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Toward a comprehensive functional typology of stormwater control measures for hydrological and water quality modeling purposes

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ABSTRACT

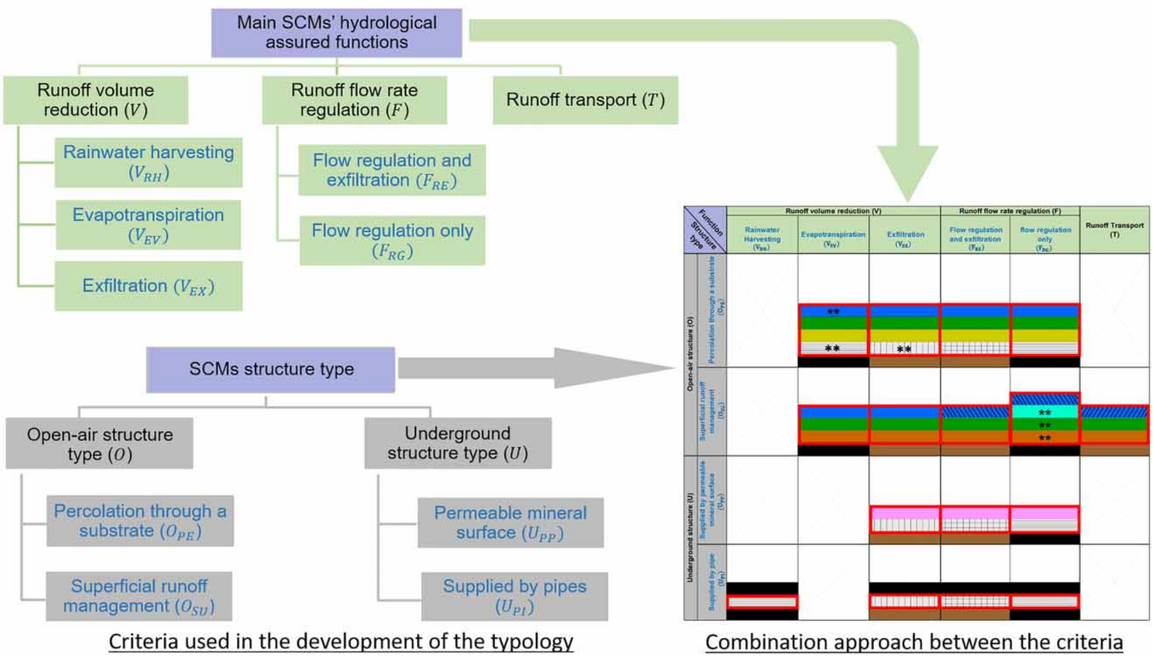
Stormwater control measures (SCMs) are designed according to different urban stormwater management criteria. These criteria are usually the basis for the conception of SCM typologies. Although these typologies are useful, there is currently no typology that can generically describe all the diversity of SCMs and that is adapted for modeling. Thus, a new typology is proposed here. This typology is based on two criteria commonly used in stormwater management: the hydrological function and the type of structure. These two criteria are combined through a cross table. This combination yields the identification of 16 groups of SCMs represented graphically by physical compartments. These groups make it possible to represent a large diversity of existing SCMs. The new typology also allows a more adequate identification and conceptualization – via a reservoir-type approach – of the different hydrological and reactive processes occurring at the SCM level.

Key words: hydrological functions, SCM structure, SUDS classification, reservoir conceptualization, urban runoff

HIGHLIGHTS

- A typology adapted to hydrological and water quality modeling of SCMs.
- Typology developed on the basis of two commonly used criteria in stormwater management.
- The typology yields a simple conceptualization (reservoir type) of the hydrological and reactive processes within the SCMs that can be easily adapted to stormwater models.

GRAPHICAL ABSTRACT



1. INTRODUCTION

After a long and gradual maturation, we are currently facing a major paradigm change in urban stormwater management. This change is reflected in the concepts of water-sensitive urban design (WSUD), sustainable urban drainage system (SUDS), stormwater control measures (SCMs) (Fletcher *et al.* 2015), and more recently sponge city (Chan *et al.* 2018) which are developing internationally. The idea is to somehow make the city 'transparent' to rain, in order to maintain the hydrological balance and water quality close to what they would be in the absence of urbanization (Li *et al.* 2019). In the current context of global changes, precipitation is also a precious resource that must be reconsidered as a vector of adaptation and resilience (Charlesworth 2010). This requires the promotion of source control measures, in diffuse structures that promote retention as close to the source as possible, infiltration and/or evapotranspiration, as well as water recovery (Eckart *et al.* 2017).

There are many technical solutions for stormwater source control. The principles implemented are multiple and derive from different points of view: hydrological, environmental, ecological, urbanistic, etc. (Flanagan *et al.* 2019; Wang *et al.* 2020). Experimental studies conducted at the scale of single SCM have confirmed the 'multi-component' advantages of these devices (Golden & Hoghooghi 2018). Nevertheless, the cumulative effect of SCMs at the scale of a neighborhood or even of a city remains rather poorly understood at the present time (Jefferson *et al.* 2017; Golden & Hoghooghi 2018). Numerical modeling is needed for such investigations since it enables the virtual testing of different configurations through what is commonly called scenario analysis (Jefferson *et al.* 2017; Cortinovis *et al.* 2022). However, modeled SCM deployment scenarios generally consider a limited number of SCM facilities that are replicated at the catchment scale (Massoudieh *et al.* 2017; Cortinovis *et al.* 2022). Yet, at an urban scale, a great diversity of SCM techniques is likely to be used, implemented in parallel or in series (Lashford *et al.* 2020).

This great diversity results in very different configurations, depending on the local context: an SCM can be exfiltrating or impermeable, with regulated outflow or uncontrolled overflow, with or without retention, detention above or below ground. However, the names of the SCMs (swale, bioretention cell, and permeable pavement) only partially reflect this variety of configurations. Thus, to our knowledge, there is no reference system that exhaustively covers all SCMs in all configurations that can be envisaged. Consequently, no hydrological model, to date, is able to represent all these configurations. For example, the stormwater management model (SWMM) (Rossman 2015), even though it has a modeling module of eight SCM techniques, none of them can model runoff flow regulation at the SCM surface. This might be done with a storage unit; however, storage units do not allow us to represent a layer of vegetated soil above an impervious lining, nor is that possible for the vegetative swale model.

The development of a model able to represent a large diversity of SCMs at the urban scale thus requires a suitable typology able to represent quasi exhaustively the different techniques. This typology could be based on generic classes described by a limited number of criteria. While several approaches have been proposed to classify SCM techniques (e.g. Fletcher *et al.* 2013; Askarizadeh *et al.* 2015; Chocat *et al.* 2022), there is currently no typology that covers all these techniques and that is adequate for modeling different SCMs at large spatial scales. Moreover, the current terminology is sometimes ambiguous, with the use of various terms to designate the same category of SCMs – e.g. bioretention, raingarden, biofiltration (Chocat *et al.* 2022), or on the contrary the use of the same term (e.g. swale) to designate SCMs which may, however, correspond quite different modes of design (e.g. swale with or without check dams, with or without flow regulation, with or without filtration media) and therefore different stormwater management objectives (Sage 2016).

