

Predicting Contamination Pathways in Mining-Affected Watersheds Using a Cellular Automaton

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Abstract

Historical mining has introduced trace elements and acid mine drainage into river systems via surface-runoff pathways from waste deposits and abandoned workings, altering sediment geochemistry and posing ecological and health risks. This study evaluates the Contaminant Mass Transfer Cellular Automaton (CMTCA), a probabilistic model that simulates slope-driven runoff trajectories using minimal inputs. Applied to the Nalón River basin (Spain), The results support CMTCA as a low-cost tool to prioritise risk assessment, guide background-sampling design by identifying non-affected reaches and inform early-stage environmental management in mining-influenced watersheds.

Keywords: Mining contamination, acid mine drainage, cellular automaton, risk assessment

Introduction

Historical and active mining activities release trace elements and generate acid mine drainage (AMD); these processes enhance metal mobilisation by surface runoff and fluvial transport, favouring their accumulation in river sediments, posing ecological and human-health risks (Álvarez *et al.*, 2018; Ordóñez *et al.*, 2013). Beyond direct releases, trace elements naturally cycle through weathering and biogeochemical processes (Izquierdo *et al.*, 2015), but mining increases metal availability and disrupts environmental equilibria (Kobina Mensah & Amoakwah, 2024). Landscape alteration exposes mineralised materials to erosion and chemical transport, often promoting soil and water acidification and enhancing metal mobility; residues such as waste rock and tailings become long-term sources affecting soils, sediments, and waters (Kim *et al.*, 2008; Álvarez *et al.*, 2018). Exposure may occur through contaminated crops (Gallego *et al.*, 2002; Hu & Ding, 2009), inhalation, dermal contact, or accidental ingestion (Han *et al.*, 2005). Also, in aquatic systems downstream

of mining areas, bioaccumulation and biomagnification of trace elements along food chains may constitute a relevant exposure pathway for ecological and human receptors.

Because trace elements concentrate in the upper soil centimetres, surface runoff is the principal mechanism for lateral transfer from sources to river corridors and sediments, especially in mountainous basins with steep slopes and intense or torrential precipitation; under favourable conditions, transfer distances may reach ≈ 3 km before entering surface waters (Álvarez *et al.*, 2018; Giuliano *et al.*, 2007; Larios *et al.*, 2012; Sims *et al.*, 2022). Delineating likely influence areas therefore requires tools that incorporate topographic control and runoff routing.

Robust risk assessment further depends on distinguishing natural variability from anthropogenic enrichment via background levels (and derived reference values) representative of unaffected conditions (De Miguel *et al.*, 2002). Background can be obtained from generic compilations, site-specific literature, or dedicated basin sampling (García-Ordiales *et al.*, 2019;



Nude *et al.*, 2011; Gallego *et al.*, 2002; Garcia-Ordiales *et al.*, 2018, Barrio-Parra *et al.*, 2025).

Within this context, the Contaminant Mass Transfer Cellular Automaton (CMTCA) offers a probabilistic, computationally efficient framework to simulate runoff-driven transport from mining/industrial sources to river receptors using minimal inputs (Barrio-Parra *et al.*, 2020). This study evaluates the suitability of CMTCA to delineate potential influence areas of historical mining on sediment trace-element concentrations in the Nalón River basin (Asturias, Spain).

Methods

Study area

The Nalón River basin (5,442 km²) is characterised by steep geomorphology (mean slope 41%), abundant precipitation (>970 mm/year), and a dense network of 614 rivers. The basin also hosts over 800 historical mining sites (coal, iron, mercury, fluorite, kaolin) that are distributed across the basin (Álvarez *et al.*, 2018). These extractive and industrial operations have generated waste rock, tailings, and acid mine drainage over time, making them potential sources of trace-element mobilisation. Their spatial distribution and topographic context are key factors influencing the potential transfer of contaminants toward river sediments.

Modelling of transport by surface runoff

The transport modelling was carried out using the Contaminant Mass Transfer Cellular Automaton (CMTCA), a probabilistic and slope-driven algorithm designed to simulate the surface-runoff-mediated movement of particles from source points to river receptors (Barrio-Parra *et al.*, 2020). The model operates on four essential input layers—Digital Elevation Model (DEM), influence points (source cells), receptors, and optional barriers—all discretized into a regular grid. For each source cell, the automaton evaluates downslope gradients toward the eight neighbouring cells and assigns transition probabilities proportional to local slope. A stochastic selection identifies the next cell in the trajectory, and the process iterates successively until a receptor is reached.

