

Article

Functional-Area-Based Spatial Variability and Source Apportionment of Urban Rainfall Runoff Pollution: Implications for Sustainable Water Management and Urban Resilience in China

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Abstract

Rainfall–runoff pollution poses a major challenge to urban water quality management, particularly in rapidly developing regions. However, its spatial variability and source characteristics remain inadequately understood. This study investigates the types, concentrations, and sources of pollutants in rainfall runoff across different urban land-use settings, with the aim of providing insights for more effective water management strategies. By quantifying pollutant occurrence frequencies, comparing reported event mean concentrations, and summarizing literature-reported pollution sources, we evaluated the spatial heterogeneity of runoff contamination from a descriptive perspective. The compiled literature data showed descriptive differences in reported pollution levels among land-use types, with relatively high pollutant concentrations frequently reported in residential and traffic areas. These differences should be interpreted as functional-area-based patterns rather than continuous geographic spatial distributions. Pollutants such as chemical oxygen demand (COD), suspended solids (SS), and total nitrogen (TN) frequently exceeded China’s Class V surface water quality standards. Atmospheric deposition and surface litter were the most frequently reported pollution sources, while traffic-related activities were frequently associated with elevated heavy metal concentrations in the reviewed studies. These findings underscore the urgent need for targeted, land-use-specific pollution control strategies that not only reduce runoff pollution but also improve source-control efficiency for sustainable urban water management. This study offers valuable insights that may be transferable to other urban environments worldwide, with important implications for policy development and urban resilience in the face of increasing environmental pressures.



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1. Introduction

Rapid urbanization and development in China over recent years have significantly expanded impervious surfaces in urban areas, fundamentally altering natural water cycle pathways [1–4]. These changes have directly impacted rainwater quality by modifying

the transport routes of pollutants. Pollutants from the atmosphere, ground surfaces, and surrounding environments are increasingly mobilized into runoff during rainfall events, thereby degrading surface water quality [1,3,5,6]. Ground-level pollutants, in particular, have been linked to factors such as the expanding transportation sector and high population density, both of which exacerbate the pollution risk to surface waters [7]. In 2020, China's average rainfall in June was 13.5% higher than the norm, characterized by widespread and prolonged precipitation. This increase in rainfall has further intensified the transfer of contaminants from the ground into stormwater runoff. As a result, surface waters are increasingly threatened by pollutants carried in rainfall runoff from both the atmosphere and ground surfaces. To safeguard surface water quality, it is essential to identify and analyze the potential pollution sources in rainfall runoff. This study, therefore, aims to summarize and investigate the key pollutants and their sources to inform future water quality management strategies.

Rainfall runoff pollution has been studied since the 1970s [7,8]. Over the years, significant attention has been given to topics such as first flush effects, pollution evaluation, process modeling, and control strategies. During rainfall events, large amounts of pollutants are typically transferred in the initial stages, with the first flush phenomenon being particularly pronounced in smaller watersheds and varying across different pollutants [9]. For example, in residential areas, the cumulative concentration of pollutants during the first flush follows the order COD > TP > SS [5,10]. The intensity of the first flush is also influenced by surface characteristics, with smoother impervious surfaces exacerbating this effect [11,12]. Thus, it is crucial to account for surface types when assessing urban rainfall runoff pollution. Additionally, heavy rainfall events are more likely to wash away surface pollutants, further complicating the pollution dynamics [13].

Various models, including the Storm Water Management Model (SWMM) and Positive Matrix Factorization (PMF), have been employed to predict pollution levels, understand pollutant transport mechanisms, and analyze pollution sources in runoff [14–16]. To mitigate rainfall runoff pollution, strategies such as source control, process management, and final treatment have been proposed. Examples include green roofs and bioretention ponds [17–19]. Pollution evaluations in different functional areas have been conducted in cities like Beijing, Chongqing, and Xi'an, providing valuable insights into the regional characteristics of runoff pollution [20–22]. However, comprehensive studies on the general characteristics of rainfall runoff pollution across China remain limited.

Understanding the occurrence frequency of typical pollutants, their concentrations across different functional areas, and the potential pollution sources is crucial for characterizing rainfall runoff pollution. Pollutant concentrations in various urban areas provide insight into the current pollution levels, while the occurrence frequency highlights the relative importance of specific pollutants. Additionally, identifying pollution sources and their occurrence frequencies can help elucidate potential pathways through which pollutants reach surface waters. Previous studies have primarily focused on pollutant concentrations on roads and other impervious surfaces for comparative analysis [23,24].

This study provides a comprehensive analysis of rainfall runoff pollution by comparing pollutant profiles across different urban functional areas, focusing on pollutant concentrations and functional-area-based differences. The distribution patterns of pollutants are summarized, and potential pollution sources in these areas are evaluated. This analysis offers critical insights for reducing pollutant concentrations in runoff and contributes to the development of more effective management strategies aimed at mitigating runoff pollution and protecting surface water quality. Based on existing data from previous studies in China, the study also offers an overview of pollution characteristics across various functional areas. Additionally, it explores pollution sources and control strategies to enhance surface water

management. Although data availability is limited, the findings present valuable guidance for more effective urban runoff pollution control and management.

