Chapter 4

Measuring the water balance in stormwater control measures

Tim D. Fletcher[1], Jean-Luc Bertrand-Krajewski[2], Jérémie Bonneau[3], Matthew J. Burns[1], Peter J. Poelsma[1] and Jasmine K. Thom[1]

[1]The University of Melbourne, Waterway Ecosystem Research Group, School of Ecosystem and Forest Sciences, Melbourne, Australia
[2]University of Lyon, INSA Lyon, Laboratory DEEP, Villeurbanne, France
[3]INRAE, UR RiverLy, Villeurbanne, France

ABSTRACT

Stormwater control measures (SCMs), also frequently referred to as sustainable urban drainage systems (SUDS), are of growing importance in cities, as part of a global move towards mitigating the impacts of stormwater on receiving environments. They need to be monitored as parts of UDSM systems but require specific and sometimes innovative methods and sensors. This is particularly the case for SCMs such as swales, rain-gardens, bioretention filters, infiltration trenches, green roofs, etc., which have complex and varied configurations and hydrologic behaviour. This chapter deals with measuring the water balance in SCMs by accounting for its various components: inflows, outflows, overflows, storage, infiltration, exfiltration, intrusion, evaporation, and evapotranspiration. It presents a range of suitable methods and tools, indicates key points to consider, and discusses possible difficulties in obtaining accurate monitoring data. Routine monitoring of decentralized and diversified SCMs is still an emerging field for both researchers and practitioners. A significant evolution is therefore expected with its generalization in the next years.

Keywords: Evaporation, evapotranspiration, exfiltration, infiltration, inflow, intrusion, outflow, overflow, water content.

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SYMBOLS

A	area (m^2)
AET	actual evapotranspiration (m^3s^{-1})
c_p	specific heat of the air
D	drainage
$e_s - e_a$	vapour pressure deficit of the air (Nm^{-2})
exf	exfiltration (m^3s^{-1})
E	transpiration
ET	evapotranspiration (m^3s^{-1})
ET_0	reference evapotranspiration (m^3s^{-1})
f	function (–)
G	soil heat flux (Wm^{-2})
h	water level (m)
i	time step index (–)
I	irrigation
K_c	crop factor (–)
K_{sat}	hydraulic conductivity at saturation
P	rainfall (m^3s^{-1})
PET	potential evapotranspiration (m^3s^{-1})
Q	discharge (m^3s^{-1})
Q_{in}	inflow (m^3s^{-1})
Q_{out}	outflow (m^3s^{-1})
Q_{over}	overflow (m^3s^{-1})
Q_{sap}	sapflow (m^3s^{-1})
r_a	aerodynamic resistance
r_s	surface resistance
R	rainfall depth (m)
R_a	extraterrestrial radiation (also known as solar constant) (Wm^{-2})
R_n	net solar radiation (Wm^{-2})
sub	as index: refers to the subsurface of an SCM (–)
$surf$	as index: refers to the surface of an SCM (–)
T_{max}	maximum temperature (K)
T_{mean}	mean temperature (K)
T_{min}	minimum temperature (K)
Vol	volume of water in a lysimeter per unit lysimeter area (m^3m^{-2})
Δ	slope of the saturation vapour pressure temperature relationship
ΔS	variation of water storage within an SCM during one step (m^3)
ΔV	change in the storage volume in a porosity measurement (m^3)
γ	psychrometric constant ($Nm^{-2}\ K^{-1}$)
ρ_a	mean air density at constant pressure (kgm^{-3})

4.1 INTRODUCTION

Fundamental to understanding the performance of a stormwater control measure (SCM) is the quantification of its water balance – inflows, storage and outflows (Figure 4.1) – or at least of the components of the water balance that are of interest. While conceptually simple, the reality is quite complex, particularly for systems where infiltration and evapotranspiration fluxes are present. In this chapter we describe methods and tools that can be used to measure or estimate the various fluxes and storages, drawing on illustrative examples.

Key messages on measuring the water balance in stormwater control measures

KM 4.1: Ensuring reliable flow measurements usually requires that (i) either new SCM facilities must be designed in order to allow and facilitate measurements by means of dedicated arrangements and structures which are usually ignored in most SCM facilities, or (ii) existing SCM facilities must be adapted and/or retrofitted.

KM 4.2: Understanding the water balance of SCMs is vital to understanding their performance, not only for hydrological aspects, but for pollution reduction also. It also provides important information on long-term maintenance and performance, which are vital for overall sustainability and asset management considerations.

KM 4.3: The specificities of SCMs require specifically adapted monitoring techniques and equipment, which are outlined by this chapter. As this is an evolving area, however, readers are advised to look for up-to-date information before designing or embarking on a monitoring campaign for SCMs.

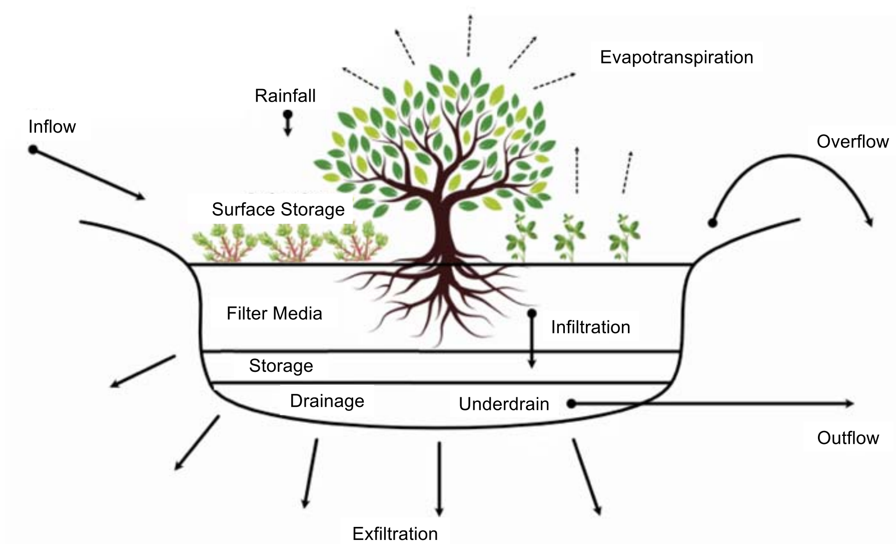

Figure 4.1 Schematic representation of the water balance of a stormwater control measure. *Source*: adapted from Jérémie Bonneau (INRAE).

4.2 DESCRIPTION OF THE WATER BALANCE

The water balance of an SCM is given, in its most general form, by the sum of the inflows and outflows (Equation (4.1)):

$$\Delta S = \sum in - \sum out \tag{4.1}$$

where ΔS is the change in storage over the time-step being considered.

The inflows and outflows depend on the configuration of the SCM of interest. For example, Equation (4.2) shows the case for a vegetated system with infiltration components, and both surface (ponding) storage and internal water storage (i.e. water stored in the substrate). In this example the possibility of groundwater intrusion into the SCM is ignored.

$$\Delta S_{surf+sub} = Q_{in} + P - Q_{out} - Q_{over} - exf - ET \tag{4.2}$$

where $\Delta S_{surf+sub}$ is the combined surface (ponding) and subsurface (substrate water content) storage volume, Q_{in} is the inflow (for example from a pipe or other inlet), P is the rainfall, Q_{out} and Q_{over} are the outflow and overflow respectively, and exf and ET are the exfiltration and evapotranspiration fluxes, respectively.

In determining the monitoring strategy for a given SCM, consideration should be given to which fluxes are important to properly quantify, and which can be estimated. For example, if the only performance metric of interest for an infiltration basin is the reduction in peak flows, measurements of infiltration or evapotranspiration may not be necessary. Conversely, if a vegetated bioretention system is being monitored for its contribution to reducing overall flow (both through surface runoff and groundwater recharge via infiltration), evapotranspiration will need to either be measured directly, or indirectly estimated through quantification of all other elements of the water balance. An appropriate monitoring strategy can only be developed once agreement on the important fluxes has been reached.

Compared to traditional centralized underground stormwater collection systems, where monitoring some key points (e.g. overflow structures, outlets) may be sufficient to get data and information about the corresponding entire catchment, SCMs are usually numerous, decentralized and spatially distributed over the entire catchment: getting data and information at this spatial scale necessitates the monitoring of several SCMs or getting appropriate and representative information about a subset of them, for extrapolation to others having similar properties and/or behaviour. Moreover, monitoring traditional underground collection systems, even if it is never obvious, benefits from well-established and various experiences, whereas monitoring SCMs is still emerging and prone to significant evolution in the coming years with e.g. the use of low-costs sensors, new data transmission technologies, the development of IoT (Internet of things), etc. (Cherqui *et al.*, 2019).

4.3 INFLOW, BYPASS, OUTFLOW AND OVERFLOW

Inflow, bypass (water diverted around the system and thus bypassing all treatment), outflow and overflow (excess water spilling from within the system) can be measured using a range of instruments, depending on the configuration of each element.

Wherever possible, design of the SCM should consider proposed or potential monitoring. Ideally, the system should be constructed with dedicated monitoring points, allowing monitoring weirs, flumes or other proposed measurement apparatus to be installed easily. For example, a bypass channel around a wetland can only be accurately measured if there is a stable cross section with easily characterized geometry, and it is not affected by backwater.