In this article, we first analyze the different criteria used for the classification of SCM techniques. Based on these criteria, a new comprehensive and functional SCM typology is then proposed. Finally, a conceptualization of hydrological and reactive processes (for pollutant removal) is developed for hydrological and water quality modeling purposes.

2. USUAL CRITERIA FOR CLASSIFYING SCMS CITED IN THE LITERATURE

2.1. Urban planning criteria

The analysis of different stormwater technical guides (e.g. CDEP 2004; MDDEP 2012; Ballard *et al.* 2015) and scientific papers (e.g. Dierkes *et al.* 2015; Romnée 2015; McPhillips & Matsler 2018) allowed us to identify criteria based on urban planning related to the location of the SCM, the characteristics of the urban environment or the landscape value of the SCM:

- The 'location' criterion is proposed to determine the possibilities of maintenance and operation. It allows first of all to distinguish the SCMs implanted in the public domain from those in the private domain. It also takes into account the location and nature of the space mobilized (e.g. SCMs on top of, within, or under a building; on top of or under a landscaped area, on top of or under an open space).
- The 'land use' criterion allows the choice of the type of SCM to be implemented based on the type and characteristics of the urban environment. First, it classifies the SCMs according to the type of land use, distinguishing between dense city centers, residential areas, business areas, roads and parking lots, squares and forecourts, parks and gardens, and open-air playgrounds. It also takes into account the physical characteristics of the urban environment such as topography, soil type, soil infiltration capacity, and the presence of green spaces and water bodies.
- The 'landscape' criterion takes into account whether water is visible or not and whether the SCMs are vegetated or not. It allows the classification of SCMs according to the way it is implemented (open air with a permanent water body, open air without a permanent water body, underground) and the modality of vegetation (totally, partially, or not vegetated).

While relevant for urban planners and developers, these SCM typologies are not adapted to hydrological modeling purposes as the associated hydrological functions of SCMs are not all explicitly taken into account.

2.2. Hydrological design function criteria

In general, a stormwater management system must address multiple objectives (Flanagan *et al.* 2019; Wang *et al.* 2020). Those objectives are associated with the management of different parts of the local precipitation spectrum – from very frequent up to very rare events (MPCA 2008; Rivard 2010) and are expressed in regulatory documents via different hydrologic design criteria (Fassman *et al.* 2013; Sage *et al.* 2015).

Water resource preservation and protection of aquatic ecosystems are stormwater management objectives that will be achieved via groundwater recharge, stormwater harvesting, pollutant load control, and local water balance restoration. They require management of the everyday rain events (Rivard 2010; Petrucci *et al.* 2013), which represent an important part of the annual runoff volume. In North America (i.e. Canada and the United States), these objectives are referred to as 'small storm hydrology' (Pitt 1999), and associated with the management of relatively small rainfall depths, often defined as the 80th–90th percentile of rain depth or as the rain depth allowing an interception of 80% of the annual runoff volume (Fassman *et al.* 2013; Sage *et al.* 2015). In the case of Montreal, for instance, refer Rivard (2010), Table 1 suggests target rain depths of less than 22 mm. In France, four levels of services are targeted for urban stormwater management, delimited by the return period of precipitation (CERTU 2003; Table 1). Pollution control and local water balance correspond to the first level and are associated with rain events with a return period of less than 1 month to less than 2 years depending on local regulations. To achieve the 'small storm' management objectives a SCM design criteria based

Table 1 | Hydrological design functions associated to different precipitation categories used in two different countries/cities of the world

Region/ Country	Precipitation category		Management issues	Reference
Montreal	Precipitation depth (mm)	0–10 (very frequent)	Groundwater recharge management (infiltration control)	Rivard (2010)
		14–22 (common)	Water quality management (pollution control)	
		22–32 (heavy)	Watercourse erosion control	
		>32 (exceptional)	Quantity control (flooding/surcharge)	
France	Precipitation returns period* (years)	<1 month to <2 years (low precipitation)	Pollution and local water balance control	CERTU (2003)
		<1–10 years (medium)	Runoff control	
		10–50 years (heavy)	Flood control	
		>50 years (exceptional)	Flood management	

*Return period depends on the local authority.

on volume (or rain depth) is usually given in the regulatory framework (Sage *et al.* 2015). It can be defined as a 'treatment volume', i.e. volume to be intercepted in the SCM and depolluted, if the only function targeted is pollution control. But a more robust criterion, allowing us to meet a wider range of targeted hydrologic functions, is the 'volume reduction' criteria, i.e. define a volume that has to be abstracted in SCMs (by infiltration, evapotranspiration, or water use) without any discharge to sewer systems or surface waters.

On the other hand, as can be seen in Table 1, watercourse erosion control and flooding/surcharge control objectives target heavy to exceptional rain events. For these events, stormwater management design criteria based on 'flow rate limitation', i.e. limitation of stormwater discharges, have been of very common application all over Europe and America in the last decades in order to control peak flows in sewer systems and receiving water bodies. SCMs that aim at meeting flow rate limitations mainly rely on temporary detention systems.

Several authors introduced classifications of SCMs based on their hydrological functions. Fletcher *et al.* (2013) classified stormwater management technologies into two groups: infiltration-based technologies that restore subsurface and groundwater flows and retention-based technologies which included both detention systems that regulate the flow and abstraction systems based on either evapotranspiration or water usage, that reduce runoff volume. Askarizadeh *et al.* (2015) classified SCMs, other than those that work only on storage and attenuation (detention systems were not considered in this work), into three hydrological functions groups: infiltration, harvesting, and hybrids (which fulfill both infiltration and harvesting). Chocat *et al.* (2022) classified SCM techniques into three groups: (i) retention systems that allow for runoff volume reduction based on either water usage, infiltration, or evapotranspiration; (ii) detention systems that regulate stormwater flow based on temporary storage in facilities equipped at their outlet with flow limitations or flow regulation devices; and (iii) transportation systems like swales. This typology adds missing functions to those proposed by Fletcher *et al.* (2013) and Askarizadeh *et al.* (2015).

Unlike typologies based on urban planning, these typologies do take into account the main hydrological function of SCMs. However, they have been developed more for decision-making support in stormwater management than for modeling SCMs at the urban scale. Moreover, a typology based only on main hydrological functions does not allow us to differentiate between SCMs with different structures (vegetated/mineral, open air/underground storage) that can involve other non-negligible secondary hydrological functions (evapotranspiration for instance).

2.3. Classification of SCMs based on their structure

The design of SCMs depends on the management objective to which they are associated but also on development constraints related to their integration into the urban environment. Based on an in-depth analysis of various stormwater technical guides, Sage (2016) proposed a typology of solutions based on three criteria: mode of runoff supply, mode of storage, and mode of discharge.

Two categories of supply modes are possible: localized supply (corresponding, for example, to a piped inflow) and diffuse supply, which can correspond to direct incident rainfall (on a permeable pavement for instance), superficial runoff inflow directly from adjacent surfaces or via a grassed strip, or underground inflow via a diffusion drain. Storage of captured runoff volumes can be at the surface or underground. Sage (2016) focused in his work on the case of SCMs allowing for runoff retention on vegetated soils, in which case the underground storage is a storage in porous media which can be a soil or a gravel layer. He did not develop the case of void underground structures, like tanks or ultra-lightweight honeycomb structures, which are of widespread use, be it for runoff recovery, detention, or storage before exfiltration. Furthermore, in the case of porous material, no exhaustive differentiation is made between cohesive materials (where free and capillary water flux coexist) and non-cohesive materials (only free water).

