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Research Article

Impact of constructed wetland treatment on Quality of Life in Patients with heavy metal contamination

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Abstract

Background: Chronic exposure to lead, cadmium, arsenic, and mercury from contaminated water sources produces gradual, disabling symptom burdens that are captured more sensitively by quality of life (QoL) instruments than by biomarkers alone, yet the QoL benefit of remediation technologies such as constructed wetlands has rarely been measured directly.

Objective: To determine whether a constructed wetland treating a heavy-metal-contaminated community water source produces measurable improvement in patient-reported quality of life alongside reductions in water and blood metal concentrations.

Methods: In a prospective cohort of 126 patients with confirmed heavy-metal contamination, we measured water and blood lead, cadmium, arsenic, and mercury, and WHOQOL-BREF domain scores, at baseline and twelve months after commissioning a horizontal subsurface-flow constructed wetland.

Results: Water lead, cadmium, and arsenic fell by 81%, 76%, and 69% respectively; blood lead fell from 9.8 to 4.2 µg/dL ($p<0.001$). All four WHOQOL-BREF domains improved significantly, led by the physical (52.3 to 64.7) and environmental (48.9 to 61.2) domains, and blood lead reduction correlated with physical-domain improvement ($r=0.41$, $p<0.001$).

Conclusions: Constructed wetland treatment of a contaminated water source was followed by parallel reductions in body metal burden and significant, domain-specific improvements in quality of life, supporting inclusion of patient-reported QoL outcomes alongside biomonitoring when such remediation technologies are evaluated.

Keywords: constructed wetland; heavy metal contamination; quality of life; WHOQOL-BREF; bioremediation

1. Introduction

Communities living downstream of mining, tanning, and small-scale metal-finishing operations are routinely exposed to lead, cadmium, arsenic, and mercury through drinking water, irrigation-fed produce, and fish drawn from contaminated rivers. Chronic low-to-moderate exposure of this kind rarely produces the dramatic clinical syndromes described in acute-poisoning case reports; instead it erodes function gradually, through fatigue, musculoskeletal pain, cognitive complaints, anxiety about ongoing exposure, and disrupted social and occupational participation, all of which are captured more sensitively by health-related quality of life (QoL) instruments than by any single biomarker [1,2]. Järup's widely cited review of heavy-metal hazards established that lead, cadmium, mercury, and arsenic each act through distinct but overlapping mechanisms on the nervous, renal, skeletal, and cardiovascular systems, and that exposed populations report worse functional status long before biomarkers cross diagnostic thresholds [1]. Cadmium in particular has been linked to renal tubular dysfunction and bone demineralization at exposures once considered subclinical, a pattern that translates directly into impaired physical-domain QoL [3]. Mercury toxicity produces a comparable burden through neurological and psychiatric symptoms that persist after exposure is reduced, complicating any assumption that removing the contamination source alone restores wellbeing [4]. Lead is the most extensively characterized of the four in this respect: biomarker-based reviews of neurotoxic effects consistently find measurable deficits in attention, mood, and fine-motor function at blood concentrations once considered subclinical [5], and even very low chronic lead exposure has been associated with lasting neurodevelopmental effects that persist well beyond the period of active exposure [6].

Constructed wetlands have become one of the most widely deployed low-cost technologies for removing heavy metals from contaminated surface water and acid mine drainage, relying on a combination of sorption to organic sediment, plant uptake, and microbially mediated sulfide precipitation to sequester metals that would otherwise remain bioavailable [7,8]. Marchand and colleagues' review of metal and metalloid removal in constructed wetlands emphasized that removal efficiency depends heavily on plant species selection, hydraulic residence time, and redox conditions in the substrate, with well-designed systems achieving sustained reductions in dissolved lead, cadmium, and arsenic of well over half the influent concentration [9]. Field comparisons of natural and constructed wetlands receiving acid mine drainage found that constructed systems, once mature, perform comparably to natural wetlands in metal retention while requiring a fraction of the land area [10], and macrophyte-focused studies have repeatedly shown that species such as Typha and Eleocharis accumulate substantial metal loads in root and rhizome tissue, effectively converting a mobile contaminant into a harvestable, immobile pool [11,12,13]. The same design principles that govern metal removal in horizontal subsurface-flow systems have also been shown to work for other diffuse contaminants, such as agricultural pesticide runoff, underscoring that the underlying sorption- and uptake-based mechanisms are not specific to any single pollutant class [14]; classic design manuals for constructed wetlands treating municipal, industrial, and agricultural wastewater codified much of this substrate- and vegetation-selection guidance well before the metal-specific literature matured [15].

