Modular design of bioretention cells for sustainable stormwater management under drivers of urbanization and climate change

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Supplementary Material



Figure S1: Pictures of the flood disaster and economic losses occurred on 14 Jan 2020 in Sao Carlos, SP, Brazil (unknown source, wide circulation images on the internet).

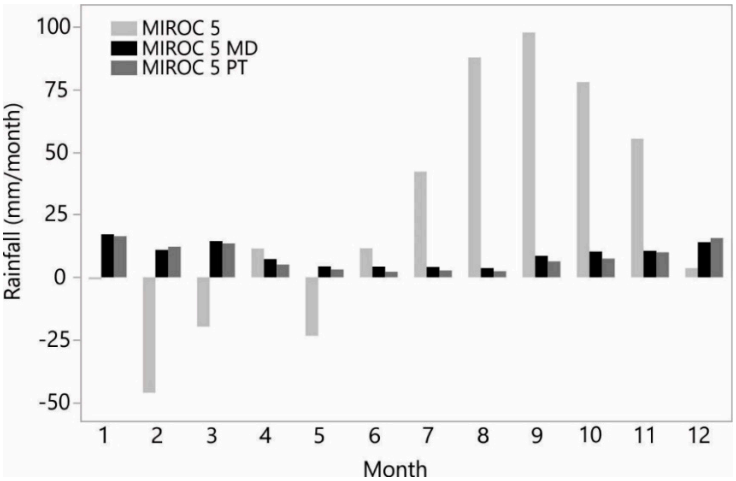

Figure S2: The difference between the observed and modeled monthly rainfall average data with and without bias correction for climate models used. For bias correction, power transformation (PT) and mapping distribution (MD) methods were used.

Table S1: The results obtained for the statistical adherence test for the Gumbel-Weibull distribution model for all combinations of RCM and bias correction.

RCM	RCP	Bias-correction	R^2	D-KS	p-value
		2015 - 2050			
Eta - MIROC5	4.5	MD	0.956	0.136	0.51
		PT	0.976	0.123	0.31
	8.5	MD	0.986	0.099	0.10
		TP	0.975	0.147	0.59
		2051 - 2099			
Eta - MIROC5	4.5	MD	0.988	0.111	0.29
		PT	0.991	0.109	0.27
	8.5	MD	0.984	0.134	0.53
		PT	0.99	0.117	0.35

Table S2: Disaggregation factors for sub-daily rainfall data for São Carlos, SP.

Disagregation factors		Absolute	
5 min/30 min	0.34	5 min	0.12
10 min/30 min	0.54	10 min	0.19
15 min/30 min	0.70	15 min	0.25
20 min/30 min	0.81	20 min	0.29
25min/30 min	0.91	25 min	0.32
30 min/1 h	0.74	30 min	0.35
1 h/24 h	0.42	60 min	0.48
6 h/24 h	0.72	360 min	0.82
8 h/24 h	0.78	480 min	0.89
10 h/24 h	0.82	600 min	0.93
12 h/24 h	0.85	720 min	0.97
24 h/1 day	1.14	1440 min	1.14

Description of the equations used in water flow model

In this model, a three-bucket approach is employed, each bucket representing the main components zones of a bioretention: ponding zone, unsaturated zone and submerged zone (if this zone exists, otherwise, drainage zone). The main simulated processes consist of infiltration from the ponding zone to the unsaturated filtering zone, infiltration from the unsaturated zone to the submerged zone, outflow from an underdrain, overflow from a weir, evapotranspiration, and capillary rise. For the underdrain and weir, the equations for the orifice and the equation for the triangular weir were used, respectively, together with a mass balance of the respective zone of influence. The infiltration process is governed by Darcy's law (if the media is saturated), or by modified Darcy's law with adjustment of hydraulic conductivity as a function of saturation of the media, if unsaturated. The evapotranspiration and capillary rise are calculated based on empirical equations proposed in the study of Shen et al. (2018) (adapted from Allen et al., 1998) and Daly et al. (2009).

