Supplementary Information (SI)

Supplementary Data:

SI Data: Description of design objectives and planning assumptions of the LID site-design

Overall objectives of site planning were volume reduction 'to the maximum extent possible' but also peak discharge retardation in order to reduce the SW impact on the small receiving stream that already exhibited degradation and risk of downstream flooding (BC 1996). In fact, the design was focused on the drainage and infiltration efficiency of the BRS as a SWM facility (ATV A-138 1990) because no specific LID design principles (e.g. as in PCG 1999 for the USA) or stream-related guidelines (e.g. BWK M-3 2007) were required in Germany at the time of planning. The initial sizing of the BRS, constructed from 1997 to 2004, and design goals were calculated during pre-constructional planning in 1996 with the Rational Method using the parameters in SI Table 1. For intense storms it was assumed that the swale system acts solely as conveyance system yielding a maximum discharge rate of 1511 L/s for a 15 min 5-year design storm (20.2 mm) as regulatory threshold. The design goals for volume reduction of single storms were derived from a variety of design storms using a design soil infiltration rate for the BRS of $5*10^{-6}$ m/s which is half of the rate defined in German technical guidelines and common practice to account for potential clogging (DWA A-138 2005). The design goal for cumulative annual volume reduction was based on long-term mean precipitation (1951-80) and estimated mean initial losses.

Necessary runoff parameters and size-distribution of the future land use were based on stipulations of the land-use plan or estimated by the planners based on standardized lot designs. LID techniques were accounted for as land use types but only for parts of the public area because many details of the current land use were not certain at that time. Although vegetated roofs were mandatory in the local plan for roofs < 5°, they could not be accounted for during planning because it was unclear where and to which extent they will be built amongst mostly private dwellings.

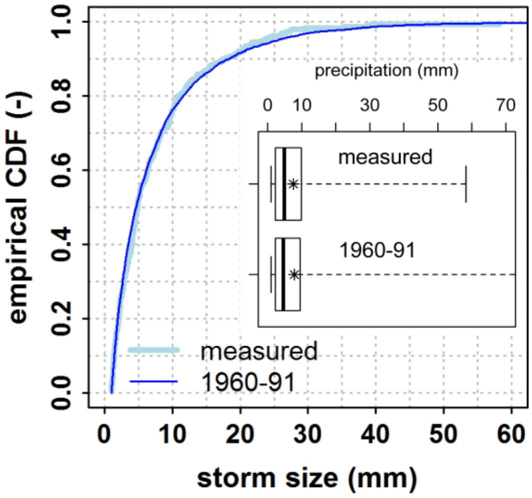
The following values were derived as design goals from the planning above-mentioned:

- Volume reduction of ≥ 87% of the storm volume for the long-term annual mean precipitation and at least 68% for single events with complete capture of storms ≤ 4.3 mm

- Reducing peak discharges as much as possible, not exceeding 940 L/s for a 15 min, 1-year design storm as approximate design value and not exceeding 1511 L/s as regulatory threshold derived from a 15 min, 5-year design storm excluding infiltration

