Journal of Environmental Management 282 (2021) 111911

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Research article

An assessment of gully pot sediment scour behaviour under current and potential future rainfall conditions

Haoyu Wei [a,*], Tone Merete Muthanna [b], Lian Lundy [a], Maria Viklander [a]

[a] Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, SE-97187, Luleå, Sweden
[b] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, NO-7491, Trondheim, Norway

ARTICLE INFO

Keywords:
Gully pot
Sediment
Scour
Maintenance
Highway runoff

ABSTRACT

Gully pots actively trap sediments transported by urban runoff to prevent in-pipe blockages and surface flooding. However, due to poor maintenance (resulting in sediment build-up) and increasingly extreme wet weather events, the scour of previously-deposited sediments from gully pots is identified as a potential contributor to EU Water Framework Directive failure. While basal sediment scour deterministic models have been developed and validated using laboratory and field gully pot data sets, the ability of these models to predict behaviour at sites other than those for which they were established has not been addressed. Nor has the impact of future rainfall predictions on the role of gully pots as sediment sources been systematically examined. As a contribution to addressing these knowledge gaps, the performance of two gully pot basal sediment scour models of distinct complexity levels are evaluated under current and future rainfall conditions. The output from Model One suggests that the scour-induced total suspended solids in gully pot discharge can be kept well below 25 mg/L if the gully pot fullness level is maintained at under 60%. Results identify the opportunity to incorporate the actual/targeted ecological status of recipients in scheduling gully pot maintenance operations and that proactive gully pots maintenance will reduce the impacts of increased rainfall intensity/duration on the magnitude of sediment scour. Results from Model Two suggest that fine sediments are particularly susceptible to in-pot scour. For example, sediment with a specific gravity of 1.1 and diameter of >63 μm accounts for 50% of scour-induced total suspended solids in gully pot discharge. The effluent suspended solids concentrations predicted by the two models differ by up to two orders of magnitude. However, without further empirical field data pertaining to their respective competences/applications, neither model could be discounted at this stage. For example, the use of Model One is more appropriate in the establishment of gully pot maintenance schedules, with Model Two more suited to the dimensioning of gully pots based on performance requirements. This application, however, relies on the development and adoption of a more stringent regulation on gully pots discharge.

1. Introduction

In contrast to point source pollution, which has been the subject of legislation for several decades, the need to address diffuse pollution was not widely recognised until the 1970s (Campbell et al., 2005). Yet, its associated negative impacts such as nutrient enrichment and sediment contamination are now acknowledged as major threats to the receiving water ecosystem health. For example, the EU Water Framework Directive (EU, WFD, 2000) specifically identifies the need to control diffuse pollution under Article 10 and Article 11 (h). Further, Annex II 1.4 identifies urban areas as a major source of diffuse pollution, which is then mobilised by rainfall and transported to receiving water bodies as urban runoff.

Total particulate matter is a key contaminant in urban runoff. A variety of terms (e.g. total suspended solids (TSS), suspended solids, suspended solids concentration and suspended particulate matter) are used in the literatures to refer to particulate matter, reflecting variations in context and method. For consistency and simplicity, the term total suspended solids (TSS) is used within this study with the filter pore size included in brackets (where reported). As well as having a direct impact on receiving water ecology e.g. blocking fish gills, TSS also constitutes a sink for hydrophobic substances. Several studies report that the majority of diffuse urban pollutants are associated with the particulate phase (e.g., Westerlund and Viklander 2006; Karlsson 2009) with sediment

---

* Corresponding author.
E-mail address: haoyu.wei@ltu.se (H. Wei).

https://doi.org/10.1016/j.jenvman.2020.111911
Received 3 June 2020; Received in revised form 21 December 2020; Accepted 26 December 2020

transport processes contributing to the movement of pollutants through the urban drainage system. However, adsorbed pollutants may also subsequently be released from sediments and re-enter overlying waters as a result of remobilisation during extreme rainfall events which may, for example, alter redox conditions (Lundy et al., 2017). Increases in precipitation extremes predicted as a result of climate change (IPCC, 2013), also brings a higher probability of sediments scour events, in terms of both scour frequency and mass discharged.

Gully pots with sand traps are a conventional urban runoff quality control system. The original purpose of such infrastructures was to prevent large debris and floatables (e.g. litter and flora) from entering and blocking the piped sewer system. With the increasing recognition of the impacts of diffuse urban pollution, the role of gully pots in providing additional functions, such as minimising the pollutant loadings on recipients, is of increasing interest to stormwater managers. However, despite the ubiquitous use of gully pots, their efficacy in trapping sediments (especially fine sediments) has long been questioned. Not only poor sediment trap efficiency but also the potential for the scour of previously-deposited gully pot sediments, is a concern for municipalities if regular maintenance cannot be performed. This has been demonstrated in both laboratory-based and field studies. For example, an artificial gully pot flushing test (at a flow rate of 16 L/s, equivalent to a local heavy rainfall event), resulted in 1% (by weight) basal sediment scour (Sartor and Boyd, 1972). Despite this relatively small proportion, the chemical analysis of sediment (from multiple gully pots within the studied catchment) suggested discharge of even this mass would represent a significant threat to receiving water quality. A field study in Stockholm, Sweden, reported elevated effluent (in comparison to influent) TSS concentrations (1.6 μm) in >50% of monitored rainfall events (Bennerstedt 2005). A long-term gully pot sediment bed monitoring study by Rietveld et al. (2020) reported episodic increasing and decreasing gully pot sediment bed depths after rainfall events, which was attributed to the episodic occurrence of sediment scour. In addition, investigations of gully pot sediments reported toxic effects associated with the release of previously bound metals into solution, indicating a potential risk to receiving water ecology (Morrison et al., 1988; Karlsson 2009). Whilst such studies highlight the value of routine gully pot maintenance programmes, infrequent – or even an absence of - gully pot emptying maintenance has been identified in many studies. For example, Ræstad (2014) reported that only 1500 out of 30,000 (equating to 5%) gully pots were emptied annually by Oslo municipality, Norway.

Previous research in this field focussed on characterising the magnitude of gully pot sediment scour events, using site-specific data to develop deterministic models which predict re-suspended sediment concentrations. Based on their underpinning assumptions, these models can be categorized into two types as follows.

Initial models typically conceptualised a gully pot as a complete stirred-tank reactor (CSTR), e.g. Fletcher (1981), Wada et al. (1987), Butler and Memon (1999), Deletic et al. (2000). The output (presented as a predicted effluent TSS) consists of a combination of uncaptured inflow sediments, scoured basal sediments, and 'in-pot' sediments which have remained in suspension from previous rainfall events. However, the failure of such models to fully simulate in-pot erosion processes during extreme rainfall events was identified by Deletic et al. (2000).

Alternatives to the original simplified gully pot as a CSTR concept were proposed by Avila (2008) and Howard et al. (2012), who established predictive models through the identification of factors which dominate the basal sediment scour process. Despite similar starting points, two completely different models (i.e. different parameters and levels of complexity) were established. The model developed by Avila (2008) is a simple low-data requirement model based on two variates. In contrast, the model put forward by Howard et al. (2012) is more complex with data on seven variates required.

Whilst both models claim to adequately predict basal sediment scour induced TSS, a limitation with both (and indeed the other models described so far) is that - to-date - their performance has not been tested at alternative sites. To better understand the transferability of developed models (i.e. how well do their respective predictions of scoured loads at further sites correspond), this study undertakes a critical review of available gully pot models and assesses the performance of gully pot sediment scour models developed by Avila (2008) and Howard et al. (2012). Both models are applied to the same field data set under both current and a series of potential future rainfall conditions. Results are then used to develop a series of condition matrices to predict conditions under which basal sediment scour will occur and to examine the effects of changes in extreme rainfall intensities on the magnitude of sediment scour events. The practical applications of both models in informing and optimising gully pot maintenance regimes in relation to stakeholder priorities are discussed and areas for further work are identified.

