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Perspective

Pesky Metals: Historical Perspective, Advances, and Challenges for Remediation of Problematic Metal Contaminants

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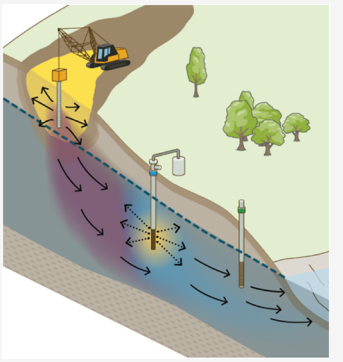
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ABSTRACT: Persistent and problematic toxic metal and metalloid pollutants (in particular, As, Hg, Pb, Cd, and Cr) have long been challenging and expensive remediation targets in contaminated surface and subsurface environments. Since the advent of environmental regulations and cleanup in the late 20th century, much progress has been made to address sites of legacy metal pollution and limit new contamination. Despite this, metal pollution remains a global problem, particularly in soils and sediments, with many large legacy sites inadequately remediated, metal contamination widespread in developed and developing nations, and new pollution occurring from informal and often illegal extraction and recycling processes. In this perspective, we highlight advances and challenges in science and technology, and key economic and social factors, that have influenced remediation of these "pesky" metals over the last ∼50 years. Through this lens, we consider emerging challenges and opportunities associated with legacy and critical metals, climate resilience, and sustainability.



KEYWORDS: *metal pollution, superfund, abandoned mines, stakeholder engagement, critical metals*

INTRODUCTION

Water, soil, and sediment contamination by metal and metalloid pollutants[1] is persistent, difficult, and expensive to remediate. The most toxic and challenging metal and metalloid pollutants are Pb, As, Cr, Cd, and Hg. Other less toxic metals, such as Ni, Cu, and Zn, are prevalent and found at concentrations of concern at many contaminated sites. Soil and sediment serve as long-term reservoirs for metal contaminants, where they can bleed into surface water or groundwater, migrate, and potentially become bioavailable. Metal contaminants are commonly mixed with each other and with organic contaminants, making both cleanup and assessment of health risks difficult.[1] In high-income nations, metal contamination is often associated with legacy sources, mostly from former mining, processing, and smelting or large industrial sites prior to the enforcement of environmental regulations. Low- and middle-income countries likewise continue to address legacy metal contamination, but new pollution sources now include illegal or poorly regulated mining and extraction, individuals and small groups engaged in artisanal and small-scale mining, unregulated recycling of used electronic products, and other informal and often unlawful activities. This perspective highlights progress in remediation and mitigation of metal pollution since the adoption of environmental regulations in the late 20th century. We focus on science and technology advances and developments, and consider key barriers and limitations to successful outcomes for the most problematic "pesky" metals using selected examples. We briefly discuss economic and social factors that most influence metal remediation progress and outcomes, and comment on emerging challenges associated with legacy and critical metals, climate resilience, and sustainability.

HISTORICAL LEGACY OF METAL POLLUTION

Developed nations with strict environmental laws have tried to address the worst sites of metal contamination and prevent future releases. The current regulatory landscape developed from environmental policies and laws beginning in the 1970s and 1980s in the US and European nations that followed public outrage over rampant industrial pollution. In the US, Congress passed the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) in 1980 that established a National Priorities List (NPL), better known as "Superfund" sites, to identify and remediate sites across the

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country with the worst pollution. A key feature of CERCLA was the principle that parties responsible for pollution should be held financially accountable (the "polluter pays").[2] It was also recognized, however, that this mechanism alone was inadequate—that the government needed to step-in and clean-up "orphaned" sites when no responsible parties could be compelled to pay or when costs exceeded the ability of polluters to pay.[3] In Europe, the polluter pays principle was embraced in environmental policies beginning in the early 1970s, but at the time, European agencies lacked mechanisms for generating centralized funding for remediation or enforcing regulations within individual countries.[4] After the establishment of the European Union (EU), the Environmental Liability Directive was adopted in 2004 (enforced in 2007) and included strong provisions for polluter liability, but individual member states rather than the EU were responsible for clean-ups in the absence of a paying polluter.[5,6] Japan was another early adopter of holding polluters accountable, influenced in part by widespread human Hg poisoning from seafood consumption linked to offshore industrial discharges that began in the 1950s in what became known as the Minamata disaster.[7,8] In the late 20th and early 21st centuries, other nations implemented various types of polluter liability laws in addition to a wide array of environmental regulations.

