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Towards effective monitoring of urban stormwater for better design and management

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Abstract. The lack of information due to insufficient data availability and an improper sampling method for stormwater generates constraint and uncertainty in addressing all storm events. In such conditions, it is difficult to assess actual concentrations and mass loads. This results in a backlog in decision-making for sustainable planning, design and policy formulation, e.g. retrofitting alternatives to traditional systems for reducing runoff and pollutants. It is essential to set standardized sampling and analysis procedures in order to achieve reliable and representative data. They need to be optimal and effective due to the costs and difficulties in sampling and analysis. The study reviews the effectiveness of largely best practiced sampling procedures in research papers. Likely site selection approaches, monitoring parameters and sample collection systems are compiled with their effectiveness, affordability and applicability. An optimal stormwater sampling programme is deducted and recommended for Tallinn stormwater catchment area. Moreover, the study provides an opportunity to select the suitable monitoring programme from the effective options such that it can be utilized to obtain coherent stormwater data.

Key words: stormwater monitoring, sample collection system, sampling programme, mass loads.

Abbreviations:

ADV – acoustic Doppler velocity
BOD – biological oxygen demand
CHIAT – Chemical Hazard Identification and Assessment Tool
COD – chemical oxygen demand
DEHP – di(2-ethylhexyl) phthalate
DO – dissolved oxygen
DOC – dissolved organic carbon
DTN – dissolved total nitrogen
EC – electrical conductivity
EMC – event mean concentration
MOH – mineral oil hydrocarbon
NA – not available
PAH – polycyclic aromatic hydrocarbon
PCB – polychlorinated biphenyl
PP – priority pollutant
SMC – site mean concentration
SS – suspended solids
TDS – total dissolved solids
TKN – total Kjeldahl nitrogen
TN – total nitrogen
TOC – total organic carbon
TP – total phosphorus
TS – total solids
TSS – total suspended solids
TTU – turbidity
USGS – US Geological Survey
WFD – Water Framework Directive
XOC – xenobiotic organic compound
γ-BHC – gamma-benzene hexachloride

INTRODUCTION

There are potential drivers that augment stormwater monitoring in different countries. The US National Pollutant Discharge Elimination System permit programme has regulated point source pollution from urban stormwater, industrial discharges and construction activities [1–3]. In Europe, the Water Framework Directive (WFD) [4] has endeavoured to protect and improve aquatic ecosystems by reducing the emissions of various pollutants, including those from point and diffuse urban pollution sources. In Estonia, in order to prevent and minimize stormwater runoff volumes and the pollution load, the Baltic Sea member states jointly pooled their efforts through the Helsinki Commission towards the ecological restoration of the Baltic Sea [5]. Furthermore, the European WFD as well as the Estonian Water Act [6] have set a target to protect all waters against pollution and to achieve the good status of all waters by promoting sustainable water and wastewater management [7].

Since stormwater contaminants are discharged from a large number of individual points over a wide range within the catchment, their characteristics and contaminant loadings are not easily understandable [8]. Runoff in stormwater is intermittent, as it depends on the magnitude of rainfall, land use and anthropological activities in the catchment area. Insufficient data availability and an improper sampling method produce constraint and uncertainty that can characterize storm events. Meanwhile, it is difficult to assess annual average and event mean concentration (EMC) and this causes troubles in decision-making for sustainable planning, design and policy formulation [9,10]. Representative data are the ultimate requirement for quality assessment. Obtaining them encounters many barriers and difficulties such as (i) the numerous monitoring locations, which may require intensive sampling and high efforts, (ii) the spatial and temporal variability of parameters and concentrations and (iii) the constraints in the budget and applicability of sampling methods. These barriers will increase the uncertainties in achieving reliable and representative data. Therefore, it is important to set standardized sampling and analysis procedures that need to be optimal and effective for that purpose [1].

Numerous guidelines and procedures have been proposed in documents for stormwater monitoring (ANZECC & ARMCANZ [11], US EPA [12], Geosyntec Consultants and Wright Water Engineers [13], etc.). Many guidelines have not been designed precisely with a deductive consideration of the objectives and sampling requirements [14,15]. In addition, the required level of uncertainty is often unclear; therefore, the appropriate frequency and timing of sampling is not well understood [15–17]. There are practical guidelines that have been illustrated for automatic sampling [18,19], which are not always feasible and/or affordable. In previous research rarely any attention has been paid to approaches for the appropriate site selection, selecting minimum parameters and choosing options based on the degree of the required certainty and cost.

The typical monitoring methods for discharge, sediment and water quality data have been classified into four categories: discharge measurement, sample collection, sample preservation/storage and laboratory analysis. Uncertainties in the sources of these methods contribute to uncertainty regarding the final estimated concentration or load of interest [20–22]. Discharge measurement and sample collection comprise a significant percentage of total uncertainty, i.e. 7–23% for discharge measurement and 14–36% for sample collection [21]. Therefore it is possible to reduce significant uncertainty of the final value by minimizing individual sources of uncertainties through a proper sampling strategy.

In Estonia, environmental monitoring is carried out on three different levels according to the Estonian Environmental Monitoring Act [23]. They are (1) national monitoring for a long-term programme undertaken under sectors including the Estonian Environmental Agency, Estonian Environmental Board and national institutions, (2) local government monitoring by local authorities and (3) the monitoring by an undertaking body for the area affected by its activities or by discharged pollutants. The regional department of the Environmental Board under the Ministry of Environment issues special water permits to water users. According to the special water permit, water users or the owner of this permit should ensure the monitoring of wastewater and stormwater volumes as well as pollution parameter concentrations based on the locations and frequency specified by the permit. The permit issued by regional Environmental Boards establishes the rights and obligations for water users, including security measures and monitoring responsibilities related to water use. The Environmental Board is responsible for the organization and verification of the compliance of monitoring activities. The local government provides a procedure for implementing the environmental monitoring programme and for processing and storing environmental monitoring data. Several research projects investigate stormwater quantity and quality, but all the studies give only a general picture of stormwater. It has been emphasized as an important activity to develop a stormwater monitoring programme in the Tallinn Development Plan 2014–2020 (Tallinn City Council Regulation No. 29, 13/06/2013) [24] and Tallinn Stormwater Strategy until 2030 (Tallinn City Council Regulation No. 18, 19/06/2012) [25]. Therefore, an effective and affordable monitoring programme is the first essential step towards stormwater management in Estonia.

The main objective of this research is to review the existing papers in the monitoring programme for the sample collection system and discharge measurement, such that an optimal and effective monitoring programme could be assessed and a sampling programme recommended for the Tallinn watershed. The paper provides the options for choosing an appropriate sampling programme that could balance the degree of certainty and resource availability. Overall, it ensures proper guidance and recommendations for all planners and designers to design the monitoring programme.

METHODOLOGICAL CONSIDERATION

The study is based on the literature reviews of relevant published papers, robust monitoring programmes, protocols and guidelines. The important aspects of a monitoring programme are the selection of monitoring locations, selection of sampling parameters, discharge measurement and the sample collection system that includes the sampling mode, frequency and storm numbers. Different methods, criteria and uncertainties from previous researches related to these aspects are studied. Effective and recommended methods are assessed so that the selection of methods for monitoring can be made according to the required criteria and certainty. In most cases, the cost of sampling methods is proportional to the increase in certainty but the constraint in the budget often intervenes to applying a more advanced method. Thus, the information about the options of methods with relative uncertainties will be helpful to pick the one that balances the budget and quality output. This information is applied to form an optimal and effective monitoring programme that is also applicable to the Tallinn watershed for which the local criteria and budget constraint are considered.

Selecting monitoring locations

Monitoring additional sites affects monitoring resources because it increases the cost of sampling and analysis. Due to budget constraints, it is not possible to sample all stormwater outlets in an area. Moreover, the stormwater quality characteristics vary significantly between sampling locations and events [26]. Therefore, there are challenges in reducing the variability of quality data, and confusion on whether to choose between sampling more locations with less detailed monitoring or sampling a limited number of locations with detailed monitoring [27,28].

The selection of monitoring locations has received little attention in the literature of stormwater monitoring. Runoff quality data can be transferred to the unmonitored sites while estimating the pollution load according to Marsalek [29]. Lee et al. [27] recommended selecting a subset (~10%) of each monitored category using the advanced sampling method (especially, composite samplers) and using grab samples for the remainder. It is a reasonable approach that may result in a lower overall cost with improved accuracy and variability. Meanwhile, Langeveld et al. [28] proposed collecting metadata during a quick scan through grab samples for all selected locations after pre-screening and screening so that a system dynamic would be determined and there would be less chance of monitoring failure at those locations. They selected three out of 700 storm sewer outfalls. The methodology they proposed and the criteria for each step during selection are summarized in Table 1.

The criteria included in pre-screening and screening are commonly considered in USGS guidelines, Caltrans, New Zealand, stormwater guidelines, etc. for characterizing the monitoring sites [19,30]. However, the quick scan method is rarely applied. This method reveals the dynamic response of the monitoring sites and minimizes substantially the probability of failure of the research or monitoring projects. Additionally, the parameters that exist in a negligible amount and do not have any impact on health and aquatic life can be discarded. This enhances not only the selection of appropriate monitoring locations, but also the subsequent detailed design of the monitoring equipment and sampling strategy. Though certain investment is necessary, it is a relatively inexpensive procedure because the dataset can be gathered using a very simple and relatively cheap (~10% of the overall research budget) approach [28].