2. Research Methods

This study adopted a literature-based statistical analysis method to investigate land-use-based spatial variability and source characteristics of rainfall runoff pollution among different urban functional areas in China. Relevant studies were retrieved from the China National Knowledge Infrastructure database using the keyword “rainfall runoff pollution”. To ensure the relevance and comparability of the collected data, only studies that reported rainfall runoff pollutant concentrations, urban functional area information, or potential pollution sources were included in the analysis. After screening, 53 related articles were selected for data extraction and statistical evaluation.

The collected data were classified according to five typical urban functional areas: traffic areas, residential areas, industrial areas, educational areas, and commercial areas. These areas were abbreviated as T, R, I, E, and C, respectively, in the figures and statistical analysis. When one study reported rainfall runoff pollution in more than one functional area, the data for each area were recorded separately to avoid underestimating the occurrence frequency of pollutants and pollution sources in specific land-use types.

For pollutant analysis, the main water quality indicators included chemical oxygen demand (COD), suspended solids (SS), total nitrogen (TN), total phosphorus (TP), ammonia nitrogen ($\text{NH}_3\text{-N}$), heavy metals, and polycyclic aromatic hydrocarbons (PAHs). The occurrence frequency of each pollutant was calculated based on the number of times it was reported in the selected literature. Event mean concentration values were extracted where available and were used to compare pollutant concentration levels among different functional areas. The pollution status of rainfall runoff was further evaluated by comparing the reported pollutant concentrations with the Environmental Quality Standards for Surface Water in China. For SS, the third-level discharge standard for municipal wastewater treatment plants was used as a reference due to the lack of a direct SS limit in the surface water quality standard.

All extracted data were organized and statistically summarized using frequency analysis and comparative analysis. The results were presented in the form of frequency distributions, concentration ranges, average values, and exceedance proportions. This methodological framework allowed the study to compare rainfall runoff pollution characteristics across different urban functional areas and to identify the main pollutants and potential sources affecting urban runoff quality.

It should be noted that the compiled dataset was derived from independent studies conducted in different cities and periods, with differences in rainfall characteristics, sampling methods, sampling frequency, runoff collection procedures, analytical methods, and data reporting formats. Therefore, the EMC data were not fully standardized across studies. In this context, the present analysis was designed as a descriptive synthesis rather than a formal meta-analysis or inferential statistical comparison. No ANOVA, post hoc test, or formal outlier test was conducted because raw replicate-level data, consistent sample sizes, and complete variance information were generally unavailable in the reviewed literature. The comparisons among functional areas were therefore based on reported concentration ranges, average values, exceedance proportions, and occurrence frequencies, and should be interpreted as descriptive trends.

To gather relevant research data on rainfall runoff pollution in China, we indexed the term “rainfall runoff pollution” on www.cnki.net, a comprehensive database of Chinese academic journals. Given the focus on urban functional areas and pollutant sources, only 53 related articles were selected for further analysis and statistical evaluation.

3. Results and Discussion

3.1. Functional-Area-Based Variability of Rainfall Runoff Pollution

The variability discussed in this section is based on urban functional areas rather than geographic coordinates or continuous spatial surfaces. Functional areas were treated as land-use-based spatial categories because runoff pollution is strongly influenced by surface characteristics, traffic intensity, population activity, commercial activity, industrial production, and green-space management. Therefore, comparisons among functional areas were used to identify descriptive land-use-related patterns in rainfall runoff pollution.

As shown in Figure 1, the distribution of studies on rainfall runoff pollution across different functional areas was uneven, with research frequency gradually decreasing in the following order: residential areas, traffic areas, commercial areas, educational areas, and industrial areas. Because the dataset was compiled from independent studies rather than from a unified monitoring program, the differences among functional areas were interpreted descriptively. These comparisons were used to identify general pollution patterns and research attention across land-use types, rather than to test statistically significant differences among functional areas. Among these, residential and traffic areas ranked first and second, respectively, indicating that greater attention has been paid to the pollution characteristics and potential pollution risks in these two types of areas. In contrast, the relatively low research frequency in commercial, educational, and industrial areas may be attributed to their smaller proportions within urban landscapes and their comparatively lower perceived pollution potential. To achieve a more comprehensive understanding of rainfall runoff pollution in urban environments, future studies should place greater emphasis on commercial, educational, and industrial areas.

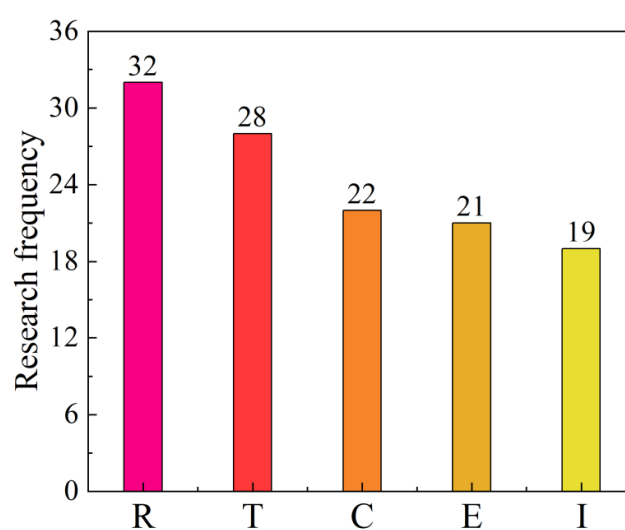


Figure 1. Research frequency on different functional areas (traffic areas, residential areas, industrial areas, educational areas, and commercial areas is marked with 'R', 'T', 'C', 'E', 'I').