Despite ∼50 years of environmental action to reduce legacy pollution and discourage new polluters, metal contamination remains widespread and challenging to reduce to levels protective of public and ecosystem health. For example, a recent review of metals in urban soils in European countries found that elevated concentrations were widespread, with Pb, Zn, Cu, Cr, and Ni the most prevalent metals that exceeded safety threshold concentrations, although study methods were variable and geographic coverage was incomplete among the compiled studies.[9] In Canada, a dedicated government program was launched in 2020, the Northern Abandoned Mine Reclamation Program (NAMRP), to address massive and complex legacy contamination at eight former mine sites in the Yukon and Northwest Territories.[10,11] In the US, the Superfund program provides a long-term record of remediation and legal actions associated with some of the largest, most polluted sites (although it does not encompass all metal-contaminated sites). Hazardous metals occur at over half to three-quarters of contaminated sites in the US mostly in soil, sediment, and groundwater, and the most prevalent metals at Superfund sites, Pb, As, Cr, Hg, and Cd, are also the most toxic.[1,12,13] Despite long listing times and funding from federal and state governments and responsible parties in many cases, the total number of NPL sites has remained relatively unchanged for the past two decades (Figure 1). These examples emphasize the difficulty in wealthy nations of addressing legacy metal pollution. Low- and middle-income nations face additional constraints in reducing human exposure to metal contaminants from both legacy pollution and new formal, informal, and illegal sources. Many of these nations lack regulations or the ability to enforce them, and often have insufficient funding and institutional capacity for remediation.[14] Thus, challenges to reducing metal pollution and exposure risk differ among countries and involve a combination of key technical, economic, and social barriers discussed below.

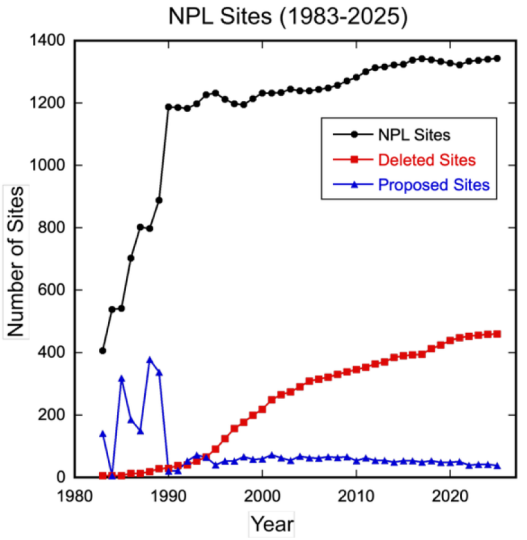


Figure 1. Proposed, deleted, and total sites on the National Priorities List (NPL) in the USEPA Superfund program from 1983 to 2025. Only site additions and deletions since NPL inception are shown; data do not account for remedial actions taken at sites (which have occurred in most instances). Compiled from USEPA.[63]

SCIENCE AND TECHNOLOGY: ADVANCES AND CHALLENGES

The most problematic metal contaminants share characteristics that make them challenging targets for remediation. They are hazardous at elevated concentrations, with some (Cd, Pb, and Hg) being highly toxic. They can change oxidation state and/or chemical speciation under environmental conditions and exhibit complex nonconservative biogeochemical behavior. Many are bioavailable or have a high exposure risk when present in water, air, or food, and some can bioaccumulate or biomagnify. Their synergistic or antagonistic behavior with organic compounds is often not completely understood. The combination of high toxicity and complex biogeochemical cycling leads to dispersal and persistence in soil, sediment, water, and biota at low levels that are considered hazardous to humans or other organisms. Table 1 summarizes the environmental speciation of the historically most problematic metal contaminants and common treatment approaches.