Similarly, when choosing between multiple SCMs as potential monitoring sites, the complexity of the system will be an important selection criterion. A system with multiple inlets will require either:

- Separate monitoring infrastructure at each inlet (thus substantially increasing both the capital and operating costs of monitoring), or
- Estimation of flows from additional inlets, using a rainfall-runoff model, or simply a catchment area *pro rata* estimation. Regardless of the approach, estimation will introduce substantial errors, which may undermine the objectives of the monitoring and bias results and conclusions.

4.3.1 Inflows

Inflows through a pipe or constructed channel can theoretically be measured using depth measurement (if a suitable rating relationship can be achieved, for example using a V-notch or other calibrated weir, or Venturi or Parshall flume – see Sections 3.4.1 and 3.4.2), although attention needs to be paid to obstruction and sediment accumulation and other limitations mentioned in Chapter 3. In such situations, flow calculations based on depth-area-velocity measurement, using technology such as acoustic Doppler, ultrasonic, laser or radar sensors are likely to be more effective. Piped inflows can be challenging to measure, due to factors described in the following three subsections: sediments accumulation, flow regime transition and backwater effect.

Low inflows or flows in small pipes, commonly encountered in SCMs (particularly at the outlet), are not easy to measure with traditional sensors due to low water levels and high relative uncertainties, low flow velocities, influence of immersed sensors themselves on water levels and flow velocity. Methods used for large sewers as presented in Chapter 3 may thus be affected by very high uncertainties and bias, and sometimes may not even be applicable. They may require other methods and devices to be measured accurately, e.g. electromagnetic flow meters in siphons, or tipping bucket gauges, as in the case of SCM outflows (see Section 4.3.2).

4.3.1.1 Obstruction of the flow sensor caused through the accumulation of sediment or debris

Weirs, flumes, or other structures used to measure inflows can accumulate sediment and debris usually present in untreated inflows (Figure 4.2). Unless inflows contain very little sediment (e.g. pre-treated by

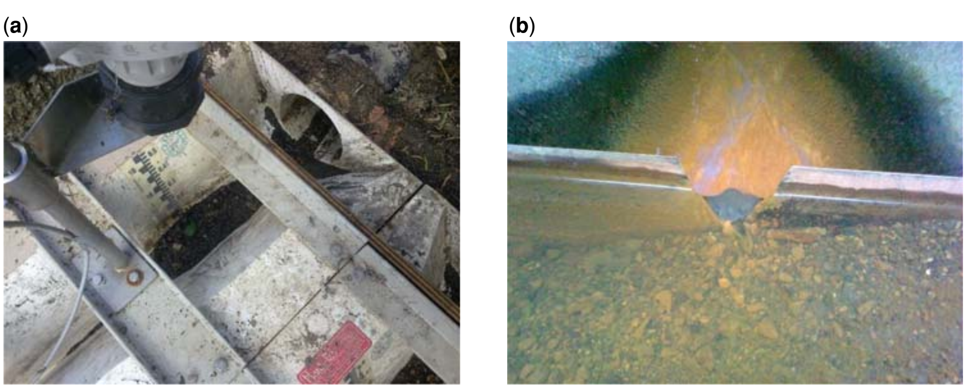

Figure 4.2 Parshall flume (a) and V-notch weir (b) rendered unusable due to sediment accumulation. *Source*: Peter Poelsma (University of Melbourne).

a gross pollutant trap or sediment basin), using such structures is not suitable. Even apparently 'clean' inflows can contain some sediment which then accumulates and requires regular removal.

Submerged sensors can also be frequently covered with sediment or debris (Figure 4.3). Large pieces of debris and litter can get caught on the sensor (ragging), or sediment can accumulate during low velocities at the end of events or in pipes with low slopes. Debris can stop the sensor from working by blocking the path of beams (e.g. Doppler sensor), or sediment can enter openings in the sensor, e.g. to measure pressure, resulting in inaccurate measurements.

Sensors covered by sediments may lose their ability to measure water levels accurately. For example, the 'weight' of sediment on a pressure sensor can lead to an inaccurate level measurement (Figure 4.4).

Sensors mounted above the water surface can also result in inaccurate water depths if sediment accumulates in the bottom pipe or channel. The water surface/level can increase because of sediment accumulation, and thus artificially increase the recorded flow rate.

If possible, measurements should be made downstream of a primary treatment which removes the litter and sediment, thus making flow measurement feasible and reliable. In some cases, it may even be

Figure 4.3 Debris caught on sensors blocking sensor beams (a, b), sediment on diaphragm of a pressure sensor (c, d). *Source*: Peter Poelsma, University of Melbourne.

Figure 4.4 Example of a flowmeter being covered by sediments after a storm event, leading to loss of reliable data. In this case sediment accumulation was due to the construction of a small weir downslope of the probe. *Source*: Peter Poelsma (University of Melbourne).

appropriate to install a dedicated sediment trap. Figure 4.5 shows a litter fence built to prevent the blockage of downstream flow diversion and monitoring infrastructure.

The maintenance of sensors is very important (see Section 7.4), especially in the challenging conditions at inlets – high sediment loads, debris, long periods of no flow, etc. Regular removal of debris or sediment may be required, as well regular cleaning and calibration of the sensors.

Steeper pipes or channels can also reduce the accumulation of sediment which causes the measurement problems mentioned above, but this introduces other issues, in terms of transition from subcritical to supercritical flows.

4.3.1.2 Transition of flows from subcritical to supercritical

A hydraulic jump happens in a pipe or a channel when the flow of water transitions from supercritical (typically in steep pipes) to subcritical (e.g. under the influence of a break in slope, an access hole, or a weir), as illustrated in Figure 4.6. As a consequence, waves and turbulence can develop on top of the probes, creating uncertainty and variability of the water level reading. Therefore, as much as possible, measurements must be made upstream of the hydraulic jump position, which may be estimated by means of hydraulic calculations for various expected flow regimes in the SCM facility.

Figure 4.5 Example of primary treatment constructed to reduce blockage of downstream monitored pipes and diversion weir. In this case, the litter fence required monthly-cleaning to maintain satisfactory operation. *Source:* Peter Poelsma (University of Melbourne).

4.3.1.3 Backwater influence from within the SCM itself during certain periods

In some circumstances, backwater influences from downstream may render flow measurements inaccurate, either because the sensor is unable to cope with transition from positive to negative velocities, because the relation between water level and flow is no longer valid, or because the backwater zone leads to accumulation of sediment on the sensor. Most velocity sensors are able to cope with such influences, but they need to be installed in a position where they are protected from sediment, such as part-way up the side of a pipe. It is important to identify, as much as possible, these potential complications before monitoring equipment is installed by conducting some detailed hydraulic analysis and modelling of the flow measurement structure jointly with its upstream and downstream parts. For example, the risk of backwater influence can be easily established by survey of the inlet pipe and SCM water level range. Very frequently, an iterative approach is necessary, once the first data are collected on site and reveal its real functioning, as there are very often differences between prior information, theory and reasoning, and posterior data, practice and observations.

4.3.1.4 Rating curve

Where inflow is conveyed through a natural channel, a rating function $Q = f(h)$ needs to be established, relating the discharge Q to the water level h, based on empirical measurements of depth and velocity or tracing experiments across the channel cross section.

Water level is measured upstream of a stable cross section where a change in discharge results in a measurable change in level which is not affected by a section further downstream. Discharge is measured

