KAPITEL 5 / *CHAPTER 5* [5]
RUNOFF LOADS FROM TRAFFIC AREAS FOR STORMWATER MANAGEMENT

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Introduction

In most cases, four types of traffic-related loads are considered when calculating mass balances and fluxes. The literature provides specific emission loads for substances, either per vehicle per kilometer traveled (mg/(vehicle·km)) or for the total vehicle kilometers traveled in a particular catchment area over a specific period (mg/(ha·km)). Annual loads can be expressed by road length (g/km) or by traffic area (g/ha). When describing traffic area pollution, it's important to differentiate between total traffic-related emission loads, atmospheric deposition (wet and/or dry), and runoff loads from traffic areas. To calculate runoff loads, long-term measurements of runoff concentrations and water volumes from a monitoring site within a specific catchment area must be recorded, analyzed, and published.

While several studies have assessed runoff concentrations from different traffic areas, only a portion of these monitoring programs have included annual load calculations. This is mainly because many monitoring programs collect a limited number of samples, and their goals do not typically require load calculations (e.g., manual samples for stormwater permit applications). However, annual heavy metal loads, normalized by impervious catchment area, are crucial for mass balance calculations and are important for various purposes (e.g., modeling stormwater quality, assessing treatment systems, and calculating regional or national mass balances) [1].

For effective stormwater management, determining runoff loads for different traffic area categories is essential in designing suitable practices. Therefore, detailed information on traffic-related sources (such as emissions from leaded gasoline, tire and brake wear, road surface abrasion, and de-icing salts) and specific traffic area categories is needed to understand their contribution to environmental pollution and develop cost-effective mitigation strategies.

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In the past, urban pollutant categories were often broadly classified into land use categories like commercial, industrial, or residential. However, this approach doesn't account for the different pollution loads from traffic areas, even though road surfaces make up 10-15% of urban areas and parking lots can constitute up to 46% of commercial and industrial areas [2]. Hence, it's essential to differentiate runoff loads due to the significant contribution of traffic areas to the total urban area. Most values for specific traffic area categories are available for highways, with fewer published for parking lots and other roads. Because many of these values are based on limited studies, reliable figures for major traffic area categories are not readily available, and the influence of climatic factors has not been adequately evaluated. Additionally, most data summaries on runoff loads are outdated and may not reflect current trends.

In traffic area runoff, substances are influenced by various processes. During dry periods, dust fall and dry deposition remove contaminants from the atmosphere. These processes are particularly relevant in urban areas. During rain events, wet deposition removes additional substances from the atmosphere, while pollutants previously deposited on road surfaces are washed off. Research suggests that pollutant wash-off from vehicles is more significant than wash-off from road surfaces [3]. Traffic-related sources, such as brake and tire wear, are relevant contributors to heavy metal pollution. Activities like braking, acceleration, and steering increase tire abrasion, brake lining wear, and exhaust emissions. Corrosion of galvanized elements during rain events also contributes to zinc (Zn) pollution. Other traffic-related sources include catalytic converters, de-icing salts, road wear, and drip losses, all of which emit heavy metals and hydrocarbons, leading to runoff pollution. Common pollutants in traffic area runoff include solids, organic compounds, heavy metals, and de-icing salt compounds. Metals like cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), antimony (Sb), and Zn are particularly concerning due to their toxicity, persistence, and widespread industrial use. Among these, Cu, Pb, and Zn are often found in the highest concentrations in traffic area runoff. Given the significant concentrations of heavy metals, treating runoff water is often necessary to protect surface water, groundwater, and aquatic life. These treatment systems can be integrated into existing stormwater management infrastructure.

This paper focuses on metals in traffic area runoff and their traffic-related emissions. The study's hypothesis is that it is possible to calculate mass balances for traffic-related metals (emissions and runoff loads) across all types of traffic areas (highways, roads, and parking lots) based on a literature review. The objectives of this paper are to summarize the distribution of annual metal loads in runoff from various traffic areas, identify relevant trends and factors, update and expand existing mass balances for heavy metal runoff loads and emissions in Germany, and determine the mass fluxes of traffic-related metals.

