Ecological Risk-Based Prioritization of Metals for Smarter Urban Runoff Management: A Meta-Analysis

Priorisation des métaux fondée sur le risque écologique pour une gestion plus intelligente du ruissellement urbain: une méta-analyse

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RÉSUMÉ

Cette méta-analyse intègre les données de 182 événements de ruissellement provenant de 15 sites suédois représentant divers usages du sol et conditions saisonnières, afin de hiérarchiser les métaux préoccupants dans les rejets urbains. À l'aide d'une évaluation des risques fondée sur les données, les concentrations et risques de 20 métaux(loïdes) ont été comparés aux bases de données internationales et aux seuils réglementaires, en tenant compte des effets aigus et chroniques ainsi que de la biodisponibilité pour sept métaux. Les analyses aux échelles des événements et des sites ont révélé une forte variabilité temporelle et spatiale, influencée par les sources d'émission, l'utilisation du sol et l'hydrologie saisonnière. Spatialement, les bassins "Parking/Route", "Route principale/Autoroute" et "Urbain mixte" contribuent le plus aux charges et risques métalliques. Saisonnellement, la fonte nivale présente des concentrations totales et des risques aigus/chroniques plus élevés (en raison de MES et pH accrus), tandis que les eaux pluviales contiennent davantage de fractions dissoutes et biodisponibles ; seuls le Co et l'Al montrent des risques chroniques biodisponibles notables durant la fonte des neiges, tandis que le Cu et le Pb le font lors des pluies. Globalement, le Zn, le Cu, l'Al, le Fe et le Co apparaissent comme les métaux les plus à risque, suivis par le Mn, le V, le Ba et le Ni. Ces résultats soulignent la nécessité d'une gestion dynamique intégrant la réduction ciblée des sources, la gestion des solides et le traitement, tout en tenant compte de la spéciation des métaux et de la chimie du ruissellement.

ABSTRACT

This meta-analysis integrates data from 182 runoff events across 15 urban catchments representing diverse land uses and seasonal conditions to prioritize metals of concern in urban discharges. Using a data-driven risk assessment, concentrations and risks of 20 metal(loid)s were compared against international databases and regulatory thresholds to consider both acute and chronic effects and bioavailability for seven metals. Event- and site-level analyses revealed large temporal and spatial variability driven by specific emission sources, land use, and seasonal hydrology. Spatially, "Parking/Road", "Main Road/Highway", and "Mixed Urban" catchments contributed most to overall metal loads and risk levels. Seasonally, snowmelt showed higher total concentrations and acute/chronic risks (due to elevated TSS and pH), while stormwater contained relatively higher dissolved and bioavailable fractions; only Co and Al showed notable chronic risk on the bioavailable fraction in snowmelt, whereas Cu and Pb did so in stormwater. Overall, Zn, Cu, Al, Fe, and Co ranked as the highest-risk metals, followed by Mn, V, Ba, and Ni. Results highlight the need for dynamic, chemistry-dependent management that integrates targeted source reduction, solids management, and treatment, while considering both metal speciation and runoff chemistry.

KEYWORDS

Metal bioavailability, Risk assessment, Snowmelt, Stormwater

1 INTRODUCTION

Urban runoff is a key non-point source of metals such as Cu, Zn, Cd, and Pb, which can reach levels several orders of magnitude above background and cause acute and chronic ecological risks[1–3]. Despite numerous monitoring studies across Europe, there is still no harmonized framework for prioritizing metals in urban runoff, particularly one that accounts for bioavailability and seasonal dynamics. Most previous research has focused on a limited short list of metals (typically Zn, Cu, Pb and Cd), while other metals, including Co, V, and Ba, remain understudied despite their occurrence in a range of infrastructure types, urban materials, and vehicle-related sources. Variability between sites, land uses, and event types (stormwater vs. snowmelt) further complicates risk interpretation, as metal partitioning and mobility depend strongly on local water chemistry and flow. For example, additional challenges arise due to snow storage practices, the application of de-icing salts and grits, and high particulate loads, which influence both metal transport and bioavailability[4,5]. Addressing these gaps requires integrating concentration data with regulatory thresholds and ecotoxicological evidence to establish site- and season-specific management priorities. This study therefore provides a comprehensive synthesis of two decades of Swedish runoff data, offering quantitative insights into concentration levels, bioavailability-adjusted risks, and the relative importance of seasonal and spatial variability for urban metal management.

