in the results as much as possible.

[7] https://www.ysi.com/flowtracker2?srsltid=AfmBOop6KXzZqRoAffaTv1q0BCwvwcdPTUZvy-GMEOlF1-KRJdAYDJaq

The aim of this survey was to monitor total discharge at each site throughout the year with a long enough time gap to any antecedent rain events to determine base flow levels based on these measurements. During periods of stream ice cover no measurements were made. Restrictions to staff time occasionally resulted in some missed weeks. However, the dataset gathered represents a significant portion of non-frozen conditions throughout the year for the chosen sites (n = 20). To estimate representability of the results, site 1 results are compared to discharge estimates made by continuously measured water level height at the same site. Continuous water level measurements were converted to discharge estimates with a discharge rating curve defined for the site.

Results and discussion

Assumed baseflow discharge varied logically between the sites, with the site closest to the stream outflow displaying the highest assumed baseflow levels and baseflow levels being lower upstream in the main channel and lower in the tributaries (Fig. 1.5). Variation of total assumed baseflow discharge within the individual sites throughout the year was also detected, as indicated by the large standard deviations for each site and shown in Figure 1.6. Assumed baseflow discharge varied between 0.02-0.91, 0-0.2, 0.002-0.2 and 0.01-0.53 m^3/s for sites 1, 2, 3 and 4 respectively.

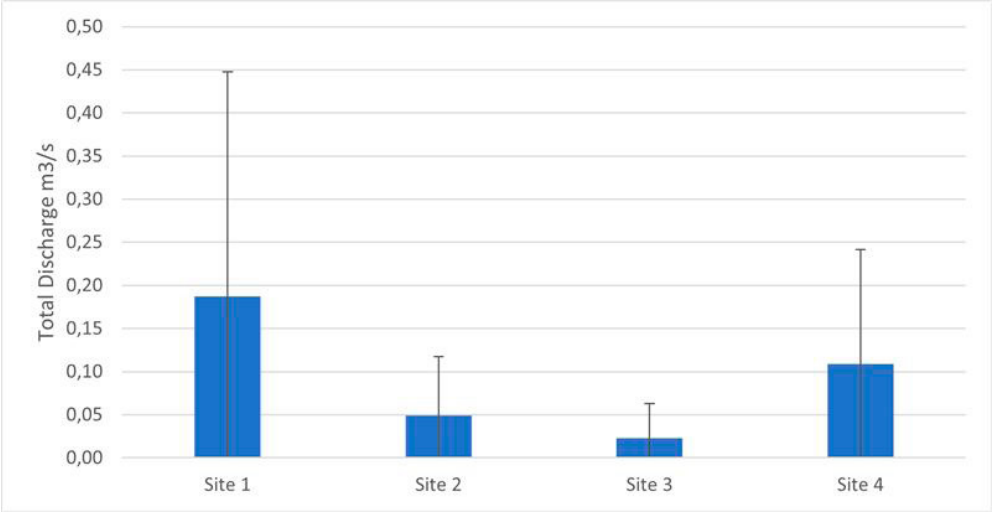


Figure 1.5. Assumed baseflow discharge average (m^3/s) and standard deviation for all monitoring sites.

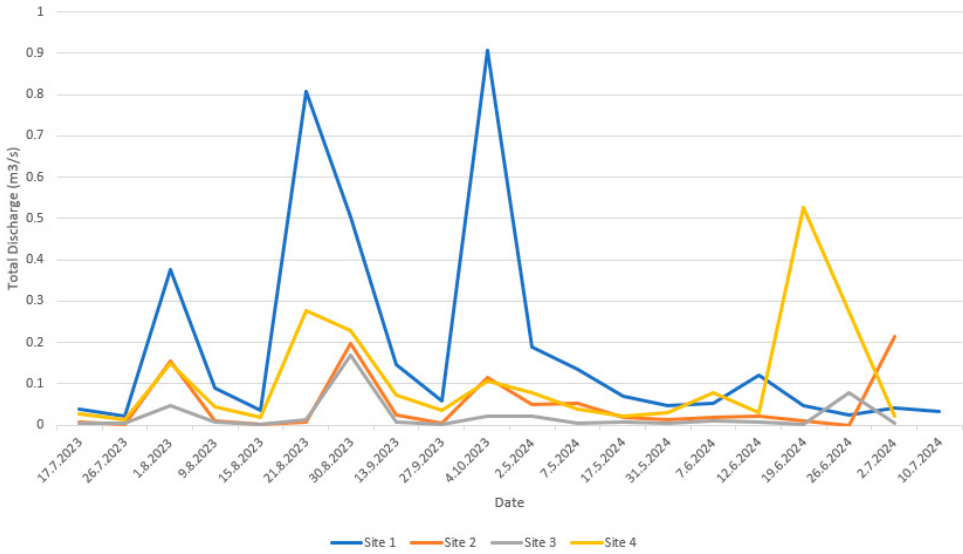


Figure 1.6. Total assumed baseflow discharge time series (m^3/s) for all monitoring sites.

Continuous discharge estimates for site 1 reveal the flow dynamics of the site (Fig. 1.7). Discharge during a period from 15 July 2023 to 11 November 2024 ranges between 0.132 and 9.82 m^3/s. Peak discharges are estimated to be 10 times larger than the maximum assumed baseflow discharge of approximately 0.9 m^3/s. The mean of assumed baseflow discharge measurements (0.19 m^3/s) seems to be in line with conclusions that can be drawn from continuous discharge measurements at site 1 (Fig. 1.7). The continuous measurements indicate a somewhat higher baseflow discharge, especially during spring months. The growth limbs of the hydrograph peaks are generally steep, showing a fast response in discharge volumes to rain events. Along with steep growing hydrograph peak limbs, the recession limbs of the hydrograph peaks are also relatively steep, both indicating efficient drainage of the land areas surrounding the stream, which is typical for urbanised areas.

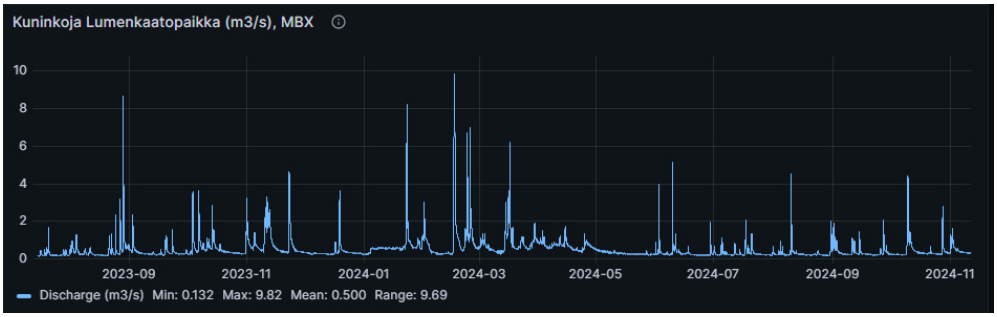


Figure 1.7. Continuous discharge estimate (m^3/s) done by measuring water level variation and converting that to discharge volume with a discharge rating curve for site 1.

The data gathered during this monitoring period provides an overview of the hydrology of four stream locations over the non-frozen months of one year for a peri-urban drainage basin. Although these measurements were conducted under baseflow conditions – typically less affected by short-term weather events – the within-site variation observed may reflect longer-term hydrological influences, such as prolonged wet periods. In these cases, saturated soils can lead to an increase in groundwater seepage into streams, causing elevated baseflows.

Average assumed baseflow discharge estimates for the sites are small, ranging from 0.19 to 0.02 m^3/s, being 50 times smaller than estimated maximum flow for one of the sites (site 1) and with the maximum estimated baseflow discharge being an order of magnitude smaller compared to maximum flow estimates. These large ranges display the urbanised characteristics of parts of the drainage basin, with a large part of the area being efficiently drained by grey infrastructure. The proportion of green spaces (approximately half of the drainage basin) and areas capable of natural water detention and retention are clearly too small to alleviate large discharge variation in the stream.

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Chapter 4.
Discussion and conclusions

The monitoring of urban stormwater systems and hydrological processes is still mostly done on a (research-) project basis or for short periods to collect snapshot information to plan for new developments. The ISMO project took a first step to establish a comprehensive monitoring system to unravel hydrologic and hydraulic processes in the Turku region. The project has collected an array of point measurements, such as baseflow and infiltration rate measurements, and established long-term online monitoring of water levels and discharge in important urban streams, and soil moisture at pilot sites for nature-based stormwater management. To overcome fragmentation and inaccessibility of monitoring data, the project has developed a cloud-based database and an online, browser-based interface for visualisation and download[8]. These are major regional developments that are already utilised by several other projects and organisations.

Despite these achievements, development needs remain. While the project maximised the use of IoT-based sensors that can transmit data through the national LoRaWAN network, not all environmental parameters can yet be monitored with such devices, or existing equipment has not yet reached the end of its lifetime. Therefore, the transition from proprietary data platforms and data management systems will continue. Further, the project revealed shortcomings of some sensors in terms of the precision, accuracy and transparency of how monitored parameters are calculated. This required intensive laboratory experiments to verify sensor performance and derive possible correction factors, e.g. for continuous soil moisture monitoring. Also, water levels in streams, drainage networks and weir systems for runoff measurements can be sufficiently measured with hydrostatic pressure or distant sensors. The translation to volumetric flow rates requires the establishment of site-specific rating curves that allow the translation of the measured water heights into discharge. While this is relatively easy for a pipe system, establishing these curves for weir systems or irregular stream beds is complex and some work remains to be done.

Despite achievements moving towards a regional, open online monitoring system, some development tasks remain to make the data useable by a wider stakeholder group and to integrate the monitoring systems with hydrological and hydraulic models. To that end, the continued development and use of the data and data systems are secured through follow-up projects and other continuous funding mechanisms.

[8] https://vesijaymparisto.turkuamk.fi/en/real-time-monitoring/

Section 2.

Steps towards a digital twin: Numerical stormwater modelling and design

One of the main objectives of the ISMO project was to develop new and improve existing numerical stormwater models. This was realised using numerical modelling techniques not commonly used in stormwater research and through the validation of models with extensive local monitoring data.

This research aimed to create the foundation for a "digital twin" of urban stormwater systems that can simulate the hydrologic and hydraulic conditions of numerical systems. To achieve this goal different numerical modelling techniques and tools have been employed to simulate stormwater systems on various scales. "Numerical modelling" here refers to computer simulations that are based on solving mathematical equations that describe physical processes of natural phenomena, such as water flow.

Two types of models have been used during the project: 1) two- and three-dimensional (2D & 3D) computational fluid dynamics (CFD) models such as OpenFOAM, and one-dimensional hydrologic and hydraulic models such as the US EPA Stormwater Management Model SWMM. Both types of models are based on similar equations but are designed to resolve processes on different scales. Due to high computational requirements, CFD models are best suited to simulate processes on a meter scale, such as the fate of stormwater in an individual management solution, while a model like SWMM is best suited to simulate stormwater runoff on a block-to-catchment scale (ha to km^2). CFD models allow the solving and visualising of hydrologic and hydraulic processes such as water infiltration, subsurface flow or sedimentation on a sub-mm scale and are therefore a promising tool for optimisation studies in support of the design and operation of individual stormwater management solutions such as bioretention cells or rain gardens. The 1-D SWMM model cannot resolve these processes but uses a simplified approach that computes runoff generation on a (user-defined) catchment scale.

The project developed catchment-scale models in which simulation results can be verified against data collected in major elements of the drainage systems, e.g. flow and water level measurements in larger urban streams, and CFD models for an experimental bioretention cell. The bioretention was implemented during a previous research project and specifically designed such that all inflow and losses can be quantified. The structure has an impervious lining that prevents infiltration to deeper and surrounding soil and seepage into the structure from these areas. In- and outflow to and from the structure are monitored and three pairs of soil moisture sensors have been deployed at two depth levels at the centre and the inlet and outlet ends of the bioretention cell. This monitoring data provides a good basis to access the water balance of the bioretention cell and allows for the evaluation of the validity of the CFD simulations.