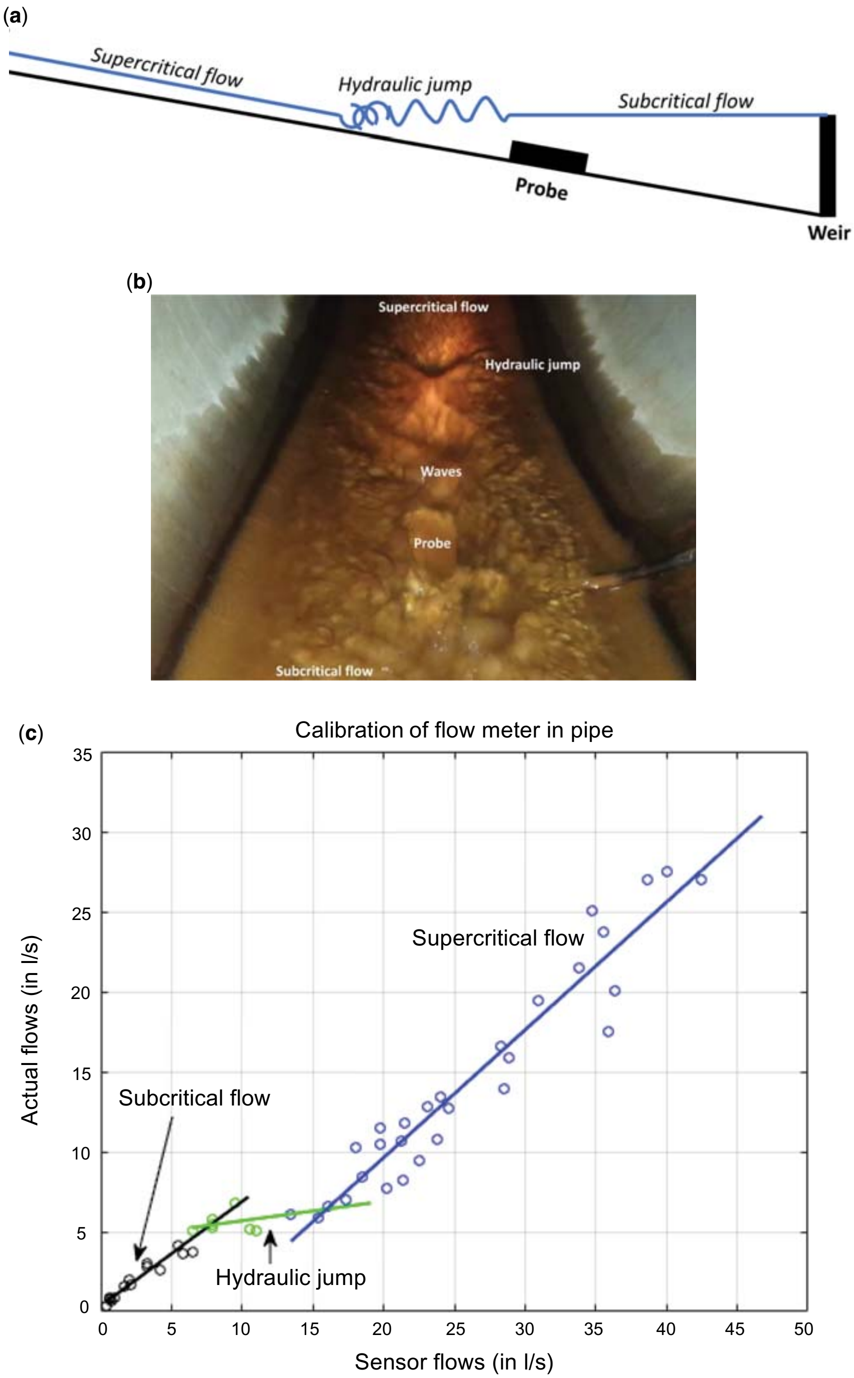

Figure 4.6 Example of transition from supercritical to subcritical flow, resulting in disturbance to flow measurement in theory (a) and in practice (b), with resultant impact on the flow rating curve (c). *Sources*: (a) and (c) adapted from Jérémie Bonneau (INRAE), (b) Jérémie Bonneau (INRAE).

at a variety of levels covering the range of levels experienced by the site. A relationship between water level and discharge is then established and used to convert level to flow. Achieving an accurate rating function is a laborious task, requiring field measurement during a wide range of conditions; sufficient accuracy will only be achieved if the necessary personnel to undertake the rating are available to go on site during times of varying flow, which may be difficult and risky during storm events (see Section 7.2). A detailed standard method for establishing rating curves is available in ISO (2013).

Chapter 3 provides details on water level sensors, flow velocity sensors, and also on velocity-area measurement methods (ISO, 2007). In selecting flow sensors, it is important to consider water quality. For example, there are occasions where the water is too clear for some sensors that rely on a signal being reflected from particles or bubbles in the water (e.g. acoustic Dopplers, laser distance measurement). This is more common in treated outflows but can also occur in the baseflow at inlets or the tail of inflow events.

4.3.2 Outflows

Outflow configurations greatly vary, ranging from a simple V-notch or square weir, to a single orifice or orifice plate, or a simple pit. In the case of a bioretention system with underdrain, outflow needs to be measured in the pipe or pit downstream, for example using depth measurement and a weir or flume or measuring depth-area-velocity. If appropriate conditions (geometry, size, flow regime, etc.) are satisfied, methods and sensors described in Section 4.3.1 for inflows and more generally in Sections 3.3 and 3.4 are possible solutions to monitor SCM outflows.

However, SCM outflows are frequently very low, for example in the range of only a few litres per hour or even less. Indeed, many SCMs are designed to maximize storage, infiltration and evapotranspiration, to delay and attenuate peak flows, resulting in outflows which are significantly lower than inflows. In such cases, most methods used to measure discharges in large pipes or even SCM inflows are no longer applicable and alternatives methods are needed.

As SCM outflows may range from $m^3\ h^{-1}$ to a few Lh^{-1} or less, no single instrument can cover such a wide range with acceptable uncertainties. Different sensors are therefore frequently combined, as shown in the examples below.

The first example deals with the measurement of the outflow from a vegetated roof, with a substrate depth from 40 to 140 mm (Figure 4.7a). Preliminary theoretical estimations indicated that the maximum outflow was expected to be between 1.8 and 9.0 $m^3\ h^{-1}$. Therefore, in a services room located under the roof, the initial vertical downspout (160 mm pipe) evacuating the roof outflow has been cut and replaced by a 25 mm pipe siphon equipped with an electromagnetic flowmeter with a measuring range of 0 to 19.8 $m^3\ h^{-1}$. In the case of blockage, a bypass above the electromagnetic flowmeter has been built (Figure 4.7b). The maximum outflow measured over the 9-month monitoring campaign Sept. 2012–May 2013 reached 2 $m^3\ h^{-1}$, i.e. just above the lowest theoretical estimation. An example of monthly data is shown in Figure 4.8 for February 2013 (Bertrand-Krajewski & Vacherie, 2014). The maximum outflow is close to 0.8 $m^3\ h^{-1}$. But the critical point was the measurement of the very low outflow. As shown in the zoom box in Figure 4.8, when the outflow is lower than approximately 55 Lh^{-1}, the velocity in the electromagnetic flowmeter is too low for the sensor and the outflow values drop abruptly to zero. Consequently, the diminishing tail of the outflow hydrograph is missed, and the water balance is biased.

In order to improve the measurement of very low outflows, a new device was created, which combines three components: a 10 mL tipping bucket (the same as in tipping bucket rain gauges – see Chapter 2), a 1 L tipping bucket and an electromagnetic flowmeter (Figure 4.9). Two control valves avoid overload and saturation of the tipping buckets. The complete device was calibrated in the laboratory with a regulated peristaltic pump associated with a scale to measure mass of water, over the range of approximately

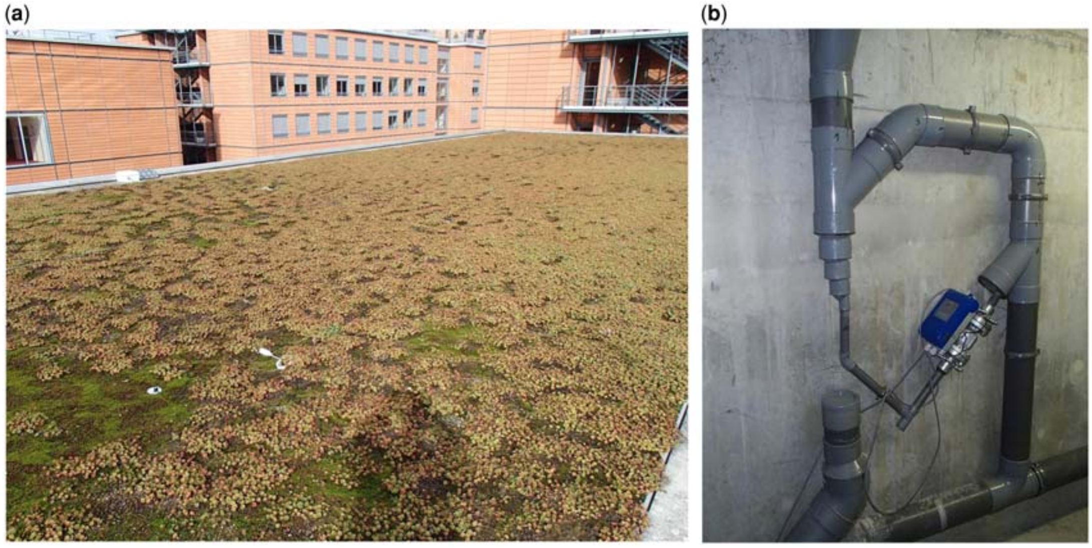

Figure 4.7 (a) Lyon Congress Centre 282 m^2 vegetated roof; (b) modified downspout equipped with an electromagnetic flowmeter and an upper bypass. *Source*: Laboratory DEEP, INSA Lyon.

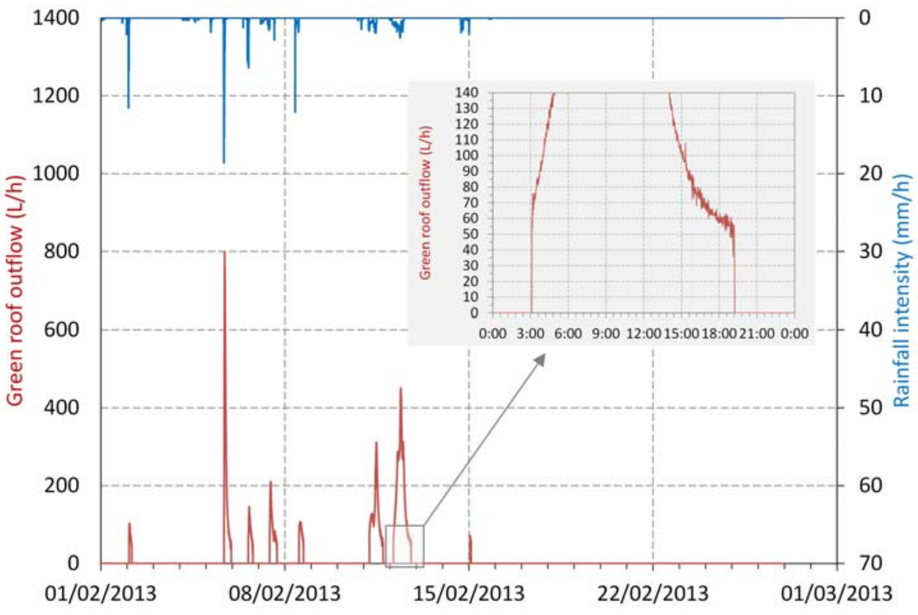

Figure 4.8 Lyon Congress Centre rainfall intensity and vegetated roof outflow measured in February 2013. *Source*: Jean-Luc Bertrand-Krajewski (INSA Lyon).