Table 1. Methodology for selection of locations [28]

Steps	Criteria	Criteria details
Pre-screening	a) General suitability	Connected impervious area, outfall location, hydraulic structure, backwater effect, etc.
	b) Representativeness	Catchment characteristics (residential/non-residential), construction period, population density, average income, type of road (high/low traffic density)
Screening	a) Personnel Safety	Traffic conditions and criminality
	b) Equipment security	Vandalism (need to house within secure cabinets/ sheds or not)
	c) Site accessibility	Travel distance
	d) Available space	For monitoring equipments, flow measurement capability
Quick scan	a) Metadata on water quality	Data collected through grab sampling (min. 3 events)
	b) Data on system dynamics	Data collected through the methods, e.g. installing surrogate water quality sensors or using water level sensors, sample using batches, etc.
Final selection	a) Representativeness	Details as in pre-screening
	b) Rank	Based on expert judgment

Selection of parameters

A broad range of contaminant profiles has been reported in previous studies about common pollutants and sources around the world [3], and large variations may even be found in a single catchment [2]. Potential influential factors for this variation are rainfall and catchment characteristics [31–33]. Due to this variation, it is difficult to predict stormwater quality characteristics, though it is highly important and feasible to get as much information as possible. One way of approaching this is to point out the few but most important parameters that will ensure broad-spectrum testing and comparable datasets [1]. This would also provide guidance to avoid potentially unnecessary parameters and thereby lower the costs of monitoring.

Potential stormwater quality parameters

Urban stormwater runoff is comprised of various substances with different hazard potential. A summary of the possible contaminants during the three decades of scientific research into stormwater is presented in tabular form by Makepeace et al. [34]. The most critical stormwater contaminants affecting humans, with respect to drinking water and the aquatic life, are presented in Table 2 with reference 'A'. Göbel et al. [3] compiled an intensive literature search for about 1300 data from 300 papers (1982–2004) on the distribution and concentration of surface-dependent runoff. They revealed that macropollutants consisting of major ions with high concentrations and trace elements with low concentrations may possess high hazard potential. Primarily, 22 pollutants have been observed from 12 different drainage surfaces in those publications, which are referenced as 'B' in Table 2. Similarly, the European WFD (2000/60/EC) defines a primary objective for member states in achieving a good ecological and chemical state in surface and groundwater bodies [7], and it sets rigorous water quality standards for priority pollutants (PPs). A list of 33 priority substances was thus regulated as part of Decision No. 2455/2001/EC issued by the European Parliament and Council.

Eriksson et al. [35] proposed a scientifically justifiable list of selected stormwater PPs to be used, e.g. for the evaluation of the chemical risks occurring in different handling strategies using the adapted version of the Chemical Hazard Identification and Assessment Tool (CHIAT) methodology. The list consists of 25 pollutants referenced as 'C' in Table 2 including eight of the PPs (Cd, Ni, Pb, polycyclic aromatic hydrocarbons (PAHs; naphthalene and benzo[a]pyrene) and di(2-ethylhexyl) phthalate (DEHP), nonylphenol, pentachlorophenol) currently identified in WFD. Nevertheless, not all pollutants were addressed for urban stormwater quality [36,37] and, thereby, Zgheib et al. [37] established an intensive list of 88 substances as PPs (i.e. 65 organic substances, 8 metals and 15 volatile organic compounds), based on the WFD list of priority substances and CHIAT. However, these pollutants are different for combined and separate sewer systems. In 2011/2012, based on the theoretical assessment of PPs and CHIAT, 55 PPs were detected in separate stormwater [38], while in a combined sewer 49 PPs (19 were priority hazardous substances) were detected in the runoff from Paris and its suburbs [36]. Separate and combined sewers have common pollutants (reference 'D' in Table 2) such as pesticides, metals (Zn, Cu, Pb), DEHP, PAH, polychlorinated biphenyls (PCBs) and organotin or tributyltin compounds, but higher hydrophobic organic pollutants and some particulate-bound metals in combined sewers. A major risk from PAHs, tributyltin compounds and chloro-alkanes persists in the combined system in relation to the environmental quality standard, whereas metals, PAHs and PCBs are potential risk substances in stormwater. Ingvertsen et al. [1] reviewed and categorized contaminants taxonomically into five groups: suspended solids (SS), heavy metals (Zn and Cu), xenobiotic organic compounds (XOCs) (phenanthrene, fluoranthene and benzo(b,k)fluoranthene), nutrients (N and P) and pathogens. Indicator pathogens and other specific contaminants (i.e. chromium, pesticides, phenols) should be included if recreational or certain catchment-scale objectives are to be met. They proposed a minimum data set of eight key contaminants (reference 'E' in Table 2) to provide a reliable and comparable measure of treatment efficiency.

In addition, physicochemical properties (reference 'F') are essential in order to obtain information on the concentration, stability, bioavailability, etc. of elements and compounds in natural processes and materials, or technical operations and products [39]. The characterization of the initial physicochemical state of the sample is a pre-condition of all further sample preparation steps because it influences the parameter concentration. Often, these properties vary greatly in time and space. The exact values, or rather mean/median values, of the concentration of elements and compounds, can serve as key parameters in exposure and risk assessment. Unless the variations in critical properties of matrices are not taken into account, they will not be meaningful and usable. Several parameters (e.g. pH, temperature and dissolved oxygen (DO)) cannot be analysed adequately after transport to the laboratory

Table 2. General stormwater monitoring parameters including selected priority pollutants. NA, not analysed

Parameter	Unit	Range	Stormwater problem		
			Human	Aquatic	Reference
Physicochemical parameters					
pH	–	3.9–7.9	Minor	Minor	ABCF
EC	µS/cm	25–2436			BF
Temperature, colour, TTU, TOC, DOC					F
BOD5; COD	mg/L	2–36; 55–146	Minor	Minor	B
DO; total solids	mg/L	0–14.0; 76–36, 200	No	Major	A; AC
TSS	mg/L	(13–937)* or 1–36 200	Major	Major	ABCEF
Nutrients					
TN; NH_4; NO_3	mg/L	0.32–16; 0.01–6.2; 0–16	Minor	Major	ABCE
TP	mg/L	0.06–0.5	No	Minor	BCE
Heavy metals					
Cd; Zn; Beryllium	µg/L	0.2–13; 15–4880; 1.0–49.0	Minor	Major	ABC; ABCDE
Cr; Pb	µg/L	2–50; 2–525	Major	Major	ABC; ABCD
Cu; Ag	µg/L	3.416–355; 0.2–14	No	Major	ABCDE; A
Ni	µg/L	2–70	Minor	Minor	BC
Pt	µg/L	NA	NA	NA	C
Fe; Al; Hg	mg/L	0.08–440.0; 0.1–16.0; 0.05–67	Major	Major	A
Main ions					
Ca; Mg	mg/L	(1–1900)*; (0.03–1.4)*	No	No	B
Cl	mg/L	3.9–669	Major	Major	AB
Na; K	mg/L	(5–474)*; (0.65–3.8)*	Minor	No	B
SO_4	mg/L	(5.1–139)*	Minor	Minor	B
Organic substances					
PAHs	µg/L	(0.24–17.1)*	Major	No	ABCD
Pyrene	µg/L	0.045–10	NA	NA	C
Benzo(a)pyrene	µg/L	0.025–10	Major	Minor[G]	AC
Di-ethylhexyl phthalate; chlordane	µg/L	7–39; 0.1–10	Minor	Major	ACD; A
Heptachlor	µg/L	<0.0002	No	Major	A
Naphthalene	mg/L	0.036–2.3	NA	No	C
Benzo(b and k)fluoranthene	µg/L	0.034–1.9; 0.012–10	NA	Major[G]	E
MOHs	mg/L	(0.108–6.5)*			B
Oil and grease	mg/L	0.001–110	Minor	Minor	
PCBs	µg/L	0.027–1.1	Minor	Major	ACD
Telrachloroethylene	µg/L	4.5–43	Major	No	A
γ-BHC	µg/L	0.052–1.1	Minor	Major	A
Other XOCs					
Fluoranthene	µg/L	0.03–56	NA	Major[G]	E
Phenanthrene	µg/L	0.045–10	NA	NA	E
Pentachlorophenol; phenol	µg/L	1–115; 3–10	Minor	Minor	CE; E
Nonylphenol ethoxylates, methyl tert-butyl ether	µg/L	NA	NA	Minor[G]	C
Organotins					
Tributyltin compounds	µg/L	<0.010–0.078	NA	Major	D
Chloroalkanes	µg/L	0.015–0.05	NA	Major[G]	D
Herbicides and pesticides					
Pendimethalin, phenmedipham and terbutylazine	mg/L	NA	NA	Major[G]	C
Glyphosate	mg/L	NA	Minor[G]	Major[G]	E
Diuron	mg/L	NA	Major[G]	Major[G]	E
Pathogens					
Enterococci	cfu/100 mL	1.2E2–3.4E5	Major	NA	AE
Fecal coliforms; streptococci	cfu/100 mL	0.2–1.9E6; 3–1.4E6	Major	NA	AE
Escherichia coli	cfu/100 mL	1.2E1–4.7E3	Minor	NA	E

A – Makepeace et al. [34]; B – Göbel et al. [3]; C – Eriksson et al. [40]; D – Gasperi et al. [36] and Zgheib et al. [37]; E – Ingvertsen et al. [1]; F – Madrid & Zayas [41] and Paschke [39]; G – Kegley et al. [42]; * Event mean concentrations.

