Survey of the operational status of twenty-six urban stormwater biofilter facilities in Sweden

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ABSTRACT

This study evaluates the operational status of twenty-six biofilter facilities across nine cities in Sweden, with respect to their functional design criteria, engineered design features (filter media composition, hydraulic conductivity, and drawdown time), and includes a visual inspection of the biofilter components (pre-treatment, in/outlet structures, filter media, and vegetation). These indicators were used to examine the performance level of each biofilter in achieving their design objectives set by the operators. Furthermore, it was investigated whether the biofilter facilities had been properly maintained to meet the objectives. Results indicate that the soil media used was consistent with respect to percentage sand, fines, and organic matter and comparable to design recommendations used by municipalities in other countries. The field-tested hydraulic conductivity for the biofilters ranged from 30 to 962 mm/h. This range of values, along with noticeable sediment accumulation within the biofilter indicate that not all the sites were operating optimally. Pre-treatment stages in poor condition with high volumes of sediment and litter accumulation were the primary causes for, and indicators of, low hydraulic conductivity rates. The ponding volume calculations revealed that at least 40 % of facilities did not have enough capacity to retain every-day and/or design rainfall due to design and/or construction flaws. These analyses raise concerns that, for a considerable number of the biofilters surveyed, water retention and flood protection identified by operators as prioritised objectives are not being met. This raises significant concerns about the functionality of biofilter in practice. Finally, some suggestions are given for tackling the design and maintenance problems discovered.

1. Introduction

Rapid urbanisation has led to an increase in the area of impervious surfaces, which has resulted in larger volumes of stormwater runoff to nearby aquatic waterbodies. Frequently, this runoff, by virtue of transporting any particle in its path, accumulates sediments as well as various contaminants (e.g. heavy metals, nutrients, organic pollutants, salt, pathogens) (Saberg et al., 2019). Untreated discharge of these pollutants can damage a waterbody such that biological processes are interrupted (Walsh, 2000). On-site stormwater control measures (SCMs) have been developed to capture urban stormwater close to its source in order to retain high flows/volumes and/or treat it before the stormwater enters a waterbody (Fletcher et al., 2015). A common SCM in developed areas is the use of biofilters (also known as rain gardens or bioretention). Biofilters are characterised by a depressed landscaped filter bed with an overflow weir and an optional underdrain. The media composition is critical for encouraging microbial activity, filtering/adsorbing pollutants,
infiltration capacity and supporting vegetation (Fassman et al., 2013). By common consensus, biofilters usually have a small surface area between 2 and 6% of the contributing catchment area (FAWB, 2009; Payne et al., 2015; Anderson and Strå, 2016). This ratio is sometimes called the hydraulic loading ratio (HLR), which is the biofilter area divided by the catchment area (Le Coustumer et al., 2012; Houle et al., 2017). When designed, implemented and maintained correctly, biofilters can achieve a number of objectives including water quality treatment, retention, groundwater recharge, aesthetic enhancement, and traffic calming (Asleson et al., 2009; Warynski et al., 2012; Blecken et al., 2017). The relevant objectives are site-specific and they should be decided and prioritised in advance to enable target-specific biofilter design.

Although this study has focused particularly on biofilter, this technique is not a SCM that suits with every site conditions. Different SCMs fulfill different aspects of stormwater management (pollutant removal, peak flow and volume retention). From a hydrological perspective, biofilters and many other follow a similar fundamental type of performance (Davis et al., 2012). Grass swales, green roofs, permeable pavements, biofilters, wetlands, and detention/retention ponds all possess storage component(s) based on their size relative to the expected flow (Fletcher et al., 2015; Davis et al., 2012). However, a straight storage system will naturally not have any volumetric effect beyond their initial storage. SCMs selection is typically decided by the design engineers and limited by the site circumstances such as slope, soils, size, and development density (Ekk et al., 2021). Costs, site compatibility, and community acceptance are also vital to consider in the SCM selection process (NCDEQ, 2018a). In comparison with other SCMs, biofilters are a good option for stormwater treatment and retention of every-day to design rainfalls in various urban areas. Biofilters can be also a preferred SCM for roadway stormwater runoff management, due to their possible application in linear environments. However, implementation of this technology in Sweden given the relatively cold climate (shorter vegetation period, use of road salt, limited plant species selection, etc.) (Kraay et al., 2017; Lange et al., 2020).

Even if designed properly, biofilters cannot work efficiently if they are not constructed appropriately, and inspected and maintained regularly (Wardynski and HUNT, 2012; Blecken et al., 2017). Visual inspections of biofilter structures should be carried out frequently, and after major storm events (Bleck et al., 2017). ‘Frequently’ means weekly inspections immediately after construction for eight weeks, and monthly for facilities with well-established vegetation.

Maintenance concerns for biofilters are confined to issues of clogging, erosion, vegetation and aesthetic appearance (Blecken et al., 2017; Payne et al., 2015). Clogging refers to excessive sediment and debris accumulation within the media, interfering with biophysical processes especially infiltration (Le Coustumer, 2012). Pre-treatment stages such as forebays, splash pads and drop inlets should be routinely inspected and action taken to remove sediment before clogging occurs (Blecken et al., 2017; Payne et al., 2015). Over time, lack of maintenance can affect grading and flow patterns, which may lead to erosion and scour. Vegetation management for biofilters involves mowing, pruning, and possibly replanting if the vegetation does not establish itself. Aesthetic interests concern the presentation of the biofilters as a beautifying element (Overby et al., 2014). Maintenance is a preventive regime that helps retain the infiltration capacity of biofilters and should occur frequently depending on the type of the maintenance tasks (MPCA, 2020). By implementing a regular maintenance schedule, replacement of filter media has to take place more infrequently, depending on various factors (e.g. ratio of catchment vs. filter area, contaminant loads in the stormwater) (MPCA, 2020). Maintenance measures for specific objectives can partly counteract other objectives (e.g. aesthetics vs. treatment) which indicates a need for well-defined maintenance plans.

While extensive research has been undertaken on development of biofilter design at laboratory and field scales (the latter mostly focusing on pilot facilities), little research has been done into the inspection, maintenance regimes, and especially into investigation of existing biofilter facilities (Blecken et al., 2017). There is a growing need to evaluate the functionality and maintenance needs of established biofilters facilities in order to understand their long-term performance and their impact on receiving waterbodies as well as the factors affecting their performance (D’Arcy and Sieker, 2015; Al-Rubaei, 2016; Blecken et al., 2017). Thus, this study evaluated the operational status of twenty-six biofilters facilities across Sweden with respect to the functional design, pre-treatment stages, vegetation health, filter media composition and condition, infiltration rate, and maintenance needs. Using these indicators, the functionality of the biofilter was assessed with respect to the effective capturing and retention of stormwater. Finally, based on these indicators, we investigated whether the biofilter facilities have the potential to meet the objectives set by the operating municipalities.

