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How Well Bucket Lysimeters Correspond with Whole-catchment Runoff and its Chemistry: A Case Study of Artificial Experimental Catchments at a Post-mining Site

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Abstract: This study evaluated efficiency of bucket lysimeters for measuring water fluxes and ion transport in four hydrologically isolated experimental catchments representing reclaimed (levelled and planted by alder) and unreclaimed (wave like topography, unvegetated) post-mining sites near Sokolov, Czech Republic. Weekly measurements of leachate from lysimeters and surface/subsurface runoff from experimental catchments, in which lysimeters were installed, were collected from 2021 to 2024. Ion concentrations (Ca^{2+}, Na^{+}, Li^{+}, NH_4^{+}, K^{+}) were quantified using ion-selective electrodes. Upscaled estimates showed higher accuracy at the unreclaimed site ($R^2 = 0.81$ for total runoff, $R^2 = 0.88$ for evapotranspiration) than at the reclaimed site ($R^2 = 0.72$ and $R^2 = 0.77$). Lysimeter leachate explained surface runoff variance at unreclaimed ($R^2 = 0.75$) and reclaimed ($R^2 = 0.47$) sites, but was not predictive for subsurface flow. Among ions, Li^{+} showed the highest predictive capacity ($R^2 = 0.44 - 0.56$), while NH_4^{+} showed consistent patterns across sites. K^{+}, Na^{+}, and Ca^{2+} showed variable transport influenced by soil and vegetation development. Lysimeters captured surface water fluxes and evapotranspiration but did not represent subsurface flow or solute transport well. Better lysimeter performance at the unreclaimed site suggests that vegetation development reduces hydrological predictability during ecosystem recovery.

Keywords: Bucket lysimeter; Leachate; Ions; Surface and subsurface flow; Experimental Catchment; Evapotranspiration.

1 INTRODUCTION

Bucket lysimeters provide controlled measurements of water and solute transport at the point scale (Howell, 2005; Evett et al., 2023; Liu et al., 1998; Gee et al., 2009), but their ability to predict field runoff across spatial scales is poorly understood (Kopp et al., 2013). This challenge is acute in heterogeneous post-mining landscapes where lysimeters, by isolating soil volumes and eliminating lateral flow, may alter the hydrological connectivity governing catchment-scale runoff.

Mining activities significantly alter natural water movement, creating complex flow patterns (Younger et al., 2002; Younger et al., 2005; Hancock et al., 2003). Flat reclaimed is more uniform, subsurface heterogeneity may appear through variable root systems, compaction patterns, and preferential flow pathways. In contrast, unreclaimed plots with wavy topography exhibit predictable hydrological behavior where wave crests consistently experience high infiltration while troughs generate surface runoff (Frouz et al., 2024). Tree species further influence water movement in clay-rich mining soils (Prach et al., 2011; Jačka et al., 2021), creating small-scale differences potentially missed by point measurements (Mudrák et al., 2010; Swanson et al., 2011).

While lysimeters correlate with runoff in forest ecosystems (Song et al., 2020) and capture snowpack dynamics (Whitaker and Sugiyama, 2005; Ala-aho et al., 2018), mining soil studies reveal discrepancies between lysimeter and field observations (Colombani et al., 2020; Roussat et al., 2008). Ion behavior may better indicate hydrological connectivity through differential transport and retention patterns (Nimmo, 2006; Dwivedi et al., 2025; Webster et al., 2006). While conservative tracers like chloride track water movement with minimal soil interaction (Kendall and McDonnell, 1998), cations provide complementary information in clay-rich environments. Major cations (Na^{+}, K^{+}, Mg^{2+}, Ca^{2+}) exhibit differential retention following the lyotropic series which is the relative binding strength to negatively charged soil particles, typically ordered: $Na^{+} < K^{+} < Mg^{2+} < Ca^{2+}$ (Williams and Coleman, 1950; Sposito, 2008). Water moving rapidly through preferential pathways carries cations in near-input proportions, while matrix flow promotes selective retention of strongly-bound cations (Jarvis, 2007). In high-CEC mining soils, this differential mobility makes cations sensitive to flow pathway differences between lysimeters and field conditions (Younger et al., 2002).