- Downstream flood attenuation and ecological relief for the receiving stream

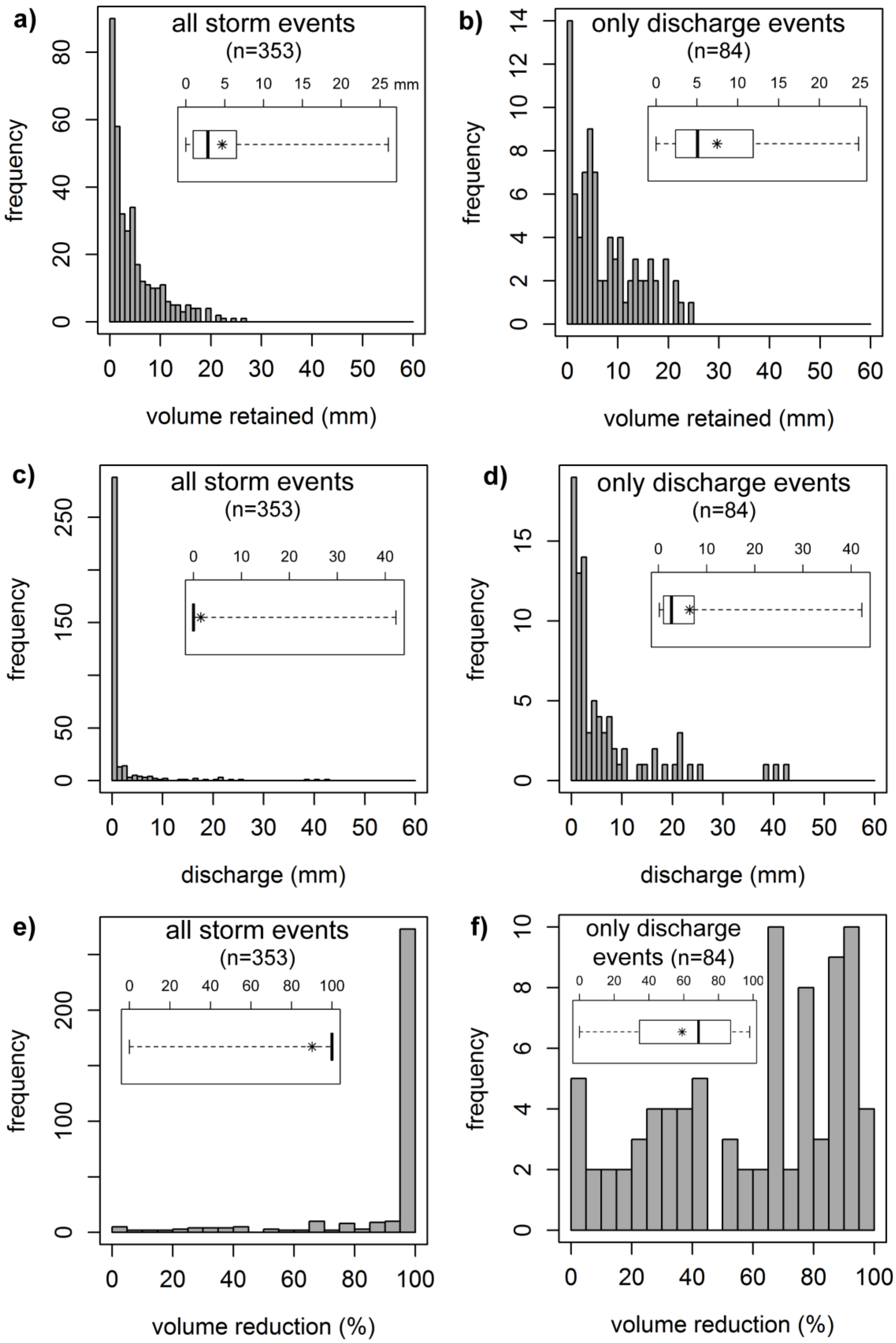
Supplementary Figures:



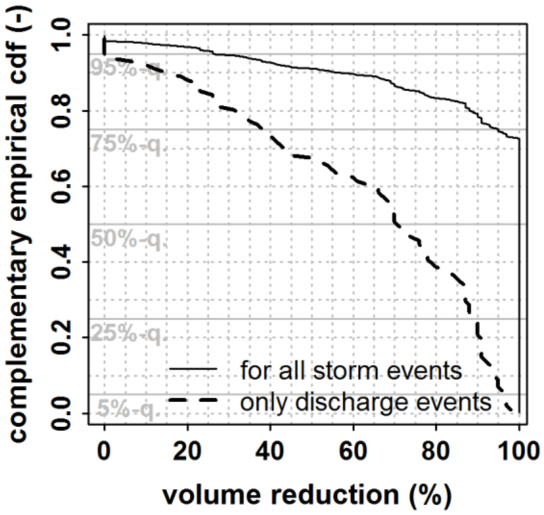
SI Fig. 1. Empirical cumulative distribution and boxplot of storm sizes ≥1 mm for the observation period compared to long-term values (1961-90, data: Ernst & CO 2003); long-term values > 60 mm not shown (13 storms with 61-182 mm).

