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Review

# Are green roofs a source or sink of runoff pollutants?

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ABSTRACT

Retention of rainwater runoff is a primary function of green roofs in their contribution as one of the main indicators of "Sponge City". However, the influence of green roofs on runoff quality and whether they are a source or sink of pollutants is ambiguous. A concept model of pollutant cycling is proposed in this paper, based on a systematic literature review, which includes the direct factors substrate and structure of the green roof system; and indirect factors such as plant species, irrigation, fertilizer, atmospheric deposition, and age of the green roof. In addition, the model identifies each factor as a pollutant source or sink and explores relations among the factors. Examples in the literature were drawn to demonstrate the factors and pollutant materials including metallic elements such as Zn, Pb, Cd, Fe, Mn, Cr, Cu, and Ca; and nutrients such as N, $NO_3^-$-N, $NH_4$-N, DON, P, $PO_4^{3-}$-P, K, and DOC. The concept of "moderate growth vigor" is proposed; moderate growth is optimal for runoff quality and low and persistent fertility, and a low benchmark to control diseases and insect pests. The concept of "clean sources and pollutant retention" should be adopted, i.e., pollutant sources such as substrate, irrigation water, fertilizer, pesticide, and other local pollution sources should be removed or cleaned, and pollutants should be detained or decreased by plant degradation, slow-release material, filter layer, and actinic and microbial degradation. These results will aid understanding of the mechanism of runoff pollution and improve stormwater runoff quality from source to sink in green roofs.



**Contents**



## 1. Introduction

The danger of stormwater pollutants and nutrients entering surface water and groundwater is one of the key concerns related to the security of a city's water supply. One way to decrease pollution is through use of green roofs, where plants and substrates are used to degrade or filter pollution (Rowe, 2011). For that reason, green roofs are believed to be capable of improving runoff quality.

However, the influence of green roofs on the municipal water supply is unclear; they may be pollutant sources or sinks. This is a topic of increasing interest. Green roofs have been shown to absorb atmospheric pollutants and particulates, thereby cleaning the air (Currie and Bass, 2008; Yang et al., 2008; Speak et al., 2012), while the pollutants retained have the potential to leach into runoff, contributing to water pollution (Berndtsson et al., 2006). Although the retention of rainwater and mitigation of stormwater runoff are two of the primary functions of green roofs, the potential for runoff pol-

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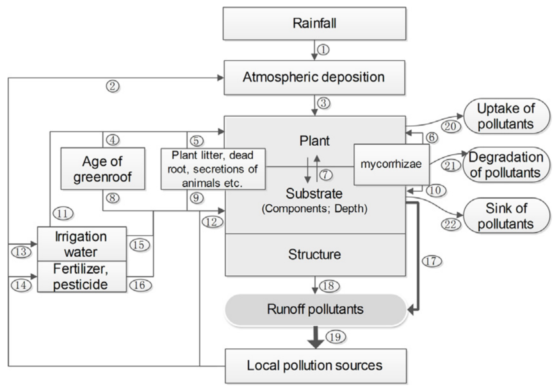


**Fig. 1.** Concept model of the cycling of runoff pollutants on green roofs.
References: ① Gnecco et al. (2013), Rowe, (2011), and Speak et al. (2014); ② Berndtsson et al. (2006) and Aitkenhead-Peterson et al. (2011); ③ Gnecco et al. (2013), Rowe, (2011), Speak et al. (2014), Berndtsson et al. (2006), Hathaway et al. (2008), and Yang et al. (2008); ④ Aitkenhead-Peterson et al. (2011) and Köhler et al. (2002); ⑤ Sutton, (2015); ⑥ John et al. (2017) and Rumble and Gange, (2017); ⑦ Rowe, (2011), Sutton, (2015), and Dusza et al. (2017); ⑧ Rowe (2011), Speak et al. (2014), Berndtsson et al. (2006), and De-Ville et al. (2017); ⑨ McDowell et al. (2006); ⑩ John et al. (2017); ⑪ Nagase et al. (2017) and Clark and Zheng, (2014); ⑫ Berndtsson et al. (2006) and Berndtsson, (2010); ⑬ Berndtsson et al. (2006) and Berndtsson, (2010); ⑭ Berndtsson, (2010); ⑮ Aitkenhead-Peterson et al. (2011); ⑯ Clark and Zheng, (2014), Monterusso et al. (2004), and Teemusk and Mander, (2007); ⑰ Speak et al. (2014), Aitkenhead-Peterson et al. (2011), Dusza et al. (2017), McDowell et al. (2006), Berndtsson et al. (2009), Dise and Wright, (1995), Gregoire and Clausen, (2011), and Vijayaraghavan et al. (2012); ⑱ Chang et al. (2004), Clark et al. (2008), and Molineux et al. (2017); ⑲ Rowe (2011) and Paul and Meyer (2008); ⑳ Rowe (2011), Speak et al. (2014), McDowell et al. (2006), and Monterusso et al. (2004); ㉑ John et al. (2017); ㉒ Beck et al. (2011), Long et al. (2006), and Wang et al. (2017).

lution restricts the ecological, economic, and social values of green roofs, which will negatively impact their wide spread utilization.