5.1. Materials and Methods

The annual metal loads discussed in this paper were meticulously selected from a comprehensive database comprising both German and international studies that detail runoff from traffic areas. This database includes vital information on the monitored traffic areas, categorized into various types such as bridges, highways, parking lots, and roads. Additionally, it provides data on substance concentrations and loads, along with all factors that influence these measurements as reported by the authors. These factors include land use characteristics, vegetation, topography, road design, operational practices, climatic conditions, sampling methods, sample preparation, and analysis techniques, as well as the calculation methods used [4].

In compiling this data, the paper considered not only peer-reviewed journal articles but also reports, books, and non-peer-reviewed journal articles that included data on metals in traffic area runoff. However, only those studies that met stringent validation criteria were included. These criteria required a detailed description of the applied methods, rigorous quality control measures, and reliable monitoring setups to ensure the accuracy of the published results.

The concentrations of metals in runoff, along with factors specific to the site and methods used (e.g., sample collection, preparation, and analysis), were reviewed in a separate study. This database, which covers over 300 monitoring sites, forms the basis of this review, focusing on studies that provided data on traffic area runoff loads for metals such as cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), antimony (Sb), and zinc (Zn). The metal concentrations were reported as total recoverable metals, which were measured following appropriate digestion procedures, including strong acid or aqua regia digestion, sometimes combined with autoclaving or microwave digestion.

The sample preparation and analysis conducted by the selected studies had minimal impact on the results due to the rigorous quality assurance and quality control procedures in place. The studies primarily employed automatic composite samplers to collect a significant number of samples for each rainfall event (active sampling) or a representative mixed sample from a portion of the total runoff (passive sampling).

Despite the comprehensive approach, the highest uncertainties in these long-term monitoring programs stem from the handling of raw data. Challenges include the time intervals for data logging, linking flow and rainfall measurements to the measured runoff concentrations, and the methods used to calculate annual loads. Additional uncertainties arise from dealing with data below detection limits and addressing missing data due to equipment malfunctions.

To streamline the analysis, all monitored traffic areas were categorized into three main categories: highways (H), parking lots (P), and roads (R). Sites where runoff loads were not entirely linked to impervious traffic areas were classified as special (S). Each monitoring site was assigned a unique identification number (ID), consisting of a capital letter corresponding to its category (H, P, R, or S) followed by two consecutive numbers (e.g., H01). These IDs are used throughout the paper.

The characteristics of the selected sites are summarized, providing information on their location (country), sampling period, land use, site-specific factors (e.g., road maintenance practices like winter services and sweeping), average annual daily traffic (AADT), the discharge area of the monitoring site (i.e., the catchment area connected to the sampler), and the annual rainfall depth [5].

This novel evaluation focuses on annual metal loads per hectare of catchment area (g/ha) across different traffic area types (H, R, and P). The values were calculated by the authors of the selected studies based on runoff concentrations from impervious surfaces without subsequent pre-treatment. For sites summarized under the special (S) category, a conversion of units was sometimes necessary (e.g., lb/acre, mg/m², or kg/ha to g/ha). Additionally, where sufficient information was available, annual metal loads originally presented as g/km were recalculated to g/ha.

Due to the variability of climatic factors at each site and numerous uncertainties, this study did not calculate loads directly from runoff concentrations and corresponding water volumes. Such uncertainties include missing data on the percentage of analyzed runoff volumes relative to total volumes, the percentage of collected rain events compared to total rain events, and the representativeness of analyzed rain events in terms of intensity and duration. Furthermore, the complex relationship between rainfall and runoff volumes adds another layer of ambiguity to these calculations.

