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► To cite this version:

Alexandre Fardel, Pierre Emmanuel Peyneau, Béatrice Bechet, Abdel Lakel, Fabrice Rodriguez. Analysis of swale factors implicated in pollutant removal efficiency using a swale database. *Environmental Science and Pollution Research*, 2019, 26, 44 p. 10.1007/s11356-018-3522-9 . hal-02000972

HAL Id: hal-02000972

<https://hal.science/hal-02000972>

Submitted on 2 Mar 2022

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1 Analysis of swale factors implicated in pollutant removal efficiency using a swale
2 database

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26 **Abstract**

27 Swales are recognized as traditional basic open-drainage systems which are obviously capable
28 to remove stormwater-borne pollutants. In spite of the numerous case studies on their
29 performances, an overall assessment of swale efficiency to reduce pollutant discharge as well
30 as an evaluation of the factors that could influence it are rare. In order to gain a better
31 understanding of these aspects, a database was designed by collecting performance results and
32 design characteristics from various swales reported in the literature. Investigations on
33 correlations amongst pollutant efficiency ratios (ERs) indicated that total trace metals (copper
34 (Cu), zinc (Zn), cadmium (Cd) and lead (Pb)), total suspended solids (TSS), total phosphorus
35 (TP) and total kjeldahl nitrogen (TKN) exhibited many cross-correlated ERs, thus suggesting
36 that they are mainly removed by the same processes in swales. Higher ERs were generally
37 related to pollutants in particulate form, suggested that sedimentation and filtration should be
38 considered as major processes involved in pollutant removal within swales. Furthermore, major
39 discrepancies amongst swale performances may be attributed to variations of site mean inflow
40 concentrations, found as the most recurrent factor influencing ER. Conversely, swale design
41 factors were rather poorly correlated with ER, except swale length, positively correlated with
42 TP and copper.

43

44 **Key words:** swales, database, stormwater, pollutant removal, efficiency ratios, design factors

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51 **1. Introduction**

52 A growing trend in stormwater management to cope with urbanisation harmful effects on both
53 stormwater runoff quality and quantity consists in implementing at subcatchment scale
54 techniques that reduce runoff discharges and improve stormwater quality (Ahiablame et al.
55 2012; Hamel et al. 2013; Petrucci et al. 2013; Sage et al. 2015). Such techniques materialize
56 implementation of new operational philosophies aiming to manage stormwater in a more
57 sustainable, aesthetical and social way than conventional pipe elements (Mitchell 2006); these
58 innovative devices are gathered under specific terminologies as low impact development (LID),
59 water sensitive urban drainage (WSUD), sustainable urban drainage systems (SUDs), best
60 management practices (BMPs) and alternative techniques (ATs) (Fletcher et al. 2015).

61 Among these new approaches, swales are traditional basic open-drainage systems
62 initially designed to mitigate peak flows arising from impervious areas such as roads or parking
63 lots (Wang et al. 1980; Clar et al. 2004). As an integral element of new stormwater management
64 philosophies (Ahiablame et al. 2012), implementation of swales attracted renewed interest for
65 (i) mimic a site's predevelopment hydrology and (ii) purify stormwater through removing
66 stormwater-borne pollutants at an affordable cost (Dierkes et al. 2000; Revitt et al. 2003;
67 Caltrans 2004; Lucke et al. 2014; Woods Ballard et al. 2015). In order to support swale
68 development, several stormwater management handbooks provide methods to efficiently
69 design these drainage infrastructures (Melbourne Water 2006; Credit Valley Conservation and
70 the Toronto and Region Conservation Authority 2010; Gromaire et al. 2011; Washington State
71 Department of Ecology 2014; Center for Watershed Protection 2015; Woods Ballard et al.
72 2015). In terms of design, these manuals generally discriminate three or four types of swales:
73 (1) standard swales, (2) wet swales, (3) dry swales and (4) bioswales (Woods Ballard et al.
74 2015). Standard swales may refer to natural grassed depressions or to graded grassed channels.
75 Dry swales can either refer to swales with a sandy soil meaning that they drained inter-event

76 (Winston et al. 2012b) or to infrastructures provided with an engineered media to promote better
77 infiltration and filtration of pollution load (Revitt et al. 2017). Wet swales gathered facilities
78 where wetland conditions dominated such as ponded water, soil moisture close to the saturation
79 (*e.g.*, swales build on soil with high water table) and emergent vegetation (Winston et al.
80 2012a). Bioswales incorporate biofiltration swales, biofilters and bioretention swales or swale-
81 trench systems; this type of swale employs an engineered filter soil media below vegetal cover
82 that may overlay an underdrain or be lined with an impervious material to prevent any
83 groundwater contamination by controlling seepage flows (Toronto and Region Conservation
84 Authority 2008).

85 Technically, hydraulic processes of swale contribute to reduce both magnitude and
86 volume of flows before potentially being discharged into either downstream drainage elements,
87 such as inlet of sewers or other LID techniques (*e.g.*, wet or dry pond), or grasslands (Lloyd et
88 al. 2001; Roinas et al. 2014; Allen et al. 2016; Xiao et al. 2017). While stormwater flowing
89 through the swale, a wide range of stormwater anthropogenic substances are candidate to be
90 sequestered within the facility. The main corresponded contaminants referred to organic or
91 inorganic substances and are of diverse nature: (i) Total Suspended Solids (TSS) which may
92 sorbed to both hydrocarbons (especially Polycyclic Aromatic Hydrocarbons (PAHs)) and trace
93 metals (Lau and Stenstrom 2005; Kim and Sansalone 2008), (ii) nutrients involving both
94 nitrogen and phosphorus species (Ingvertsen et al. 2011) and (iii) trace metals (*e.g.*, lead (Pb),
95 zinc (Zn), copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni)) (Kayhanian et al. 2012).

96 Distinct treatment processes related to swale hydraulics are involved in the stormwater
97 pollutant removal. On the one hand, stormwater transport over gentle slope area as the swale
98 bed promotes trapping of contaminants in particulate form through sedimentation and vegetal
99 filtration (Deletic 1999; Purvis et al. 2018). On the other hand, subsurface flows within swale
100 materials are involved in the implementation of retention, degradation and transport

101 mechanisms of pollutants in soil (LeFevre et al. 2014; Tedoldi et al. 2016). Since attenuation
102 of runoff flow is in favor of a pollutant removal, hydraulics driving factors affecting the
103 hydraulic residence time (HRT) may be addressed as influent variables for pollutant removal
104 in swales (Yu et al. 2001; Johnson et al. 2003). In this particular regard, a few case studies have
105 examined the effects of swale geometry, swale materials and swale vegetal cover on pollutant
106 removal (Yousef et al. 1985; Bäckström 2002; Roseen et al. 2009; Stagge et al. 2012; Winston
107 et al. 2012a; Lucke et al. 2014; Powell 2015; Leroy et al. 2016b). Results of these studies
108 suggested that several design variables could be important to pollutant removal, such as swale
109 length, centerline slope (Yu et al. 2001), presence of check dams (Stagge et al. 2012), vegetation
110 (Mazer et al. 2001) and type of swale (Winston et al. 2012a).

111 The performance of swales for improving water quality may be expressed in two distinct
112 terms (Fassman 2012): (i) percent removals, which are directly calculated from raw data as
113 concentrations or loads and (ii) characterization of outflows, including either a comparison with
114 inflows or an analysis of the distribution of the data (e.g., probability plot). Among these
115 methods, efficiency ratio (ER) is a ratio between mean pollutant input and output (Roseen et al.
116 2009) and could be considered to a long term average percent removal rate for each constituent
117 analysed (Urbonas 1994). Using a single concentration reduces scatter in the data caused by
118 influent quality heterogeneity, so giving ER results in a more stable estimation of overall
119 treatment performance rather than adopting mean or median removal efficiencies based on a
120 storm-by-storm basis (Roseen et al. 2009). In that way, this descriptor could be useful to
121 evaluate the potential of treatment for such devices (Fassman 2012), as well as identify the
122 factors of influence on their ability to remove pollutants.

123 The exact nature of factors influencing ERs by swales remains to be fully characterized.
124 To gain insight about this point, the present study was designed to investigate relationships
125 between ERs and factors concerning swale design and runoff quality. For this purpose, we have

126 established an original swale database by collecting performance results and design features
127 from various distinct swales characterized in the literature. Potential relationships between ERs
128 were studied to credit the supremacy of specific removal processes in stormwater treatment
129 within swales. Additional statistical analyses were performed to investigate the influence of
130 certain design criteria and inflow concentration on swale efficiency.