Evapotranspiration:

$$Q_{et}{}^{i} = \begin{cases} 0\,, & if\ S_t{}^{i} \le S_w \\ A_b K_c ET_0 \frac{S_t{}^{i} - S_w}{S_s - S_w}\,, & if\ S_w < S_t{}^{i} \le S_s \\ A_b K_c ET_0\,, & if\ S_s < S_t{}^{i} \le 1 \end{cases} \text{ (mm/min)}$$

$$Q_{et}{}^{i} = Q_{et}{}^{i}/(1000.60) \text{ (m3/s)}$$

$$S_t{}^{i} = \frac{S^i n_{usz}{}^{i} h_{usz}{}^{i} + n_{sz}{}^{i} h_{sz}{}^{i}}{n_{usz}{}^{i} h_{usz}{}^{i} + n_{sz}{}^{i} h_{sz}{}^{i}}$$

Ponding zone:

Water mass balance

$$\frac{\partial S_{pz}}{\partial t} = Q_{in}{}^{i} + Q_{rain}{}^{i} - Q_{pf}{}^{i} - Q_{over}{}^{i} - Q_{inf,p}{}^{i}$$

State variables equations

$$S_{pz}{}^{i} = h_{pz}{}^{i} . A_b$$

$$Q_{pf}{}^{i} = \min\left(\frac{k_s A_p (h_{pz}{}^{i} + h_{usz}{}^{i})}{h_{usz}{}^{i}},\ \frac{h_{pz}{}^{i} A_b}{dt} - Q_{inf,p}{}^{i},\ \frac{(1 - S^i)\, n_{usz}{}^{i} h_{usz}{}^{i} A_p}{dt}\right)$$

$$Q_{over}{}^{i} = \begin{cases} 0 & ,\ if\ h_{pz}{}^{i} \le P_v \\ \min\left(\frac{A_p (h_{pz}{}^{i} - P_v)}{dt},\ kweir\ 2g^{0.5}\left(h_{pz}{}^{i} - P_v\right)^{kexp}\right), & if\ h_{pz}{}^{i} > P_v \end{cases}$$

$$Q_{inf,pz}{}^{i} = K_f\left[\left(A_b - A_p\right) + C_s P_p h_{pz}{}^{i}\right]$$

$$h_{pz}{}^{i} = h_{pz}{}^{i-1} + \frac{\left(Q_{in}{}^{i} + Q_{rain}{}^{i} - Q_{pf}{}^{i} - Q_{over}{}^{i} - Q_{inf,p}{}^{i}\right) dt}{A_b}$$

Unsaturated zone (USZ):

Water mass balance

$$\frac{\partial S_{usz}}{\partial t} = Q_{pf}{}^{i} + Q_{hc}{}^{i} - Q_{fs}{}^{i} - Q_{et,usz}{}^{i}$$

State variables equations

$$Q_{et,usz}{}^{i} = Q_{et}{}^{i} \frac{S_{usz}{}^{i} n_{usz}{}^{i} h_{usz}{}^{i}}{n_{usz}{}^{i} h_{usz}{}^{i} + n_{sz}{}^{i} h_{sz}{}^{i}}$$

$$Q_{hc}{}^{i} = \begin{cases} A_p Cr\left(S_{usz}{}^{i} - S_s\right)\left(S_{fc} - S_{usz}{}^{i}\right), & if\ S_s \le S_{usz}{}^{i} \le S_{fc} \\ 0 \end{cases}$$

$$Cr = \frac{4 K_c ET_0}{2.5\left(S_{fc} - S_s\right)^2}$$

$$Q_{fs}{}^{i} = \begin{cases} min\left(\frac{k_s A_p (h_{pz}{}^{i} + h_{usz}{}^{i})}{h_{usz}{}^{i}}\ S^{i\gamma},\ \frac{(S_{usz}{}^{i} - S_{fc}) A_p h_{usz}{}^{i} n_{usz}{}^{i}}{dt}\right), if\ S_{usz}{}^{i} \ge S_{fc} \\ 0, if\ S_{usz}{}^{i} < S_{fc} \end{cases}$$

$$h_{usz}{}^{i} = L - h_{sz}{}^{i-1}$$

$$n_{usz}{}^{i} = \begin{cases} \frac{n_f D_f + n_g\left(D_g - h_{sz}{}^{i-1}\right)}{h_{usz}{}^{i}} = \ , \ if\ h_{sz}{}^{i-1} < D_g \\ n_f\ , \quad if\ h_{sz}{}^{i-1} \geq D_g \end{cases}$$

$$\theta_{usz}{}^{i} = S_{usz}{}^{i} n_{usz}{}^{i}$$

$$S_{usz}{}^{i} = max\left[min\left(1,\ S_{usz}{}^{i-1} h_{usz}{}^{i-1} n_{usz}{}^{i-1} + \frac{\left(Q_{pf}{}^{i} + Q_{hc}{}^{i} - Q_{fs}{}^{i} - Q_{et,usz}{}^{i}\right)dt}{A_p h_{usz}{}^{i} n_{usz}{}^{i}}\right), S_h\right]$$