[39,41]. Therefore, in most sampling operations, measurements will be carried out on site, possibly even in situ. Regarding worldwide (ISO), European (EN), or German (DIN) standardized determination methods, several important physicochemical properties of aqueous matrices are temperature, colour, turbidity, pH, electrical conductivity (EC), SS, total organic carbon (TOC) and dissolved organic carbon (DOC).

Use of the surrogate parameter

The contaminant profile of stormwater runoff is broad and the investigation of a large number of parameters is time-consuming and resource-intensive [33,43]. Also, it is challenging to develop cost-effective and robust methods for the continuous measurement of pollutant concentrations [44]. The approach of identifying a set of easy-to-measure parameters which act as surrogate parameters can be used to correlate to water quality parameters of interest [15,43,45]. It is a convenient approach to evaluate water quality directly, without having to carry out resource-intensive laboratory experiments. The adoption of this approach will enable greater quality control in data collection with a decrease in the costs of the collection and measurement of stormwater runoff quality data.

Several studies have been performed to identify surrogate parameters for key urban stormwater quality parameters. Usually, the evaluation of solids and phosphorus in urban stormwater is undertaken by physicochemical monitoring programmes, which sample stormflow for laboratory assessment. Settle et al. [46] investigated the physical and chemical behaviour of solids and phosphorus by univariate and multivariate data analysis techniques. Relationships were developed for SS based on turbidity, dissolved solids based on EC, dissolved phosphorus based on SS and particulate phosphorus based on dissolved solids. Solids can be predicted with higher certainty (0.74–0.93) but phosphorus is less certain by 50%. This study has limited success in developing statistically acceptable relationships, thereby limiting the transferability between catchments. Similarly, Fletcher & Deletic [15] and Grayson et al. [44] considered turbidity as an effective surrogate measure for estimating total suspended solids (TSS). Fletcher & Deletic [15] found that the use of continuously measured turbidity through grab samples had errors in long-term load estimates of less than 5%, though it did not increase more than 10% where routine grab sampling of 3-day interval was used.

Miguntanna et al. [45] identified surrogate parameters for nutrients and solids using rainfall simulation in a small homogeneous residential road area. Good predictive relationships were derived between the selected surrogate [total dissolved solids (TDS), DOC, total solids (TS), TOC, turbidity (TTU) and EC] and the key water quality parameters of interest [dissolved total nitrogen (DTN), total Kjedahl nitrogen (TKN), total phosphorus (TP), TSS, TDS, TS] [45–48]. Though it is not straightforward to find the transferability of the relationship between different geographical locations, the study tried to compare the results with the dataset from near sites that have the typical characteristics of residential, light industrial and commercial areas and their portability was validated. The relationship DTN–TDS and DOC, TP–TS has the highest probability for transferability, whereas TSS–TTU and TS–TTU have medium probability. The relationships TP–TOC, TDS–EC and TS–EC have unsatisfactory transferability.

Discharge measurement

Stormwater discharge data are vital in the sampling programme because they are necessary to assess the contaminant load (e.g. EMC and annual average mass load) and flow-related determinants. Instantaneous flow is to document flow under certain conditions or to develop a database for a stage-discharge rating. Peak flow measurement has wide application in drainage design, flood management and habitat restoration projects where high flows shape the physical habitat of the stream. Continuous discharge data are essential for any watershed project that focuses on the pollutant load. In terms of the estimation of average total mass emission, it is viable to measure continuous flow for grab sampling over a specific time period (day, week, month), instead of instantaneous flow measurement [49,50]. According to the US Geological Survey (USGS), instantaneous discharge measurements and annual station discharge records may produce uncertainty estimates [51]. Comparing weekly, biweekly and monthly grab sampling, monthly sampling produces the best results with this method.

Much of the information regarding flow measurement methods is found in many books and documents such as *Field Manual for Research in Agricultural Hydrology* [52], streamflow measurement in *Handbook of Hydrology* [53] and in selected *Techniques of Water Resources Investigation of the USGS*, e.g., [54,55]. Discharge is estimated either by establishing a relationship with a series of stage and discharge measurements or by following the existing relationship with pre-calibrated structures such as weirs and flumes. A general description of stage discharge relationships and their development is provided in most applied hydrology texts and USGS documents [52–59]. However, the rapid stage changes, small or high flow rates and short event durations of urban stormwater systems complicate the developing stage of discharge relationships. The uncertainty in continuous stage measurement is mainly determined by stage sensor accuracy, the presence/absence of a stilling well and channel bed conditions [21,60]. The details about uncertainties of different discharge measurement methods are tabulated in the paper by Harmel et al. [20].

The velocity–area method, which measures instantaneous flow and is repeated to cover the entire range of discharges for a particular outfall, is the most commonly used to develop the stage-discharge relationships. The velocity–area method for individual discharge measurement can range in uncertainty from 20% at poor to 2% at ideal or the best conditions. In a good condition with higher equipment accuracy, it can provide an error from 3% to 8% [60]. For the continuous monitoring of stages, it is cost-effective and reliable to install a stilling well/float system [56]. Stage sensors such as bubblers, pressure transducers, non-contact sensors (e.g. radar, acoustic, laser methods) are also commonly practiced to provide continuous stage data [54,56]. With an established stage-discharge relationship, continuous stage data are measured and translated into discharge.

In-stream velocity meters are also commonly used to provide continuous discharge data based on measured velocities and the cross-sectional flow area estimated from stage measurement and cross-sectional survey data. Another technique uses a single instrument to measure both stage and velocity concurrently. The acoustic Doppler velocity (ADV) meters are the most common of these for stormwater or stream flows because they are relatively cheap, cause no head loss and are easy to install and maintain [61]. The accuracy of ADV meters (e.g. Starflow) after calibration was found to be reasonable (<20% at 95% confidence level) in open channels but not necessarily in natural channels [61,62]. However, they are more useful for higher flows without gauging. Flow velocity values by this method may not adequately represent the mean velocity of the entire flow cross section. In this method, velocity is usually measured at 0.6 of depth or at 0.2 and 0.8 of depth to get the mean value. Further, smaller storm events account for the majority of stormwater runoff. It is essential that any device used to measure stormwater flow is capable of accurately measuring at the lower range of the expected flows [63]. Other methods, such as the Manning's equation or the slope area method [53], direct volumetric method and dilution methods are also used to measure discharges. The Manning's equation method estimates discharges based on roughness, slope and cross-sectional geometry, but there is substantial uncertainty (15–35%) depending on the stability and channel uniformity. Therefore, it can be the final alternative for the estimation of continuous discharge measurement.

Selecting sampling methods

The sampling method can be the dominant source of measurement uncertainty in environmental investigations [64], because it contributes to a higher uncertainty in concentration and load estimation though its amount depends on the characteristics of contaminants and whether they are particulate or dissolved [21]. For example, the collection of dissolved N and P samples is much easier than of representative sediment, TN and TP samples, since these constituents are typically distributed uniformly within the channel [65–67]. The variation in these contaminants depends on the rainfall patterns and land use of the catchment. It is also difficult to sample parameters at numerous locations at the same time and the distance between locations matters in terms of time and expense, substantially building uncertainty. Furthermore, constraints of resources, budget and available knowledge restrict the choice of specific sampling methods. These factors are crucial and important drivers while selecting the effective methods of sampling.

Manual or grab/automatic sampling

A sample can be collected manually as a grab sample in the field and transported back to a laboratory for analysis, or with an automatic sampler, retrieved at a later time and analysed in a laboratory. More information on sampling methods can be found in *Standard Methods* [68] and/or *Urban Stormwater BMP Performance Monitoring* [13,63].

Grab samples only represent a snapshot of the water quality at the time of collection. It is easy to observe that the various grab samples may be 10 times greater or smaller than the mean or EMC. Hence, the use of a single grab sample to estimate mass emission rates may have a large error [27]. Unless a sufficient number of grab samples are taken to represent the concentration changes over the period of runoff, and flow measurements are taken at the same time, it is not possible to calculate the pollution load (e.g. EMC) [69]. However, some studies have verified that grab samples can be used for estimating mass load if they are taken for a long time [15,16,27]. Several water quality parameters, such as oil and grease, toxicity and indicator bacteria, are not easily measured by automatic composite samplers [27,70], and therefore require grab sampling. For example, oil and grease in the sample can adsorb in the collection tubing and sample containers, which will cause the EMC to be underestimated. The primary advantage of grab sampling is that set-up costs are small. Nevertheless, collecting grab samples can be more difficult and less practical during storm events for several reasons: (i) the sampling team must wait for rainfall and may miss important parts of a storm event, (ii) they may need to travel a great distance in a short time to reach all sampling locations, (iii) they may not have safe access to sampling locations during rainfall and (iv) because of the cost associated with manually collecting more grab samples [70,71].

Automatic samplers are the most commonly used for stormwater monitoring operations because of their ability to accurately sample parameters. The temporal nature and uncertainty of the timing of storm events usually makes automatic samplers more practical than manual sampling. However, automated samplers are typically limited by their ability to solely collect samples at a single fixed intake point, although movable intakes are seldom used [72]. The automated sampling equipment is also expensive and requires a considerable financial and personnel resource investment for installation, maintenance and repair to ensure proper operation.