This study uses the FALCON artificial catchment array, designed to study ecosystem development between flat and wavelike microtopography (Frouz et al., 2020). The system provides hydrologically isolated catchments monitoring surface and subsurface runoff under two treatments: conventional reclamation with leveled surfaces and alder plantations, versus spontaneous succession with wavy topography and unmanaged vegetation.

We hypothesized that lysimeter drainage would better reflect surface runoff on unreclaimed plots due to predictable hydrological patterns, while subsurface runoff would be poorly represented due to preferential flow pathways. We expected lysimeter-derived water balance to align with catchment-scale evapotranspiration estimates calculated from the residual water balance approach, especially on reclaimed sites where more uniform conditions should facilitate upscaling. Finally, we hypothesized that ion concentrations in lysimeter leachate would correlate with runoff concentrations, with stronger agreement in subsurface flow following lyotropic series patterns.

2 MATERIALS AND METHODS

2.1 Study site

The FALCON experimental catchments investigate ecosystem development in post-mining sites under different restoration approaches: reclaimed sites which have flat surfaces and are planted with alder, and unreclaimed sites with wavy terrain left for unassisted recovery (Fig. 1). FALCON is located in a post-mining landscape near Sokolov, Czech Republic (50.2218908 N, 12.7071839 E), and forms a part of the Long-Term Ecological Research (LTER) network. The area receives 650 mm precipitation annually, with a mean temperature of 6.8 °C, at 428 m elevation.

The facility comprises four adjacent catchments, each measuring 40 × 60 m (2400 m²), sloping 0.6% toward the southwest. Each catchment is bordered at the upslope edge by a drainage trench to prevent water inflow from higher elevations (Fig. 1). During construction, each catchment was excavated and a compacted clay layer was placed at 2.5 m depth to act as a seal, forming a basin. This was filled with fragmented clay-stone derived from slightly alkaline (pH 8) Miocene sediments. The substrate has a silt loam texture with granulometric composition of clay = 18-9%, silt = 51-58%, and sand = 24-30% (Kuráž et al., 2012). The substrate exhibits high water retention capacity due to its high clay content (Kuráž et al., 2012), with bulk density values typical of young post-mining soils in the region ranging from 1.3 to 1.6 g cm⁻³ (Cejpek et al., 2013). The Miocene clay-stone material contains naturally elevated lithium concentrations, typical of sedimentary deposits in the North Bohemian Basin. These sediments are derived from weathered volcanic tuffs and claystones of the Cypris Formation, which are enriched in lithium-bearing clay minerals (Rouhani et al., 2023). The alkaline pH and clay-rich composition of the substrate contribute to lithium release during weathering processes. Construction was completed in September 2019.

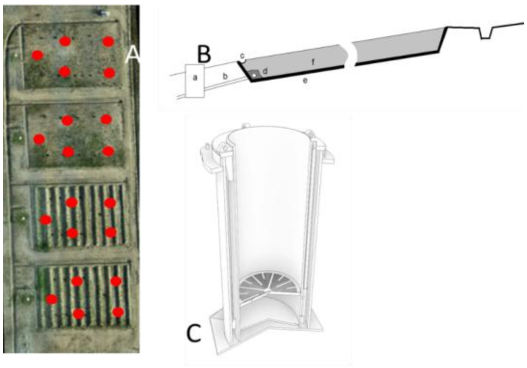

Fig. 1. Aerial photograph of FALCON catchment array A), scale bar represents 20 m and red dots position of individual bucket lysimeters. Cross section on individual experimental catchment B) a measuring shaft for subsurface run off, b and d drainage system for subsurface runoff collection, c surface runoff collection, e. impermeable clay sealing, and f overburden back fill, C represent schematic of bucket lysimeters used.