The method of evacuation is essentially determined by the hydrologic function assigned to the SCMs but also by the type of storage used. It can be done above or below ground. In both cases, it is possible to distinguish between discharge modes that result in water abstraction (infiltration and evapotranspiration or water usage) and those that only constitute a downstream discharge (overflow or regulated outflow, underground drain connected to the sewer).

3. PROPOSAL OF A NEW TYPOLOGY OF SCMS

As noticed, there is currently no SCM typology describing in a generic form the diversity of SCMs and suitable for SCMs modeling. Thus, a new typology is proposed here, based on the different criteria analyzed in the preceding section, namely the hydrological criteria, hereafter referred to as **main SCMs' hydrological assured functions**, and a structure-based criterion, hereafter referred to as **SCMs' structure type.** The structure-based criteria are refined so as to describe the different physical compartments of the SCM that have an incidence on hydrological processes**.**

3.1. Main SCMs' hydrological assured functions

For the construction of the typology, three main hydrological assured functions have been taken into account: runoff volume reduction (V), runoff flow rate regulation (F), and runoff transport (T).

3.1.1. Runoff volume reduction (V)

SCMs that are specifically designed to meet runoff volume reduction can rely on **evapotranspiration** (V_{EV})**, exfiltration to the underground** (V_{EX}), or **rainwater harvesting** (V_{RH})**.** Temporary storage of the targeted runoff volume inside the SCMs is generally needed before its complete evapotranspiration, exfiltration, or reuse.

The term 'exfiltration' is used here to designate water flow from the SCMs (surface or underground storage volume) to the natural surrounding soil. Therefore, it is distinct from 'infiltration' which is used to designate a water flow from the surface into the structure of the SCMs. The hydraulic conductivity of the natural soil is a key factor when exfiltration is an assured hydrological function of SCMs.

Evapotranspiration (i.e. evaporation from plants and land surface plus transpiration from plants) is an important post-storm element of the water cycle and plays a major role in the performance of vegetated SCMs (Ballard *et al.* 2015; Ebrahimian *et al.* 2019). After a rain event, evapotranspiration reduces soil moisture, restoring the soil's natural storage capacity and thus allowing runoff to infiltrate during the next rain event. The evapotranspiration process continues during the non-rainfall period as long as sufficient water is available (Berland *et al.* 2017) which can be beneficial for thermal comfort (Santamouris 2014). The process of evapotranspiration becomes the main hydrologic function when the SCMs are completely waterproof (without exfiltration processes), such SCMs primarily retain water in their soil substrate and evapotranspirate it over time.

Runoff from roofs can be collected in barrels, tanks or cisterns and used for outdoor uses (watering, irrigation) and for indoor uses (non-drinking water supply for toilets, with separate internal network, laundry) (Ballard *et al.* 2015). The collected water storage compartment can be located either at the surface and/or underground level (Ballard *et al.* 2015). An overflow will eventually allow larger flows to be properly evacuated.

3.1.2. Runoff flow rate regulation (F)

Runoff exfiltration into the natural soil is usually targeted in the conception of SCMs since it could more accurately mimic the natural hydrological cycle (Bhaskar *et al.* 2018; Zhang *et al.* 2020). However, the possibilities of using exfiltration may be limited by many factors, the most important of which is the hydraulic conductivity of the soil where the SCMs will be placed (MDDEP 2012; Ballard *et al.* 2015). Other factors, such as geotechnical or topographical constraints, distance to groundwater table, high level of soil contamination, can make the exfiltration process into the natural soil difficult. For these reasons, in addition to or instead of the exfiltration process in the SCMs' storage compartment, a flow-regulated outlet can be implemented to evacuate the runoff into an existing sewer network (MDDEP 2012; Ballard *et al.* 2015). SCMs intercept runoff, then a fraction of this water volume may return to the sewer network while the other fraction may return to the natural soil. It may also happen that all runoff is evacuated to the sewer network. This hydrological function can be divided into two sub-categories:

- Flow regulation and exfiltration (F_{RE}): such SCMs allow for both exfiltration of a part of the runoff and flow regulation of excess waters, including heavy rain events. They thus target both flood control objectives for heavy rains and runoff volume reduction of frequent rain. The relative fraction of exfiltration can be very variable depending on the structure of the SCM, its design and the underground conditions.
- Flow regulation only (F_{RG}): such SCMs are completely waterproof, consequently runoff cannot be exfiltrated into the natural soil, and the most part (or all) of the runoff is discharged to the stormwater network. Some minor volume reduction may however take place through evaporation or evapotranspiration, especially when the waterproof lining of the storage facility is covered with a vegetated soil layer.

3.1.3. Runoff transport (T)

The representative SCM of this assured hydrological function is the transport swale or the ditch. Transport swales are broad, shallow, linear vegetated channels which can transport runoff surface water toward an outlet, or convey it to another SCM. While transport is the primary function targeted here, the transport swale can also be designed to enhance runoff rate reduction and volume reduction (Davis *et al.* 2012; Charlesworth *et al.* 2016) as well as pollutant removal (Davis *et al.* 2012; Ballard *et al.* 2015).

3.2. SCMs' structure type

The second criterion that we have taken into account for the construction of this new typology is the SCMs structure type, i.e. the physical compartments in the SCMs where the runoff volume (collected by the SCMs) is handled. The SCM's structure is important as it determines which will be the processes taking place in the technique (hydrological, hydroclimatic, and reactive processes in the case of pollutants). For example, SCMs with no water retention on the surface or inside a substrate do not allow for evapotranspiration. Another example is if the water retained on the SCMs surface percolates through a substrate, the dominant (reactive) SCM processes will be filtration and adsorption of pollutants. In this regard, this criterion can be divided into two subgroups: **Open-air structure type** (*O*) and **Underground structure type** (*U*).

3.2.1. Open-air structure type (*O*)

SCMs often present an open-air water storage compartment at their surface that allows for temporary storage until the runoff is either evacuated at regulated flow to superficial outlet or infiltrated into the underlying substrate layers. An overflow structure or a bypass may be present to evacuate excess runoff (Lisenbee *et al.* 2021). The surface level often consists of vegetated spaces integrated into the urban environment; however, it may also consist in impervious depressions (concrete, cobblestone). Beyond the obvious landscape interest, the presence of vegetation has a positive influence on the hydrological and water quality performances of the SCMs (Zhang *et al.* 2020). We can distinguish between two types of open-air structures: those that involve water flow percolation through one or several pervious engineered substrates (O_{PE}) and those where the runoff is handled on the topsoil (O_{SU}).

In the case of **open-air structure with percolation through a substrate** (O_{PE}) the whole stored runoff volume will be infiltrated into the underlying substrate layer. The substrate is a layer of engineered soil, which allows efficient infiltration but also provides the necessary green water storage (Falkenmark & Rockström 2006) needed to support the vegetation. It can also be designed for pollution control (Ali & Pickering 2023). Percolation water can be evacuated by exfiltration to the surrounding ground or/and by an underdrain. A supplementary internal water storage (IWS) layer may be present under the substrate compartment. This layer is needed when the exfiltration or drainage rate is lower than the percolation rate. It can also be implemented to support vegetation during dry periods or to create anaerobic conditions favorable to nitrogen removal (Brown & Hunt 2011; Lisenbee *et al.* 2021).