Reference:

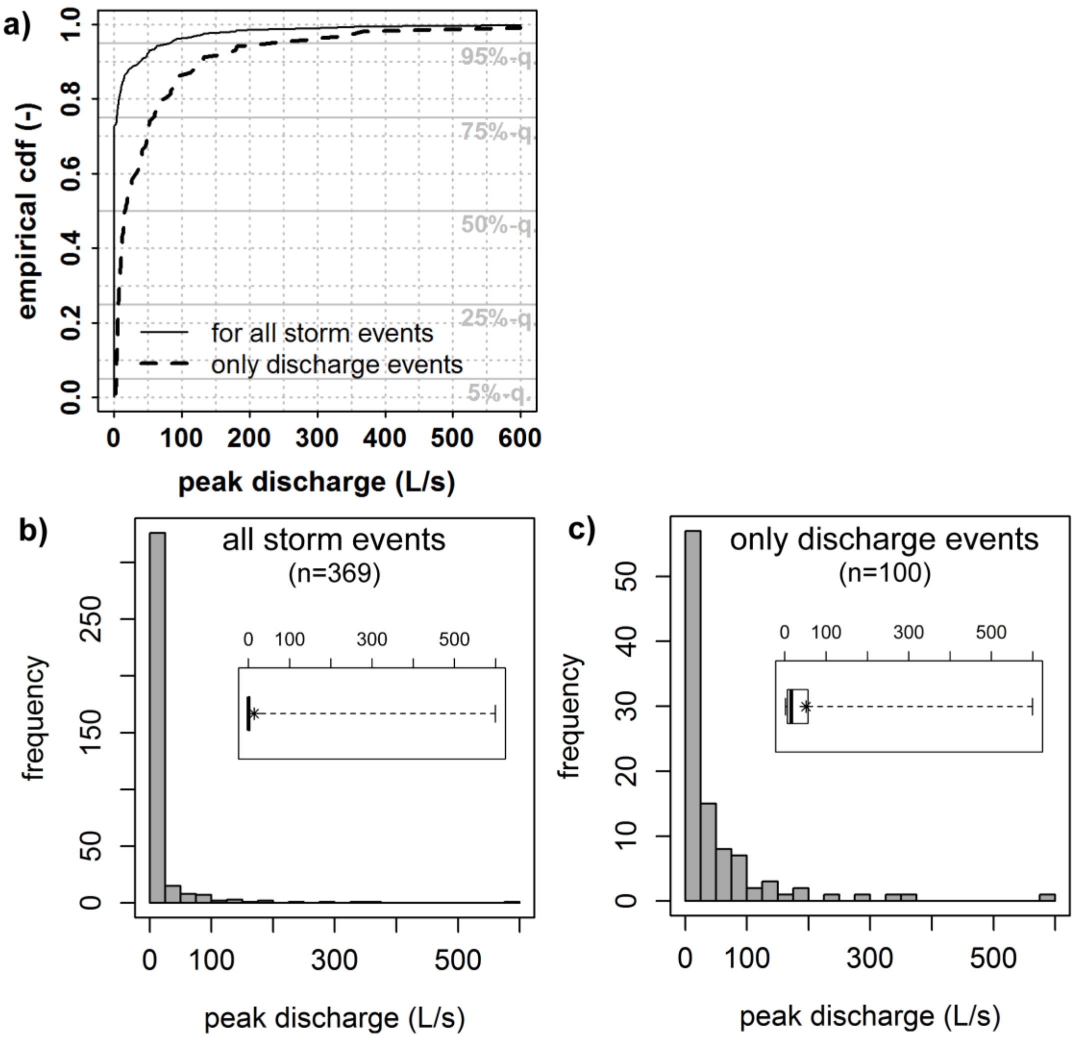
Ernst & CO Engineering, 2003. *Analysis of compound precipitation data Freiburg-Badenweiler ≥ 1 mm 1961-90 [data: N7035ERG-DAT]*. Stations Badenweiler (1961-70, no. 7027), Freiburg city (1971-80, no. 7035), Badenweiler (1981-90, no. 7027), GEP (general drainage plan) city of Freiburg.