2.1.1 Sampling and measurement

Twenty weighable bucket lysimeters (688 cm² surface area, 60 cm depth) were installed across four field plots. Each lysimeter consists of an outer watertight case and an inner soil-filled container. The inner container was weighed using a portable balance (±1–2 mm rainfall equivalent accuracy), and percolating leachate was sucked out using a pressure pump and collected in vials for storage and analysis in the laboratory.

From 2021 to 2024, weekly measurements were conducted on both lysimeters and catchment plots. Catchment surface and subsurface runoff volumes were collected weekly and measured at collection points (as described in Fig. 1). Lysimeter leachate drainage volumes were recorded in the field and inner containers were weighed to assess water storage changes. Water samples (0.5 L) were collected from lysimeter leachate and catchment runoff, transported on ice to the laboratory, filtered using 0.45 µm membrane filters, and stored at 4°C until analysis.

Concentrations of calcium (Ca^{2+}), sodium (Na^+), lithium (Li^+), ammonium (NH_4^+), and potassium (K^+) were measured using a Mettler Toledo SevenDirect SD60 ion meter equipped with ion-selective electrodes. Calibration was performed using standard solutions (1, 10, and 100 ppm) prepared fresh for each session, with periodic verification throughout analysis. Electrodes were rinsed thoroughly with deionized water between measurements. Lysimeter-scale ET was calculated for individual lysimeters as:

$$ET_{lysimeter} = P - L_{lysimeter} \tag{1}$$

where P is precipitation and L lysimeter is the measured lysimeter drainage volume (in mm). This represents point-scale water loss through evapotranspiration, with lateral flow eliminated by the lysimeter design.

Catchment-scale ET was estimated using the residual water balance approach:

$$ET_{catchment} = P - (L_{upscaled} + Q_s + Q_b) \tag{2}$$

where P is precipitation, L upscaled is lysimeter drainage upscaled to catchment area, Qs is surface runoff, and Qb is subsurface runoff. Weekly precipitation was measured with a tipping-bucket rain gauge (Onset RG3-M, ±1% accuracy). All water fluxes were converted to depth units (mm) by normalizing volumes to the 2,400 m² catchment area. Lysimeter drainage volumes were upscaled using the catchment-to-lysimeter area ratio (38,400), calculated as catchment area (2,400 m²) divided by lysimeter area (0.0625 m²). ET proportions were calculated as the fraction of precipitation lost to evapotranspiration (ET/P) at each scale, enabling direct comparison between lysimeter-derived and catchment-scale estimates (Fig. 3c).

Changes in soil water storage (ΔS) were assumed negligible on weekly to monthly timescales, supported by lysimeter weight measurements before and after drainage events, although site-specific heterogeneity may cause deviations in some plots. Uncertainty in weekly ET was assessed by propagating errors from individual components: rainfall (±1%), lysimeter drainage (±2%), and runoff (±3%), resulting in ET uncertainty of ±4.6 mm at 95% confidence level. This method was applied consistently across all sites and years, enabling direct comparisons between reclaimed and unreclaimed plots.

2.1.2 Data processing

Simple linear regression was used to examine the relationships between lysimeter water volume, surface and subsurface runoff, and ion concentrations in these. All computational analyses were done using the R software version 4.5.1.

3 RESULTS

3.1 Relationship between bucket lysimeter water volume and flow

At the reclaimed site (Fig. 2a), lysimeter leachate volume was significantly correlated with surface runoff ($R = 0.69$, $R^2 = 0.47$, $p = 0.028$) but had a nonsignificant correlation with subsurface runoff ($R = 0.47$, $R^2 = 0.22$, $p = 0.168$).