Single sample/integrated sampling

While sampling manual or automatic samples, there is always the question of whether a single intake sample is enough to represent the flow over the cross section of the channel. The only known evaluations of a single-intake are available in [65,71–73]. Ging [65] detected dissolved calcium, TP and dissolved and suspended organic carbon among 26 constituents which showed statistically significant differences in median values from integrated and single-intake automated sample collection. Selbig et al. [73] found that by sampling at the bottom of the pipe only, the median concentration of suspended sediment at a fixed point overestimated the actual concentration by 96%, whereas samples collected at three and four points vertically throughout the water column reduced overestimation to 49% and 7%, respectively. Though integrated sampling is applied, the uncertainty of a single sample for a storm event is greater than of multiple samples for the same storm [20,74].

At field-scale sites and in small streams or storm drains, a single sample intake is often assumed to be adequate for sampling well-mixed and/or shallow flows. Indeed, McCarthy et al. [74,75] showed the concentrations of *Escherichia coli* and TN at the bottom and top of the flow in a 600 mm pipe during stormwater events were statistically indifferent, suggesting that one sampling intake at the bottom of the drain would be sufficient for constituents associated with fine particulates in urban stormwater [76]. However, for constituents commonly associated with larger particulates (e.g. TSS and TP), 90% of urban stormwater samples collected from the bottom had equal or slightly higher concentrations than those collected from the top of the water column [74,75]. Uncertainty is higher for TSS and phosphorus than for nitrogen and pathogens when taking a single intake sample [20,74]. As such, caution is still needed even in these constrained well-mixed urban stormwater drains.

Baseline sampling/intensive sampling

The primary goal of baseline monitoring or less intensive sampling is to determine the existing water quality and/or ecological conditions in a receiving water body. This long-term monitoring is primarily done at regular time intervals and, therefore, mainly in dry weather or baseflow conditions where intensive sampling is mainly performed for stormflows. It needs to be cautious about the bias between them because the collection of water samples only during storm events may positively bias annual load estimates, while sampling strategies when baseflow is mainly targeted may underestimate constituent loads.

Dry weather flow or baseflow in many catchments can discharge a substantial quantity of runoff and contaminants [77,78], mainly dissolved components [76,79]. It is often intercepted by groundwater inputs and the variability in nutrients among sites is related in part to the connectivity of the storm drains to upstream sources [78]. Thus, continuous monitoring through at least the baseline sampling of water quality indicators or common contaminants can be particularly useful in those catchments where there are possibilities of intermittent dry weather discharges, illegal discharges, spills or leaks [77].

The sampling of dry weather urban stormwater flows is often conducted using the grab sampling methodology (e.g. [15,16]). The in situ measurement of contaminants indicators (EC, turbidity, ammonical-N, nitrate-N, chloride, BOD, temperature and pH) or contaminants themselves can be applied in stormwater monitoring points using either probes manually or installing at sites. Many studies have revealed that a less intensive sampling programme like grab sampling is required if there is small variation in stormwater quality, but if temporal variation is high, more frequent sampling or an intensive sampling programme is necessary [31,32,77,80]. In the analysis of the coefficient of variance for the quality data range (65 to 3765 observations) in the *National Stormwater Quality Database* (version 1.1, USA) [80], parameters such as EC, oil and grease, TDS, TSS, BOD_5, *E. coli*, coliforms, NH_3, P (mainly particulate P) and dissolved metals (As, Cd, Cr, Cu, Pb, Ni and Zn) have a higher variability than temperature, N (nitrite 'NO_2', nitrate 'NO_3', TKN), filtered or particulate metals.

Several research papers have shown that N, P [65–67] and particulate metals are less variable than other parameters but it depends on the catchment and rainfall characteristics [31,32,77,80]. Nevertheless, stormwater quality parameters during storm events are highly variable within a single site and can vary more when different sites are considered [80,81]. Therefore, the specific variability is difficult to define for the particular parameter. Once less variable parameters are determined through assessment from the existing data for a particular catchment and rainfall range, it is possible to apply less intensive or grab sampling for those less variable parameters.

Discrete/composite-volume-weighted, time-weighted and flow-weighted sampling

Discrete and composite samples can be collected both manually and automatically. Discrete (time or flow or volume interval) samples are single samples collected over a certain period of time, which individually give a snapshot of water quality at a given time and discharge. These samples, if collected over the storm events with flow, provide EMC and site mean concentration (SMC). This sampling method also provides peak concentration during storm events. On the other hand, composite samples are produced by combining samples manually or automatically to provide an estimate of average concentration or total loads. Samples can be achieved as flow-weighted composite (variable volumes of samples proportional to stormwater flow are collected at an equal interval of time increments), volume-weighted composite (fixed volumes are collected at variable time intervals after a constant volume has passed) and time-weighted composite (fixed volumes are taken at equal time increments). The composite sample is usually produced using flow- or volume-weighted sampling [19], which allows determination of the EMC for the constituent(s) of interest.

Composite sampling introduces fewer errors than increasing minimum flow thresholds or increasing sampling intervals, especially for volume-proportional sampling [82–86]. An alternative to collecting automatic composite samples in the field involves manually compositing discretely collected samples in the laboratory [74]. Manual compositing can minimize the errors associated with sampler failure during an event (i.e. missing one sample in a volume-proportional, composite strategy).

Purposes of sampling in selecting sampling methods

Many countries have policies, laws and regulations for stormwater monitoring. According to the national or regional goal, the monitoring of stormwater may have different purposes. Consideration of the specific objectives for monitoring is the first step to determine how the sampling programme needs to proceed. The common objectives are (i) assessing maximum discharge and/or concentrations for comparison with the maximum limit of consent conditions, (ii) assessing mass load and/or EMC and/or SMC, (iii) assessing temporal variability, (iv) identifying sources of particular contaminants at the catchment and (v) assessing stormwater treatment performances.

In countries where stormwater management is at an initial phase and where stormwater treatment facilities still need to be retrofitted, the main concern is on the first two objectives. According to the first objective, the downstream receiving environment quality is of the greatest interest. In order to compare measurements of concentration directly to consent limits or water quality guidelines, the sample(s) measured accurately should represent the poorest water quality discharged during a storm. The second objective is more common in many stormwater monitoring programmes because the average concentration and annual emission loads are always an issue for the receiving water bodies or estuary. This provides a scope for comparing sites and modelling the benefits of stormwater treatment facilities. Data from the monitoring to achieve the third objective are mainly essential for the calibration and validation of catchment scale models, but also for comparison between sites and modelling benefits. The fourth objective has more in-depth investigation to determine the extent of contamination and trace the likely sources. It requires multiple sites upstream and downstream of the suspected sources of contaminants. Samples are collected for the same storm events to compare between sites. The fifth objective is to evaluate the performance of stormwater treatment facilities relative to the design. In achieving these objectives, the monitoring programme usually targets the estimation of peak flow/concentration, EMC, SMC and/or mass load and temporal variability and/or their combinations. Therefore, four purposes are possible: (i) peak flow/concentration (P1), (ii) temporal variability (P2), (iii) EMC and/or SMC and/or event mass load (P3) and (iv) annual mass load (P4), and their combinations: CP1–P1 and P2, CP2–P3 and P4, CP3–combined purpose not including P4, CP1 and CP2, and CP4–combined purpose including P4 but not CP1 and CP2. Based on these purposes and the required accuracy, an appropriate sampling method can be selected from different sample collection methods (grab sampling, discrete sampling, composite sampling, combination of discrete and composite sampling, combination of grab and composite sampling, etc.), which are illustrated in the section 'Results and discussion'.

Sampling threshold

The increase in the sampling threshold introduces substantial uncertainty from 2% to 20% for low to high thresholds during storm sampling [20,74,82], which can again increase to 35% when not extrapolating flow and concentration outside the sampling period. Therefore, the threshold needs to be set such that the sampling method could address the entire storm event.

Typically, the sampling of storm events requires more than 2 mm of rainfall, as a lesser amount will not result in runoff due to evaporation and depression storage [87]. The intensity greater than a threshold value of 5 mm/h was considered as the start and end of a selected rainfall event since the rainfall intensity lower than 5 mm/h has no significant effect on pollutants wash-off due to low kinetic energy [88,89]. Though this depends on catchment sizes and topography, generally, the threshold is provided with rainfall measurement. However, the threshold point is determined by changes in flow levels and is ensured by the change in the turbidity, EC or temperature for automatic sampling.

Sampling frequency and timing

The frequency of sampling determines the number and the interval of samples that need to be taken for stormflow and baseflow. It mainly depends on the purposes of sampling as to whether it is to assess peak flow/concentration, EMC and mass load, SMC and annual load or temporal variability.