131

132 **2. Materials and methods**

133 **2.1 Overview of the method used for collecting and analyzing data**

134 The methodology used to collect and analyze data is summarized through a diagram (Figure 1).
135 This conceptual scheme gathered four steps together, presented below; (1) raw data collection,
136 (2) data filtration to feed the final data set, (3) data range representations and (4) statistical
137 approaches to analyze the data.

138

139 **2.2. Data collection**

140 To produce a database containing indicative information about pollutant removal in swales, a
141 literature search was conducted using standard research database (e.g., Web of Science,
142 ScienceDirect, Google Scholar). For this purpose, we used keywords related to swale type (e.g.,
143 ‘swale’, ‘grassed swale’, ‘dry swale’, ‘wet swale’, ‘bioswale’, ‘bioretention swale’), pollution
144 removal (e.g., ‘swale pollutant removal’, ‘swale performances’ and so on) and swale inputs
145 (e.g., ‘swale stormwater’). In addition to peer-reviewed journal papers, reports, technical notes,
146 proceedings, master thesis and Ph.D dissertations were considered. This online search
147 comprises studies conducted up to May 2018. The produced data set has been filtered again to
148 exclude studies either with (i) weak number of monitoring events (*i.e.*, $n < 3$) or (ii) several
149 locations of outflow (*i.e.*, two distinct outlets to discharge surface and subsurface outflows) or

150 (iii) median values without access to raw data. On this last point, mean as an estimator was
151 chosen because more studies provided their results through this parameter.

152 All appropriate studies used one of the three sampling designs that are often considered:
153 flow interval, time-interval, and random grab sampling (Leecaster et al. 2002). On this point,
154 continuous auto-sampling using time-weighted or flow-weighted methods is often considered
155 the most robust for creating a mixed sample of a part of the complete runoff, which gives direct
156 access to the event mean concentration (EMC) (Lee et al. 2007). Although mixing grab samples
157 does not necessarily provide access to EMC, studies using this sampling method were also
158 included in the database. Among the selected studies, ER was used by the authors as the
159 reference metric to assess swale performance; it can be defined mathematically as: $ER = 1 -$
160 $\text{average EMC}_{\text{Outlet}}/\text{average EMC}_{\text{Inlet}}$ (Roseen et al. 2009). ERs were either set for in the screened
161 documents or calculated from concentrations for the purpose of this study.

162 It is worth mentioning that one document can discuss about several swales; the largest
163 contributor document fed the database with six swales. The whole selection process finally
164 yielded 59 swales fulfilling the aforementioned criteria, against 103 swales at the beginning of
165 the filtration process. One important step was to ensure that each swale was only considered
166 once, although it might have been described in distinct documents. Exceptions to this rule have
167 been taken for either discontinuous monitoring program involving the same swale or swale
168 design modifications (e.g., length divided by 2, retrofitting swale with check dams).

169 Following the database constitution, an identification number (ID) has been imputed to
170 each swale in order to facilitate its referencing. The generic characteristics of the swales used
171 for this study, such as the site name, the location (country) and the land use (i.e., catchment
172 specifications), are summarized in Table S1. This table includes data about the facility scale
173 which has three levels of details: (i) field-scale swale refers to a monitoring facility which is
174 already in operation (i.e., not designed by the investigators), (ii) technical field-scale swale

175 means that the facility or the contributing area have been designed or retrofitted by researchers
176 and implemented on the field for the purpose of the study and (iii) technical-scale swale defines
177 a facility which has been designed and implemented in a pilot system, e.g., a test bed system
178 (Hood et al., 2013) or any other type of device structures (Bäckström, 2002; Li et al., 2016;
179 Nara and Pitt, 2006). Furthermore, the water supply of swales is also considered as a parameter,
180 since runoff could be generated by a storm event or a simulated event.

181 Other relevant factors including the surface of the drainage catchment, the ratio area and
182 the type of swale are also informed in Table S1. When not reported, the swale area and the ratio
183 area were determined by multiplying the swale top or average width by its length and by divided
184 the swale area by the drainage area, respectively. To determine the type of swales, four
185 categories were selected: standard swale, dry swale, wet swale and bioswale. All facilities called
186 ‘swale’, ‘grass swale’, ‘grassy swale’, ‘grassed swale’, ‘planted swale’, ‘vegetated roadside
187 swale’, ‘grassy median’ were indexed as standard swales. Swales described as wet or dry swales
188 are indexed as such, as well as sandy soil swale monitored by Hood et al. (2013) indexed as
189 ‘dry swale’ considering its good capacity of drainage (sandy soil). Remaining facilities were
190 indexed as bioswales; this is the case for ‘bioswale’, ‘biofiltration swale’, ‘bioretention swale’,
191 ‘infiltration swale-trench’ and ‘stone-lined swale’.

192 Swale geometry involving swale length, top or average width, bottom width, cross-
193 section shape, centerline slope, side slopes and swale area was schematically represented in
194 Figure S1. Information about the design of each swale included in the database is available in
195 Table S2. Moreover, inlet and outlet mean concentrations, as well as ERs and design
196 considerations are gathered together for each pollutant in Table S3 to Table S13 (See
197 Supplementary content).

198

199 **2.3. Data analysis**

200 The efficiency of swales to treat stormwater was evaluated through ERs. In order to evaluate
201 the effective capacity of swale to remove a specific pollutant, data were examined through box
202 and whisker plots to show the shape of the distribution, the central value, and its variability.
203 Censored or range values were not reported in the graphical representations.

204 In addition, the quality of incoming runoff and apparently important design variables,
205 such as length, ratio area, centerline slope and side slope, have been selected to potentially
206 reveal correlations with ERs. Because of the non-normal distribution of most parameters,
207 nonparametric statistical approaches were subsequently used in this study, following the
208 example of Huber and Helmreich (2016).

209 Correlations between pollutant ERs were conducted using the Spearman's ρ correlation.
210 Each coefficient obtained from this analysis measures the strength and direction of a monotonic
211 relationship between two paired data (Pavlineri et al. 2017). Hence, for correlated data, degree
212 of correlation was analyzed through ρ interpretation as a small ρ value (≤ 0.39) means a weak
213 correlation, a medium ρ value ($0.40 \leq \rho \leq 0.59$) means a medium correlation and a high ρ value
214 (≥ 0.60) expresses a strong correlation (Huber and Helmreich 2016). Similarly, exploration
215 regarding potential relationships between ERs and selected factors was performed using the
216 Spearman method. The relationships between the relevant factors, i.e., whether they are or not
217 independent, were subsequently examined using Spearman tests. All statistical calculations
218 were performed using the Graph Pad Prism Software. An alpha p value of 0.05 was used for all
219 statistical tests to reach significance.

220

221 **3. Results**

222 **3.1. Database elements and swale design parameters**

223 **The overall characteristics of the swale database are summarized in**

224 Table 1. Seventy-five percents of the facilities are from the USA. Standard swales and
225 bioswales each accounted for about half of the whole dataset. The majority of swales were both
226 implemented on the field (68%) and supplied with natural storm events (93%). In terms of
227 contributive area specifications, roadside swales are the most prevalent facilities in the database
228 (64%), far before parking lot swales (27 %) and suburban/urban residential swales (9%). This
229 partly explained that swales in the database were predominantly fed by direct diffuse runoff
230 (61% of the dataset), since roadside swales or parking lot swales widely received lateral inflow
231 from the edge of pavement (Figure S1 c). Pollutant removal processes occurring in the soil of
232 swales are less considered in the studies, as the surface waters were mainly sampled (78%).
233 Furthermore, the database shows variability concerning the nature of analyzed pollutants;
234 classification of pollutants according to the number of collected data is the following: TSS >
235 total phosphorus (TP) > zinc > Total Nitrogen (TN), copper > lead. Although TSS is nearly
236 ubiquitous in the database (98%), data available for dissolved nutrients (nitrate and nitrite (NO_x^-
237 -N) and nitrate ($\text{NO}_3\text{-N}$)) are more limited (32%).