2 METHODS

Water quality data from 182 stormwater and snowmelt events across 15 Swedish sites representing six land-use types ("Green area", "Commercial/Industrial", "Mixed Urban", "Parking/Road", "Residential", and "Main Road/Highway") and spanning three different Köppen-Geiger climate classifications were compiled. Concentrations of 20 metal(loid)s (Al, As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, V, Zn, and other major metals) were analyzed in total and dissolved fractions, along with pH, DOC, hardness, EC, TSS, turbidity, and flow. Bioavailability adjustments were also applied using BLM or MLR models for Cu, Co, Ni, Pb, Zn, Al, and Fe[6–9]. Event mean concentrations (EMCs) were calculated as volume-weighted means, and site mean concentrations (SMCs) represented long-term averages for each site. Acute and chronic risk quotients (RQs) were respectively computed as EMC/PV_{acute} and $SMC/PV_{chronic}$ ratios, where protective values (PV) were collected from 12 international/national EQSs and ecotoxicological database values for freshwater: the EU Directive, the National Recommended Water Quality Criteria of the US Environmental Protection Agency (USNRWQC), Swedish Agency for Marine and Water Management (HVMFS), Danish Ministry of Environment and Food (MFVM), Dutch Institute for Public Health and the Environment (RIVM), International Commission for the Protection of the Rhine (IKSR), Canadian Environmental Quality Guidelines (CAWQG), the UKTAG's recommendations for the Water Framework Directive (UKTAG and WFDUK), as well as the no-effect concentration (NEC) thresholds from ecotoxicology databases used in NORMAN, Johnson et al.[10], and Alves Miranda et al.[11]. Variabilities were assessed using coefficients of variation (CVs) across events, sites, and seasons[12], Wilcoxon and Peto&Peto tests for differences and Kendall's or Spearman's tests for correlations.

3 RESULTS AND DISCUSSION

Metal concentrations and RQs varied by up to three orders of magnitude across events and sites, reflecting diverse source conditions, climatic drivers, and hydrological variability (Figures 1 and 2). Snowmelt showed higher total concentrations and particle-bound fractions due to elevated TSS and pH, whereas stormwater carried higher dissolved and bioavailable loads, consistent with patterns observed in other cold-climate studies[5,13]. Spatially, "Parking/Road" and "Main Road/Highway" catchments showed the highest RQs, especially for Zn, Cu, and Co, driven by tire wear (rubber and stud), brake abrasion, and surface dust resuspension. Zn, Cu, Al, Fe, and Co consistently ranked as the most critical metals, with Mn, V, Ba, and Ni forming a secondary group. In contrast, Hg, Cd, As, Mo, and Pb presented low-to-negligible risks, reflecting the impacts of ongoing source control and regulation[14–16]. At the event scale, snowmelt produced 1.5–3 times higher total metal concentrations but often 2–10 times lower dissolved fractions, highlighting strong phase partitioning under varying turbid and alkaline conditions. Of the metals for which bioavailable fraction could be predicted (i.e., Zn, Cu, Co, Pb, Ni, Fe, Al), Co and Al demonstrated the highest bioavailable chronic risks during snowmelt, while Cu and Pb dominated in stormwater, linked to DOC and hardness variabilities. Acute/chronic RQ ratios further revealed that Cu and Zn frequently exceeded the critical risk characterization ratio of RQ=1 during stormwater events, which can pose localized acute risks in small receiving waters with limited dilution. Spatial and temporal analyses demonstrated that land-use type explained only 30–40% of RQ variability, emphasizing the influence of local materials and infrastructure (e.g., metallic roofs, building runoff, brake dust). Overall, results underline the need for chemistryresponsive management approaches that combine land-use-based prioritization with site-specific monitoring to improve prediction and control of metal risks across variable urban conditions.