2. Material and methods

2.1. Study site

A well-characterised sub-catchment in Luleå, Sweden, is adopted as a pseudo-site (i.e. field data previously collected from this site was used within the models) for the evaluation of gully pot sediment scour under current conditions. This catchment is rectangular with a total surface area of 540 m^2 (72 m long x 7.5 m width), consisting of a two-lane road (total width = 6 m) with a crossfall of 2.6% and a grassed area (width = 1.5 m). The gully pot located within the catchment receives runoff from both the carriageway and the grassed area. No new field measurements were made for this study.

2.2. Model description

The two basal sediment scour models for gully pots selected and evaluated in this study are described below.

2.2.1. Model One

Avila (2008) proposed two regression models for gully pot scour; one for gully pots with a pipe entry and one for gully pots with a curb entry. Since the latter inlet type is more commonly employed within a European context, the regression model for gully pots with a curb entry is chosen for this study. This regression model has two functions for the outflow; the first applies to the first 5 min and the second to the subsequent 5–20 min time interval, as written below:

$$0-5\text{ min: }\mathrm{C}=(670)^{2}*\mathrm{H}^{-3.32}*\mathrm{Q}^{\left(0.92\mathrm{H}^{-0.15}\right)} \tag{1}$$

$$5-25\text{ min: }\mathrm{C}=(115)^{2}*\mathrm{H}^{3}*[\ln(\mathrm{H})]^{-15}*\mathrm{Q}^{\left(1.6\mathrm{H}^{-0.19}\right)} \tag{2}$$

Where C, the TSS in the effluent, mg/L; H, the overlying water depth (depth of water above the sediment bed surface), cm; Q, the runoff inflow rate, L/s.

2.2.2. Model two

The Howard et al. (2012) model is a regression model for the washout of single-sized sediments in gully pots using the following equations:

$$C=\left(8.3*10^{-6}\Big/\left(P\Big/F_j^2\right)+4.7*10^{-4}e^{-3.18P/F_j^2}\right)*\rho_w SG\Big/(SG-1) \tag{3}$$

$$P\Big/F_j^2=U_s hgD^2\Big/\bar{\mathrm{u}}_j^2 Q \tag{4}$$

$$F_j^2=\overline{U}_j^2\Big/gD \tag{5}$$

Where C, the effluent TSS concentration, mg/L; P, the Péclet number adopted to express the ratio of convective particle transport by settling to transport by turbulent diffusion; F_j, Froude number of the influent jet velocity, defined by equation (5); ρ_w, the density of gully pot standing liquor, kg/m^3; SG, the specific gravity of sediment particles; U_s, sediment settling velocity, m/s; h, the gully pot sand trap depth, m; g, the gravitational acceleration, 9.81 m/s^2; D, the inner diameter of gully pot, m; $\bar{u}_j$, mean inflow jet velocity, m/s; Q, runoff inflow rate, L/s. To facilitate the comparison between models, the predicted TSS for each sediment characterisation (i.e. its size and specific gravity) were summed. Both models assume an unlimited supply of basal sediments available for scour during each simulated event without assuming that it will all be scoured.

2.3. Model inputs

The two models have distinct requirements for input data, with two variates for Model One (overlying water depth and runoff inflow rate) and seven variates for Model Two (inflow rate, mean inflow jet velocity, sediment settling velocity, gully pot sand trap depth, gully pot diameter, sediment specific gravity and the density of in-gully pot standing liquor). To facilitate model comparison, both models were applied to the same field data set. Model inputs were divided into three categories: rainfall event characterisation, sediment and in-pot liquor characterisation, and gully pot conditions. Approaches to benchmarking each model parameter are outlined in the following sections.

2.3.1. Rainfall event characterisation under current rainfall conditions

Flow input conditions (i.e. runoff inflow rate and mean inflow jet velocity) are a function of precipitation and catchment characteristics. To evaluate the magnitude of sediment scour under different rainfall regimes associated with current rainfall conditions, rainfall events of different intensities and duration times were simulated and the corresponding inflow rates calculated via the rational method (Eq. (6)):

$$Q = \phi i A \tag{6}$$

Where Q stands for inflow rate, L/s; ϕ stands for runoff coefficient; i stands for rainfall intensity, L/(s•ha); A stands for drainage area, ha.

Rainfall data adopted in this study is derived from the national Intensity-Duration-Frequency (IDF) curve developed by Dahlström (2010). This national IDF curve is recommended for use in the design and dimensioning of urban drainage system by all Swedish municipalities (Swedish Water 2016). 18 rainfall events (see Table S1 for rainfall intensity and duration) with nine return periods (3-month, 6-month, 1-year, 2-year, 5-year, 10-year, 20-year, 50-year, and 100-year), and two duration times (5 min, 10 min) were simulated. The 5 min duration time is based on a typical gutter flow velocity of 0.5 m/s (Swedish Water 2016), with a resulting concentration-time of 5 min. The selection of 10 min duration time is based on the Swedish stormwater design standard for a 10-year return period recommended by Swedish Traffic Agency (2008). Regarding identifying rainfall coefficients, the corresponding runoff coefficients for the road carriageway and grassed area are set at 0.9 and 0.25, respectively (Butler and Davies 2017).

2.3.2. Sediment and in-pot liquor characterisation

Sediment settling velocity was calculated for twelve different particle characterisations across three sediment diameters (d_s) (63 μm, 110 μm and 160 μm) and four specific gravity (SG) values (1.1, 1.6, 2.35 and 2.65).

The inputs of sediment settling velocity were determined by Eq. (7) and Eq. (8) developed by Cheng (1997).

$$U_s = \left(\sqrt{25 + 1.2d_*^2} - 5\right)^{1.5} *\nu \Big/ d_s \tag{7}$$

$$d_* = \left(g(\rho_s - \rho_w) \,/\, \rho\nu^2\right)(1 \,/\, \hat{3})^* d_s \tag{8}$$

Where V, the settling velocity of a sediment particle, m/s; d_*, a dimensionless parameter; ν, the kinematic viscosity of the fluid, m^2/s; d_s, the sediment particle diameter, m; ρ_s, the density of particles, kg/m^3; ρ, the density of standing liquor in gully pot, kg/m^3; g, the gravitational acceleration, m/s^2. At an environmental temperature of 15 °C, the corresponding kinematic viscosity and density are $1.1386*10^{-6}$ m^2/s and 999.1 kg/m^3 respectively (Schmidt and Grigull 1989).

2.3.3. Gully pot conditions

Table 1 summarises gully pot input conditions. Since both models utilised the ‘gully pot optimal design’ (Lager et al., 1977), the gully pot design with an effective volume of 0.1 m^3 was used in this study.

Inflow jet velocity is a function of inlet structure design. For simplification, the inlet structure for the gully pot is assumed to be an ideal curb opening. The Manning equation can thus be applied as follows:

$$Q = (0.377 \,/\, n) * S_X^{1.67} * S^{0.5} * T^{2.67} \tag{9}$$

Where Q, runoff flow rate, L/s; n, Manning’s value; S_x, crossfall; S, longitudinal slop; T, top width of water spread, m.

Accordingly, the average inflow jet velocity (u_j, m/s) was estimated as:

$$u_j = Q \,/\, \left(T^2 S_X * 0.5\right) \tag{10}$$

Ten overlying water depths (expressed as a percentage of overlying water depth to gully pot sand trap depth as follows: 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%) were evaluated. These inputted overlying water depths represent gully pot maintenance conditions with corresponding sediment fullness levels of 95%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, and 10% of the gully pot sand trap depth are based on the assumption that the standing water in the gully pot reaches the outlet level when sediment scour takes place.

2.3.4. Future scenarios

Precipitation data for future rainfall conditions were based on six projected climate scenarios (see Table 2) with three future time horizons (2011–2040, 2041–2070, and 2071–2100) under two sets of Representative greenhouse gas emissions and Concentration Pathways (i.e. rcp

Table 1
Overview of benchmarked gully pot input parameters.

Gully Pot Dimension		Inlet	Overlying water depth (% of sand trap depth)
Gully pot diameter [mm]	500	Road crossfall: 2.6%	5%
Gully pot sand trap depth [mm]	500	Road longitudinal slope: 2.0%	10%
Top of gully pot to top of outlet [mm]	187.5	Road surface Manning coefficient: 0.013	20%
Maximum sand trap volume [L]	100		30%
			40%
			50%
			60%
			70%
			80%
			90%

Table 2
Simulated future scenarios.