The following chapters provide brief summaries of the CFD simulations that were made to create a first online simulation tool to predict water flow through user-defined bioretention cell designs and a design optimisation study that aimed to identify the best designs for stormwater filtration. This is followed by an overview of the 1-D stormwater model developed for a major urban stream catchment, and a discussion of how these results can be incorporated into future stormwater forecasting systems.

Chapter 1.

Two-dimensional stormwater filter design

Mohamed Mohamed Sayed

The rapid expansion of urban areas has led to a significant increase in impervious surfaces, such as roads, buildings and car parks. This shift from natural landscapes to surfaces sealed with buildings, concrete and asphalt reduces the ground's ability to absorb rainfall, resulting in higher volumes of stormwater runoff. Excess runoff may contribute to flooding and serves as a conduit for pollutants, including oils, heavy metals and sediment, which degrade water quality in rivers, lakes and oceans. To address these challenges, effective stormwater management strategies are essential. Stormwater filtration systems are among the most effective tools for mitigating the adverse effects of urban runoff. By capturing, filtering and slowly releasing stormwater, these systems help to reduce flooding, protect water quality and prevent erosion.

Stormwater filtration systems are vital for mitigating the adverse impacts of urban runoff. These systems are designed to capture, filter and slowly release stormwater, reducing the volume and speed at which it reaches natural waterways. By intercepting contaminants, stormwater filtration systems help maintain water quality, manage flood risks and prevent soil erosion. As cities continue to grow, the need for efficient and adaptable stormwater filtration solutions becomes increasingly pressing.

The research work investigates a two-dimensional (2D) model of a stormwater filter with the goal of optimising its design to maximise filtration efficiency while minimising hydraulic resistance. Computational fluid dynamics (CFD) modelling was utilised to simulate the flow dynamics and filtration processes within a filter represented by a packed-bed porous media. Through a parametric analysis, various grain characteristics – including grain size, distribution and porosity of the porous media – were evaluated to determine their impact on filter performance. This research aims to offer insights that can guide the development of more effective stormwater filtration systems, contributing to better urban water management and environmental protection.

Two-dimensional filter design

The filter design under study is based on a two-dimensional model that simulates the flow and movement of stormwater in a porous medium. This model is governed by fundamental equations of fluid dynamics. The continuity equation ensures mass conservation, while the Navier-Stokes equations describe the conservation of momentum. Additionally, the advection-diffusion equation accounts for the transport of particles through the medium.

The filter is modelled as a square area with a side length of 5 mm, discretised into a 500x500 grid, yielding a cell resolution of 0.01 mm. To achieve a higher numerical efficiency the filter size was reduce to a mm scale instead of a typical stormwater filter size. Within this square, circular grains are distributed to create a porous structure, with the grains acting as the medium through which stormwater flows. The grain size, distribution and spacing are critical parameters in determining the filter's performance. The study explores both monodisperse and polydisperse grain distributions, as shown in Figure 2.1, with grain radii varying between 0.05 mm and 0.15 mm. The spacing between grains was tested at 0.02 mm, 0.03 mm and 0.04 mm, while porosity levels were adjusted to 0.55, 0.60 and 0.65.

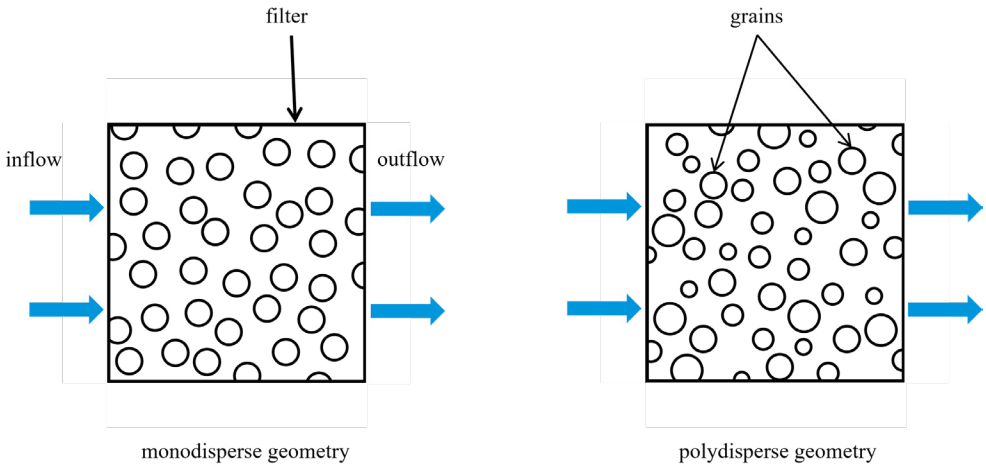

Figure 2.1. Monodisperse and polydisperse geometries.

In total, 15 configurations were analysed, each representing a different combination of grain size, distribution and porosity. This approach allowed for a comprehensive examination of how these variables affect the filtration rate and hydraulic resistance. By examining multiple configurations, the research aimed to identify trends and optimise the filter design for both high filtration efficiency and low resistance to flow.

Optimising filter design

Optimisation of the stormwater filter design required a careful balance between maximising the filtration rate and minimising the pressure gradient across the filter (i.e. hydraulic resistance). A high filtration rate is desirable as it indicates efficient removal of contaminants, while a low-pressure gradient ensures that water flows easily through the filter without significant resistance. These two performance metrics were normalised to enable a fair comparison between different configurations, with scores calculated based on a combination of normalised filtration rate and normalised pressure gradient. This scoring system emphasises designs that provide high filtration performance with minimal hydraulic resistance.

Results from the parametric analysis revealed that the grain characteristics significantly influence the filtration performance. Smaller grain sizes were generally associated with higher filtration rates, as they provide a larger surface area for particle capture. However, the optimal grain size range identified was between 0.05 mm and 0.10 mm. This range strikes a balance between offering sufficient filtration efficiency while avoiding excessive pressure gradients. Furthermore, a porosity level of 0.60 was found to be optimal for maximising filtration efficiency without imposing too much resistance to water flow.

The study tested each configuration across 3443 individual cases, evaluating performance under various conditions. For instance, Case F, which featured a grain radius range of 0.05 mm to 0.10 mm and a porosity of 0.60, achieved a high filtration score with a relatively low-pressure gradient. This configuration outperformed others by effectively balancing the competing demands of high filtration efficiency and low resistance, making it the best candidate for real-world stormwater filtration applications. In contrast, configurations with larger grain sizes or lower porosity levels tended to have lower filtration rates and higher-pressure gradients, underscoring the importance of fine-tuning these parameters to achieve optimal performance.

The findings suggest that adjusting grain size, distribution and porosity within specific ranges can substantially improve filter performance, allowing for better handling of stormwater in urban environments. The results also highlight the potential for multi-objective optimisation in stormwater filter design, where both filtration efficiency and hydraulic resistance are considered together to identify the best possible configuration.

Chapter 2.

Numerical modelling of a bioretention cell

Ashish Pawar & Ashvin Chaudhari

Computational fluid dynamics (CFD)-based numerical models are widely used for understanding fluid flow behaviour, but they are not commonly used in stormwater modelling or the design of stormwater management solutions. These models use mathematical equations to simulate the physical processes involved in stormwater runoff and infiltration. These numerical models eliminate the need for expensive physical prototyping. Multiple scenarios can be tested virtually, reducing the cost of physical design iterations. Unlike physical experiments, where probes and sensors may cause disturbances in the flow and affect the measuring parameter, CFD measurements are non-intrusive. By utilising these models, engineers, urban planners and landscape architects can design stormwater management solutions and evaluate their efficiency under varying runoff conditions.

Nature-based stormwater management solutions such as bioretention cells gain popularity for managing stormwater in urban areas. A bioretention cell captures rain and surface runoff from smaller areas and either infiltrate the water to the ground and evaporate it, or slowly release the water to conventional drainage systems or receiving water bodies. The main purpose of a decentralised solution, such as a bioretention cell, is to decrease peak flows in drainage systems during heavy rains to prevent local flooding. Reducing peak flows in receiving rivers reduces flood risk, erosion, and negative impacts of large flow variations on aquatic biota. Reduced erosion of stream banks and beds can at the same time retain pollutants. Schematics of one such decentralised solution, a water-retention cell, is illustrated in Figure 2.2a. To support the design of effective decentralised stormwater management solutions and to guide the operation and management of existing structures, a CFD model for the experimental site described above has been developed.

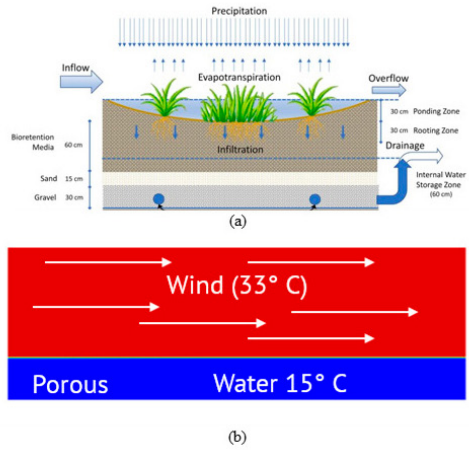

Figure 2.2. (a) Schematics of bioretention cell (b) Simplified CFD model (without vegetation).

Implemented CFD models

A CFD-based numerical model was implemented to predict evaporation, infiltration and runoff within the bioretention cell, the computational domain of which is shown in Figure 2.2. Schematics in Figure 2.2a show the actual modes of water transport in the bioretention cell that include inflow, overflow, infiltration, evaporation, transpiration and precipitation. Figure 2.2b shows the computational domain of the numerical model in which the red colour depicts the air domain having a temperature of 33°C, whereas blue specifies the soil domain with a temperature of 15°C. The initial temperature values of water and air were chosen for an ideal case so that the evaporation process is started rapidly in the initial phase of the numerical simulation. The porosity of the soil domain is set to 0.25. The inlet flow rate is 1 kg/s. The Navier-Stokes and Darcy equations are used to solve the flow equations. Each simulation is carried out for 50 seconds of the flow time.

Evaporation and mass fraction of water at the instance of 50^{th} seconds are shown in Figures 2.3a and 2.3b respectively. The evaporation rate over the period of 50 seconds is shown in Figure 2.3c. It is found that the total amount of water evaporated within 50 s is 0.00285 kg (Figure 2.3d), which means that the amount of water that evaporated during this time is small (approximately 2% of the total) compared to the amount that infiltrated (Figure 2.3e). As the simulation of evaporation is computationally expensive, it was excluded from subsequent numerical models as its relevance during short periods is negligible. Separate models have been developed that consider diurnal temperature effects on evaporation.

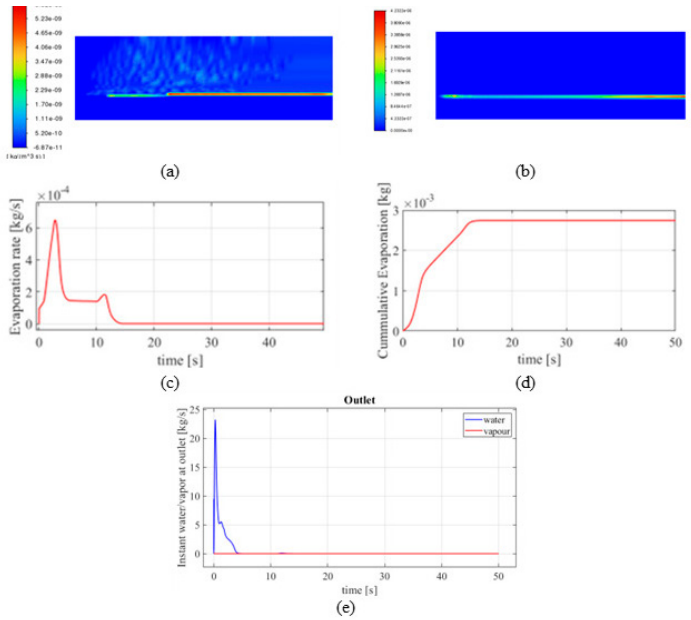

Figure 2.3. (a) Evaporation and (b) Mass fraction of water at the instance of 50th sec (c) Evaporation rate (d) cumulative evaporation (e) Water and water vapour at outlet.