3.1.1. Pollutants in Rainfall Runoff Across Urban Functional Areas

COD, SS, TN, TP, and $\text{NH}_3\text{-N}$ were commonly used as the evaluation parameters of rainfall runoff. In addition, heavy metals (Cu, Zn, Pb, Cr, etc.), polycyclic aromatic hydrocarbons (PAHs) and other parameters were also analyzed accordingly to confirm the potential pollution in rainfall runoff.

The occurrence frequency of pollutants in urban functional areas is shown in Figure 2. COD, SS, TN, TP, and $\text{NH}_3\text{-N}$ were obviously paid more attention in rainfall runoff pollution in all functional areas. COD, TN and TP in rainfall runoff attracted the most attention in all functional areas. SS in traffic areas and residential areas occurred more than other

functional areas, which might be due to the large tire wears in traffic areas and frequent human activities in residential areas.

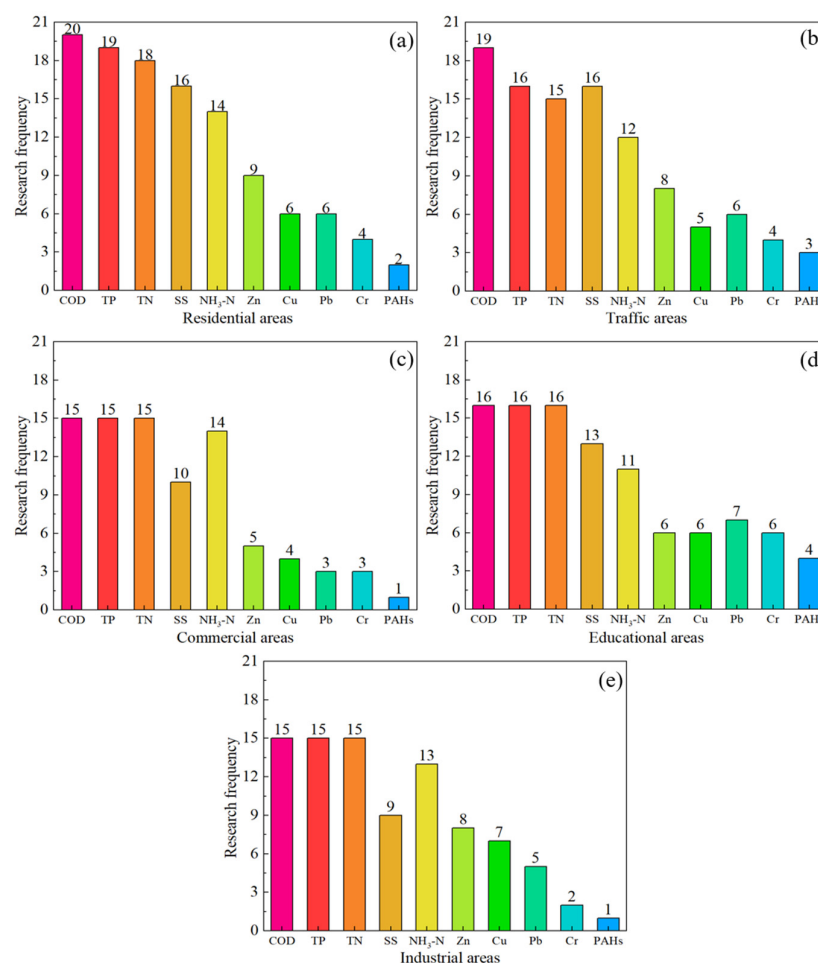


Figure 2. Research frequency of pollutants in different urban areas: (a) Residential areas, (b) Traffic areas, (c) Commercial areas, (d) Educational areas, (e) Industrial areas.

Correspondingly, heavy metals, including Cr, Cu, Zn, and Pb, together with PAHs, were less frequently reported than COD, SS, TN, TP, and NH₃-N in studies on rainfall runoff pollution. However, considering their potential environmental risks and the possibility of unidentified pollutant discharges, these pollutants should also be incorporated into urban runoff monitoring programs [25,26]. Among the investigated heavy metals, Zn was generally reported more frequently than Cr, Cu, and Pb, as well as PAHs, in most functional areas except educational areas. This pattern may be associated with traffic-related wear, such as tire and brake abrasion, in urban environments. PAHs were seldom reported in urban runoff studies, which may reflect the limited attention given to PAH pollution in rainfall runoff. Nevertheless, the low reporting frequency does not necessarily indicate that PAH pollution is negligible. Overall, the relatively high occurrence frequencies of COD, SS, TN, TP, and NH₃-N suggest that existing studies have mainly focused on conventional runoff pollution indicators.