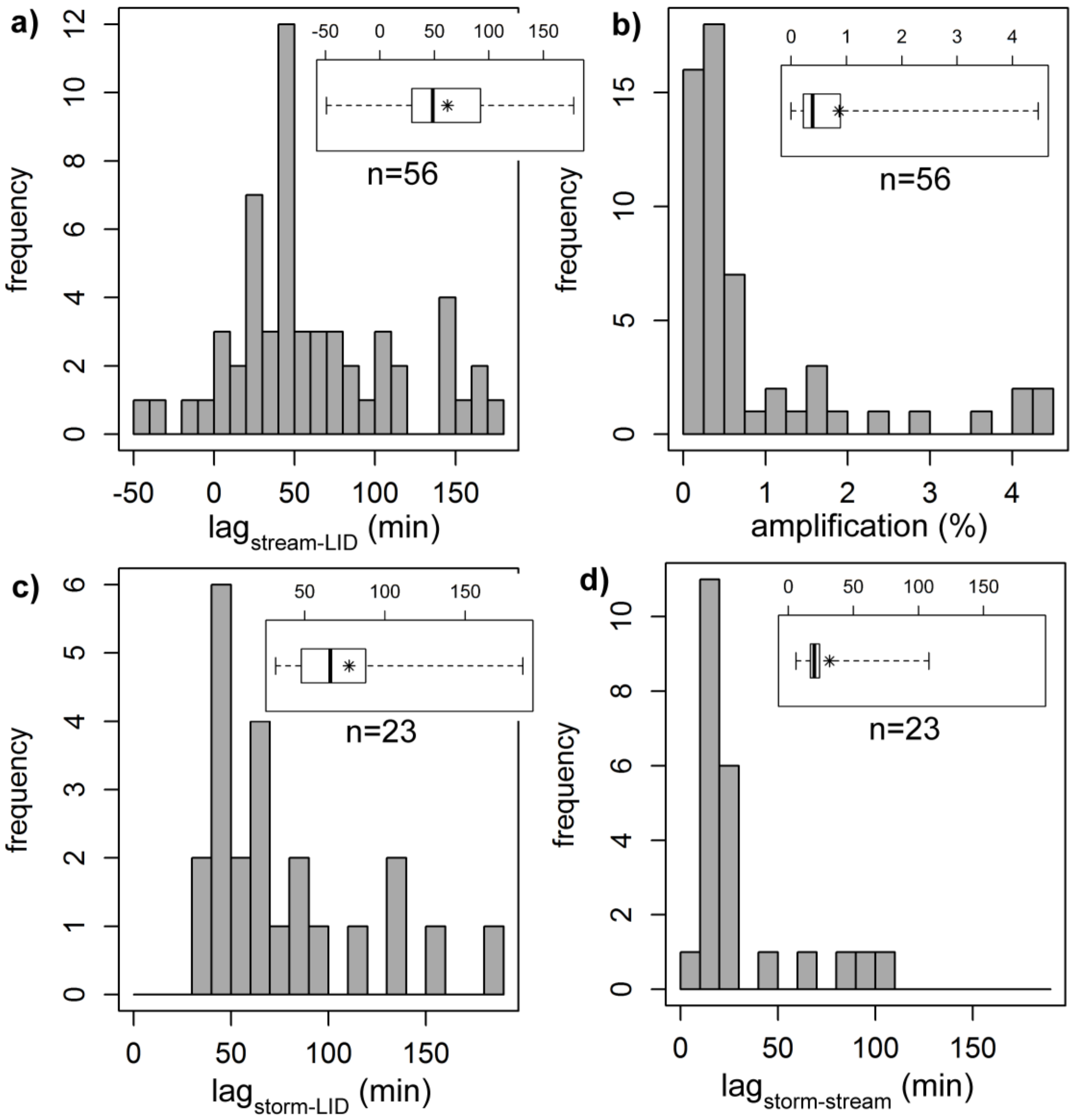
SI Fig. 2. Frequency distributions and boxplots of: a) event volume retained for all storm events and b) for only discharge events (only partial volume reduction); c) event discharge volumes for all storm events and d) for only discharge events; e) relative event volume reduction for all storm events and f) only discharge events. Negative values were set to zero (see SI Table 4).