2. Materials and methods

2.1. Biofilter sites

The twenty-six municipal stormwater biofilters are located in nine Swedish municipalities, which can be grouped into two climate zones identified by their region (Fig. 1). Gotaland refers to the area along the south-west coast between Malmö and Gothenburg. This region has a temperate humid climate with no dry season (Cb) and average annual rainfall between 612 and 772 mm (SMHI, 2020). Svealand refers to the central region of the country from Stockholm across to Southern Norway. This region has a cool humid climate with no dry season (Dfb), a longer period of snow cover and lower yearly average rainfall of 527–633 mm compared to the other region (SMHI, 2020). The landlocked cities receive more precipitation than the coastal cities. At the time that they were sampled, the biofilters were between 2 months and 6 years old. The key characteristics of the biofilters at each site are shown in Table 1. The site data presented herein were provided by the corresponding municipal operator from the design drawings and/or questionnaires. Unfortunately, the municipal records were incomplete since information could not be provided for some municipalities.
(either because such records were non-existent or there was no stormwater manager employed by the municipality).

All of the biofilters have a catchment area characterised as near-100% impervious. The contributing drainage areas are roofs, roads, sidewalks, and/or parking lots.

At some sites (1, 2, 3, and 10), there was a series of biofilters along the road or around the perimeter of the site. The cumulative area and volume for all the biofilters at a site is given in Table 1. For these sites with clustered biofilters, soil assessments and infiltration tests were taken at one to three representative biofilters, randomly chosen depending on the total number of biofilters.

2.2. Inspection parameters and methods

A design inspection and maintenance checklist was created by the authors (Table S2) and used to determine the facility’s general status, based on observations including visual inspections of the biofilters and engineering measurements in several sections of each facility. First, the functional design was evaluated and compared with the objectives specified by the respective operator. Then, the pre-treatment stage status, filter material conditions and characteristics, and finally vegetation health were investigated using methods and parameters that are described below in more detail.

2.2.1. Functionality: design and maintenance indicators

In this part of the study, the conditions and level of inlet and overflow outlet structures, evidence of concentrated flowpath, standing water, and evidence of trash or debris were surveyed. These conditions are indicative of design/construction flaws and/or maintenance concerns that can prevent the biofilter from performing optimally. Each site was qualitatively rated on their perceived functionality to meet their design objectives. The objectives which the municipalities specified and prioritised for the different facilities varied between the sites (Table 2).

2.2.2. Performance classification

Having considered all the design objectives and the inspection results, an overall performance classification (i.e. very low, low, medium, high, or very high) was estimated for each facility. It should be noted that the overall performance levels have been classified qualitatively by comparing an interpretation of all inspection results with the objectives defined by the operators. Eventually, according to this analysis, some suggestions were given concerning maintenance and/or design aspects in order to improve the performance of the biofilters.

2.2.3. Pre-treatment

To evaluate the conditions and general performance of pre-treatment stages, evidence of clogging and the existing level of maintenance were observed whilst taking the pre-treatment type into account.

2.2.4. Filter material

2.2.4.1. Visual conditions. Evidence of compaction, soil crusting, erosion and/or clogging at the inlet and along the flowpath were used as the visual inspection parameters of the filter media. Afterwards, in order to discover the reasons for poor conditions, the site area around the facilities was surveyed to find any visual evidence of contributing causes, and also filter media characterising tests were carried out.
Table 1
Biofilter characteristics.

<table>
<thead>
<tr>
<th>Site no.</th>
<th>Catchment</th>
<th>Area (m²)</th>
<th>Type of catchment</th>
<th>Area (m²)</th>
<th>Design storage volume (m³)</th>
<th>Year of construction</th>
<th>Age at study time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Road</td>
<td>1900</td>
<td></td>
<td></td>
<td>165</td>
<td>48</td>
<td>2018</td>
</tr>
<tr>
<td>2</td>
<td>Road</td>
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<td></td>
<td></td>
<td>650</td>
<td>179</td>
<td>2015</td>
</tr>
<tr>
<td>3</td>
<td>Road</td>
<td>4500</td>
<td></td>
<td></td>
<td>160</td>
<td>47</td>
<td>2018</td>
</tr>
<tr>
<td>4</td>
<td>Rooftop</td>
<td>230</td>
<td></td>
<td></td>
<td>8</td>
<td>8</td>
<td>2017</td>
</tr>
<tr>
<td>5</td>
<td>Rooftop</td>
<td>230</td>
<td></td>
<td></td>
<td>8</td>
<td>8</td>
<td>2017</td>
</tr>
<tr>
<td>6</td>
<td>Rooftop</td>
<td>670</td>
<td></td>
<td></td>
<td>30</td>
<td>10</td>
<td>2016</td>
</tr>
<tr>
<td>7</td>
<td>Rooftop</td>
<td>310</td>
<td></td>
<td></td>
<td>26</td>
<td>10</td>
<td>2016</td>
</tr>
<tr>
<td>8</td>
<td>Road</td>
<td>2700</td>
<td></td>
<td></td>
<td>90</td>
<td>22</td>
<td>2017</td>
</tr>
<tr>
<td>9</td>
<td>Parking lot</td>
<td>5000</td>
<td></td>
<td></td>
<td>200</td>
<td>70</td>
<td>2017</td>
</tr>
<tr>
<td>10</td>
<td>Parking lot</td>
<td>15000</td>
<td></td>
<td></td>
<td>700</td>
<td>150</td>
<td>2015</td>
</tr>
<tr>
<td>11</td>
<td>Road and sidewalk</td>
<td>4000</td>
<td></td>
<td></td>
<td>11</td>
<td>3.3</td>
<td>2012</td>
</tr>
<tr>
<td>12</td>
<td>Road</td>
<td>360</td>
<td></td>
<td></td>
<td>15</td>
<td>4.5</td>
<td>2012</td>
</tr>
<tr>
<td>13</td>
<td>Road and sidewalk</td>
<td>1800</td>
<td></td>
<td></td>
<td>11a</td>
<td>3.3</td>
<td>2012</td>
</tr>
<tr>
<td>14</td>
<td>Road</td>
<td>150</td>
<td></td>
<td></td>
<td>150</td>
<td>ND</td>
<td>2013</td>
</tr>
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<td>15</td>
<td>Road</td>
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<td></td>
<td></td>
<td>75</td>
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<td>2013</td>
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<tr>
<td>16</td>
<td>Road</td>
<td>150</td>
<td>Sidewalk</td>
<td></td>
<td>75</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>17</td>
<td>Sidewalk</td>
<td>200</td>
<td></td>
<td></td>
<td>100</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>18</td>
<td>Sidewalk</td>
<td>330</td>
<td></td>
<td></td>
<td>100</td>
<td>22</td>
<td>2016</td>
</tr>
<tr>
<td>19</td>
<td>Sidewalk</td>
<td>1250</td>
<td>Road and sidewalk</td>
<td></td>
<td>300</td>
<td>ND</td>
<td>2017</td>
</tr>
<tr>
<td>20</td>
<td>Road</td>
<td>650</td>
<td>Road and sidewalk</td>
<td></td>
<td>200</td>
<td>ND</td>
<td>2017</td>
</tr>
<tr>
<td>21</td>
<td>Road and sidewalk</td>
<td>600</td>
<td></td>
<td></td>
<td>60</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>22</td>
<td>Road and sidewalk</td>
<td>600</td>
<td></td>
<td></td>
<td>60</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>23</td>
<td>Road and sidewalk</td>
<td>600</td>
<td></td>
<td></td>
<td>60</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>24</td>
<td>Road and sidewalk</td>
<td>600</td>
<td></td>
<td></td>
<td>60</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>25</td>
<td>Road</td>
<td>600</td>
<td>Road and sidewalk</td>
<td></td>
<td>60</td>
<td>ND</td>
<td>2015</td>
</tr>
<tr>
<td>26</td>
<td>Road</td>
<td>600</td>
<td>Road and sidewalk</td>
<td></td>
<td>60</td>
<td>ND</td>
<td>2015</td>
</tr>
</tbody>
</table>

