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Can we use urban runoff to mitigate street tree water stress? An analysis of annual water demand of street trees and resulting pollution loads

Peut-on utiliser le ruissellement urbain pour atténuer le stress hydrique des arbres de rue? Une analyse de la demande annuelle en eau des arbres de rue et des charges polluantes qui en résultent

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RÉSUMÉ

La décentralisation du cycle de l'eau en milieu urbain peut atténuer les phénomènes météorologiques extrêmes tels que des crues soudaines ou des périodes de sécheresse. En particulier, les arbres présents dans des zones urbaines très denses pourraient bénéficier d'une irrigation supplémentaire en eau provenant du ruissellement environnant. Nous avons donc calculé la demande en eau - et le stress hydrique - des arbres urbains (vieux, moyens, jeunes) dont la surface environnante est étanche, au cours d'une année humide et d'une année sèche. Dans un second temps, nous avons estimé les charges polluantes annuelles résultantes dans les fosses des arbres si l'eau manquante avait été remplacée par de l'eau de ruissellement provenant de deux surfaces urbaines relativement propres (route résidentielle et toit en tuiles d'argile), en nous concentrant sur les apports en MEST, Cd, Cu et Zn.

Les résultats montrent que la quantité d'eau nécessaire et les charges polluantes annuelles dépendent fortement de l'âge de l'arbre et des conditions météorologiques. Donc, afin de mettre en œuvre la décentralisation et d'irriguer les arbres avec l'eau de ruissellement, nous avons encore besoin de plus de recherches sur la distribution de la pollution dans le sol ainsi que sur les réponses des arbres aux conditions changeantes.

ABSTRACT

Decentralization of the urban water cycle can mitigate extreme weather events like flash floods or dry periods. Especially street trees in highly dense areas could benefit from additional irrigation of surrounding runoff water. Thus, we calculated water demand - and water stress for urban trees (old, adult, young) with sealed surface surrounding in a wet and a dry year. In a next step, we estimated the resulting annual pollution loads in the tree pits if the lacking water had been replaced by surface runoff water from two relatively clean urban surfaces (residential road and clay tile roof), focusing on TSS, Cd, Cu and Zn inputs.

The results show, that the amount of water needed and the resulting pollution loads highly depend on tree age and weather conditions. Therefore, in order to implement decentralization and irrigate trees with runoff water, we still need more investigations on pollution distribution within the soil and the trees responses to changing conditions.

KEYWORDS

irrigation, pollution, urban runoff, street tree, water stress, water demand

1 INTRODUCTION

The urban environment is confronted with extreme weather events like droughts or flash floods. Especially the urban vegetation suffers from dry periods in the highly sealed surrounding (Haase and Hellwig 2022). At the same time storm water overflows into surface waters have a severe impact and can cause damages to infrastructure (Orta-Ortiz and Geneletti 2022). To deal with this increasing exposure to heavy rainfalls within the city and counteract water stress for urban vegetation, current discussions emphasize the importance of decentralized drainage systems (Walsh et al. 2012). The runoff water, usually collected in centralized system and disposed off to a treatment plant (a), is now infiltrated at site (b) (Figure 1), increasing infiltration and evapotranspiration and therefore reducing runoff (Paton and Haacke 2021). However, the long-term effect of changes in pollution pathways and resulting deposition patterns, have not been considered fully.

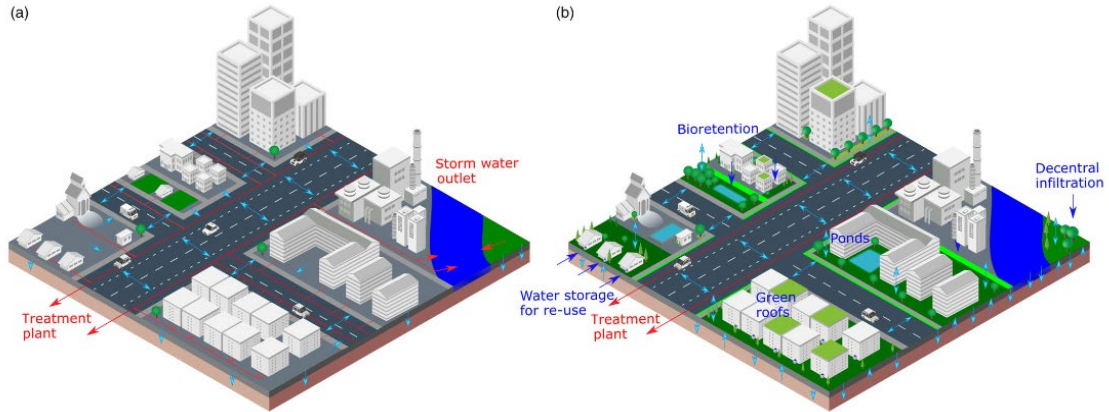


Figure 1: (a) Centralized versus (b) decentralized urban drainage (Red line: drainage network, red arrows: stormwater outlet points into rivers, blue arrows: street runoff, infiltration and evapotranspiration (Paton and Haacke 2021).