Several studies have confirmed the statistical theory about sampling that the smaller the sampling interval (the higher the number of samples), the better the actual population characteristics and the lower the uncertainty [83–85,90], as can also be noted in Table 3. King & Harmel [84] and Harmel et al. [91] provide guidance on selecting time and volume intervals for automated sampling on small catchments. Moreover, based on averages from the 300 storm events, King & Harmel [84] concluded that time-discrete sampling at a 15-min interval or less was required to produce a load estimate that was not significantly different ($\alpha = 0.05$) from the total pollutant load. The same accuracy can be obtained for discrete flow-paced sampling at or above

Table 3. Discrete and composite sample collection frequency and timing with relative uncertainty [20,21,74,84,92]

Frequency and timing	Uncertainty[a]	Reference
Discrete flow-interval sampling strategies:		
0.2–1.25 mm	±0% to 22%	A, B
0.5 mm at initial runoff and 1.5–2.5 mm for remainder	<10%	C
1–2.54 mm over storm duration for small storm events	Significantly indifferent at $\alpha = 0.05$	D, E
1–2.54 mm at initial runoff and 6 mm at remainder for medium to large storm	Significantly indifferent at $\alpha = 0.05$	D, E
6 mm for large storm	Significantly indifferent at $\alpha = 0.05$	D, E
12 flow-interval discrete samples	Small bias and standard error	F
Discrete time-interval sampling strategies:		
5 min, discrete	±0% to 18%	A, E
10 min, discrete	±0% to 40%	A
15 min, discrete	Significantly indifferent at $\alpha = 0.05$	D, E
30 min, discrete	±3% to 72%	A, E, B
120 min, discrete	−15% to 13%	E, B
42 time-interval samples	Small bias and standard error	F
Time-interval composite sampling:		
5 min, with up to six composite samples	−5% to 4%	E, B
30 min, with up to six composite samples	−32% to 25%	E, B
60 min, with up to six composite samples	±0% to 19%	H
120 min, with up to six composite samples	−65% to 51%	E, B
5–360 min, with up to three composite samples	±1% to 33%	E, G
5–360 min, with up to six composite samples	±5% to 50%	E, G
Flow-interval composite sampling strategies: *f*(flow interval)		
2.5–15 mm, with up to three composite samples	±0% to 5%	E, G
2.5–15 mm, with up to six composite samples	±0% to 8%	E, G
1.32, 2.64 and 5.28 mm, with up to six composite samples	−9% to +3%; median ±0.4	I, G

[a] Error estimates are presented as their ±% range for bidirectional error or as their actual % range.
A − Miller et al. [83], B − Harmel et al. [20], C − McCarthy et al. [74], D − King et al. [92], E − King & Harmel [84], F − Leecaster et al. [16], G − Harmel et al. [21], H − Miller et al. [93] as cited by Harmel et al. [21], I − Harmel & King [85].

volume-proportional depth intervals of 2.5 mm. King et al. [92] developed a procedure to determine sampling intervals based on catchment and constituent characteristics. Although they concluded that volume-proportional depth intervals up to 6 mm may be appropriate in certain conditions, smaller intervals (1–2.54 mm) are more widely applicable. These smaller intervals allow smaller storm events to be sampled and moderate-to-large storm events to be sampled more intensively with little to no increase in uncertainty, especially if composite sampling is utilized. The flow-stratified approach had a smaller absolute error than did the time-based approach when an equal number of samples was obtained [84] and thus many studies have recommended the flow-stratified approach over the time-based approach [83–85,94,95].

If the purpose of sampling is to measure the peak concentration, the sampling interval over the storm events may be different. The peak concentration may occur at the beginning of a storm event (i.e. during the 'first flush'), with the peak flow [96–98], or even at the end of the storm event [99]. There is some evidence that constituent concentrations are more variable on the initial portion of storm events where sometimes the first flush exists [95,99]. McCarthy et al. [74] used every 0.5 mm to more adequately capture initial conditions and every 1.5–2.5 mm for the remainder of the event. They showed that the estimated error between such a sampling regime and an estimated 'true' value of the EMC for turbidity in a stormwater system was less than 10% across the four sites observed.

The sampling programme mostly concerns a lesser number of samples because a rise in the number of samples considerably increases the cost for sampling and analysis and not necessarily aggregates uncertainties. The variations in stormwater flows and constituent concentrations inherently govern the sample numbers in the sampling regime [31,32,77,80]. For example, a constituent that does not vary considerably during stormflow will require significantly fewer samples to characterize. Many monitoring programmes suggest performing composite sampling. This method increases sampler capacity, making it a valuable and cost-saving alternative. Composite sampling with two or four aliquots per bottle reduces sample numbers to 50% and 25% of those are collected by discrete sampling. This method introduces less error than discrete sampling [82,84,85]. However, composite sampling reduces information on the distribution of within-event constituent behaviour, which limits the study of various transport mechanisms. It is a powerful option for making a single composite sample from flow interval subsamples for the entire event duration [19,84,100]. In single composite samples (if 16 L of bottle capacity), 80 (of 200 mL) to 160 (of 100 mL) of subsamples can be composited but this depends on the storm volume.

The constraint to perform discrete sampling has introduced composite sampling, but the cost is again considerable, though it reduces the number of samples for analysis. In countries where budget is always a constraint, grab sampling is an alternative. It is challenging to represent all intra- and interstorm event characteristics. However, many studies have tried to provide an effective frequencies and timing process for grab sampling as presented in Table 4.

Table 4. Grab sample collection frequency and timing with relative uncertainty. NA, not analysed

Frequency and timing	Specific condition	Accuracy	Reference
Single point, random time	NA	Uncertainty (±25% dissolved; >50% suspended)	Slade [59]; Harmel et al. [20]
Single random sample within storm Single random sample 1 h after commencement of storm Routine single sample at 3-day interval not responding to storm	Large catchment area	Around 10%	Fletcher et al. [15]
12 random samples	Large catchment basin, variable contaminant, wet season	Bias and standard error >12 flow-interval discrete samples but <42 time interval samples	Leecaster et al. [16]
Single sample after 1–6 h of runoff (depending on rainfall and site-specific characteristics)	Impervious highway sites, mainly for oil and grease, i.e. not correlated with TSS	Close to flow-weighted composite sample	Khan et al. [70]
Single sample middle of storm	For TSS and Zn	Representative	Lee et al. [27]

Fletcher et al. [15] collected a single grab sample within the storm event randomly and 1 h after the commencement of the storm for seven storms. They compared the mass load or SMC of TSS, TN, TP, Pb and Zn with true load and detected around 10% difference from true load. On the other hand, a routine grab sampling campaign which does not specifically respond to storm events showed that the errors increased with the sampling interval and a 3-day interval was required to maintain errors within 10% of the continuously measured load of TSS. They concluded that autosamplers were not essential if only long-term load estimates were required. However, they did not show the variability of contaminants within the storm events and most of the catchments studied by them are of large areas, which may provide long-period hydrographs and pollutographs. If the variability of contaminants is not high, the samples at any time within a storm do not significantly affect mass load. This limitation was overcome by Leecaster et al. [16] who compared the flow interval, time interval and simple random sampling to estimate EMCs and mass load as well as SMCs and annual mass load. They suggested a minimum of 12 flow-interval samples (Table 4), using a volume-weighted estimator of mass emissions, to characterize a storm event most efficiently with a small bias and standard error. They showed that 12 simple random samples are less accurate than 12 flow-interval samples but these provide a better result than 42 time-interval samples. In this study, the catchment basin is large (where peak flow occurs 3 h after the commencement of the storm due to rain 0.8 cm/h), constituent variability is high and the study period is unnaturally wet [16,101].

Khan et al. [70] examined 22 oil and grease pollutographs from small impervious highway sites to determine when a single grab sample most closely approximates a flow-weighted composite sample. They concluded that collecting a single grab sample 1–6 h after the beginning of runoff within a storm more closely approximates the EMC than sampling earlier or later in the storm. The results depend on storm characteristics (total rain and storm duration) and site-specific characteristics (antecedent dry days and total rain). Samples early in a storm event should be collected if the peak or maximum concentrations are desired. This result is particularly for oil and grease, which have weak correlation with SS. However, a similar conclusion is suggested by Lee et al. [27] for TSS and Zn. They emphasize that the sampling time during the storm event will affect results for grab samples, since the samples collected early in the storm will have higher and those collected late in the storm will have lower concentrations than the EMC. They agreed with the Khan et al. [70] conclusion and recommended grab sample collection in the middle of the storm which is more representative, however, the appropriate time is site-specific and needs to be investigated. They added that the samples collected early in the season would better represent maximum concentrations.

Sampling frequency and time for dry weather flow

Dry weather flow samples were taken manually at biweekly or monthly intervals (a monthly interval can be specially adopted halfway through the study) to characterize baseflow and facilitate the determination of sources (groundwater, illicit discharges, etc.) [102]. Most of the dry weather flow samples are taken after a period of at least three days without rain [103,104] when the runoff does not exceed the minimum sampling threshold as explained above [105]. The monitoring period should be sufficiently long so that potential seasonal effects on water quality can be investigated and can represent reasonably average flow conditions. The sampling frequency should also ensure that the samples are statistically independent. To account for seasonal variability, one sample per month can be collected [106] over a twelve-month period. A technique by NSW EPA [107] can be applied to determining the minimum number of samples for a desired statistical confidence level. The variability of concentrations has a large influence on the accuracy of certain sampling strategies on load estimations. For example, a pollutant whose concentration varies quite considerably during dry weather flows cannot have its weekly or monthly loading accurately estimated by one random sample per day. On the other hand, a pollutant that is fairly constant during dry weather periods could have its load accurately estimated using the monthly sampling regime [77].

Number of storms

Stormwater constituent concentration varies between storm events and it is essential to monitor more than one event in order to adequately characterize the site [108]. Due to time and cost constraint [109,110], the determination of the minimum number of storm events that should be sampled is necessary to estimate the pollutant mean concentration or SMC, peak concentration and temporal variability for model calibration within a given level of uncertainty [27,110–112].

