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Static and dynamic source identification of trace elements in river and soil environments under anthropogenic activities in the Haraz plain, Northern Iran

MAZIAR MOHAMMADI KHANGHAH[1], MARKUS EGLI[2], ATAOLLAH KAVIAN[3] AND IVAN LIZAGA[4]

[1]University of Zurich
[2]University of Zurich, Switzerland
[3]Sari Agricultural Sciences and Natural Resources University
[4]Ghent University

Presenting Author: maziar.mohammadi@geo.uzh.ch

Unsustainable human activities have disrupted the natural cycle of trace elements, causing the accumulation of chemical pollutants and making it challenging to determine their sources due to interwoven natural and human-induced processes. A novel approach was introduced for identifying the sources and for quantifying the contribution of trace elements discharge from rivers to soils. We integrated fingerprinting techniques, soil and sediment geochemical data, geographically weighted regression model (GWR) and soil quality indices. The FingerPro package and the state-of-the-art tracer selection techniques including the conservative index (CI) and consensus ranking (CR) were used to quantify the relative contribution of different upland sub-watersheds in trace element discharge soil. Our analysis revealed that off-site sources (upland watersheds) and in-site sources (land use) both play an important role in transferring trace elements to the Haraz plain (northern Iran). The unmixing model's results suggest that the Haraz sub-watersheds exhibit a higher contribution to trace elements transfer in the Haraz plain, and therefore, require greater attention in terms of implementing soil and water conservation strategies. However, it is noteworthy that the Babolroud (adjacent to Haraz) exhibited a better performance of the model. A spatial correlation between certain heavy metals, such as As and Cu, and rice cultivation existed. Additionally, we found a significant spatial correlation between Pb and residential areas, particularly in the Amol region. Our result highlights the importance of using advanced spatial statistical techniques, such as GWR, to identify subtle but critical associations between environmental variables and sources of pollution. The methodology used comprehensively identifies dynamic trace element sourcing at the watershed scale, allowing for pollutant source identification and practical strategies for soil and water quality control. Tracer selection techniques (CI and CR) based on conservatives and consensus improve unmixing model accuracy and flexibility for precise fingerprinting.