Saturated zone (SZ):

Water mass balance

$$\frac{\partial S_{sz}}{\partial t} = Q_{fs}{}^{i} - Q_{hc}{}^{i} - Q_{et,sz}{}^{i} - Q_{pipe}{}^{i} - Q_{inf,sz}{}^{i}$$

$S_{sz} = 1$ (constant)

State variables equations

$$Q_{et,sz}{}^{i} = Q_{et}{}^{i} - Q_{et,usz}{}^{i}$$

$$Q_{pipe}{}^{i} = \begin{cases} min\left(\frac{\left(h_{sz}{}^{i} - h_{pipe}\right) A_p n_{usz}{}^{i}}{dt} - Q_{inf,sz}{}^{i},\ C_d A_{pipe}\left[\left(h_{sz}{}^{i} - h_{pipe}\right) 2g\right]^{1/2}\right),\ if\ h_{sz}{}^{i} \geq h_{pipe} \\ 0\ ,\ if\ \ h_{sz}{}^{i} < h_{pipe} \end{cases}$$

$$Q_{inf,sz}{}^{i} = K_f\left(A_p + C_s P_p h_{sz}{}^{i}\right)$$

$$h_{sz}{}^{i} = h_{sz}{}^{i-1} + \frac{\left(Q_{fs}{}^{i} - Q_{hc}{}^{i} - Q_{et,sz}{}^{i} - Q_{pipe}{}^{i} - Q_{inf,sz}{}^{i}\right)dt}{A_p\, n_{sz}{}^{i-1}}$$

$$n_{sz}{}^{i} = \begin{cases} \frac{n_g D_g + n_t D_t + n_f\left(h_{sz}{}^{i} - D_g - D_t\right)}{h_{sz}{}^{i}},\ if\ D_t + D_g < h_{sz}{}^{i} \leq L \\ \frac{n_g D_g + n_t\left(h_{sz}{}^{i} - D_g\right)}{h_{sz}{}^{i}},\ if\ D_g < h_{sz}{}^{i} \leq D_t + D_g \\ n_g\ ,\ if\ \ h_{sz}{}^{i} \leq D_g \end{cases}$$

$$\theta_{sz}{}^{i} = n_{sz}{}^{i}$$

Table S3: Variables of the model.

Symbol	Meaning	Dimensions
$Q_{in,i}$	Biofilter inflow, in time i	m^3/s
$Q_{inf,p,i}$	Infiltration to surrounding soil, in time i	m^3/s
$S_{pz,i}$	Storage in ponding zone, in time i	m^3
$Q_{over,i}$	Overflow through weir, in time i	m^3/s
$Q_{pf,i}$	Infiltration to USZ, in time i	m^3/s
$S_{usz,i}$	Storage in soil mix, in time i	m^3
$h_{usz,i}$	Depth of the unsaturated zone, in time i	m
$Q_{fs,i}$	Infiltration to SZ, in time i	m^3/s
$h_{sz,i}$	Depth of the saturated zone, in time i	m
$Q_{et,i}$	Total evapotranspiration flow, in time i	m^3/s
$Q_{et,usz,i}$	Total evapotranspiration flow in USZ, in time i	m^3/s
$Q_{et,sz,i}$	Total evapotranspiration flow in SZ, in time i	m^3/s
$Q_{hc,i}$	Capillary rise flow, in time i	m^3/s
$Q_{pipe,i}$	Drainage pipe flow, in time i	m^3/s
$Q_{inf,sz,i}$	Infiltration to bottom surrounding soil, in time i	m^3/s
$h_{pz,i}$	Ponding depth, in time i	m
$n_{usz,i}$	Porosity in unsaturated zone	
$n_{sz,i}$	Porosity in saturated zone	
$\theta_{usz,i}$	Soil water fraction by volume in unsaturated zone	
$\theta_{sz,i}$	Soil water fraction by volume in saturated zone	

Table S4. Parameters of the model.