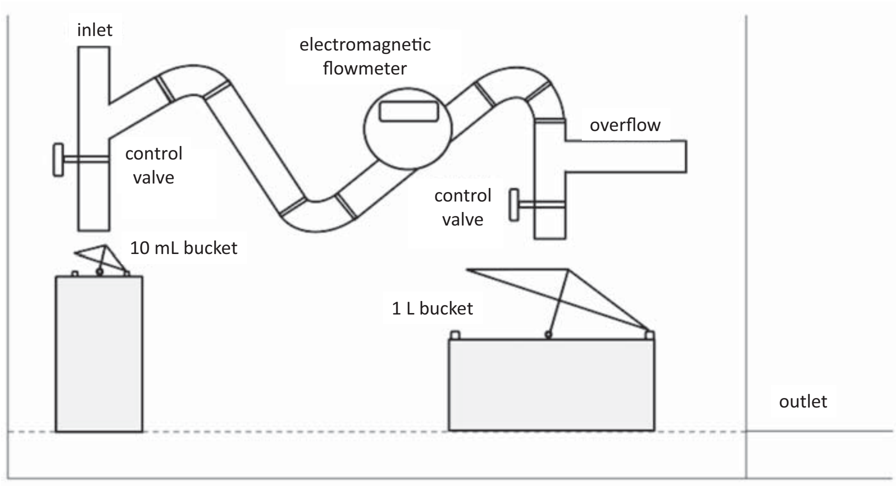

Figure 4.9 Scheme of a flowmeter combining a 10 mL tipping bucket, a 1 L tipping bucket and an electromagnetic flowmeter (manufactured by Précis-Mécanique as the Trio flowmeter and as the Duo flowmeter without the electromagnetic flowmeter). *Source*: Laboratory DEEP, INSA Lyon.

0.0035 to 0.55 $m^3\ h^{-1}$ (Arias *et al.*, 2016b). The measuring range of the 1 L tipping bucket has some overlap with both the 10 mL tipping bucket and the electromagnetic flowmeter, to ensure continuity between the components and avoid gaps or jumps in the measured values. This equipment was first implemented (Figure 4.10) to monitor the outflows of three experimental green roofs. An example of data (Arias *et al.*, 2016a) is given in Figure 4.11 for two green roofs: compared to Figure 4.8, the diminishing tail of the outflow hydrograph is not interrupted, and the water balance can be calculated accurately.

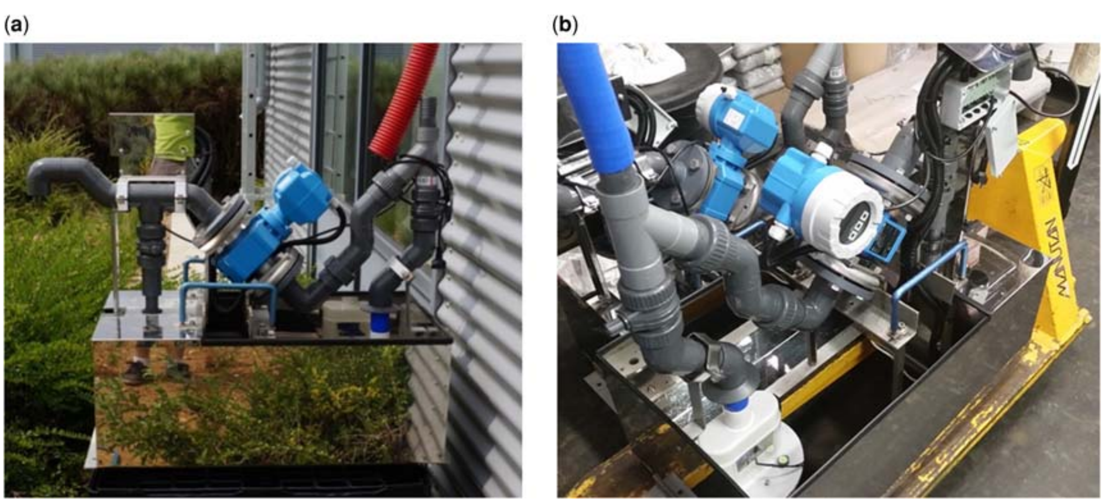

Figure 4.10 (a) installation of a Duo flowmeter to measure the outflow of a green roof; (b) view of a Trio flowmeter. *Sources*: (a) Rémy Bournique (INSA Lyon & Le Prieuré-Vegetal ID), (b) Le Prieuré-Vegetal ID, Moisy.

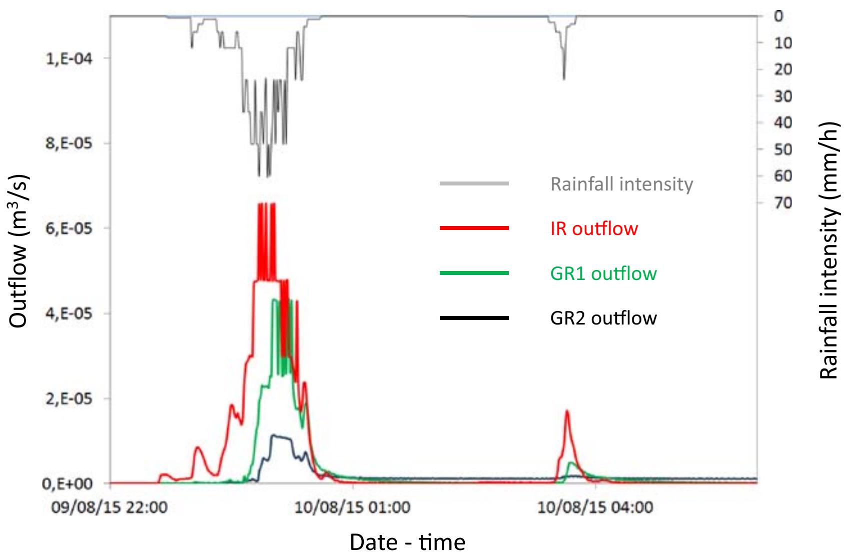

Figure 4.11 Gepeto experimental green roof outflows: example of data on 09–10 Aug. 2015. IR: impervious reference green roof; GR1: basic green roof with 60 mm thick substrate and GR2: GR1 with a 95 mm additional underlying storage reservoir. *Source*: Luis Arias (INSA Lyon).

Similar devices, with local adaptations, have also been used more recently to monitor the outflows from a permeable parking lot and an infiltration trench (Figure 4.12), where space is much more limited (Garnier *et al.*, 2017).

A critical consideration in the monitoring of SCM outlets is ensuring that they are regularly inspected to minimize the effect of blockage. Partial blockages are of particular concern, because they may not be apparent in looking at the measured water level/discharge data. Figure 4.13 shows an example of a partially blocked orifice place, where the discharge is greatly reduced, meaning that the measured water level behind the plate no longer reflects the observed discharge.

4.3.3 Bypass

Bypass occurs when the flow is bypassed around the stormwater control measure, usually through means such as a diversion weir into a pipe or channel. Measuring the flow over a bypass can be difficult, particularly where the diversion weir is subject to highly turbulent flows. A common approach is to measure both the upstream and downstream flow, with downstream flow being measured either in the system or the bypass, or both. In the case where only one of the two is measured, simple subtraction can be used to infer one from the other. Subtraction is simple but may lead to high uncertainties.

4.4 STORAGE VOLUMES

Storages within SCMs may be either surface storage (i.e. ponding), or subsurface (water contained within the substrate, for example in an infiltration, bioretention system or green roof).

Measurement of storage volumes in a stormwater control measure is conceptually simple. Surface ponding volume can be calculated from water depth (which can be obtained using a range of sensors,

(a)

(b)

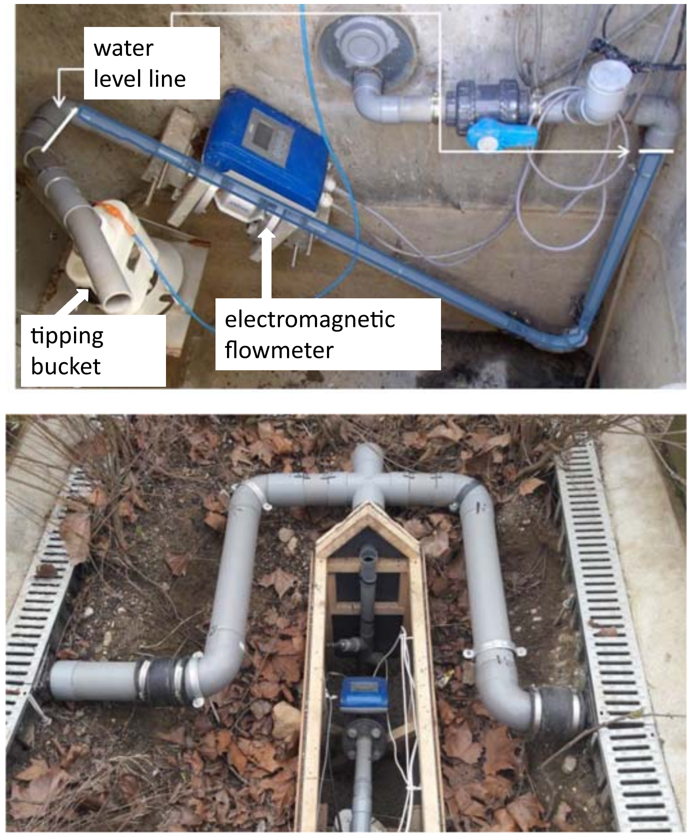

Figure 4.12 Installation of a two-component (a 20 mL tipping bucket and an electromagnetic flowmeter) flowmeter to measure the outflow of an infiltration trench. (a) permeable parking; (b) infiltration trench. *Source*: courtesy Robin Garnier (INSA Lyon).