Factors affecting the quality of green roof runoff are diverse, and include rainfall, local pollution sources, plant species, plant litter, dead roots, substrate components and depth, quality of irrigation water, fertilizer, and age of the green roof (Bliss et al., 2009; Rowe, 2011; Aitkenhead-Peterson et al., 2011; Alsup et al., 2011; Speak et al., 2014; Sutton, 2015). We undertook a systematic review of these factors and tried to answer the following questions: a) What are the mechanisms of runoff pollution from green roofs? b) According to the literature, what are the sources and sinks of green roof runoff pollution? c) How can the quality of green roof stormwater runoff be optimized from source to sink?

## 2. Mechanisms of runoff pollution on green roofs

Runoff usually occurs when rainfall intensity is beyond the retention capacity of green roofs. The limitation of rainwater retention is often reached during storm events. Runoff quality is influenced by the green roof system, which includes inherent factors such as structural layers of the base membrane, waterproofing, root barrier, water storage, drainage layer, filter layer, soil substrate, and vegetation; and external factors such as rainwater, irrigation, and fertilizer. These factors are relevant to both the source and sink of potential pollutants and form an integral cycling of pollutants. A concept model represents the cycling of runoff pollutants on green roofs (Fig. 1). The cycle has two parts: the source of runoff pollutants, and the sink. The first part has two direct sources (substrate and structure layers) and nine indirect sources (plant, animal, irrigation water, fertilizer, pesticides, atmospheric deposition, rainfall, age of green roof, and local pollutant source). The substrate, including component materials and depth, may contain heavy metals such as Zn, Pb, and Fe and nutrients such as C, N, and P that could contribute to leachate (Dusza et al., 2017). Structural layers of the green roof system may contribute to heavy metal accumulation because of metal, plastic, and polymer materials used in construction (Clark et al., 2008). Plants are an ambiguous factor. On one hand, plants can act as an uptake of contaminants. On the other hand, the nutrient component of the substrate will be changed by plant litter, dead roots, decomposition of regenerated roots, feces of birds and animals, secretion of soil microorganisms, and metabolites of soil microbial processes, all of which will increase pollutant sources (Sutton, 2015). Irrigation water may be affected by contamination of local ground water and surface water, especially reclaimed water, with diverse nutrients such as N and P (Aitkenhead-Peterson et al., 2011). Fertilizer, including organic and chemical fertilizers, leaches surplus nutrients such as N, P, and K irrespective of application method (foliar or substrate) (Clark and Zheng, 2014). Pesticides including organic phosphor, chlorine, and nitrogen attach to the surface of the plant or exist as residue within the plant and substrate, thereby becoming an accumulated pollutant (Berndtsson, 2010). Atmospheric deposition, including dry and wet deposition resulting from gravity and rainfall respectively, can accumulate aerial pollutants on the surface of plants and substrates, leading to infiltration (Speak et al., 2014). Over time, the plant biomass and ecological functions of the green roof as well as levels of metal pollutants will increase, and substrate nutrients will decrease (De-Ville et al., 2017). Runoff pollutants will flow into soil as well as ground and surface water, aggravating the local pollution burden, which will further influence soil substrate and irrigation water in the form of negative feedback (Rowe, 2011; Berndtsson, 2010). The second part of the cycle includes plants, mycorrhizae, and substrate as pollutant sinks. Plants behave as an uptake of contaminants by physiological metabolism of plant tissue and rhizospheric microorganisms resulting in biodegradation and mineralization of nutrients, as well as absorption, volatilization, transition, degradation, and fixation of pollutants (Speak et al., 2014; Rowe, 2011). Artificial substrates have the capacity of nutrient retention because of addition (e.g., biochar) and significantly decrease the discharge of total nitrogen, total phosphorus, nitrate, phosphate and organic carbon (Beck et al., 2011). Mycorrhizae, a key element of soil ecosystems integrated with plants and substrate, can decompose, absorb and retain nutrients and metals effectively so as to degrade contaminants. Mycorrhizal fungi are also beneficial to both the nutrient uptake of host plants and substrate aggregation (John et al., 2017; Molineux et al., 2017).

## 3. Review of pollutant sources and sinks

There are 29 studies concerning the factors encapsulated in the concept model of runoff pollution from green roofs that must be identified as sources or sinks of runoff pollution (Table 1). Pollution includes metal elements (Zn, Pb, Cd, Fe, Mn, Cr, Cu, Ca, and general forms of metal) and nutrients (N, $NO_3^-$-N, $NH_4$-N, DON, P, $PO_4^{3-}$-P, K, DOC, and general forms of nutrient), and is related to the factors in the following ways.

(1) Rooftop materials, such as waterproof membrane, pitch, adhesives, drainpipes, and guttering, are potential sources of pollutants, including metal (e.g., Al, Cu, Zn, and galvanized iron), plastics, and high molecular weight polyester that can lead to high concentrations of heavy metal ions ($Pb^{2+}$, $Cd^{2+}$, $Mn^{2+}$, $Zn^{2+}$, $Mg^{2+}$, $Al^{3+}$, and $Fe^{2+}$) (Chang et al., 2004; Gnecco et al., 2005; Schriewer et al., 2008; Alsup et al., 2011). For example, runoff leachate from metallic roofing materials has Zn concentrations