Similarly, at the unreclaimed site (Fig. 2b), lysimeter leachate volume was significantly correlated with surface runoff ($R = 0.87$, $R^2 = 0.75$, $p = 0.001$), but with a weaker correlation with subsurface runoff ($R = 0.59$, $R^2 = 0.35$, $p = 0.074$).

3.2 Runoff and evapotranspiration scaling analysis from lysimeter to whole catchment

Upscaled lysimeter runoff closely matched catchment-scale total runoff at both sites. At the unreclaimed site, the regression slope between upscaled lysimeter runoff and actual catchment runoff was 1.05 ($R^2 = 0.81$), indicating near-perfect agreement with the 1:1 line (Table 1, Fig. 3a). The reclaimed site showed a slope of 0.95 with slightly lower fit ($R^2 = 0.72$) and greater scatter at higher runoff volumes (Fig. 3a). Average scaling deviation was 10% for the unreclaimed site and 18% for the reclaimed site, with wider spread at the reclaimed site (Table 1, Fig. 3b).

Lysimeter-derived evapotranspiration (ET) estimates also aligned well with catchment-scale ET proportions. The ET proportion calculated from lysimeter measurements was 0.96 at the unreclaimed site ($R^2 = 0.88$) and 0.89 at the reclaimed site ($R^2 = 0.77$), matching the catchment-scale ET proportions at both sites (Table 1, Fig. 3c). Scaling deviation showed no systematic bias with lysimeter volume between 5 and 100 mL. The slopes of scaling deviation versus lysimeter volume were near zero (0.05 for reclaimed, 0.00 for unreclaimed), indicating no volume-dependent bias in the upscaling approach (Table 1, Fig. 3d).

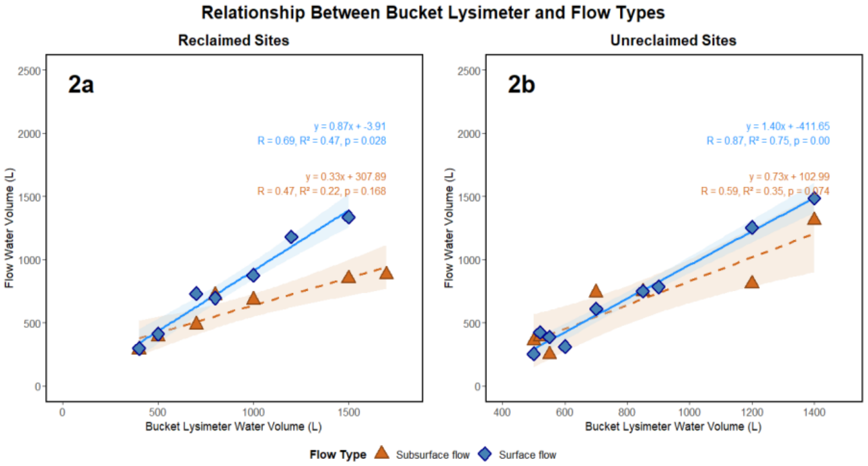

Fig. 2. Relationship between bucket lysimeter water volume and flow water volume for reclaimed (a) and unreclaimed site (b), showing surface and subsurface flow correlations with associated statistics ($p < 0.050$). Shaded areas represent 95% confidence intervals.