(a) (b)

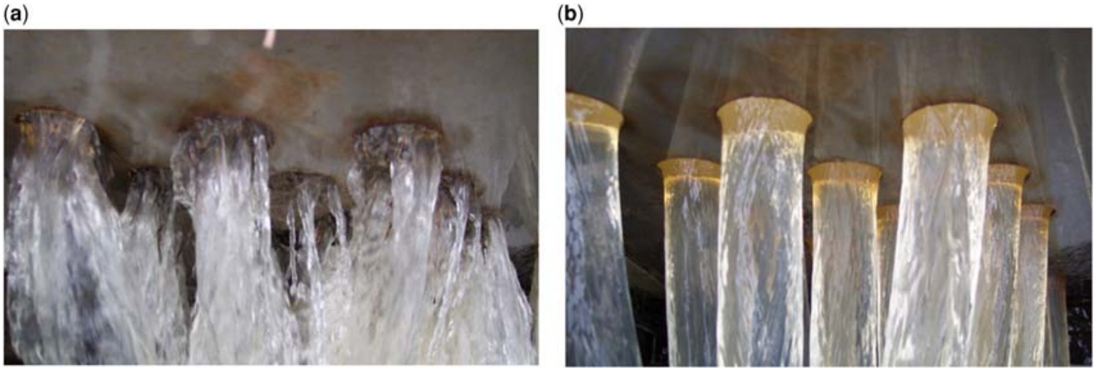

Figure 4.13 Blocked (a) and unblocked (b) orifices in wetland outlet demonstrating the need to ensure regular maintenance to obtain accurate outflow estimates. *Source*: Peter Poelsma (University of Melbourne).

such as pressure, capacitance, ultrasonic or radar sensors (see Section 3.2 for more information on water level sensors) matched to an accurate survey of the bathymetry of the system. ISO (2010) provides useful guidance on volume measurement in this manner (cubature method). It is important to note that the bathymetric survey should be as-constructed and not as-designed, as the difference can be quite large and introduce a substantial error into estimated storage volumes. There may also be the need to account for changes in storage volume over time, such as the decrease due to sediment accretion in the inlet zone. Rapid accurate survey is now readily accessible using drones equipped with LiDAR.

Many SCMs also contain subsurface storage. Examples include infiltration systems, bioretention systems, sand filters, green roofs, etc. Storage volume estimation in the substrate(s) of such systems can be undertaken using depth sensors as listed above, coupled with bathymetry of the subsurface component, and a reliable measurement of the porosity of the substrate. In many cases this requires measurement of the porosity of each of the substrate layers, such as in a bioretention system, which typically has a loamy sand substrate sitting over a gravel drainage layer, with one or several transition layers (Figure 4.14). In such systems, the water balance may require porosity to be taken into account, by one of the following methods:

- Direct measurement of porosity, typically taken by coring the substrate and undertaking a laboratory analysis. Standard methods for such analysis are widely published (see for example ISO, 2017). Ideally, analysis of the substrate porosity should be undertaken close to the period for which the water balance analysis is being undertaken, as the substrate properties will change over time due to the growth and death of plant roots and other biomass.

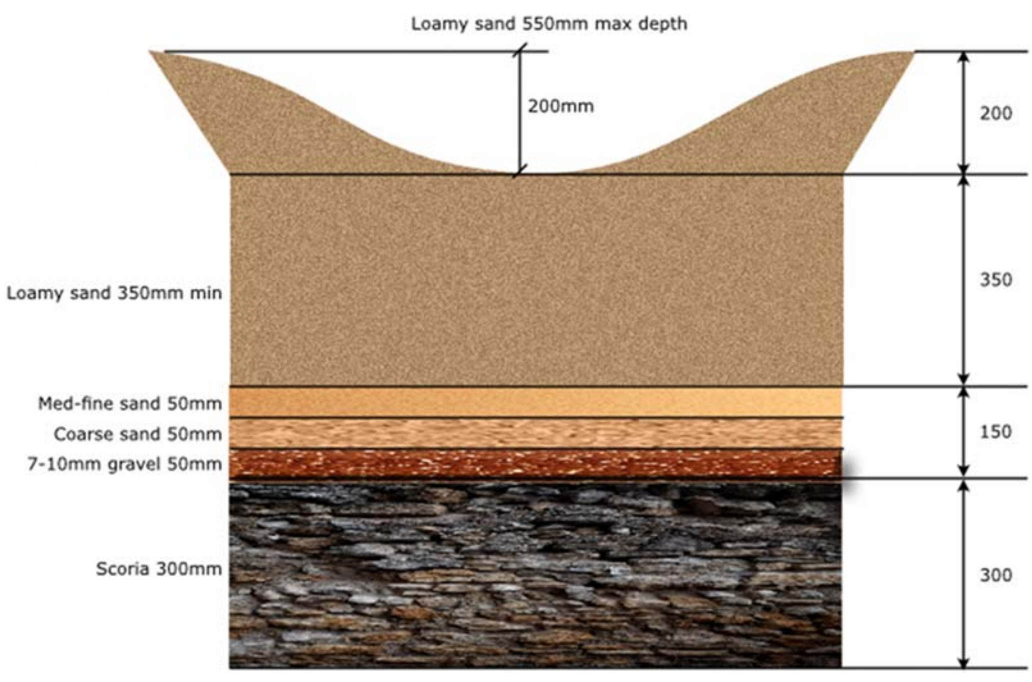

Figure 4.14 Example of filter media profile of a bioretention system. *Source*: Tim Fletcher (University of Melbourne).

- Estimation of porosity from known properties of the substrate (provided for example during the construction). This method is not as accurate as direct measurement, because it does not account for changes which occur to the material *in situ*.
- Direct measurement of water volume, by closing the water balance such that the change in subsurface water level can be calculated from a known inflow volume. For example, observing the change in water level within a system closed off from any input and output during a rainfall event of known depth allows an *in situ* estimation of the substrate porosity by means of Equation (4.3).

$$\text{Porosity} = R \times A/\Delta V \tag{4.3}$$

where R is the observed rainfall depth, A is the area of the system considered and ΔV is the change in storage volume.

Sensors used to measure the subsurface water level should be installed in such a way that water from the surface storage above does not leak down along the sensor housing in such a way that it gives a false water level reading in the substrate.

4.5 INFILTRATION AND EXFILTRATION

For many SCMs such as infiltration basins and bioretention systems (often called biofiltration systems or rain-gardens), the movement of water from the ponding zone through the filter media substrate (referred to herein as infiltration), or from the filter media substrate to the underlying soil (referred to herein as exfiltration) are important fluxes to quantify (Figure 4.15). In some situations, there may also be an intrusion of groundwater into the SCM from adjacent soil, and it may be necessary to quantify this, for example to analyse seasonal variation in performance.

Infiltration can be measured either using the water level in the entire system or measured at specific locations using experimental apparatus. The former method is preferable wherever possible, because it gives an integrated measurement of the performance of the whole system. Conversely, where the interest is whether there is clogging in a particular part of the system (typically this more likely occurs around the inlet), location-specific infiltrometer testing will be most helpful. The reader should refer to

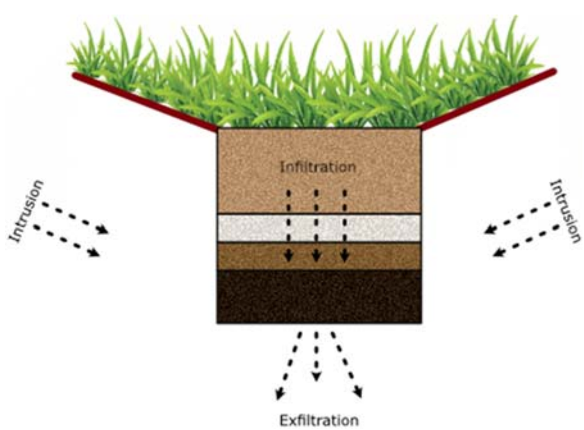

Figure 4.15 Conceptual definition of infiltration, exfiltration, and intrusion fluxes. *Source*: Tim Fletcher (University of Melbourne).

Bertrand-Krajewski *et al.* (2007) for guidance on methods for determining the spatial distribution of such infiltration testing within a large infiltration system.