A CFD model that takes into account the effects of different porosity layers in the simulated bioretention cell has been utilised (Carillo et al., 2020). Its computational domain is shown in Figure 2.4. Porosities of the top, middle and bottom layers of the cell are 0.4, 0.34 and 0.43 respectively. Here, three scenarios are considered for computational analysis. The first one is the filling of the bioretention cell with a constant inlet flow rate (1 kg/s) and open outlet (Figure 2.5). The second scenario is the emptying of the cell through an open outlet (Figure 2.6), and the third scenario simulates an intermittent inlet flow rate. For the third scenario, the inlet flow rate is defined by a step function (flow rate 1 kg/s for every 10 s, otherwise it is zero), which represents an intermittent inlet flow rate. The starting condition for the second scenario is a fully saturated soil domain (Figure 2.6a).

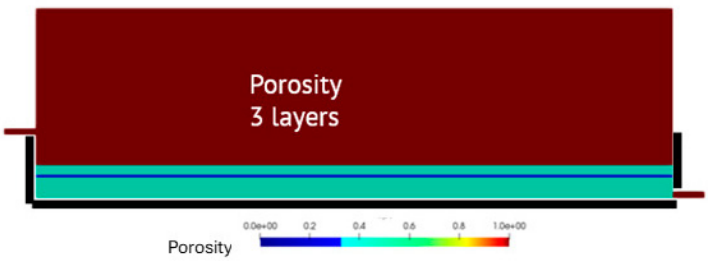

Figure 2.4. Bioretention cell with porosity layers.

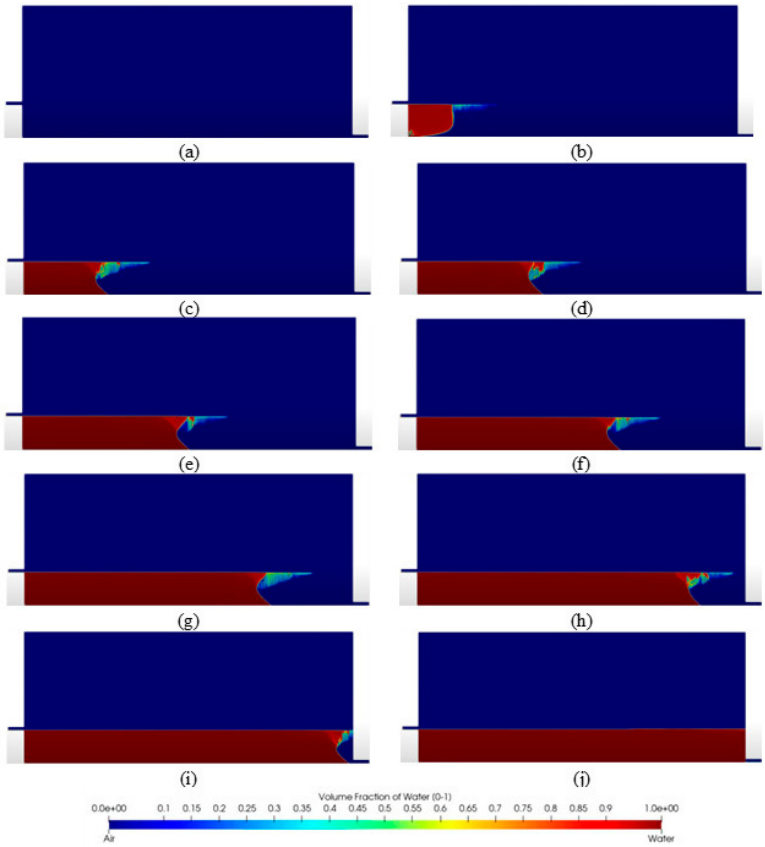

Figure 2.5. Filling of bioretention cell for time(s) (a)0, (b)50, (c)100, (d)150, (e)200, (f)250, (g)300, (h)350, (i)400.

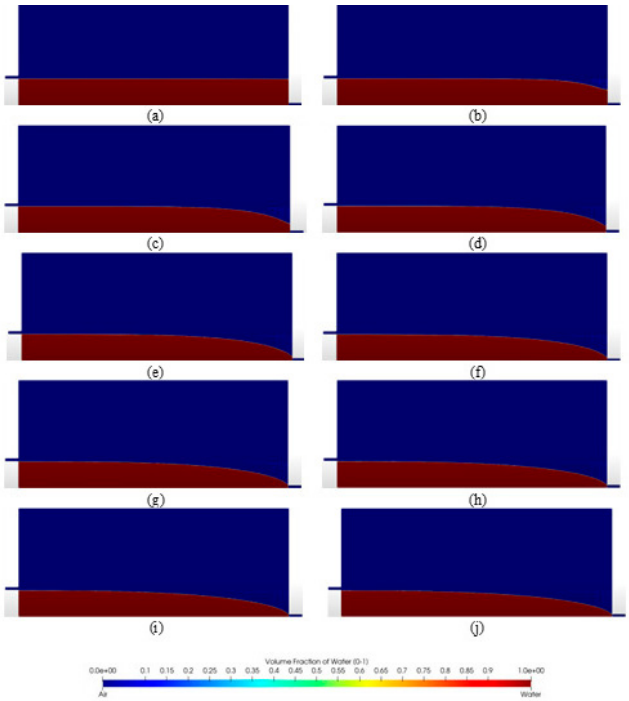

Figure 2.6. Emptying of bioretention cell for time(s) (a)0, (b)25, (c)50, (d)75, (e)100, (f)125, (g)150, (h)175, (i)200, (j)225.

Numerical results

Figure 2.7a shows outflow (runoff + infiltration) for the case of filling the bioretention cell. It is clear from Figure 2.7a that runoff starts when the retention cell is completely filled after 400 s. Also, there is a sudden jump in infiltration at 400 s. Figure 2.7b shows the outflow for the second scenario (emptying of the bioretention cell. Figure 2.7c shows the volume of the water available in the bioretention cell as a function of the simulated time for the second scenario (emptying the domain). The water volume is normalised by the initial water volume. Figure 2.8a shows the inflow, infiltration and overflow rates in the case of the intermittent inlet flow rate. Figure 2.8b shows the ratio of volume of water to the volume of water initially in the bioretention cell throughout the simulation period.

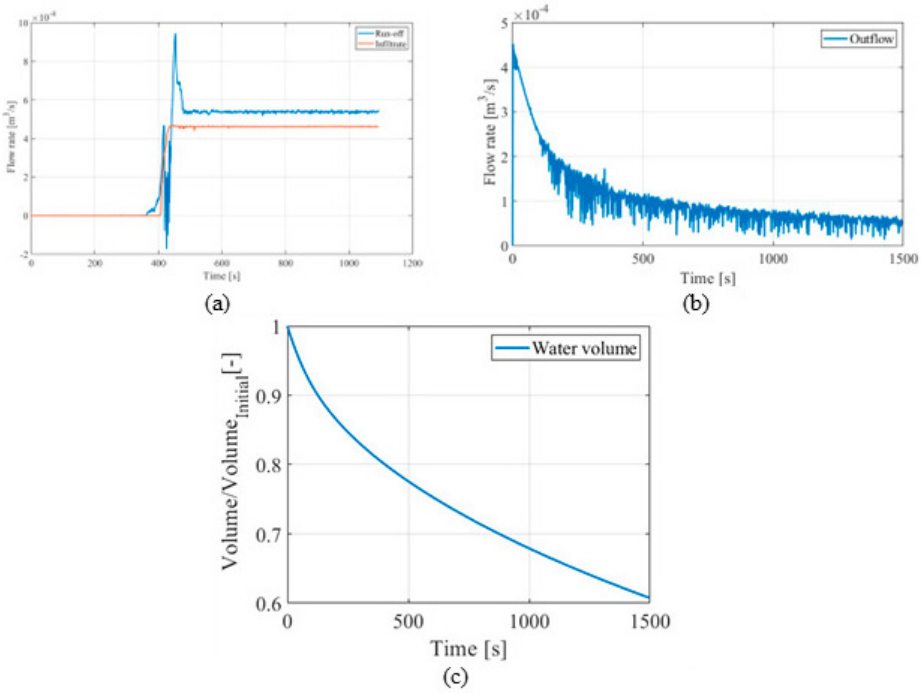

Figure 2.7. (a) Run-off, infiltration for the case filling of bioretention cell (b) Outflow for the case emptying of bioretention cell (c) Ratio of volume of water in bioretention cell at any instant of time to the original volume of water in the tank for the case emptying of bioretention cell.

For long-term simulations, water losses through evaporation can become substantial due to the effect of diurnal solar irradiance cycles. Hence, the effects of the diurnal cycle on the water balance in a bioretention cell have been studied. For these long-term simulations, the same computational domains and spatial extents as described in Figure 2.9a have been used. In the figure, domain 1 corresponds to air whereas domain 2 corresponds to the soil domain of the bioretention cell. Simulations have been carried out for 10 days and for various soil types, such as sand and silt. Selected wind velocities are 1 and 10 m/s. The initial temperature of both domains is kept at 15°C. Properties of soils and other simulation conditions were obtained from (Heck et al., 2020). The simulation results show that the evaporation rate is greatly affected by soil types and air velocity (figure 2.9b). Further, the results suggest that for a given radiation rate (Figure 2.9c), the surface temperature changes substantially between the two soil types (Figure 2.9d).

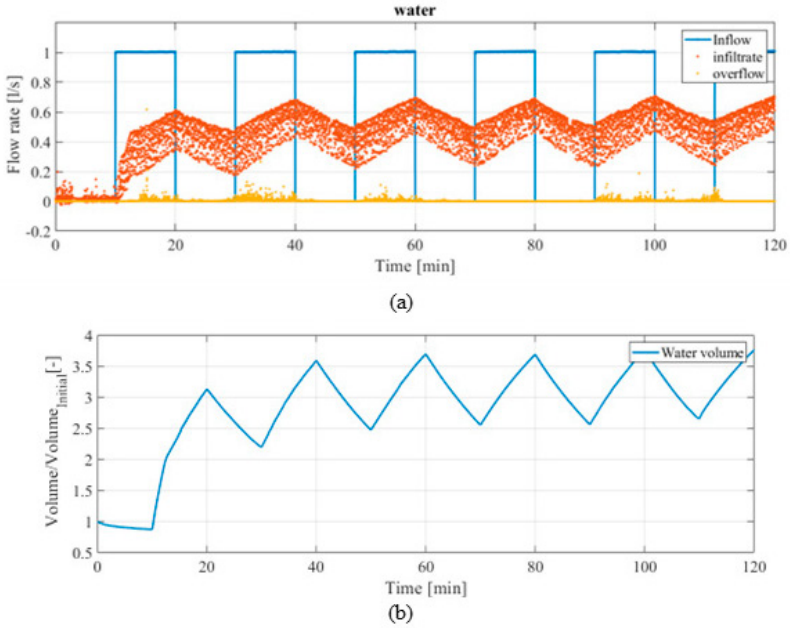

Figure 2.8. (a) Flow distribution and (b) Ratio of volume of water in bioretention cell at any instant of time to the original volume of water in the bioretention cell for the time-dependent inflow.

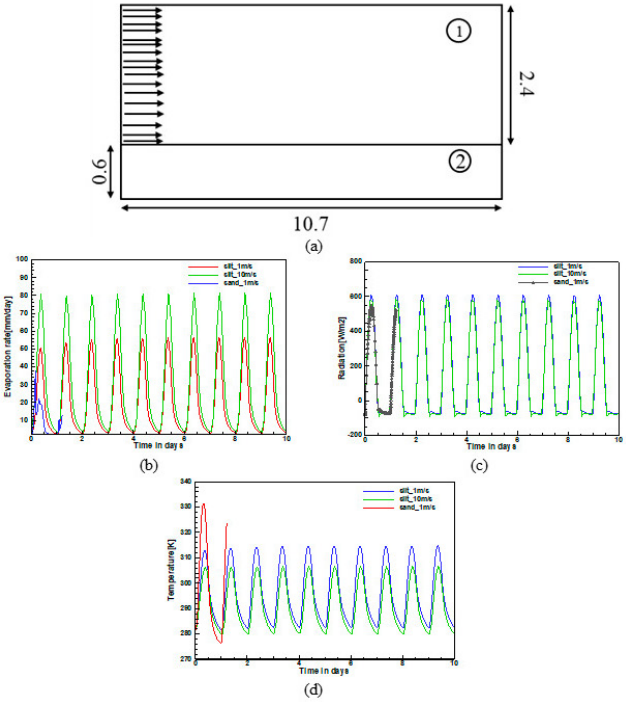

Figure 2.9. (a) Computational domain with dimensions in metres and effect of diurnal cycles on (b) evaporation rate, (c) net radiation at soil surface and (d) surface temperature.