Therefore, the aim of this study was (1) to identify the additional water amount needed to prevent water stress for trees of different ages in a wet and a dry year, and (2) to calculate resulting yearly pollution loads of TSS, Zn, Cd and Cu from two relatively clean urban surfaces (tile roof and residential road).

2 METHODS

In order to identify variations in water stress period length for one of various urban vegetations, the water demand of lime trees with different ages (young, adult-age, old) were calculated for a wet year (2017) and a dry year (2018) for urban street trees in Germany. To calculate potential and actual evapotranspiration the UrbanTRee model was used (Tams et al. 2023). The model uses the R package “water” based on Penman-Monteith (Allen et al. 1998; Olmedo et al. 2016). Plant water availability and runoff processes of the tree pit are described with a bucket model implemented in R (R Core Team 2021) and includes routines for interception, infiltration, runoff and percolation losses. For the model input, the climate data from the German meteorological station Potsdam (DWD 2022) was used. Depending on tree age, different variables for canopy size and rooting depth and Kc factor were used (Wessolek and Kluge 2021, Table 2). Furthermore, Wessolek and Kluge developed thresholds to categorized water stress based on the ratio of potential evapotranspiration (ET_0) and actual evapotranspiration (ET_a):

$$c_D = ET_a / ET_0 \quad (1)$$

With c_D as the deficit factor, describing the state of water stress. Depending on tree age, a c_D of 0.4-0.6 refers to moderate water stress (ibid.). We used the mean of $c_D = 0.5$ to calculate additional water needed to prevent water stress and the resulting water deficit (D):

$$D = ET_0 * c_D - ET_a \quad (2)$$

In order to avoid water stress, irrigation with surface water can be a sustainable solution. To calculate the annual pollutant loads (unit/tree/year) that could result from surface water irrigation, we used the determined water deficit amounts (Table 2) and pollutant concentrations from the literature (Table 1). In this study, we compared two relatively clean surfaces: a roof with concrete tiles and a residential road, focusing on total suspended solids (TSS) and three heavy metals: zinc (Zn), copper (Cu) and cadmium (Cd). For the calculation the mean concentrations from two studies were used (Charters et al. 2016; Göbel et al. 2007).

Table 1: Mean pollution concentrations of total suspended solids (TSS), zinc (Zn), cadmium (Cd) and cooper (Cu), from a field study of Charters et al. (2016) and a review of Göbel et al. (2007), for a tile roof and a residential road.

| | TSS (mg/l) | Zn (µg/l) | Cd (µg/l) | Cu (µg/l) | Source |
|--------------------|------------|-----------|-----------|-----------|--|
| Tile roof | 22.9 | 261.5 | 0.8 | 56 | (Charters et al. 2016;Göbel et al. 2007) |
| Residential street | 106.6 | 251 | 1.2 | 56 | (Charters et al. 2016;Göbel et al. 2007) |

3 RESULTS AND DISCUSSION

The simulations showed that the additional water needed to avoid water stress heavily depended on weather conditions and tree age (Figure 2), where the cumulative sums of required water ranged from 700 l to 4000 l in 2017 and 2400 l to 14.200 l in 2018 (Figure 2, Table 2). Resulting pollution loads showed the same pattern with a considerable higher pollution for the big tree in the dry year (Table 2). The distribution within the tree pit nor the size of the tree pit were considered yet. In further discussions of pollution distributions within the tree pit, the pollution compatibility of trees with different ages needs to be discussed additionally, because younger trees have a less pronounce rooting system and might therefore be more vulnerable (Wessolek and Kluge 2021).