This procedure represents a single simulation; in this study, 1000 simulations were performed per source cell, and the resulting ensemble was aggregated into a pathway-frequency surface in which each cell value corresponds to the number of realisations in which it was traversed, thus providing a probabilistic estimate of runoff-driven transport likelihood (Figure 1). A 5 m × 5 m grid was used as the baseline spatial resolution, and an additional 200 m grid was evaluated to assess scale effects. For comparison, two simplified approaches were also incorporated: the Trace Downstream tool in ArcGIS Pro - based in the maximum slope preference path from an origin point - and a 3 km fixed influence buffer, representing a conservative upper-bound assumption for maximum transport distance by runoff.

Results

The initial output consisted of the compilation of a basinwide database, which made it possible to visualise the large number of historical and operational activities potentially influencing trace element concentrations in sediments. Most of these activities correspond to mining operations, although several industrial facilities are also present. Even prior to the application of any modelling technique, the spatial distribution of influence points provides a valuable qualitative overview of possible anthropogenic pressures. While the specific objective of this study concerns the alteration of sediment trace element concentrations, the typology and location of human activities across the basin are relevant for a wide range of environmental assessments.

As shown in Figure 2, the maps of sediments affected or non-affected that has been obtained with the different methodologies. In this case, the influence of all activity types is jointly considered; however, the complete analysis was also carried out for each mining and industrial category separately.

A key outcome observable in these maps is the identification of sediment reaches that remain unaffected under all methodologies. These areas are of particular interest because they represent suitable locations for establishing geochemical background

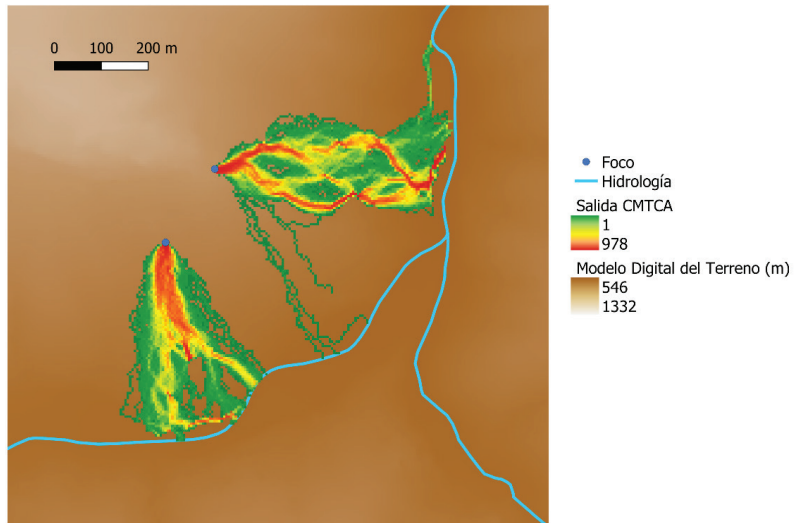


Figure 1 Example of surface runoff pathways predicted with CMTCA for two source zones (blue dots).