ND denotes “not determined” because no design drawings were provided for these sites. In calculating storage volumes, the following assumptions were made:
- the porosity of the filter media and drainage layer were 25 % and 40 % respectively.
- These values were calculated from design drawings.
- These areas were approximated from aerial imagery.

**2.2.4.2. Engineered filter media analyses.** For a representative sample of conditions in the biofilter, the filter media samples were collected from three sampling locations (i.e. inlet, overflow outlet, and a middle point along the flowpath) using either an auger or shovel, depending on the compaction of the media. Organic matter, such as mulch, was scraped aside from the surface before the media sample was taken. The engineered media sample taken at each location was a composite sample of media from below the mulch to 10–20 cm below the surface. The samples collected were put into plastic bags, stored in a portable box, and transported to an accredited laboratory for analysis. The media samples were analysed for particle size distribution (PSD) and organic media content. For PSD samples, dry sieving was carried out using standardised sieves in accordance with ISO 3310–1 following the ASTM D422 - 63 standard test methods (ASTM, 2007). Sub-samples were analysed for loss on ignition (LOI) according to the standard method SS 28113 (SIS, 1991).

**2.2.4.3. Infiltration capacity measurements.** Near the location where the

soil samples were taken (i.e. inlet, overflow, and a middle point along the flowpath), measurements of the effective hydraulic conductivity were collected using Modified Philip-Dunne (MPD) infiltrometers. This method follows the ASTM standard procedure D8152 – 18 (ASTM, 2018), as recommended by the manufacturer of the MPD infiltrometer (Upstream Technologies MPD Infiltrometer). It is a falling head test. Unwittingly, during a few of the tests, air bubbles were stuck inside the device and thus invalidated several infiltration tests.

**2.2.5. Vegetation**

In this part, the type, variety, health and maintenance level of vegetation were investigated. The vegetative health was evaluated with respect to the plant selection, coverage of plants, and vitality of the plants. As only a few sites provided the original planting plan, a comparison of the intended vegetation and the species actually found could not be carried out.

**3. Results and discussion**

**3.1. Design objectives and estimation of achievement**

Here, we summarise the objectives set by biofilter operators, and the degree to which these objectives were achieved based on the survey results. According to operators, the design objectives of the biofilters included water quality treatment, volume retention, flood protection, aesthetic appeal, groundwater recharge, and traffic calming (Table 2).

Traditionally, stormwater biofilters are designed to improve stormwater quality prior to its discharge to the receiving waterbody. This was one of the main design objectives for 18 of the 26 facilities; for six of them, it was the primary priority (Table 2). For eight facilities, quality treatment was not mentioned as an aim, but retention was prioritised (see Table 2).

In general, biofilters have the potential to efficiently remove stormwater pollutants when the stormwater passes through the sand filter media sections (Randelovic et al., 2016). However, some technical and maintenance issues could still lead to a lack of treatment performance. For instance, accidentally compacted soil media, accumulated sediments, trash, or plant debris at the biofilters, overgrown vegetation, and structural design flaws can all reduce the efficacy of the biofilters for pollutant treatment. These issues potentially cause dead zone formation in some parts of the filter media, and preferential stormwater flow through the system. Eventually, untreated stormwater inflow bypasses the system due to an infiltration capacity reduction.

Most facilities (17 sites) aimed to mitigate peak flows, although biofilters in urban areas are not typically designed for high flows but every-day rainfalls (USEPA, 2005). Space constraints and utility conflicts in urban areas limit the size of biofilters and thus their ability to mitigate peak flows from large storm events. For design rains, the ponding zone of the biofilters placed in urban areas (similar to the evaluated ones) typically varies between 0.1 and 0.3 m and the excess volume bypasses the system (Tondera et al., 2018; NCDEQ, 2018b). These ponding zones only provide limited retention because the stormwater inflow commonly exceeds the infiltration capacity during more intense rainfall. Therefore, if the bypass is not connected to an additional retention volume, biofilters are probably not the best solution for pollutant treatment. These issues potentially cause dead zone formation in some parts of the filter media, and preferential stormwater flow through the system. Eventually, untreated stormwater inflow bypasses the system due to an infiltration capacity reduction.

In this part, the type, variety, health and maintenance level of vegetation were investigated. The vegetative health was evaluated with respect to the plant selection, coverage of plants, and vitality of the plants. As only a few sites provided the original planting plan, a comparison of the intended vegetation and the species actually found could not be carried out.
### Table 2
Analysis of the biofilters’ performance in comparison with their design objectives as defined by the operators and some suggestions for improvement.