4.5.1 Measuring infiltration

4.5.1.1 Whole-of-system measurement

Infiltration from the ponding zone into the filter media can be most simply determined by measuring the depth of ponded water, using water level sensors (see Chapter 3). The change in storage depth (or, more precisely, the change over time in storage volume/infiltration area, to account for changes in the surface and subsurface bathymetry) gives the infiltration rate. Calculation of the infiltration rate depends on the configuration of the system. For example, where infiltration then passes to an underdrain, which is considered to be non-limiting, the infiltration rate can be calculated using Darcy's equation, with the hydraulic gradient given as the ratio of the total depth (ponding depth + substrate depth) to the substrate depth. Where it is suspected that the pipe may be restricting outflows, measurement of the pipe outflow should be made (see Section 4.3.2) and compared to the infiltration rate.

4.5.1.2 Infiltrometer-based measurement

Infiltration rates can be measured using infiltration rings (often called infiltrometers), where water is applied to a ring inserted into the media, either a single- or double-ring, with either a constant head or falling head. Other commonly used methods include an air-entry permeameter or using boreholes. The commonly used methods have been reviewed by several authors (e.g. in Angulo-Jaramillo *et al.*, 2000; Philips & Kitch, 2011). The constant head test is simple to apply, is generally considered to be reliable and aims to measure infiltration rate after a steady state has been achieved. In theory, it measures the infiltration rate under saturated conditions (K_{sat}), allowing measurements at different locations or times to be compared.

One recent innovation in the measurement of *in situ* infiltration rate is that of Di Prima *et al.* (2016), using an automated single-ring infiltrometer operating with a quasi-constant head to measure steady state infiltration, and connected to an Arduino-controlled pressure transducer, thus recording infiltration rate to a logger (Figure 4.16). This dramatically reduces the personnel hours required to complete such *in situ* testing. In addition, Di Prima (2015) provides (in Appendix B) a free software code to automatically process the data.

4.5.2 Measuring exfiltration

Exfiltration from a stormwater control measure is of particular interest for determining, for example, its contribution to groundwater recharge. The suitable method for its measurement depends on the SCM configuration. For a system with temporary ponding, and without any infiltration medium, an infiltrometer approach is feasible, but for all other systems, the only suitable approach is to derive infiltration from change in water storage, taking into account both the surface water and subsurface storages, as described in Section 4.3.2. Again, it is noted that this approach requires that other components of the water balance (other inflows and outflows) can either be accurately quantified or can be ignored (for example, only data from periods with zero inflows and during the night, when evapotranspiration is minimal, may be considered).

In an SCM containing both surface and subsurface storages, a separate water level sensor is needed for each component, along with details of porosity and subsurface bathymetry.

Figure 4.16 (a) example application of single-ring infiltration testing using laborious manual measurement or, (b) automated systems. *Sources*: (a) Peter Poelsma (University of Melbourne); (b) Simone Di Prima (Università degli Studi di Palermo).

4.5.3 Measuring groundwater intrusion

Intrusion of groundwater into an SCM is perhaps the most difficult flux to quantify, given that its source will be diffuse. The approach to estimating this flux is the inverse of the whole-of-system infiltration measurement described above. For example, intrusion could be estimated at times when all other fluxes are either zero or known, so that the water balance can be closed. In systems with a measurable outlet (e.g. an outlet pipe or underdrain), long periods of zero inflow could thus be used to directly measure intrusion, assuming that discharge remaining after the normal system draining period is due to intrusion. However, in systems where there is no outlet, estimation is very difficult, as the water level in the system likely equilibrates with surrounding groundwater. It is thus recommended that a series of piezometer wells be installed around the SCM to measure groundwater level, so that it can be matched to water level measured within the SCM itself. Continuously measured groundwater levels can thus be used to estimate groundwater intrusion into the SCM.

4.6 EVAPOTRANSPIRATION

The importance of measuring evaporation and transpiration depends on (i) the aim of the monitoring and (ii) the configuration of the SCM being investigated. In an infiltration system with high infiltration rates, where water remains ponding for a matter of only a few hours after rain ceases, evaporation will not play a major role in the water balance. Conversely, in a vegetated bioretention system without an underdrain, and sitting on heavy clay soils, both evapotranspiration and transpiration could be important. Green roofs are also characterized by high transpiration and evapotranspiration rates. Table 4.1 gives the definitions of various quantities related to both transpiration and evapotranspiration.

Table 4.1 List of definitions.

Names	Definitions
Transpiration (*E*)	Transpiration (mm) refers to the movement of water through a plant from roots, to leaf surfaces, where it is released by stomata (small pores at the leaf surface) and is transferred to the atmosphere as vapour.
Evapotranspiration (*ET*)	Evapotranspiration (mm) refers to the combined movement of water from transpiration and evaporation of water (from vegetation or other surfaces) across a given area.
Reference Evapotranspiration (ET_0)	Reference evapotranspiration (mm) refers to the evapotranspiration derived from meteorological measurements for a given reference crop (e.g. grass).
Potential Evapotranspiration (*PET*)	Potential evapotranspiration (mm) refers to the maximum evapotranspiration estimated for a given surface area (or SCM), derived from reference evapotranspiration equations or pan evaporation.
Actual Evapotranspiration (*AET*)	Actual evapotranspiration (mm) refers to *PET* that has been modified by soil or crop coefficients to estimate evapotranspiration for given vegetation or soil conditions.
Crop factor (K_c)	A unitless coefficient that modified ET_0 according to the maximum transpiration of a given plant under well-watered conditions, relative to well-watered grass.
Sap flux density	Sap flux density ($cm^3\ cm^{-2}$) refers to the movement of sap through the xylem of woody vegetation, it can be positive, (representing movement from the roots), or negative (movement toward the roots) and is comprised of both transpiration, and stem refilling
Sapflow (*Q*)	Sapflow (L) refers to volumetric whole-plant water use estimated from sap flux density and the sapwood area of woody vegetation.

In non-vegetated systems, where transpiration can be ignored, evaporation can be readily estimated from local pan evaporation data (Locatelli *et al.*, 2017), noting that local microclimate factors may influence this estimate. In particular, daily shading of the SCM (affecting solar exposure) and local site factors such as surrounding buildings or vegetation (affecting relative humidity, air temperature, and wind speed) will strongly influence evaporation rates, as these are key microclimate drivers of evaporation.

For vegetated systems, evapotranspiration can be derived using several possible approaches:

- Calculation from meteorological data.
- Direct measurement of evapotranspiration or transpiration.
- Indirect estimation from the water balance.

4.6.1 Calculation of PET from meteorological data

Potential evapotranspiration can be derived from meteorological data, obtained either from an onsite or nearby weather station. Several equations are commonly used for this purpose, drawing on methods developed by Penman, Monteith and others (see Table 4.2). These equations estimate the reference

Table 4.2 Commonly used methods for calculation of *PET* from meteorological data.

Method	Equation	Crop/Conditions	Source & Comment
FAO Penman-Monteith (FAO56-PM)	$ET_0 = \frac{\Delta(R_n - G) + \rho_a c_p((e_s - e_a)/r_a)}{\Delta + \gamma(1 + r_s/r_a)}$ where R_n is the net solar radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances.	Reference crop (alfalfa & grass)	(Monteith, 1965) This is the standard method recommended by the FAO (Food and Agriculture Organization).
Hargreaves	$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a$ where T_{mean} is the mean air temperature, T_{max} is the maximum air temperature, T_{min} is the minimum air temperature, and R_a is the extraterrestrial radiation, also known as the solar constant, which varies geographically.	Well-watered short green crop	(Hargreaves *et al.*, 1985) This is a simplified version of the FAO56-PM equation used when solar radiation, relative humidity and wind speed data are not available. This approach tends to underestimate *ET* during high wind speeds and overestimate *ET* during high relative humidity. Considered as a good substitute for the Penman-Monteith equation at a monthly timestep.
Oudin	$ET_0 = 0.408 \cdot R_a \cdot [0.01 \cdot (T_{mean} + 5)]$ where the variables have already been defined above		(Oudin *et al.*, 2010) Similar to Hargreaves, a simplified version of the FAO56-PM equation utilized when climate data availability is limited. Suitable for coarse temporal scales such as monthly or annual.

evapotranspiration (ET_0) based on a well-watered reference crop (typically grass), which assumes that soil water content is not a limiting factor. Use of these equations without consideration of soil moisture limitations may result in significant errors during dry periods, especially for vegetation that quickly respond to drought by down-regulating transpiration. For example, Johannessen *et al.* (2019) demonstrated that the use of a simplified calculation of reference *ET* (Hargreaves equation in Table 4.2) combined with a single coefficient for soil recovery does not adequately estimate the volume of *ET* under soil drying.

The models for deriving *ET* from meteorological data presented in Table 4.2 were developed by their authors for a given reference crop, ranging from grass (for example for the Penman and FAO-24 Penman equations) to alfalfa for the Kimberly-Penman equation. There is thus a need to apply an adjustment – a crop factor noted K_c – to determine the potential evapotranspiration by accounting for different rates of transpiration likely from the vegetation in the SCM of interest (Grey *et al.*, 2018; Talebi *et al.*, 2019), such that:

$$PET = ET_0 \cdot K_c \tag{4.4}$$

where *PET* is the potential evapotranspiration from an SCM, ET_0 is the reference evapotranspiration, and K_c is the crop factor.