Symbol	Meaning	Dimensions
A_b	Bioretention surface area	m^2
Ap	Filter surface area	m^2
nf	Soil mix porosity	
nt	Transition layer porosity	
ng	Gravel porosity	
Df	Soil mix height	m
Dt	Transition layer height	m
Dg	Gravel height	m
P_v	Weir height	m
kexp	Weir exponential coefficient	
kweir	Weir coefficient	
S_{fc}	Field capacity/effective moisture	
S_h	Hygroscopic point moisture	
S_w	Wilting point moisture	
S_s	Saturation as threshold for plants to reach potential ET	
γ	Saturated curve parameter	
k_s	Hydraulic conductivity coefficient of soil mix	m/s
Cd	Discharge coefficient	
d_{orif}	Hole diameter	mm
Kf	Hydraulic conductivity coefficient of surrounding soil	m/s
g	Gravity aceleration	m/s^2
h_{pipe}	Height of underdrain	m
Kc	Plant coefficient for evapotranspiration	

Table S5. Characteristics of the laboratory events used to calibrate and validate the water flow model.

Event	Date	Type	FR (m/h)	AR (%)	d (min)	API (mm)	Dry days	Quality monitoring	V_{in} (L)	V_{out} (L)	V_{over} (L)	$V_{storage}$ (L)	Q_{in} (L/h)	$Q_{peak,out}$ (L/h)	$Q_{peak,over}$ (L/h)	Type
1	2/4/2019	1.c.I	1.0	251.0	30.4	29.5	2	No	735.95	633.55	0	102.4	1451	792	0	Calibration
2	3/19/2019	2.c.I	1.6	396.0	30.8	37.7	4	No	1162.98	860	177.8	125.18	2268	864	1188	Validation
3	6/26/2019	1.c.I	1.0	255.0	31.1	7.4	15	Yes	747.9	520.7	0	227.2	1442.89	498	0	Calibration
4	8/21/2019	c.I	1.0	82.0	10.0	43.9	0	No	255.71	224.3	0	31.41	1442.89	536	0	Validation
5	9/2/2019	1.c.I	1.0	161.0	20.5	10.8	11	Yes	240.48	214	0	26.48	1442.89	336	0	Validation
6	9/30/2019	1.c.I	1.0	236.0	30.0	6.7	27	Yes	240.48	265.2	0	-24.72	1442.89	348	0	Calibration

FR - Flow rate, AR - Aplication rate, d - Duration, API - Antecedent precipitation index, Dry days - days with 0mm of precipitation, $V_{storage}$ - final stored volume, Q_{in} - inflow, Qpeak,out - outflow peak