In the case of **open-air structure with a superficial runoff management** (O_{SU}), most of the runoff volume is evacuated superficially. Part of the stored runoff may be infiltrated, but unlike the previous subgroup, this will occur directly on the natural topsoil and not on a modified infiltration substrate and as long as the soil permeability and groundwater recharge conditions of the site allow it (MDDEP 2012; Ballard *et al.* 2015).

3.2.2. Underground structure type (*U*)

In this case the SCMs' structure is located underground. It consists in a storage/drainage compartment that allows for temporary storage until the runoff volume is either exfiltrated to the natural underground, or evacuated at limited flow to a sewer network, or both.

This type of structure can be divided into two subgroups according to how the runoff is supplied to the storage compartment. Runoff can be supplied to the underground storage facility through a **permeable mineral surface** (U_{PP}). In this case water retention and evaporation as well as pollution/depollution processes (filtration, adsorption or on the contrary contamination by lixiviation of the permeable material) have to be considered (Tziampou *et al.* 2020; Yu *et al.* 2021). The importance of these processes depends on the nature and thickness of the permeable mineral surface layer. This permeable mineral surface can be made with a permeable surfacing material such as porous asphalt, pervious concrete, or with non-permeable blocks with spaces allowing the water to flow in between such as permeable interlocking concrete pavement or grid paver systems (Tziampou *et al.* 2020).

The surface of the SCMs can also be totally impermeable. In this case the storage compartment is **supplied by pipes** (U_{PI}) and the SCM does not have any interactions with the atmosphere.

3.3. Combining the two main classification criteria of SCMs

The combination of these two classification criteria, i.e. (1) main hydrological assured functions and (2) SCM structure type, in a cross table allows us to classify all SCMs into 16 groups (Figure 1) which are described in the following.

3.3.1. Runoff reduction via evapotranspiration in open-air SCMs based on percolation through a substrate ($V_{EV} \times O_{PE}$)

This group contains green roofs (intensive, semi-intensive, and extensive, Vijayaraghavan 2016), green walls (Manso & Castro-Gomes 2015), and planter boxes, as well as some types of vegetated parking lots (Varnède 2020). In this group, most of the rainwater will be stored in the vegetation and substrate compartments, to be later evacuated mostly by evapotranspiration. The excess rainwater fraction will be evacuated by the drainage compartment and possibly by an overflow. A supplementary storage layer can be implemented under the substrate layer so as to create a water reserve for the plants. There may or not be a temporary water storage layer at the top for this SCM. For techniques in this category the bottom is either impervious (lined or implemented on a slab) or shows very low permeability (e.g. compacted clay soil beneath a vegetated parking lot structure) so that exfiltration is negligible.

3.3.2. Runoff reduction via exfiltration in open-air SCMs based on percolation through a substrate ($V_{EX} \times O_{PE}$)

This group contains all SCMs that function as non-lined bioretention systems, for instance, rain gardens, tree box filters, bioswale, and biofilters (MPCA 2008), as well as infiltration basins and infiltration swales. A part of the runoff will be intercepted by the vegetation, most of the runoff volume is infiltrated through a substrate compartment, with (e.g. bioretention cells, bioswales, infiltration basin) or without (e.g. vegetated parking lots) prior storage at the surface and is finally exfiltrated into the deep natural soil. The substrate compartment may consist of a specifically engineered substrate (for depollution purposes for instance, Ali & Pickering 2023), or a topsoil

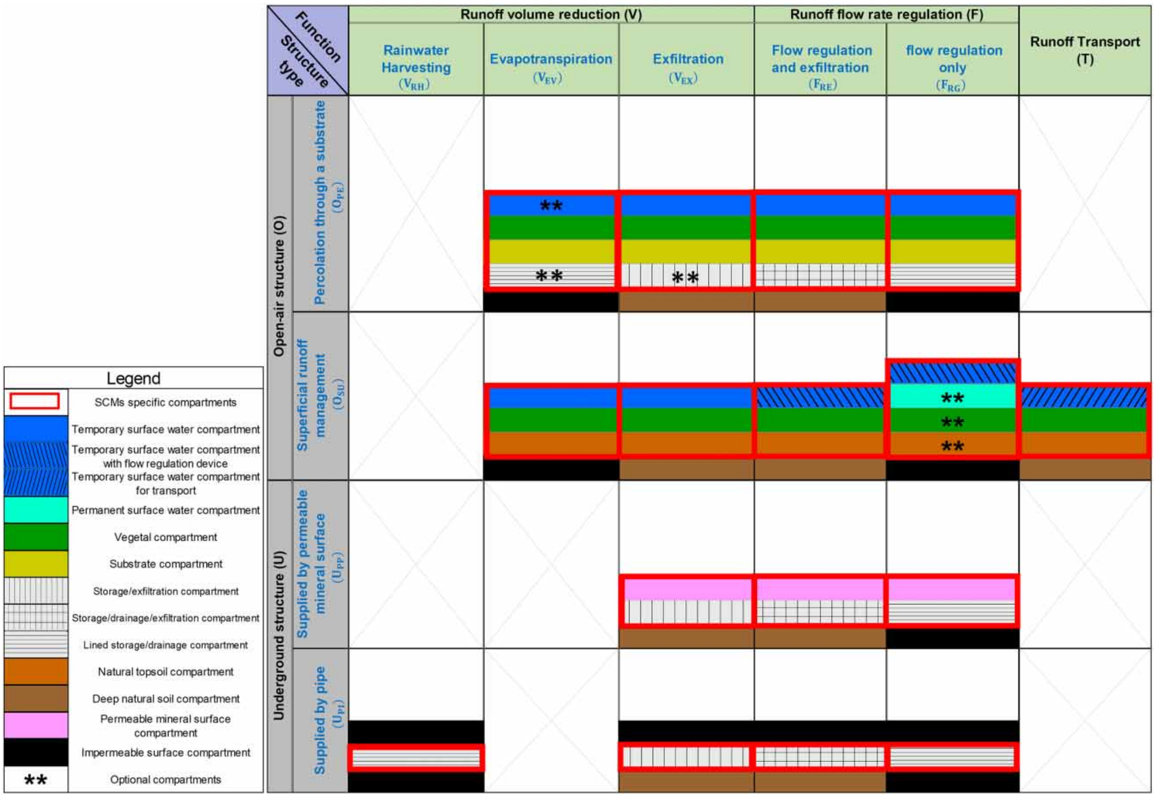


Figure 1 | Cross-table between the two main criteria used to create a functional typology for SCMs. The compartments inside the red box are those that belong to the SCMs and participate directly in runoff mitigation. The compartments outside the red box are complementary for better referencing of the SCMs. Please check and confirm this is correct. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/bgs.2023.026.

layer implemented for planting purposes or even the natural topsoil layer formed over time. The underground storage compartment is optional and will be used if the soil is not sufficiently permeable in order to improve exfiltration performance (MDDEP 2012). Though these techniques also allow for temporary water storage in the substrate and it is later evapotranspirated, exfiltration is here the dominant outflow pass way. In this, SCMs' group evapotranspiration is limited by the quantity of the water that can be stored through field capacity in the soil layer. While evapotranspiration is usually not the dominant flux for this type, it can still be significant and should be taken into account in continuous hydrological simulation.