Conclusions

CFD-based numerical models for the experimental bioretention cell at Länsikeskus, Turku were implemented to predict evaporation, infiltration and runoff. Initial simulations demonstrated minimal evaporation compared to infiltration during short-term simulations. This led to the exclusion of evaporation in subsequent models due to the high computational costs of evaporation simulations. Later models accounted for the effects of diurnal cycles on evaporation, indicating substantial water loss over longer periods. These model results show that a higher wind speed leads to a higher evaporation rate and importantly soil properties are more dominating over wind speed in evaporation process.

CFD models were utilised to analyse the effects of different porosity layers within the water-retention cell, exploring scenarios such as constant inlet flow, intermittent flow and complete saturation. These models provided insights into outflow dynamics, infiltration rates and overall water retention performance. They also provided the basis for the online tool for the evaluation of different bioretention cell designs presented in the following chapter.

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Chapter 3.
SWMM

Jan-Hendrik Körber

Urban stormwater systems are composed of different elements, such as specially designed stormwater drainage networks of pipes, drains and various detention structures, and more natural elements such as brooks, rivers and other surface water bodies. The latter are usually affected by the urban infrastructure by being channelled or directed into pipes for some parts. In between drainage networks and natural drainage elements are nature-based solutions, which are engineered solutions for stormwater management that aim to mimic natural systems.

The complex combination of planned and unplanned drainage elements has the primary function of managing stormwater runoff, i.e. precipitation that turns into surface water flow. Runoff generated by regular rains does not usually have noticeable effects on urban environments besides wet surfaces and puddles. However, heavy rains might cause local flooding or damage to basements and other infrastructure. To avoid damage, urban planners must design stormwater systems that can handle a large range of precipitation events and include contingencies for exceptional events. At the same time, not all precipitation should be drained – sufficient water should remain to maintain a healthy hydrologic balance that supports green spaces and aquatic systems.

Commonly, stormwater models are used to support stormwater planning and to evaluate different design scenarios. Numerous open-source and proprietary models exist with different functionalities but in general, each model is based on a parameterised description of the relevant hydrologic and hydraulic elements. e.g. catchments, land use and landcover, pipes and streams. One well-established model is the US EPA Stormwater Management Model SWMM. SWMM is a 1D dynamic rainfall-runoff model, primarily used to simulate pipe flow but with capabilities to simulate flow in streams.

Briefly, a SWMM model is composed of catchments described by parameters as percentage of impervious areas, average slope, initial retention, and drainage elements such as pipes, drains or streams. Rain is generated by one or several “rain gauges” that must be assigned to each catchment and can be fed with monitored or self-generated data.

The model then computes runoff for each catchment which is fed into one node in the drainage network. Therefore, the information used for the model setup must be accurate and up to date. Even if catchment characteristics are described well enough to mimic real-world conditions, models usually need validation and possibly calibration against measured runoff. Usually, stormwater models are built for case- or project-specific purposes but are kept updated. That is, if the land use changes in a modelled catchment or the drainage network is updated, these changes are not mirrored in existing models, rendering them useless. The ISMO project evaluated several options to keep stormwater models updated. These are described briefly in the following paragraphs.

Linking spatial data and infrastructure databases to stormwater models

Building information models

One research objective was to explore whether building-specific information stored in building information models (BIM), e.g. roof types, rain drainage systems or physical properties of the surrounding estate, can be utilised to parameterise block-scale SWMM models better than by using traditional cadastral and topographic information. As BIM is used to document a building's components and changes to them, it promises to reflect any changes in a building's properties. The main foreseen challenge was that BIM is building-specific and usually not openly available.

The project gained access to the BIM data of a pilot building to explore its potential for stormwater model setup. While the data was useful for visual inspection of the building properties, it was not suitable for improving the modelling processes, due to the lack of relevant information such as roof type and the building's rainwater drainage system. For example, it was not possible to derive information on which parts of the building were directly connected to the storm sewer and which parts drained to the surrounding surface areas, both being important information for the setup of a block-scale SWMM model. Dialogue with practitioners also revealed that BIM systems are often not kept updated and that the lack of certain infrastructure element codes hampers the documentation of all building assets. Some stormwater-relevant code is being developed, but the creation of detailed models based on BIM information is currently not feasible.

Municipal databases

As stormwater models depend on detailed and up-to-date spatial information describing catchment properties and drainage infrastructure, the project evaluated the opportunities to connect models directly to existing spatial databases. The City of Turku maintains comprehensive spatial databases with data including all elements of urban fabric,

such as roads, buildings, properties, water bodies, urban green space, and road and other furniture. Much of this data is openly available through a web map, web-map services (WMS), or web-feature services (WFS). The most complete dataset is available as a topographic map through a WMS, that is as one image with all information, with a zoom-dependent level of detail. Similar WMS layers are provided with orthophotos and other spatial information. The WMS topographic data is an excellent basis for the manual delineation of data relevant for stormwater modelling, but it provides little potential for an automatic approach to catchment description or the periodic update of stormwater models.

The vector data provided through the municipal WFS promised an opportunity to achieve this. However, the public WFS database includes only a fraction of the elements of the WMS topographic data. Workshops with experts from the City's data management department were held to explore ways of accessing detailed topographic data in vector format and combining the non-open data with stormwater models. The discussion revealed that such data cannot be accessed outside the City's data systems for security reasons. Similarly, stormwater drainage infrastructure is non-open data, and its use requires a case-specific request. The only option to directly link a stormwater model with the municipal spatial databases would be to manage the model inside the municipality data infrastructure. This option would require the city to be involved in the development process and demand significant resources and was thus not pursued.

The SWMM sandbox

To test different approaches to parameterise a SWMM stormwater model, the catchment of the urban/peri-urban stream "Kuninkoja" (Fig. 2.10) was chosen. The Kuninkoja is Turku's largest stream after the major river Aurajoki. Including its tributaries it has a catchment of approximately 26 km^2, which is composed of urban and rural fabric including fields and meadows and dense urban build-up areas. The Kuninkoja catchment was selected as a sandbox due to its natural and recreational value, and conservation and research interests connected to that. Several previous research projects collected monitoring data in the stream, including flow measurements and water quality samples. Therefore, its hydrology and environmental hotspots are relatively well known. Further data was collected during the project (Section 1) to support the validation of stormwater models.

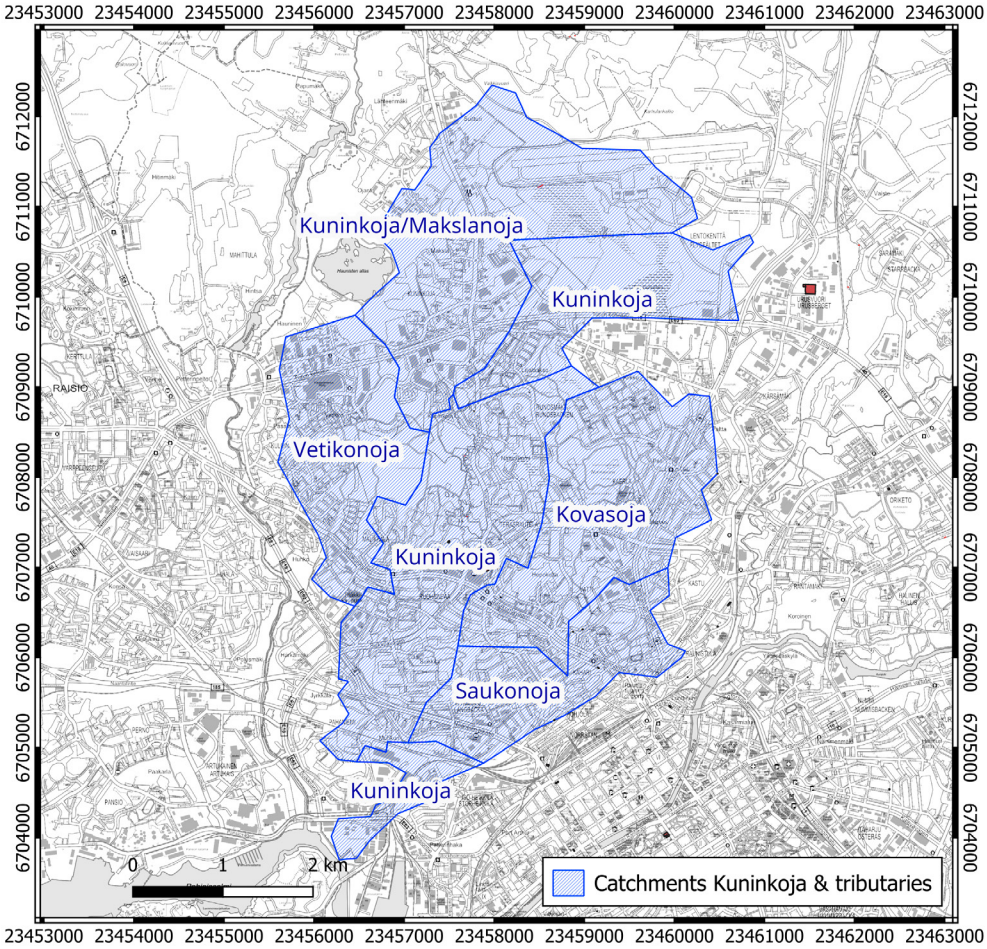


Figure 2.10. The Kuninkoja catchment area with sub-catchments.

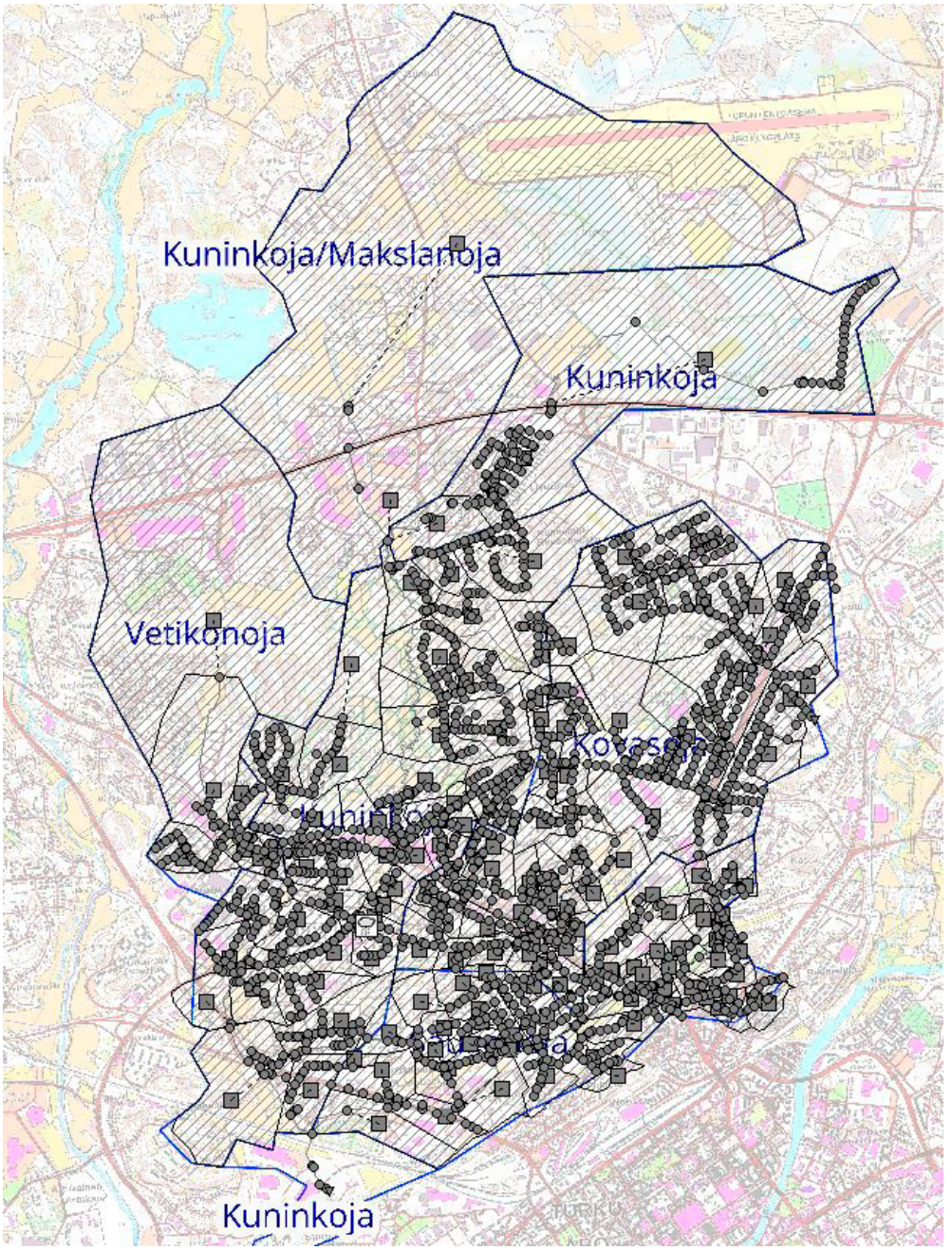


Figure 2.11. The Kuninkoja catchments and main drainage elements (pipes, drains, streams).