	Rainfall Return Period	Duration Time	Simulated Period	Representative Concentration Pathway	Gully Pot Fullness	Sediment Dimension [μm]	Sediment Specific Gravity
Model One	10-year	5 min	2011–2040	rcp 4.5	50%, 95%	/	/
Model Two	100-year		2041–2070	rcp 8.5	/	63/110/160	2.35
			2071–2100				

4.5 and rcp 8.5) as described in IPCC (2013). The future rainfall conditions were predicted using Swedish Meteorological and Hydrological Institute (SMHI)'s regional climate model RCA4 linked to eight further global climate scenario models (DHI Sweden, 2018). The inclusion of all eight global climate scenario models yielded maximum, median and minimum rainfall intensity values for each scenario (see Table 2).

The precipitation data for future rainfall conditions is available at a resolution of 50 km by 50 km cells, leading to the selection of Piteå (located 40 km from the study site) for use in this study (Table S2, for rainfall data). For the downscaled climate models, rainfall intensity data was only available for 5-min duration time events.

Simulations of future rainfall conditions with Model One only considered a gully pot fullness of 50% and 95%, representing two different gully pot maintenance schedules. Currently, a common strategy of emptying gully pots at least once per year was recommended (Lager et al., 1977; Lindholm 2015). Such a maintenance frequency corresponds to emptying gully pots when they are approximately 50% full (Leikanger and Roseth 2016). By contrast, simulating gully pots with 95% fullness level represents emptying gully pots in a reactive manner (i.e. when gully pot blockage-induced flooding occurs). Application of the simulated future rainfall conditions to Model Two included comparing their impact on three particle size dimensions (63 μm, 110 μm and 160 μm) with an assumed sediment specific gravity of 2.35 (as identified by Butler et al., 1992). To facilitate comparison with current rainfall conditions, results for future rainfall conditions were presented as percentage change relative to that predicted under current rainfall conditions.

2.4. *Condition matrices*

For Model One, all possible combinations of 18 rainfall events under current climate conditions in relation to ten overlying water depths (i.e. a total of 180 scenarios) were evaluated. Likewise, for Model Two, all possible combinations of 18 rainfall events, and 12 sediment settling velocities, in total 216 conditions, were evaluated.

2.5. *Guideline values for effluent suspended solids concentration*

In the absence of specific water quality standards or guidelines for gully pot discharges, TSS guideline values for receiving waters were reviewed as a way to benchmark gully pot effluent water quality (see Table 3).

3. Results and discussion

3.1. *Outputs from Model One*

3.1.1. *Scour-induced effluent TSS in relation to gully pot fullness levels*

Fig. 1 presents the predicted scour-induced effluent TSS at different gully pot fullness levels (ranging from 95% to 10%) for the 0-5-min and subsequent 5–20 min outflows respectively. As could be envisaged, higher gully pot fullness level leads to an increasing TSS discharge concentration, ranging from a maximum of 152,539 mg/L (95% fullness) to a minimum of 4.6 mg/L (10% fullness; see Fig. 1). Sharp drops in predicted TSS are also noticed with decreasing fullness levels with, for example, a more than an eightfold drop of TSS occurring when the fullness level falls from 95% to 90%. Declines of a similar magnitude can also be found as the fullness level falls from 90% to 80% and from 80% to 70%, indicating that emptying gully pots when <40% full would achieve an effluent TSS concentration of less than the 25 mg/L guideline value.

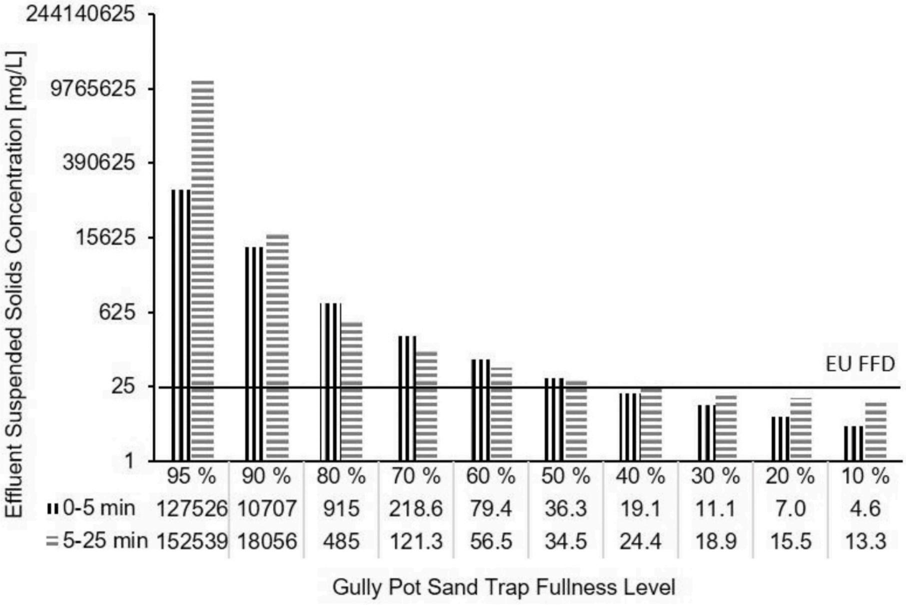
The simulation result is represented by two time steps (0–5 min and the subsequent 5–20 min). A conspicuous feature when comparing the simulated TSS by these two steps is that - when the gully pot fullness level falls in between 80% and 50% - the TSS discharge concentration predicted during the first time step is greater than that for associated with the latter stage. However, when gully pot fullness level is ≥ 90% or ≤40%, an inverse relationship is displayed. The behaviour of a higher TSS during the initial stage was also reported (Butler and Karunaratne 1995; Butler and Memon 1999). Butler and Karunaratne (1995) suggested the development of a graded bed could potentially lead to the observed behaviour. This mechanism involves the transport of runoff through the sediment bed surface, with the associated turbulence re-sorting particles to develop a 'graded bed', whereby particles become ordered in a way that, given sufficient time, leads to the development of a sediment bed surface which offers the least resistance to a horizontal current. This 'graded bed' thus inhibits further erosion, though the occurrence of this proposed mechanism has yet to be validated. In contrast, Avila (2008) suggested that this same phenomenon could be a result of a coupling effect between the development of 'armouring layer' and the depth of 'overlying waters'. According to this study, the development of an armouring layer (a function of elevated kinetic energy associated with the inflow scour of fine sediments leaving a layer of larger particulates on the bed surface which can prevent further basal sediments entrainment) inhibits the scour process. In addition to the

Table 3
Summarised TSS guideline values for discharges into nature recipients.

Authority	Name of Standard	Adopted year	Guideline value [mg/L]	Reference
European Union	2006/44/EC Freshwater Fisheries Directive (EU FFD)	2006[a]	25	European Union Freshwater Fisheries Directive et al. (2006)
Gothenburg City Environment Management Group	Environmental management guidelines and guideline values for discharges of polluted water to recipients and stormwater system	2013	25	Gothenburg City Environment Management Group (2013)
-	–	1992	10	Quinn et al. (1992) [b]

[a] Since European Union Water Framework EU Water Framework Directive, 2000/60/EC does not include guideline value for TSS (0.45 μm), the already-repealed 2006/44/EC Fish Directive is thus displayed here as a surrogate.

[b] Identified as an effect-based standard for comparison within this study. A TSS (pore size unspecified) of ≥10 mg/L in natural streams was reported to result in a 40% reduction in algal biomass.

