Potential Impacts of Stormwater Infiltration on Groundwater Quality

Impacts potentiels de l'infiltration des eaux pluviales sur la qualité des eaux souterraines

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RÉSUMÉ

L'infiltration des eaux pluviales (SW) est de plus en plus utilisée pour restaurer l'hydrologie urbaine, mais ses effets sur la qualité des eaux souterraines (GW) selon l'occupation du sol restent mal connus. Nous avons étudié la contamination de cinq aquifères du nord de Stockholm influencés par les eaux pluviales depuis plusieurs décennies, à partir de 121 échantillons prélevés sur 31 sites couvrant des bassins naturels, agricoles, mixtes et urbains. Les sites ont été caractérisés par leur vulnérabilité hydrogéologique et leur proximité de sources potentielles (axes de transport de matières dangereuses, sites suspects de PFAS, sites contaminés). Soixante-six paramètres ont été analysés, dont nutriments, ions majeurs, métaux traces, radon, COV chlorés et 21 PFAS. De nombreux métaux traces, PFAS à chaîne courte et PFAS4 ont été fréquemment détectés, tandis que la plupart des PFAS à chaîne plus longue et plusieurs COV l'ont été rarement ou jamais. L'analyse de redondance a montré que l'occupation du sol, l'aquifère et la proximité (<500 m) de sources suspectes de PFAS expliquent 29 % de la variabilité des concentrations. Les PFAS et métaux traces sont positivement associés aux zones urbaines, alors que les bassins naturels, agricoles et mixtes présentent des associations plus faibles ou négatives, indiquant que l'infiltration des eaux pluviales peut mobiliser des contaminants conventionnels et émergents vers les eaux souterraines, avec des impacts modulés par l'occupation du sol, les conditions aquifères et la proximité de sources de pollution.

ABSTRACT

Stormwater (SW) infiltration is increasingly used to restore urban hydrology, but its effects on groundwater (GW) quality across different land uses remain poorly constrained. We investigated GW contamination in five aquifers in northern Stockholm that have been influenced by SW for several decades of urbanization. In total, 121 GW samples from 31 locations were analyzed, covering, natural lands, arable, mixed, and urban catchments. Sites were characterized by hydrogeological vulnerability and proximity to potential sources, including hazardous goods routes, suspected PFAS sites, and known contaminated sites. Sixty-six parameters were analyzed, including nutrients, major ions, trace metals, radon, 13 chlorinated VOCs, and 21 PFASs. Many trace metals, short-chain PFASs, and PFAS4 were frequently detected, whereas most longer-chain PFASs (C9−C13 PFSAs and C11−C13 PFCAs) and several VOCs were rarely or never quantified. Redundancy analysis showed that land use, aquifer identity, and proximity (<500 m) to suspected PFAS sources together explained 29% of the variability in GW concentrations. PFASs and trace metals were positively associated with urban areas, while natural, arable, and mixed catchments showed weaker or negative associations. The results indicate that SW infiltration can mobilize both conventional and emerging contaminants into GW, with impacts that are altered by land use, aquifer conditions, and nearby pollution sources.

KEYWORDS

Groundwater, Stormwater infiltration, Land use, PFAS, Metals

1 INTRODUCTION

Stormwater (SW) infiltration is widely promoted as a nature-based solution to restore urban hydrology, yet its impacts on groundwater (GW) quality remain comparatively poorly understood relative to the extensive literature on SW treatment and on GW contamination considered separately. In fact, SW infiltration can introduce a wide range of dissolved and colloidal pollutants into GW, including heavy metals, nutrients, and organic micropollutants (OMPs), e.g., pharmaceuticals, pesticides, PFASs, and VOCs.[1–4] Studies have shown SW infiltration is associated with increased occurrence and concentrations of trace metals, e.g., Cu and Cd,[5] petroleum hydrocarbons,[6] certain pesticides,[6] and PFASs in GW[4]. There is a consensus that soil properties, hydrogeological characteristics, land-use type, seasonal changes, and rainfall patterns can influence the extent and transport of contamination, yet most existing work focuses on a limited set of pollutants (nutrients, metals, chloride) or on individual infiltration facilities rather than across multiple land-use types at the catchment scale. Additionally, there are still data gaps and uncertainties regarding the impacts of long-term urbanization and land-use types, as well as the behavior of emerging contaminants, highlighting the need for further research and monitoring.[7,8] This study, therefore, investigates the potential impacts of SW infiltration on GW contamination as a function of land-use and aquifer characteristics, focusing on a wide range of conventional and emerging contaminants: nutrients, ions, trace metals, radon, and OMPs (PFASs and chlorinated VOCs).