As automatic or semi-automatic approaches for stormwater sub-catchment parameterisation using online data services were rendered impractical, a conventional SWMM model was set up for the Kuninkoja. Due to its size and complex drainage infrastructure, a reduced resolution model was set up (Fig. 2.11). That is, major stormwater pipes and drains are included, but lot-level infrastructure is discarded. The Kuninkoja and its tributaries are described with a reduced number of links and nodes, with links usually connecting known culverts and pipe sections. Stream profiles have been obtained from digital elevation models and through fieldwork related to baseflow measurements. Parameters describing the sub-catchments, such as the ratio of impervious to pervious area, average surface roughness and average surface slope have been estimated based on topographic information, orthophotos and a 1 m digital elevation model produced from the City of Turku's open LiDAR data set.

While all data concerning the drainage system (pipes, drains, stream sections) were kept constant, three alternative approaches to determine the pervious and impervious areas of the sub-catchments were tested in QGIS: 1) based on automatic LiDAR point cloud classification, 2) based on semi-automatic orthophoto classification, and 3) based on image analysis of topographic maps. Approaches 1 and 2 did not result in significant differences in terms of percentage of impervious area and average roughness values derived from the sub-catchment scale. Approach 3 did allow for the extraction of water bodies and buildings, but other features were not reliably detected due to the lack of distinct map symbology.

Conclusion

The project explored several options to keep SWMM-based stormwater models up to date to avoid having to create new models following changes to the built infrastructure or land use, but the results of this research remained inconclusive. While the essential data needed for model parameterisation is continuously updated in municipal databases, this data is not directly openly available. Therefore, any automatic or semi-automatic approach can only utilise openly available data such as LiDAR, orthophotos and topographic maps. The first two data sets are not regularly updated and therefore do not reflect all changes in urban fabric. Topographic maps available through online map services are updated regularly but have limited usability for automatic land use classification and change detection.

The most promising approach for future work is the division of larger urban catchments with a uniform size, an approach developed by Warsta et al. (2017), and to establish a workflow in which changes in the drainage system or detailed plans are manually

ported to the model. A basis for such development could be the open-source GISWATER tool (giswater.org) which allows for the automatic generation of SWMM models from a centralised infrastructure database. Though this database would still require manual updates for individual elements, these could be done through a regular GIS inface without the need to edit non-spatial data in SWMM.

References

Warsta, L., Niemi, T. J., Taka, M., Krebs, G., Haahti, K., Koivusalo, H., Kokkonen, T. (2017): Development and application of an automated subcatchment generator for SWMM using open data. Urban Water Journal, 14, 9.

Chapter 4.

Model fusion and digital twin development

Ashish Pawar, Ashvin Chaudhari & Jan-Hendrik Körber

The ISMO project also aimed at developing digital twins (DT) for stormwater management applications based on the CFD models developed during this project. There is no single definition of a "digital twin". We define it as a digital replicate of a real environment that allows the stimulation of stormwater-related processes that mimic reality. The goal of a digital twin is to first reliably simulate hydraulic and hydrologic processes that can be verified against measured data and then be used to test different scenarios. The digital twin developed in this project is for individual stormwater management structures, e.g. a bioretention cell, and it allows for the testing and optimising of the effect of different soil layers and their properties on water filtration, runoff and retention within the structure.

The DT focuses on the replication of the physical processes and environmental boundary conditions to obtain simulation results as close to reality as possible, but puts less emphasis on the visual replication of reality, i.e. the objective is not to produce photo-realistic visualisations of the simulated environment and simulation results. As the DT requires extensive data for the calibration and validation of simulations, a major objective of the project is to collect relevant data. Data collection includes laboratory tests (e.g. soil type analyses, infiltration measurements, sensor calibrations), field campaigns (e.g. infiltration measurements, base flow measurements, mapping of vegetation states, measurement of surface temperature variations), and continuous online measurements (e.g. meteorological observations, water level and discharge, water temperature and conductivity).

The digital twin

The DT developed here is accessible using the link: https://lknbs.rahtiapp.fi/. The link takes you to an online tool that allows the running of a two-dimensional computational fluid dynamic (CFD) simulation for a virtual "bioretention cell" utilising OpenFOAM code. This tool is meant to help non-expert users evaluate the effect of soil properties on the detention properties of a bioretention cell used to manage stormwater runoff. The graphic user interface (GUI) of this digital twin is shown in Figure 2.12.

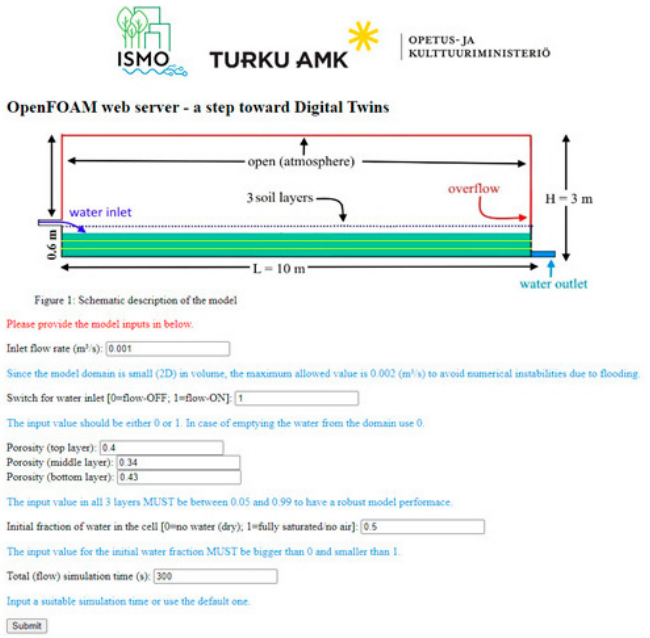


Figure 2.12. GUI of the digital twin.

In this DT, the flow simulation is carried out on a fixed domain size (10 m long and 1 m high, of which the lowest 0.53 m represent soil, and 0.47 m allows for ponding of water). The soil domain consists of three separate layers. The user can define porosities for three soil layers as well as a constant water inflow rate. It only simulates the movement of water on the surface and through the soil but ignores evaporation, and the effects of temperature and wind on evaporation. There are no other losses of water except through the outflow to the lower right or overflow. This corresponds to a bioretention cell that is lined with an impermeable layer.

Once a user submits the simulation request, the simulation runs on a server of the IT Center for Science (CSC) and results will be displayed on the DT GUI web page. In the current version, the tool shows the volume fraction of water saturation (fig. 2.13) and the inlet, outlet and runoff flowrates (Fig. 2.14). The volume fraction is a dimensionless number with 0 indicating pure air (i.e. no water) and 1 only water (i.e. no air).

This tool is a first proof-of-concept version. More development is needed to make this tool useable for multiple simultaneous users as it is not able to run simultaneous simulations in its current version. Moreover, for future development, more parameters like radiation, temperature and wind will be added, as well as the option to modify the geometry of the model (length and depths).

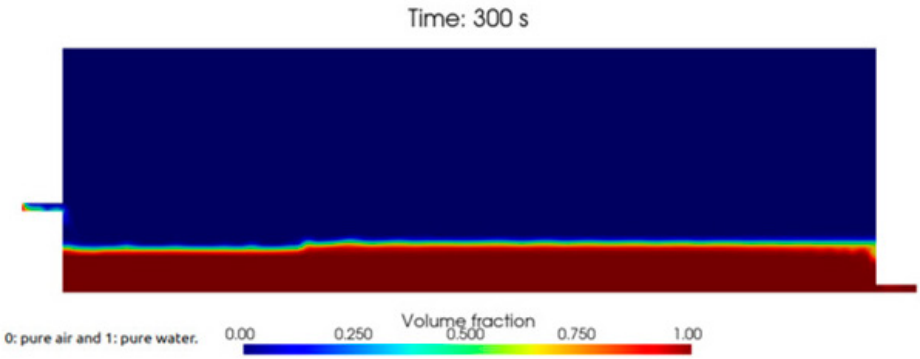


Figure 2.13. Volume fraction of water. 0: pure air and 1: pure water.

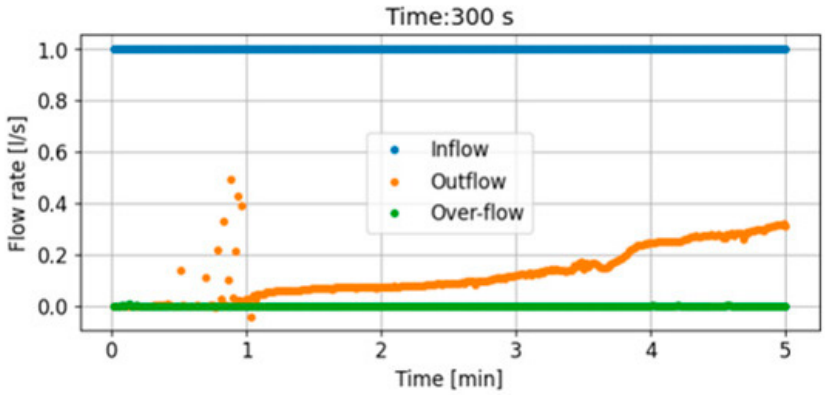


Figure 2.14. Distribution of stormwater in bioretention cell.

Use of the DT tool

Users are allowed to modify the following parameters:

1) Inlet flow rate [m^3/s]

A constant inflow of water can be set that flows "on top" of the cell, like a stormwater drain that would discharge on the surface of a bioretention cell. The water is then able to flow on the surface and infiltrate into the soil below. The soil is comprised of three equally spaced individual layers, for each of which a porosity must be set. This could be, for example, to simulate a top layer of topsoil or mulch, a middle layer with lower porosity like coarse sand, and a lower drainage layer, e.g. gravel.

The user can modify the volume of water that enters the simulated structure (from the left), measured in cubic metres per second [m^3/s]. Example: one hour of rainfall with a uniform rain intensity of 10 mm/hr falling on a 1,000 m^2 area of smooth tarmac with a minor inclination will generate a peak flow of approximately 2.5 l/s or 0.0025 m^3/s.

2) Switch for water inlet [0 = flow-OFF; 1 = flow-ON]

This can be used to simulate inflow of water (1) or no inflow (0). When choosing "no inflow" (0) an initial water fraction (see below modifiable parameter 4) should be chosen. In this scenario only the emptying of the cell is simulated. If no inflow and no initial water fraction is set, nothing will be simulated. Note: the inflow cannot be switched on/off while a simulation is running.

3) Porosity (top, middle, bottom layer)

Soil porosity refers to the empty spaces, or pores, between soil particles. Much like a sponge, soil has empty spaces between soil particles that can hold water when it is dry. Soil porosity affects how water moves through the soil and how much water the soil can hold. If the soil has high porosity, it can hold more water and allow it to move through the soil matrix more easily. Conversely, if it has low porosity, water cannot move as well, slowing down the flow rates through the system and causing ponding. The tool can be used to try different combinations of soil layer porosities to strike a balance between water detention and throughflow, without causing ponding for different estimated inflow rates.