238 Some geometrical aspects of swale design, such as the structurally interrelated
239 parameters length, swale area and ratio area, exhibit rather important dispersions, as
240 demonstrated by boxplot representation of the data (Figure 2) and determination of basic
241 descriptive statistical parameters (Table S2). In the case of swale length for example, its
242 distribution displayed a central value of 51.5 m encase by a wide extend between 4 m and 1055
243 m (Figure 2), with a coefficient variation of 152 % (Table S2). Ratio area varies between 0.1
244 and 192%; its median (20%) is however at the upper boundary or slightly higher than the
245 recommended intervals (e.g., 5-10% or 5-20%) which can be found in technical manuals
246 (Beenen and Boogaard 2007; Credit Valley Conservation and the Toronto and Region
247 Conservation Authority 2010). Conversely, coefficient variations for side slopes and top and

248 bottom widths (about 60 – 100 %), were smaller than for those for length and swale area (Table
249 S2). This is likely due either to the narrow intervals which are suggested in the manuals to
250 prevent erosion (for slopes) or to the visual definition of swales – a shallow ditch (for width).
251 Regarding cross-section shape, results show most of the swales were either triangular (16
252 swales) or trapezoidal (24 swales) (Table S2); this again may reflect the content of design
253 handbooks where trapezoidal shape is spotlighting for its traditional good hydraulic
254 performance and longer operation life (Woods Ballard et al. 2015).

255 **Most of the swales referenced in the database were covered by vegetation. Although grass**
256 **was traditionally selected, mix of plants is increasingly incorporated into swales (planted**
257 **swale) either to be adequate to site condition (e.g., hydric soils, deicing salts in stormwater)**
258 **or to favor sedimentation and improve contaminants biodegradation (Leroy et al. 2016a).**
259 **As presented in**

260 Table 1 and Table S2, grassed swales prevailed over planted swales and constituted at
261 least 75% of the dataset. Among grassed swales, grass mixtures contribute to almost half of the
262 vegetal covers (Table S2). It is noticeable that planted swales quasi exclusively referred to either
263 wet swales or bioswales (Table S2).

264

265 **3.2. Pollutant removal in swales**

266 The distribution patterns of ERs for pollutants are presented in Figure 3. Among pollutants,
267 proportions of positive ERs emphasized important variations. Thus, for TSS, TKN, nitrate, and
268 trace metals such as lead, zinc, copper and cadmium, ERs were positive for at least 70% of the
269 involved swales. By contrast, 40 to 74% of the swales did not reduce NO_x^- -N, TN, TP and
270 dissolved phosphorus (DP). Therefore, pollutants in particulate form (trace metals and TKN)
271 seem to be mainly retained in swales. In agreement with this conclusion, ER for TSS was found
272 to be rather strongly positively correlated ($\rho \geq 0.60$) with those for TKN, copper and cadmium
273 (Table 2); it was additionally correlated to those for TP, TN, lead and zinc, but in a more

274 moderate manner ($\rho < 0.60$). NO_x^- -N, NO_3 -N and DP were the only pollutants not correlated to
275 TSS (Table 2). Significant Spearman correlations were found between ERs for the nitrogen
276 species TN and TKN and ER for TP (Table 2). ER for TN was logically strongly positively
277 correlated to ERs for other N-related parameters such as TKN, NO_x^- -N and NO_3 -N ($\rho \geq 0.60$); it
278 is additionally strongly correlated with ERs for the trace metals lead, zinc and copper (Table
279 2). ER for TP was correlated to those for DP and copper (Table 2). Other significant positive
280 correlations for ERs were found for TKN with zinc, copper and cadmium, and for NO_3 -N with
281 zinc (Table 2). Finally, ERs for the trace metals lead, zinc, copper and cadmium were strongly
282 correlated between them (Table 2). A schematic graphical representation of significant
283 correlations between ERs for pollutants is shown in Figure 4. It clearly illustrates the fact that
284 TSS, TKN and the trace metals zinc and copper were the pollutants exhibiting the higher
285 number of significant correlations with ERs of other pollutants.

286

287 **3.3. Factors involved in swale efficiency**

288 Implication of various factors, *i.e.*, inflow pollutant concentrations and various swale design
289 characteristics, in swale efficiency was studied through analyzing correlations between these
290 factors and pollutant ERs. As shown in Table 3, pollutant inflow concentrations were found to
291 be significantly and positively correlated with ERs for all the pollutants, except for NO_3 -N, lead
292 and cadmium. Swale length was correlated with ERs for TP, TN, NO_x^- -N, zinc and copper.
293 Additionally, centerline slope was correlated with ERs for NO_x^- -N and lead, and side slope with
294 ER for TN (Table 3). No pollutant ER was correlated with the ratio area. To determine whether
295 swale design parameters found to be correlated with pollutants ER may be linked to inflow
296 concentrations, additional Spearman correlations were performed (Table 4). As indicated in
297 Table 4, pollutant inflow concentrations were significantly correlated to swale length for TN
298 and NO_x^- -N; pollutant inflow concentration was also correlated to swale side slope for TN. A

299 trend to correlation was also observed for zinc inflow concentration and swale length
300 ($p=0.0599$), and $\text{NO}_x\text{-N}$ inflow concentration and swale centerline slope ($p=0.0820$). Only
301 copper and TP inflows were not correlated at all to swale length (Table 4), thus suggesting that
302 length may constitute robust inflow-independent parameters implicated in copper and TP
303 removal by swales.

304

305 **4. Discussion**

306 The original database designed for this study provides representative information on the
307 variability of swale performances through a data compilation from geographically and
308 climatically diverse sources. Although three quarters of its studies were from the USA, our
309 database was more extensive than the International Stormwater BMP Database (ISBD, (Clary
310 et al. 2017)) which quasi exclusively contains swale case studies from the USA. Furthermore,
311 our database compiled very diverse information in terms of swale design, installation or
312 maintenance, as well as sites exposed to contrast levels of runoff pollution and hydrological
313 conditions. All these aspects have enabled us not only to assess swale efficiency in removing
314 pollutants but also to investigate from a variety of data some selected factors that could
315 influence it.

316 The greatest swale efficiencies were observed in pollutants which tend to attach to solid
317 particles, i.e., TSS, total trace metals and nutrients including a particular form. These results
318 were in accordance with previous findings from the ISBD; for example Barrett (2008) has
319 shown median concentration attenuation of 60%, 60% and 62% for TSS, zinc and copper,
320 respectively. In addition, median ERs of trace metals fluctuate between 60% and 75% in our
321 database, so close to the recurring removal threshold of 75% mentioned by Leroy et al. (2016b).
322 Concerning effluent quality at surface outlet, TSS, TP, TN, TKN and trace metals are
323 effectively removed in swales via physical mechanisms such as sedimentation and vegetal

324 filtration (Stagge et al. 2012; Boger et al. 2018), which are likely to be the main treatment
325 processes occurring as water flows within the facility (Deletic 1999; Bäckström 2002; Deletic
326 and Fletcher 2006). Additionally, positive correlations observed between ERs of trace metals
327 and TSS could firstly be explained through their physical speciation in runoff, that means
328 pollutants fully or partially bound to particles (Djukić et al. 2016), and subsequently may
329 emphasize the importance of efficient suspended solids removal, through settling or filtration,
330 in mitigating trace metal concentrations in swales (Stagge et al. 2012).

331 Further exploration on the removal hierarchy of particular pollutants need to be examine
332 through their occurrence and partitioning in urban runoff. Concerning removal of trace metals
333 in the present study, the grading established from median ERs and interquartile ranges (IQR)
334 followed the order: zinc > lead – cadmium > copper. This classification is slightly distinct from
335 other swale studies where copper may be ranked either ahead of zinc (Leroy et al. 2016b) or
336 lead and cadmium (Stagge et al. 2012; Revitt et al. 2017). From previous studies, lead should
337 be mostly in the particulate phase (Legret and Pagotto 1999; Ingvertsen et al. 2011; Kayhanian
338 2012) whereas cadmium could be freer or associated with dissolved solids (Makepeace et al.
339 1995), as well as zinc and copper may have the highest dissolved concentrations in urban runoff
340 (Gromaire-Mertz et al. 1999; Mosley and Peake 2001; Huber et al. 2016). Additionally, copper
341 is known to be mostly attached to organic particles and colloids in the form of complexes
342 smaller than 0.45 μm (Bäckström et al. 2006). Since swales could preferentially remove larger
343 particles than about 20 μm (Bäckström et al. 2006; Deletic and Fletcher 2006; Nara and Pitt
344 2006; Lucke et al. 2014), this may explain why copper was removed in swales to a lesser degree
345 than other metals. Conversely, possible explanation for the greatest removal shown by zinc
346 could be its prevalence in urban runoff (Kayhanian et al. 2012; Stagge et al. 2012; Huber et al.
347 2016). At first sight, degrees of correlations between ERs of trace metals and TSS are a bit
348 surprising because deviate from the aforementioned traditional observations. Unlike weak

349 correlation with TSS involved lead, copper and cadmium were strongly associated with
350 suspended solids. These dissimilarities might be partly explained by the variability of particle
351 size distributions (PSD) of water samples that likely populate the dataset used in this study
352 (Ingvertsen et al. 2011; Kayhanian et al. 2012). Considering the fine particle fraction often
353 carries the largest load of particle-associated pollutant (Sansalone and Buchberger 1997; Lau
354 and Stenstrom 2005), a predominance of small particles (e.g., $< 63 \mu\text{m}$) in stormwater inflow
355 makes their removal by sedimentation difficult. Another possible explanation for weak
356 correlation between ERs of lead and TSS could be that the distribution of lead inflow
357 concentration in the database is mainly dominated by lower concentration than that of copper,
358 which could lead to lower efficiency ratios (Winston et al. 2012a). This, however, is considered
359 a very conservative assumption because correlation results assign to cadmium ER the strongest
360 relationship with TSS, despite extremely low inflow concentrations ($< 3 \mu\text{g/L}$).

