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Sources of Contaminated Flood Sediments in a Rural–urban Catchment: Johnson Creek, Oregon

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Sources of contaminated flood sediments in a rural-urban catchment: Johnson Creek, Oregon

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Abstract

This study investigated the delivery of contaminated sediments to the channel network by urban drainage systems in Johnson Creek in Oregon, USA. Concentrations of five heavy metal concentrations measured in 136 samples collected from 37 stormwater outfalls and 99 bed sampling points were analysed. While concentrations of zinc, cadmium and lead increased with distance downstream in Johnson Creek, this was not the case for chromium and copper. Zinc, copper, and cadmium concentrations in outfalls were significantly higher than those in the stream bed, indicating that stormwater runoff is responsible for delivering contaminated sediments to Johnson Creek. Zinc concentrations in outfalls were negatively associated with elevation and slope in the contributing sub-catchment, and positively with impervious cover. However, no statistically significant relationships were found between the other heavy metal concentrations and sub-catchment variables. These findings demonstrate that relationships between sediment-related, heavy metal concentrations and sub-catchment characteristics in this heterogeneous, rural-urban catchment are more complex than those found in situations where land-use is more segregated, questioning the applicability of commonly held assumptions regarding changes in the sources and delivery paths of flood-related, sediment-associated pollutants that accompany urbanisation.

Keywords:

Land use, Sediment, Urban drainage, Water quality

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Introduction

The risks associated with flood water inundation are generally well known and understood, however, further risks stem from deposition of contaminated, flood-derived sediments (Brinkmann et al. 2000; Dennis et al. 2003). Heavy metals in urban streams are of particular concern for human and ecological health. Heavy metals accumulate in the tissues of aquatic species and long-term health concerns can arise if, for example, humans consume contaminated species that have high levels of heavy metals (Dalu et al. 2017).

In urban environments, heavy metals are primarily transported during surface water flooding (Gobel et al. 2007; Berndtsson 2014) and accumulate in low-energy locations such as drain outfalls and slack water areas in streams and floodplains. Kang et al. (2009) found that in a highly urbanised catchment, storm runoff contributed up to 93% of the annual, heavy metal yield, with the sediment quantity and related heavy metal concentration increasing with annual rainfall.

In urban areas, heavy metal pollutants mostly occur through their attachment to fine-grained, suspended load sediments carried to the stream network by surface water runoff during flood events (Van Metre and Mahler 2003, Zanders 2004, Hubbart 2012). For example, Wei and Yang (2010) showed that ~85% of the heavy metal pollutants derived from urban surfaces are conveyed adsorbed to fine ($D < 500\mu m$) sediment particles. Where urban stormwater is conveyed to streams via piped drainage networks, it is therefore likely that significant heavy metal contributions originate from stormwater outfalls. Urban inputs of heavy metals may be derived from vehicles (e.g., tyres, brake linings and petrochemicals), commercial and industrial sources, construction activities and degradation of old buildings.

As mixed rural-urban catchments typically exhibit spatially-distinct patterns of topography and development between the upper and lower areas of the catchment, heavy metal concentrations may be expected to increase with distance downstream in the drainage network (Sharley et al. 2016). However, the influence of contrasts in sub-catchment land-use and intra-catchment transport are less well understood (Goodwin et al. 2003). When assessing pollution-related flood risks, it is important to identify which sub-catchments, land-uses and topographic factors are associated with sources, mobilisation and delivery of flood-sediment related heavy metals. Understanding sediment sources and pathways as they relate to heavy metals is also necessary to provide insights into the potential for changes in land-use within and between sub-catchments to influence stormwater delivery of pollutants to sediment hot spots.

To address these issues, this paper investigated spatial variation in heavy metal concentrations in an urban drainage system and what factors affect heavy metal concentrations. The research was performed as part of the ‘Clean Water for All’ initiative, sponsored jointly by the UK EPSRC Blue-Green Cities (B-GC) Research Consortium and the US Portland-Vancouver ULTRA (Urban Long-term Research Area) project. The study reports the preliminary outcomes of analysis of the data and identifies that further analyses are required to find answers to questions posed by the initial findings reported here.

Study area

The study was performed in Johnson Creek Oregon, which rises in the foothills of the Cascade Mountain Range and flows west for 42km, before joining the Willamette River (Figure 1). The creek drains a diverse landscape ranging from forests and agricultural areas in the headwaters to suburban and urban areas further downstream.