Extending beyond these technical details, this paper aims to provide a comprehensive understanding of how different traffic areas contribute to environmental pollution, specifically focusing on heavy metal runoff. By integrating and expanding upon previous studies, this work seeks to identify trends and offer insights into the development of more effective mitigation strategies. Ultimately, this research contributes to the broader goal of improving urban stormwater management practices and protecting environmental and public health.

In analyzing historical trends, the focus was placed on the period during which the monitoring programs were conducted, rather than the publication date of the studies. This approach was chosen to capture the temporal dynamics of the data more accurately. Given that most of the parameters did not follow a normal distribution, the non-parametric Spearman rank-order correlation was employed for the correlation analysis. This method is robust to deviations from normality and follows the precedent set by Mosley and Peake in their study.

This methodological approach allowed for a nuanced understanding of the data, accounting for variations over time and across different monitoring sites. By employing robust statistical techniques, this analysis aimed to uncover meaningful patterns and correlations in the data, ultimately contributing to a more comprehensive understanding of the environmental impacts associated with heavy metal loads in runoff.

5.2. Annula Metal Runoff Loads for Different Traffic Areas

One frequently discussed factor in the context of runoff pollution from traffic areas is the impact of Average Annual Daily Traffic (AADT). However, AADT alone accounts for only about 30% of the variability observed across different sites. In this review, AADT values ranged from 2,000 to 120,000 vehicles per day for highway and road sites (Table 1). Notably, significant correlations between AADT and certain heavy metals—specifically cadmium (Cd), chromium (Cr), and copper (Cu)—were identified, with chromium showing the strongest correlation ($r = 0.66$). This indicates that additional site-specific factors significantly influence the annual runoff loads. A comprehensive description of these site-specific factors affecting metal runoff concentrations and loads from traffic areas can be found in a previous study [6, 7].

In the current analysis, only the fixed site-specific factors contributing to extreme values across the 45 sites are discussed, with the exception of lead (Pb). The highest annual loads were recorded at the urban site, which experiences heavy traffic with an AADT of 57,600 vehicles per day. Other contributing factors to the elevated runoff concentrations at this site include the extensive use of de-icing salts by winter services, which contain high metal content, frequent congestion during rush hours, and the road design, such as a section of the monitoring site being a bridge with concrete pillars. Additionally, uncertainties regarding the discharge area—due to a steep slope at the drainage area's edges, which caused extra water to flow into the monitored area—might have further increased the calculated annual runoff loads. The proximity of a zinc (Zn) smelter was responsible for the elevated Zn runoff loads [8].

Data also showed increased runoff loads due to the complete drainage of the catchment area through curbs and gutters, which was exacerbated by the presence of guardrails and stop-and-go traffic. In this case, runoff volumes were estimated based on rainfall depths and an assumed runoff coefficient of 0.9. Category S includes the highway sites S01–S04 and parking lot sites S05–S10. Most of the metal runoff loads in category S are significantly lower than those reported for non-pre-treated runoff at comparable sites. For example, at site S01, only 39.6% of the surface was sealed with asphalt, while the rest of the drainage area consisted of adjacent grassy areas. At site S02, the catchment area was 61% asphalt, with the remainder being a grassy shoulder, both of which were monitored [10].

These findings on runoff load reductions through pervious surfaces and vegetated swales can be instrumental in designing effective stormwater management practices. When designing vegetated swales, it is essential to consider additional site-specific factors, such as road design features (e.g., intersections and roundabouts) and the level of congestion (e.g., areas with frequent stop-and-go traffic.