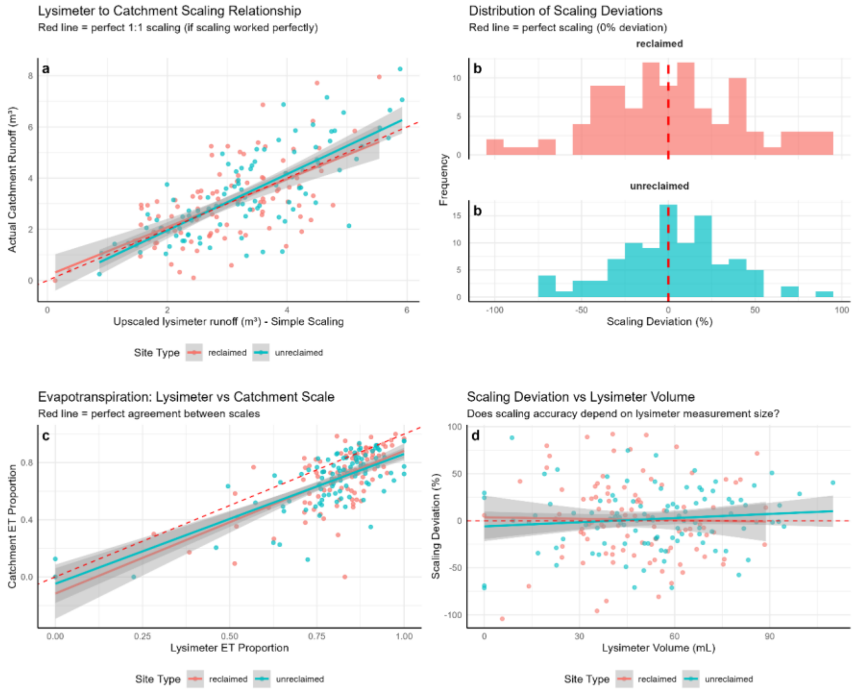

Fig. 3. Scaled runoff and ET from lysimeter (1/16 m²) to catchment area (2,400 m²) using a factor of 38,400mL.

Table. 1. Summary of runoff and ET scaling relationship and between the bucket lysimeter and catchment.

Metric	Reclaimed	Unreclaimed
Average scaling deviation (%)	18	10
Scaling R^2 (Runoff)	0.72	0.81
Lysimeter ET proportion	0.89	0.96
Catchment ET proportion	0.89	0.96
ET scaling R^2	0.77	0.88
Regression slope (R^2)	0.95	1.05
Regression slope (ET)	0.89	0.96
Scaling deviation vs. Lysimeter volume slope	0.05	0

Table. 2. Summary of regression results. Bucket Lysimeter vs Flow and Ion Measurements Cations are ordered according to lyotropic series proposed by Williams and Coleman (1950).

Site	Flow types	Parameter	Equation	R	R^2	P value
Reclaimed	Surface	Li$^+$	$y = 0.97x + 3.79$	0.75	0.56	<0.001
Reclaimed	Subsurface	Li$^+$	$y = 1.45x – 6.67$	0.66	0.44	<0.001
Unreclaimed	Surface	Li$^+$	$y = 0.85x + 4.26$	0.73	0.53	<0.001
Unreclaimed	Subsurface	Li$^+$	$y = 1.35x + 0.83$	0.46	0.23	<0.001
Reclaimed	Surface	Na$^+$	$y = -0.28x + 63.53$	-0.17	0.03	<0.001
Reclaimed	Subsurface	Na$^+$	$y = 0.53x + 27.34$	0.29	0.08	<0.001
Unreclaimed	Surface	Na$^+$	$y = 0.43x + 35.06$	0.16	0.03	<0.001
Unreclaimed	Subsurface	Na$^+$	$y = -0.07x + 59.94$	-0.05	0	<0.001
Reclaimed	Surface	K$^+$	$y = 0.67x + 10.35$	0.53	0.28	<0.001
Reclaimed	Subsurface	K$^+$	$y = 0.73x + 4.11$	0.5	0.28	<0.001
Unreclaimed	Surface	K$^+$	$y = 0.49x + 19.95$	0.14	0.02	<0.001
Unreclaimed	Subsurface	K$^+$	$y = 0.56x + 12.12$	0.48	0.23	<0.001
Reclaimed	Surface	NH$_4^+$	$y = 0.43x + 22.13$	0.55	0.3	<0.001
Reclaimed	Subsurface	NH$_4^+$	$y = 0.60x + 14.63$	0.55	0.3	<0.001
Unreclaimed	Surface	NH$_4^+$	$y = 1.34x + 3.47$	0.66	0.44	<0.001
Unreclaimed	Subsurface	NH$_4^+$	$y = 0.79x + 15.15$	0.49	0.24	<0.001
Reclaimed	Surface	Ca^{2+}	$y = 0.16x + 34.38$	0.24	0.06	<0.001
Reclaimed	Subsurface	Ca^{2+}	$y = 0.32x + 28.78$	0.44	0.19	<0.001
Unreclaimed	Surface	Ca^{2+}	$y = 0.20x + 36.04$	0.23	0.05	<0.001
Unreclaimed	Subsurface	Ca^{2+}	$y = 0.10x + 41.29$	0.13	0.02	<0.001