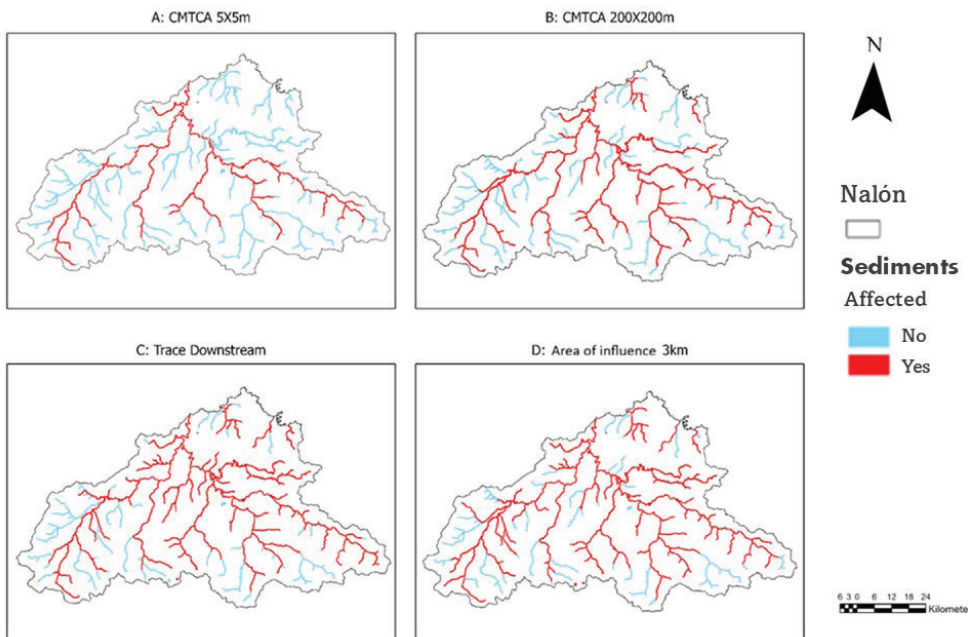


Figure 2: Maps of sediments potentially affected (red) and non-affected (blue) by legacy mining and industrial activities, obtained through different methodologies.

samples. Another relevant observation concerns the activities associated with the greatest potential influence—namely coal, fluorite, iron and mercury mining, together with thermal power plants. This behaviour

can be attributed to two factors: (i) the high density of these activity types, and (ii) their preferential location in the upper basin, resulting in a large proportion of downstream sediment being potentially affected.



Notable differences arise when comparing the 5×5 m CMTCA model (Figure 1A) with the alternative methods. Using the 5 m-resolution DEM, sediments in 36% of the streams in the river basin could be affected by human activity. This proportion increased to 61% when the automaton was applied at 200×200 m DEM and reached 74% when using both the Trace Downstream tool and the 3 km influence-area criterion. Differences were also evident in the diversity of activities identified as potential sources: the application of CMTCA with a 5 m resolution DEM yield that only coal, mercury, iron, fluorite and magnesite sites could have a potential effect to river sediments, whereas all three complementary methods attributed a potential influence on every activity type.

These discrepancies stem from the operational logic of the automaton, which excludes flat or upslope cells (zero or positive slope), as they do not contribute to surface-runoff transport. Consequently, the model avoids overestimating influence in areas where runoff cannot realistically occur.

The application of the Trace Downstream tool resulted in the largest proportion of potentially affected sediment (reaches 74%), a value identical to that obtained using the fixed 3 km influence area. This outcome reflects the intrinsic conservatism of Trace Downstream, which assigns a deterministic downstream pathway from each source point, systematically reaching the fluvial network and marking all downstream segments as potentially affected. The 3 km buffer assumes maximum influence regardless of topographic constraints – potentially marking as “potentially affected” sediments of water streams located upslope from influence points, which is physically implausible and must therefore be interpreted with caution.

The probabilistic nature of the CMTCA also provides additional insight by indicating areas where runoff pathways diverge or converge, which is not captured by deterministic approaches. This approach account for key geomorphological constraints on surface-runoff transport, such as the presence of flat or inverse-slope areas,

depositional zones, or attenuation processes that limit sediment delivery. This information is particularly relevant for studies aimed at evaluating contaminant accumulation zones, as the automaton highlights the areas where surface runoff is more likely to decelerate or terminate, thus favouring deposition.

Conclusions

The CMTCA proves to be an interesting approach to characterise the potential influence of anthropogenic activities on sediment trace-element concentrations. Its advantages are threefold: (i) parsimony of inputs (DEM, hydrological network, and locations of influence points), (ii) a probabilistic representation of transport (multiple plausible pathways rather than a single deterministic route), and (iii) more accurate delineation of influence zones by incorporating slope both to weight transitions and to exclude flat/upslope cells that do not contribute to surface runoff. While flat areas may favour contaminant accumulation, they are not involved in downstream transfer toward sediment-sampling reaches.

Applied to the Nalón basin at 5×5 m resolution, the CMTCA indicates that approximately 64% of sediment reaches remain unaffected by anthropogenic pressure and are therefore appropriate candidates for establishing background values. The remaining 36% appears potentially affected, mainly in association with coal, fluorite, iron, magnesite and mercury mining, in line with the spatial distribution of activities and their known geochemical signatures.

Beyond the modelling exercise, the compiled database evidences a high density of abandoned mining sites, many lacking adequate restorations. This pattern—observed in the Nalón basin and common elsewhere—reinforces the need for continued investigation and management actions to protect ecosystems and nearby communities.

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