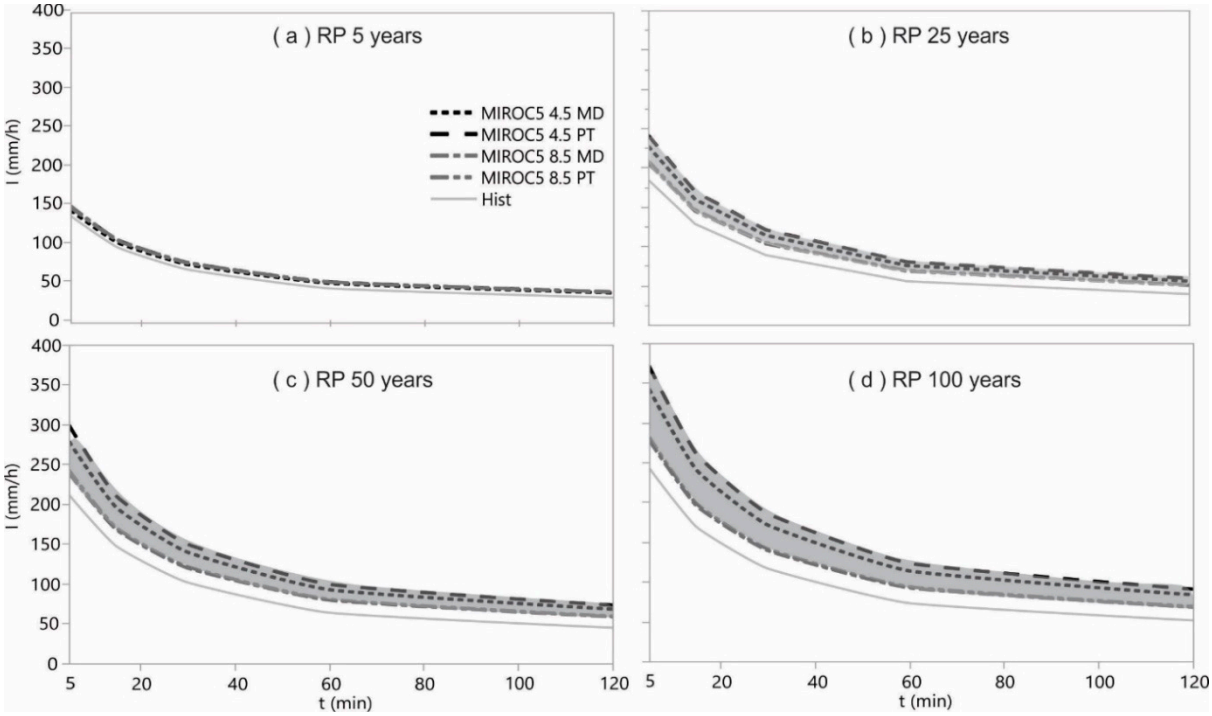

Figure S3: Projected future IDF curves for the period 2015–2050 for the city of Sao Carlos, SP, Brazil, and return periods of (a) 5 years, (b) 25 years, (c) 50 years and (d) 100 years. For bias correction, power transformation (PT) and mapping distribution (MD) methods were used.

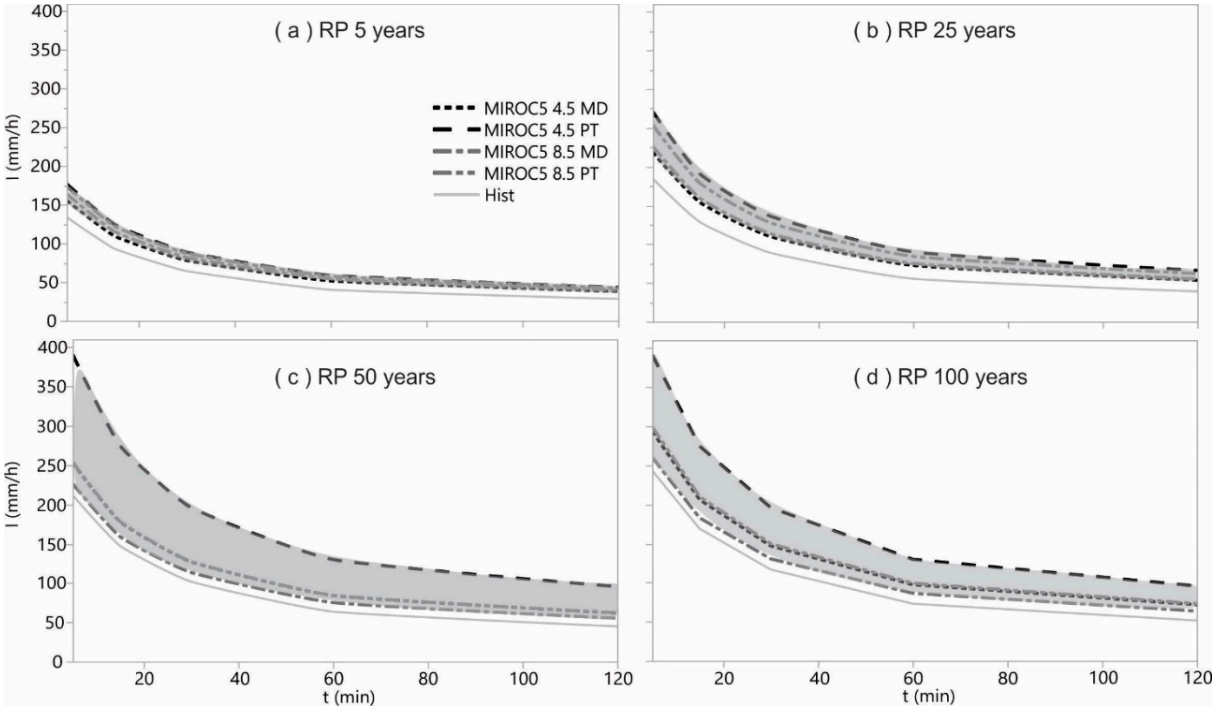

Figure S4: Projected future IDF curves for the period 2050–2100 for the city of Sao Carlos, SP, Brazil, and return periods of (a) 5 years, (b) 25 years, (c) 50 years and (d) 100 years. For bias correction, power transformation (PT) and mapping distribution (MD) methods were used.