Some researchers have attempted to quantify the number of storms required to adequately characterize the site (see Table 5). In 1993, Smoley [113], cited by Pandit & Gopalakrishnan [105], put forward a concept of representative storms that could be used to derive the approximation of SMC. The minimum number suggested was three storms, which have characteristics such as

Table 5. Number of storms for sample collection with relative accuracy

No. of storms	Specific condition	Accuracy	Reference
Minimum three	(i) The antecedent dry period >72 h, (ii) the storm depth >2.5 mm and (iii) the storm duration and depth <50% the average storm size	Small bias	Smoley [113] as cited by Pandit & Gopalakrishnan [105]
Seven storms per year (~50% of the storms)	Mass emissions or concentration estimate	10% uncertainty	Leecaster et al. [16]
Three storms per 5 years	Mass emissions or concentration estimate	20% uncertainty	Leecaster et al. [16]
Seven medium and large storms per year with 12 random samples	Mass emissions or concentration estimate	~accurate (<10% uncertainty)	Leecaster et al. [16]
Minimum of 5–7 storms/avg six storms	SMC estimate (of phosphorus)	Relatively accurate/ 40% less cost of 12 storms	May & Sivakumar [110]
Minimum of 6–8 storms (5–6 during wet season and 1–2 during dry season)	SMC estimate	Relative standard error <20%.	Maniquiz-Redillas et al. [111]
Max 10 storms	Temporal variability for model calibration, SMC prediction	Narrower confidence intervals	Mourad et al. [114]
At least 10 storms	Temporal variability for model calibration, EMC prediction	Narrower confidence intervals	Bertrand-Krajewski [115]

(i) the antecedent dry period must be greater than 72 h, (ii) the storm depth should be greater than 2.5 mm and (iii) the duration and depth of the representative storm should not be greater than 50% the size of the average storm at the catchment. These characteristics reduce the bias due to outliers in SMC calculation. However, this method may not be efficient in all circumstances because either whole storm events need to be captured to sort out representative storms or they require long-term rainfall data, but the average still may not be static as it varies from year to year.

Leecaster et al. [16] concluded that sampling seven storms (approximately 50% of the storms in a typical year) is the most efficient method for attaining small confidence interval width with 10% uncertainty for annual concentration. When coupled with the simple random sample (at least 12 per storm) of medium and large storms within a season, the ratio estimator most accurately estimated the concentration and mass emissions and had low bias over all of the designs. Sampling three storms per year allows a 20% trend to be detected in mass emissions over five years. The results are mainly based on TSS concentration, which they found highly correlated with other constituents such as trace metals, TOC and TN. It was observed that in most studies SS was often used as the predominant pollutant monitored in determining the errors associated with the number of sampled storms [16,114,115]. May & Sivakumar [110] used phosphorus data from 17 urban catchments to derive the optimum number of storms by evaluating the balance between total sampling cost and the degree of uncertainty. Total phosphorus is log-normally distributed [116]. It is monitored as a predominant variable in the Nationwide Urban Runoff Program study [110]. The study suggested that a minimum of 5–7 storms was sufficient to derive a relatively accurate estimate of SMC. However, it was concluded that the number of storms varied slightly depending upon the catchment and the error measure analysed. The study also deduced that monitoring six storm events would be approximately 40% cheaper than monitoring 12 events.

It is also essential to associate the degree of uncertainty and variability in the number of storms according to seasons and water quality parameters. Maniquiz-Redillas et al. [111] showed that a minimum of 6–8 storm events were adequate to estimate the SMC of TSS at a relative standard error of less than 20%. The standard error significantly increased from 40% to 65% when the number of storms decreased from five to three for TSS, TP, COD and BOD, while TN and DOC need 8–10 storm events to reduce the standard error by only 30–40%. During most of rainfall (in spring and summer), the storm event sampling was preferably to be conducted five to six times, but only once or twice during the autumn and winter seasons.

Some researchers have analysed the number of storms using stormwater models. Mourad et al. [112] analysed SS data from a combined sewer network to determine the sensitivity of stormwater quality models to calibration data. When fewer than 10 storms were used for model calibration, they observed that an SMC model produced narrower confidence intervals associated with total load predictions than regression models and a build-up wash-off model. In contrast, Bertrand-Krajewski [115] suggested that confidence intervals associated with EMC predictions were very large when fewer than 10 sampled storms were used to calibrate multiple regression models. Mourad et al. [117] conducted another study using BOD, COD and SS data from 13 out of the same catchments to estimate the SMC as a flow-weighted mean. The authors concluded that it was not possible to identify a universal minimum number of events to be monitored at a catchment that would approximate the SMC with a specified level of uncertainty.

RESULTS AND DISCUSSION

Tables 1–5, prepared based on literature reviews, present the approaches to site selection, sampling parameter selection and sample collection systems. The results from these reviews are summarized below as suitable sampling approaches. This information was used to create an efficient sampling programme that is presented in Table 6. Selected parameters in the watershed of Tallinn are described in Table 7 for which three sampling sites are selected out of 66.

Suitable sampling approaches

Site selection

Table 1 presents a reviewed approach of pre-screening, screening, quick scan and final selection of sites. The selection of sites is important since not all sites can be monitored due to difficulties in the mobilization of the staff and equipment as well as financial constraints. Moreover, it is applicable and cost-effective to categorize sites into intensive and less intensive sites.

Selecting potential parameters

In reviewing the broad range of parameters, the list of parameters is prepared as shown in Table 2, which includes selected priority pollutants and physicochemical parameters. These parameters have a major impact on

Table 6. General monitoring programme

Aspect	Sites A requiring intensive sampling	Sites B not requiring intensive sampling	References
Location	At point of discharge into receiving environment; and/or downstream of discharge in well-mixed area	At point of discharge into receiving environment; and/or downstream of discharge in well-mixed area	Table 1
Flow measurement	Preference 1* or Preference 2* (required as a surrogate for flow hydrograph) or Preference 3*	Automatic stage measurement with surrogate parameters	Section ‘Discharge measurement’
Sampling method for stormflow			
Sampling mode	Volume/flow-proportional automatic, but grab samples may also be feasible in some circumstances (e.g. short distance to sampling site, for oil and grease parameters)	Grab sampling	Section ‘Selecting sampling methods’
Mimimum threshold	At least three days and/or rainfall intensity 2 mm/h	At least three days and/or rainfall intensity 5 mm/h	Section ‘Sampling threshold’
Sampling frequency	Sample collection is more frequent during periods of higher or at initial runoff (0.5 mm) and greater interval for remainder (1.5–2.5 mm) as specified by McCarthy et al. [74]	Within first 1 h for peak concentration during first flush and seasonal first flush; within 1–6 h of storm event for EMC, SMC or annual loads as specified by Lee et al. [27] and Khan et al. [70]	Tables 3 and 4
Number of samples	At least 12 discrete samples per event; at least one composite sample	At least one sample for peak flow; at least one sample for EMC, SMC or annual loads	Tables 3 and 4
Storm size	At least seven medium and large storms	Seven medium and large storms	Table 5
Parameters	Primary and secondary parameters	Primary and secondary parameters	Tables 2 and 7

Preference 1*: stage-discharge measurement with the precalibrated structure installed preferably on the stable channel; Preference 2*: stage measurement using stillwell; Preference 3*: velocity area method using the acoustic doppler flow meter.

Table 7. Recommended parameters for the monitoring programme in Tallinn

	Primary parameters	Secondary parameters	Adopted from
Physicochemical	pH and SS		A
	EC, TTU, TDS, TOC and DOC		B
Micropollutants	Hydrocarbon,		A
	PAH and PCB	DEPH, phenols, benzo(a)pyrene	C
Oxygen demanding compounds	BOD_7 and COD		A
Nutrients	TN and TP		A
Metals	Zn, Cu, Pb	Cd, Cr, Hg	AC
Ions	Cl^-		C
Pathogens	*E. coli*, enterococci		D
		Faecal coliform	C

A – Estonian Water Act, Regulation No. 99; B – surrogate parameters; C – major pollutants on literature (from Table 1); D – potential parameter for good bathing water quality (EU and Estonia).

either human or aquatic life or both. It is a contaminant profile where each parameter from different papers is considered as a potential element that needs to be monitored. These parameters are area-sensitive since a potential parameter at one place might not be potential at another place. However, the most pronounced parameters noticed in above literature are physicochemical (pH, TSS), nutrients, heavy metals (Cd, Cr, Cu, Pb, Zn), PAH and PCB. Therefore, at a very early stage of monitoring when there is no sufficient data for parameters, this list can be used to compile a minimum set of parameters that have major impacts on the local area.

While compiling a minimum set of parameters, the approach of surrogate parameters to reduce the cost of monitoring can be applied. Several researchers have noted that EC, TTU, TSS, TDS, TOC and DOC have the potential to act as surrogate parameters for other key water quality parameters such as solids, nitrogen and phosphorus [15,44–46,98]. It is possible to apply the combined sampling of surrogate parameters measured continuously and target parameters measured intermittently. It will significantly reduce the cost of measuring the concentration without compromising accuracy. Should this method not be affordable, the continuous measurement of surrogate parameters can be applied and the concentration of target parameters can be estimated using the correlation coefficient. The result may provide considerable uncertainty but the grab-sampled concentration can be used to verify them.

In Finland, the more recent monitoring programmes used in the projects ‘Stormwater-Research Programme (2008–2010)’ [118] and ‘Urban Laboratory for Sustainable Environment (2012–2014)’ [119,120] include the above-mentioned parameters as water quality variables for study. Likewise, in Lithuania, the subjects of research were usually common water parameters (BOD, pH, TSS, COD, hydrocarbons) [121] and metals (Cd, Cu, Pb, Zn) [122,123].