2 METHODS

GW was sampled from 31 locations in five SW-affected aquifers that are highly valued drinking water resources in the northern Stockholm region: Norrsunda, Hammarby, Rotsunda, Edsviken, and Ulriksdal. The sampling points comprised 26 GW wells, four springs, and one tap connected to GW, and were classified as either operational water-supply points (18 sites) or monitoring sites (13 sites)**.** Each site was assigned a vulnerability class based on existing hydrogeological descriptions, with most sites categorized as highly vulnerable GW aquifers, either directly exposed or overlain by clay and silt. Sites were selected to represent SW-influenced catchments with different land-use types: four natural lands (meadows, grassland, or forest), three arable/croplands, 14 urban (mainly residential, commercial, and roads), and 10 mixed (i.e., a mixture of other land-use types). For each site, we also compiled spatial indicators of potential contaminant sources: whether the sampling point was located within 10 or 100 m of hazardous goods transport roads (10m or 100mFGods)**,** within 100 or 500 m of a suspected PFAS source (100m or 500mPFAS) such as AFFF-affected sites**,** and within 100 m of a known contaminated site/risk object (100mMIFO). A total of 121 GW samples were collected between May 2024 and February 2025, corresponding to one to four sampling events per site. For each sampling event, field measurements included GW level, pH, EC, temperature, and DO. Laboratory analyses covered 66 chemical parameters**,** including four nutrients, eight major ions, nine trace metals**,** radon (Rn), uranium (U), 13 chlorinated volatile organic compounds and related VOCs**,** and 21 PFASs (perfluoroalkyl sulfonic acids (PFSAs), perfluoroalkyl carboxylic acids (PFCAs), and a fluorotelomer sulfonate (6:2 FTS)**.** All chemical analyses were performed at accredited laboratories following standard methods. Redundancy analysis (RDA) was conducted to identify potential relationships between concentrations and land-use, aquifer, and source-proximity descriptors.

3 RESULTS AND DISCUSSION

Regarding the occurrence of targeted pollutants, nutrients (ammonium, nitrite, nitrate), all major ions (Ca, Mg, Na, K, Cl, SO_4, Fe, Mn), trace metals (Al, As, Cd, Cu, Ni, Pb, U, Zn), Rn, three chlorinated VOCs including PCE, TCE, and cis-1,2-DCE, 6:2 FTS, and all short-chain (SC) and some long-chain (LC) PFASs (C4−C9 PFCAs and C4−C5,C8 PFSAs), were quantified in at least 20% of GW samples. Phosphate, Cr, $CHCl_3$, PFHpS, and PFDA were occasionally detected (<20% samples), while other chlorinated VOCs (1,1,1-TCA, 1,1,2-TCA, 1,1-DCA, 1,1-DCE, 1,2-DCA, trans-1,2-DCE, DCM, CCl_4, vinyl chloride), benzene, and most longer-chain PFASs (C9−C13 PFSAs and C11−C13 PFCAs) were not quantified in any sample. Figure 1 shows the concentration plots of selected more frequently quantified pollutants across various land uses and aquifers. The first two components of the RDA model showed that land-use types, aquifer characteristics, degree of area development, and “500mPFAS” (the significant explanatory variables) together explained 28.5% of the variance in GW concentrations across sites and sampling locations (R^2= 0.39, p= 0.001, indicating a moderate regression). Concentrations under urban land uses (esp. in the Hammarby and Rotsunda aquifers) varied the most compared to other classifications (type 1 RDA polygon/symbol clusters in Figure 2), followed by mixed, arable, and natural land uses in descending order.