361 Removal of nutrients in swales requires also to be discussed through their speciation.
362 Regarding phosphorus, Morquecho et al. (2005) found that TP could be highly removed from
363 stormwater through retaining particles taller than $20 \mu\text{m}$ so its attenuation in swales may mainly
364 drive by sedimentation (Boger et al. 2018). This expectation tends to be confirmed by two
365 results of our database, (i) the significant correlation between ERs of TP and TSS and (ii) the
366 wide extent of TP ERs. Large fluctuations of TP removal has been reported in other studies
367 (Mazer et al. 2001; Yu et al. 2013; Jiang et al. 2017) and could be partly explained by the trend
368 for phosphorus to be adsorbed to very fine particles ($< 50 \mu\text{m}$) which hardly settled (Stagge et
369 al. 2012), so efficiency of sedimentation is reduced in this case. Meanwhile, TP contains a
370 dissolved form (dissolved phosphorus) which remains more of a challenge to remove according
371 to the quasi-exclusive negative DP ER values stored in the database. DP attenuation could be
372 attributable to geochemical processes occurring after infiltration, such as sorption to aluminium
373 (Al) and iron (Fe) oxides, and precipitation (Li and Davis 2016). Nonetheless, the

374 aforementioned inefficient performances suggest that swales could easily enrich stormwater
375 with soluble phosphorus. For surface runoff, this export of phosphorus may result from
376 resuspension or scouring of organic matter (OM) and for percolated water, leaching of OM is
377 generally incriminated (LeFevre et al. 2014; Li and Davis 2016). Such increases in discharge
378 of DP should be a matter of concern for the preservation of aquatic ecosystems since it is more
379 bioavailable than TP (Cederkvist et al. 2016).

380 Similar to phosphorus, distinctive results for nitrogen species suggest that treatment
381 patterns depend on the nature of each component. The strong correlations between ERs of TKN
382 and TSS may be the consequence of settling of TKN, caused by its particulate organic
383 component (Stagge et al. 2012; Boger et al. 2018). Conversely, the slightly lower removal of
384 TN coupled with a medium correlation with TSS ER may be explained by its predominant
385 dissolved form in runoff (Taylor et al. 2005); this potentially involved weaker removal by
386 sedimentation than for TKN (Stagge et al. 2012). Although ER's distributions of oxidized
387 nitrogen compounds (nitrate and nitrite) display frequent positive values, the absence of
388 correlations with TSS ER suggests that sedimentation should not be a particular contributor to
389 their removal. Performances reported in this study could thus be expected to depend on
390 infiltration, plant uptake and denitrification (Stagge et al. 2012; Winston et al. 2012a).
391 Additionally, the variability of NO_x^- -N ER validates the consensus regarding the complexity to
392 predict nitrogen species removal in swales (Revitt et al. 2017). When soluble and organic
393 nitrogen enrichment of stormwater occurring within the facility, this suggests there is a
394 supplementary source of nitrogen that is readily mobilized and mixed with runoff. Runoff
395 enrichment in nitrogen could be due to degradation of organic elements or discharge of high
396 quantities of grass and weed debris deposited on swale bed after frequent maintenance periods
397 (Yousef et al. 1985; Yu et al. 2001).

398 For investigating potential influential factors of ERs in the study reported herein, the
399 preference was given to variables already be highlighted from previous studies. As reported by
400 others (Yu et al. 2001; Barrett 2005; Stagge et al. 2012; Winston et al. 2012a; Leroy et al.
401 2016a), efficiency of pollutant removal in swales may be dependent on incoming runoff quality
402 and swale design. In this study, only site mean influent concentration as well as major factors
403 which drive swale capacity to manage runoff and were well documented in the database, as
404 swale length, centerline slope, side slope and ratio area, were used to attempt to explain
405 discrepancies between swales. Our data indicate that pollutant inflow concentration is a main
406 factor correlated with ER, for various pollutants, including TSS, TP, TN, TKN, $\text{NO}_x\text{-N}$, zinc,
407 copper and cadmium. For these pollutants, ERs increase with inflow pollutant concentrations,
408 suggesting that their removal mechanisms are more efficient by increasing inflow pollutant.
409 Such data also support the idea that low inflow pollutant concentrations may results in low ER.
410 This hypothesis is fully supported by the fact that negative ERs were often reached in low
411 influent concentration conditions. It is particularly reported for influent TSS concentrations in
412 the range of 0-50 mg/L (Bäckström et al. 2006; Andrés-Valeri et al. 2014; Purvis et al. 2018),
413 which could be enriched by scouring of sediments during water flow in swale (Lucke et al.
414 2014). In contrast, removal of dissolved pollutants (nitrate) seems to be much less sensitive to
415 the “influent effect”, implying that other factors (e.g. soil physicochemical properties) may
416 mainly regulate their attenuation within swales.

417 With respect to swale design factors, length was found as an inflow-independent factor
418 positively correlated to ER only for TP and copper, but not for other pollutants. The reason for
419 which TP and copper ERs depend on swale length remains to be determined. Indeed, although
420 length have repeatedly been considered as an influent factor on the trapping of particles (Yu et
421 al. 2001; Bäckström 2002; Winston et al. 2016), the trend to increase sediment reduction by
422 raising length could rapidly reach an asymptote in sloped grassed areas (Deletic 1999), and

423 most of our results were consistent with the fact that installation of long swales (e.g., length >
424 15 - 30 m) is not necessary to efficiently remove particles (Lucke et al. 2014). In the same way,
425 increasing centerline slope could slightly attenuate TSS reduction in swales (Yu et al. 2001;
426 Winston et al. 2016) but there is no evidence to validate this trend since more than 75% of
427 centerline slopes in the database were below 2%. The reason why lead ER was correlated to
428 centerline slope also remains to be determined. Overall, it is noteworthy that most of swale
429 designs parameters were not correlated to pollutant ER. This suggests that the variations in
430 swale factors found in our database did not influence ER, excepted for length and ERs of TP
431 and copper.