3.1.2. Pollution Characteristics of Rainfall Runoff in Urban Functional Areas

As illustrated in Figure 3a, COD concentrations in rainfall runoff showed considerable variability across different functional areas. Overall, 76.7% of the reported COD concentrations exceeded the Class V threshold of 40 mg/L specified in the surface water quality standard [27], suggesting that rainfall runoff pollution in the investigated areas

was more severe than anticipated. As further indicated by the boxplots, the median COD concentrations in all functional areas were higher than the Class V threshold, although the exceedance degree varied among areas. The medians in commercial and traffic areas were clearly higher than 40 mg/L, indicating generally elevated COD pollution levels, while those in industrial and residential areas also exceeded the Class V limit. In comparison, the median COD concentration in educational areas was relatively lower, but still above the Class V threshold, suggesting that COD pollution was not limited to highly urbanized or traffic-intensive areas. Although most COD concentrations were concentrated within the range of 0–200 mg/L, values higher than 200 mg/L were also reported in traffic, residential, industrial, and commercial areas. For instance, Zhang et al. [28] reported an event mean concentration (EMC) of COD as high as 1169.62 mg/L in rainfall runoff from residential areas in Chengdu. This value was retained in the textual discussion as an extremely high reported value. The exceptionally high COD concentration may be associated with intensive traffic emissions and human activities around the residential sampling sites.

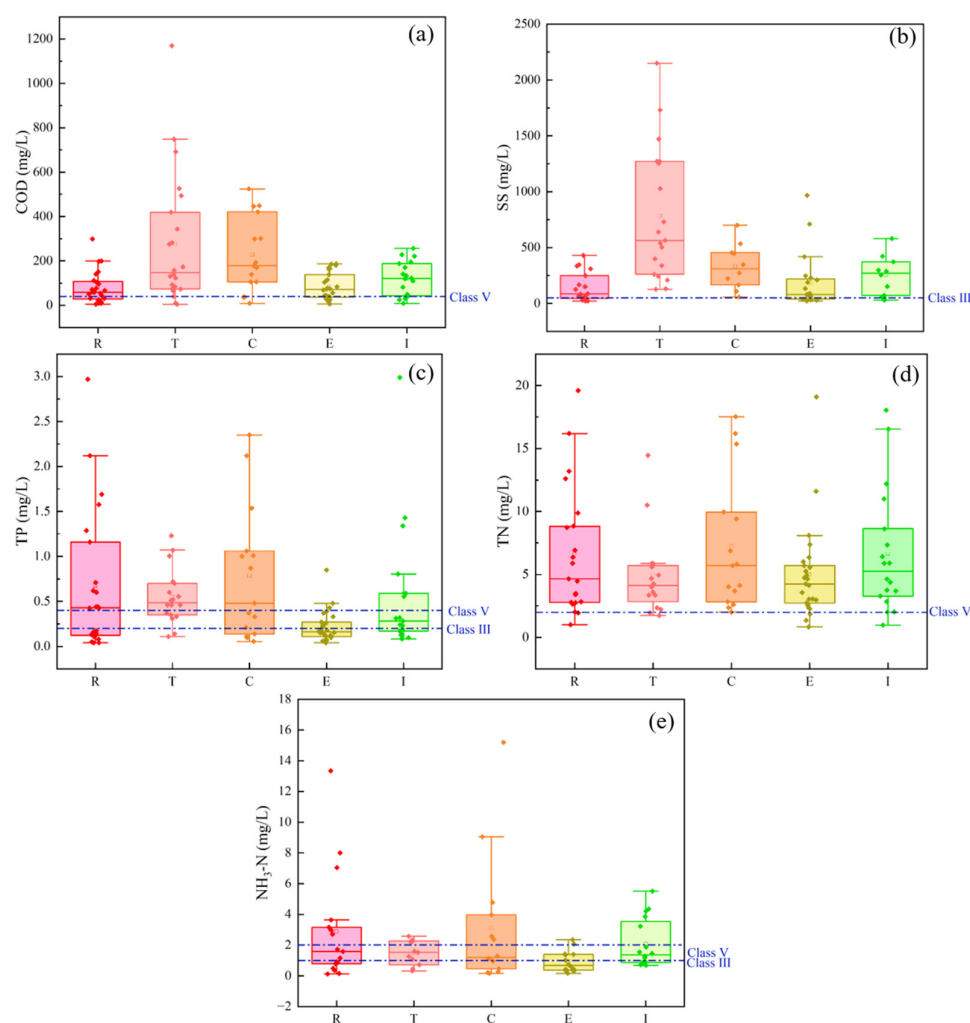


Figure 3. EMC distribution of rainfall runoff pollutants in different functional areas (a) COD, (b) SS, (c) TN, (d) TP, (e) $\text{NH}_3\text{-N}$.