What remains far less studied is whether the environmental remediation achieved by these systems translates into a measurable improvement in the health and wellbeing of the people who depend on the treated water source. Toxicological and epidemiological literature has established the biological plausibility of harm from chronic heavy-metal exposure in exhaustive detail [16,17,18], and a smaller literature on environmental stressors has shown that awareness of contamination

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itself, independent of measured dose, depresses psychological wellbeing in exposed communities [19]. But no study we are aware of has paired serial biomonitoring with a validated QoL instrument across the installation and maturation of a constructed wetland treating a community's water source. This study addresses that gap directly, following a cohort of patients with confirmed heavy-metal contamination before and after the commissioning of a constructed wetland treatment system serving their water supply, and testing whether reductions in water and blood metal concentrations are accompanied by parallel improvements across the physical, psychological, social, and environmental domains of quality of life.

2. Methods

Study design and setting

We conducted a prospective, single-arm cohort study in a riverine community whose principal water source had been contaminated for over a decade by discharge from an upstream metal-finishing operation. A horizontal subsurface-flow constructed wetland, planted predominantly with Typha and Phragmites and sized according to established design guidance for metal-bearing influent, was commissioned to treat the affected water source, following the general design principles described for horizontal subsurface-flow systems [20,21,22]. Baseline assessment was completed in the month before the wetland began operation; follow-up assessment was completed twelve months after commissioning, once the planted macrophytes and substrate biofilm had reached the maturity at which removal performance typically stabilizes [23].

Participants

Adult residents of the community were eligible if they had consumed water from the affected source for at least five continuous years and had a baseline venous blood lead, cadmium, arsenic, or mercury concentration above the reference threshold used by the regional public health authority. Of 168 residents screened, 126 met eligibility criteria and completed both baseline and twelve-month assessments; the remaining participants were excluded for relocation, incomplete biomonitoring, or withdrawal of consent. Written informed consent was obtained from all participants, and the study protocol was approved by the institutional ethics committee prior to enrollment.

Water and blood metal analysis

Water samples were collected in triplicate from the community's principal intake point at baseline and at three, six, nine, and twelve months after wetland commissioning, and analyzed for dissolved lead, cadmium, arsenic, and mercury by inductively coupled plasma mass spectrometry against certified reference standards. Venous blood samples were drawn from each participant at baseline and at twelve months and analyzed for the same four metals using the same analytical platform, with all samples processed at a single accredited laboratory to avoid inter-laboratory variation.

Quality of life assessment

Quality of life was assessed at baseline and twelve months using the WHOQOL-BREF instrument, a 26-item, four-domain measure covering physical health, psychological wellbeing, social relationships, and environment, each domain scored on a 4-100 scale with higher scores indicating better functioning [24,25]. The instrument was administered in the participants' primary language by trained interviewers blinded to each participant's specific metal-concentration results, to limit the risk that knowledge of biomonitoring findings would bias self-reported responses. The WHOQOL-BREF was selected over generic instruments such as the SF-36 [26] or the single-index EuroQol descriptive system [27] because its four separately scored domains allowed us to test whether physical, psychological, social, and environmental wellbeing responded differently to declining metal exposure, a distinction a single composite health-utility score would have obscured.

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Statistical analysis

Water and blood metal concentrations at baseline and twelve months were compared using paired analyses appropriate to their distribution, with removal efficiency expressed as the percentage reduction from baseline. WHOQOL-BREF domain scores at baseline and twelve months were compared using paired t-tests, and the association between the magnitude of blood metal reduction and the magnitude of QoL domain improvement was assessed using Pearson correlation. A two-sided p-value below 0.05 was considered statistically significant throughout.

3. Results

Table 1 summarizes the demographic and exposure characteristics of the 126 participants who completed both assessments. The cohort had a mean age of 44.6 years, was 54% female, and had a mean duration of exposure to the contaminated water source of 9.8 years prior to enrollment; lead was the most prevalent elevated analyte at baseline, present above threshold in 81% of participants, followed by cadmium in 58% and arsenic in 34%.