The historical trends in traffic area runoff loads for copper (Cu), lead (Pb), and zinc (Zn) from the 1970s to the present were analyzed based on literature. These loads were grouped into five decades and visualized using box and whisker plots. A significant reduction in Pb loads over time was observed, primarily due to the phase-out and replacement of leaded gasoline. In the United States, this reduction began in the mid-1980s and was completed by 1996. In Europe, the process was less uniform; for instance, Germany and several other Western European countries had almost entirely phased out leaded gasoline by 1986. The European Union completed its phase-out in January 2002, when Italy eliminated leaded gasoline, coinciding with a similar ban in China. Further reductions in Pb usage are attributed to the replacement of Pb in various products, including tires, brake linings, lubricating oils, greases, and tire balance weights. These developments explain the high Pb loads reported in older studies. However, Pb is still present in tires and in gasoline used for classic cars, leading to its continued presence in runoff samples and in younger vegetated infiltration swales, albeit at low levels. Consequently, only Pb data from the 21st century should be used for current mass balance calculations.

For Cu and Zn, no clear historical trends were detected. Since most sampling periods lasted only 1 to 2 years, data on annual runoff loads and rainfall depths are available for each monitored year at three traffic area sites. At EU, a nine-year monitoring program revealed variations in annual runoff loads, with minimum and maximum values ranging from 0.5–3.1 g/ha for Cd, 17–76 g/ha for Cr, 116–324 g/ha for Cu, 20–60 g/ha for Ni, 28–143 g/ha for Pb, 10–23 g/ha for Sb, and 1530–3550 g/ha for Zn. The coefficients of variation for these loads were 56% for Cd, 51% for Cr, 33% for Cu, 43% for Ni, 44% for Pb, 27% for Sb, and 30% for Zn [9]. The catchment area, sampling procedures, and most fixed site-specific factors (such as the presence of a guardrail) remained consistent throughout the monitoring period. A slight increase in AADT was observed (from 6,100 vehicles per day at the start to approximately 6,800 vehicles per day in the latter half of the program), and a change in agricultural land use occurred to the east of the site. Despite this, most annual metal loads in the second half of the program were lower than those in the first half, indicating that the influence of AADT on these loads was not significant. Therefore, the variation in heavy metal loads may be more closely correlated with climatic factors, such as annual rainfall depth, which varied significantly between 334 mm and 863 mm (mean 667 mm; coefficient of variation 26%). However, a strong correlation ($r \geq 0.60$) between the seven metals and annual rainfall depth was only found for Sb ($r = 0.68$, $p < 0.05$). Thus, annual rainfall depth did not significantly influence the variability of annual heavy metal runoff loads at this site, although most of the lowest loads were recorded during a year with low rainfall and prolonged dry periods in spring and summer [10, 11, 12].

At USA, the variation in annual rainfall depths was similar (coefficient of variation 22%), but the variation in metal runoff loads was much higher. These differences may be attributed to a variety of climatic conditions (not limited to rainfall depth) that can affect deposition and wash-off processes, as well as fixed site-specific factors. These factors include differences in AADT, speed limits (50 km/h at R02 and 120 km/h at H28), and the presence of noise barriers, a forest, and hard shoulders at H28, which may reduce the impact of climatic factors like wind turbulence on runoff loads. The annual rainfall depths were 876 mm in 2006 and 1184 mm in 2007, leading to increased runoff loads for Pb and Zn but not for Cu. This suggests that using median runoff concentrations from the literature, multiplied by different annual rainfall depths for a specific site, is insufficient to capture the variance in annual runoff loads due to climatic variations [13].