According to the COD concentrations in different functional areas and surface water quality, it could be concluded that 83.3%, 80%, and 85.7% COD concentrations of rainfall runoff in industrial areas, commercial areas, and traffic areas were worsen than Class V in surface water standards. This was consistent with the median comparison in the boxplots, where the central COD levels of these functional areas were all above the Class V

threshold, confirming that COD pollution was not only caused by a few extreme values but also reflected in the overall distribution of the datasets. More than 70% of the rainfall runoff in the functional areas are faced with COD pollution. Therefore, the prevention and purification of rainfall runoff pollution must be paid more attention in future, which could be achieved by modified rainfall inlet, bioretention ponds, and pollution source control.

As shown in Figure 3b, SS in rainfall runoff was found to range from 0 to 500 mg/L in all functional areas. SS concentrations reported for traffic areas were relatively higher than those reported for other functional areas. Compared with the third-level standard (50 mg/L) for municipal wastewater treatment plant [29], 81.25% SS concentration of rainfall runoff could not meet the discharge standard for treated wastewater. The comparison between the Class III threshold and the boxplot medians further indicated the general exceedance of SS concentrations in rainfall runoff. The median SS concentrations in industrial, commercial, and traffic areas were obviously higher than the Class III threshold, especially in traffic areas, where the median value was far above 50 mg/L. This suggested that high SS pollution in these areas was not only caused by isolated extreme values, but also reflected in the central tendency of the datasets. In contrast, the medians in residential and educational areas were relatively close to the Class III threshold, but still higher than 50 mg/L, indicating that SS pollution also occurred commonly in these functional areas. The average SS concentrations in residential areas, industrial areas, commercial areas, educational areas and traffic areas were around 2.9 times, 5 times, 6.6 times, 3.8 times, and 15.6 times the third-level standard for wastewater discharge. The concentration of suspended solids seemed to be high in rainfall runoff, which could result in the accumulation of organic suspended particles and nutrients in surface water [28]. The high SS concentration of rainfall runoff in the traffic areas might be closely related to the large traffic loading, which could be formed during the wearing of tires and road surface in daily life.

As shown in Figure 3c, TN concentrations in rainfall runoff across different functional areas were mainly distributed within the range of 0–20 mg/L. Specifically, TN concentrations in industrial, residential, commercial, and educational areas were primarily concentrated between 2 and 8 mg/L, whereas those in traffic areas were mostly within the range of 2–6 mg/L. Considering that the Class V limit for TN in surface water quality is 2 mg/L, approximately 90% of the reported TN concentrations in rainfall runoff exceeded this standard. The comparison between the Class V threshold and the boxplot medians further confirmed the widespread TN pollution in rainfall runoff. The median TN concentrations in all functional areas were higher than the Class V limit, indicating that the exceedance was not only associated with scattered high values but also reflected in the central tendency of the datasets. Among them, the median TN concentrations in industrial, residential, commercial, and educational areas were clearly above 2 mg/L, while the median value in traffic areas was also higher than the Class V threshold, although relatively lower than those in several other functional areas. The average TN concentrations in rainfall runoff from industrial, residential, commercial, educational, and traffic areas were 6.64, 7.32, 7.23, 4.97, and 4.92 mg/L, respectively, which were 3.31, 3.66, 3.61, 2.48, and 2.46 times higher than the Class V surface water quality standard. These results indicate that TN pollution in rainfall runoff was severe across all functional areas and should not be overlooked. Therefore, greater efforts should be made to strengthen source control and runoff pollution treatment, particularly in industrial, residential, and commercial areas.

As illustrated in Figure 3d, most TP concentrations in urban rainfall runoff were below the Class III surface water quality standard (0.2 mg/L), although some values exceeded the Class V standard (0.4 mg/L). The comparison between the Class III and Class V thresholds and the boxplot medians further showed clear differences among functional areas. The median TP concentration in educational areas was lower than the Class III standard,

indicating relatively slight phosphorus pollution in this functional area. In contrast, the median TP concentrations in industrial, residential, commercial, and traffic areas were higher than the Class III standard, suggesting that TP pollution was more common in these areas. Among them, the medians in residential, commercial, and traffic areas were also slightly higher than or close to the Class V standard, implying a higher risk of phosphorus pollution compared with educational and industrial areas. In educational and traffic areas, TP concentrations were generally lower than 1.5 mg/L. Based on the compiled dataset for all urban functional areas, 62% and 43% of the reported TP concentrations exceeded the Class III and Class V standards, respectively, suggesting that TP pollution in urban rainfall runoff remains a concern and should be further addressed in runoff management. The proportions of TP concentrations exceeding the Class V standard in industrial, residential, commercial, educational, and traffic areas were 38.9%, 56.5%, 53.3%, 11.5%, and 66.7%, respectively. The corresponding proportions exceeding the Class III standard were 66.7%, 56.5%, 73.3%, 38.5%, and 88.9%, respectively. These results further demonstrate the pollution status of TP in rainfall runoff among different functional areas. Overall, phosphorus pollution was less severe in educational areas than in the other functional areas. Potential sources of phosphorus in urban runoff may include the irregular discharge of catering wastewater and the leaching of fertilizers from urban green spaces during rainfall events. The transfer of phosphorus from runoff into receiving waters can elevate the risk of eutrophication, thereby further degrading surface water quality [30].