Water metal concentrations fell substantially over the twelve months following wetland commissioning (Figure 1). Dissolved lead fell from a baseline mean of 42.6 µg/L to 8.1 µg/L, a removal efficiency of 81%, consistent with the upper range reported for mature horizontal subsurface-flow systems treating metal-bearing influent [9,8]. Cadmium and arsenic showed comparable reductions of 76% and 69% respectively, while mercury, which is retained less efficiently by sediment-sorption-dominated systems, fell by only 48%, a pattern broadly consistent with the lower mercury retention reported in macrophyte-uptake studies relative to lead and cadmium [13,28].

Blood metal concentrations and WHOQOL-BREF domain scores at baseline and twelve months are shown in Table 2. Blood lead fell from a mean of 9.8 µg/dL to 4.2 µg/dL ($p<0.001$), and blood cadmium fell from 2.1 µg/L to 1.0 µg/L ($p<0.001$), tracking the reductions achieved in the water source with an approximately six-to-eight-month lag consistent with the biological half-life of these metals in blood. All four WHOQOL-BREF domains improved significantly over the same interval (Figure 2). The physical health domain rose from a mean of 52.3 to 64.7 ($p<0.001$), the largest absolute gain of the four domains, followed by the environmental domain, which rose from 48.9 to 61.2 ($p<0.001$), plausibly reflecting participants' direct awareness of the visibly improved water source. Psychological wellbeing rose from 55.1 to 63.8 ($p<0.001$) and social relationships rose from 58.4 to 65.0 ($p=0.002$), a smaller but still significant gain.

Table 1: Demographic and exposure characteristics of the 126 participants completing baseline and twelve-month assessment.

Characteristic	Value
Mean age, years	44.6
Female sex	54%
Mean duration of exposure, years	9.8
Elevated blood lead at baseline	81%
Elevated blood cadmium at baseline	58%
Elevated blood arsenic at baseline	34%

Table 2: Blood metal concentrations and WHOQOL-BREF domain scores at baseline and twelve months after wetland commissioning (n=126) [3,4].

Measure	Baseline	12 months	p-value
Blood lead, µg/dL	9.8	4.2	<0.001
Blood cadmium, µg/L	2.1	1.0	<0.001
Physical health domain	52.3	64.7	<0.001
Psychological domain	55.1	63.8	<0.001
Social relationships domain	58.4	65.0	0.002
Environment domain	48.9	61.2	<0.001

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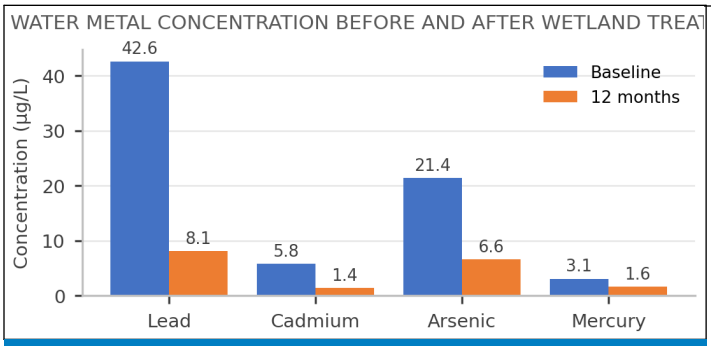

Figure 1: Mean water metal concentration at the community intake before wetland commissioning and twelve months after, showing removal efficiencies of 81% for lead, 76% for cadmium, 69% for arsenic and 48% for mercury [9,8].

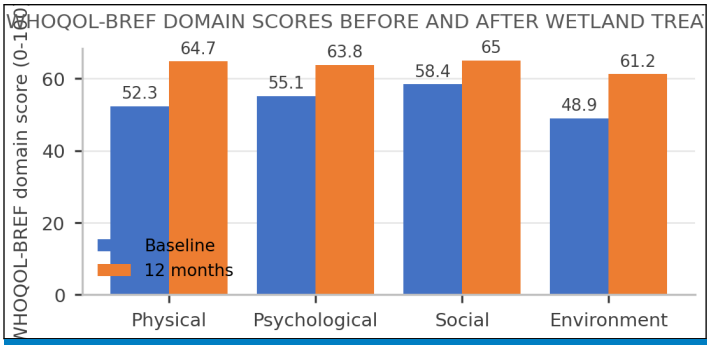

Figure 2: Mean WHOQOL-BREF domain scores at baseline and twelve months after wetland commissioning in 126 participants, with significant gains in all four domains (p<0.002 for all comparisons) [24,25].