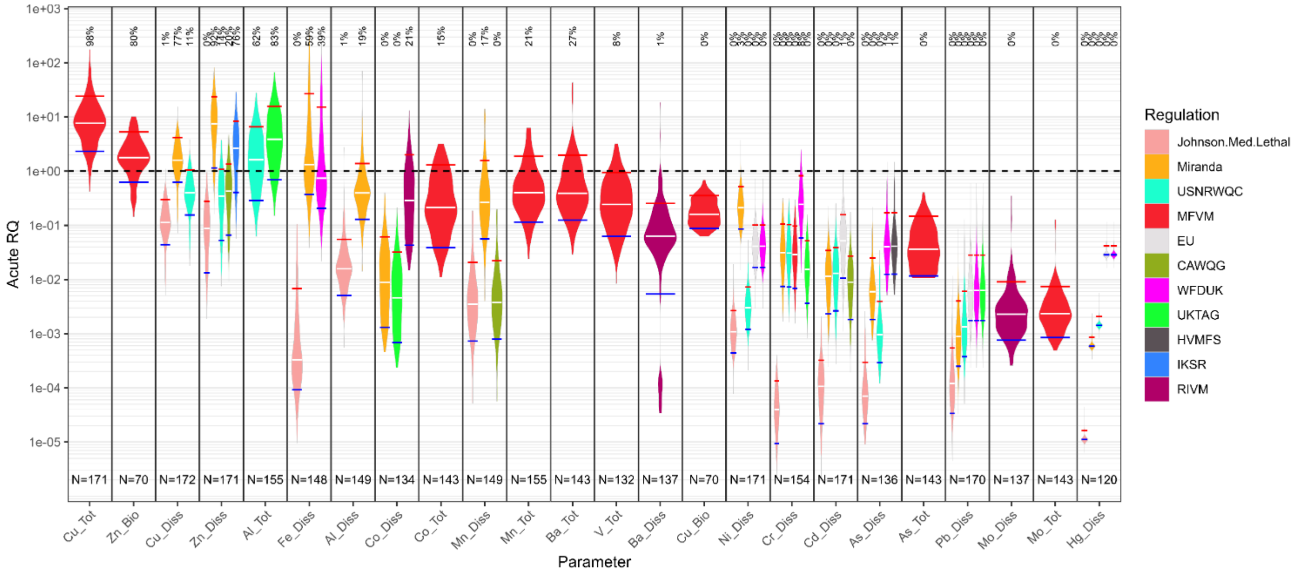

Figure 1. Acute risk quotients (ARQs) of metals based on various ecotoxicology databases and regulations. The number of events (N) used for RQ calculation of each parameter is shown at the bottom of the violin plots. The percentage of RQs that exceed the critical threshold of one is displayed above each violin plot. Blue, white, and red lines represent the 10th, 50th, and 90th percentiles. "Johnson.Med.Lethal" refers to the median lethal NECs in the database used by Johnson et al.[10]. "Miranda" refers to the MAC-PNECs suggested by Alves Miranda et al.[11].