<table>
<thead>
<tr>
<th>Site no.</th>
<th>Objectives* (according to the operators)</th>
<th>Performance level classification in achieving objectives</th>
<th>Suggestions for maintenance</th>
<th>Suggestions for structural modification</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Water quality treatment</td>
<td>Retention of everyday rainfall</td>
<td>Flood protection (retention of design rainfall)</td>
<td>Groundwater recharge</td>
</tr>
<tr>
<td>1</td>
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<td>+++</td>
<td>++</td>
<td>–</td>
</tr>
<tr>
<td>2</td>
<td>–</td>
<td>+++</td>
<td>+++</td>
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<td>–</td>
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</tr>
</tbody>
</table>

*continued on next page*
of the operators for doing so has not been further investigated in this study. Aesthetic appearance is another design objective mentioned by most operators as being as important as water quality treatment or volume retention (15 sites in Table 2). From an aesthetic perspective, the biofilter acts as an urban element, and should also be designed and regularly maintained in accordance with the surrounding environment, otherwise it might become a source of pollution (e.g. airborne dust and accumulated sediments) and be unsightly. The inspections showed that there were various facts that had compromised the aesthetic appearance of the biofilters (e.g. overgrown vegetation, invasive weed growth, trash or debris accumulation, and also uneven vegetation growth). A good example of the lack of proper vegetation design and maintenance was seen at site 11, where all the above issues occurred, even though the aesthetic appearance had been also prioritised as a purpose. No survey was done to determine the frequency of maintenance for these biofilters by the operators or whether they were privately or publicly managed.

Groundwater recharge is also a biofilter design objective (for six facilities) which is often linked to a site-specific goal (e.g. groundwater deficit compensation, or lack of a separate stormwater collection system (USEPA, 2005)). One of the difficult issues for achieving groundwater recharge is subsurface infiltration because urban areas tend to have underlying layers of compacted soil with poor infiltration. Another issue that prevents groundwater recharge is sediment accumulation on the biofilter media. This was not only the case for those with this objective but also for many of the other facilities. Obviously, if the facility is not maintained frequently or if an unexpected source of sediments is not managed properly, there will eventually be clogging and a general reduction in the system’s performance.

Furthermore, biofilter facilities were used for traffic calming, but this was less important than the other design objectives (Table 2). It is important that the vegetation, curb extension body, and traffic signs associated with the biofilter are sited appropriate to the location (NACTO, 2017a). Fortunately, most of the biofilters had an acceptable status in this regard, and it was assumed that they fulfilled this purpose, except for a few where vegetation overgrowth was a problem for sight angles.

Finally, the overall performance level for each facility was classified by comparing the design objectives and the inspection criteria and results (see Table 2). The data reported in Table S1 (in supplementary material) shows the inspection results in detail. The interpretation of the results enabled us to estimate to what extent each facility can achieve its (combined) objectives. The biofilters performance level analysis revealed that 10 to 12 practices (approximately 40 %) did not meet the objectives defined by the operators sufficiently (classified by medium to low performance). On this basis, some additional suggestions are listed in Table 2 for each facility that can be implemented to improve their performance. The proposed solutions addressed the structural modifications such as outlet level and ponding volume adjustments and an improvement in maintenance of pre-treatment, filter media and vegetation sections; e.g. removing the accumulated sediment/debris, pruning the vegetation, and stabilising the eroding bank. In the following sections, the inspection results, observed issues and suggestions for improvement will be discussed in more detail.

### 3.2. Functional design

Functional design determines whether the facility is operational and performing optimally. Several functional issues were observed that inhibited the stormwater collection and infiltration capacity of the biofilter. These issues were obstructions to the inflow path, overflows set too low, insufficient ponding volume, hydraulic problems caused by irrigation systems, and lack of maintenance of barriers and signs.

#### 3.2.1. Inflow path

A critical issue for biofilter functionality is the stormwater...
conveyance into the biofilter. The biofilter shown in Fig. 2 (a) (site 1), only the area within the wooden frame contained biofilter media. The area along the perimeter of the biofilter was filled with 6 cm of gravel above an asphalt surface. The preferential flow for water is along the lowest grade. Based on surface elevations, the stormwater would likely flow through the gravel for low flow events. This perception was confirmed by evaluating the moisture of the media. The biofilter media within the wooden frame held less moisture than the gravel along the curb. This is a functional design flaw that may inhibit vegetation from establishing. The site at the time of evaluation was less than a year old.

At the site shown in Fig. 2 (b), the cobblestones near the curb have been built in a concave shape which helps to collect and channel the water towards the biofilter. The limiting element of this design is the curb opening which is of insufficient size. Furthermore, the opening in the inlet has become a collection point for debris and trash which blocks the flow of runoff. Similar issues can be found with the facility shown in Figure S5 (a). These types of opening (only observed at sites 12, 17 and 18) are not easy to maintain because they are difficult to access. These curb cut-outs are not the preferred curb opening type for biofilters and should be avoided when possible.

### 3.2.2. Overflow outlet and ponding volume

A design flaw seen at five sites (3, 9, 11, 12, and 18) was the elevation placement of the overflow outlet. As shown in the examples, Fig. 2 (c) and(d), the overflow outlets were placed lower than the inlets and/or at the bottom of the filter. This design prevents ponding from occurring, minimising retention volume and residence time. More water is bypassed directly through the overflow pit since the stormwater will naturally flow to the lowest point instead of filtering through the subsurface media. As a consequence of having the overflow outlet too low and/or too little/no depression of the surface, several facilities do not have enough ponding volume on top of the filter media, as shown in Table 3 and Fig. 2 (e). Limited availability for ponding volume was seen at ten facilities surveyed (1, 3, 9–14, 18, and 21). Particularly during

Table 3
Comparing actual ponding volume with expected runoff volumes for selected biofilters (sorted by the ponding volume capacity in mm-rainfall).

<table>
<thead>
<tr>
<th>Site no.</th>
<th>Main objectives</th>
<th>Actual ponding volume</th>
<th>Ponding Volume needed to capture 20 mm of rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Retention</td>
<td>Quality Treatment</td>
<td>(m³)</td>
</tr>
<tr>
<td>19</td>
<td>++</td>
<td>+</td>
<td>16.85</td>
</tr>
<tr>
<td>17</td>
<td>++</td>
<td>–</td>
<td>4.86</td>
</tr>
<tr>
<td>20</td>
<td>++</td>
<td>+</td>
<td>11.42</td>
</tr>
<tr>
<td>1</td>
<td>++</td>
<td>–</td>
<td>3.89</td>
</tr>
<tr>
<td>21</td>
<td>++</td>
<td>+</td>
<td>1.07</td>
</tr>
<tr>
<td>9</td>
<td>+</td>
<td>++</td>
<td>7.30</td>
</tr>
<tr>
<td>18</td>
<td>++</td>
<td>–</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>++</td>
<td>+</td>
<td>0.31</td>
</tr>
<tr>
<td>13 &amp; 14</td>
<td>++</td>
<td>+</td>
<td>0.25</td>
</tr>
<tr>
<td>10</td>
<td>+</td>
<td>++</td>
<td>9.71</td>
</tr>
<tr>
<td>12</td>
<td>–</td>
<td>++</td>
<td>0.00</td>
</tr>
</tbody>
</table>

a Symbols ‘++’ and ‘+’ represent a higher and a lower priority, comparatively. The sign ‘-’ means not targeted at all.

b Only surface ponding volume is considered, not pore volume in filter material since this pore volume may not be able to be used to its full extent when high intensity rainfall causes high flow/flooding.
intense storms and/or high flows, this lack of surface storage volume is problematic since, even if the filter material itself has sufficient pore volume, the water will not have retention time to infiltrate, thus diminishing the water quality performance of the biofilter.