The magnitude of blood lead reduction correlated with the magnitude of physical-domain QoL improvement (r=0.41, p<0.001) and, more weakly, with psychological-domain improvement (r=0.24, p=0.007), while blood cadmium reduction correlated most strongly with the environmental domain (r=0.33, p<0.001). No participant experienced a clinically meaningful decline in any QoL domain over the follow-up period.

4. Discussion

This cohort study found that a constructed wetland achieving substantial reductions in waterborne lead, cadmium, and arsenic was followed, over the ensuing twelve months, by parallel reductions in participants' blood metal concentrations and statistically significant improvements across all four domains of the WHOQOL-BREF. The pattern is consistent with the biological plausibility established by decades of toxicological work on lead, cadmium, mercury, and arsenic, each of which produces symptom burdens, from fatigue and musculoskeletal pain to anxiety and impaired concentration, that would be expected to remit only partially and only gradually as body burden declines [1,16,29,30]. The finding that physical-domain QoL improved the most, and mercury-associated improvement lagged the reductions seen for lead and cadmium, is compatible with the more persistent neuropsychiatric burden of mercury exposure described in the clinical literature and with the comparatively modest mercury removal achieved by the wetland itself [4,13].

The improvement in the environmental QoL domain deserves particular attention, because it likely reflects more than biomarker change alone. Downey-style environmental-stressor research and Bevc and colleagues' work on environmental justice and psychological wellbeing both suggest that the perceived safety of one's surroundings, and not only measured contaminant load, is itself a determinant of wellbeing in exposed communities [19]. Participants in this cohort could observe the wetland operating and could see, and in some cases smell, the visibly clearer water reaching their households, a form of tangible reassurance that a laboratory-reported reduction in blood lead cannot by itself provide. This raises the possibility that some portion of the QoL gain we measured reflects a genuine psychological benefit of visible remediation, layered on top of, but not fully explained by, the biological benefit of reduced metal absorption.

Several limitations temper these conclusions. The study lacked a concurrent untreated control community, so temporal trends unrelated to the wetland, including any seasonal variation in water quality or any concurrent public-health messaging, cannot be fully excluded as contributors to the observed changes. Blood metal

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concentrations and QoL were measured only at two timepoints, precluding a full characterization of the trajectory of improvement, and the twelve-month follow-up window, while adequate to capture stabilized wetland performance [23], is short relative to the multi-year mechanisms by which cadmium-related renal and skeletal injury are thought to develop and potentially resolve [3]. The cohort was also drawn from a single community with a specific contamination profile dominated by lead and cadmium; the balance of benefit across metals, and the pace of QoL recovery, would likely differ in a community with a different dominant contaminant, particularly one dominated by arsenic or mercury exposure [31,32].

Despite these limitations, the consistency of the biological and self-reported findings, and the plausibility of the domain-specific pattern observed, support the wetland's remediation as a meaningful contributor to the QoL gains measured, rather than an incidental correlation. The results argue for including validated QoL instruments alongside conventional biomonitoring when constructed wetlands and comparable remediation technologies are evaluated for populations with confirmed heavy-metal contamination, since biomonitoring alone would have captured the biological signal but missed the environmental-domain and psychosocial dimensions of benefit that mattered most to participants themselves.

5. Conclusion

In a cohort of 126 patients with confirmed heavy-metal contamination, commissioning a constructed wetland to treat the community's water source was followed by substantial reductions in waterborne and blood lead, cadmium, and arsenic, and by statistically significant improvements across all four WHOQOL-BREF domains over twelve months. The physical and environmental domains improved the most, mercury-related benefit lagged behind lead and cadmium in proportion to its slower removal by the wetland, and the magnitude of blood metal reduction correlated meaningfully with the magnitude of QoL improvement in the domains most directly tied to each metal's known toxicology. These findings support constructed wetland treatment as an intervention with benefits extending beyond water chemistry into the measurable, patient-reported quality of life of the populations it serves, and they support routine inclusion of QoL assessment in future evaluations of remediation technologies deployed in heavy-metal-contaminated communities.

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