The demand for cleanup of metal-contaminated sites that began in the 1980s stimulated the development of new methods and technologies that have matured into standard industry practices. Increasingly stringent environmental regulations and effective treatment technologies required better understanding of the complex biogeochemical behavior of some of the more prevalent chemically labile metals, with As, Cr, and Hg receiving particular attention. This need drove basic research on the fascinating environmental biogeochemistry of metal contaminants, including their speciation, transport, toxicity, and interactions with minerals and microorganisms. Fundamental knowledge of metal behavior is critical for conceptual site models now commonly used in remediation design and has spurred the development of approaches and technologies to address multiple contaminants and short- and long-term risks. At the same time, site remediation has shifted from a strict concentration-based cleanup approach to a more practical and achievable risk-based framework, with remedial actions increasingly aimed at hazard mitigation to achieve risk reduction rather than elimination of

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Table 1. Environmental Speciation and Treatment Methods for Historically Problematic Metal Contaminants

Element	Environmental Forms	Treatment[a]
As	As(V), As(III) oxyanions; Fe-oxide and sulfide partitioning	Fe/Al-oxide sorption or coprecipitation; ZVI; reduction and sulfide precipitation
Hg	Sulfide precipitation, binding to S-organic ligands; microbial methylation; Hg(0) volatility	Source control, capping, sorbents, sulfide binding, and redox management
Pb	Pb(II) sorption; carbonate, phosphate, or sulfide partitioning	Phosphate amendment, precipitation, sorption, solidification, or removal
Cd	Cd(II) sorption; carbonate and sulfide partitioning	Sorption, sulfide/carbonate precipitation, stabilization, or removal
Cr	Cr(VI) oxyanion, Cr(III) sorption and oxide precipitation	Reduction to Cr(III), precipitation, adsorption, and ZVI barriers
Ni, Cu, Zn	Divalent cations; partitioning to oxides, organic matter, and sulfides	pH control, sorption, sulfide/carbonate precipitation, stabilization
Se	Se(VI), Se(IV) oxyanions; reduced Se(0), selenides	Biotic or abiotic reduction, sorption, PRBs, and biological treatment
Sb	Sb(III), Sb(V) oxyanions; sulfide precipitation, sorption to Fe-oxide	Fe-oxide sorption/coprecipitation, reduction and sulfide formation

[a]ZVI: zerovalent iron; PRB: permeable reactive barrier.