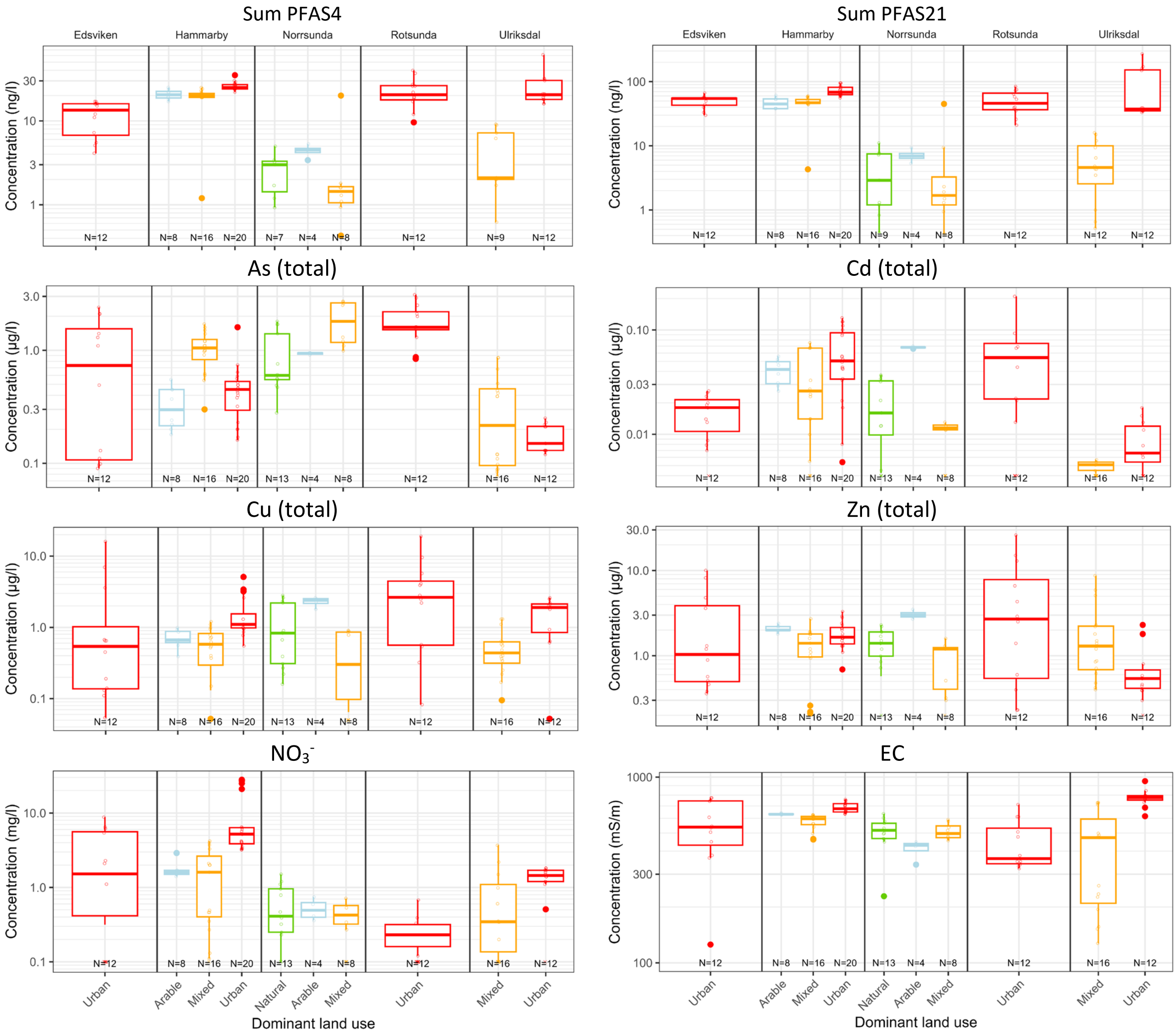

Figure 1. Concentration of selected parameters in groundwater across aquifers (top) and land use types (color-coded)