Porosity is expressed as a ratio in this application. For example, 50% porosity is 0.5 here. A value of 1 would be air, while 0 would be solid without any holes.

Some examples of soil porosities are given in Table 2.1. Note that these are averages – every soil class covers a range of porosities.

Table 2.1. Porosity values for a few simple soil types.

Material	Porosity
Gravel	0.2–0.4
Sand	0.3–0.5
Silt	0.4–0.5
Clay	0.4–0.6

4) Initial water fraction in the domain

In this field, the user can set the initial volume of the water in the domain. A value of 0 means no water at all (i.e. the entire domain is initialised with air) and a value of 1 indicates that the domain is initialised with water only (i.e. no air at all). Users are allowed to set any value between 0 and 1; however, the exact values of either 0 or 1 should avoided in order to stabilise the simulation. For example, a value of 0.001 can be set if the user wishes to initialise the domain with air. If no value is given, then system will assume the default value of 0.5. This modifiable parameter is a dimensionless value.

5) Total flow simulation time

In this field, users can set the value of total simulation time. Depending on the value inputted, the DT will simulate the case and fetch the results (every 10 s) on the web server. The default value for this input is 300 s.

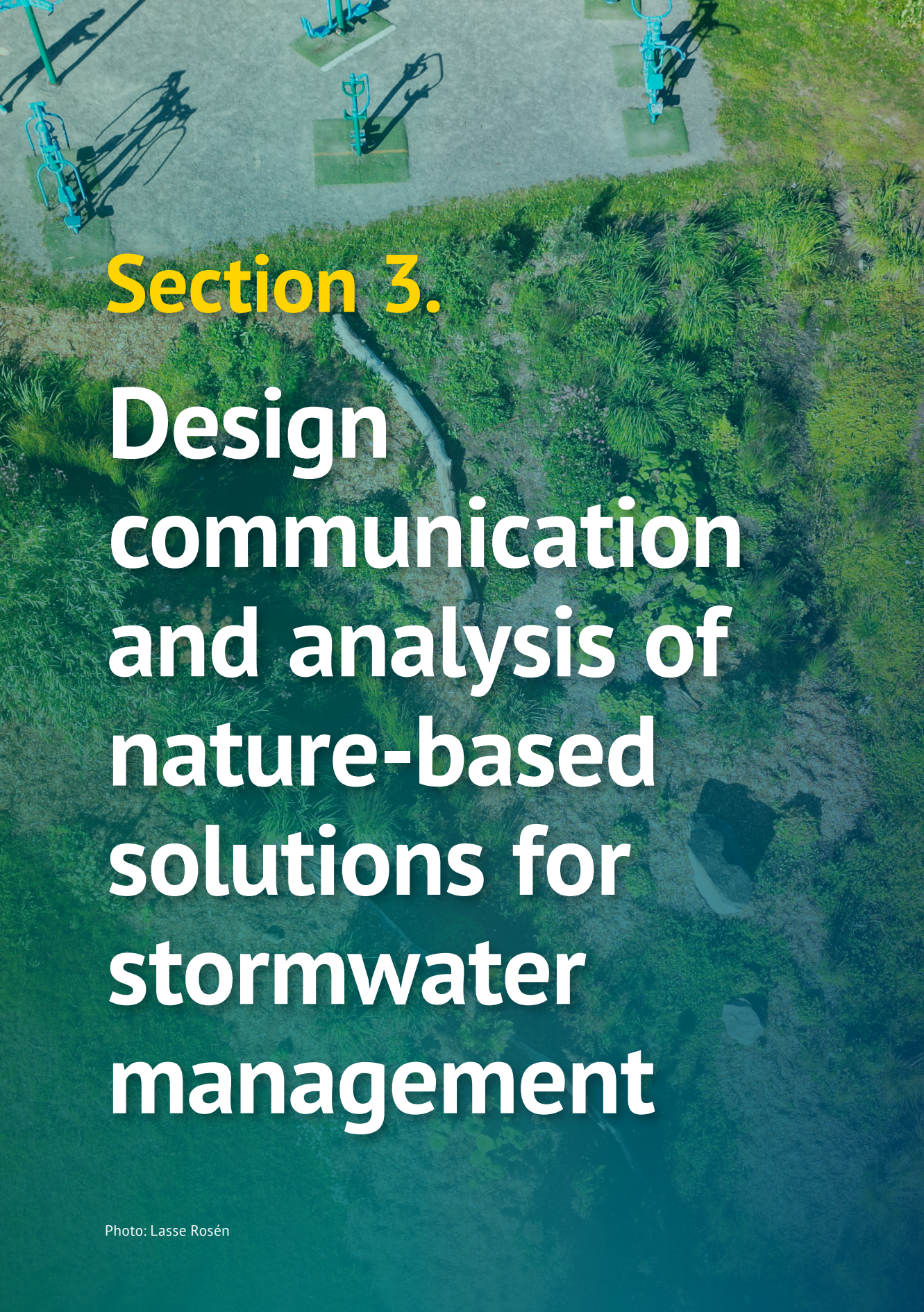
Chapter 5.
Discussion and conclusions

One major objective of the project was to improve existing and develop new modelling tools and techniques to reliably simulate urban stormwater systems and to pave the way for online digital twins (DT) that can mimic and predict urban runoff conditions. As part of this ambition, the potential of multidimensional and high-resolution CFD models and conventional well-established one-dimensional stormwater models was explored. While the US EPA Stormwater Management Model (SWMM) can reliably simulate catchment-scale stormwater runoff-related processes when set up correctly and calibrated against real data, it fails to resolve spatially distributed, small-scale processes such as water transport through soil, infiltration or surface runoff patterns. This is the gap that CFD modelling is promising to fill.

The project has demonstrated that existing CFD models can help to find the optimal combination of soil properties if particulate pollutant removal is the prime objective of a decentralised stormwater management solution, such as a bioretention cell. It has also shown it is capable of simulating subsurface and infiltrated flow patterns in a bioretention cell, albeit at high computational costs. These two techniques are a promising foundation for developing future design optimisation tools. Further, the online version of the bioretention cell digital twin that allows the simulation of user-defined evaluation of different design variables is a major step towards making the optimisation process fully automatic and expert-independent.

However, further developments are still needed to solve the integration of 2D and 3D CFD models of urban hotspot areas with 1D catchment-scale models. Moreover, the computational load of the employed CFD simulations required some simplification of natural processes, e.g. the exclusion of evaporation from near-real-time simulations. The inclusion of complex processes such as evapotranspiration that are not governed by simple mathematical equations also remains a challenge in CFD models. Implementation of these processes will help to improve the parameterisation of stormwater system components in models such as SWMM.

The set up of conventional stormwater models for the pilot catchments remained labour-intensive, as it was not possible to integrate existing landcover and infrastructure databases with the model. This is due to both technical obstacles and data protection-related issues. While some potential tools to link SWMM models with infrastructure information have been explored, e.g. through the open-source GISWATER tool, it remains a future development target. Problems like missing drainage infrastructure information such as pipe diameters and node elevations are inherent to stormwater modelling and require continued cooperation between relevant stakeholders to update and maintain infrastructure databases. The emergence of tools that can semi-automatically correct faulty network information, such as the Fluidit network toolkit, are promising approaches to further improving stormwater models. The creation of a local database and monitoring of relevant environmental parameters (Section 1) is a major step towards the creation of reliable and sustainable models.



Section 3.

Design communication and analysis of nature-based solutions for stormwater management

Photo: Lasse Rosén

Chapter 1.

Introduction – Aerial data for visual analysis of design

Urbanisation and climate change have heightened the need for effective stormwater management. Nature-based solutions (NBS) offer sustainable approaches by integrating natural processes into urban environments. Communicating and co-creating such solutions are crucial for informed decision-making, enabling stakeholders to understand both the functional and aesthetic benefits of NBS.

Urban stormwater management (USM) is necessary because urban stormwater runoff poses a serious environmental threat to ecological and human health in cities around the world (Burns et al., 2012; Goulden et al., 2018; Islam et al., 2021; Vasconcelos & Barbassa, 2021; Xu et al., 2023). The issue has deteriorated due to ongoing urbanisation and climate change (Bai et al., 2014; Grimm et al., 2008), which emphasises the need for efficient stormwater management strategies. However, the combined functionality and design quality of conventionally engineered stormwater systems are frequently lacking, leaving much to be desired in terms of the artistic rainwater design's (ARD) visual and architectural quality (Echols & Pennypacker, 2008). The goals of the ARD concept and the previous "infra-garden" strategy to support social and ecological values in stormwater management are similar (MacElroy & Winterbottom, 1997). The objective of both methodologies is to integrate aesthetic, visual and emotional elements with practical functionality to create architectural experiences that support resilient and liveable urban environments.

The use of nature-based solutions (NBSs) in the design of urban rainwater systems is suggested by novel trends in stormwater management, which have mostly been observed in the European Union since 2015 (Li et al., 2023). The social benefits of NBSs, along with their aesthetic and place-making qualities, are regarded as essential characteristics in addition to their functional performance (Martín et al., 2020). Small-scale NBSs connected to the urban fabric, however, are only effective when implemented

widely and consistently (Ruangpan et al., 2020). Therefore, it is necessary to investigate ways to promote and increase the use of NBSs in the urban drainage systems. The visualisation and features enabling functional analysis of the performance of NBSs aims to support the adoption and implementation of integrated nature-based drainage systems in cities.

The sub-project of the Built Environment research group within the ISMO project looked at the visualisation and functional analysis aimed to demonstrate a drone-based data collection and design workflow that offers a method for evaluating a design's utility performance and amenities for a particular project area. In this study, the workflow was created, tested and demonstrated on a case study area of a campus building's green roof. While the investigation of utilities provides parameters with metrics, such as the ground's ability to absorb stormwater, to analyse the stormwater system's functionality computationally the analysis of NBS's amenities is based on subjective and project-specific design aspirations.

The tasks of the sub-project were divided into two sections: 1) an examination of the ways in which drone data is currently used in stormwater management system design, and 2) an investigation into the design workflow's implementation and evaluation on the case study premises. The goal of the first phase was to determine the degree to which current practices and workflows aid in the decision-making process regarding the stormwater systems' usability and aesthetic quality in small- to medium-sized urban projects that are often the subject of real estate investments. In the second phase, a design workflow was examined to offer researchers, software developers and design practitioners prescriptive guidance for the future development of workflows based on modelling, design software and aerial imagery to achieve more informative design methods for decision-making in projects that may involve small-scale NBSs.

Chapter 2.

Drone-based aerial data for nature-based urban design

Harry Edelman

The effectiveness of stormwater systems has been questioned because of deficiencies in our understanding of stormwater management practices, the effects of urbanisation and grey infrastructure on local and regional hydrology, pollution in runoff waters, and other factors (Cao et al., 2021; Lu & Hughes, 2017; McDonald, 2019; Roodsari & Chandler, 2017; Wagner, 2005). Municipalities frequently face resource constraints when it comes to stormwater management, which makes it necessary to focus on the actions that will have the biggest effects on the quality of the water. It has been suggested that active monitoring should be implemented to ensure compliance if the measures' effectiveness falls short of the design intentions (Markell & Glicksman, 2015). However, the ability to directly offer prescriptive advice and guidance for designing stormwater solutions in other areas and specific sites is limited by the laborious active monitoring and data collection on the properties of water, such as the surface flow or water quality. Conversely, in the local design context, aerial data can provide tools for data-driven decision-making. The taxonomy for drone applications put forth by MacDonald (2019) in the developing field of employing unmanned aerial vehicles (UAVs) in stormwater management and system design is as follows:

1. ***An asset management tool.*** This category includes the gathering and examination of data from both constructed environments, like sewer inlets (Moy de Vitry et al., 2018), and green infrastructure, which makes it possible to monitor plant health, for example (Robinson et al., 2022). Conventionally, crowd-sourcing approaches have been used to collect imagery of the sewer inlets and their location by incentivising citizens to send pictures to the city authorities for a reward. This practice can easily be replaced by aerial imagery and AI tools detecting the desired objects. Further, the solution is scalable and replicable at low cost.