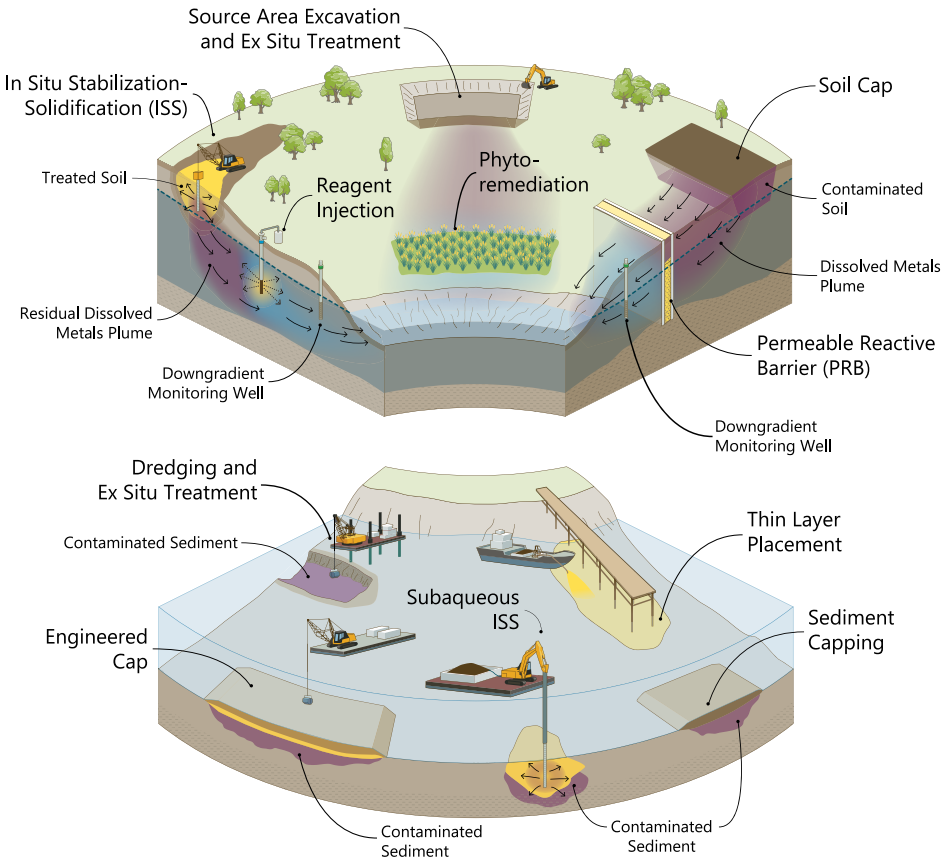


Figure 2. Conceptual diagram illustrating methods that have been employed for metal remediation in soil and groundwater (upper) and sediments (lower). Permeable reactive barriers are installed for passive treatment of groundwater, while reagent injection creates a reactive zone *in situ*. *Ex situ* treatment methods may include soil washing; chemical, physical, or biological extractions; and thermal treatments, solidification, or vitrification before on- or off-site disposal. Engineered caps and thin layer placement may include various sorbents (such as activated carbon, metal oxides, or zerovalent iron) or materials engineered for treatment processes tailored to specific metals.

contaminant mass.[2,15] Thus, many remediation methods tend to focus on reducing metal mobilization and transport by water or air to decrease the risk of migration, bioavailability, or exposure.

Remedial actions commonly combine *ex situ* methods, such as excavation, disposal, soil washing, and treatment, with *in situ* approaches that may include amendments, stabilization/solidification, bioremediation, phytoremediation, capping, and permeable reactive barriers (PRBs) (summarized in Figure 2).[13,16] Physical removal is often preferred for small areas containing highly contaminated material, but removal (by excavation or dredging) and off-site disposal become increasingly costly and disruptive at large sites. *In situ* methods are therefore especially important where contamination is distributed through large volumes of soil, sediment, or aquifer material or inaccessible due to infrastructure. The most difficult sites typically have large spatial footprints, dispersed contamination, mixtures of metals and organic contaminants, potential for aerial transport, and/or complex groundwater, surface water, sediment, or geochemical conditions. Remediation may also require habitat restoration, revegetation, wind or water erosion controls, wetland replacement, or stream and shoreline modification.[12] Long-term monitoring can continue for decades to verify that migration of residual metals remains

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Table 2. Selected Field Examples of Metal-Contaminated Sites Grouped by Remediation Maturity and Contaminant Challenges