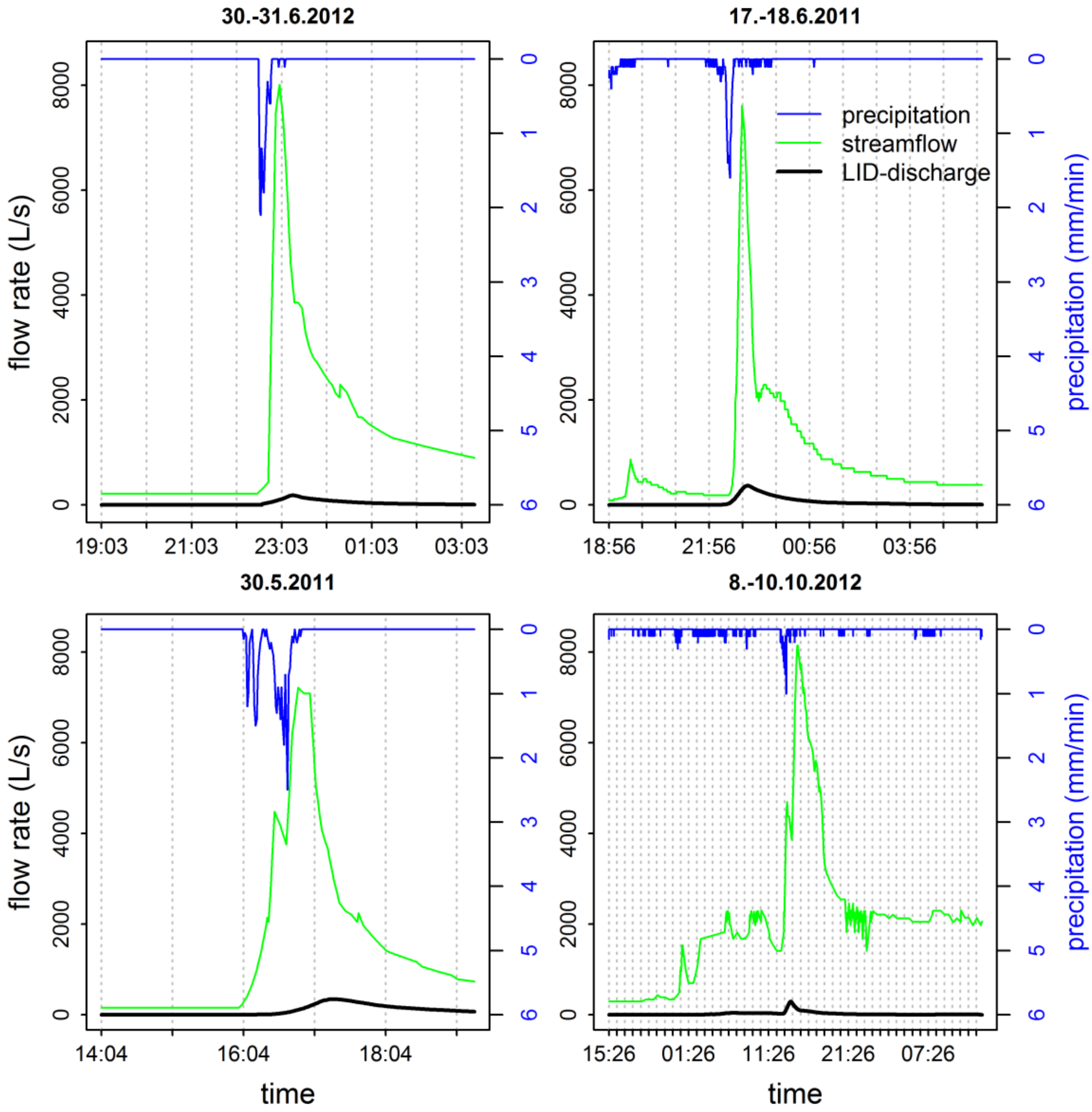
SI Fig. 3. Complementary empirical distribution function showing exceedance probabilities of relative event volume reduction for all storm events (n=353) and for only discharge events (n=84).



SI Fig. 4. a) Empirical cumulative distribution of peak discharges for all storm events (n=369) and only discharge events (n=100). a) and b) Frequency distributions and boxplots of peak discharges of all storm events (a) and only discharge events (b). Potential pre-development discharge (pnpd) was estimated at 216 L/s.



SI Fig. 5. Frequency distributions and boxplots of: a) Time lag between streamflow and discharge peak ($lag_{stream\text{-}LID}$) ; b) relative amplification of peak streamflow rate by inflowing discharge; c) time lag between LID-discharge and storm ($lag_{storm\text{-}LID}$); d) time lag between streamflow and storm ($lag_{storm\text{-}stream}$).