3.3.3. Runoff flow regulation and exfiltration in open-air SCMs based on percolation through a substrate ($F_{RE} \times O_{PE}$)

In this case, only a fraction of runoff collected by the SCMs can be exfiltrated to the natural soil, therefore a drainage compartment will be incorporated into the SCMs' structure to evacuate the rest of the runoff volume to the sewer network. Depending on where the evacuation drain is located (e.g. in the middle of the storage compartment), an IWS zone may also be available (Lisenbee *et al.* 2021).

3.3.4. Runoff flow regulation in open-air SCMs based on percolation through a substrate ($F_{RG} \times O_{PE}$)

This group typically contains all SCMs that function as lined bioretention systems (e.g. stormwater planters, reed bed filters, MPCA 2008) where the percolation water is collected into an underdrain and discharged at a regulated flow to surface waters (usually via a storm sewer). In this case, the runoff captured by the SCMs cannot be exfiltrated to the natural soil, part of the runoff is retained in the substrate and later on evapotranspirated, however, restitution is the dominant outlet, especially for heavier rain events and during the winter period when transpiration is limited. Flow limitation can be achieved naturally through the permeability of the substrate and/or through a flow control device.

3.3.5. Runoff reduction via evapotranspiration in open-air SCMs with superficial runoff management ($V_{EV} \times O_{SU}$)

Unlike $V_{EX} \times O_{PE}$, in this group water percolation through the lined porous media is limited by the absence of an underdrain. Some part of the rainwater/runoff will be stored in vegetation and soil compartments, and possibly also at the surface, to be later evacuated by evapotranspiration. While not very common, wet swales can be considered here, and some configurations of small detention ponds or non-drained planter boxes.

3.3.6. Runoff reduction via exfiltration in open-air SCMs with superficial runoff management ($V_{EX} \times O_{SU}$)

This group corresponds to SCMs that evacuate runoff by infiltration into open ground. Hydrologic functioning is relatively similar to $V_{EX} \times O_{PE}$ but the subsurface compartment does not have an underground storage compartment and thus no capillary rupture between the top substrate layer and the underground. Runoff mitigation is achieved through the combined work of the SCMs' surface and the natural soil where it is placed. We can consider in this group (among others) SCMs such as simple rain gardens and infiltration basins.

3.3.7. Runoff flow regulation and exfiltration in open-air SCMs with superficial runoff management ($F_{RE} \times O_{SU}$)

This group corresponds to various types of detention techniques implemented on vegetated ground (e.g. detention basins, detention swales). Runoff is stored at the surface compartment of the SCMs. A major part of this volume is evacuated at regulated flow to the sewer network, and the rest is infiltrated into the natural topsoil.

3.3.8. Runoff flow regulation in open-air SCMs with superficial runoff management ($F_{RG} \times O_{SU}$)

This group contains various types of lined detention techniques (retention ponds, impervious detention basins, rooftop detention, lined storage swales, surface flow constructed wetlands, sedimentation basins). The impervious lining can be visible or covered with a small layer on vegetated soil. Runoff will be stored in the open-air surface compartment of the SCMs. All or most part of the runoff is evacuated at regulated flow to the sewer network. Part of it can remain permanently at the surface of the SCMs in the case of wet ponds. Some retention in the topsoil and later on evapotranspiration is possible when the impervious layer is covered with topsoil.

3.3.9. Runoff transportation in open-air SCM with superficial runoff management ($T \times O_{SU}$)

This group contains SCMs that allow for open-air collection and transportation of runoff, such as transport swales and vegetated ditches (Davis *et al.* 2012; Ballard *et al.* 2015). Runoff is collected at the surface compartment and transported downstream. If possible, a part of the runoff will be infiltrated through the superficial natural soil. These techniques can be used to convey runoff to another SCM or to evacuate runoff for extreme rainfalls that exceed on-site management targets.

3.3.10. Runoff reduction via exfiltration in underground SCMs supplied by permeable surface ($V_{EX} \times U_{PP}$)

In this SCMs group incident rainfall and potential runoff from adjacent surfaces is infiltrated through non-vegetated permeable surfaces. It can be momentarily stored in an underground storage compartment (porous media or granular media or ultralight alveolar structure), and finally exfiltrated into the natural surrounding soil. Though some runoff losses can be attributed to water retention on the permeable layer and later to evaporation, the exfiltration flux remains the main one. Vegetated permeable pavement which does enhance evapotranspiration fluxes is not considered here but, in the group, $V_{EX} \times O_{PE}$. The $V_{EX} \times U_{PP}$ group encompasses different types of permeable pavements but also infiltration trenches.

3.3.11. Runoff exfiltration and flow regulation in underground SCMs supplied by permeable surface ($F_{RE} \times U_{PP}$)

SCMs in this group are similar in structure to $V_{EX} \times U_{PP}$, however, in this case not all of the runoff collected by the SCMs can be exfiltrated to the natural soil. Therefore, part of the storage compartment becomes also a drainage compartment to evacuate the remaining fraction of the runoff at regulated flow to the sewer network.

3.3.12. Flow regulation in underground SCMs supplied by permeable surface ($F_{RG} \times U_{PP}$)

SCMs in this group are similar in structure to $V_{EX} \times U_{PP}$ and $F_{RE} \times U_{PP}$, but in this case the storage compartment is totally waterproof, exfiltration is completely prevented and the whole runoff volume is evacuated at a regulated flow to the sewer network.

3.3.13. Runoff reduction via rainwater harvesting ($V_{RH} \times U_{PI}$)

This group corresponds to various types of rainwater harvesting systems: rainwater barrels, rainwater tanks and cisterns, that store rainwater coming from the roofs (Ballard *et al.* 2015) or from other impervious surfaces. These SCMs were assimilated to 'underground' techniques even if the storage tank can be implemented outside, as the water is managed in a closed compartment that does not allow exchanges with the atmosphere.

3.3.14. Runoff reduction via exfiltration from an underground SCM supplied by pipe ($V_{EX} \times U_{PI}$)

SCMs from this group store the water temporarily in underground reservoir structures supplied by storm pipes or street gullies, before exfiltrating it to the surrounding natural soil. It covers for instance underground infiltration tanks, infiltration wells and soakaways (Ballard *et al.* 2015).

3.3.15. Runoff exfiltration and flow regulation in underground SCMs supplied by pipe ($F_{RE} \times U_{PI}$)

SCMs in this group are similar in structure to $V_{EX} \times U_{PI}$; however, in this case not all the runoff collected by the SCMs can be exfiltrated to the natural ground. Therefore, part of the storage compartment becomes also a drainage compartment to evacuate the remaining fraction of the runoff at regulated flow to the sewer network.

3.3.16. Flow regulation in underground SCMs supplied by pipe ($F_{RG} \times U_{PI}$)

SCMs in this group are similar in structure to $V_{EX} \times U_{PI}$ and $F_{RE} \times U_{PI}$ but in this case the storage compartment is totally waterproof, exfiltration is completely prevented and the whole runoff volume is evacuated at a regulated flow to the sewer network.

4. USE OF SCMS TYPOLOGY FOR HYDROLOGICAL AND REACTIVE PROCESSES MODELING

Thanks to the typology developed (Figure 1), 16 groups have been identified that adequately assemble different SCM techniques according to their main hydrological functions and structure types. They make it possible to develop an adequate conceptualization of the different hydrological and reactive processes (biological and physico-chemical, for water quality improvement).