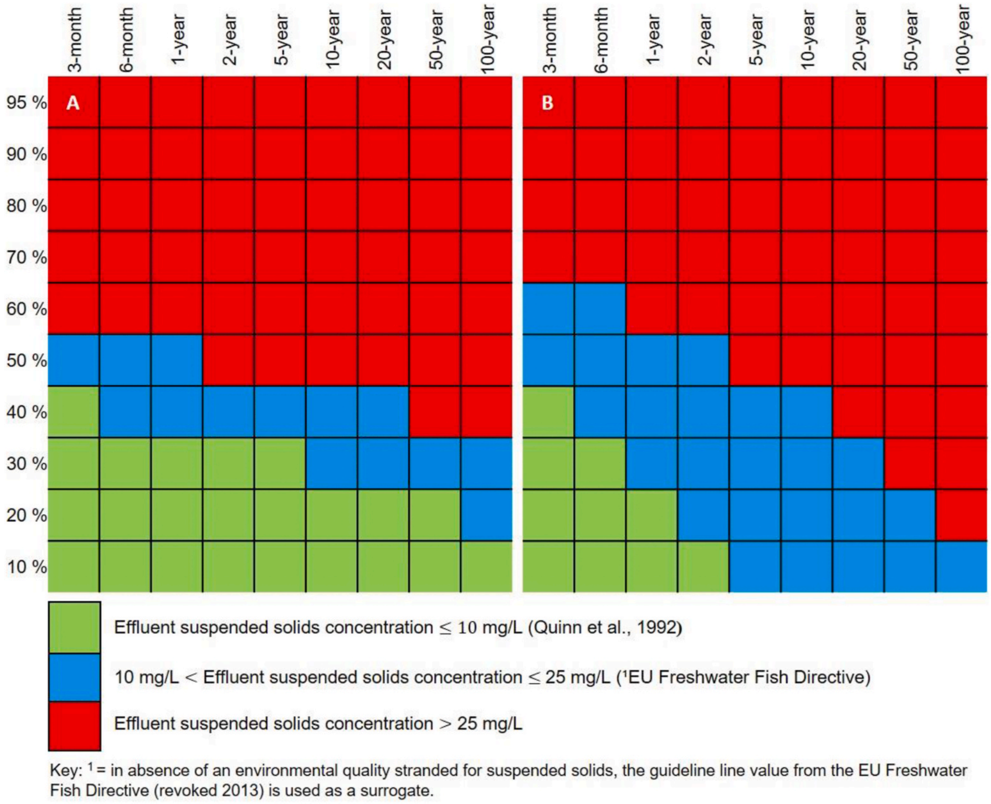


	95 %	90 %	80 %	70 %	60 %	50 %	40 %	30 %	20 %	10 %
▮ 0-5 min	127526	10707	915	218.6	79.4	36.3	19.1	11.1	7.0	4.6
= 5-25 min	152539	18056	485	121.3	56.5	34.5	24.4	18.9	15.5	13.3

Fig. 1. Model One: effluent TSS by gully pot fullness levels, for both the first 5-min and subsequent 20-min outflows respectively. The displayed rainfall events are of 10-year return period with a duration time of 10-min. The guideline value of 25 mg/L by EU Freshwater Fisheries Directive (EU FFD) is also displayed here as a benchmark.

formation of this 'armouring layer', increasing 'overlying water depth' also inhibits erosion by dampening the associated kinetic energy of the plunging inflow containing "entrapped air" (Avila 2008).

However, neither suggested mechanism fully explains the results seen when the gully pot is extremely full (95% and 90% full) or falls below a 40% fullness level i.e. higher TSS during the latter 5–20 min time interval. The current results also contradict the findings of Avila (2008) which reported that the modelled TSS for the latter 20-min was usually 40%–80% lower than that for the first 5 min. A possible explanation for this apparent contradiction could be the extreme conditions in the current study i.e. large inflow rate (max flow rate of 80 L/s for simulations compared with 10 L/s in Avila (2008)), and the shallower



A

	3-month	6-month	1-year	2-year	5-year	10-year	20-year	50-year	100-year
95 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
90 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
80 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
70 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
60 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
50 %	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥
40 %	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥
30 %	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦
20 %	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦
10 %	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

B

	3-month	6-month	1-year	2-year	5-year	10-year	20-year	50-year	100-year
95 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
90 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
80 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
70 %	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
60 %	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥
50 %	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥
40 %	🟩	🟦	🟦	🟦	🟦	🟦	🟥	🟥	🟥
30 %	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟥	🟥
20 %	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟥
10 %	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦

🟩 Effluent suspended solids concentration ≤ 10 mg/L (Quinn et al., 1992)

🟦 10 mg/L < Effluent suspended solids concentration ≤ 25 mg/L (^{1}EU Freshwater Fish Directive)

🟥 Effluent suspended solids concentration > 25 mg/L

Key: ^{1} = in absence of an environmental quality stranded for suspended solids, the guideline line value from the EU Freshwater Fish Directive (revoked 2013) is used as a surrogate.

Fig. 2. Condition matrices for rainfall events with 10-min duration time under current rainfall conditions. Component A and component B present effluent TSS concentration during 0-5-min and 5-25-min respectively.

overlying water depth in this study (minimum overlying water depth of 5% for simulations compared with 9% in Avila (2008)). Under such extreme conditions, 5-min may not be sufficient time for the formation of either an 'armouring layer' or a 'graded layer'. The high residual kinetic energy due to the large volume inflow, or the shallow overlying water depth as a limited potential to dampen the inflow kinetic energy, resulting in a comparatively greater level of turbulence in such scenarios. However, further empirical research is required to confirm this hypothesis.

3.1.2. Synthesised condition matrices based on Model One predictions

Based on the output of Model One, Fig. 2 presents a set of condition matrices pertaining to a range of return periods and gully pot fullness levels which enable the combination of circumstances under which TSS guideline values are expected to be exceeded in gully pot discharge flows to be identified. In keeping with the Swedish stormwater design standard, these condition matrices were based on rainfall events with 10 min duration time.

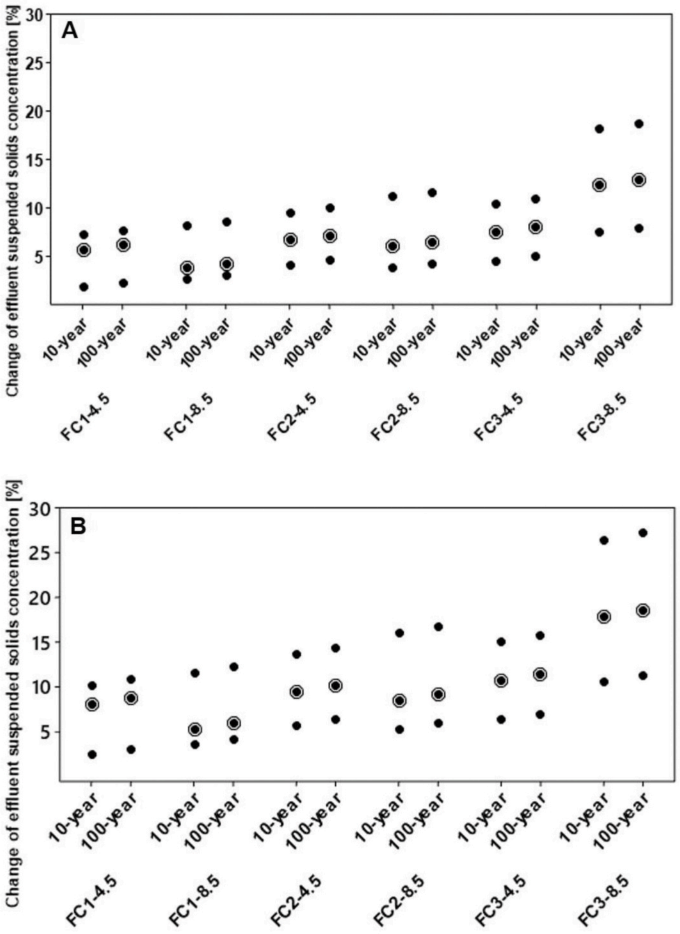
A key use of the above data is for timing of gully pot maintenance operations to reduce scour-induced sediment outflow TSS. The condition matrices imply a deterioration in effluent quality due to the sediment scour when the gully pot reaches a comparatively high fullness level i.e. 60 %. These matrices can therefore be used for planning of gully pot maintenance schedules from the perspective of local water body priorities. For example, if a greater importance is attached to the receiving water quality (i.e. an emphasis placed on low TSS discharges), the maintenance operations should be conducted more frequently to minimise the chronic negative impact on recipients due to gully pot sediment scour. However, under a no maintenance scenario, even a marginal rainfall event of a 3-month return period could exceed relevant guideline TSS values when gully pots reach 60% fullness.