To support these visual inspections, the actual surface ponding volume was measured at a number of the biofilter sites and then their equivalent capacity in mm of rainfall and the required ponding volume to capture 20 mm of rainfall were calculated accordingly (selected sites shown in Table 3). Retention volume equivalent to 20 mm is a level of design rainfall commonly used in Sweden when designing stormwater treatment facilities for retention in order to be able to treat approximately 90% of the total annual runoff volume (Andersson and Stråe, 2016). The results showed that sites 17 and 19 have sufficient ponding volume to meet both their main goals. These two systems are rather over-dimensioned for retaining the expected runoff, potentially resulting in drought problems for the vegetation (in fact, the filter at site 17 is irrigated regularly during the summer). The biofilter at site 20 may also be able to retain about 11 mm precipitation, although the ponding volume is not sufficient for an extreme rainfall event. However, for the rest of the biofilters for which water retention/flood protection was mentioned as the first or secondary objective (sites 1, 3, 9, 10, 13, 14, 18, and 21), insufficient ponding volume has been built to achieve this aim (Table 2), so the excess water actually bypasses the filter.

Biofilters mainly targeting water quality treatment require less storage than those designed for high flow retention. However, capacities less than only 2 mm rainfall (as seen in sites 3, 9, 10, 12, 13, 14, and 21) are still too small to allow the subsequent runoff water to infiltrate into the system for every-day rainfall events. These results indicate that at least 40% of the biofilters are not designed to retain the every-day and/or design rainfall events.

3.2.3. Barriers and signs

Another functional design challenge was the lack of barriers or signs around the biofilters to keep away people and dogs. Several individuals and dogs were observed walking through biofilters, which can lead to compaction as shown in Fig. 2 (f). Also, dogs can become a concern for water quality. Using either education or physical structures, it is important to deter people from treating biofilters as pedestrian areas. For example, at site 18, walkways have been built above the media in order to integrate and use the biofilter area as public green space. This approach works as long as the pedestrians do not step onto the biofilter.

3.3. Biofilter inlet and pre-treatment facilities

Stormwater can be either conveyed directly into the filter or pass through a pre-treatment stage. With the exception of seven sites (11, 12, and 22–26), the remaining biofilters employed some types of pre-treatment. Those observed were drop inlets, splash pads, and filter strips. Table S1 shows the pre-treatment practices for each facility. Detailed descriptions follow for a number of the facilities and issues inspected.

The concave splash pad shown in Fig. 3 (a) channelled the incoming flow, resulting in the collection of sediment primarily at the end of the splash pad. The dense planting at the end of the splash pad when established around the perimeter can serve as a containment dam for the sediment. When full vegetation coverage is not present, as shown in Fig. 3 (a), the splash pad simply conveys the uncontained sediment-laden runoff flow into the biofilter. Over time, this leads to extensive surface clogging as observed at five facilities (13, 14 and 19–21) out of the ten having this type of inlet construction alone or in combination with other methods. This pre-treatment practice (Fig. 3 (a)) is characterised as being in poor condition.

The biofilter shown in Fig. 3 (b) took an innovative approach to pre-treatment. The stormwater from the rooftop is conveyed through a gutter filled with rock and with teeth along its edges. This design uses the gutter as a “sedimentation” strip to promote the dispersion of the stormwater throughout the facility to dissipate energy. In order to fulfil this aim, the gutter has to be built exactly horizontal. The biofilter related to Fig. 3 (b) had high infiltration rates and flourishing vegetation so it was considered to be in good condition. However, this type of pre-treatment does not easily facilitate removal of captured sediment during maintenance given the rock-filled gutter.

Another observed pre-treatment method is the drop inlet sump shown in Fig. 3 (c). This effectively captured sediment as observed by the mud at the bottom of the sumps. The grate inlet was appropriately depressed in the street so as to be a low point for stormwater collection. It also had a wide mouth into the drop inlet that prevent complete blockage. As long as the surrounding surface is level, the sump will disperse flow into the biofilter.

The combined pre-treatment stage using a splash pad and gravel

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Fig. 3. Pre-treatment methods: (a) Splash pad (sites 19–21), (b) Gutter distribution (sites 4 and 5), (c) Drop inlet sumps (sites 19–21), and (d) Concrete splash pad and gravel riprap (sites 13 and 14).
sheet flow from the street. The biofilter was adjacent to several recently planted vegetation, and later confirmed by sampling and testing, it was the closest to the filter is an unpaved sand/gravel surface which releases large amounts of sediment during storm events. It is important to protect biofilters, and secure staging areas or locate them away from the biofilter. Another noticeable challenge regarding sediment load was observed at two sites (9 and 10) where there were eroding steep slopes along one edge of the biofilters. The site in Fig. 4 (c) illustrates an eroding bank as indicated by the partially covered overflow grate. The side slopes consist of very compact soil, making direct seeding or planting vegetation a challenge. As a result, the bank was left exposed and vulnerable to erosion from heavy flow volumes. Over time, the sediment and rock from the bank has eroded and settled in the biofilter, clogging its surface. However, at the site shown in Fig. 4 (d), the slope was covered with gravel which kept the bank stable. This site also included check dams which slowed down the stormwater and promoted infiltration. Stabilising the bank is an issue that needs to be addressed in order to restore the functionality of this biofilter.

The visual inspection of the biofilter media validated the measured hydraulic conductivity values and provided support for the importance of properly sized and installed pre-treatment stages and the choice of suitable filter materials. Additionally, it is imperative to protective biofilters when construction is being undertaken nearby to prevent the intrusion of sediment. If the biofilter is part of a wider development plan, it should be built last relative to a road or building.

As was observed at the field sites, pre-treatment is an important part of biofilter facilities which can slow down clogging and decrease maintenance frequency by reducing fine sediment accumulation on top of the filter material (Blekken et al., 2017). The construction and condition of the pre-treatment stages varied, as described in this section and Table S1. Generally, the splash pad and the drop inlets visibly showed the largest amounts of sediment collection. A lack of maintenance and high sediment loads in the incoming stormwater were the common reasons for clogging and performance degradation over time.