For conceptualization, the simplest approach has been used: reservoirs. Four types of reservoirs are identified in the typology (in relation to the compartments of the SCMs):

- Interception (IP)
- Free water at the surface (FWS)

- Water in the topsoil/substrate (free and capillary water)
- Free water in the underground storage (FWU).

Through this approach, we can observe that many SCMs can be represented by the same type of conceptualization, which we have denominated as **process modeling class**. Five classes were then identified in the typology (Figure 2):

1. **Class** $VF \times O_{PE}$: that assembles all SCM groups of *open-air structure with percolation through a substrate* (O_{PE}) structure type.
2. **Class** $VF \times O_{SU}$: that assembles the SCM groups $V_{EV} \times O_{SU}$, $V_{EX} \times O_{SU}$, $F_{RE} \times O_{SU}$, and $F_{RG} \times O_{SU}$ where runoff management can be managed at the surface of the SCM.
3. **Class** $T \times O_{SU}$**:** only for the SCM group $T \times O_{SU}$, characterized by the transport of water.
4. **Class** VF $\times$ U_{PP}**:** that assembles all SCM groups supplied *by permeable mineral surface* structure type.
5. **Class** VF $\times$ U_{PI}**:** that assembles all SCM groups supplied *by pipe* structure type.

In this paper, **the first class** (VF $\times$ O_{PE}) is explained in detail (Figure 3) as it is the most complex class with almost all the reservoirs. The conceptualization of the other four classes is provided in the supplementary material section and only the hydrologic and reactive processes that are specific to these classes will be briefly discussed here. In the case of the reactive processes, the materials in the SCM compartments play a significant role. Then, a combination of water reservoirs and textures of the materials has been used for the water quality conceptualization (Figure 3). All the different acronyms used in the conceptualization (Figure 3) of the first class are described in Figure 4.

4.1. Conceptualization of hydrological processes of the VF $\times$ O_{PE} class (Figure 3)

The SCM can be fed by direct precipitation (P) and by runoff (direct or piped) from upstream surfaces connected to the SCM (Q_{in}). The SCM can also be fed indirectly, for example through runoff from another SCM. All these types of water inflow can be managed through the adequate parameterization of the surface reservoirs (i.e. IP and

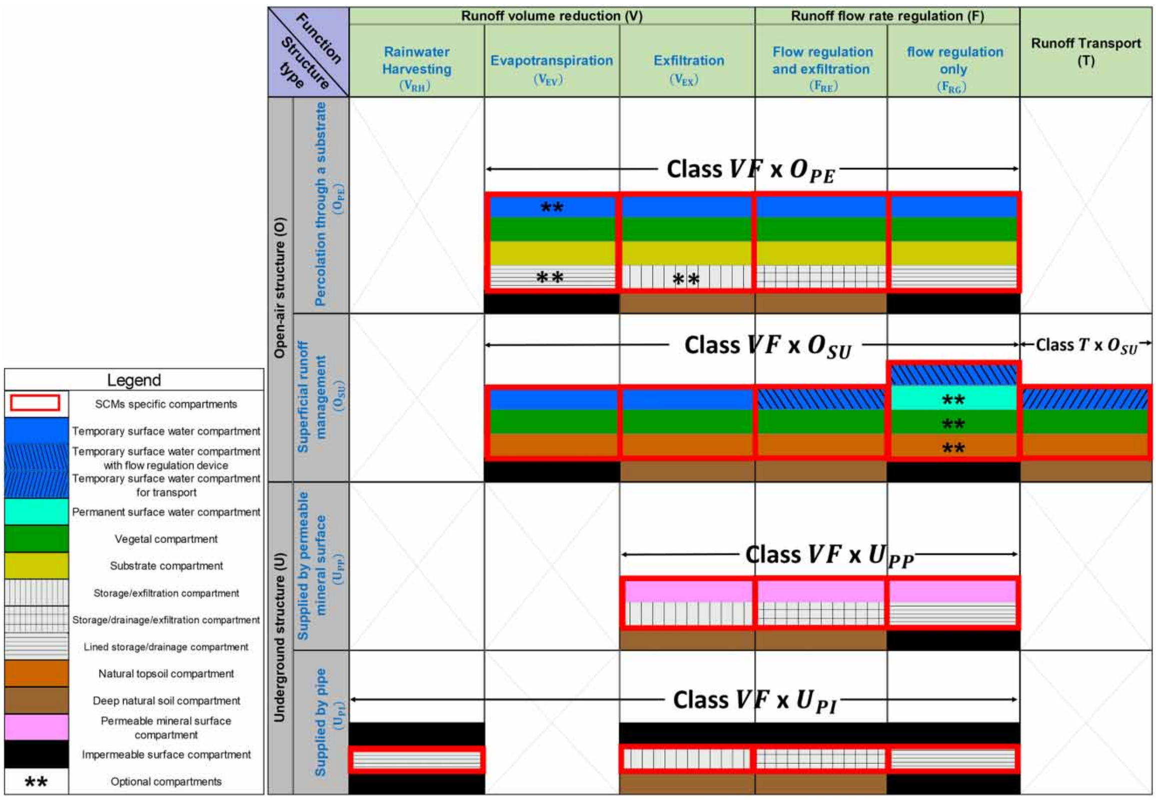


Figure 2 | Classes that can be formed for a synthesized representation of the conceptualization of hydrologic and reactive processes of the SCM groups of the typology.