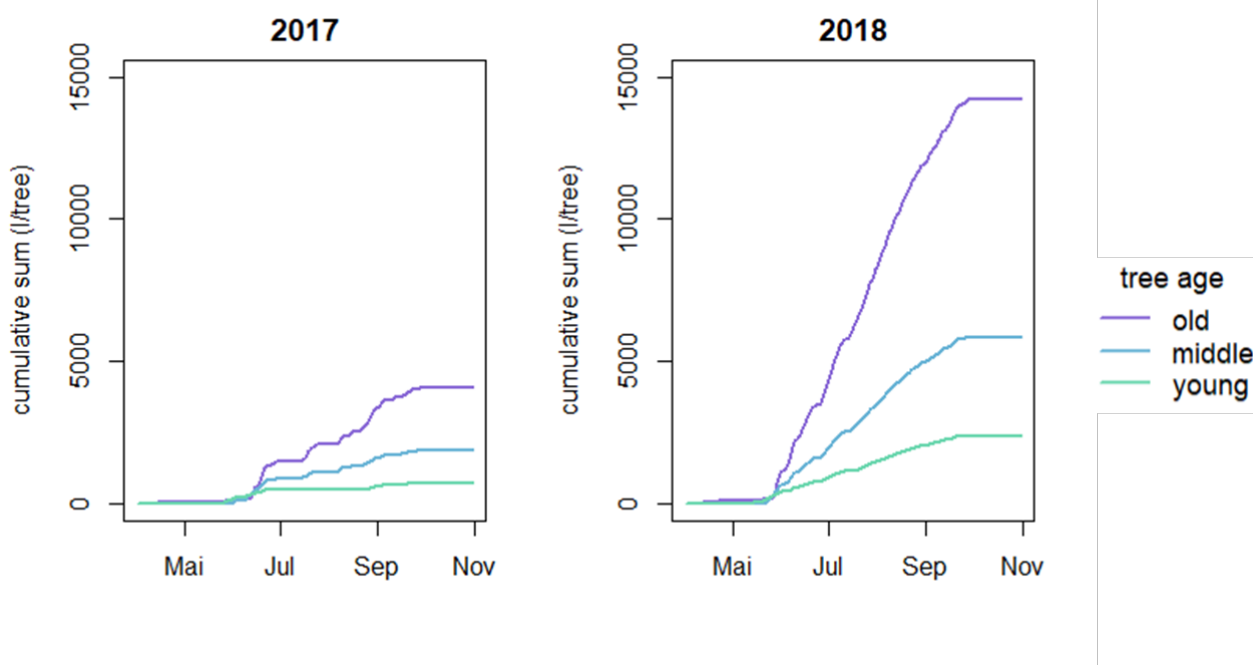


Figure 2: Cumulative sum of additional water needed to prevent water stress for street trees of three different ages: young, adult, old during a wet year (2017) and a dry year (2018).

Table 2: Water deficit for all tree ages: young, adult, old in 2017 and 2018 and resulting pollution loads from surface water of a tile roof and a residential street, focusing on: total suspended solids (TSS), zinc (Zn), cadmium (Cd) and cooper (Cu).

| | Crown size (m ²) | Rooting depth (m) | Kc-factor (-) | Water deficit (l) | Pollution load (unit/tree/year) | | | | | | | | |
|-------------------|------------------------------|-------------------|---------------|-------------------|---------------------------------|--------|--------|---------|--------------------|---------|---------|---------|--|
| | | | | | Tile roof | | | | Residential street | | | | |
| | | | | | TSS (g) | Cd(mg) | Zn(mg) | Cu (mg) | TSS (g) | Cd (mg) | Zn (mg) | Cu (mg) | |
| Young tree | | | | | | | | | | | | | |
| 2017 | 12 | 0.8 | 1.6 | 695 | 15.9 | 0.6 | 181.8 | 56.1 | 74.1 | 0.8 | 174.5 | 38.9 | |
| 2018 | 12 | 0.8 | 1.6 | 2369 | 54.2 | 1.9 | 619.4 | 191.0 | 252.5 | 2.8 | 594.5 | 132.6 | |

| Adult tree | | | | | | | | | | | | |
|------------|----|-----|-----|-------|-------|------|--------|--------|--------|------|--------|-------|
| 2017 | 28 | 1.2 | 1.2 | 1858 | 42.5 | 1.5 | 485.8 | 149.8 | 198.0 | 2.2 | 466.3 | 104.0 |
| 2018 | 28 | 1.2 | 1.2 | 5848 | 133.9 | 4.7 | 1529.4 | 471.7 | 623.4 | 7.0 | 1467.9 | 327.5 |
| Old tree | | | | | | | | | | | | |
| 2017 | 64 | 1 | 2 | 4092 | 93.7 | 3.3 | 1070.0 | 330.0 | 436.2 | 4.9 | 1027.1 | 229.1 |
| 2018 | 64 | 1 | 2 | 14217 | 325.6 | 11.4 | 3717.7 | 1146.6 | 1515.5 | 17.1 | 3568.4 | 796.1 |

4 CONCLUSION

In conclusion, pollution load was determined by tree age (characteristics), climate conditions and resulting water deficits. In this study, only a small number of the possible runoff pollutions were mapped. In a next step, we will gather detailed spatial information on a much wider range of typical urban surface combinations, that can be used for irrigation, considering contaminant accumulation processes and actual rainfall-runoff relationships to determine pollution load dynamics, transfer processes into lower soil layers and potential adverse effects on tree health.

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