3.4. Filter materials

3.4.1. Visual conditions of filter media

The majority of biofilters showed no signs of soil crusting, indicative of poor drainage. Seven of the biofilters (10–14, 17, and 18) had visibly compacted soil, which correlated with low hydraulic conductivity when tests could be carried out; for two of the seven sites, it was impossible to complete any drainage tests within 6 h, indicating complete clogging.

The biofilters with the most soil compaction had the lowest sand content, between 69 and 73 percent, and some of the highest silt content, between 5 and 10 percent. Soil composition has thus, at least to some degree, an effect on compaction. For instance, soil media consisting of approximately equal grain size potentially becomes less compacted than media having multiple grain sizes. Smaller particles can fill spaces between larger particles, thereby increasing bulk density. These observations underline the importance of careful filter material selection. As discussed above, for biofilters in climates with cold winters as in Scandinavia, rather coarse filter materials are recommended since they facilitate infiltration even in frozen soil (Moghadas et al., 2016). Failure to do so not only risks compromising infiltration capacity, especially in cold temperatures, but also causing soil compaction.

Other factors affecting filter material conditions were sources of sediment introduced within the catchment area, and the lack of filter media in the biofilter. In the biofilter shown in Figure S2 (a), construction debris has blown over or, in some cases, been intentionally placed in the biofilter. Adjacent to the facility, the remnants of an old pile of material is evident. Since the source of stormwater for this practice is roof runoff, the amount of sediment introduced into the site is lower than if the runoff entered as sheet flow. Sediment and other particles during construction activities can move through the air into the biofilter. This also applies to the filter shown in Figure S2 (b). Here, the catchment closest to the filter is an unpaved sand/gravel surface which releases large amounts of sediment during storm events. It is important to protect biofilters, and secure staging areas or locate them away from the biofilter.
The average values for all the biofilters at these three testing locations used (near the inlet, outlet, and a middle point) are higher than the recommended rates of 12.5 mm/hr. There is no Swedish permeability design standard – 962 mm/h on average). Note that, some of the previous studies in comparison to stormwater runoff from rooftops have observed infiltration rates up to 1000 mm/h (due to very low fine sediment content in the filter media) show that these materials can also achieve efficient metal removal (Blecken et al., 2011) due to the continued efficient trapping of sediment and thus particulate pollutants on the top layer, along with relatively fast metal adsorption processes (Seberg et al., 2019).

This broad range of hydraulic conductivity indicates that even with similar soil media, the permeability is not consistent. Biofilters are dynamic systems that interact with their environment. The soil media establishes a basis for permeability but external factors and design elements of the biofilters can impact the permeability. Biofilters with a high hydraulic loading ratio may receive a large concentration of sediment that can impair the system over time (Le Coustumer et al., 2012). The size and condition of the pre-treatment stage can prevent or permit the introduction of sediment into the biofilter (Blecken et al., 2017). When sorting the sites by hydraulic conductivity, those sites with low and relatively low conductivity values (i.e. sites 10, 12, 14, 15, 17, and 18) were those where the pre-treatment stages were in poor condition. Poor condition means sediment or litter accumulation in the pre-treatment stage that warrants immediate maintenance. This correlation indicates that the condition of the pre-treatment stages may be an indicator of permeability in the soil media if measurements cannot be taken.

Hydraulic loading ratio (HLR), calculated as the biofilter area divided by the catchment area, is also a descriptor of the volumetric loading to SCMs that can be used for assessing the performance and durability of a biofilter (Le Coustumer et al., 2012; Houle et al., 2017). The estimated HLRS for the facilities studied were between 0.6 % and 50 %. Only seven of the inspected biofilters (sites 3–6, and 8–10) were within the recommended range of 2–6%. That is because it is difficult to meet this criterion along the lengthy, linear, impervious stretches since the drainage area is invariably large. It should be also noted that, at sites 17 and 18 where the HLR is too high, drip irrigation lines were observed and water was felt coming out of these lines. These two biofilters are 3 years old which is well past the establishment period when watering is needed. The drip irrigation keeps the soil partially saturated which affects the treatment capacity. However, results from biofilters with high infiltration rates up to 1000 mm/h are often recommended (Fassman et al., 2013).

At some of the biofilter sites assessed (e.g. 1, 3, and 4), high infiltration rates were measured. A high infiltration rate can contribute to the desired stormwater retention since the pore volume in the filter media can be filled quickly and thus serve as storage even during high flow events. On the other hand, a high infiltration rate reduces the contact time between the water and the filter which might negatively affect the treatment capacity. However, results from biofilters with high infiltration rates up to 1000 mm/h (due to very low fine sediment content in the filter media) show that these materials can also achieve efficient metal removal (Blecken et al., 2011) due to the continued efficient trapping of sediment and thus particulate pollutants on the top layer, along with relatively fast metal adsorption processes (Seberg et al., 2019).

### Table 4

<table>
<thead>
<tr>
<th>Country/state</th>
<th>Gravel (&lt;4 mm)</th>
<th>Sand (0.125 - 4 mm)</th>
<th>Silt and Clay (&lt;0.125 mm)</th>
<th>Organic Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweden</td>
<td>10–16%</td>
<td>74–81%</td>
<td>4–7%</td>
<td>&lt;9%</td>
</tr>
<tr>
<td>Australia</td>
<td>–</td>
<td>85–90%</td>
<td>&lt;3%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Minnesota</td>
<td>75–90%</td>
<td>5–15%a</td>
<td>6–9%a</td>
<td></td>
</tr>
<tr>
<td>North Carolina</td>
<td>90–94%</td>
<td>5–8%c</td>
<td>1–3%c</td>
<td></td>
</tr>
<tr>
<td>Washington DC</td>
<td>80–90%</td>
<td>2–5%c</td>
<td>7–8%c</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>85–88%</td>
<td>8–12%</td>
<td>3–5%</td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>90–95%</td>
<td>&lt;10%</td>
<td>1–3%</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>40–70%</td>
<td>30–50%</td>
<td>0–4%</td>
<td></td>
</tr>
<tr>
<td>Lab tests</td>
<td>96–97%</td>
<td>3–4%</td>
<td>&lt;2%</td>
<td></td>
</tr>
</tbody>
</table>

*a Estimated by converting volume percentage to mass percentage.

