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Evaluation of site-specific factors influencing heavy metal contents in the topsoil of vegetated infiltration swales

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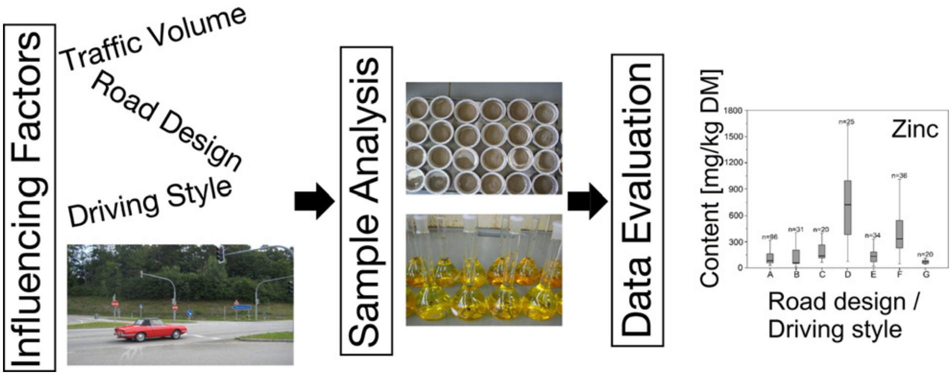
HIGHLIGHTS

- Correlation of contents with traffic volume, road design, and stop-and-go traffic
- Increased heavy metal contents at stop-and-go sites, roundabouts, and crossings
- Different soil contents and behavior of cadmium, chromium, copper, lead, and zinc
- Identification of factors influencing the variability of zinc in topsoil samples

GRAPHICAL ABSTRACT



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ABSTRACT

Stormwater runoff of traffic areas is usually polluted by organic and inorganic substances and must be treated prior to discharge into groundwater. One widely used treatment method is infiltrating the runoff over the topsoil of vegetated swales. The aim of this study was to evaluate the factors influencing the heavy metal contents in such topsoil layers of vegetated infiltration swales near highways, roads, and parking lots. In total, 262 topsoil samples were taken from 35 sampling sites, which varied in age, traffic volume, road design, driving style, and site-specific conditions. In the evaluation of all soil samples, the median heavy metal values of cadmium, chromium, copper, lead, and zinc were yielding 0.36 (mean: 1.21) mg/kg DM, 37.0 (mean: 44.5) mg/kg DM, 28.0 (mean: 61.5) mg/kg DM, 27.0 (mean: 71.9) mg/kg DM, and 120 (mean: 257) mg/kg DM, respectively. The main purpose was to evaluate the site-specific data (i.e., surrounding land use characteristics, traffic area site data, and operational characteristics). In general, heavy metal contents increased with increasing traffic volumes. However, other factors also had a notable impact. Factors such as road design (e.g., curves, crossings, and roundabouts) and grade of congestion significantly influenced the heavy metal contents. High heavy metal contents were detected for stop-and-go areas, roundabouts, crossings, and sites with traffic lights, signs, and guardrails. Findings of this study can be used to identify highly polluted traffic areas and to verify or improve standards regarding the treatment of runoff from traffic areas.

1. Introduction

Traffic area runoff water commonly contains organic substances such as volatile organic compounds and polycyclic aromatic

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hydrocarbons, inorganic substances, such as heavy metals (e.g., cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn)), and de-icing salts including chloride (Sörme and Lagerkvist, 2002; Brown and Peake, 2006; Kayhanian et al., 2012; Hilliges et al., 2013). Heavy metals are of concern in stormwater runoff because they are persistent and some have low toxicity threshold levels (Roeva et al., 1996; Lundy et al., 2012). The pollution of traffic area runoff is influenced by site-specific characteristics (e.g., driving speed, traffic volume, road design, grade of congestion, and type of fuel) and climatic factors such as the antecedent dry weather period, rain intensity, rain duration, and seasons (Lee et al., 2004; Crabtree et al., 2006; Helmreich et al., 2010; Huber et al., 2016). For example, annual average daily traffic (AADT) has an influence on runoff concentrations of heavy metals (Kayhanian et al., 2003; Mangani et al., 2005; Crabtree et al., 2008).

The contamination of urban (Manta et al., 2002) and roadside soils (Warren and Birch, 1987; Ward, 1990; Münch, 1993; Reinirkens, 1996) has already been subject of a variety of previous investigations (Werkenthin et al., 2014). Generally, the contents and concentrations of pollutants in roadside soils decrease with distance from the road, increasing soil depth, and with decreasing traffic volume (Dierkes and Geiger, 1999; Turer and Maynard, 2003; Li, 2006; Kluge et al., 2014). Among ten roadside soils, Chen et al. (2010) reported the highest contents of Cd, Cu, Pb, and Zn at the site with the highest traffic volume and highest tendency for traffic jams. In general, Pb contents correlated with the AADT for each of the ten sites in this study. Kelly et al. (1996) also measured the highest Pb contents at road junctions and roundabouts of roads with high AADT indicating that several site-specific characteristics can influence the metal content in topsoil.

Apeagyei et al. (2011) stated that vehicle-related metals in road dust are not only correlated with traffic volumes but also with traffic behavior (e.g., frequent braking and acceleration). Other studies confirmed that driving styles influence air pollution (Lyons et al., 1990). Charlesworth et al. (2003) identified high heavy metal values in road dust samples in association with junctions controlled by traffic lights. Johansson et al. (2009) found that increased stop-and-go driving releases more metals from brake wear.