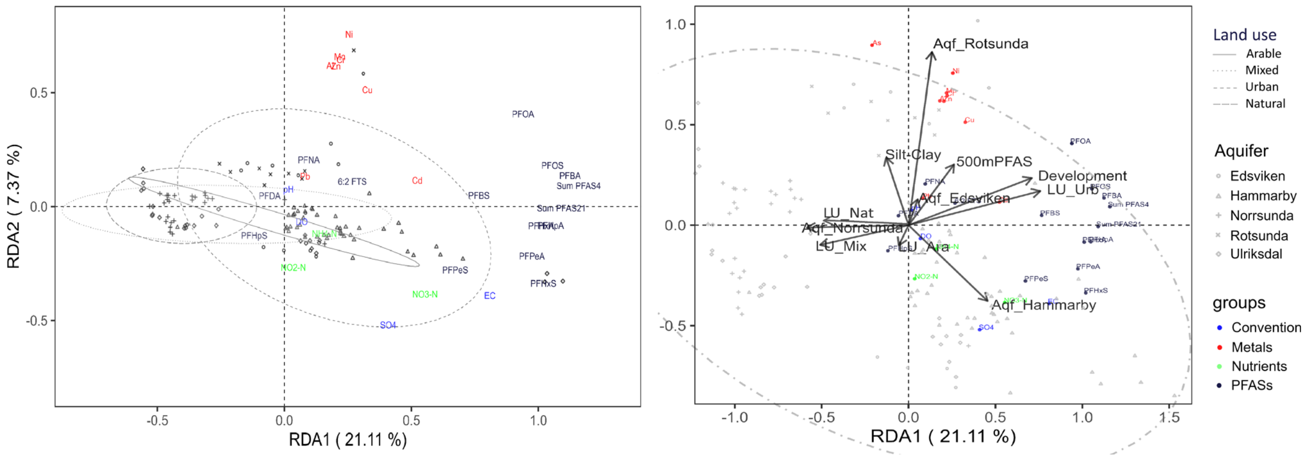

Figure 2. Type I (left) and type II (right) scaling plots as RDA1 and RDA2, the two most important components of the model. The type I plot illustrates the similarities in the response variables (concentrations), and type II the effect and correlation of only the significant explanatory variables in explaining the response variations. Site scores: symbols represent five different aquifers, and 95% confidence ellipses represent seven different land use groups. Coloured names show the scores of the pollutant groups. Arrows from the centroid show the effect of explanatory variables.

PFASs, metals, and nutrients were largely clustered separately, suggesting that these groups behave differently with respect to their sources, levels/occurrences (availability) in SW, and/or fate and transport. There were exceptions within each group: some LC-PFASs (PFHpS, PFNA, PFDA), 6:2 FTS, and metals (Pb, As, Cd) stood out from their group clusters, indicating that their concentrations were less similar across sites, mostly due to lower mobility, resulting in lower quantification rates in GW. The transformation of PFAS precursors could explain the 6:2 FTS's different behavior. Another reason could be the naturally occurring As in GW from bedrock, alongside the normally low levels in SW (global median dissolved: 1 µg/L), as confirmed by the lack of a significant difference in Rn concentrations (another naturally occurring element in GW) between land uses. Urban land use, degree of area development, and "500mPFAS" more strongly affect the variation concentration datasets than the other explanatory factors (Figure 2 type II RDA plot). Urban areas were positively correlated with trace metal and particularly PFAS concentrations, suggesting that these developed areas were most likely sources of PFASs and metals in GW. "500mPFAS" also positively correlated with the observed PFAS concentrations, indicating that the presumptive PFAS-contaminated sites within 500 m distance from the sampling points might have influenced the GW quality. Additionally, PFAS and nitrate concentrations were positively associated with the Hammarby aquifer (Upplands Vasby municipality), which is recharged by SW infiltration facilities, while trace metals were associated with the Rotsunda aquifer (Sollentuna municipality), again reflecting the specific sources and the necessity of SW management in these two areas. Nutrients were also weakly positively correlated with arable/cropland areas. PFASs and trace metals showed no significant or negative association with natural, arable, and mixed land-use types, with notably lower concentrations found in the Norrsunda aquifer, which is dominated by these land uses. The presence of low-permeability layers above the aquifers ("Silt-Clay") did not appear to be a major factor in preventing contamination, indicating that the aquifers have remained vulnerable to SW infiltration over time.

4 FUTURE WORK

Future work should target longer-term monitoring and refined source characterization, particularly for pesticides, (ultra-)short PFASs, and other persistent and mobile emerging contaminants, to enable more accurate risk quantification and to support land-use planning and SW management strategies that protect groundwater resources. Effective integrated SW and GW management practices and monitoring are essential to mitigate the risks associated with SW infiltration into GW. While SW infiltration can be beneficial for reducing SW contamination and GW recharge, it may pose potential risks to GW quality, particularly concerning dissolved pollutants. In these cases, therefore, effective management, including more advanced treatment and/or complementary blue-green infrastructure (BGI) strategies, is crucial to mitigate these risks and protect GW quality, especially vulnerable resources (e.g., those used for drinking water). Given the variability in local conditions driving the quality impacts, temporally denser site-specific monitoring of both SW and GW quality is also recommended before and after the installation of infiltration systems. Monitoring should be sufficient to capture seasonal trends and should include both SW and GW quality assessments to detect any short-term or long-term detrimental effects.

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