Figure 1 near here

The catchment underwent substantial development during the 20th Century, involving deforestation, wetland drainage, agricultural expansion, industrialisation and urbanisation. Expansion of agricultural, residential and industrial areas, coupled with implementation of piped drainage in approximately 75% of the catchment and channelisation of the drainage network, increased stormwater runoff, flood peak flows and delivery of pollutants to the Johnson Creek drainage network (Chang 2007, Chen and Chang 2014). Industrial development included the establishment of numerous small manufacturing works, a number of car dismantling businesses and several large, metal component manufacturers, mainly located along Johnson Creek itself (Figure 2). Many reaches of Johnson Creek have been designated as 'impaired' by the US Environmental Protection Agency due to elevated stream temperatures, the presence of e-coli, and concentrations of heavy metals that exceed applicable limits (Chang et al. 2014). The piped drainage system is separate from the sewer network and stormwater runoff is conveyed directly to Johnson Creek without treatment (Johnson Creek Watershed Council, 2005). Consequently, elevated concentrations of pollutants in stormwater can be attributed directly to catchment characteristics and anthropogenic activities in the contributing sub-catchment.

Figure 2 near here

More recently, stream restoration efforts have been implemented at multiple sites along Johnson Creek and its tributaries, involving floodplain reconnection (Levell and Chang 2006, Ahilan et al. 2018), riparian planting, and installation of green infrastructure to trap pollutants in pocket-wetlands and at set-back stormwater outfalls (Janes et al., 2017).

Sample collection and heavy metal analysis

Sediment samples were collected in May 2014 during a period of low rainfall and runoff. Samples were collected from stormwater outfalls and the channel bed upstream, adjacent to and downstream of the outfall, at 37 locations spread along the main stem of Johnson Creek (Figure 1). Outfall sediment samples were collected within the stormwater structure and above the stream surface elevation, minimising the influence of stream flow in the receiving water, so that concentrations of sediment-adsorbed pollutants would reflect inputs from the contributing sub-catchment, rather than sources upstream in the Johnson Creek catchment.

Samples were sieved, with particles finer than 2mm retained for laboratory analysis. Samples were dried at 105°C for 24 hours and then subjected to strong acid digestion, in preparation for analysis by Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES, Tyler and Longjumeau, 1995). ICP

OES analysis allows pollutant concentrations to be measured with a precision of 0.1 ppb with confidence. ICP OES analyses were performed for eight key urban pollutants: Cu, Zn, Pb, Ni, Ca, Ba, Sn, Mn. This short communication reports results generated for the five heavy metals: Cu, Zn, Pb, Cr, Cd.

Maps were created to visually inspect downstream trends in heavy metal concentrations. Non-parametric, Mann-Whitney U-tests were conducted to test the significance of differences in mean heavy metal concentrations between outfall and stream bed sediment samples. Spearman's rank correlations were used to explore relationships between catchment characteristics and sediment-related metal concentrations. All statistical tests used a 95% level of confidence to determine statistical significance.

Contributing sub-catchments for the outfalls were delineated using the ArcHydro tool in ArcGIS 10.4. Catchment variables derived for each sub-catchment were based on 2011 National Land Cover Data, hydrologic soil groups, and selected topographic parameters (e.g., elevation and slope) derived from an available, 10m Digital Elevation Model (USGS 2015). The results were used to add outfall sub-catchment characteristics to the sediment contamination database. All data were spatially referenced and mapped in a GIS. The database may be downloaded free for non-commercial research applications. Details of how to access the database are included at the end of this short contribution.

Within each sub-catchment, distance-weighted catchment variables were then derived using the method of Watson and Chang (2018). Using this method, the influence of each catchment driver of pollution was weighted in proportion to the hydrologically-defined distance between the outfall and the area in the sub-catchment where the driver operates. This approach has the potential to increase the explanatory power of statistical relationships derived between observed metal concentrations and driving variables.

Results

Downstream trends in heavy metal concentrations

Overall heavy metal concentrations in stream bed sediment samples did not exhibit a clear downstream trend in Johnson Creek (Figure 3). This was unexpected because urban development, piped drainage and traffic movements all increase with distance downstream in the study catchment (Figure 1).