432 The present study suffers from various limits arising from (i) the heterogeneity of
433 monitoring methods used in each study to sample events and analyse pollutant concentrations,
434 and (ii) the adopted methodology to analyse the database. Concerning the first point, studies of
435 the database exhibited various types of sampling method, which may affect the
436 representativeness of resultant concentrations in terms of pollutant discharges by storm events.
437 On this aspect, flow-weighted or time-weighted sampling might give access to EMC whereas
438 manual (grab) sampling produces several subsamples which could be subsequently mixed to
439 estimate an average concentration of pollutant discharge. Since most of the database studies
440 used the first type of sampling, concentrations utilised to calculate ER might be regarded as
441 representative of entire storm event discharges. Additionally, further differences occur in
442 sample preparation and analytical methods used. Although sample collection and sample
443 preparation seem to be the two main sources of deviation (Huber et al. 2016), determining
444 concentration of pollutant could be highly dependent on detection limits, especially for
445 pollutants generally found in trace concentrations in runoff (e.g., trace metals). In this study,
446 very low concentrations of cadmium in inflow and outflow (0.1 µg/L – 3 µg/L) may suggest
447 that a considerable uncertainty could affect Cd ERs. Furthermore, the adopted methodology to

448 analyse raw data from literature represents a significant part of overall uncertainty. While
449 various sources of discrepancies referred to number of sampled events and duration of the
450 monitoring period, i.e., whether case study covered part of a year or a single year or several
451 years, we consider each ER weighted equally to assess swale efficiency. Since level of runoff
452 contamination as well as hydrological conditions could be highly variable at swale inlet, an ER
453 calculated from a large number of sampled events would generally be more exact in the
454 potential assessment of a site to treat stormwater (Fassman 2012). Previous studies suggested
455 that reliable TSS, TN and zinc site mean concentrations could be achieved through monitoring
456 for 15 to 20 runoff events (Thomson et al. 1997; Drapper et al. 2000), knowing that this
457 minimum threshold could be dependent on the nature of pollutant (McCarthy et al. 2018). In
458 the database, several studies monitored a limited number of storm events (i.e., <15), so their
459 site ERs may be considered as less relevant than those of sites with large number of sampled
460 events (i.e., ≥ 15). Additionally, the selection process of studies to feed the database did not
461 consider hydrological conditions, i.e., inflow flow-rates, initial soil moisture and duration of
462 event, which could directly impinge on ER. While these data were not systematically available
463 in the studies, such information could be useful to explain higher particular pollutant ERs in
464 cases where most of the sampled events for a site had low flow rates, which are likely to favor
465 sedimentation.

466 In addition, this study dealt with pollutant removal in swales only from the perspective
467 of ER to investigate its potential influential factors. Nonetheless, using these approaches on
468 their own can be misleading the evaluation of swale effectiveness because of their strong
469 reliance on additional inputs, e.g., inflow concentrations and influent flow-rate. This is why
470 percent removals, notwithstanding their historic prevalence, are increasingly being criticized as
471 stand-alone parameter (Barrett 2005; Wright Water Engineers and Geosyntec Consultants
472 2007). In addition, there is a current need to investigate the management practice of SUDs in

473 terms of quality assessment to remove pollutant (facility efficiency) without relating to
474 achievements in terms of project goals or effectiveness (Scholes et al. 2008; Fassman 2012).
475 For this reason, other analytic metric tools has been developed such as the probability plots
476 (Fassman 2012; Stagge et al. 2012) which better suit than methods based on a change from an
477 arbitrary starting value. For evaluating effluent stormwater quality variability in the sight of
478 water quality standards, probability plots focus on whether the discharges are likely to adversely
479 affects the receiving ecosystems (Fassman 2012). A complementary method to investigate
480 SUDs efficiency is to examine EMC distributions. On the one hand, such approach leads to
481 explore on whether differences between influent and effluent concentration distributions are
482 statistically significant (Geosyntec Consultants and Wright Water Engineers 2011). On the
483 other hand, specific data from the distributions (e.g., mean, median, IQR) could be selected as
484 a basis for a comparison procedure against regulatory environmental quality standard (EQS) to
485 highlight the environmental risk assessment of stormwater discharge (Ellis et al. 2012).
486 Nonetheless, applying one of these recent methods requires to get raw data, which were not
487 always available in the case of the studies reviewed in our database.

488

489 **5. Conclusion**

490 In the present study, the efficiency of swales to remove TSS, nutrients and total trace metals
491 was investigated by establishing an original database, including ER, design and inflow
492 concentration data. This overall assessment has evidenced that pollutants with a particulate
493 form were generally more attenuated in swales than soluble contaminants. Additionally,
494 statistical analysis has highlighted strong relationships between removals of TSS and other
495 contaminants with a particulate form. This supported that settling and filtration processes
496 mainly drive the sequestration of pollutants from incoming runoff in swales, with an apparent
497 limited effect on the dissolved phase. Moreover, instability of pollutant ER may partly be

498 explained by variations of site mean inflow concentration, emerging as the most striking
499 influential factor on ER. Conversely, various swale design factors, such as length, centerline
500 slope, side slope and ratio area, were not or only poorly correlated with ERs. Such a lack of
501 implication of these design parameters remains however to be confirmed by further studies.
502 Future works should also gain insight on the mitigation of stormwater contaminants during
503 water transfer in soil, while pursuing the current monitoring practices by characterizing more
504 micropollutants, such as PAHs and pesticides, in the particulate and dissolved phases.

505

506 **Funding information**

507 This work, part of the Matriochkas Project, was supported by French Water Agencies, Centre
508 Scientifique et Technique du Bâtiment and Institut Français des Sciences et Technologies des
509 Transports, de l'Aménagement et des Réseaux.

510

511 **References**

512 Ahiablame LM, Engel BA, Chaubey I (2012) Effectiveness of Low Impact Development Practices:
513 Literature Review and Suggestions for Future Research. *Water Air Soil Pollut* 223:4253–4273.
514 doi: 10.1007/s11270-012-1189-2

515 Allen D, Arthur S, Haynes H, Olive V (2016) Multiple rainfall event pollution transport by sustainable
516 drainage systems: the fate of fine sediment pollution. *Int J Environ Sci Technol*. doi:
517 10.1007/s13762-016-1177-y

518 Andrés-Valeri VC, Castro-Fresno D, Sañudo-Fontaneda LA, Rodriguez-Hernandez J (2014) Comparative
519 analysis of the outflow water quality of two sustainable linear drainage systems. *Water Sci*
520 *Technol* 70:1341. doi: 10.2166/wst.2014.382

521 Bäckström M (2002) Sediment transport in grassed swales during simulated runoff events. *Water Sci*
522 *Technol* 45:41–49. doi: <https://doi.org/10.2166/wst.2002.0115>

523 Bäckström M, Viklander M, Malmqvist P-A (2006) Transport of stormwater pollutants through a
524 roadside grassed swale. *Urban Water J* 3:55–67. doi: 10.1080/15730620600855985

525 Barrett ME (2008) Comparison of BMP Performance Using the International BMP Database. *J Irrig Drain*
526 *Eng* 134:556–561. doi: 10.1061/(ASCE)0733-9437(2008)134:5(556)

527 Barrett ME (2005) Performance comparison of structural stormwater best management practices.
528 *Water Environ Res* 77:78–86. doi: <https://doi.org/10.2175/106143005X41654>

- 529 Beenen AS, Boogaard FC (2007) Lessons from ten years storm water infiltration in the Dutch Delta. In:
530 Novatech. Lyon, pp 1139–1146
- 531 Boger A, Ahiablame L, Mosase E, Beck D (2018) Effectiveness of Roadside Vegetated Filter Strips and
532 Swales at Treating Roadway Runoff: A Tutorial Review. *Environ Sci Water Res Technol*. doi:
533 10.1039/C7EW00230K
- 534 Caltrans (2004) BMP Retrofit Pilot Progral. Division of Environmental Analysis, California Department
535 of Transportation, Sacramento, CA
- 536 Cederkvist K, Jensen M, Ingvertsen S, Holm P (2016) Controlling Stormwater Quality with Filter Soil—
537 Event and Dry Weather Testing. *Water* 8:349. doi: 10.3390/w8080349
- 538 Center for Watershed Protection (2015) New York State Stormwater Management Design Manual.
539 Department of Environmental Conservation, NY
- 540 Clar ML, Barfield BJ, O'Connor TP (2004) Stormwater Best Management Practice Design Guide Volume
541 2 Vegetative Biofilters. National Risk Management Research Laboratory. Office of Research
542 and Development. U.S. Environmental Protection Agency, Cincinnati, OH
- 543 Clary J, Jones J, Leisenring M, et al (2017) International Stormwater BMP database: 2016 Summary
544 statistics. Water Environment & Reuse Foundation
- 545 Credit Valley Conservation, the Toronto and Region Conservation Authority (2010) Low Impact
546 Development Stormwater Management Planning and Design Guide, Version 1.0
- 547 Deletic A (1999) Sediment behaviour in grass filter strips. *Water Sci Technol* 39:129–136. doi:
548 <https://doi.org/10.2166/wst.1999.0459>
- 549 Deletic A, Fletcher TD (2006) Performance of grass filters used for stormwater treatment—a field and
550 modelling study. *J Hydrol* 317:261–275. doi: 10.1016/j.jhydrol.2005.05.021
- 551 Dierkes C, Göbel P, Benze W, Wells J (2000) Next generation water sensitive storm water management
552 techniques. In: 2nd National Conference on Water Sensitive Urban Design (2–4 September
553 2000), Brisbane, Australia. p 16
- 554 Djukić A, Lekić B, Rajaković-Ognjanović V, et al (2016) Further insight into the mechanism of heavy
555 metals partitioning in stormwater runoff. *J Environ Manage* 168:104–110. doi:
556 10.1016/j.jenvman.2015.11.035
- 557 Drapper D, Tomlinson R, Williams P (2000) Pollutant Concentrations in Road Runoff: Southeast
558 Queensland Case Study. *J Environ Eng* 126:313–320. doi: 10.1061/(ASCE)0733-
559 9372(2000)126:4(313)
- 560 Ellis JB, Revitt DM, Lundy L (2012) An impact assessment methodology for urban surface runoff quality
561 following best practice treatment. *Sci Total Environ* 416:172–179. doi:
562 10.1016/j.scitotenv.2011.12.003
- 563 Fassman E (2012) Stormwater BMP treatment performance variability for sediment and heavy metals.
564 *Sep Purif Technol* 84:95–103. doi: 10.1016/j.seppur.2011.06.033