Site Location	Contaminants. Remediation or Management Approach[a]	Challenges to Remediation
	Mature sites and long-term stewardship	
Britannia Mine, British Columbia, Canada[64−66]	Cu, Zn, Cd, acidity. Mine-water interception and treatment; marine sediment treatment	Large interconnected mine-workings system generates seasonally variable acidic drainage containing Cu, Zn, Cd, and other metals; requires coordinated clean-water diversion, groundwater interception, hydraulic storage, active treatment, and monitoring.
Former ASRACO lead smelter, Helena, Montana, USA[67,68]	As, Se. Groundwater ZVI-PRB	ZVI-PRB removed As(III) and As(V) from groundwater, but effectiveness was limited by heterogeneous groundwater flow beneath the barrier. Leaching of residual metals from vadose-zone sediments requires long-term treatment and monitoring.
Giant Mine, Northwest Territories, Canada[69−71]	As, Sb, Zn, Pb. Frozen-block containment of mine workings; water treatment	Containment of large underground As contamination requires engineered freezing, water management, monitoring, and perpetual institutional stewardship; heterogeneous redox-sensitive wastes and As mobility complicate predictions of long-term performance.
Iron Mountain Mine, California, USA[72−74]	Cu, Zn, Cd, As; acid drainage and sediment. Diversions, capture, and high-density-sludge treatment	Microbially mediated sulfide oxidation produces extreme acidity and metal loading; successful remedy depends on continuous collection, hydraulic storage, lime treatment, sludge disposal, infrastructure maintenance, and secure long-term funding.
Onondaga Lake, New York, USA[75,76]	Hg, methyl-Hg, organic contaminants. Sediment dredging and capping, nitrate addition to lake hypolimnion	Contaminants in lake sediment, groundwater, and tributary inputs; dredging and capping reduced major sources; nitrate addition mitigates seasonal Hg methylation. Residual contamination and fish Hg bioaccumulation requires long-term monitoring and remedy maintenance.
	Large mining districts and continuing remediation challenges	
Aznalcóllar-Guadiamar, Spain[77−79]	Zn, Cd, Pb, Cu, As. Contaminant removal and amendment to tailings and soil; revegetation	Bulk removal and soil amendments greatly reduced contamination but residual sulfides oxidize and regenerate acidity that release metals and As; long-term performance depends on amendment stability, revegetation, and monitoring.
Berkeley Pit, Montana, USA[35,80]	Cu, Zn, Fe, Mn, As, acidity. Pumping and water treatment of pit lake	Large acidic pit lake is hydraulically connected to groundwater and continues to accumulate contaminated water; pumping and treatment must maintain the lake below a critical elevation while managing changing chemistry and treatment residuals indefinitely.
Coeur d'Alene/Bunker Hill Basin, Idaho, USA[81−83]	Pb, Zn, Cd, As. Removal, repositories; source and floodplain controls and restoration	Metal-rich sediments stored across a large river and floodplain network are repeatedly eroded and redistributed during floods; continuing groundwater inputs and downstream sediment transport limit the durability of localized removals and source controls.
Kabwe, Zambia[84−86]	Pb, Zn, Cd. Mine waste and tailings controls, dust reduction, residential soil remediation	Large Pb-rich source lies within an inhabited urban environment; contaminated soil, tailings, and dust create overlapping exposure pathways; source control, maintenance, health intervention, and community participation needed to limit human exposure.
Sulphur Bank Mercury Mine/Clear Lake, California, USA[87,88]	Hg, methyl-Hg, As, Sb. Residential-soil cleanup; mine-waste burial and capping; acid lake neutralization; residential soil clean-up and erosion controls	Mine waste, groundwater, wetlands, lake sediment, and fish form a connected Hg exposure and bioaccumulation system; remediation focused on former mine site but not Hg in Clear Lake; historical tribal subsistence uses complicate attribution, risk management, and cleanup goals.
Tar Creek, Oklahoma, USA[89−91]	Pb, Zn, Cd. Mine waste and soil removal; well plugging; wetland restoration	Removal of chat piles and contaminated residential soil reduced exposure from surface contaminants; extensive flooded underground mine system continues to discharge contaminated water; subsidence, mixed wastes, and recontamination require ongoing watershed-scale management.
	Critical elements/minerals and mixed-contaminant cases	
Deloro Mine/Industrial Site, Ontario, Canada[92,93]	Co, As, Ni, Cu. Soil, sediment covers; water collection and treatment	Co-contaminant wastes in soil, groundwater, leachate, and river sediment; engineered covers and treatment control releases; residual contamination and releases require management permanently as a hazardous-waste facility.
Exide Baton Rouge, Louisiana, USA[94,95]	Sb, Pb, As, Mn, Zn. Leachate capture and treatment; soil, groundwater remediation	Secondary Pb and battery processing produced mixed Pb−Sb-metal contamination in soil, groundwater, and leachate; remediation must control particulate Pb and mobile dissolved Sb while maintaining leachate collection and treatment.
Foote Mineral Co., Pennsylvania, USA[96,97]	Li, Sb, As, Cr, Tl, B, VOCs. Groundwater plume and source management; alternate water sources	Historical Li processing produced a large mixed-metal−organic contaminant groundwater plume; weak sorption and ineffective precipitation controls for Li require hydraulic containment or active water treatment.
Gay Mine, Idaho, USA[98−100]	Se, Cd, V, Ni. Soil, water, and biota sampling for remedial investigation and feasibility study	Large disturbed footprint and dispersed phosphate-mine wastes; Se and metals release to water, vegetation, and biota; ecological exposure and livestock risks persist even where conventional groundwater or soil criteria are met.
Su Suergiu, Sardinia, Italy[101,102]	Sb, As. Surface waste and soil source management; surface water and groundwater mitigation	Highly enriched Sb−As wastes and slags exposed to weathering; stable, potential for Sb(V) release under oxidized conditions requires source control rather than *in situ* precipitation or sorption treatments.
Xikuangshan, Hunan, China[103−105]	Sb, As. Waste remediation, restoration, and attenuation	Extensive Sb mining wastes contaminate groundwater, drainage, soil, and surface waters; natural attenuation and conventional strategies limited for controlling mobile Sb(V) under oxidizing conditions.
Zambian Copperbelt, Zambia[106−108]	Co, Cu. Tailings rehabilitation; groundwater, surface water controls	Regional contamination from large historical tailings overlaps with continued mining, settlement, agriculture, and informal activities; source removal impractical; remediation constrained by funding, infrastructure, and institutional capacity.