Finding values of crop factors can be difficult. A starting point could be to consider the table of crop factors provided by the Food and Agriculture Organization (FAO, 2019) and consider species which could be used as appropriate analogues for the species being considered (Grey *et al.*, 2018; Kristvik *et al.*, 2019). Alternatively, a literature review could be conducted for water use studies of the species of interest. A combined approach can derive crop factors from direct measurements (see below) of species of interest (Jahanfar *et al.*, 2018; Szota *et al.*, 2017).

Adjusting reference evapotranspiration (ET_0) to estimate the potential evapotranspiration (*PET*) by a crop factor is an important first step. However, Szota *et al.* (2018) suggest that including additional species-specific coefficients that capture sensitivity to soil drying represented by drought stress (leaf water potential) and transpiration rates will not only provide a more accurate estimation of *ET* in the water balance, but critically, give insight to the likely exposure and response of vegetation in SCMs (e.g. rain-gardens, green roofs, street-tree rain-gardens) to drought.

The most commonly used equations for calculating PET from meteorological data are summarized in Table 4.2. It is important to note, however, that a wide range of methods exist. Guo *et al.* (2019), for example, provide an R package 'Evapotranspiration' which calculates the potential or actual *ET* using up to 17 different methods.

4.6.2 Direct measurement of evapotranspiration, transpiration and evaporation

Evaporation can be simply measured using a pan (Figure 4.17), using standard methods (World Meteorological Organization [WMO], 2019). Where measurement of actual evapotranspiration is important, it can be directly measured using: (i) flux chambers or (ii) lysimeters, while transpiration alone can be estimated from measurements of (iii) sap flux or (iv) leaf stomatal conductance. A summary of these methods is given in Table 4.3.

4.6.2.1 Flux chambers

One direct way of measuring evapotranspiration is through the use of flux chambers, designed to quantify the flux of water vapour (and potentially of other gases, such as carbon dioxide), as shown in Figure 4.18.

Figure 4.17 Direct measurement of evaporation in a pan by means of a water level radar sensor installed above the pan. *Source*: courtesy Adama Kone (INSA Lyon).

Table 4.3 Summary of methods for direct measurement of evapotranspiration.

Method	Description	Advantages	Limitations	Application
Lysimetry	Measures total evapotranspiration from changes in weight of vegetation planted in a container.	Continuous data Can separate transpiration from evaporation	Measure between watering events	Glasshouse
Sapflow	Estimates transpiration from temperature changes in the xylem of woody vegetation following the application of heat.	Continuous data Measure during watering events	Damage to plants Requires scaling Requires sapwood properties Measures transpiration only	Field Glasshouse
Stomatal conductance	Estimates transpiration from the measurement of the stomatal conductance of a representative leaf (sunlit and shaded)	Measure transpiration during watering events	Point data Requires scaling Requires leaf area and fraction of shaded: sunlit leaves Measures transpiration only	Field Glasshouse
Flux chamber	Estimates transpiration from changes in the relative humidity in a closed chamber within a given time period quantified	Continuous measurements	Measures total evapotranspiration only Not suitable for large vegetation, Complex to establish	Field Glasshouse

Figure 4.18 Example of application of flux chambers to measure evapotranspiration in a vegetated infiltration system ("rain-garden") and in surrounding grass. *Source*: adapted from Hamel *et al.* (2014).

Flux chambers work by measuring changes in the relative humidity within a given time period, allowing the amount of water vapour emitted from the soil and vegetation surface to be quantified. Such a system has practical limitations in terms of its size, with chambers typically being limited to measurement of fluxes in grasses through to small shrubs (Figure 4.18). A review of chamber design options is outlined by Hamel *et al.* (2014), and includes open-flow, closed chamber and dynamic closed chamber. The reader is referred to papers by Deguchi *et al.* (2008) and McLeod *et al.* (2004) for a full description of the theory, design, application and validation of flux chambers. It should be noted that these systems can be quite complex to construct, and that their accuracy depends on system-specific calibration, as outlined by Hamel *et al.* (2014).

4.6.2.2 Lysimetry

A lysimeter refers to a device that measures actual plant-soil evapotranspiration from a bounded soil volume in a tank or container. It provides a way of estimating *ET* of experimental SCMs from the change in water fluxes of mass weight to allow the measurement of the overall water balance. There are two types of lysimeter (i) drainage and (ii) weighing. Drainage lysimeters can calculate *ET* using a water balance approach, whereby drainage is subtracted from a known quantity of water applied to the soil volume (either precipitation or irrigation) to determine *ET*. Drainage can be measured using tipping-bucket devices or weighing collected drainage on a separate load cell to the lysimeter. Weighing lysimeters measure *ET* through changes in mass between two time periods where no irrigation or precipitation occurs. The water balance of a lysimeter is therefore given as (Howell, 2005):

$$Vol_i = Vol_{i-1} + P_i + I_i - D_i - ET \tag{4.5}$$

where Vol_i is the volume of water in the lysimeter per unit lysimeter area (mm) at time i, Vol_{i-1} is the volume of water in the lysimeter per unit lysimeter area (mm) at time $i-1$, P_i is precipitation (mm) at time i, I_i is irrigation (mm) at time i, D_i is drainage from the lysimeter (mm) at time i and ET is evapotranspiration (mm).

Lysimeter systems are well equipped to determine both infiltration during a rainfall event and the evapotranspiration that occurs between events. However, they are limited in that they cannot measure *ET* during a rainfall event. Fortunately, *ET* during a rainfall event is normally minimal due to high relative humidity and low solar radiation, which are primary drivers for transpiration.

Lysimeters are highly diverse in form and design (Figure 4.19), ranging from large-scale in-ground tanks on a large load cell, to small potting containers on a small load cell. They have been used to determine the impact of *ET* on the water balance for experimental SCMs such as green roofs (Kemp *et al.*, 2019; Wadzuk *et al.*, 2013), or biofilters (Hess *et al.*, 2017; Szota *et al.*, 2018). This approach is widely used to measure transpiration of plants in a glasshouse setting and to calibrate other methods of measuring evapotranspiration from vegetated modules (Bleby *et al.*, 2004; Forster, 2017; Wadzuk *et al.*, 2013), as it is the most accurate measure of whole-plant transpiration. For weighing lysimeters, the accuracy of this approach is directly related to the accuracy of the load cell. Despite its accuracy, the reliance of this method on bounded soil volume means it is rarely applicable for SCMs in the field. In addition, the applicability of this approach to large SCMs is limited, as increasing plant or system size requires larger load cells at the cost of decreased accuracy and increased expense. Indeed, for full *in situ* systems, lysimetry is not possible.

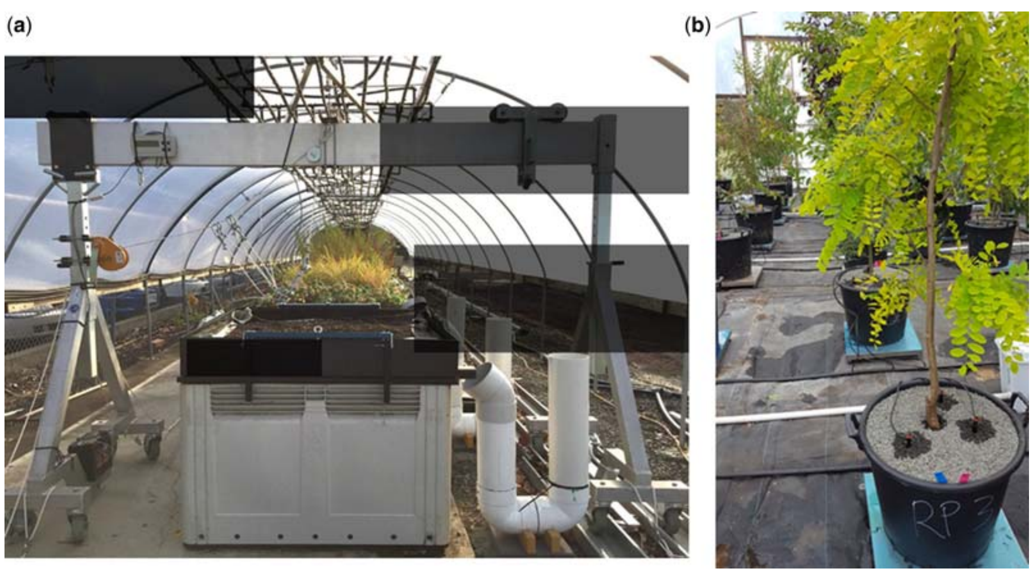

Figure 4.19 Examples of direct measurement of evapotranspiration from changes in weight measured by load cells (lysimeter approach): (a) experimental green roof using mobile load cell above the module to collect periodic weight measurements, to determine evapotranspiration from change in module weights between simulated rainfall events. (b) advanced trees in potting containers atop load cells continuously logging weight to a central datalogger, to determine daily evapotranspiration as the change in container weight from morning (pre-dawn) to evening (dusk). *Sources*: (a) Zhang *et al.*, 2018; (b) Jasmine Thom (University of Melbourne).

4.6.2.3 Sapflow

In practice, vegetation planted in SCMs can rarely be weighed to determine the contribution of evapotranspiration to the water balance in the field. It is therefore necessary to utilize alternative methods. Sapflow sensors can estimate transpiration from SCMs, but are mostly limited to measurements of woody vegetation, such as trees, shrubs, or vines. Sapflow sensors measure the movement of water (sap flux density) through a plant, from temperature changes in the xylem (conducting wood), following the application of heat (Forster, 2017). The movement of heat through the plant is corrected for specific wood properties (to calculate sap flux density) and scaled up to estimate whole-plant transpiration from sapwood area.