The Model One well connects the scour-induced TSS discharge with the fullness level of gully pots and hence the implementation of this model can potentially inform and facilitate municipalities' precautionary approach to the maintenance of gully pots and how this could be enhanced by integrating maintenance scheduling with weather forecast systems.

3.1.3. Sensitivity to changes in the climatic input

Percentage change of scour-induced effluent TSS for future climate scenarios (relative to the current climate) is presented in Fig. 3 for gully pot fullness levels of 50% and 95%, respectively. Overall, the magnitude of effluent TSS is expected to show an overall increase towards the end of the 21st century due to the increasing rainfall intensities projected for future periods.

Although the percentage changes for gully pots with 50% and 95% fullness levels show a similar trend across climate scenarios, simulations for the latter conditions generally display a higher percentage change



Notation	FC1-4.5	FC1-8.5	FC2-4.5	FC2-8.5	FC3-4.5	FC3-8.5
Scenarios	2011-2040, rcp 4.5	2011-2040, rcp 8.5	2041-2070, rcp 4.5	2041-2070, rcp 8.5	2071-2100, rcp 4.5	2071-2100, rcp 8.5

Fig. 3. Relationship between different future climate scenarios and percentage change of effluent suspended solids concentration (relative to current climate), assuming a gully pot fullness level of 50% (A) and 95% (B) respectively. As the rainfall intensities for each future climate scenario were given as max, median and min values, the simulation results are also presented here as max, median and min values correspondingly.

than those reported for the former conditions (see Fig. 3). Therefore, regarding sediment scour, gully pots emptied reactively are predicted to be a greater concern under future rainfall conditions in comparison to gully pots emptied proactively. This indicates that a more stringent gully pot maintenance strategy is needed to address the increasing magnitude of sediment scour under future climates.

3.2. *Outputs from model two*

3.2.1. *Effluent suspended solids concentration in relation to rainfall return periods*

Unlike Model One, Model Two does not consider gully pot fullness. Fig. 4 (A) exhibits the modelled scour-induced effluent TSS for nine rainfall return periods ranging from 3-months to a 100-year event, with an event duration time of 10-min. The modelled effluent TSS exhibits a positive relationship with rainfall return periods. Results indicate that, even during a rainfall event of 10 min and a return period of 3-months, the predicted TSS concentrations in the discharge will exceed the guideline value of 25 mg/L. However, the assumption on which this model is based (an unlimited supply of basal sediments with a range of characteristics) is unlikely to be satisfied in the field and therefore results should be treated with caution. For example, Fig. 4 (B) presents the percentage of each particulate type (in terms of particulate size and gravity) contributing to the total effluent TSS, for a simulated event with 10-year return period, and 10-min duration time. Particulates with an SG of 1.1 and d of 63 μm account for nearly 50% of total effluent TSS, corresponding to a value of approximately 6000 mg/L. However, particulates with a specific gravity of 1.1 account for a relatively low proportion of particulates found in gully pots. Therefore, simply adding up TSS for all particulate characterisations may lead to an overestimation of the magnitude of sediment scour.

3.2.2. *Synthesised condition matrices based on model two predictions*

Instead of presenting outputs as a sum of all particulate characterisations, Fig. 5 presents the condition matrices by rainfall return periods and respective sediment characterisation based on simulations in Model Two. Sediments with relatively lower specific gravity and smaller diameter are more susceptible to scour. This is a concern from a water

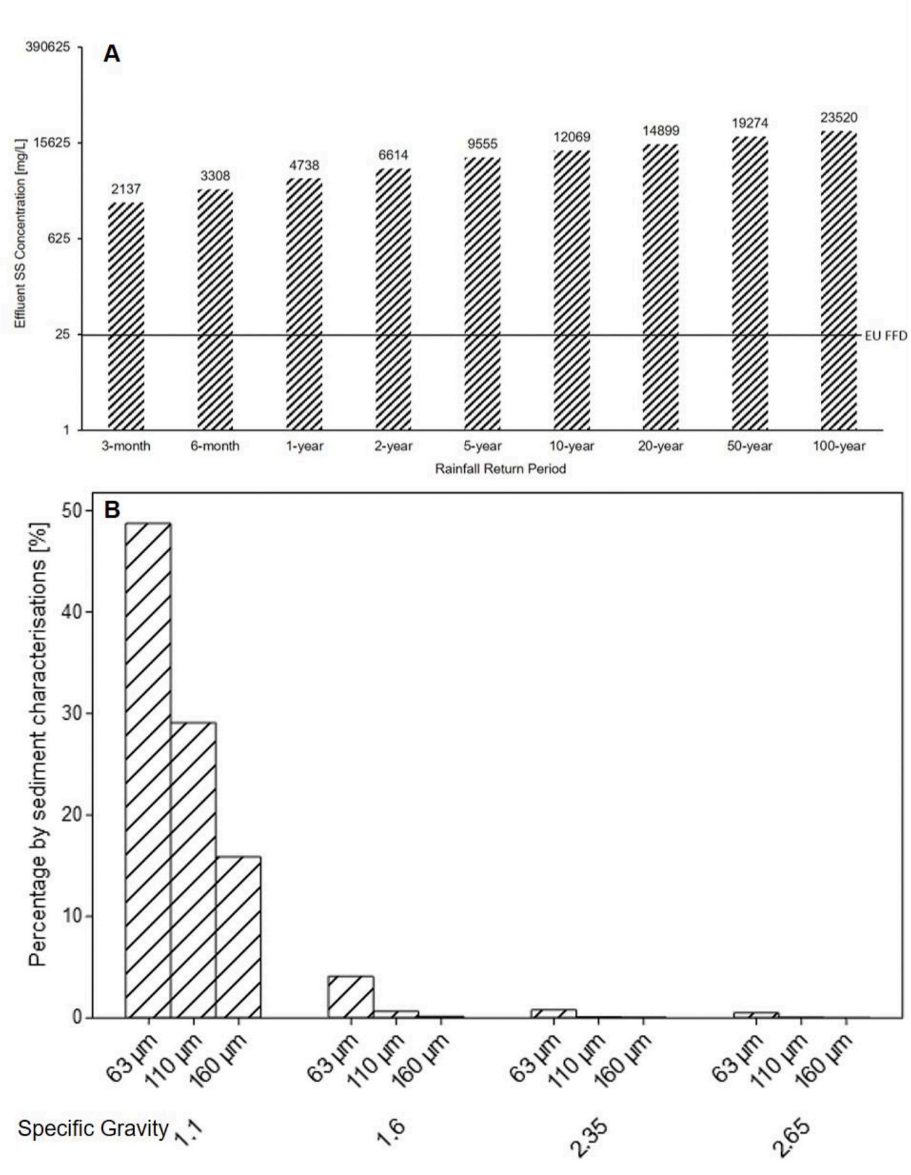
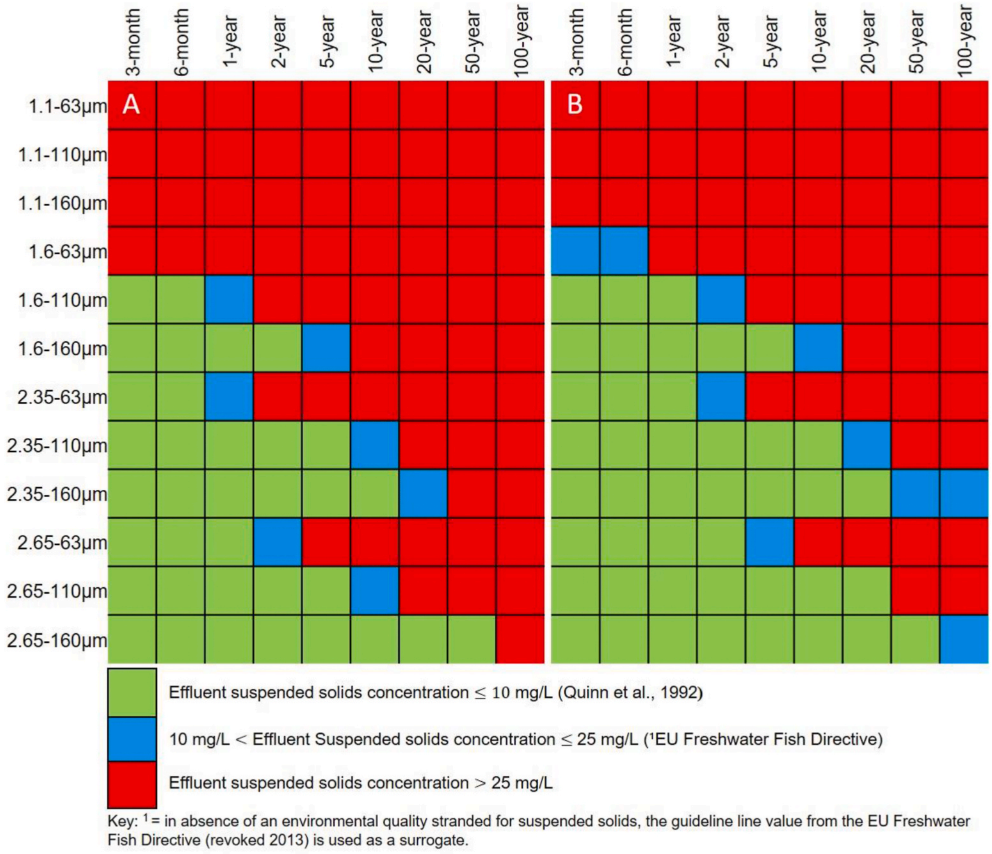