- 565 Fletcher TD, Shuster W, Hunt WF, et al (2015) SUDS, LID, BMPs, WSUD and more – The evolution and
566 application of terminology surrounding urban drainage. *Urban Water J* 12:525–542. doi:
567 10.1080/1573062X.2014.916314
- 568 Geosyntec Consultants, Wright Water Engineers (2011) International Stormwater Best Management
569 Practices (BMP) Categorical Summary of BMP Performance Data for Metals Contained in the
570 International Stormwater BMP Database. Water Environment Research Foundation, Federal
571 Highway Administration Environment and Water Resources Institute of the American Society
572 of Civil Engineers
- 573 Gromaire M-C, Veiga L, Grimaldi M, Aires N (2011) Outils de bonne gestion des eaux de ruissellement
574 en zones urbaines. Document d’orientation pour une meilleure maîtrise des pollutions dès
575 l’origine du ruissellement. *Eau Seine Normandie* (in French)
- 576 Gromaire-Mertz M-C, Garnaud S, Gonzalez A, Chebbo G (1999) Characterisation of urban runoff
577 pollution in Paris. *Water Sci Technol* 39:1–8. doi: <https://doi.org/10.2166/wst.1999.0071>
- 578 Hamel P, Daly E, Fletcher TD (2013) Source-control stormwater management for mitigating the impacts
579 of urbanisation on baseflow: A review. *J Hydrol* 485:201–211. doi:
580 10.1016/j.jhydrol.2013.01.001
- 581 Hood A, Chopra M, Wanielista M (2013) Assessment of Biosorption Activated Media Under Roadside
582 Swales for the Removal of Phosphorus from Stormwater. *Water* 5:53–66. doi:
583 10.3390/w5010053
- 584 Huber M, Helmreich B (2016) Stormwater Management: Calculation of Traffic Area Runoff Loads and
585 Traffic Related Emissions. *Water* 8:294. doi: 10.3390/w8070294
- 586 Huber M, Welker A, Helmreich B (2016) Critical review of heavy metal pollution of traffic area runoff:
587 Occurrence, influencing factors, and partitioning. *Sci Total Environ* 541:895–919. doi:
588 10.1016/j.scitotenv.2015.09.033
- 589 Ingvertsen ST, Jensen MB, Magid J (2011) A Minimum Data Set of Water Quality Parameters to Assess
590 and Compare Treatment Efficiency of Stormwater Facilities. *J Environ Qual* 40:1488. doi:
591 10.2134/jeq2010.0420
- 592 Jiang C, Li J, Li H, et al (2017) Field Performance of Bioretention Systems for Runoff Quantity Regulation
593 and Pollutant Removal. *Water Air Soil Pollut* 228:. doi: 10.1007/s11270-017-3636-6
- 594 Johnson PD, Clark S, Pitt R, et al (2003) Metals removal technologies for stormwater. In: *Industrial*
595 *Waster Conference*, WEF, San Antonio, pp 739–763
- 596 Kayhanian M (2012) Trend and concentrations of legacy lead (Pb) in highway runoff. *Environ Pollut*
597 160:169–177. doi: 10.1016/j.envpol.2011.09.009
- 598 Kayhanian M, Fruchtman BD, Gulliver JS, et al (2012) Review of highway runoff characteristics:
599 Comparative analysis and universal implications. *Water Res* 46:6609–6624. doi:
600 10.1016/j.watres.2012.07.026
- 601 Kim J-Y, Sansalone JJ (2008) Event-based size distributions of particulate matter transported during
602 urban rainfall-runoff events. *Water Res* 42:2756–2768. doi: 10.1016/j.watres.2008.02.005

- 603 Lau S-L, Stenstrom MK (2005) Metals and PAHs adsorbed to street particles. *Water Res* 39:4083–4092.
604 doi: 10.1016/j.watres.2005.08.002
- 605 Lee H, Swamikannu X, Radulescu D, et al (2007) Design of stormwater monitoring programs. *Water Res*
606 41:4186–4196. doi: 10.1016/j.watres.2007.05.016
- 607 Leecaster MK, Schiff K, Tiefenthaler LL (2002) Assessment of efficient sampling designs for urban
608 stormwater monitoring. *Water Res* 36:1556–1564. doi: [https://doi.org/10.1016/S0043-1354\(01\)00353-0](https://doi.org/10.1016/S0043-1354(01)00353-0)
- 610 LeFevre GH, Paus KH, Natarajan P, et al (2014) Review of dissolved pollutants in urban storm water
611 and their removal and fate in bioretention cells. *J Environ Eng* 141:4014050. doi:
612 [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.0000876](https://doi.org/10.1061/(ASCE)EE.1943-7870.0000876)
- 613 Legret M, Pagotto C (1999) Evaluation of pollutant loadings in the runoff waters from a major rural
614 highway. *Sci Total Environ* 235:143–150. doi: [https://doi.org/10.1016/S0048-9697\(99\)00207-7](https://doi.org/10.1016/S0048-9697(99)00207-7)
615 7
- 616 Leroy MC, Marcotte S, Legras M, et al (2016a) Influence of the vegetative cover on the fate of trace
617 metals in retention systems simulating roadside infiltration swales. *Sci Total Environ*. doi:
618 10.1016/j.scitotenv.2016.11.195
- 619 Leroy M-C, Portet-Koltalo F, Legras M, et al (2016b) Performance of vegetated swales for improving
620 road runoff quality in a moderate traffic urban area. *Sci Total Environ* 566–567:113–121. doi:
621 10.1016/j.scitotenv.2016.05.027
- 622 Li J, Davis AP (2016) A unified look at phosphorus treatment using bioretention. *Water Res* 90:141–
623 155. doi: 10.1016/j.watres.2015.12.015
- 624 Lloyd SD, Fletcher TD, Wong THF, Wootton RM (2001) Assessment of Pollutant Removal in a Newly
625 Constructed Bio-retention System. In: 2nd South Pacific Stormwater Conference (27 – 29 June
626 2001), Auckland, New Zealand, pp 20-30
- 627 Lucke T, Mohamed M, Tindale N (2014) Pollutant Removal and Hydraulic Reduction Performance of
628 Field Grassed Swales during Runoff Simulation Experiments. *Water* 6:1887–1904. doi:
629 10.3390/w6071887
- 630 Makepeace DK, Smith DW, Stanley SJ (1995) Urban stormwater quality: Summary of contaminant data.
631 *Crit Rev Environ Sci Technol* 25:93–139. doi: 10.1080/10643389509388476
- 632 Mazer G, Booth D, Ewing K (2001) Limitations to vegetation establishment and growth in biofiltration
633 swales. *Ecol Eng* 17:429–443. doi: [https://doi.org/10.1016/S0925-8574\(00\)00173-7](https://doi.org/10.1016/S0925-8574(00)00173-7)
- 634 McCarthy DT, Zhang K, Westerlund C, et al (2018) Assessment of sampling strategies for estimation of
635 site mean concentrations of stormwater pollutants. *Water Res* 129:297–304. doi:
636 10.1016/j.watres.2017.10.001
- 637 Melbourne Water (2006) City of Melbourne WSUD Guidelines. Melbourne, Australia
- 638 Mitchell VG (2006) Applying Integrated Urban Water Management Concepts: A Review of Australian
639 Experience. *Environ Manage* 37:589–605. doi: 10.1007/s00267-004-0252-1