Figure 3 near here

However, concentrations of zinc and cadmium did increase with distance downstream (Figure 3a and 3e). High zinc and cadmium concentrations are usually associated with industrial emissions and/or high traffic densities (Berndtsson 2015). In this regard, a downstream increase in concentrations would be expected in the increasingly urbanised, industrialised and traffic-clogged lower catchment. Further, the highest concentrations are associated with proximity to known industrial point sources listed in an inventory of known toxic release sites and other environment cleanup sites (see Figure 1 & Figure 2). Conversely, higher concentrations of copper, chromium, and lead were found in both upstream and downstream reaches where listed cleanup sites are closely located (Figure 3b, 3c, and 3d), suggesting that point industrial sources as well as land use based non-point sources (e.g., traffic) are potential sources of metal pollution in streams.

Differences between outfall and stream bed samples

Concentrations of zinc, cadmium, and copper were all significantly higher in outfall samples than stream bed samples (Figure 4), indicating that stormwater drainage may be an important sources of metal-contaminated sediments to Johnson Creek. Concentrations of lead were also higher in outfall samples, though the difference is not statistically different. Chromium concentrations were slightly higher in stream bed samples, but the difference was not statistically significant ($p>0.05$), suggesting that chromium sources may differ from those of the other four heavy metals investigated in this study.

Figure 4 near here

Correlations between catchment characteristics and metal concentrations

Concentrations of zinc were positively correlated with the percentage of developed land-cover and the average curve number (a measure of surface runoff generation) within the contributing sub-catchment ($r = 0.34, 0.30$, respectively). Concentrations were negatively correlated with elevation and slope (Figure 5) ($r = -0.3$ and -0.34 respectively). These correlations were weak, but statistically significant. No statistically significant relationships were found between concentrations of the other four heavy metals and variables defining catchment characteristics. These findings indicate that conditions in the contributing sub-catchments alone are insufficient to explain variations observed in sediment-related, heavy metal concentrations in Johnson Creek.

Figure 5 near here

Discussion

In a catchment that is predominantly rural in its headwaters and upper catchment, but mainly suburban and urban in its lower catchment, heavy metal concentrations would be expected to be higher in outfalls lower in the catchment (e.g. see Akdogan et al. 2016), which receive stormwater from sub-catchments with lower, flatter terrains, more urban development and more extensive impervious surfaces. This is the case for zinc and cadmium, but not for chromium or copper or lead, which were found in high concentrations in both upstream and downstream reaches. Conventional wisdom would also suggest that heavy metal concentrations associated with fine sediments delivered to Johnson Creek stormwater outfalls would increase in proportion to the percentages of developed land and impervious surfaces in the contributing sub-catchments, while decreasing as those sub-catchments become lower and flatter (Zafra et al. 2017). However, initial analysis of measured data reveals that this is clearly the case only for zinc (Figure 5). This may be because, of the five metals investigated, zinc is most easily adsorbed onto fine sediment and transported to streams via stormwater runoff during surface water flood events (Sharley et al. 2016). It follows that the more complicated processes involved in mobilisation and delivery of other sediment-related heavy metals in developed catchments like Johnson Creek (where sub-catchment land-use is spatially heterogeneous), may be responsible for more nuanced relationships than are currently assumed. Additionally, the potential influence of other environmental cleanup sites near monitoring sites on the elevated levels of other heavy metal concentrations need further investigation.

The finding that spatial relationships are nuanced is consistent with the outcomes of other multi-disciplinary fieldwork performed during the 'Clean Water for All' study (Ahilan et al. 2018; Janes et al. 2017), which establish that mixed development within sub-catchments distributed throughout the catchment of Johnson Creek has produced a fine-grained mosaic of land-uses, often exhibiting stark contrasts at sub-decimetre scales. In places, surface runoff from industrial sites located adjacent to the mainstream drains directly to Johnson Creek via simple, piped outfalls, with no buffering because urban green spaces are absent and the riparian corridor is non-existent. In other sub-catchments, floodwater passes through bioswales in green streets, pocket wetlands and intact riparian corridors before reaching Johnson Creek. It is hypothesised here that subtle changes in land-use patterns, runoff paths, outfall designs and the degree to which blue-green stormwater 'treatment trains' manage stormwater *quality* as well as *quantity* significantly affect the sources, mobilisation, and delivery of sediment-related, heavy metals by the drainage system.