3.3 Relationship between ion concentration in surface and subsurface flows and bucket lysimeter

Li$^+$ showed the highest correlation between lysimeter and runoff concentrations across both sites, with significant relationships for surface runoff at the reclaimed ($r = 0.75$, $R^2 = 0.56$, $p < 0.001$; Fig. 4a) and unreclaimed sites ($r = 0.73$, $R^2 = 0.53$, $p < 0.001$; Fig. 4c), and weaker correlations for subsurface flow at the reclaimed ($r = 0.66$, $R^2 = 0.44$, $p < 0.001$; Fig. 4b) and unreclaimed sites ($r = 0.46$, $R^2 = 0.23$, $p < 0.001$; Fig. 4d).

NH$_4^+$ showed moderate and consistent correlations across both sites, with equivalent relationships for surface and subsurface flow at the reclaimed site ($r = 0.55$, $R^2 = 0.30$, $p < 0.001$), and stronger correlation with surface runoff ($r = 0.66$, $R^2 = 0.44$, $p < 0.001$) than subsurface flow ($r = 0.49$, $R^2 = 0.24$, $p < 0.001$) at the unreclaimed site, suggesting more direct surface transport.

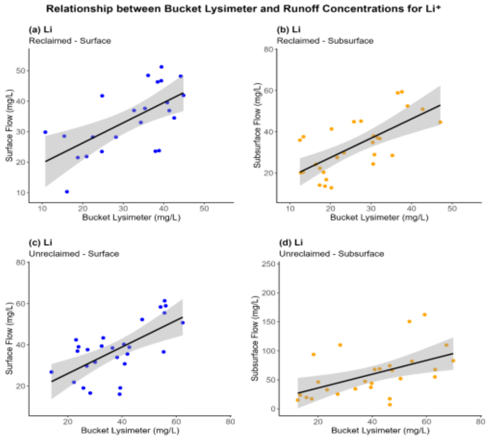

Fig. 4. Ion transport relationships at the reclaimed and unreclaimed sites. Regression analysis shows relationships between lysimeter concentrations and surface and subsurface flows for Li$^+$ ($p < 0.050$).

K^+ displayed moderate predictive strength at the reclaimed site for both surface ($r = 0.53$, $R^2 = 0.28$, $p < 0.001$) and subsurface flow ($r = 0.50$, $R^2 = 0.25$, $p < 0.001$), but weak correlation with surface runoff at the unreclaimed site ($r = 0.14$, $R^2 = 0.02$, $p < 0.001$), while subsurface flow remained moderately correlated ($r = 0.48$, $R^2 = 0.23$, $p < 0.001$), pointing to site-specific variation in K^+ transport.

Na^+ had a negative relationship with surface runoff at the reclaimed site ($r = -0.17$, $R^2 = 0.03$, $p < 0.001$) and minimal correlations under other conditions ($R^2 \leq 0.08$). Ca^{2+} remained weakly correlated across all site and flow types ($R^2 = 0.02$–0.19), suggesting limited representativeness in lysimeter measurements.