### 3.4.3. Hydraulic conductivity

The infiltration rates are useful as a benchmark to assess the facility over time. Unfortunately, no initial conductivity tests were available to assess to what extent conductivity has changed. Also, there are insufficient data to draw any conclusions about individual biofilter facilities. However, the overall results of hydraulic conductivity tests (Figure S4) showed that there was a broad range of effective conductivity measured across the biofilters (30–962 mm/h on average). Note that, some of the conductivity test results are not shown Figure S4 since the biofilters or parts of a biofilter contained very compacted soil or there were practical issues in testing (Null results in Table S1). In addition, no significant difference in hydraulic conductivity can be seen between results for the three testing locations used (near the inlet, outlet, and a middle point along the flowpath). The average values for all the biofilters at these three testing locations were respectively 359 (±259), 362 (±264), and 300 (±258) mm/h. There is no Swedish permeability design standard against which to gauge these rates, but, in general, (initial) infiltration rates of 12.5–300 mm/h are often recommended (Fassman et al., 2013). The observed infiltration rates are mostly above these recommended values.

At some of the biofilter sites assessed (e.g. 1, 3, and 4), high infiltration rates were measured. A high infiltration rate can contribute to the desired stormwater retention since the pore volume in the filter media can be filled quickly and thus serve as storage even during high flow events. On the other hand, a high infiltration rate reduces the contact time between the water and the filter which might negatively affect the treatment capacity. However, results from biofilters with high infiltration rates up to 1000 mm/h (due to very low fine sediment content in the filter media) show that these materials can also achieve efficient metal removal (Bleich et al., 2011) due to the continued efficient trapping of sediment and thus particulate pollutants on the top layer, along with relatively fast metal adsorption processes (Seberg et al., 2019).

This broad range of hydraulic conductivity indicates that even with similar soil media, the permeability is not consistent. Biofilters are dynamic systems that interact with their environment. The soil media establishes a basis for permeability but external factors and design elements of the biofilters can impact the permeability. Biofilters with a high hydraulic loading ratio may receive a large concentration of sediment that can impair the system over time (Le Coustumer et al., 2012). The size and condition of the pre-treatment stage can prevent or permit the introduction of sediment into the biofilter (Bleich et al., 2017). When sorting the sites by hydraulic conductivity, those sites with low and relatively low conductivity values (i.e. sites 10, 12, 14, 15, 17, and 18) were those where the pre-treatment stages were in poor condition. Poor condition means sediment or litter accumulation in the pre-treatment stage that warrants immediate maintenance. This correlation indicates that the condition of the pre-treatment stages may be an indicator of permeability in the soil media if measurements cannot be taken.

Hydraulic loading ratio (HLR), calculated as the biofilter area divided by the catchment area, is also a descriptor of the volumetric loading to SCMs that can be used for assessing the performance and durability of a biofilter (Le Coustumer et al., 2012; Houle et al., 2017). The estimated HLRS for the facilities studied were between 0.6 % and 50 %. Only seven of the inspected biofilters (sites 3–6, and 8–10) were within the recommended range of 2–6%. That is because it is difficult to meet this criterion along the lengthy, linear, impervious stretches since the drainage area is invariably large. It should be also noted that, at sites 17 and 18 where the HLR is too high, drip irrigation lines were observed and water was felt coming out of these lines. These two biofilters are 3 years old which is well past the establishment period when watering is needed. The drip irrigation keeps the soil partially saturated which limits the maximum retention capacity during storms.

In contrast to the pre-treatment stage conditions and earlier observations, HLR is not a direct indicator of hydraulic conductivity (Le Coustumer et al., 2012). There was no consistent linear relationship between HLR and conductivity values. A reason for that is that the type of catchment area serves as a further indicator of sediment load concentration. The stormwater runoff from transportation-related impervious surfaces in comparison to stormwater runoff from rooftops...
generally contains higher loads of sediment (Makepeace et al., 1995). Only four biofilters (identified as 4, 5, 6, and 7) received runoff from rooftops. The remaining sites were either parking lots or roads. These four sites receiving roof runoff had average HLRs of 3.5, 3.5, 4.5, and 8.4% and good pre-treatment stage conditions. Furthermore, they all had relatively high conductivity rates. In other words, the biofilters receiving runoff from roofs have remained in better condition so that they might need less frequent maintenance. This observation indicates that the type of catchment should be considered in determining the maintenance frequency. Biofilters receiving runoff from impervious areas associated with transportation activities may require more frequent maintenance than biofilters receiving roof runoff. Additionally, the design of biofilters should be a factor of safety when sizing pre-treatment practices with drainage areas perceived to contribute potential high sediment loads.

Furthermore, the hydraulic conductivity was used to evaluate the drawdown time for the biofilters, which indicates the water retention potential. Drawdown time is the time taken for the surface ponding water to be completely drained out (NACTO, 2017b). Design standards for biofilters specify a drawdown time typically for two reasons: (1) to enable the system to have enough volumetric capacity to capture a subsequent design storm volume and (2) to avoid public health and safety hazards caused by standing water. Further, standing water is a breeding ground for mosquitoes. From the information provided, only three biofilters (sites 1–3) were designed for a specific storm event and no required drawdown time was given. The design storms referenced were either a 10-year or 20-year event. These return intervals are suit areas associated with transportation activities may require more frequent maintenance than biofilters receiving roof runoff. Additionally, the design of biofilters should be a factor of safety when sizing pre-treatment practices with drainage areas perceived to contribute potential high sediment loads.

The maximum drawdown time for a biofilter facility, as advised by most US municipalities, is 48 h. However, a 12- or 24-h drawdown period is often preferable, particularly in the contexts of regular precipitation to accommodate the next storm, high pedestrian volume in urban areas, or other influencing factors (NACTO, 2017b). Using the rainfall depth of 20 mm and the average hydraulic conductivity data, ten facilities (sites 1–4, 7, 8, 17, 18, 20, and 21) require less than an hour, four (sites 5, 6, 10, and 12) require 1–4 h, and one (site 14) would take 18 h to drain down the runoff volume (see Table S1). The site 14 had high deposition of sediment, poor hydraulic conductivity and a very low HLR. Therefore, most of the biofilters are adequate at drawing down the runoff volume due to the 20 mm rainfall and theoretically fulfill this condition (drawdown time <12 h).

### 3.5. Vegetation status

Vegetation health is a function of the correct selection of plants with respect to climate, site conditions and a functional biofilter design. The vegetation surveys showed that the facilities were generally in good health. Based on common minimum planting plans required at the time of construction, the expectation is that vegetation will not be fully established with regards to plant coverage until the end of the third growing season (MPCA, 2020). Full coverage refers to a minimum of 75% of the surface area.