- 640 Morquecho R, Pitt R, Clark SE (2005) Pollutant associations with particulates in stormwater. In:
641 Proceeding of the water environment federation, WEFTEC. Anchorage, AK, pp 4973–4999
- 642 Mosley LM, Peake BM (2001) Partitioning of metals (Fe, Pb, Cu, Zn) in urban run-off from the Kaikorai
643 Valley, Dunedin, New Zealand. *N Z J Mar Freshw Res* 35:615–624. doi:
644 10.1080/00288330.2001.9517027
- 645 Nara Y, Pitt RE (2006) Sediment Transport in Grass Swales. *J Water Manag Model*. doi:
646 10.14796/JWMM.R225-16
- 647 Pavlineri N, Skoulikidis NT, Tsihrintzis VA (2017) Constructed Floating Wetlands: A review of research,
648 design, operation and management aspects, and data meta-analysis. *Chem Eng J* 308:1120–
649 1132. doi: 10.1016/j.cej.2016.09.140
- 650 Petrucci G, Rioust E, Deroubaix J-F, Tassin B (2013) Do stormwater source control policies deliver the
651 right hydrologic outcomes? *J Hydrol* 485:188–200. doi: 10.1016/j.jhydrol.2012.06.018
- 652 Powell JT (2015) Evaluating the Hydrologic and Water Quality Benefits Associated with Retrofitting
653 Vegetated Swales with Check Dams. M.S. Thesis, North Carolina State University
- 654 Purvis R, Winston R, Hunt W, et al (2018) Evaluating the Water Quality Benefits of a Bioswale in
655 Brunswick County, North Carolina (NC), USA. *Water* 10:134. doi: 10.3390/w10020134
- 656 Revitt DM, Ellis JB, Lundy L (2017) Assessing the impact of swales on receiving water quality. *Urban*
657 *Water J* 1–7. doi: 10.1080/1573062X.2017.1279187
- 658 Revitt M, Ellis B, Scholes L (2003) Review of the Use of Stormwater BMPs in Europe. DayWater project,
659 Middlesex University, London
- 660 Roinas G, Tsavdaris A, Williams JB, Mant C (2014) Fate and Behavior of Pollutants in a Vegetated Pond
661 System for Road Runoff: Pollutants in Vegetated Ponds. *CLEAN - Soil Air Water* 42:169–177.
662 doi: 10.1002/clen.201300159
- 663 Roseen RM, Ballesteros TP, Houle JJ, et al (2009) Seasonal performance variations for storm-water
664 management systems in cold climate conditions. *J Environ Eng* 135:128–137. doi:
665 [https://doi.org/10.1061/\(ASCE\)0733-9372\(2009\)135:3\(128\)](https://doi.org/10.1061/(ASCE)0733-9372(2009)135:3(128))
- 666 Sage J, Berthier E, Gromaire M-C (2015) Stormwater Management Criteria for On-Site Pollution
667 Control: A Comparative Assessment of International Practices. *Environ Manage* 56:66–80. doi:
668 10.1007/s00267-015-0485-1
- 669 Sansalone JJ, Buchberger SG (1997) Partitioning and First Flush of Metals in Urban Roadway Storm
670 Water. *J Environ Eng* 123:134–143. doi: 10.1061/(ASCE)0733-9372(1997)123:2(134)
- 671 Scholes L, Revitt DM, Ellis JB (2008) A systematic approach for the comparative assessment of
672 stormwater pollutant removal potentials. *J Environ Manage* 88:467–478. doi:
673 10.1016/j.jenvman.2007.03.003
- 674 Stagge JH, Davis AP, Jamil E, Kim H (2012) Performance of grass swales for improving water quality
675 from highway runoff. *Water Res* 46:6731–6742. doi: 10.1016/j.watres.2012.02.037
- 676 Taylor GD, Fletcher TD, Wong THF, et al (2005) Nitrogen composition in urban runoff—implications for
677 stormwater management. *Water Res* 39:1982–1989. doi: 10.1016/j.watres.2005.03.022

678 Tedoldi D, Chebbo G, Pierlot D, et al (2016) Impact of runoff infiltration on contaminant accumulation
679 and transport in the soil/filter media of Sustainable Urban Drainage Systems: A literature
680 review. *Sci Total Environ* 569–570:904–926. doi: 10.1016/j.scitotenv.2016.04.215

681 Thomson NR, McBean EA, Snodgrass W, Mostrenko I (1997) Sample size needs for characterizing
682 pollutant concentrations in highway runoff. *J Environ Eng* 123:1061–1065. doi:
683 [https://doi.org/10.1061/\(ASCE\)0733-9372\(1997\)123:10\(1061\)](https://doi.org/10.1061/(ASCE)0733-9372(1997)123:10(1061))

684 Toronto and Region Conservation Authority (2008) Performance Evaluation of Permeable Pavement
685 and a Bioretention Swale. Seneca College, King City, ON

686 Urbonas BR (1994) Parameters to report with BMP monitoring data. In: Engineering Foundation
687 Conferece, Crested Butte, CO

688 Wang TS, Spyridakis DE, Mar BW, Horner RR (1980) Transport Deposition and Control of Heavy Metals
689 in Highway Runoff. Department of Civil Engineering, University of Washington, Seattle, WA

690 Washington State Department of Ecology (2014) Stormwater Management Manual for Western
691 Washington. As Amended in December 2014, WA

692 Winston RJ, Anderson AR, Hunt WF (2016) Modeling Sediment Reduction in Grass Swales and
693 Vegetated Filter Strips Using Particle Settling Theory. *J Environ Eng* 4016075. doi:
694 10.1061/(ASCE)EE.1943-7870.0001162

695 Winston RJ, Hunt WF, Kennedy SG, et al (2012a) Field Evaluation of Storm-Water Control Measures for
696 Highway Runoff Treatment. *J Environ Eng* 138:101–111. doi: 10.1061/(ASCE)EE.1943-
697 7870.0000454

698 Winston RJ, Hunt WF, Kennedy SG, Wright JD (2012b) Evaluation of Permeable Friction Course (PFC),
699 Roadside Filter Strips, Dry Swales, and Wetland Swales for Treatment of Highway Stormwater
700 Runoff. North Carolina Department of Transportation, NC

701 Woods Ballard B, Udale-Clarke H, Illman S, et al (2015) The SuDS manual. CIRIA Report C753, Ciria,
702 London

703 Wright Water Engineers and Geosyntec Consultants (2007) Frequently Asked Questions: Why does the
704 International Stormwater BMP Database Project omit percent removal as a measure of BMP
705 performance?

706 Xiao Q, McPherson E, Zhang Q, et al (2017) Performance of Two Bioswales on Urban Runoff
707 Management. *Infrastructures* 2:12. doi: 10.3390/infrastructures2040012

708 Yousef YA, Wanielista MP, Harper HH, et al (1985) Removal of Highway Contaminants By Roadside
709 Swales. Civil Engineering & Environmental Science Department, University of Central Florida,
710 Orlando, FL

711 Yu J, Yu H, Xu L (2013) Performance evaluation of various stormwater best management practices.
712 *Environ Sci Pollut Res* 20:6160–6171. doi: 10.1007/s11356-013-1655-4

713 Yu SL, Kuo J-T, Fassman EA, Pan H (2001) Field Test of Grassed-Swale Performance in Removing Runoff
714 Pollution. *J Water Resour Plan Manag* 127:168–171. doi: 10.1061/(ASCE)0733-
715 9496(2001)127:3(168)

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721 **Legend to Figures**

722

723 **Fig. 1** Diagram describing the following methods used to filter and analyse the database

724

725 **Fig. 2** Design characteristics of swales registered in the database. **a** Boxplots for the design
726 factors characterizing swale database. **b** Legend for boxplots

727

728 **Fig. 3** Range of ER values for pollutants from the database. Boxplots were used to display data
729 spread (see **Fig. 2 b** for the legend of a boxplot)

730

731 **Fig. 4** Graphical representation of correlations between pollutant ERs; strong correlations
732 ($\rho > 0.60$) are represented by thick lines and weaker correlations ($\rho < 0.60$) by dotted lines.
733 Pollutants were grouped by type (i.e., suspended solids, nutrient and trace metal) and speciation
734 was indicated for each substance (i.e., total (t), particulate (p) and dissolved (d))