2. ***A water measurement tool.*** A strategy that contains both sampling (Sanim et al., 2022), and imaging techniques like RGB and multi-spectral image fusion (Alevizos et al., 2022). For example, multispectral remote sensing can be used for monitoring the water quality of urban rivers and watersheds (Yan et al., 2023).

3. ***A vehicle for better model parametrisation.*** Compared to other georeferenced data with low resolution and granularity, aerial data can provide spatial data on-demand for higher spatial accuracy, improving model performance (Hoffmann et al., 2016; Vivoni et al., 2014). Additionally, the ground surface temperatures (Wu et al., 2022) and surface imperviousness (Francos et al., 2021) can be estimated using thermal imaging. From the perspective of functional landscape architecture, the specific characteristics of the ground can aid in the development of modelling approaches.

4. ***A way to support smart and connected stormwater systems.*** UAVs are thought to be instruments for gathering information and enhancing situational awareness (Josipovic & Viergutz, 2023). Real-time and frequent aerial data updates are possible with emerging autonomous and frequent drone operations as a by-product of other smart city solutions like first responders' operations or drone logistics. The use of data-driven stormwater design and management techniques is supported by the increased availability of comprehensive and high-resolution data.

Next, we will view how the state-of-the-art contributes to the aims of the ISMO project. The taxonomy above helps in three ways to consider the development of a design review framework that allows the functionality and architectural properties of the urban NBSs to be considered.

First, a mesh model established with photogrammetry can be used as an early model to study the stormwater design features of an NBS by changing the assigned mesh properties, such as colour and texture, and functional properties, such as imperviousness and roughness of the surface impacting water flow and infiltration of stormwater. Further, the mesh model delivers the surrounding context data of the design area to which the 3D model of the nature-based design solution can be inserted for analysing the utilities and amenities of the solution. The method can help to estimate the planned design solution's qualitative and quantitative performance without modelling the NBS in detail, which is still time consuming and expensive with the current design software.

The method can be manually applied to smaller surface areas by picking the desired mesh segments. However, machine learning employing semantic segmentation could be used for efficiency and larger surface areas (Zamani et al., 2022). When compared to high-altitude aerial imagery, UAV aerial data can help with this task by offering more

detailed and unobstructed imagery. Tree canopies frequently obstruct the surface analysis of aerial photos obtained at higher altitudes. Fig. 3.1 depicts data collections under the tree canopy in the Kupittaa NBS site in Turku (3.1A) and the resulting surface model (3.1B). Furthermore, the resolution or point cloud densities in these aerial photos are insufficient for identifying extremely precise surface geometries, like sloping surfaces or intricate kerb sides, or to precisely analyse surface water flows and water pooling. For this reason, more thorough information about the surrounding area is necessary for the assessment of functional landscape architectural design.

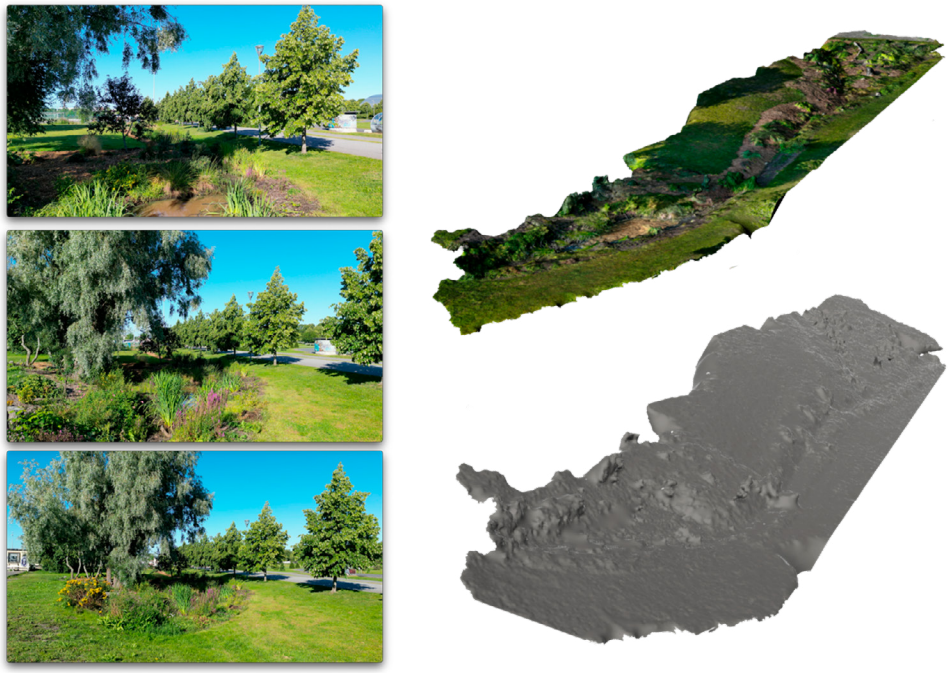


Figure 3.1. Aerial data collection under the tree canopy (A) and resulting surface model (B).

Second, the measurement-based estimates of imperviousness for each soil and surface type can be used to improve the parametrisation of physical model parameters. These estimates can then be assigned to corresponding areas of the surface mesh to simulate the infiltration and flow of stormwater. To these ends, the imperviousness and surface types should be established to connect the model to the real-world data. However, the dynamic nature of infiltration capacities of the soil impose complexity on the modelling. Therefore, if the aspiration is a true representation of a real-world situation, the infiltration parameters of the mesh model representing the performance of the soil should

be adjusted as the infiltration slows down towards the saturation point. To that end, an important research question is to what extent the model needs to represent the real-world performance of the soil in contrast to sufficient approximations and performance categories relevant to the practice of NBS design. From the design practice point of view, approximations of typical soil and surface types depending on the geology will satisfy the needs for the parameters necessary for the practice and design process.

To increase the complexity further, extremely dry surfaces increase surface flows before the infiltration of the stormwater begins to take place. This may occur during extreme weather events over a period of hot summer days, causing urban floods. In turn, continuous rain causes the saturation of the soil, thus reducing the infiltration of stormwater. Both factors should be acknowledged in the approximations. Additionally, evaporation poses a third factor, but its relevance is smaller from the urban flooding point of view, but it may impose a success factor for the NBS design from an irrigation point of view in case there are no other solutions for irrigation, such as by storing the stormwater during heavy rain events.

Third, individual projects and investment choices pertaining to NBSs are the foundation of intelligent and networked stormwater systems. Therefore, every project and associated nature-based design contributes to the lessening of loads on the network and is a part of a larger evolving network of site-specific stormwater solutions. As a result, the project-level decision-making process ought to offer a well-informed method to consider the growing utilisation of NBSs to facilitate the coordinated construction of the network. Visualisation is essential in the planning, design and implementation of NBS for stormwater management. It helps in:

- **Communicating design intentions:** Visual tools effectively convey the design and functionality of NBS to stakeholders, including policy-makers, urban planners and the public.
- **Enhancing decision-making:** Clear representations of NBS functionality and appearance aid in evaluating unique design alternatives and their potential impacts.
- **Supporting stakeholder engagement:** Engaging visuals foster community support and involvement in NBS projects, ensuring solutions are well received and maintained.

In summary, the goal of the sub-project is to learn more about the data collection methods currently employed by drones to assist in the design and implementation of nature-based stormwater management strategies in urban development projects. The work also aims to present a workflow based on design software that supports these kinds of decision-making processes. The idea that there is a gap in the current design workflows for evaluating the aesthetic and practical stormwater qualities of architectural nature-based solutions was the basis of the study's research problem.

Chapter 3.

Use case demonstrator of nature-based design for stormwater solutions

Harry Edelman

A demonstrator was used for the aims of the research to provide a real-life setting for the analysis and visualisation of an NBS. The green roof of the Turku University of Applied Sciences campus building was selected as the case area (Fig. 3.2). The selection of the site was made based on the size and form of the NBS, which can be scaled in a modular fashion both on rooftops and other locations in the urban fabric, such as urban green space in the courtyards of urban blocks. In other words, the selected size of the NBS solutions is applicable in other embodiments than green roofs.

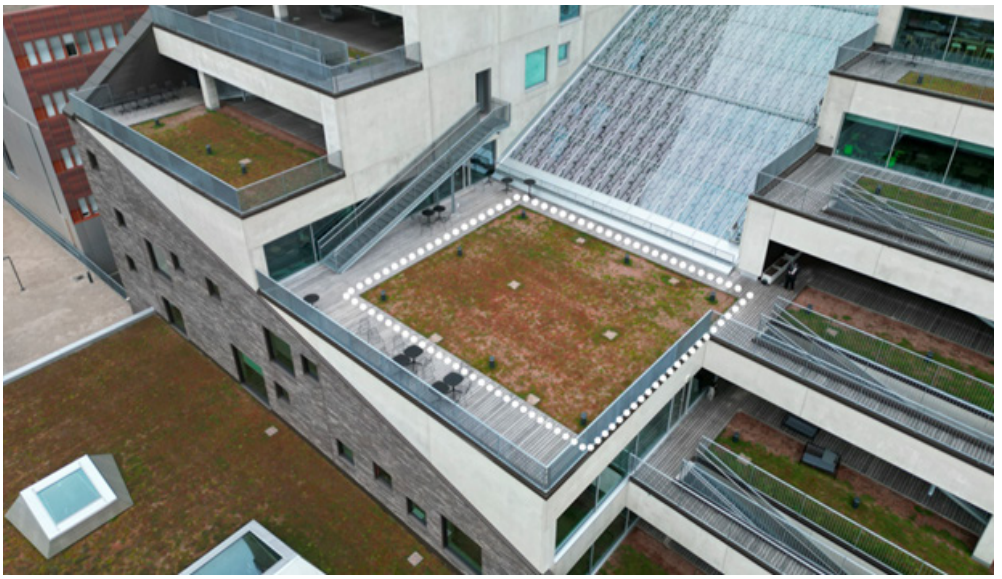


Figure 3.2. Green roof of the EduCity campus building.

The application of similar modular solutions on a large scale in the urban fabric allows for the creation of a network of NBS solutions. This distributed, local stormwater management then enables the transition towards a network approach with local NBSs, reducing the stress on the stormwater piping system and potentially allowing new NBS-based urban systems that are more sustainable, liveable with urban green space, and life-cycle efficient with reduced piping infrastructure.

The aim of the demonstrator was to create a design workflow for the aesthetic, architectural and functional analysis of an urban NBS for design review and stakeholder communication. The demonstrator was created using a single open-source software platform, Blender 4.0. The reason for that is the features of Blender offer an integrated development platform for the approach by using only one software platform. For a commercial and easy-to-use version, an alternative software application such as Unigine should be explored as well as Python-scripted apps inside Blender to streamline the workflow. Figure 3.3 shows an example of the workspace of Blender.

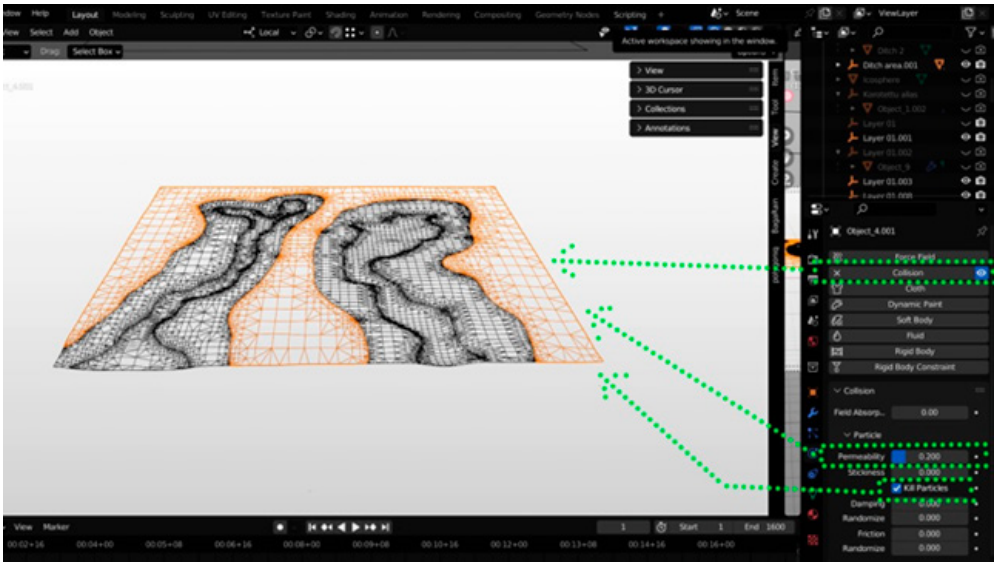


Figure 3.3. Assigning physics properties in Blender to the surface model of ground.