4 DISCUSSION

4.1 Relationship between bucket lysimeter water volume and flow

Lysimeter water correlated with surface runoff but not subsurface runoff, partially supporting our hypothesis. Both lysimeter leachates and surface runoff respond directly to rainfall, while subsurface runoff follows complex temporal patterns (Lin et al., 2008). The correlation was significantly stronger at the unreclaimed site compared to the reclaimed site because reclamation activities alter soil structure, porosity, and hydraulic conductivity, creating heterogeneous flow pathways that reduce lysimeter representativeness (Zhang et al., 2025). Heavy machinery during reclamation increases soil compaction and bulk density while reducing infiltration rates, leading to greater spatial variability in surface flow generation (Ephron et al., 2016). Lysimeters poorly predicted subsurface flow at both sites due to the scale mismatch between point measurements and subsurface processes that operate through preferential flow networks and macropore systems at larger scales (Blöschl and Sivapalan, 1995; Colombani et al., 2020).

4.2 Runoff and evapotranspiration scaling analysis from lysimeter to whole catchment

Lysimeters provided reliable estimates of total runoff and evapotranspiration (ET) for post-mining water balance studies, though performance varied by site condition. The unreclaimed site showed stronger agreement with catchment-scale runoff compared to the reclaimed site. This difference reflects vegetation development effects: the unreclaimed site exhibits homogeneous infiltration and flow patterns due to sparse vegetation, while the reclaimed site develops root systems and preferential pathways, leading to spatial variability in water movement (Jačka et al., 2021). These results support findings by Meissner et al. (2020) and the scaling framework proposed by Blöschl and Sivapalan (1995), which emphasizes that upscaling is most effective when hydrological processes are spatially uniform.

Despite these differences in runoff prediction, lysimeters captured ET patterns well at both sites, with ET proportions consistent across scales. This supports Allen et al. (1998) that ET processes are more spatially uniform than runoff. Lower ET proportions at the reclaimed site may reflect reduced water use efficiency in early successional vegetation, aligning with observations by Bradshaw (1997) and Cooke and Johnson (2002) on physiological differences in young plant communities.

4.3. Ion in lysimeters and catchment runoff

All ions correlated with surface and subsurface runoff, but correlations varied between ions, indicating different transport processes in disturbed soils (Radcliffe and Šimůnek, 2010). Results aligned with the lyotropic series (Williams and Coleman, 1950) where ions that replace H^+ in the sorption complex remain bound, leading to regression slopes deviating from one (Bolt et al., 1976; Fletcher and Sposito, 1989), although exceptions occurred (Appelo and Postma, 2005).

Li^+ showed the highest predictive capacity across both sites and flow types, with regression slopes close to 1.0 for surface runoff, confirming its utility as a conservative tracer. The elevated Li^+ concentrations observed in both lysimeter leachate and catchment runoff reflect natural enrichment in the Miocene clay-stone substrate, which contains lithium-bearing minerals typical of sedimentary formations in the North Bohemian Basin (Rouhani et al., 2023). Li^+ functions effectively as a conservative tracer due to its minimal sorption to soil particles, limited biological uptake, and high solubility (Ptak et al., 2004; Vengosh et al., 2002). Compared to chloride (Cl^-), the most widely used conservative tracer, Li^+ offers several advantages in clay-rich mining environments such as lower background concentrations in natural waters, providing better signal-to-noise ratios, minimal but measurable retention that can help differentiate flow pathways, and less susceptibility to atmospheric deposition and anthropogenic contamination (Kendall and McDonnell, 1998). However, Cl^- remains preferable in studies requiring truly conservative behavior with zero soil interaction. In high cation exchange capacity post-mining soils, Li^+'s weak binding affinity (lowest in the lyotropic series) makes it more mobile than other cations while still providing information about hydrological connectivity that purely conservative tracers cannot capture (Williams and Coleman, 1950; Sposito, 2008; Omar et al., 2025). The strong correlations observed in this study demonstrate that Li^+ effectively tracks water movement through both surface and subsurface pathways in heterogeneous post-mining landscapes.