Fig. 4. Model Two, A: effluent SS concentration by nine rainfall return periods with a duration time of 10-min, in relation to a guideline value of 25 mg/L by EU Freshwater Fisheries Directive (EU FFD). B: Percentage of each sediment characterisation contributing to the total effluent suspended solids concentration, for a modelled event (10-year return period, 10-min duration time).



A

	3-month	6-month	1-year	2-year	5-year	10-year	20-year	50-year	100-year
1.1-63μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.1-110μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.1-160μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.6-63μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.6-110μm	🟩	🟩	🟦	🟥	🟥	🟥	🟥	🟥	🟥
1.6-160μm	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟥
2.35-63μm	🟩	🟩	🟦	🟥	🟥	🟥	🟥	🟥	🟥
2.35-110μm	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥
2.35-160μm	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥
2.65-63μm	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟥	🟥
2.65-110μm	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥
2.65-160μm	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥

B

	3-month	6-month	1-year	2-year	5-year	10-year	20-year	50-year	100-year
1.1-63μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.1-110μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.1-160μm	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.6-63μm	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥
1.6-110μm	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟥	🟥
1.6-160μm	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥
2.35-63μm	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟥	🟥
2.35-110μm	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟥	🟥
2.35-160μm	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦
2.65-63μm	🟩	🟩	🟩	🟩	🟦	🟥	🟥	🟥	🟥
2.65-110μm	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥
2.65-160μm	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦

🟩 Effluent suspended solids concentration ≤ 10 mg/L (Quinn et al., 1992)

🟦 10 mg/L < Effluent Suspended solids concentration ≤ 25 mg/L (^{1}EU Freshwater Fish Directive)

🟥 Effluent suspended solids concentration > 25 mg/L

Key: ^{1} = in absence of an environmental quality stranded for suspended solids, the guideline line value from the EU Freshwater Fish Directive (revoked 2013) is used as a surrogate.

Fig. 5. Model Two condition matrices for rainfall events with 5-min (A) and 10-min (B) duration time under current rainfall conditions.

quality point of view, as finer sediments adsorb a proportionally higher pollutant loading (Lee et al., 1997), and their relatively greater mobility poses a threat to recipients. Irrespective of the original design function of gully pots (i.e. capturing of large debris), several studies e.g. Grottker (1990) and Karlsson (2009) reported that particles < 100 μm could account for up to 15% (by weight) of total sediments. A more recent study by Adler (2020) reported approximately 50% (by weight) of gully pots sediment were sized < 100 μm. Considering the number of gully pots in urban catchments, the availability of fine sediment for scour should not be overlooked.

The Model Two condition matrices indicate a coherent relationship between rainfall return periods and sediment characterisations (i.e. the greater susceptibility of lighter and smaller sediment to more intensive rainfall events). Condition matrices can therefore be utilised to inform measures to target the reduction of gully pot scour-induced sediments. However, in practice this application would be highly dependent on: a) whether regulators target specific urban pollutants, b) The understanding of interactions between targeted pollutants and sediments is sufficient to inform practice. However, as the distribution of urban pollutants typically shows a site-specific feature, the application of the proposed condition matrices should also be based on site characteristics as opposed to a solely holistic approach.

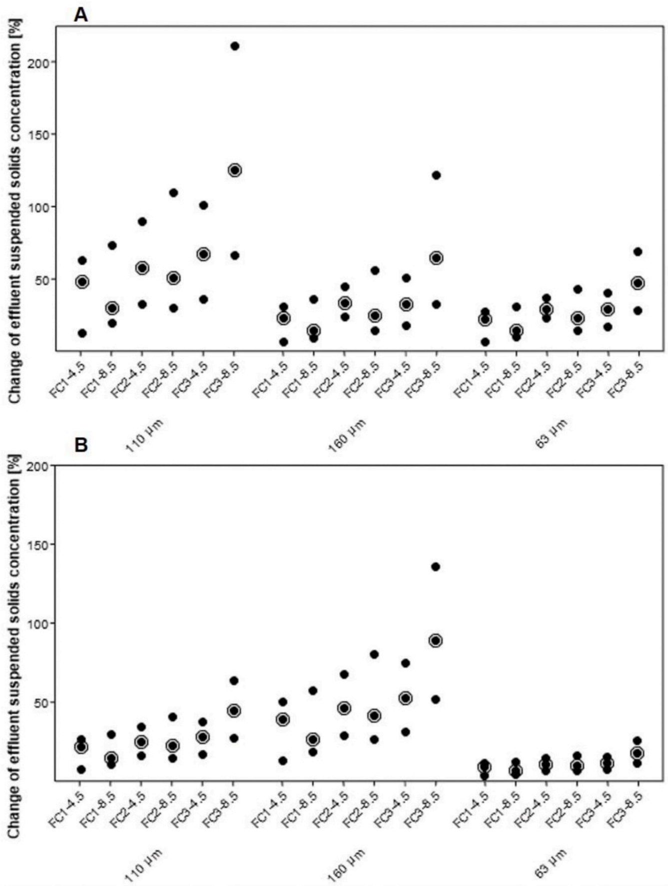
3.2.3. Sensitivity to changes in the climatic input

In Fig. 6, the percentage changes in scour-induced effluent TSS relating to three sediment sizes are plotted in relation to six future climate scenarios for a rainfall event with a 10-year return period and 100-year return period, respectively. The increasing rainfall intensities for short-time extreme events projected for future climate scenarios will enlarge the expected magnitude of effluent TSS of all three particle sizes.

The magnitude of scour-induced effluent TSS exhibited different sensitivities to future climate scenarios in relation to the return period. Simulations of rainfall events with a 10-year return period and 5 min duration time principally exhibited a higher percentage change than simulations using a 100-year return period and 5 min duration time rainfall events. Variations in relation to different particle sizes were also were noted. For example, up to twice the amount of <110 μm-particles (specific gravity of 2.35) are expected to be scoured during a 10-year return period and 5 min duration time rainfall event under the "2071–2100 rcp 8.5" scenario, relative to that of current rainfall conditions. Whilst, the percentage change for <63 μm-particles exhibited a comparatively smaller change (up to 50%) during a 10-year return period and 5 min duration time rainfall event for the same future climate scenario.

