Resilience of urban drainage systems - Proposition of a quantitative approach

Résilience des systèmes de gestion des eaux pluviales urbaines : une approche quantitative

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RÉSUMÉ

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ABSTRACT

Urban water infrastructure is increasingly expected to be resilient to change. To support such resilience goals of cities we propose an approach, which quantifies resilience based on observed or simulated system performance and a tolerable threshold of performance.

The approach is demonstrated for the performance of urban drainage systems during storm events regarding their impact on receiving surface waters. The exemplary application underlines that resilience can be quantified and that it may support the understanding of system performance. Moreover, different disturbances (such as storm events or technical system failures) can be assessed separately or in combination.

The presented approach is suggested as a starting point to be tested and developed further. In order to allow this development, all the functions used were joined in an R package and made freely available online.

KEYWORDS

kwb.resilience , resilience, recovery time, urban surface waters, stormwater,

1 INTRODUCTION

Urban water infrastructure and cities in general are increasingly expected to be "resilient to change". The increasing importance of resilience as a city goal is contrasted by a lack in approaches to asses this goal. A meta-analysis by Juan-Garcia et al. (2017) showed that this is also true for research: of 289 articles on waste water and resilience only 17 dealt specifically with resilience and only one (Mugume et al. 2015) looked at the resilience of urban drainage systems during storm events. Based on these existing works we propose a simple, general approach on how resilience can be quantified for urban drainage systems. The approach is applied exemplarily for the performance on surface water protection, but could be used for any other expected function of urban drainage.

2 MATERIALS AND METHODS

2.1 Quantification of resilience

The proposed approach is based on works by Mugume et al. (2015) and Sweetapple et al. (2017). Mugume et al. (2015) introduced a resilience index Res_0, which is normalized between 0 (= non-functional) and 1 (= fully functional at all times):

$$Res_0 = 1 - Sev \quad (1)$$

where *Sev* is the severity of malfunction/damage from a disturbance. The calculation approach for *Sev* by Mugume et al. (2015) was extended by introducing an acceptable performance P_a (i.e. a threshold), as suggested by Sweetapple et al. (2017):

$$Sev = \frac{1}{P_a - P_{max}} \times \frac{1}{t_n - t_0} \times \int_{t_0}^{t_n} P_a - P(t)\, dt$$

$$\text{mit } P(t) = \begin{cases} P_a, & \frac{P_a - P(t)}{P_a - P_{max}} < 0 \\ P(t), & \frac{P_a - P(t)}{P_a - P_{max}} \geq 0 \end{cases} \quad (2)$$

The equation integrates performance *P(t)* over all the time periods for which *P(t)* is worse than P_a, both for upper and lower thresholds P_a (compare Fig. 1). The integral is normalized by the difference between P_a and maximal failure P_{max}, *as* well as the time interval.

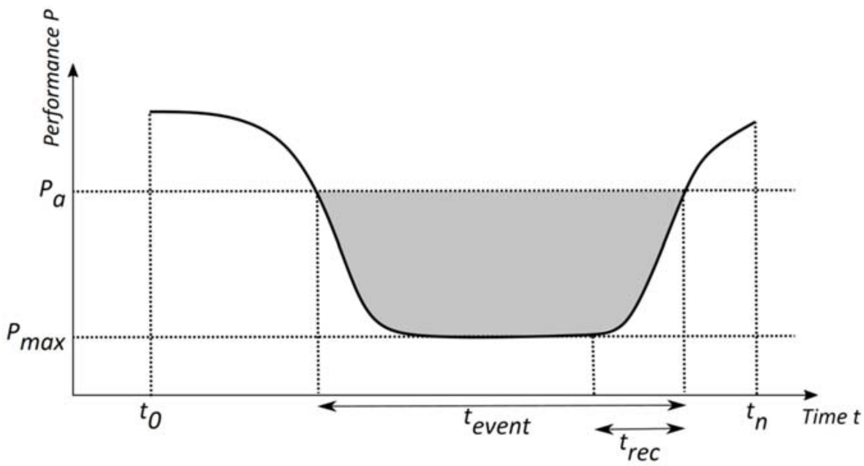

Figure 1: Schematics of equ. 2, adapted from Mugume et al. (2015). The grey area shows the integral in equ. 2.

In addition to overall resilience we defined the recovery time t_{rec} as the time period between maximal failure and returning to P_a. Since events in a longer time series vary in duration, we related t_{rec} to the event duration t_{event}:

$$t_{rec,\%} = \frac{t_{rec}}{t_{event}} \times 100\% \quad (3)$$

All the equations were implemented into R functions in the freely available package kwb.resilience (Matzinger et al. 2018).

2.2 Case studies

Equations (1-3) were applied to two case studies regarding the protection of receiving surface waters (Tab. 1). Case study 1 assesses the hydraulic stress of an urban river from a hypothetical impervious area, which consists to equal shares of roofs and roads. Apart from a comparison of scenarios, case studies 1.2 and 1.3 are also tested for partial system failure, assuming a volume reduction of the central filter by 25 %. Case study 2 evaluates the effect of different measure scenarios on the oxygen situation in the Berlin River Spree for an entire year, as outlined in Riechel et al. (2016).