Aging of drainage pipes and other urban water infrastructure could also affect outfall and stream bed heavy metal concentrations. The majority of the study outfalls are fed by relatively old networks and, as old pipes deteriorate, they could become either sources of additional heavy metals (due to corrosion) or potential sinks (due to leakage of contaminated sediments). The degrees of corrosion and/or leakiness of these pipe networks are currently unknown. Conversely, some neighbourhoods feature new infill developments, upgraded drainage systems, and/or retro-fitted, blue-green infrastructure. These neighbourhoods benefit from blue-green stormwater treatment trains that effectively reduce peak storm runoff volumes while also slowing the transport of fine sediments and retaining contaminants. However, the effectiveness of blue-green infrastructure in reducing pollutant delivery to drainage outfalls is, as yet, unproven. Sediment outfall sampling and analysis should, therefore, continue in order to help understand and explain the pollutant removal functionality of blue-green infrastructure.

An additional confounding factor is that runoff from three-quarters of the study catchment is collected and drained via complex pipe networks, further complicating the analysis of the delivery of flood sediments to Johnson Creek. The boundaries of sub-catchments in the piped drainage system are very difficult to define, but it is known that they do not necessarily coincide with the topographically-defined sub-catchment watersheds used in this study. Hence, further analysis is warranted to establish the true spatial distributions of flood water sub-catchments discharging to Johnson Creek.

To improve our understanding of the relationship between catchment characteristics, development and sediment-related, heavy metal concentrations, monitoring should continue as the results will help elucidate the nuanced sources and dynamics of heavy metals in Johnson Creek. Future analyses should include additional, explanatory variables that better represent historical and changing catchment land-uses, site-specific, industrial emitters and the impacts of multi-functional, blue-green infrastructure. To this end, the authors have made available the 2014 database and invite researchers to investigate and supplement it through further analyses and the addition of new data. The contaminated sediment database may be freely downloaded for non-commercial, research applications from either the Blue-Green Cities project CWfA data repository (https://rdmc.nottingham.ac.uk/handle/XX) or the corresponding author's research page at https://www.pdx.edu/geography/hydrology-and-water-resources.

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Figure legends

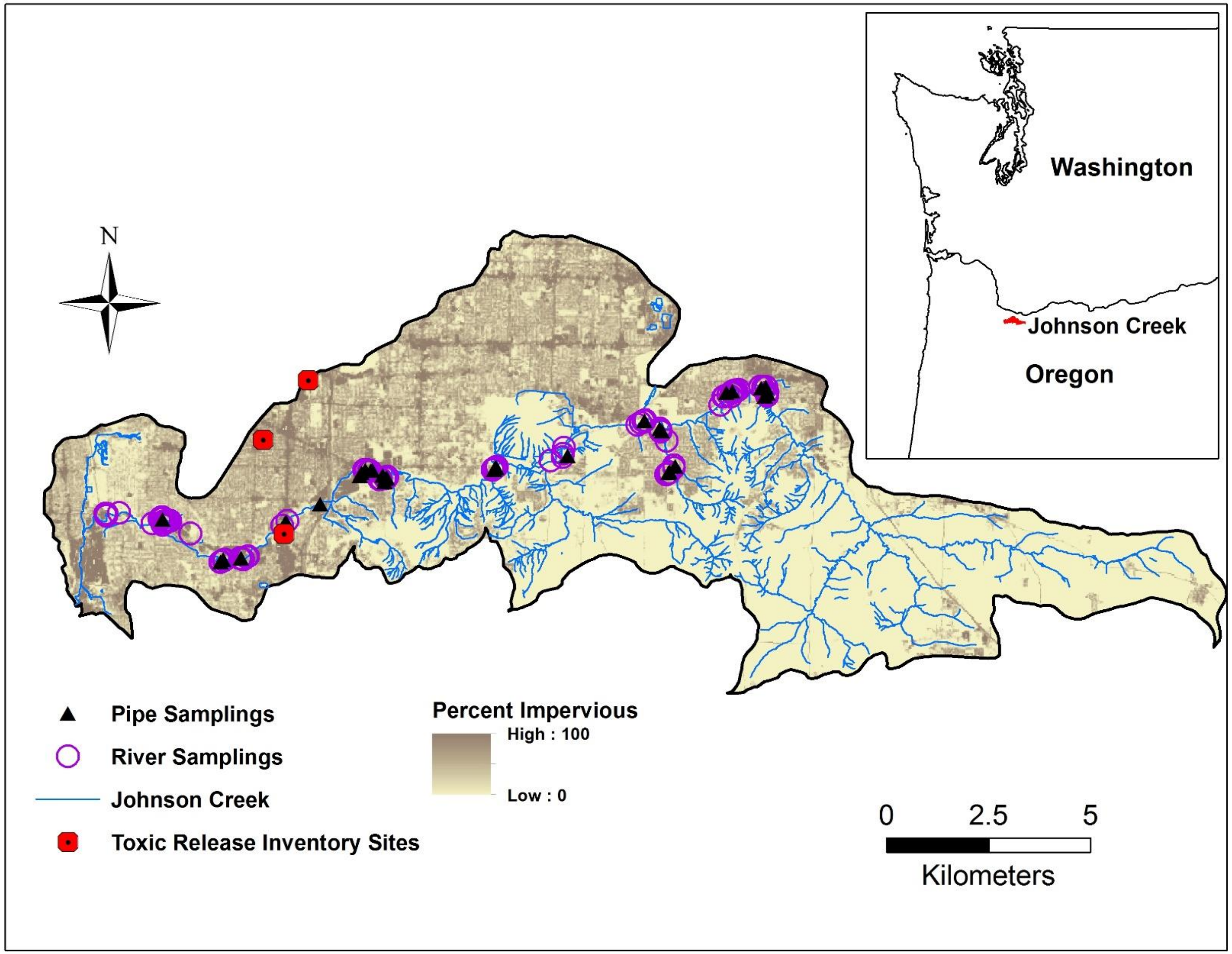
Figure 1. Location map for the study catchment: Johnson Creek, Oregon. Note extensive impervious area, mostly located in the lower catchment.