SI Fig. 6. Exemplary streamflow hydrographs as observed ca. 100 m upstream the outlet (left axis, green, 10 min time interval) with corresponding hyetograph on top (right axis, blue, 1 min time interval) and LID-discharge at the bottom (black, 1 min time interval) for 4 high flow events, mostly during summer (top and bottom left).

Supplementary Tables:

SI Tab. 1. Pre-constructional planning assumptions and design goals as of 1996 (source: BC 1996)

Parameter	Value	Remarks
LID Site		
Initial loss	2.5 mm	Interception and depression losses of land cover
Total connected area	16.1 ha	
Total reduced area (A_{red})	6.7 ha	
Runoff Coefficient	0.42	Mean design runoff coefficient, determined from area-weighted runoff coefficients for estimated lot designs and land use plan
Time of concentration	15 min	Estimated by planning
Mean annual precipitation	933 mm	Long-term annual mean (1951-80)
BRS only		
Ponding depth swales	10-30 cm	As designed
Storage volume swales (BRS)	1.8 mm (286 m^3)	Design surface storage
Storage volume trenches (BRS)	1.3 mm (206 m^3)	Design underground storage
Saturated hydraulic conductivity swales	$5*10^{-6}/10^{-5}$ m/s	Accord. to ATV-A 138 (1990) with/without a safety factor of 2
Total swale infiltration rate*	5.3 / 26.5 L/s	With/without safety factor of 2
Max. swale emptying time	24 h	Accord. to ATV-A 138 (1990)
Design storm for BRS infiltration and conveyance design $r_{15min,n=0.2}$	20.2 mm (224 L/s/ha)	5-year design storm for 15 min duration interval
Resulting maximum annual peak discharge*	1511 L/s	Maximum open channel flow of outlet structure
Design storm for maximum flood carrying capacity of BRS (freeboard) $r_{15min,n=0.02}$	31.2 mm (347 L/s/ha)	50-year design storm for 15 min duration interval

Mean annual inflow volume to BRS*	37,000 m^3	≡ 25% of long-term mean annual precipitation (1951-80)
Mean annual infiltration*	19,000 – 35,000 m^3	≡ 13% of long-term mean annual precipitation (1951-80)
Mean annual discharge*	< 19,000 m^3	≡ 13% of long-term mean annual precipitation (1951-80)
Mean annual site volume reduction*	131,120 m^3	≡ 87% of long-term mean annual precipitation (1951-80)

* regulatory design goals

SI Tab. 2. Current, post-constructional geometry and specifications of the bioretention system (BRS) as of 2011

BRS parameter	**Value**	**Remarks**
Storage volume swales	0.4 mm	Surface storage
Pore volume trenches	3.8 mm (578 m^3)	Underground storage
Pore volume amended soils	0.4 mm (67 m^3)	Soil storage
Void ratios backfill material trenches	0.35 - 0.95	Gravel and/or polypropylene body (RigoFill® Fränkische)
Vegetation	Grass, wild herbs	Trimmed 2 times per year (June-July, Sept.-Oct.)
Saturated hydraulic conductivity swales	$3*10^{-5}$ m/s	Mean over double-ring infiltrometer tests in 23 swales
Total swale infiltration rate	23 L/s	
Mean ponding depth	0.1 m	Mean over leveling measurements in 27 swales
Swale lengths (head to outlet)	540.5 m, 423.5 m	Acts as vegetated conveyance