Across all monitoring sites, annual rainfall depths ranged from 254 mm to 2540 mm (median 792 mm; 90th percentile 1200 mm). A strong correlation between annual rainfall depths and heavy metals was only found for Cd ($r = 0.64$, $p < 0.01$) across all sites. Seasonal influences on traffic area runoff pollution were evaluated by Helmreich et al., who found a considerable increase in pollutants during the cold season. However, a seasonal correlation could not be performed in this study because all published annual loads did not differentiate between seasons. Therefore, only single-event data can be used for such analyses. For instance, the first storm of each season in (semi)arid regions often results in higher runoff loads. Additionally, atmospheric deposition (both wet and dry) must be considered a climatic factor affecting runoff loads. Deposition fluxes on traffic areas are strongly influenced by site-specific factors. For example, the absence of curbs, hard shoulders, and noise barriers can reduce runoff concentrations by lowering deposition rates and subsequent wash-off. Deposition is also affected by traffic volume and surrounding land use. Limited data are available for urban traffic area sites, particularly roads and parking lots, where higher fractions of metal emissions may be deposited and washed off compared to non-urban sites. These rates are also influenced by the length of antecedent dry periods. However, some studies have concluded that splashing and washing pollutants from vehicles is more important than the wash-off of pollutants accumulated on road surfaces by precipitation (wet deposition). In industrial zones, precipitation plays a more significant role in runoff pollution, and this effect varies greatly for each metal. Dry deposition at industrial sites is also important, while traffic-related emissions are more influential at non-industrial urban sites. For non-urban sites, the impact of wet and dry deposition on annual runoff loads was quantified. The ratios of deposition loads to runoff loads at these sites were 35%/31%/42% for Cd, 65%/2%/125% for Cr, 36%/23%/46% for Cu, 24%/27%/50% for Pb, and 54%/31%/80% for Zn [14, 15]. These findings demonstrate that deposition significantly affects runoff loads at these non-urban highway sites, with the extent of the impact depending on both the site and the specific metal.

Conclusion

For effective stormwater management, it is crucial to have a deeper understanding of runoff loads from various traffic area categories. This paper provides a summary of these loads for highways, roads, and parking lots, highlighting that the highest runoff loads are typically found on highways, roads, and parking lots with heavy usage, especially those frequently used by trucks. Unlike highways and roads, parking lots require individual consideration due to site-specific factors that can significantly influence runoff loads.

In Germany, traffic-related emissions have been estimated for seven distinct sources: tire wear, brake lining wear, roadway abrasion, weights used for tire balancing, guardrails, lampposts/signs, and de-icing salts. Among these, zinc (Zn) is predominantly emitted from galvanized elements and tires, while copper (Cu) and lead (Pb) mainly originate from brake wear, and cadmium (Cd) is largely released by the use of de-icing salts. The calculated metal loads in this study are generally consistent with findings from other research for most metals. However, conducting a comprehensive statistical analysis of traffic-related metal mass fluxes—such as quantifying the contribution of metal emissions to runoff loads across different traffic area categories and land uses—remains challenging due to the scarcity of monitoring data. This data gap includes missing information on metal content from various sources, emission factors, deposition rates across different traffic area categories and land use types, and detailed size characterizations of catchment areas for these categories.

Despite these limitations, the study's estimates indicate that vehicles, road design, and winter maintenance services contribute substantially to heavy metal emissions in Germany. Specifically, the estimated annual emissions are 0.93 tonnes of cadmium

(Cd), 935 tonnes of copper (Cu), 84.4 tonnes of lead (Pb), and 2,094 tonnes of zinc (Zn). Correspondingly, runoff from traffic areas also carries significant metal loads each year. Of particular concern are copper and zinc, as lead emissions have significantly decreased in recent decades, and traffic-related emissions of cadmium and nickel now contribute only 5% and 11% of Germany's total emissions, respectively. Nevertheless, the runoff loads of other metals, including cadmium and antimony (Sb), remain a serious environmental threat due to their toxicity, especially for aquatic ecosystems.

Given these findings, it is imperative to intensify efforts to reduce traffic-related metal loads—both from emissions and runoff—to minimize their impact on receiving waters and soils. This reduction would not only mitigate the adverse effects on aquatic biota but also contribute to the broader goal of improving environmental quality.

Looking ahead, there is a pressing need for more long-term monitoring data that encompass a wide range of substances and provide detailed accounts of climatic factors. Such data are essential to enhance the accuracy of metal load calculations, mass balances, and flux assessments. Additionally, improving the availability of reliable data will help reduce the significant uncertainties that currently exist in many of the values used in this review for various calculations. By addressing these data gaps, future research can contribute to more effective stormwater management strategies and the protection of water and soil resources from heavy metal contamination.