Figure 2. Subcatchment boundaries and the location of environment cleanup sites

Figure 3. Downstream distributions of heavy metal concentrations in bed sediments sampled around drain stormwater outfalls in Johnson Creek (unit: ppb).

Figure 4. Comparison of sediment-related heavy metal concentrations sampled in outfalls (37) and the stream bed (99) of Johnson Creek (unit: ppb).

Figure 5. Relationships between zinc concentrations at outfalls along Johnson Creek and distance-weighted, catchment characteristics in the contributing sub-catchments. All trend lines are statistically significant at the 5% level.



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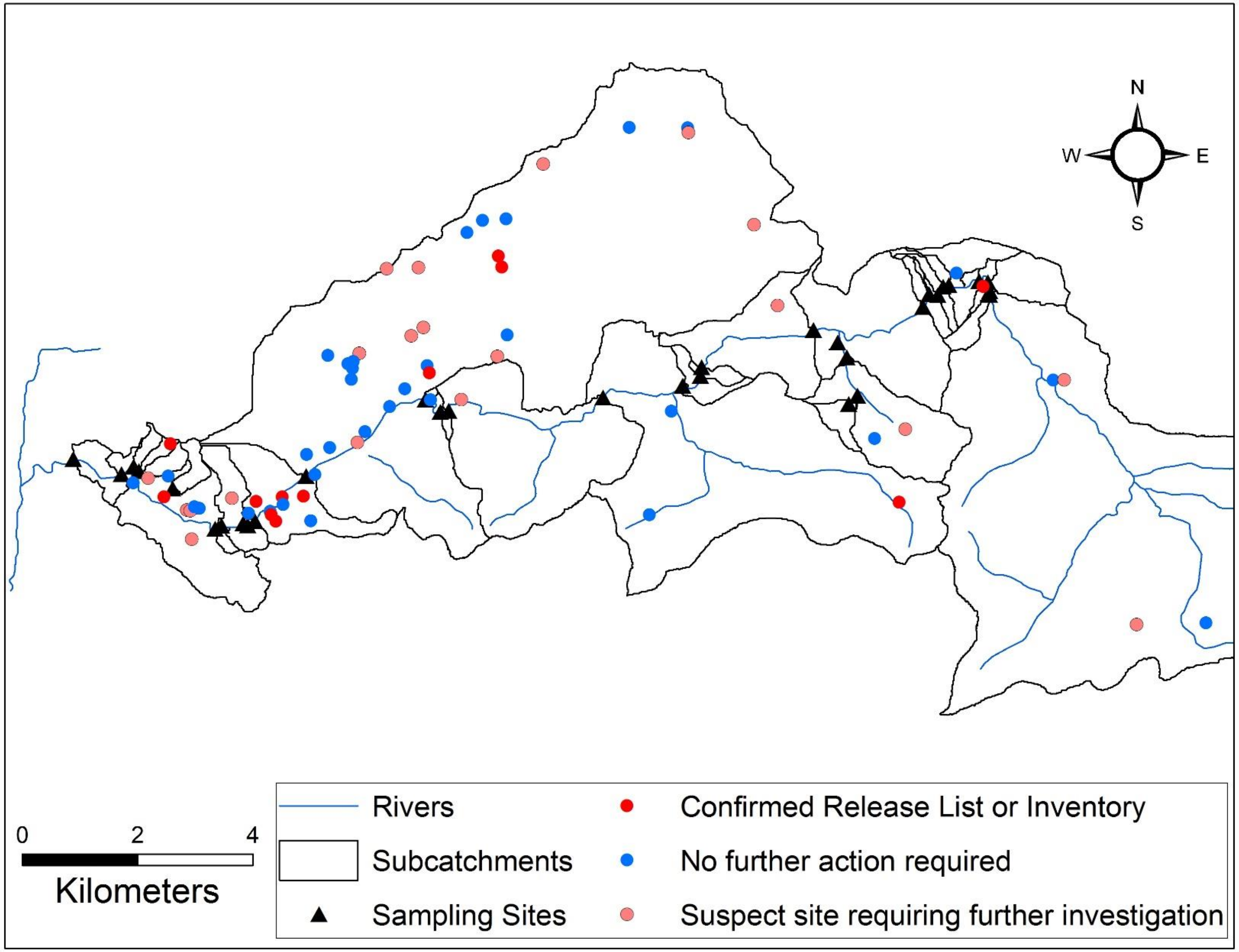