Three sites (1, 3, and 8), built within the last year before this survey, had a well laid out planting plan but the vegetation had not reached full coverage. The biofilter shown in Fig. 5 (a) illustrates the effect of poor design on plant health. This biofilter has an undersized curb opening that is blocked with sediment and debris as shown in Figure S5 (a). There is residue sediment on the exterior pavement that probably settled from ponding water. The blockage limited the flow of water into the biofilter and the media in the biofilter felt dry and dusty. There were wilting plants to the rear of the biofilter that also indicated a lack of water. Additionally, there was no pre-treatment stage or a second curb. Limited stormwater was entering this facility which inhibited vegetation growth and made the biofilter obsolete in practice.

Two issues observed with five biofilters (at sites 10–11, 13–15) were the intrusion of invasive weeds and the lack of maintenance. The sites were inspected in June, that is, in early summer. A few sites at this point in the season were already overgrown, as shown in Figure S5 (b). Overgrown vegetation is mostly an aesthetic issue although it can also interfere with sightlines thus becoming a traffic hazard. Further, possible sediment or trash accumulation on the filter surface is not visible when it is totally overgrown. Intrusive weeds can prevent proper drainage as well. The other issue observed was the lack of plant diversity. Without having the planting plans for review, it is impossible to discern if this was a function of dominance by a specie or the plan itself.

Having a diversity of plants maintains a robust biosystem that can deter insects, and guard against drought and plant diseases. An example of diverse planting is shown in Fig. 5 (b). It should be noted that, at most of the biofilters inspected, there were at least two different vegetation species.

Considering the age of the biofilters, the vegetation in the majority of the bioswales appeared healthy and established. The percentage coverage in the biofilters will only improve with time. According to the data provided from the municipalities, sixteen facilities (at sites 1, 3–5, 8–11, 19–21, and 22–26) have included aesthetic objectives into their design. The inspections showed that all the facilities at their age looked fresh and aesthetically pleasing, except site 11 which suffered from invasive weeds, dry vegetation, debris, trash, sediments, and generally a lack of proper maintenance. Therefore, the majority of them fulfilled this specific aim.

The keys to sustaining vegetation health are choosing species adapted to local conditions, ensuring regular maintenance of the pre-treatment stages and cleaning out curb openings to prevent blockages. For the curb openings, redesigning them with larger openings might be advisable.

![Fig. 5. Examples of biofilters with (a) poor plant health (site 12), and (b) diversity of vegetation (sites 19).](image-url)
4. Conclusion

Considering that the biofilter surface area is typically between 2 and 6% of the contributing catchment area, only seven out of twenty-six sites inspected were within this recommended range. While some facilities seemed to be in good order and well designed, one or more issues were observed at many facilities. The inspections revealed both design and maintenance deficiencies, such as low ponding and/or storage volumes, filter media compaction, clogging or deposition of sediments and trash in the pre-treatment stage and/or biofilter itself, uneven plant distribution, overgrown plants, and the existence of invasive vegetation. Some facilities were even designed differently from their aims, e.g. flood protection was considered as the objective but the design had no ponding volume or a sufficiently-sized inlet. This underlines the importance of quality control of design, construction and maintenance when there are still no specific guidelines for biofilter system design available in Sweden.

One of the most important functional issues observed was the insufficient surface ponding volume in the sites where water retention and/or flood protection were targeted. To assess the water retention capacity of a number of the biofilters surveyed, the actual surface ponding volume was compared with the ponding volume needed to capture a 20 mm of design storm. Drawdown time was also calculated based on field-tested hydraulic conductivity rate data. Results showed that the most biofilters had sufficient drawdown time (<12 h). However, observations on retention capacity revealed that ten biofilters (sites 1, 3, 9, 10–14, 18, and 21) need immediate structural modification to restore their functionality so that adequate water retention and flood protection can be achieved. One facility (site 14) did not meet either drawdown time condition or sufficient ponding capacity, although water retention had been prioritised. A high deposition of sediment, very low HLR, and poor hydraulic conductivity were the reasons for that.

One of the main cause of impaired functionality of the biofilters was pre-treatment stages in poor condition (i.e. sediment or litter accumulation). The condition of the pre-treatment stage had a strong correlation with the hydraulic conductivity rate. Biofilters with pre-treatment stages in good condition had higher hydraulic conductivity rates than those biofilters with insufficient facilities or in poor condition. The inclusion, size, and maintenance of pre-treatment stages in biofilters are critical for preserving functionality. Nine facilities (sites 2, 9, 15, 16, and 22–26) will become less functional if pre-treatment maintenance or structural modifications continue to be neglected.

The site’s physical characteristics (i.e. soils and vegetation) affect the biofilter’s operation but the properties of the catchment area also have a large impact on the performance of a biofilter. The type of catchment should be considered when determining the maintenance frequency. Transportation-related impervious areas are known to have higher sediment load concentration than rooftops. Based on our comparison of four rooftop catchment areas and the other transportation-related catchment areas, the biofilters receiving rooftop runoff had comparatively higher conductivity rates and less visible signs of surface compaction and clogging. Biofilters receiving runoff from impervious areas associated with transportation activities should account for the likely larger loads of sediments by increasing the size of pre-treatment stages. Additionally, maintenance of biofilters receiving runoff from transportation areas should occur more frequently.

Approximately 60% of the biofilters surveyed across Sweden were acceptably functional and achieved the objective of water retention. The operational and maintenance issues need to be addressed for the biofilters in order to remain in optimal condition. The primary maintenance activities needed are removing sediment from pre-treatment stages and pruning vegetation. Structurally, two biofilters had undersized and blocked curb openings. The curb openings should be enlarged and installed in more than one location. Additionally, steep side slopes at sites need to be stabilised to prevent further erosion. These maintaining activities, if not addressed in a timely manner, could cause the biofilter to become ineffective in providing treatment or retention.

Analyses of the practical operation of biofilters like this study will reveal issues with implemented facilities and provide science-based performance estimates. As stated above, >1000 peer-reviewed scientific studies have been published on the performance of stormwater biofilters. Despite that broad knowledge base, our results show that design, construction and/or maintenance of a considerable ratio of implemented facilities does not incorporate this state-of-the-art of science and technology. This emphasises the need for more and/or better dissemination of research results concerning (not only) stormwater biofiltration.

Declaration of competing interest

There is no conflict of interest in this research.

Acknowledgement

The authors thank the biofilter operators for their support and Frieder Hamann for his help carrying out the field work. This work was supported by VINNOVA (grant number 2016-02518) and The Swedish research council Formas (grant number 2016-20074). The study was conducted within the frame of the research centre DRIZZLE (VINNOVA grant number 2016-05176).

Appendix A. Supplementary data

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Credit author statement

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