Table 1: Overview of case studies

	Disturbance	**System**	**Performance P**	**Calculation of *P***	**Threshold P_a**
1	Heavy rain event	Separate sewer system: (1.1) status quo (1.2) central soil filter (1.3) smaller central soil filter combined with green roofs and swales	Hydraulic loading to receiving river	Runoff model: KOSIM	10 L s^{-1} ha^{-1} (maximal)
2	Heavy rain event	Combined sewer system: (2.1) status quo (2.2) reduced impervious area (2.3) oxygen addition in overflow sewer	Oxygen level in receiving river	Model chain: InfoWorks - QSim	2 mg O_2 L^{-1} (minimal)

3 RESULTS AND DISCUSSION

3.1 Resilience calculation

Equations (1-3) were successfully applied to lower and upper thresholds in case studies 1 and 2, respectively. They are applicable for single events (see example in Fig. 2), as well as longer time series.

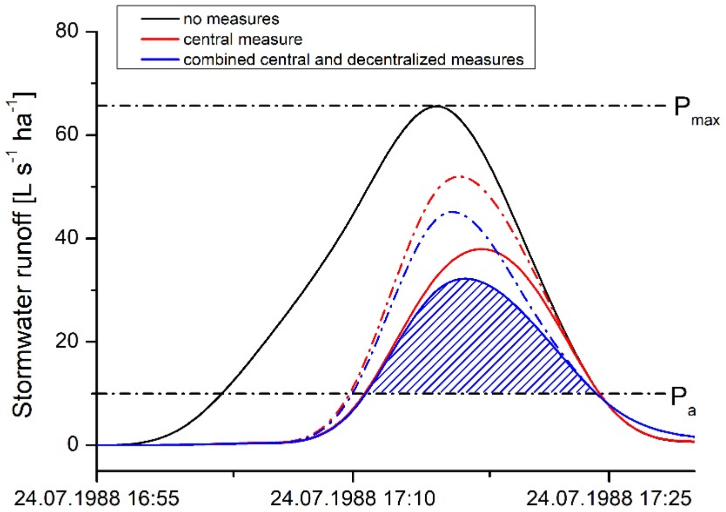

Figure 2: Stormwater runoff P(t) to urban river for three scenarios (case study 1). The hatched area exemplifies the integral in equation (2) for one scenario. The dashed lines show the effect of a reduced retention volume of the central measure by 25 %.

3.2 Robustness and Rapidity

Single event analysis in case study 1 results in an increase in Res_0 from 0.59 (1.1) to 0.83 (1.2) and 0.87 (1.3), indicating that measures turn the drainage system more robust (compare Fig. 2). The measures also affect the rapidity of recovery. While $t_{rec,\%}$ is reduced from ca. 40 % to 30 % by a unique central measure (1.2), it is increased to almost 70 % by the combined measures (1.3), due to the runoff delay and the runoff tail of green roofs. The example shows that $t_{rec,\%}$ is a good indicator for changes in performance/failure dynamics; however, an increase does not necessarily signify a reduction in resilience.

In case study 2, equations (1-3) were applied for an entire year (Tab. 2). Results show that rare failures in a long time series lead to values of for Res_0 close to one, despite a relevant difference in failure (fish-lethal) events. Alternatively, the relative change in ΔSev is outlined in Tab. 2. ΔSev shows that scenarios 2.2 and 2.3 lead to a reduction in the severity of system failures by 78 and 70 %, respectively. The reduction in *Sev* is higher than in total duration, since *Sev* also covers the extent in oxygen depressions (Tab. 2). Average $t_{rec,\%}$ over all the events remains at about 50% for oxygen addition (2.3) but declines to 41% for reduced impervious area (2.2). The reason could lie in the lower amount of emitted organic material in 2.2 than in 2.1 and 2.3, which reduces time needed for decomposition in the river.

Table 2: Results for case study 2 for entire rain year

Scenario	classical assessment			resilience assessment				
	# events < P_a	total duration	mininmal O_2-conc.	Res_0	Sev	ΔSev	$\overline{t_{rec}}$	$\overline{t_{rec,\%}}$
	[-]	[h]	[mg L^{-1}]	[-]	[-]	[%]	[h]	[%]
2.1	4	22	0.5	1.00	$1.4 \cdot 10^{-3}$	0	2.6	50
2.2	2	7	1.2	1.00	$0.3 \cdot 10^{-3}$	78	1.6	41
2.3	3	11	1.1	1.00	$0.4 \cdot 10^{-3}$	70	1.8	49

3.3 Redundancy

The effect of a reduced storage volume of the soil filter is shown as dashed lines in Fig. 2. The corresponding reduction in Res_0 was higher for 1.2 with 9% than for 1.3 with 7 %. The reason for this effect lies probably in the partial redundancy of the serial decentralized and central measures in scenario 1.3.

4 CONCLUSIONS

Resilience of urban drainage systems can be quantified. Resilience assessment has the advantage that duration and extent of system failure is quantified. Different disturbances (such as storm events, climate change or technical system failures) can be assessed separately or in combination. Additionally, the recovery time is an interesting parameter. In the example of oxygen depressions in the receiving river it is expected that the recovery of the oxygen level is only the first step and recovery of the entire river ecosystem may take longer, which could in turn be considered by further performance indicators.

Generally, it is expected that resilience can be quantified for very different expected performances of urban drainage systems, from secure drainage of waste water, via flood prevention, surface water protection to reduction in urban heat islands. Thanks to normalization, such different performance goals can be compared. On the other hand, normalization may also turn into a weakness, since the result depends on the chosen time interval and performance parameters and can become subjective. As a result, it is suggested to always quantify a number of performance indicators as shown in Tab. 2 for improved interpretation.

The proposed approach is not a final solution but is suggested as a starting point for testing, adaptation and extension. The applied functions can be downloaded, commented and extended via the KWB github (Matzinger et al. 2018).

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