[a]ZVI: zerovalent iron; PRB: permeable reactive barrier; VOCs: volatile organic compounds.

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below regulated levels and risks are acceptable. Where source control is effective, natural recovery can contribute substantially to long-term improvement and reduction in contaminant mobility and bioavailability.

Despite decades of advances in knowledge and technology, remediation fails to progress at many sites (see Table 2 for examples). One persistent barrier to cleanup is translating effective laboratory technologies to reliable field-scale remedies. Laboratory experiments can establish mechanisms and identify promising approaches, but field applications must contend with subsurface heterogeneity, groundwater flow, complex biogeochemistry, contaminant mixtures, aging of reactive materials, and variable contaminant distributions. At many legacy sites, emergency or temporary actions were done decades ago to eliminate active health threats or stabilize immediate risks, such as removing contaminated materials and hazardous equipment, implementing hydrologic, dust, and erosion controls, or temporarily capping or burying contaminated solids.[17] However, the process of developing and implementing permanent actions, which includes site characterization, risk assessment, feasibility studies, and remedial design, takes years or decades and commonly impedes progress.

Arsenic treatment using zerovalent iron (ZVI) illustrates both the progress and limitations of technology transfer. Conventional treatment methods for As in water and soil include pump-and-treat, adsorption, coagulation, membrane filtration, and excavation. Beginning in the 1990s, PRBs containing ZVI and other reactive media emerged as an *in situ* alternative. Following extensive laboratory development, an estimated 120 pilot- and full-scale PRB systems have been installed worldwide for organic and inorganic contaminants, using combinations of sorption, coprecipitation, precipitation, and redox reactions.[18] Research now extends to nanoscale ZVI, which provides greater reactive surface area,[19] and lower-cost sustainable sorbents such as modified biochar.[20] Although treatment technology has advanced, As contamination of groundwater and soil from natural sources and anthropogenic activities such as mining, agriculture, and industrial use remains a major public health concern affecting millions of people worldwide.[21] Implementation of advanced technologies is often not feasible or too expensive when a contaminant is widely dispersed rather than concentrated at a point source, particularly in underresourced countries.

Mercury is another example of a problematic metal because risk is determined not simply by total Hg but also by microbially mediated production of methylmercury, which bioaccumulates and biomagnifies in aquatic food webs and poses a health risk to humans and biota. Lakes and reservoirs are especially susceptible because organic matter accumulation, stratification, and fluctuating redox conditions can stimulate methylation. Remediation approaches include source control, sediment dredging and capping, sorbent amendments, waterbody operational changes, food-web manipulation, and redox management.[22,23] Studies show that sorbents employing activated carbon can lower porewater methylmercury but may increase methylmercury in solids or release inorganic Hg or sulfate,[24,25] which highlights the importance of assessing unintended side effects of treatment approaches. Alternatively, hypolimnetic oxygenation or nitrate addition is used to suppress reducing conditions conducive to Hg methylation and may also reduce nutrient release and improve cold-water habitat.[26] Results from full-scale application of these approaches, however, show that controlling methylmercury production in water does not necessarily translate directly to reductions in fish tissue methylmercury.

Opportunities remain for new innovations in technology and application methods to make problematic metal remediation more effective and economical. Engineered materials, including nanomaterials and nanotechnologies, have been tailored to bind specific species or to manipulate local pH and redox conditions.[27] Chemical amendments can be designed to promote precipitation, adsorption, oxidation, or reduction that is specific to a contaminant or site conditions. A range of biological remediation methods is commonly used, and new methods continue to emerge. Phytoextraction and phytostabilization are established approaches and may use plants with an affinity for a specific metal. Microbial remediation, either stimulating native microbial communities or adding engineered microorganisms, is used to promote passive or active metal sorption or bioaccumulation, local redox changes, or dissolution or precipitation reactions.[16,28] Monitoring has similarly improved through the development of passive samplers, automated sampling systems, field sensors, and hand-held X-ray fluorescence instruments for rapid detection of metals in solids. Yet, adoption of new remediation technologies remains slow. Many promising approaches never progress beyond bench scale because field testing is expensive, performance is uncertain, and established methods are easier to permit and defend. Developing incentives and opportunities for field-scale demonstration and comparison with conventional technologies therefore remain a major need.