Discharge measurement

In general, continuous discharge measurement is essential, especially for the estimation of mass load and runoff volume. Uncertainty is smaller for stage discharge measurement with the pre-calibrated structures preferably installed on the stable channel. They are highly recommended because they have an associated stage-discharge relationship and provide reliable and accurate flow data for a number of years with minimal maintenance [20,59]. Monitoring stillwell is also a good option for stage measurement, as it is cost-effective and reliable for the long run. If there is location constraint, the final option will be the velocity area method using an ADV meter. This methodology in concept is excellent for determining an accurate discharge because of the ability of the flow monitor to account for variable and backwater conditions.

Sampling mode

Automatic sampling is recommended for continuous measurement as it reduces a human error but grab sampling also has substantial certainty when properly applied. Grab sampling is mostly preferred for certain parameters such as oil and grease. The parameters that do not have large variation throughout the storm can be monitored using grab sampling or baseline sampling. A single intake sample is taken at the well-mixed flow because the concentration can vary over the cross section of flow.

Flow interval/proportional sampling is superior to time interval/proportional sampling and grab sampling. However, whether to proceed with discrete or composite sampling or a combination of both depends on the purpose of sampling. Figure 1 shows the flowchart to decide the sampling method according to the purpose of sampling.

The most appropriate sampling methods for attaining purposes are selected based on accuracy explained in the sections 'Selecting sampling methods' and 'Frequency and timing of sampling'. Those methods are presented prioritywise in Fig. 1 as i – first priority, ii – second priority and iii – third priority. Discrete flow proportional sampling is preferred for assessing peak flow/concentration and temporal variability, while composite flow proportional sampling is preferred for estimating EMC and SMC, though some parameters such as oil and grease need grab sampling. Dry weather flow and concentration are not ignored and can be monitored by grab sampling, which is used to estimate mass emission. Some studies have found that grab sampling can be used to estimate EMC, SMC and mass load, but it should be applied as the last alternative when it is limited by budget and resource constraints because the results depend on the catchment and contaminant properties. In Lithuania, sampling methods were changed from grab sampling irrespective of the storm event at early research [121] to flow proportional composite sampling at recent research [122]. More up-to-date funded projects in Finland have used flow proportional composite sampling methods in order to attain higher certainty of EMCs and pollutant loads [118–120,124]. Nevertheless, it is not always the case when available resources are limited and there are more than just a few sites involved. The optimal programme has to be selected to meet these resources. The details of this programme are discussed below in the section 'An optimal and effective sampling programme'.

Sampling frequency

Table 3 presents the frequencies for discrete and composite sampling, whereas Table 4 presents frequencies for grab sampling to choose based on uncertainty and resource availability. When analysing discrete and composite sampling frequency and timing, it is clear from Table 3 that the uncertainty decreases as the sampling frequency increases. Flow interval sampling can be recommended as the first priority of sampling. Indeed, increasing frequency aggregates the number of samples, which increases the cost of analysis. Therefore, sampling intervals depend on how much degree of certainty is required and how much can be afforded. To achieve a sufficient degree of certainty at a reasonable cost, the flow interval sampling frequency provided by King et al. [92] and King & Harmel [84] can be recommended for discrete sampling when the purpose

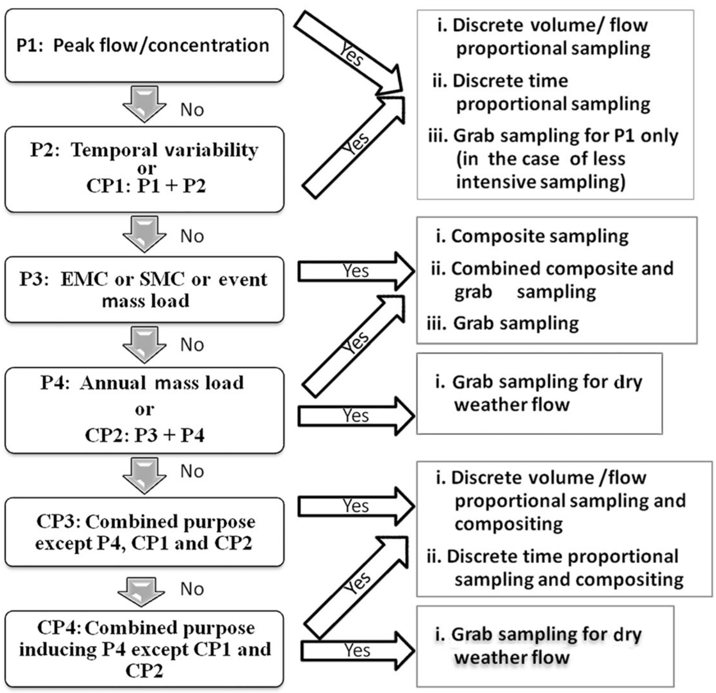

Fig. 1. Sampling method according to different purposes of sampling. P1–P4 are purposes and CP1–CP4 are combined purposes.

is estimating the peak flow/concentration, temporal variability and/or their combinations. A comparatively better sampling for the estimation of EMC, SMC and mass load is flow interval composite sampling. It can also be noted from Table 3 that uncertainty decreases as the number of composite samples decreases. Harmel et al. [20], King & Harmel [84] and Shih et al. [100] have noticed that a single composite sample for the entire event can provide sufficient accuracy.

If the budget is not sufficient to proceed with the above recommended discrete and composite sampling, the 12 flow interval discrete sampling method can be employed (as in Table 3) for the purpose of EMC, SMC, mass loads and their combination, which provides a small bias and error and is comparatively easy to apply on site [16]. If manual sampling has to be performed, 12 random samples (as in Table 4) could be the first priority [16] in comparison to other grab sampling frequency and timing because it could address the variability of contaminants in a storm event and rainfall effects. The final alternative, if the first priority is not affordable, is to take a grab sample between 1 and 6 h of runoff or in the middle of the storm.

Number of storms

Review of papers for the optimum number of storms to be sampled as in Table 5 showed that many researchers have recommended that seven storms are appropriate for low error estimate of EMC, SMC and mass emissions. As May & Sivakumar [110] found, it can be substantial increment of cost once the sampling is increased from 6 to 12. In such a condition, seven storms per year does not abruptly increase the cost of sampling. However, for temporal variability to calibrate models, a maximum of 10 storms can be recommended. If grab sampling has to be performed further to reduce the cost of sampling, 12 random samples for seven medium and large storms over the year can be chosen.

An optimal and effective sampling programme

In this study, the usual condition is considered, which means (i) the purpose of sampling is common, i.e. to obtain the concentration in order to compare with the permissible limit as in the Tallinn stormwater monitoring system and (ii) there is constraint of budget and resources. Table 6 presents the general monitoring programme on the usual condition based on the results from literature reviews. According to Lee et al. [27] and Langeveld et al. [28], it is more reasonable and cost-effective to use two sampling methods. One is intensive sampling for the final selected sites (sites A) and the other is baseline or less intensive sampling for sites (sites B) selected after pre-screening and screening, excluding sites A. The procedures for selection of sites A and sites B are described in detail for Tallinn in the section 'Site selection in Tallinn'. The selected parameters can be categorized into primary parameters requiring intensive sampling and secondary parameters requiring less intensive sampling. Details of these parameters are discussed in the section 'Sampling parameters in Tallinn' as in Table 7. The sampling method depends on the purpose of sampling as mentioned above. The sampling programme is to capture the peak concentration or the poorest concentration during storm events. Due to the behaviour of peak concentration, it is ideal to collect a large number of samples throughout the storm event, but it is expensive to do such sampling in all outlets. Therefore, it is practical and reasonable to perform intensive sampling for sites A and grab sampling for sites B as shown in Table 6.

Though the purposes are different from estimating EMC, SMC and annual loads, the samples collected for peak concentration can be composited manually or automatically during intensive sampling in order to use them to calculate EMC, SMC and annual loads. For intensive sampling, grab sampling is not recommended, unless there is a single site and short distance to the site because it is difficult to mobilize the sampling staff and equipment to different sites at the same time. To find the peak concentration, grab sampling or less intensive sampling can be performed in sites B where a single sample is taken within 1 h of storm commencement during the first flush or seasonal first flush. It is recommended to install automatic water level measurement devices, which can also measure some surrogate parameters continuously. Due to the similar conditions, this general sampling programme can be recommended for the Tallinn watershed.