It could be seen from Figure 3e that most of $\text{NH}_3\text{-N}$ in each functional area were in the range of 0~4 mg/L, with the average $\text{NH}_3\text{-N}$ concentrations in urban rainfall runoff of 2.16 mg/L, showing slight pollution of $\text{NH}_3\text{-N}$ in rainfall runoff. However, high $\text{NH}_3\text{-N}$ concentration in residential and commercial areas were reported in some cases. Hong et al. [31] monitored the samples in three different residential areas and found that the average concentrations of $\text{NH}_3\text{-N}$ in rainfall runoff were 13.345 mg/L, 7.045 mg/L, and 8.05 mg/L, indicating the serious ammonia pollution. Poultry and pet excreta on road surface and discharging of domestic sewage might be the main reason for high concentrated $\text{NH}_3\text{-N}$ in rainfall runoff in residential areas [32–34]. The $\text{NH}_3\text{-N}$ concentration of 15.2 mg/L was also reported in commercial area [35], which might be attributed to the transferring of food residues and wastewater from catering shops into catchment wells [24,36]. According to statistical data, the percentages of $\text{NH}_3\text{-N}$ in industrial, residential, commercial, educational, and traffic areas exceeding the surface water standard of Class III (1 mg/L) were 62.5%, 58.8%, 64.3%, 42.9%, 72.7%. While the proportions exceeding Class V (2 mg/L) were 31.3%, 41.2%, 42.9%, 14.3%, and 36.4%. Above all, much work remains to be done to improve the $\text{NH}_3\text{-N}$ pollution in rainfall runoff.

Based on the compiled pollutant dataset, Zn concentrations in rainfall runoff were generally below the Class III surface water quality standard of 1 mg/L, indicating a relatively low level of Zn contamination. Zn in urban runoff is commonly associated with zinc-based building materials [36]. Under natural conditions, zinc-containing materials may gradually weather and dissolve during rainfall events, resulting in the release and accumulation of Zn in runoff [37,38]. Nevertheless, the low Zn concentrations observed in this study suggest that Zn pollution in rainfall runoff was not pronounced. Accordingly, more attention should be given to conventional runoff pollutants, such as COD, SS, TN, TP, and $\text{NH}_3\text{-N}$, to support the improvement in urban rainfall runoff quality.

3.2. Pollution Sources in Urban Rainfall Runoff

Due to the difference in urban functional areas, human activities, land use types and so on, pollution source analysis of rainfall runoff should be conducted with the characteristics of functional areas. Traffic wear, exhaust emissions, surface garbage, surface material

decomposition, roof material decomposition, atmospheric deposition, discharge of sewage, industrial production, and dissolution of soil material in green belt could be taken as the possible pollution routes of rainfall runoff.

To have a full understanding of the pollution sources of rainfall runoff, all the possible pollution routes and occurrence frequency in the scope of this research were analyzed and summarized in Figure 4. Pollution sources with higher reporting frequencies were considered as commonly recognized potential sources of urban rainfall runoff pollution in the reviewed literature. However, these frequencies do not represent quantitative source contributions, because the original studies did not provide a consistent chemical dataset suitable for receptor modeling. Among them, atmospheric deposition was found with the highest frequency in source analysis. Dry deposition and wet deposition were the common forms in atmospheric deposition [39]. Under the action of atmospheric transportation, pollutants in different areas could be migrated into the atmosphere [40], and then accumulated on the underlying surface through dry or wet deposition [41]. Rainwater was mainly contaminated by pollutants in atmosphere [42,43]. According to research by ref. [44], atmospheric deposition accounted for 57~100% of heavy metals in rainfall runoff. In addition, Taylor et al. [45] found that wet deposition contributed to more than 70% nitrogen and 13% phosphorus in rainfall runoff.

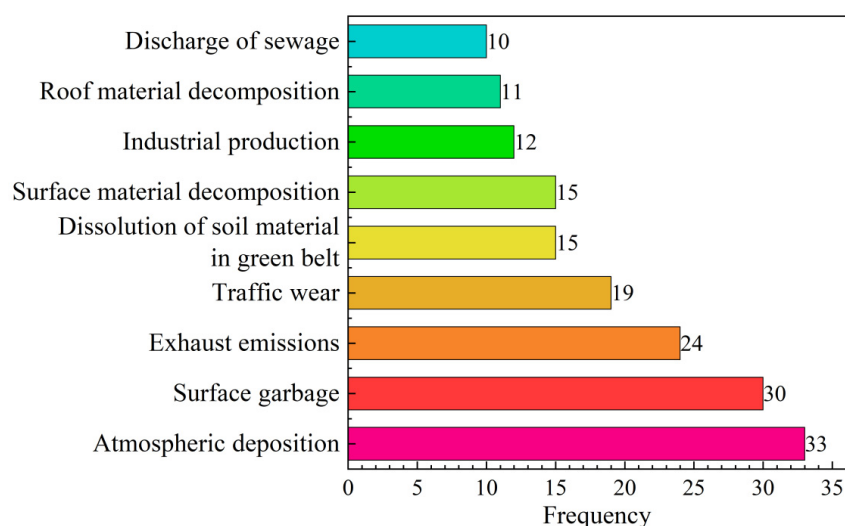


Figure 4. Frequency of pollution sources of rainfall runoff.