3.3. Comparisons between Model One and model two

Applying both models to the same dataset yielded markedly different results with the minimum and maximum values generated by Model One exceeding those generated by Model Two by two orders of magnitude. Such noticeable differences (summarised in Table 4) in outputs from these two models originate from their distinct identification of controlling factors within a scour process. For example, Avila (2008) empirically identified the significance of overlying water depth and inflow rate and concluded that (though both factors are inherent in the proposed regression model) particle size in combination with specific gravity was a relatively less important factors. By contrast, Howard et al. (2012) empirically identified the energy consumed to overcome sediment settling and the energy introduced by plunging water as key indicators of scour rate. Consequently, the differing bases for model development lead to the divergent outputs of these two models. Another factor which may contribute to the differences in output is the initial basal sediment conditions established for the respective physical experiments from which these two models were established. In contrast to



Notation	FC1-4.5	FC1-8.5	FC2-4.5	FC2-8.5	FC3-4.5	FC3-8.5
Scenarios	2011-2040, rcp 4.5	2011-2040, rcp 8.5	2041-2070, rcp 4.5	2041-2070, rcp 8.5	2071-2100, rcp 4.5	2071-2100, rcp 8.5

Fig. 6. Relationship between different future climate scenarios and percentage change of effluent suspended solids concentration (relative to current climate) by particle sizes, for rainfall of 10-year return period (A) and 100-year return period (B) respectively. Sediments are assumed with a specific gravity of 2.35. As the rainfall intensities for each future climate scenario were given as max, median and min values, the simulation results are also presented here as max, median and min values correspondingly.

Table 4
Summarised predicted min and max effluent TSS from two models, for rainfall event of 10-year return period and 10 min duration time.

	Min effluent TSS [mg/L]	Max effluent TSS [mg/L]
Model One	3.8	163123
Model Two	0.014 (SG = 2.65, d_s = 160 μm)	5893 (SG = 1.1, d_s = 63 μm)

the heterogeneous sediment composites adopted by Avila (2008), Howard et al. (2012) adopted sediment composites with a single size range. Hence, the 'armouring layer' effect may not be included in model two.

Comparison of the condition matrices developed from each model (see Figs. 2 and 5), indicate two distinct potential applications on adoption by practitioners. Model One highlights the role of gully pot fullness level in sediment scour processes, and can inform the magnitude of scour under different gully pot maintenance conditions. Model Two, by contrast, emphasises the characterisation (i.e. particle size and specific gravity) of sediments which can potentially be adopted at the gully pot dimensioning stage. The utility of both models, however, relies on the development of regulations on gully pots discharges.

3.4. *Challenges and future*

Whilst the role of models is valuable for understanding and quantifying gully pot sediment scour, this study shows limitations for their application by practitioners. The following sections summarise the key challenges faced and ways in which these could be addressed in future studies.

3.4.1. *Role of particulate characteristics and supply*

One of the main assumptions for Model Twooncerns the SG values allocated to sediment particles. The SG allocated to gully pot basal sediments in most studies is a value of approximately 2.65 (e.g., Butler and Karunaratne 1995; Howard et al., 2012), equivalent to the specific gravity of quartz. Research undertaken by Avila (2008) identified minimum and maximum SGs of 1.5 and 2.5 respectively, for gully pot basal sediments. An empirical study by Butler et al. (1992) identified the SG of sediments in urban runoff as ranging from 1.89 to 2.78 (mean 2.35), without a clear correlation between SG and sediment size. Another empirical study by Karamalegos et al. (2005) suggested that the SG of particles in urban runoff ranges from 1.1 to 2.65, with the majority of values ranging from 1.4 to 1.8. In this study, four SG values were selected to cover the range of values identified in the literature.

The second assumption concerns the estimation of sediment settling velocity. Using the equation proposed by Cheng (1997), both the particle SG and particle size are required. However, the size range reported for in-pot deposited sediments varies considerably within the literatures (see in Table 5), with a strong site-by-site attribute. In this study, the conclusion from a study by Butler and Memon (1999) (that only

Table 5
Concluded gully pot basal sediment size characterisations from literatures.

	d_{10} [μm]	d_{50} [μm]	d_{90} [μm]
Pratt et al. (1987)	120	200	/
Grottker (1990)	80	1000+	/
Deletic et al. (2000) (Site 1)	120	3000	8000
Deletic et al. (2000) (Site 2)	80	200	4000
Karlsson (2009)	63	/	/

sediment $\leq$ 160 μm has the potential of being scoured) was used. However, this finding was developed based on the sediment settling velocity, which is a simplification of the scour process. The in-pot sediment scour involves a wide range of interacting processes including shear stress and high momentum transfer in any direction (Avila 2008). Accordingly, in future work, a more detailed approach should be developed to determine a particle's potential of being scoured.

Both Model One and Model Two assume an unlimited supply of basal sediment irrespective of the sediment characterisation, as a widely accepted simplification for modelling. The concept of basal sediment exhaustion was defined as an "unavailability of suitable material for release" by Fletcher (1981) with this definition revised by Butler and Karunaratne (1995) to "the size of material on the bed surface is suitable for release", and "how the particles are arranged on the bed surface is suitable for release". The corresponding mechanisms e.g. 'armouring layer' by Avila (2008) and Butler and Karunaratne's (1995) 'graded bed' illustrated these two definitions, respectively. In either case, the processes can lead to an inhibition of scour indicating that there is no available suitable material for release at a certain time point, given a critical condition.

3.4.2. Model structure

Both models were established through a set of full-scale physical experiments in which the tested gully pot followed the 'optimal gully pot design' put forward by Lager et al. (1977). This optimal design was put forward as achieving the best sediment trap efficiency at the lowest manufacturing cost. To avoid the potential unfitness, the tested gully pot in this study was therefore assumed as have an 'optimal gully pot design'.

The second intrinsic limitation concerns the simplified inlet structure of gully pots. The physical experiments where these two models were established either adopted a curb-opening or a pipe entry as an inlet to the tested gully pot. Nevertheless, the curb-opening and pipe entry inlet structure only account for a small fraction of all the existing inlet designs. More regularly, inlet designs such as grated inlet of various configurations are found in Europe. Whether these two developed models are capable of handling gully pot of various inlet structures awaits further investigations as well.

3.5. Future perspective

In terms of managing the potential risks associated with gully pot basal sediment scour, the absence of legislation/guidelines makes it difficult to gain the attention of stormwater managers already struggling to address, for example, EU WFD compliance requirements. However, data on the scour-induced TSS discharged from gully pots under current and future scenarios suggest that the impact of the simultaneous discharge of multiple gully pots should not be overlooked. The available recommended/guideline values provided by i.e. the EU FFD and regionally (e.g. Gothenburg city) were established to reduce ecological impacts on recipient ecosystems. However, research by Bilotta et al. (2012) reported that the mean background TSS (0.7 μm) (without specifying the weather conditions when background TSS were gathered) in more than 78% of studied recipients is $<$ 12.5 mg/L. This suggests that the current guideline value of 25 mg/L may not be sufficiently stringent, and could lead to a deteriorating ecosystem.

A guideline value for recipient TSS has been absent at a European directive level since the repeal of EU FFD. In comparison with the increasingly stringent water quality standards for many other pollutants, the omission of suspended solids from the EU WFD is surprising. A fitness check of the 20-year-old EU WFD is currently on-going, and it is highly recommended that any future revisions should include a TSS standard for receiving water bodies. Meanwhile, the development of a new protocol which includes the effluent TSS as one of the performance criteria for gully pots should be considered.

4. Conclusions and recommendations

The increasingly frequent wet weather extremes, combined with lack of routine maintenance of gully pots, are expected to intensify the scour of previously-deposited sediments. Depending on catchment conditions, these scoured sediments may carry a substantial pollutant load, and thus pose a risk to receiving water ecology, contributing to EU WFD failure. Two models developed to quantify sediment scour were critically tested under a wide range of scenarios including current and potential future rainfall conditions.

Simulations with both models consistently exhibited a positive correlation between the scour rate and rainfall return periods, confirming the role of rainfall intensity in scour processes. Outputs from both models were not consistent despite the same set of inputs. Additional field measurements are needed to validate/reject either scour-induced effluent TSS prediction model, with differences in model outputs attributed to their differing respective competences. Model One primarily drew on gully pot fullness level in determining the scour rate. In contrast, Model Two focused on the role of particle characteristics (i.e. SG and diameter) in predicting scouring behaviour. Simulations with Model One suggested a critical condition (fullness level of 60%) for gully pot maintenance as the risk of scour is expected to be substantially lowered under this fullness level. This is especially important as the reactive maintenance of gully pots is predicted to be more affected under potential future rainfall conditions. Model Two, in comparison, can inform the dimensioning gully pots to increase resistance against the scour of sediments of certain characterisations. The strategic priorities of local authorities, as well as regulatory drivers of regulations and practitioners' priorities, can hence inform model selection. Above all, the conservation objectives of the recipient water bodies can play a decisive role in evidencing the need for optimising the gully pot maintenance regime.