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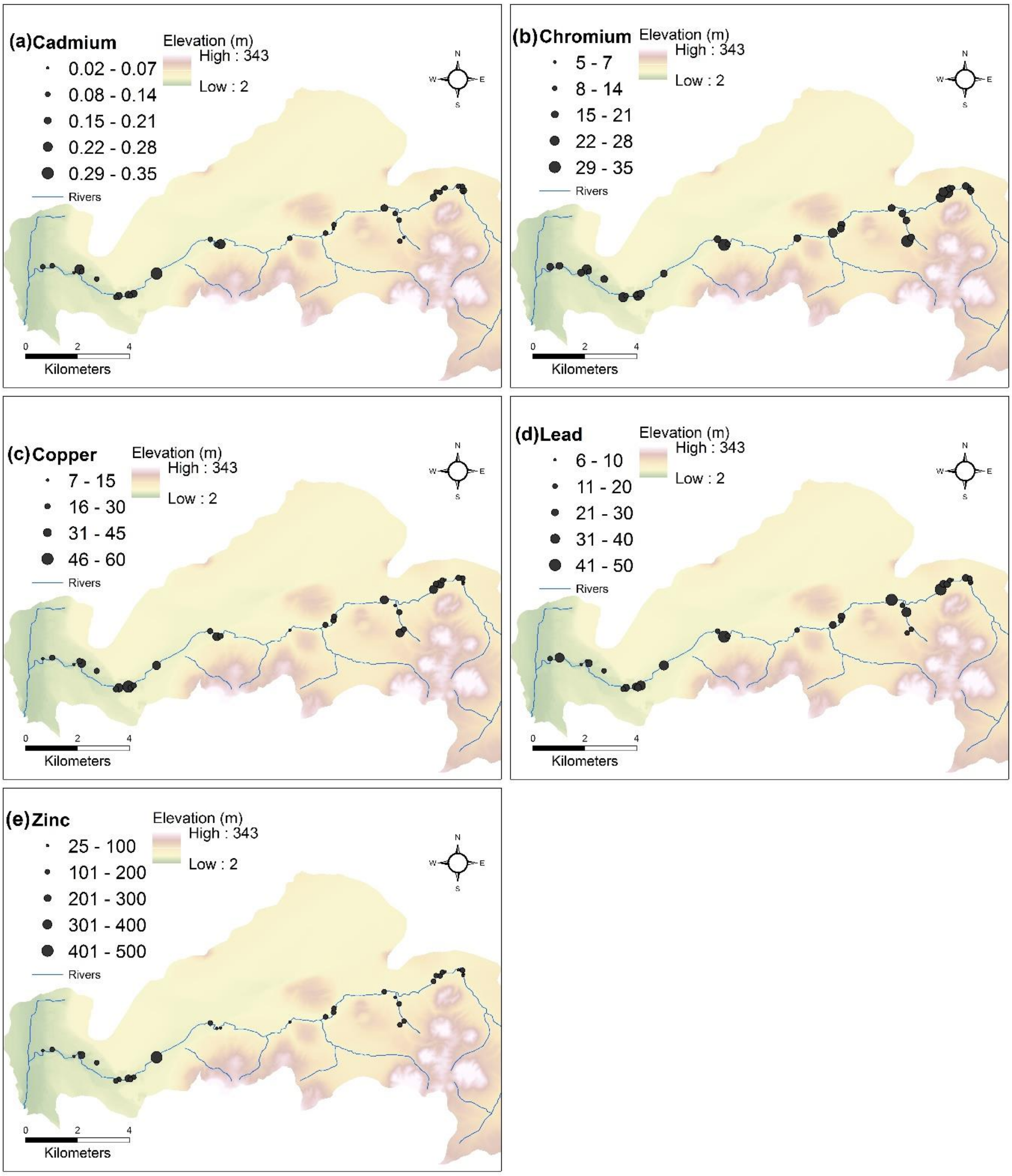