SI Tab. 3. Monthly values for observed hydrologic performance metrics

Month/year	**No. of storms**	**No. of discharges**	**Relative discharge frequency (-)**	**Cumulative Precipitation (mm)**	**Cumulative Discharge (mm)**	**Cumulative Volume retained (mm)**	**Cumulative Relative volume reduction (%)**	**Long-term mean precipitation 1961-90* (mm)**
7/10	12	0	0	52.7	0	52.7	100	95.7
8/10	21	6	0.29	164.1	12.4	151.7	92.5	102.1
9/10	10	1	0.1	53.8	1.7	52.1	96.7	71.4
10/10	8	1	0.12	43.5	0.2	43.3	99.5	66.2
11/10	12	2	0.17	75.5	5.4	70.1	92.8	72.5
12/10	10	6	0.6	102.7	95.5	7.2	7	65.6
1/11	12	8	0.67	50.3	28.9	21.4	42.6	60
2/11	10	1	0.1	29.5	0.5	29	98.4	53.8
3/11	9	1	0.11	39.7	1.1	38.6	97.3	64.2
4/11	7	1	0.14	33.6	4.4	29.2	86.9	80.8
5/11	9	0	0	51.3	0	51.3	100	105.6
6/11	16	6	0.38	124.3	28.8	95.5	76.8	117
7/11	13	3	0.23	108.1	15.8	92.3	85.4	95.7
8/11	14	2	0.14	73.1	7.1	66	90.2	102.1
9/11	10	1	0.1	49.3	0.3	49	99.3	71.4
10/11	7	0	0	57.5	0	57.5	100	66.2
11/11	1	0	0	1.2	0	1.2	100	72.5
12/11	23	7	0.3	107	7	100	93.4	65.6
1/12	19	5	0.26	59.9	7.6	52.3	87.3	60
2/12	2	0	0	25.8	0	25.8	100	53.8
3/12	5	0	0	22.2	0	22.2	100	64.2
4/12	16	0	0	66.3	0	66.3	100	80.8
5/12	20	6	0.3	116.6	25.7	90.9	77.9	105.6
6/12	15	9	0.6	167.1	115	52.1	31.2	117
7/12	16	5	0.31	82.2	14.2	68	82.7	95.7
8/12	16	1	0.06	89.3	2.5	86.8	97.2	102.1
9/12	12	4	0.33	100.8	17.7	83.1	82.4	71.4
10/12	10	4	0.4	90.8	24.4	66.4	73.2	66.2
11/12	10	5	0.5	132.2	84.1	48.1	36.4	72.5
12/12	24	15	0.62	106.4	63.7	42.7	40.1	65.6

* data source: LUBW b)

SI Tab. 4. Statistics of event values and performance metrics over 30 months observation period (RC = runoff coefficient)

	Number of discharges per month (all observed discharges)	**Relative monthly discharge** frequency (all observed discharges)	**Storm volumes** (all storms)	**Volume reduction**[*] (all storms)	**Volume reduction**[*] (only discharge events)	**Volume retained**[*] (all storm)	**Volume retained**[*] (only discharge events)	**Discharge volume** (all storms)	**Discharge volume** (only discharge events)	**Peak discharge** (all storms)	**Peak discharge** (only discharge events)	**Lag $_{\text{storm-LID}}$**	**Lag $_{\text{storm-stream}}$**	**Lag $_{\text{stream-LID}}$**	**Amplification**
Unit:	-	-	mm	%	%	mm	mm	mm	mm	L/s[♣]	L/s[♣]	min	min	min	%
Samples:	100	369	353	353	84	353	84	353	84	369	100	23	23	56	56
Minimum:	0	0	0.4	0	0	0	0	0	0.2	0	2[×]	32	6	-49	0
Maximim:	15	0.67	58.2	100	98	26.1	24.8	42.3	42.3	600	600	186	108	178	4.5
95th percentile:	8.6	0.61	21.1	29[+]	1[+]	15.8	19.8	8.8	23	80	184	78	95	158	4.1
50th perc. (median):	2	0.16	3.5	100	69 (RC: 0.31)	2.8	5.1	0	2.7	0	16	66	20	49	0.4
arithmetic mean:	3.3	0.23	6.1	90	59 (RC: 0.41)	4.7	7.5	1.6	6.5	14	52	78	32	62	0.9
25th percentile:	1	0.07	1.2	100[+]	87[+]	1	2.4	0	1.1	0	7	48	17	30	0.2
75th percentile:	5.8	0.33	8.1	100[+]	35[+]	6.5	11.8	0	7.3	4[×]	54	88	24	90	0.8
Interquartile range:	4.8	0.26	7.9	0	52	5.5	9.6	0	6.2	4[×]	47	40	7	60	0.6

[*] negative values were set to zero for the analysis [+] exceedance probability (complementary empirical cdf) [×] value is below detection limit
[♣] conversion factor to specific peak discharge (L/ha/s): 0.065