Given the identified limitations in this study, the applicability of both models to gully pots which do not conform the 'optimal design' needs to be further investigated. Further, the development of a new protocol for gully pot performance evaluation which includes the assessment of effluent suspended solids concentration is recommended.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We gratefully acknowledge the financial support provided by the FORMAS (Swedish Research Council) under JPI INXCES (Grant no. WaterWorks2014 - INXCES 229) and the VINNOVA (Swedish Governmental Agency for Innovation Systems) DRIZZLE – Centre for Stormwater Management (Grant no. 2016–05176). We also gratefully acknowledge the technical expertise provided by the Stormwater&Sewers network.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111911.

Credit author statement

Haoyu Wei: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Project administration, Investigation, Visualization, Writing – original draft, Writing – review & editing. Tone Merete Muthanna: Conceptualization, Methodology, Supervision, Writing – review & editing. Lian Lundy: Conceptualization, Methodology, Supervision, Project administration, Writing – review & editing. Maria Viklander: Conceptualization, Supervision, Methodology, Funding acquisition, Project administration, Writing – review & editing.

References

Adler, N., 2020. Performance of Roadside Gully Pots in Trondheim for Sediment Removal-Evaluated Based Land Use and Annual Traffic Loads. NTNU.

Avila, H., 2008. Scour of Captured Sediment from a Stormwater Hydrodynamic Device. Doctoral Dissertation. The University of Alabama.

Bennerstedt, K., 2005. Treatment of Stormwater from Roads (Lokal Refining Av Trafikdagvatten).

Bilotta, G.S., Burnside, N.G., Cheek, L., Dunbar, M.J., Grove, M.K., Harrison, C., Joyce, C., Peacock, C., Davy-Bowker, J., 2012. Developing environment-specific water quality guidelines for suspended particulate matter. Water Res. 46 (7), 2324–2332. https://doi.org/10.1016/j.watres.2012.01.055.

Butler, D., Davies, J., 2017. Urban Drainage. CRC Press.

Butler, D., Karunaratne, S.H.P.G., 1995. The suspended solids trap efficiency of the roadside gully pot. Water Res. 29 (2), 719–729. https://doi.org/10.1016/0043-1354(94)00149-2.

Butler, D., Memon, F.A., 1999. Dynamic modelling of roadside gully pots during wet weather. Water Res. 33 (15), 3364–3372. https://doi.org/10.1016/S0043-1354(99)00050-0.

Butler, D., Thedchanamoorthy, S., Payne, J.A., 1992. Aspects of surface sediment characteristics on an urban catchment in London. Water Sci. Technol. 25 (8), 13–19. https://doi.org/10.2166/wst.1992.0174.

Campbell, N., D'Arcy, B., Frost, A., Novotny, V., Sansom, A., 2005. Diffuse Pollution. IWA publishing. https://doi.org/10.2166/9781780402956.

Cheng, N.-S., 1997. Simplified settling velocity formula for sediment particle. J. Hydraul. Eng. 123 (2), 149–152. https://doi.org/10.1061/(ASCE)0733-9429(1997)123:2(149).

Dahlström, B., 2010. Rain intensity - a cloud physical observation (Regnintensitet - en molnfysikalisk betraktelse) (2010-05).

Deletic, A., Ashley, R., Rest, D., 2000. Modelling input of fine granular sediment into drainage systems via gully-pots. Water Res. 34 (15), 3836–3844. https://doi.org/10.1016/S0043-1354(00)00133-0.

EU Water Framework Directive, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy.

European Union Freshwater Fisheries Directive, 2006. In: Directive 2006/44/EC of the European Parliament and of the Council of 6 September 2006 on the Quality of Freshwaters Needing Protection or Improvement in Order to Support Fish Life. European Union. European Parliament, C.o.t. E.U.

Fletcher, I.J., 1981. Mathematical Simulation of Pollutant Contributions to Urban Runoff from Roadside Gully Ponds, pp. 116–124.

Gothenburg City Environment Management Group, 2013. Environmental Management Guidelines and Guideline Values for Discharges of Polluted Water to Recipients and Stormwater System. R 2013: 10.

Grottker, M., 1990. Pollutant removal by gully pots in different catchment areas. Sci. Total Environ. 93, 515–522.

Howard, A.K., Mohseni, O., Gulliver, J.S., Stefan, H.G., 2012. Hydraulic analysis of suspended sediment removal from storm water in a standard sump. J. Hydraul. Eng. 138 (6), 491–502. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000544.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Karamalegos, A.M., Barrett, M.E., Lawler, D.F., Malina, J.F., 2005. Particle Size Distribution of Highway Runoff and Modification through Stormwater Treatment (05-10).

Karlsson, K., 2009. Characterisation of Pollutants in Stormwater Treatment Facilities. Luleå University of Technology.

Lager, J.A., Smith, W.G., Tchobanoglous, G., 1977. Catchbasin Technology Overview and Assessment.

Lee, P.-K., Touray, J.-C., Baillif, P., Ildefonse, J.-P., 1997. Heavy metal contamination of settling particles in a retention pond along the A-71 motorway in Sologne, France. Sci. Total Environ. 201 (1), 1–15. https://doi.org/10.1016/S0048-9697(97)84048-X.

Leikanger, E., Roseth, R., 2016. Veiavrenning Og Driftstiltak. Overvåking Av Avrenning Samt Oppfølging Av Feie-og Sandfangmasser Ved Ulik Veidrift. NIBIO Rapport.

Lindholm, O., 2015. Pollution from roads and the importance of emptying gully pots (Forurensingstilførsler fra veg og betydningen av å tømme sandfang).

Lundy, L., Alves, L., Revitt, M., Wildeboer, D., 2017. Metal water-sediment interactions and impacts on an urban ecosystem. Int. J. Environ. Res. Publ. Health 14 (7), 722. https://doi.org/10.3390/ijerph14070722.

Morrison, G.M., Revitt, D.M., Ellis, J.B., Svensson, G., Balmer, P., 1988. Transport mechanisms and processes for metal species in a gully pot system. Water Res. 22 (11), 1417–1427. https://doi.org/10.1016/0043-1354(88)90099-1.

Pratt, C.J., Elliott, G.E.P., Fulcher, G.A., 1987. Suspended solids discharge from highway gully pots in a residential catchment. Sci. Total Environ. 59, 355–364. https://doi.org/10.1016/0048-9697(87)90459-1.

Quinn, J.M., Davies-Colley, R.J., Hickey, C.W., Vickers, M.L., Ryan, P.A., 1992. Effects of clay discharges on streams. Hydrobiologia 248 (3), 235–247. https://doi.org/10.1007/BF00006149.

Ræstad, C., 2014. Urban runoff management (Håndtering av overvann fra urbane veger).

Rietveld, M.W.J., Clemens, F.H.L.R., Langeveld, J.G., 2020. Monitoring and statistical modelling of the solids accumulation rate in gully pots. Urban Water J. 17 (6), 549–559. https://doi.org/10.1080/1573062X.2020.1800760.

Schmidt, E., Grigull, U., 1989. Properties of Water and Steam in SI-Units, vol. 4.

Swedish Traffic Agency, 2008. Hydraulic Dimensioning (Vägverket).

Swedish Water, 2016. Diversion of Drainage Water and Wastewater (P110 Avledning Av Dag-, Drän-Och Spillvatten).

Wada, Y., Miura, H., Hasegawa, K., 1987. Model Building and Analysis of Runoff Water Quality of Flush from the Street Gully Pots, pp. 60–65.

Westerlund, C., Viklander, M., 2006. Particles and associated metals in road runoff during snowmelt and rainfall. Sci. Total Environ. 362 (1), 143–156. https://doi.org/10.1016/j.scitotenv.2005.06.031.