APPLICATION OF THE SITE AND PARAMETER SELECTION APPROACH

Site selection in Tallinn

According to the Estonian Nature Information System [125], 66 stormwater outlets exist in Tallinn. The methodology by Langeveld et al. [28] can be applied to select appropriate locations (see Table 1). These outlets can be divided into three categories based on the receiving bodies after final discharge as shown in Fig. 2. Forty-eight outlets that discharge water directly into the coastal sea are included in category I, seven outlets that discharge to the watercourse are in category II and 11

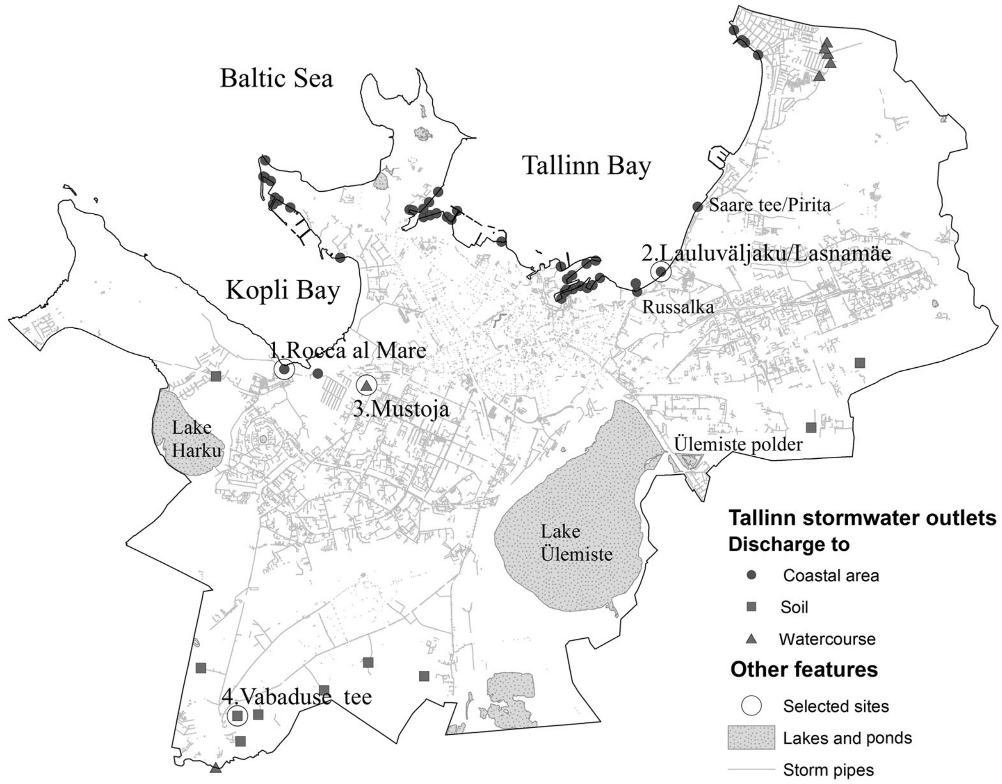

Fig. 2. Stormwater outlets in Tallinn.

that discharge to soil in the Tallinn catchment area are in category III. During pre-screening, 14 storm outlets can be selected from 66 storm outlets (10 in category I, 2 in category II and 2 in category III) on the basis of general suitability and representativeness. The main criteria for this selection are outfall location, catchment properties and special activities within the catchment as described in Table 1: for example, selecting one from each group of outlets near to each other; the Mustoja basin has a combination of industrial, commercial and residential area; the Saare tee basin has mostly residential areas with private houses; Lauluväljak is a densely residential area; Rocca al Mare has the impact of the zoo; Russalka has discharges from the Ülemiste polder. When these outlets are compared to personal safety, equipment security and accessibility during the screening phase, they reduce to eight storm outlets (6–I, 1–II, 1–III).

For a quick overview, the database of stormwater quantity and quality is available for six major storm outlets: Saare tee, Lauluväljak, Russalka, Ülemiste polder, Rocca al Mare and Mustoja Paldiski Road. The monitoring programme was organized by the Tallinn City Environment Department. Tallinn University of Technology, the Environmental Engineering Department and AS Tallinna Vesi got involved in 2012. The monitoring frequency is six times per year. Twelve parameters such as flow, temperature, conductivity, oxygen, BOD, SS, TN, TP, PAH, *Escherichia coli*, enterococci and Salmonella are measured and grab sampling is used. SonTek Flowtracker is used for the instantaneous flow rate measurement. Grab sampling is carried out randomly not responding to storm events. Analysis of data from 2005 and 2008–2012 shows that the average concentration for most of the parameters does not exceed the permissible level, aside from microbiological parameters, but the variation in the concentration and confidence interval is high [126]. The concentration exceeds the permissible level several times in Saare tee, Rocca al Mare and Mustoja. The databases for categories II and III were retrieved from the Estonian Nature Information System [125], which have quarterly data examined for three years.

The system dynamics of the outlets is still uncertain because the samples may not address storm events. However, considering the representativeness of the catchment basin and special activities, the final selection of locations may include four outlets (2–I, 1–II and 1–III) where the measuring instruments can be installed for intensive sampling and which are grouped as sites A similar to the recommendation by Lee et al. [27]. Those possible four outlets (as in Fig. 2) for sites A are Lauluväljak and Rocca al Mare of category I, Mustoja of category II and Vabaduse tee of category III. The other four outlets in category I can be installed with a less intensive sampling method and are grouped as sites B.

Sampling parameters in Tallinn

The Estonian Water Act, Regulation No. 99 of the Government of Estonia, 1 Jan 2013, 'The wastewater treatment and requirements of wastewater and stormwater discharges into the receiving water bodies; wastewater and stormwater pollutant thresholds; and compliance verification measures' provided limit values for SS – 40 mg/L, hydrocarbon – 5 mg/L, BOD_7 – 15 mg/L, COD – 125 mg/L, TP – 1 mg/L and TN – 45 mg/L in stormwater runoff [127]. Wastewater and stormwater effluents should not worsen the state of aquatic and terrestrial ecosystems. Trace metals (Zn, Cu, Pb, Cd, Cr, Hg) are also considered potential pollutants [128]. The European Union, as well as Estonia, has restricted microbiological parameters exceeding 1000 cfu/100 mL *E. coli* and 400 cfu/100 mL enterococci for good bathing water quality [129,130].

Generally, many other potential parameters are found in urban stormwater. As in Table 2, several reports mentioned metals (Zn, Cu, Pb, Cd, Cr), ions (Cl^-), micropollutants (PAH, PCB, DEPH) and pesticides, which are prevalent in urban stormwater and hazardous to either human or aquatic life; however, their quantity depends on the upstream rainfall and catchment characteristics. Moreover, surrogate parameters can be supplemented, as they can be measured in situ. Such surrogate parameters are EC, TTU, TDS, TOC and DOC, and they are applicable to estimating target parameters that reduce the burden of intensive sampling and expensive analysis. It is essential to ensure that stormwater should not either contain hazardous pollutants or their content should be less than the acceptable limit.

These parameters are categorized into primary and secondary parameters as in Table 7. The primary parameters mainly include those that are mandatory to monitor and adopted from the Estonian Water Act, Regulation No. 99. In addition, the parameters that have a potential risk and a great chance of occurrence in stormwater are added to this category. Secondary parameters include those that pose a potential risk to human or aquatic life if they are present in stormwater, but their presence often depends on upstream catchment characteristics and special activities. Primary parameters need comparatively more intensive sampling than secondary parameters. These recommended parameters can be used for all of Estonia according to local conditions.

CONCLUSION AND RECOMMENDATIONS

Sampling strategy is an important aspect of the monitoring programme through which quality stormwater data can be obtained. By reviewing the effectiveness of best-practiced sampling procedures in different research papers, site selection approaches, selection of monitoring parameters and the sample collection system are compiled. Site selection approaches have minimized the number of sites to monitor, the selection of parameters has fixed the potential parameters and options in sampling methods have provided the decision capability to choose the one which balances resource availability and effectiveness. Based on these reviewed approaches, the possible stations and sampling parameters were assessed for Tallinn. In addition, an optimal and effective sampling programme was developed which is recommended for stormwater monitoring in Tallinn. This sampling programme, in general, is affordable, applicable and effective.

The study is based on the literature reviews and has compiled the effective approaches but the uncertainties are not analysed through statistical measures. The real cost is not incorporated to analyse affordability, thus there is a possibility of further study to provide cost-based scenarios. Effectiveness is evaluated based on available uncertainties. However, there are options to choose between the approaches but still an appropriate approach depends on the land use and rainfall patterns in the watershed. The optimal sampling programme, though containing cost-effective methods, does not provide higher certainty in all cases. In addition, the reviews on passive sampling are not discussed in this paper. Nevertheless, the study has attempted to use an approach with a smaller error and low-cost sampling. It provides decision capability to select the suitable monitoring programme in terms of effectiveness, applicability and affordability such that it can be used to obtain coherent data about stormwater runoff which will be helpful to plan, design and manage urban stormwater.

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Linnade sademevee tõhusama seire, parema planeerimise ja juhtimise suunas

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Sademevee andmete ebapiisavast kättesaadavusest tingitud vähene teave ei võimalda hinnata saasteainete tegelikke kontsentratsioone ja koormusi. Sellises olukorras on keeruline teha pädevaid otsuseid jätkusuutliku planeerimise, projekteerimise ja poliitika kujundamisel, samuti kavandada sademevee äravoolu ning saasteainete vähendamiseks sademeveesüsteeme, sh alternatiivseid keskkonnasõbralikke lahendusi.

Usaldusväärsete ja esinduslike andmete saamiseks on oluline lähtuda standardiseeritud seireprogrammist ning proovivõtu- ja analüüsiprotseduuridest. Seireprogramm peab olema optimaalne ja tõhus ning samal ajal arvestama proovivõtu ja analüüsimise maksumust ning tehnilisi raskusi.

Uurimuses on antud ülevaade teadusartiklites sagedamini mainitud seireprogrammide ja proovivõtuviiside tõhususest. Tõenäolisi lähenemisviise koha valikule, seire parameetritele ja proovide kogumise süsteemile on võrreldud nende tõhususe, taskukohasuse ja rakendatavuse alusel. Selle teabe põhjal on Tallinna linna sademeveevalgalale pakutud sobivaim proovivõtuprogramm. Veelgi enam, uurimus annab otsusetegijatele võimaluse valida erinevate variantide seast sobivaim seireprogramm, mille rakendamine tagab sademevee kohta ühtsed võrreldavad andmed.