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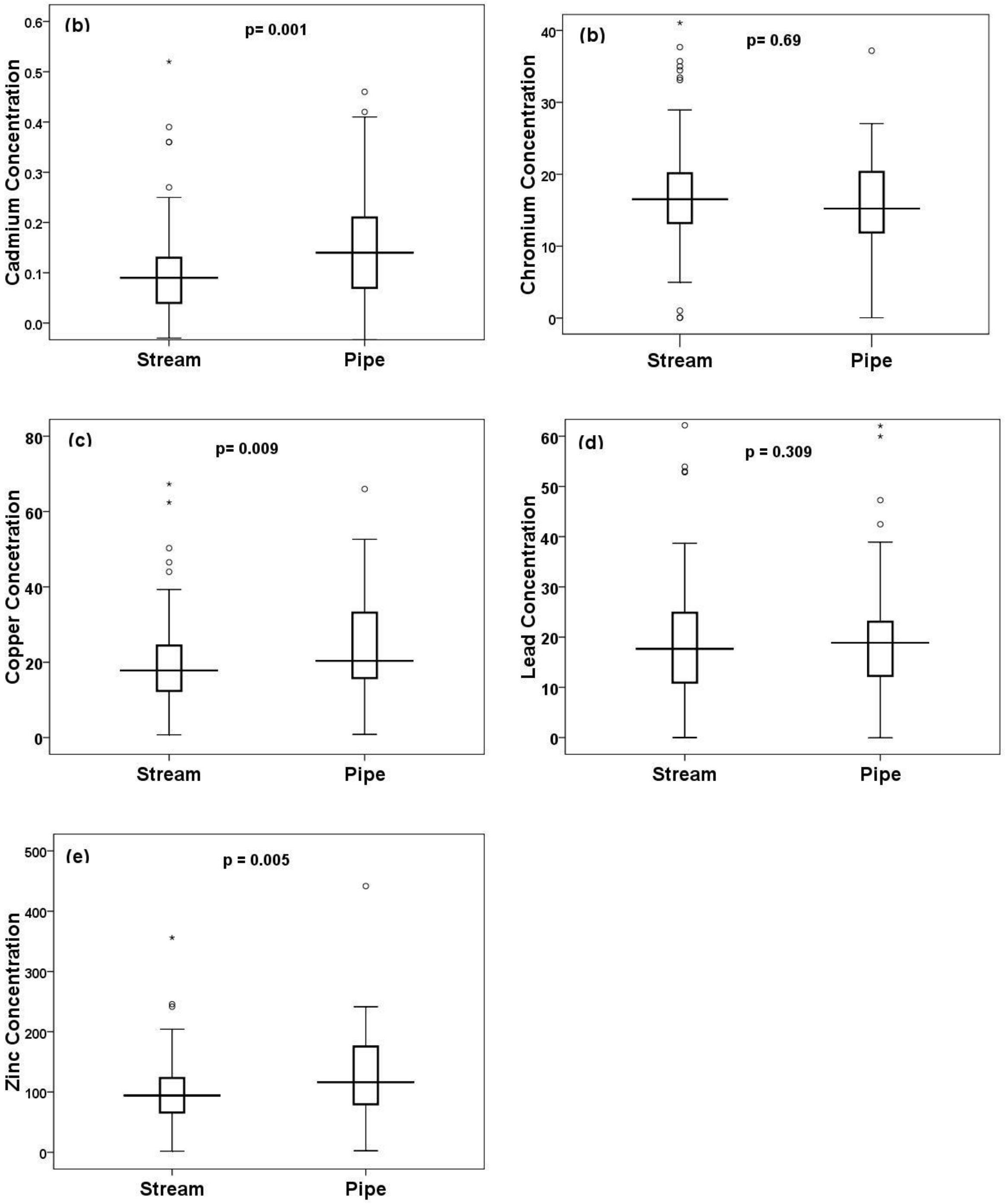