736 **Table 1** Characteristics of the swale database

Parameter	Description (n=number of swales)
Total number of analyzed swales	n=59
Type of swales	Standard swales (n=24), Dry swales (n=6), Wet swales (n=5), Bioswales (n=24)
Country	Australia (n=1), Canada (n=1), China (n=2), Denmark (n=2), France (n=2), New Zealand (n=2), Spain (n=2), Sweden (n=1), Taiwan (n=1), UK (n=1), USA (n=44)
Facility-scale	Field (n=40), technical field (n=17), technical (n=2)
Water supply	Storm events (n=55), simulated events (n=4)
Flow direction	Single inflow (n=19), Lateral inflow (n=36), Lateral and single inflow (n=3), n.a. ^a (n=1)
Sampling flow origin	Surface flow (n=46), subsurface flow (n=10), surface and subsurface flow mixture (n=3)
Catchment specifications	Road (n=38), parking lot (n=16), urban/suburban residential area (n=5)
Vegetal cover	Bare soil (n=1), grassed swale (n=44), planted swale (n=11), vegetated swale, i.e. grassed or planted facility (n=3)
Pollutant with available ER	TSS (n=58), TN (n=32), TKN (n=26), NO _x -N (n=19), NO ₃ -N (n=19), TP (n=49), DP (n=27), Pb (n=31), Zn (n=37), Cu (n=32)

737 ^an. a., not available

738 **Table 2** Analysis of correlations between swale ERs for various pollutants

ER ^a	TSS	TP	DP	TN	TKN	NO _x -N	NO ₃ -N	Pb	Zn	Cu
TP	ρ 0.40 p 0.0054** n = 48									
DP	ρ 0.15 p 0.4547 n = 26	0.77 <0.0001*** n = 26								
TN	ρ 0.43 p 0.0161* n = 31	0.40 0.0257* n = 31	-0.13 0.6155 n = 17							
TKN	ρ 0.66 p 0.0002*** n = 26	0.45 0.0206* n = 26	0.12 0.7074 n = 13	0.80 0.0003*** n = 15						
NO _x -N	ρ -0.20 p 0.4206 n = 18	-0.17 0.4912 n = 18	-0.33 0.2706 n = 13	0.77 0.0007*** n = 15	0.07 0.8346 n = 12					
NO ₃ -N	ρ 0.27 p 0.2645 n = 19	0.02 0.9233 n = 19	-0.01 0.9910 n = 12	0.62 0.0478* n = 11	-0.24 0.4434 n = 12					
Pb	ρ 0.36 p 0.0484* n = 31	0.15 0.4618 n = 25	0.38 0.1521 n = 16	0.81 0.0008*** n = 13	0.42 0.1187 n = 15	ND ^b	0.47 0.0509 n = 18			
Zn	ρ 0.58 p 0.0002*** n = 37	0.31 0.0944 n = 31	0.15 0.5435 n = 18	0.85 <0.0001*** n = 16	0.54 0.0238* n = 17	ND ^b	0.66 0.0028** n = 18	0.67 <0.0001*** n = 31		
Cu	ρ 0.70 p <0.0001*** n = 32	0.39 0.0487* n = 26	0.27 0.2902 n = 17	0.64 0.0076** n = 16	0.88 <0.0001*** n = 15	ND ^b	0.45 0.0812 n = 16	0.75 <0.0001*** n = 29	0.79 <0.0001*** n = 32	
Cd	ρ 0.74 p 0.0002*** n = 20	0.15 0.5567 n = 17	0.20 0.5837 n = 10	ND ^b	0.74 0.0023** n = 14	ND ^b	-0.35 0.3129 n = 10	0.64 0.0033** n = 19	0.63 0.0028** n = 20	0.74 0.0002*** n = 20

739 ^aCorrelations between pollutant ERs were analyzed using the non-parametric Spearman rank method. The Spearman's rank correlation coefficient ρ , as well as the p value and
740 the number of swales analyzed are indicated in bold when the correlation is significant ($p < 0.05$); these data are additionally underlined when the correlation is considered to be
741 rather strong ($\rho \geq 0.60$). ^bND, not done ($n < 10$). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

742 **Table 3** Analysis of correlations between ERs for various pollutants and swale parameters

Pollutant ^a		Swale Parameter				
		Inflow Concentration	Length	Centerline slope	Side slope	Ratio area
TSS	ρ	0.57	0.18	0.25	0.17	-0.26
	p	0.003**	<i>0.1799</i>	<i>0.1037</i>	<i>0.3686</i>	<i>0.116</i>
		n = 57	n = 55	n = 45	n = 29	n = 40
TP	ρ	0.46	0.38	0.10	-0.11	0.01
	p	0.001**	0.0078**	<i>0.5255</i>	<i>0.6081</i>	<i>0.9377</i>
		n = 49	n = 47	n = 39	n = 24	n = 33
TN	ρ	0.54	0.62	-0.25	0.51	0.11
	p	0.0017**	0.0003***	<i>0.2143</i>	0.0418*	<i>0.6325</i>
		n = 31	n = 30	n = 26	n = 16	n = 23
TKN	ρ	0.69	0.28	0.32	0.41	0.10
	p	<0.0001***	<i>0.1721</i>	<i>0.1395</i>	<i>0.0621</i>	<i>0.6770</i>
		n = 26	n = 26	n = 23	n = 21	n = 19
NO _x ⁻ -N	ρ	0.52	0.51	-0.56	0.32	0.06
	p	0.0231*	0.0248*	0.0184*	<i>0.2607</i>	<i>0.8029</i>
		n = 19	n = 19	n = 17	n = 14	n = 18
NO ₃ -N	ρ	0.17	0.43	-0.10	0.17	ND ^b
	p	<i>0.4796</i>	<i>0.0667</i>	<i>0.6819</i>	<i>0.6321</i>	
		n = 19	n = 19	n = 18	n = 10	
Pb	ρ	0.26	0.08	0.47	0.26	0.21
	p	<i>0.166</i>	<i>0.6853</i>	0.0195*	<i>0.3684</i>	<i>0.4450</i>
		n = 31	n = 28	n = 24	n = 14	n = 15
Zn	ρ	0.67	0.49	-0.05	0.24	0.16
	p	<0.0001***	0.035*	<i>0.8085</i>	<i>0.3489</i>	<i>0.4922</i>
		n = 37	n = 34	n = 28	n = 17	n = 21
Cu	ρ	0.52	0.56	0.07	0.49	0.43
	p	0.0022**	0.0017**	<i>0.7465</i>	<i>0.0738</i>	<i>0.0828</i>
		n = 32	n = 29	n = 25	n = 14	n = 17
Cd	ρ	0.22	0.30	0.43	ND ^b	-0.07
	p	<i>0.3924</i>	<i>0.2469</i>	<i>0.1401</i>		<i>0.8154</i>
		n = 17	n = 17	n = 13		n = 13

743 ^aCorrelations between pollutant ERs were analyzed using the non-parametric Spearman rank method. The
 744 Spearman's rank correlation coefficient ρ , as well as the p value and the number of swales analyzed are indicated
 745 in bold when the correlation is significant ($p < 0.05$); these data are additionally underlined when the correlation is
 746 considered to be rather strong ($\rho \geq 0.60$). ^bND, not done ($n < 10$). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

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763 **Table 4** Analysis of correlations between inflow concentration and various swale parameters
 764 when a design characteristics was flagged as potentially

Pollutant ^a	Tested correlation	Results
TP	Inflow concentration vs. Swale length	$\rho = 0.07$ $p = 0.6345$ $n = 47$
	Inflow concentration vs. Swale length	$\rho = 0.45$ $p = 0.015^*$ $n = 29$
TN	Inflow concentration vs. Swale side slope	$\rho = 0.59$ $p = 0.0165^*$ $n = 29$
	Inflow concentration vs. Swale Length	$\rho = 0.46$ $p = 0.0465^*$ $n = 19$
NO _x -N	Inflow concentration vs. Swale centerline slope	$\rho = 0.433$ $p = 0.0820$ $n = 17$
	Inflow concentration vs. Swale Length	$\rho = 0.33$ $p = 0.0599$ $n = 34$
Zn	Inflow concentration vs. Swale Length	$\rho = 0.22$ $p = 0.2476$ $n = 29$
Cu	Inflow concentration vs. Swale Length	$\rho = 0.22$ $p = 0.2476$ $n = 29$

765 ^aCorrelations between inflow pollutant concentrations and various swale parameters were analyzed using the non-
 766 parametric Spearman rank method. The Spearman's rank correlation coefficient ρ , as well as the p value and the
 767 number of swales analyzed are indicated in bold when the correlation is significant ($p < 0.05$). * $p < 0.05$; ** $p < 0.01$;
 768 *** $p < 0.001$