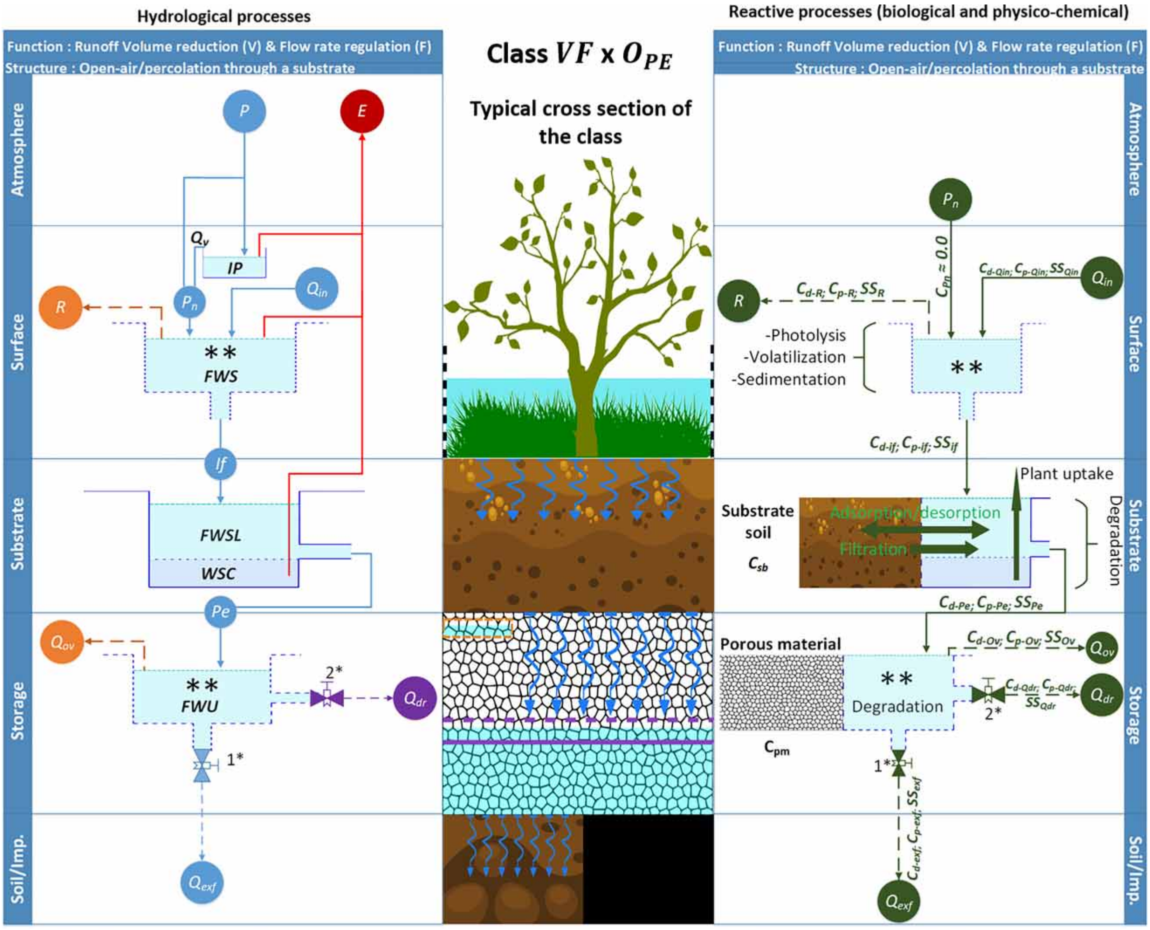


Figure 3 | Conceptualization of hydrological and biological and physico-chemical processes of the VF $\times$ O_{PE} class. The two asterisks (and thus the reservoirs drawn with dashed lines) indicate that the reservoir may be optional (based on the SCM compartments in Figure 2).

FWS). The precipitation is partially intercepted by vegetation. The intercepted water remains on the vegetation until it evaporates or flows to the surface reservoir when the maximal capacity of the interception reservoir is exceeded (Xiao *et al.* 2007). This is represented by the interception reservoir (IP).

The surface reservoir (FWS) receives two inflows: net precipitation (P_n) which is the sum of the non-intercepted precipitation (P) and the overflow (Q_v), and the incident runoff (Q_{in}). They are momentarily stored before being infiltrated (If) through the substrate or evaporated (E). Runoff (R) occurs when the water level stored in the surface reservoir exceeds its maximal capacity (Rossman 2015; Lisenbee *et al.* 2021). The runoff produced in the SCM can be connected to another SCM for further management.

Water infiltration (If) penetrates the SCMs' substrate compartment. In this compartment the water flow can be conceptualized through a reservoir with two compartments: one to represent the percolation processes between the different SCM soil layers (FWSL), and the other to represent capillary water retention in the substrate (WSC). It is considered that WSC has to be completely filled before percolation happens. WSC reservoir can only be emptied by evapotranspiration fluxes (E), while the FWSL reservoir empties with a flux (Pe) that is controlled either by the substrate permeability or by the surrounding natural soil permeability. Substrate water percolation (Pe) can then be handled under two scenarios:

1. The SCM substrate compartment is in direct contact with the natural soil (SCMs from group $V_{\text{EV}} \times O_{\text{PE}}$ in Figure 1) thus there is no storage reservoir. The water percolation becomes water exfiltration from the SCM substrate to the natural soil ($Q_{\text{exf}} = \text{Pe}$) and is controlled by the lowest value between substrate permeability and natural soil permeability.
2. A storage compartment is located below the SCM substrate compartment, thus the storage compartment can be modeled as a reservoir (FWU) whose water level can be obtained through a water balance equation

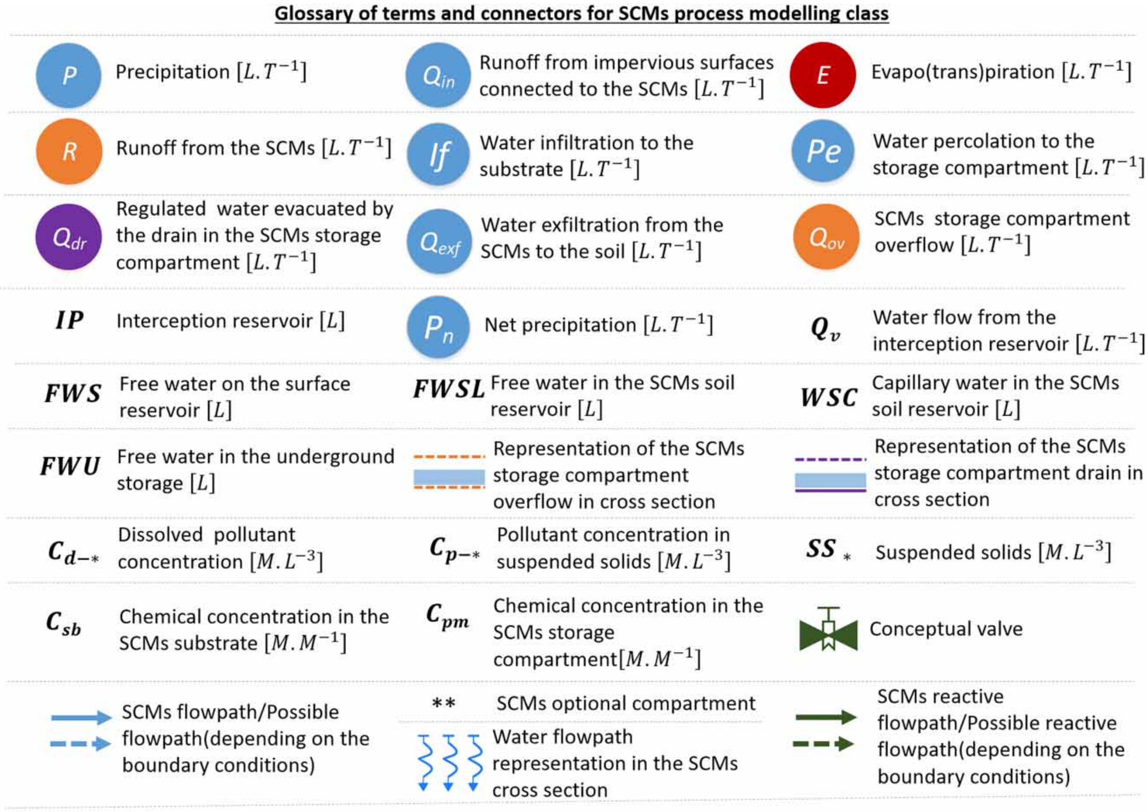


Figure 4 | Glossary of terms and connectors appearing in the process modeling class VF × O_{PE} (i.e. Figure 3).

between the inflow, which here is the substrate water percolation (Pe) and the potential outflows as the water exfiltration (Q_{exf}), the water evacuated by a regulated flow drain (Q_{dr}) connected to the sewer network or other SCM and the overflow (Q_{ov}) when Q_{exf} and/or Q_{dr} are not enough to discharge the water stored in the FWU reservoir. The evapotranspiration can be neglected because the storage compartment is not directly exposed to the atmosphere and the roots of the plants theoretically do not reach this compartment (Lee *et al.* 2015).