NH_4^+ showed consistent correlations across sites and flow paths, contrasting with less disturbed environments where nitrogen species display high spatial variability (Wollheim et al., 2001). This may reflect simplified biogeochemical cycling where reduced microbial diversity and plant biomass result in uniform nitrogen cycling (Bradshaw, 1997; Cooke and Johnson, 2002). K^+ behaviour was site-dependent, with strong correlations at the reclaimed site but poor surface flow correlations at the unreclaimed site (Wiegleb and Felinks, 2001; Mengel et al., 2001). Wavy topography and heterogeneous soil development at the unreclaimed site contribute to complex K^+ transport dynamics (Bendfeldt et al., 2001; Zipper et al., 2011).

Na^+ and Ca^{2+} showed weak predictive relationships, departing from lysimeter studies where major cations typically show correlations (Liu et al., 1998; Howell, 2005; Gee et al., 2009). For Ca^{2+}, this reflects mineral weathering in mining spoils where diverse mineral assemblages result in inconsistent Ca^{2+} release (Strömberg and Banwart, 1999; White and Brantley, 2003), while Na^+ shows variable transport governed by sorption and soil exchange processes, including negative correlations between lysimeter and surface runoff concentrations at the reclaimed site.

Regression slopes across ions and flow types indicate solute retention and release mechanisms. Steeper slopes for Li^+ in subsurface flow at the reclaimed site suggest enhanced mobilization compared to lysimeter concentrations (Beven and Germann, 2013; Šimůnek et al., 2003). This may reflect preferential flow pathways or chemical processes that concentrate solutes during transport (Jarvis, 2007).

4.4 Practical outcome

Lysimeters predicted surface runoff more effectively than subsurface runoff because surface processes are more directly linked to local conditions (Schmocker-Fackel et al., 2007; Durner et al., 2008; Weihermüller et al., 2007). Better performance at the unreclaimed site suggests that the absence of established vegetation and root-induced heterogeneity results in more uniform infiltration and runoff, while reclaimed sites develop spatially variable pathways over time. Lysimeter data can represent field conditions well for stable tracers such as Li^+ (Hertel and von Unold, 2014; Meissner et al., 2020), but for nutrients and reactive solutes additional field-scale measurements are needed to capture flow and transport processes (Beven and Germann, 2013; Singh et al., 2018; Šimůnek et al., 2003).

The role of time in these patterns is not well understood and needs further study. The stronger predictability at the unreclaimed site may be temporary and could decline as vegetation grows and soil structure becomes more complex (Antoneli et al., 2018; Bradshaw, 1997; Shrestha and Lal, 2011). Long-term monitoring is important to understand how lysimeter performance changes as post-mining sites recover (Moreno-de las Heras et al., 2008; Pietrzykowski and Krzaklewski, 2010).

5 CONCLUSIONS

Bucket lysimeters predict surface runoff and ion transport in post-mining landscapes under specific conditions. Lysimeters performed better at the unreclaimed site, where hydrological uniformity enhances predictability. Conservative tracers like Li^+ correlated with surface and subsurface flows, while other ions showed site-specific behaviour influenced by vegetation and topography. Lysimeters failed to predict subsurface flow, confirming scale limitations and the need to supplement point measurements with catchment observations.

Context-specific monitoring strategies are required in post-mining environments as ecosystems evolve. Long-term studies are needed to understand how vegetation recovery and soil development affect lysimeter-field relationships and to develop monitoring frameworks for disturbed landscapes. Future research should also explore more sophisticated statistical approaches, including multivariate analysis to examine interactions between environmental variables (vegetation cover, soil properties, topography) and nonlinear modeling to capture complex threshold behaviors as post-mining ecosystems evolve. Such approaches may reveal nuanced relationships that emerge as vegetation recovery and soil development progress over longer timescales.

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