The creation of the workflow inside Blender took place after collecting enough aerial data of the case study location. A DJI Mini 3 Pro drone was used for collecting 550 aerial images of the site. Then the images were uploaded into the open-source WebODM photogrammetry software to construct the mesh model used in the visualisation and simulation of the rain events at the site. The mesh model was used for simulating rain events, showing how water infiltrates, flows and accumulates on the green roof. Two approaches were tested: first, a rapid approach that only changed the colour properties of the mesh model for indicating specific surface types with designated physics and infiltration properties; and second, a more sophisticated method of fusing the designed NBS to the mesh model showing the visual qualities of the solution in detail.

The latter approach was then tested with different interventions such as altering surface topography and adding stormwater reservoirs, to analyse their impact on stormwater management. Physics properties, such as permeability and surface roughness, are assigned to the model to simulate stormwater behaviour depending on the assigned roof properties. Three diverse types of roof surfaces were investigated: bitumen roof, extensive green roofs with sedum, and intensive green roofs with vegetation requiring a deeper soil depth (200mm).

The results showed clear benefits both from the aesthetic and functional performance. While the bitumen roof showed extraordinarily little stormwater retention capacity, the intensive green roof was able to retain all the stormwater during a rain event lasting 1:06min and accumulating 34.23 mm/m^2 of stormwater. Figure 3.4 shows the end state of the simulation and the collection of stormwater in a retention tank. To summarise, in the best case the stormwater barely reaches the retention tank while the NBS can delay the stormwater flow.

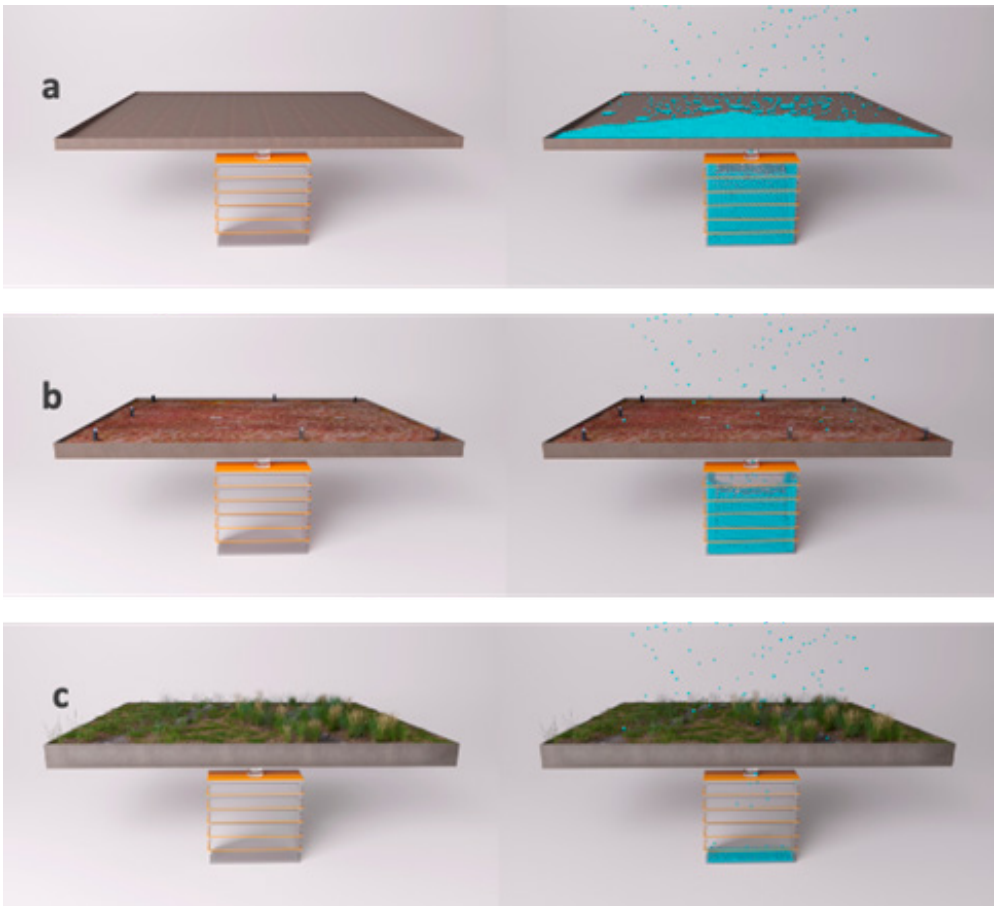


Figure 3.4. Simulation of a rain event and the retention of stormwater in three scenarios: a) bitumen roof, b) sedum roof, and c) intensive green roof (200mm).

Chapter 4.
Discussion and conclusions

The Built Environment sub-project of ISMO presented, to the best of our knowledge, the first integrated approach to a qualitative and quantitative design analysis framework for urban NBSs. For efficiency, the framework was developed and demonstrated with the Blender open-source software stack, allowing combined workflows of visual and functional analysis.

For practitioners and commercial applications, the minimum requirement for further development would be Python-coded easy-to-use add-ons in Blender to guide the user through the various stages of building the digital twin of the site and performing the qualitative and quantitative analysis with desired parameters. Beyond the use of Blender, an additional software stack should be considered during further development such as Unigine, which is a powerful real-time 3D engine. Unigine is commercial software, designed initially for engineering and scientific simulation beyond mere gamified use cases. However, unlike in the case of open-source software, the downside of the vendor lock-in software is the limited space for community and research-driven inputs for development.

There are some limitations to the study. The intention of installing stormwater measuring equipment to the outlet drainage of the green roof was not possible due to the liability concerns and policies of the owner of the property. The current implementation of the green roof was not fully satisfactory and potentially under dispute. Installing third-party equipment to the roof-top drainage may have caused grounds for versatile functionality of the green roof.

For future research, it is expected that the rapid development of generative machine learning will increase the analysis capabilities and autonomy of the model, thus making the creation and operation of the model easier. To that end, the creation and visualisation of NBSs are expected to become more widely available to different users with various backgrounds and skills.

In conclusion, the functional analysis combined with the visualisation is an essential component of designing and implementing NBS for stormwater management. By leveraging advanced tools and techniques, stakeholders can gain a comprehensive understanding of how NBS will function and look in the urban landscape. This not only enhances decision-making but also fosters community support and ensures the successful adoption of sustainable stormwater solutions.

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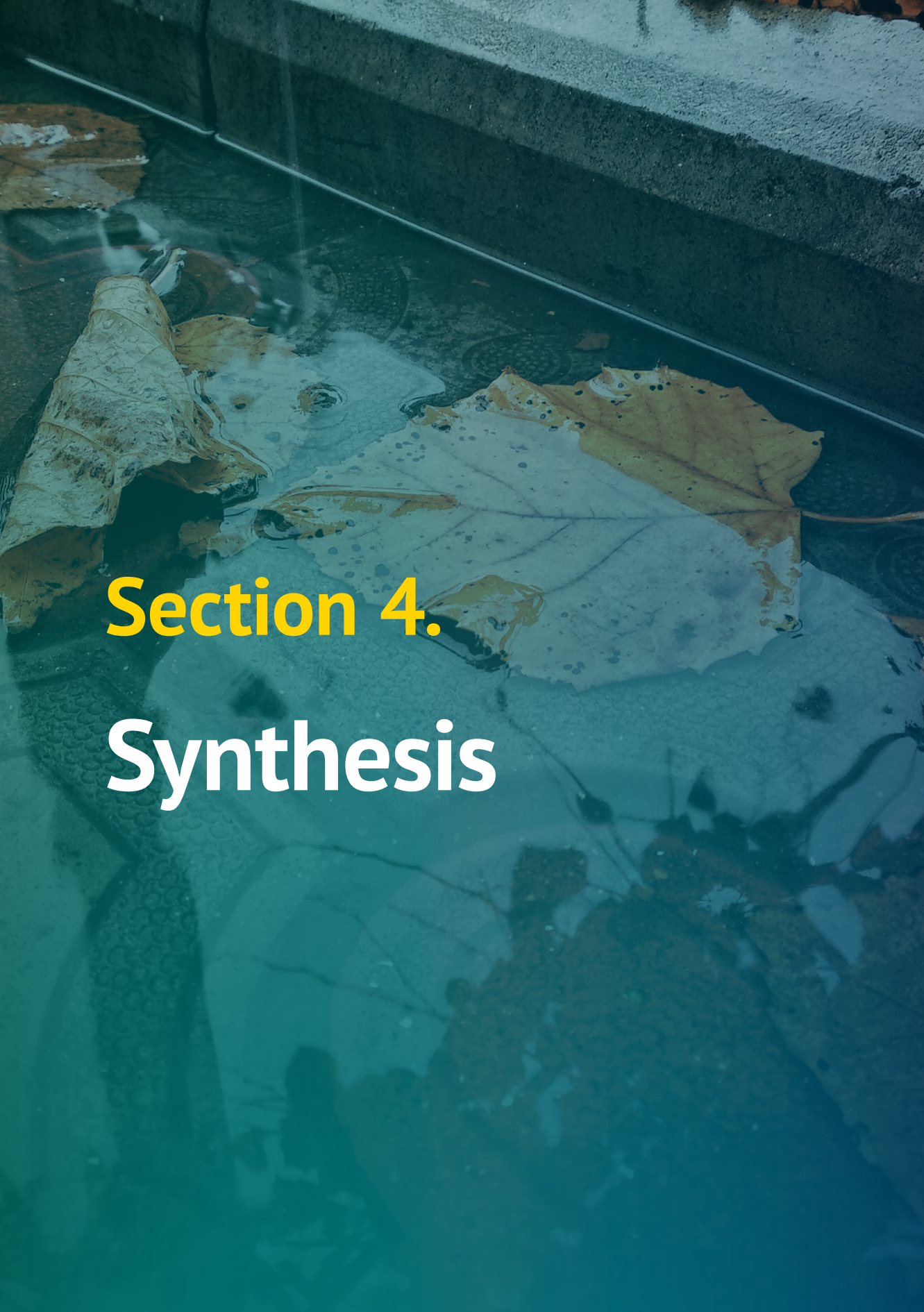

Section 4.

Synthesis

The objective of the ISMO project was to strengthen Turku UAS's capacities in multi-disciplinary urban stormwater-related research by bringing together expertise from environmental engineering, computational engineering and architecture. The long-term vision of the project was to develop a competence centre for applied stormwater research and development that closely collaborates with regional stakeholders from municipalities, NGOs, industry and business, and other research organisations. To this end the project allowed Turku UAS to significantly increase its expertise.

The development and implementation of the IoT-based monitoring network were only possible through collaboration with experts in wireless communication technologies. The development of monitoring plans and locations was done in cooperation with other projects and involving partners from public services and the research community. The work resulted in new projects to continue the development and expand the work and goals set out for the ISMO project. The use and development of different stormwater models delivered prototypes for several novel applications, such as an online tool to test different NBS design scenarios or procedures to create photorealistic visualisation of architectural design alternatives, with simultaneous capabilities to assess aesthetic and functional aspects of different design alternatives for stormwater detention. Both examples have multiple benefits, such as being a thus-far underutilised planning and communication tool for experts and non-experts alike.

The achievements made during the project provide a basis for continued development in the future. These include the sustainable integration of local data sets with urban stormwater models to minimise the resource-intensive work of catchment or city-wide stormwater model development, and the extension and purpose-driven design of the monitoring network to include further sensor types and monitored parameters and optimise monitoring site locations to provide comprehensive near-real-time analysed information to stakeholders.

Furthermore, the development of specific data products and services for the needs of different stakeholders is an objective that emerged during the ISMO project. This will be brought forward in follow-up projects that have been secured thanks to the achievements of the ISMO project.