Surface litter derived from human activities was identified as the second-most frequently reported source of rainfall runoff pollution. Motor vehicle exhaust emissions and traffic-related wear were also recognized as common sources, especially in traffic areas, where they contributed substantially to runoff pollution. Therefore, based on the pollution characteristics and potential sources associated with different functional areas, targeted and effective technical strategies should be adopted to mitigate rainfall runoff pollution and improve receiving surface water quality.

3.2.1. Source Analysis of Rainfall Runoff Pollution

To gain a comprehensive understanding of pollution sources in rainfall runoff across different urban functional areas, the occurrence frequencies of potential sources were analyzed by functional area and pollutant type. In industrial areas, runoff pollutants were primarily derived from industrial production processes. Mechanical brake wear and losses of production materials may further intensify runoff pollution. Large amounts of surface garbage were frequently summarized in residential and commercial areas due to

the high intensity of human activities. Figure 5a,c confirmed that surface garbage was the main source of COD and TN in residential areas and the main source of COD, SS, TP in commercial areas. Delayed collection of surface garbage produced by human activities in residential areas and catering shops in commercial areas would result in the transferring of pollutants with rainwater [3]. TP pollution was mainly caused by the leaching of organic soil material in the green belt in residential areas. Fertilization was another reason for the enriched TP in soil, which could be dissolved into rainfall runoff. Occasionally, excess rainwater in green belt and overflowed into the surface runoff, with TP transferred in the rainfall runoff [46,47]. Due to the nitrogenous pollutants in exhaust gas from vehicles on roads of commercial areas, TN pollution could be observed in commercial areas [48].

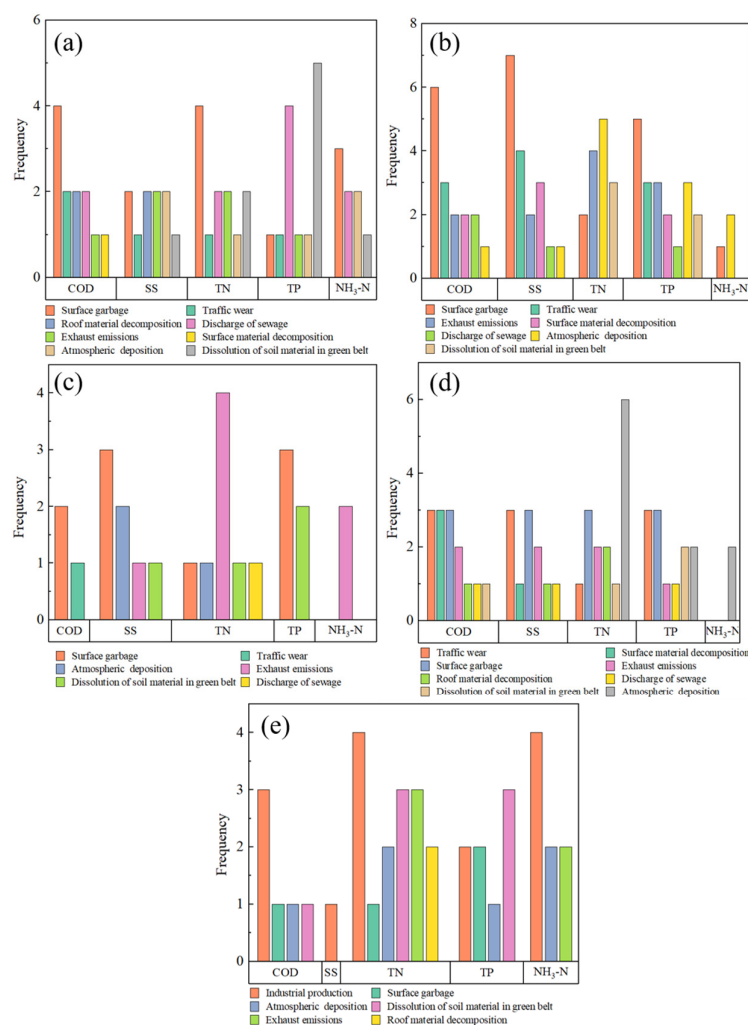


Figure 5. Frequency of each pollution source: (a) Residential areas, (b) Traffic areas, (c,d) Educational areas, (e) Industrial areas.

Due to the specific function of traffic areas, surface runoff pollution in traffic areas was frequently associated with transportation-related processes in the reviewed studies. It was clearly shown in Figure 5b that traffic wear, exhaust emissions and surface garbage were the main sources of rainfall runoff pollution in traffic areas. The pollution degree of rainfall runoff in traffic areas was related to the traffic intensity in previous research by ref. [7,49]. Hence, the rainfall runoff pollution control in traffic areas was dependent on vehicles, road and traffic management strategies.