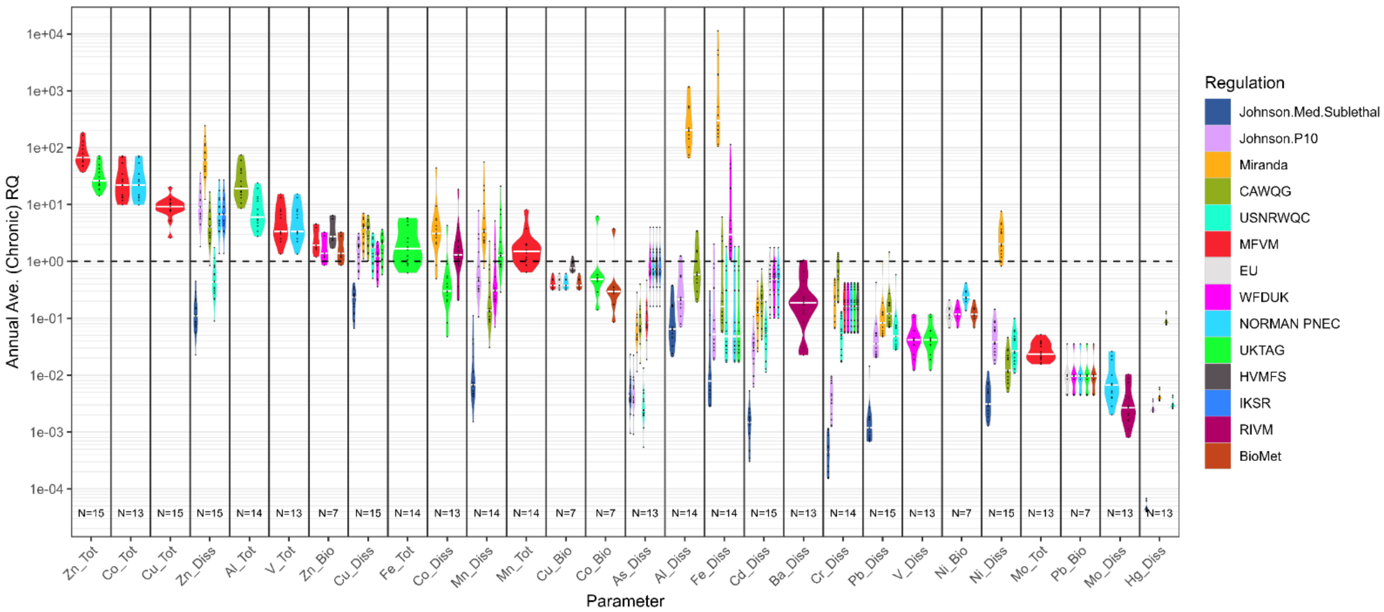

Figure 2. Chronic risk quotients (CRQs) of metals based on various ecotoxicology databases and regulations. White lines represent the 50th percentiles. The violin plots are based on a maximum of 15 data points (i.e., the number of sites). "Johnson.Med.Sublethal" and "Johnson.P10" refer to the median and 10th percentile sub-lethal NECs in the database used by Johnson et al.[10], respectively. "Miranda" refers to the AA-PNECs reported by Alves Miranda et al.[11].

4 MANAGEMENT AND POLICY IMPLICATIONS

Effective mitigation should prioritize high-risk metals (Zn, Cu, Al, Co) through targeted source control (reducing emissions from brake pads, tires, galvanized surfaces, and metal roofs) and optimizing water quality treatment strategies. Nature-based solutions, such as biofiltration systems with engineered sorptive media (biochar, Fe/Al-oxide, zeolite, compost) and wetlands, can efficiently remove dissolved metals, while conventional biofiltration and sedimentation ponds can capture particulate fractions sufficiently. Snowmelt may be managed in protected stockpile areas, where coagulant/flocculant-aided clarification can treat colloidal loads[17]. Regulatory frameworks should integrate seasonal differentiation, prioritizing solids control during snowmelt and dissolved-phase removal during rainfall, as well as interpret RQs between 0.1 and 1 as requiring establishment of a precautionary management zone. Ultimately, chemistry-informed, site- and season-specific management is essential for sustainable reduction of metal risks in urban runoff, which complements evolving regulations and material substitution efforts.

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