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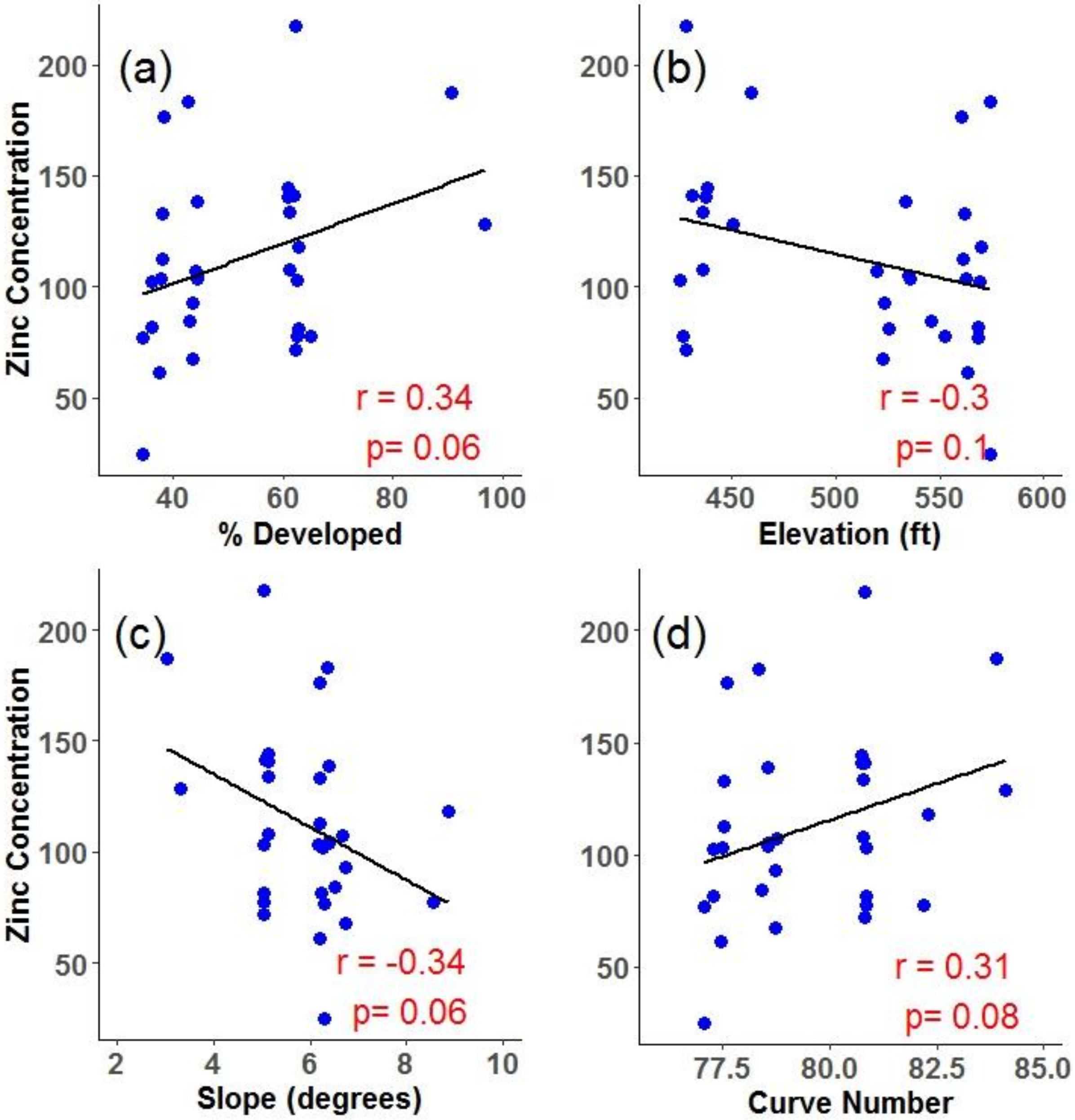

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