Previous investigations were mostly related to adjacent roadside soils, not to structural Best Management Practice (BMP) systems, which are widely used to reduce the quantity and quality of stormwater runoff entering the receiving water environment (Eriksson et al., 2007).Swales – often vegetated – are systems classified as green BMPs (Dierkes et al., 2015). In general, vegetated swales are constructed channels that provide an infiltration of the runoff by the topsoil and they have low construction costs compared with other BMP systems (Yu et al., 2001; Fletcher et al., 2002). In Germany, the construction and maintenance of infiltration swales is performed in accordance with the Standard DWA-A 138E (2005). The thickness of the topsoil, which is specifically designed for the treatment of traffic area runoff in Germany, must be 20–30 cm, the pH of the soil must be between 6 and 8, the permeability is defined as 10^{-3}–10^{-6} m/s, the humus content must be 1–3%, and the soil is not allowed to be pre-contaminated. Thus, they are constructed in order to absorb the maximum quantity of runoff from one day and to reduce pollutants from the traffic area runoff. Heavy metals can be retained in the soil by filtration and physicochemical processes, including sorption, complexation, and precipitation (Dechesne et al., 2004). Kaighn and Yu (1996) measured the removal of total suspended solids and Zn by two grass swales treating highway runoff. Other studies on infiltration swales were also performed on the retention of different pollutants (e.g., Yousef et al., 1987). The influence of site-specific factors (e.g., AADT, land use, guardrails, road design, and stop-and-go traffic) on the heavy metal contents of the topsoil layers of vegetated swales, which have been in operation for years, were not evaluated. In addition, the influence of the road design (e.g., crossings, roundabouts, and parking lots) on the metal contents was not previously determined for a large amount of infiltration swales that are commonly used as a green infrastructure to remove metals from stormwater runoff.

The aim of this study is to evaluate the impact of the AADT, road design, and site-specific conditions (e.g., land use, guardrails, and stop-and-go) on the heavy metal contents of vegetated infiltration swales. Recognizing the exposure of such infiltration swales to site-specific factors can provide assistance for their maintenance and operation.

2. Material and methods

2.1. Sampling sites

In total, 262 topsoil samples of vegetated swales for subsequent infiltration were taken at 35 sampling sites along different highways, roads, and parking lots in the counties of Bad Tölz-Wolfratshausen, Freising, Munich, Pfaffenhofen an der Ilm, and Starnberg, Germany. The investigated swales had a similar construction and were made in accordance with DWA-A 138E (2005). The selected infiltration swales consisted of one soil layer and the treated water was subsequently discharged into the groundwater. Most swales had a ratio of the drainage area to the infiltration area of approximately 15:1 and had no artificial underdrain. The main parameters of the soil types (including pH, total organic carbon (TOC), total carbon (C), and total nitrogen (N)) are summarized in Table 1. The variability of most values are small between the sampling sites and within the sampling sites (standard deviation between sampling sites: pH 0.37, TOC 3.28 mg/kg DM, C 3.66 mg/kg DM, and N 0.33 mg/kg DM; standard deviation within the sampling sites: pH 0.03–0.61, TOC 0.25–4.28 mg/kg DM, C 0.80–3.03 mg/kg DM, and N 0.11–0.34 mg/kg DM). The pH value varied between 5.8 and 8.4 (mean: 7.4) for all samples. The counties chosen are all characterized by similar climate conditions to minimize climatic impacts on the results. To detect a uniform loading of the infiltration swales, samples were taken at every sampling site at the following four locations: directly at the inflow to the vegetated swale, in the middle of the descending part, at the deepest point of the swale, and in the middle of the ascending part in the entire depth of the topsoil.

The selected sample sites varied in the age of the topsoil and site-specific factors (i.e., surrounding land use characteristics, traffic area site data, and operational characteristics). The surrounding land use characteristics were specified as urban and non-urban. The collected traffic area site data consisted of vegetation, topography, and road design. The site-specific conditions considered were: slope and configuration of the traffic area (e.g., exit lanes, interchange, or bus stop), grade of congestion (stop-and-go), AADT, HGV (heavy goods vehicles; buses, trucks >3.5 t maximum authorized mass) (BAYSIS, 2016), land use, vegetation, and the presence of guardrails, noise barriers, safety fences, signs, traffic signals, and other drainage systems (summarized in Table 1). The surface of all traffic areas was asphalt (exceptions: PL02: partially paver; PL03: crushed stones). The configuration of the cross sections of all traffic areas was at grade (neither cut nor elevated).

2.2. Sampling procedure

A stainless steel soil sampler (Göttinger Bohrstock) was used to take topsoil samples of the vegetated infiltration swales at four locations and different depths (depths 20–30 cm depending on the thickness of the topsoil layer) to obtain a representative set of samples per site. The natural gravel below the topsoil was not analyzed. The soil sampler was lowered into the ground and then pulled with a 180 degree turn upward. Samples were filled in polyethylene sampling bags and stored at 4 °C ± 1 °C until preparation. After sampling, sample bores were filled with topsoil to prevent bypass infiltration into deeper soil layers.