Compared with other functional areas, the people and traffic density in educational areas was relatively small. But serious traffic wear was observed for the frequent braking

of vehicles in educational areas [50], which correlated to the pollution of COD, SS, and TP in educational areas, as shown in Figure 5d. In addition, larger open-air traffic areas and outdoor parts in educational areas could be affected by atmospheric deposition. Atmospheric deposition had been confirmed to be the main nitrogenous pollution source in educational areas. The nitrogenous pollutants in the air could be dissolved into the raindrop and then reached the surface ground, resulting in the accumulation of nitrogenous pollution in rainfall runoff [51].

As illustrated in Figure 5e, industrial production was the dominant source of COD, SS, and TN in rainfall runoff from industrial areas. Previous studies have indicated that outdoor industrial equipment exposed to rainfall, together with materials and wastes generated during storage and production, may serve as major sources of runoff pollution in industrial areas [52,53]. Accordingly, collecting and treating pollutants released during production, strengthening the management of volatile or easily mobilized materials, and optimizing production processes are essential for mitigating rainfall runoff pollution in industrial areas.

3.2.2. Source Analysis of Heavy Metals in Rainfall Runoff

Although studies on heavy metal pollution in rainfall runoff remain limited, the potential risk posed by heavy metals to surface water quality should not be neglected. The potential pathways of heavy metal pollution in rainfall runoff across different functional areas are summarized in Figure 6, indicating that traffic-related wear was the most frequently reported potential source of heavy metal contamination in rainfall runoff. Tire wear, brake wear, and vehicle exhaust emissions in traffic areas were the major pathways by which heavy metals, such as Zn and Pb, entered runoff. Moreover, the degree of runoff pollution has been reported to be strongly correlated with traffic volume and vehicle speed [54,55]. Atmospheric deposition also plays an important role in heavy metal contamination of rainfall runoff and has been identified as a major source of Cd, Cu, and Pb [56]. Industrial production represents another significant source of heavy metals. Jeong et al. [57] found that the average loads of Cu and Ni from industrial areas exceeded 90%, suggesting that these metals were primarily associated with industrial activities. In addition, winter heating may contribute to the occurrence of Pb and Cd in rainfall runoff, possibly as a result of coal combustion and the release of heavy metals via fly ash [58].

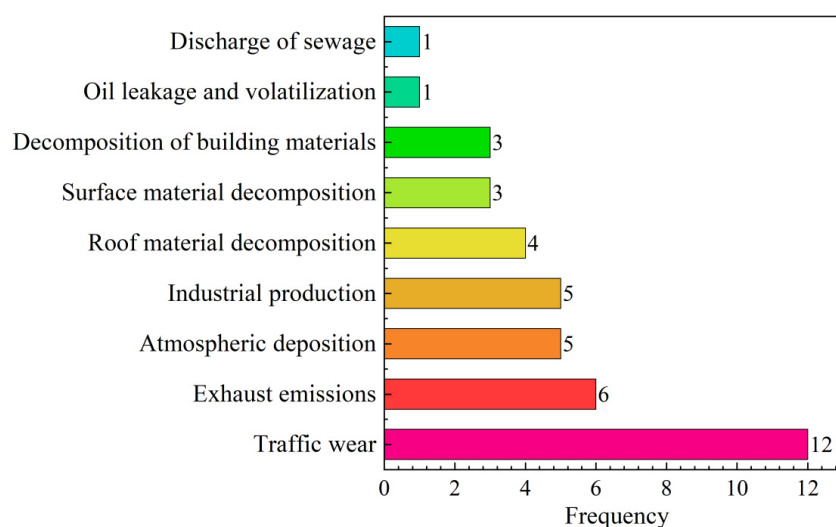


Figure 6. Frequency of the sources of heavy metals.

4. Conclusions

This study systematically evaluated the frequency and distribution of pollutants in rainfall runoff across various urban land-use types, as well as their potential pollution sources. The main conclusions are as follows:

- (1) The compiled literature data showed clear differences in reported rainfall runoff pollution levels across different urban areas, with relatively high pollution levels frequently observed in residential and traffic areas. These differences were interpreted as descriptive patterns rather than statistically verified differences.
- (2) The primary pollutants in rainfall runoff across urban areas were COD, TN, and TP. Over 70%, 80%, and 90% of runoff samples exceeded the Class V surface water quality standards for COD, suspended solids (SS), and TN, respectively, indicating widespread water quality degradation.
- (3) Atmospheric deposition and surface litter were the most frequently reported potential sources of rainfall runoff pollution in the reviewed studies. Educational and traffic areas were predominantly affected by atmospheric deposition, while residential and commercial areas were more influenced by surface litter and residual stains. In industrial areas, runoff pollution was primarily attributed to industrial activities.
- (4) Heavy metals in rainfall runoff were frequently associated with traffic activities in the reviewed studies, while atmospheric deposition and industrial production were also reported as important potential sources.

These findings highlight the need for targeted pollution control strategies tailored to specific urban land-use types, with a focus on mitigating the impacts of atmospheric deposition, surface litter, and industrial runoff.

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