There are several types of sapflow sensors that utilize three main approaches: thermal dissipation, heat velocity (Burgess *et al.*, 2001), or heat balance, each with their limitations and advantages (see Forster, 2017 for further detail). The advantage of using sapflow sensors is their discrete application in the field (Figure 4.20), continuous data, and ability to measure *ET* during stormwater events. However, despite careful installation and the application of correction factors for specific wood properties, accurately scaling sap flux density to whole-tree transpiration remains a challenge (Looker *et al.*, 2016; Wullschleger *et al.*, 2011).

While there are a number of studies that utilize sapflow measurements to describe the water use of crops (Silva *et al.*, 2008), forests (Pfautsch *et al.*, 2010), and urban trees (Litvak *et al.*, 2017), their application for estimating transpiration from SCMs has, so far, been limited. The only relevant study to date, Tirpak *et al.* (2018), describes patterns of sap flux density for trees planted in bioretention systems (suspended

Figure 4.20 Sapflow probes used to directly measure transpiration from SCMs with establishing trees. *Source*: Jasmine Thom (University of Melbourne).

pavements), but stops short of estimating the contribution of these trees to the overall water balance. Both researchers and practitioners are increasingly advocating for the inclusion of trees in SCMs to bolster the benefits of SCMs and urban forests concurrently (Berland *et al.*, 2017). Urban trees can transpire large quantities of water daily (up to 260 $\mathrm{L\,day^{-1}}$; Pataki *et al.*, 2011), so their contribution to the water balance of tree-based SCMs is substantial. Therefore, this method is likely to become an important part of measuring the water balance of tree-based SCMs in the field.

4.6.3 Stomatal conductance

Leaf stomatal conductance measurements are an alternative approach for measuring transpiration in field applications using a leaf porometer. These instruments measure the amount of water vapour passing through stomata at the surface of a leaf (stomatal conductance) by determining the difference in vapour pressure between the leaf and the air in a porometer chamber. Measurements are conducted on both sunlit and shaded leaves throughout the day to account for temporal and spatial differences in transpiration for a plant of interest. Values are then scaled for all leaves according to total leaf area and proportioned for sunlit or shaded leaves (Konarska *et al.*, 2016; Scharenbroch *et al.*, 2016). Using this method, Scharenbroch *et al*. (2016) was the first study to estimate the contribution of transpiration from tree-based SCMs to the water balance in the field. They suggested transpiration from trees in a 'green parking lot' in Illinois (that included stormwater control measures such as permeable pavements and bioswales) represents a substantial proportion of the water balance (46–72%). The challenge in using this method, as with sapflow measurements, is accurately scaling flow rates to the whole tree canopy. Unlike sapflow measurements, stomatal conductance also needs to be temporally scaled from point measurements to estimate continuous or daily data. This requires an understanding of tree characteristics (e.g. total leaf area, proportion of sunlit to shaded leaves) as well as the temporal variability of stomatal conductance across a range of climatic conditions. Given the limitations of using lysimetry in field applications, both stomatal conductance and sapflow measurements are the best approximation we have for estimating the contribution of transpiration from large woody vegetation, such as trees, to the water balance of SCMs.

4.6.4 Estimation of *ET* from the water balance

Evapotranspiration can be estimated from the water balance, provided that other parts of the balance can be estimated to give a closed balance. In this approach, the data are separated into periods where the *ET* flux can be separated from the exfiltration flux (if present). To do so, changes in storage are calculated when there is no inflow or outflow. The data are then separated into 'day' and 'night', on the basis that during the night there will be no *ET*, or that night-time *ET* is a negligible fraction of daily *ET*; any change in water level will be a result of exfiltration. This allows the exfiltration flux to be estimated, meaning that it can be subtracted from daytime changes in water storage, to derive net *ET* (Figure 4.21).

Inflow and outflow data are used to isolate periods when exfiltration and evapotranspiration are the only fluxes influencing the water level (i.e. stored volume) within the filter media of the bioretention basin. By isolating night time (with no *ET*), the infiltration rate can be estimated, and then subtracted from the rate of storage change within the filter media during the day (Bonneau *et al.*, 2018). It should be acknowledged that the assumption of no night-time transpiration may result in overestimation of exfiltration at night and subsequent underestimation of transpiration, since night-time transpiration has been shown to occur across a range of species, biomes, and seasons (Forster, 2014). For example, night-time transpiration rate of street trees in Sweden was measured as 11% of daytime transpiration for sun-exposed leaves and 23% of that for shaded leaves (Konarska *et al.*, 2016). How much this influences the overall water balance

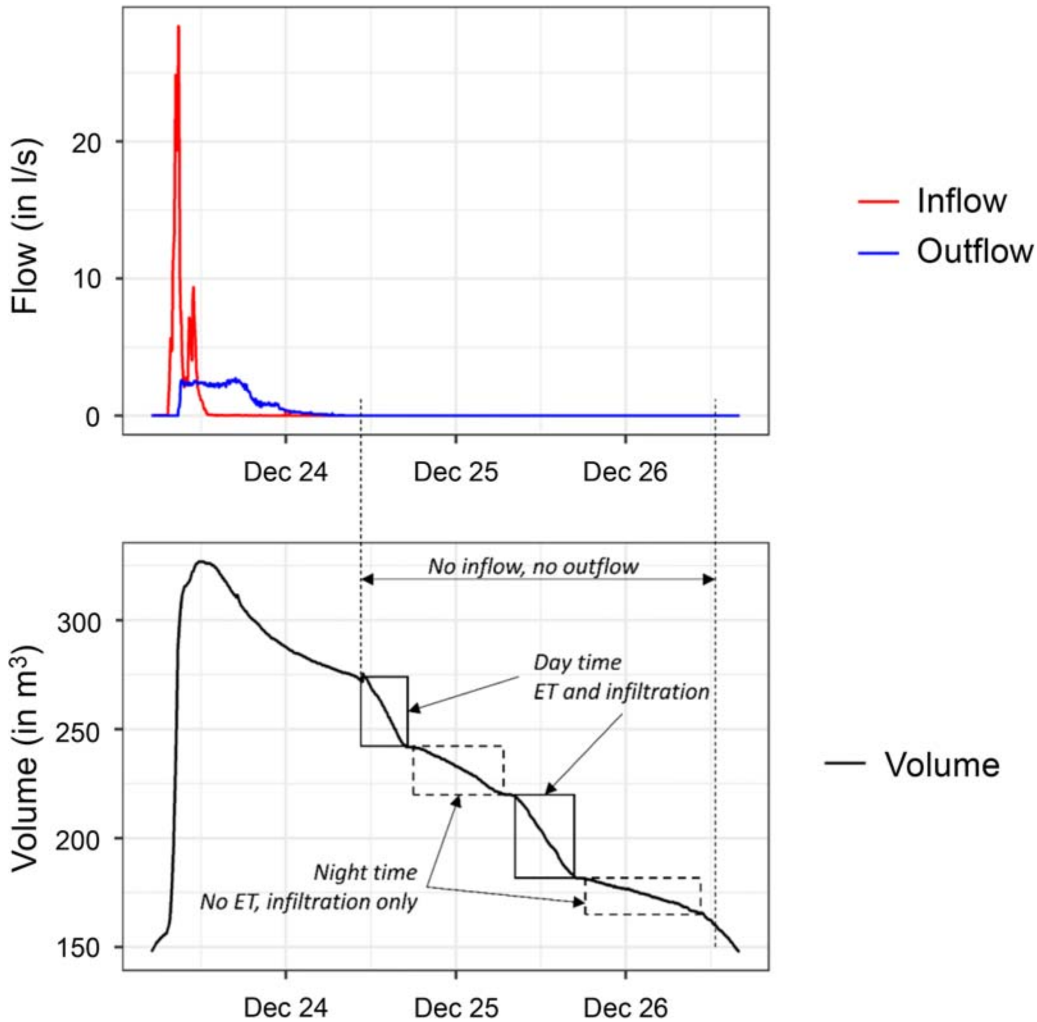

Figure 4.21 Example of using water volume in an SCM during periods free of other inflows or outflow, to derive evapotranspiration rate. *Source*: Jérémie Bonneau (INRAE).

will largely depend on the size, type, and distribution of vegetation in the SCM. In most cases, this error is likely to be within the uncertainty of other aspects of the water balance, and thus should not be an impediment to use of this approach to *ET* estimation.

4.7 SUMMARY AND TRANSITION

This chapter detailed the latest research experiences for SCM (or sustainable urban drainage systems [SUDS]) monitoring, with a focus on the water balance which is considered an important driver of urban hydrology. This new topic raised some questions/challenges, but due to the development of measuring technologies most of them have been overcome or will be overcome in the future. The progress on those systems is being updated regularly and a regular literature review is strongly advised to be aware of the latest findings, before embarking on any given monitoring programme or design.

Various processes occur in SCMs (infiltration, evaporation, etc.) and are central to the way in which SCMs operate and perform their design functions: special monitoring set-ups and technologies are required to collect data in these stormwater infrastructures. The often dispersed or decentralized nature of SCMs must also be taken into account in the design of SCM monitoring.

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