The SCM hydrological conceptualization proposed allows us to simultaneously represent the hydrological functioning of the storage compartment of the four SCM groups developed in the typology: $V_{EV} \times O_{PE}$, $V_{EX} \times O_{PE}$, $F_{RE} \times O_{PE}$, and $F_{RG} \times O_{PE}$ (Figure 1). These four SCM groups are differentiated in the storage compartment by the way the stored water is further treated: (i) only exfiltration process ($V_{EX} \times O_{PE}$, Figure 1) (ii) exfiltration process and evacuation of the stored water to the sewer network or other SCM via a regulated flow drain ($F_{RE} \times O_{PE}$, Figure 1), or (iii) only evacuation process of the stored water (waterproof storage compartment) to the sewer network or other SCM via a regulated flow drain ($V_{EV} \times O_{PE}$ and $F_{RG} \times O_{PE}$, Figure 1). These three processes described above can be represented through two conceptual open or closed valves placed in the storage compartment reservoir.

Finally, it is important to point out that the conceptualization proposed here for the hydrological processes is very similar to the one implemented in the well-known SWMM model (Rossman 2015) for SCMs of bioretention type.

4.2. Conceptualization of reactive processes of the VF × O_{PE} class (Figure 3)

Pollutant concentrations in each flux/reservoir are divided into dissolved concentrations of pollutants (C_{d-*}), as well as suspended solids (SS_*) and the pollutant content of suspended solids with their own concentration of pollutants (C_{p-*}).

At the surface level, the reactive processes of the vegetation (which could occur in the IP reservoir) are not considered. It is also assumed that the pollutants that could be found in net precipitation (P_n) are minimal (Müller *et al.* 2020), thus their inputs are not considered in the conceptualization. Consequently, only pollutants inputs from runoff (Q_{in}) of areas connected to the SCMs are considered. In the surface reservoir, which can be considered continuously mixed, a part of the pollutants can be removed by photolysis (i.e. using sunlight ultraviolet radiation), volatilization (i.e. conversion of an aqueous pollutant to gas) and sedimentation.

In contrast to the hydrological conceptualization, here the substrate is conceptualized by the combination of a water reservoir representing the interstitial water, divided in a free water reservoir and a capillary water reservoir considered to be continuously mixed together, and the solid part of the substrate (with a chemical concentration C_{sb}). The solid part interacts with the pollutants present in the water reservoir by physical filtration of particulate pollutants as well as sorption/desorption of dissolved pollutants (Ali & Pickering 2023). Some pollutants can also be removed through plant uptake (Turk *et al.* 2017), yet this process is usually limited compared to pollutant storage in the soil and takes place mainly in the root compartment (Seeger *et al.* 2011; da Costa *et al.* 2015; Dagenais *et al.* 2018). Dissolved pollutants present in the interstitial water reservoir are subject to biodegradation processes (Huber *et al.* 2006).

The storage compartment is represented by the combination of the non-cohesive porous solid part of the compartment (usually gravel) and a continuously stirred reservoir representing the free water circulating between the voids of the porous material. Assuming that the storage solid material is neutral (i.e. does not contain components that could contaminate the water percolation and has limited adsorption capacity), and that filterable suspended solids have already been removed by the substrate compartment, only the degradation process is considered a reactive process in this compartment.

As in the case of the hydrological conceptualization, the proposed reactive process conceptualization also represents processes and flow paths similar to those used in urban water quality models (e.g. MPiRe, Randelovic *et al.* 2016).

4.3. Conceptual hydrological and reactive processes specific to the other classes

In the case of the Class VF $\times$ O_{SU} hydrological conceptualization (Figure 6), the runoff flow regulation (Q_{rg}) is performed at the FWS reservoir (SCM surface). Also in this reservoir, a compartment has been included to represent the permanent water body (CWS) that can exist in the SCMs represented by this class.

In the hydrologic conceptualization of the Class $T \times O_{SU}$ (Figure 7), the longitudinal water transport (Q_{tr}) is the main runoff management process at the SCM surface.

In the Class VF $\times$ U_{PP} (Figure 8), precipitation (P) and runoff (Q_{in}) are intercepted and stored momentarily (IP) by the permeable mineral surface compartment. Then most of this water is percolated into the underground storage compartment, and the remaining part is evacuated by evaporation process (E). In the permeable mineral surface compartment, the reactive adsorption/degradation and filtration processes involved in the removal of pollutants from the runoff also take place.

For SCMs representing rainwater harvesting in the Class VF $\times$ U_{PI} (Figure 9), the water demand (D) for indoor and outdoor uses (Fewkes 2000) should be considered an outflow from the FWU reservoir.

For these classes as well, inflows can come from direct rainfall (P), runoff produced by impervious surfaces connected to the SCM, or produced by other SCMs (Q_{in}). In the case of outflows (i.e. regulated flow – Q_{rg}, Q_{dr} and overflow – Q_{ov}) these can be connected to the sewer network or to another SCM.

5. CONCLUSION AND PERSPECTIVES

A new generic SCM typology that describes the large diversity of these techniques is proposed for hydrological and water quality modeling purposes. This typology aims at an exhaustive representation of SCMs based on a limited number of criteria. Based on a state of the art, two main criteria have been selected: the hydrological function and the type of structure. Three main hydrological functions, associated with different management objectives and different rainfall categories, have been considered: runoff volume reduction, flow regulation and transport. Four types of SCM structures, leading to different hydrological processes, have been taken into account: open-air structure with percolation through a substrate, open-air structure with superficial runoff management, underground structure supplied by pipe, underground structure supplied by permeable surface. The hydrological and structure criteria are combined via a cross table, producing 16 generic groups of SCMs.

This typology, thus structured, identifies the different physical compartments corresponding to each group and takes into consideration the main hydrological processes driving the system. It thus facilitates the conceptualization of hydrological and reactive processes within and between these compartments, using a reservoir approach, widely used in many hydrological models. The development of the parameterization of the SCM in a hydrologic model is then possible.

The proposed typology and conceptualizations can facilitate the representation of different SCMs in urban stormwater models to study the hydrologic effects of the diffusion of different SCMs at the urban catchment scale. Current models generally represent only a limited number of SCMs – the application of this typology provides an opportunity to increase the number of modeled SCMs and thus aid in the accurate selection of SCMs for different stormwater management objectives.

However, the very first objective of the proposed typology is a pedagogical one. This typology allows us to get out of the confusions and possible misunderstandings linked to the imprecision of the current terminologies, where the same name (bioretention, swale) is often used to designate SCMs with various functions and concepts, thus responding to different hydrological objectives and different rainfall levels. It can support a clearer understanding of the hydrological differences between various SCM designs, which is crucial considering that development projects involving SCMs engage a diversity of urban stakeholders, some of whom are not completely familiar with urban hydrology. Sharing a common grid of analysis and a common vocabulary will facilitate discussions between the various stakeholders in a development project and facilitate appropriate SCM planning.

In the near future we expect the typology and conceptualization approach to serve as a decision-making tool for both researchers and stakeholders in the development of stormwater management scenarios at the urban catchment scale. To ensure that the typology can be used by urban stakeholders, it will be necessary to implement specific communication modes (technical sheets and explanatory talks) that explains in a simple way the functioning of the typology, its main benefits, and its possible limitations.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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