■ ECONOMIC AND SOCIAL CONSIDERATIONS

Laws and regulations implemented over the last half century to address environmental pollution stimulated government funding to clean up sites and hold polluters accountable, which in turn helped create a global industry of services and products related to environmental remediation, reclamation, abatement, and prevention.[29] According to different estimates, roughly half of the global remediation services market is funded by the public sector and half by the private sector.[30,31] Regulations and enforcement of environmental laws together with public demand for cleanup of legacy pollution, prevention of new contamination, and protection of human and ecological health continue to drive public and private spending. Because legacy metal contamination is often the most expensive and technically difficult to remediate, potentially responsible polluters are motivated to litigate, settle with regulators for a fraction of the total cost, or walk away. In the US Superfund program, for example, key nontechnical factors cited for delays in closure of NPL sites were the lack of paying responsible parties and insufficient government funding or staff.[17] As a result, many small, less complex sites have undergone remediation, leaving large, expensive sites associated with mining, metal processing, and smelting either orphaned or without adequate funding.[3,32] Canada's NAMRP also illustrates the challenge of cleanup at large legacy sites. The government assumed liability and remediation responsibility for eight high-risk abandoned mines in 2020. A 2024 audit found that remediation had started for only one of eight sites, and that costs increased by 95% since 2019, bringing total funding for the program to CAD 9.1 billion over its 15-year lifespan. NAMRP now accounts for over half of the federal government's estimated total liability for contamination cleanup.[11] These examples show that adequate and sustained funding for

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metal remediation remains a key barrier, and institutional capacity can be limiting even in wealthy countries.

In addition to economic drivers, stakeholder and community engagement in site remediation is well established as an important component of speeding clean-ups and producing better outcomes.[14,33,34] Minority and low-income communities are disproportionately affected by pollution as measured by health outcomes and economic impact in both developed and developing nations, but addressing needs is community specific. For complex metal-contaminated sites, the time from initial investigations defining scope and approach to completion of remediation goals and establishing long-term monitoring is easily decades. Throughout the process, new information and initial feasibility studies often lead to changes in risk assessment, scope and the type of remedial actions, and project costs, which can be difficult for local communities and stakeholders to follow and understand. Studies of US Superfund sites point to a disconnect between public perceptions, remediation activities, and actual health risk even when communities were engaged, partly due to lengthy cleanup times.[34,35] In China, a recent assessment of metal pollution in soils noted a demand for more participation by the public and stakeholder groups, and calls for the government to hold polluters accountable and ensure that remediation standards are met.[15] Indigenous communities in Canada's NAMRP reported a lack of meaningful consultation and engagement with decision-making about remediation projects, burdensome administration, and limited socio-economic benefits.[11] In low-income nations, remediation and mitigation of metal pollution often rely on foreign aid and expertise, and project delays and failures were attributed in part to poor participation of stakeholders or inappropriate identification of stakeholder groups.[14]

Effective engagement should therefore begin at the start of the remediation process and be adaptive, supported by data, and responsive to specific groups as project scope and actions progress.[33,36,37] Stakeholders may include local government representatives and community and business organizations in addition to the local populace. Important practices include identifying relevant and potentially impacted groups early, engaging groups in dialogue about site investigations and decision-making, and maintaining connections and communication over time.[33,38] Recent studies emphasize the importance of articulating how specific remedial actions are protective of human health and recommend integrating remediation more closely with reuse, redevelopment, and community economic benefit, i.e., a stronger component of "future use planning".[35,38] Linking remediation to tangible community benefits can improve acceptance and long-term outcomes.

OUTLOOK: PERSISTENT LEGACY METALS AND EMERGING METAL CONTAMINANTS

Three of the most hazardous legacy metals, Pb, Hg, and As, remain major global concerns, despite progress in remediation and reductions in use. The World Health Organization identifies Pb as one of 10 chemicals that is a major public health concern globally.[39] Lead is still widely used in batteries and as an additive to industrial materials. Legacy Pb in water pipes and paint, and atmospheric releases from fossil fuel combustion and smelting, continue to pose health risks. Metal waste recovery and recycling of Pb in the informal sector or illegally presents a significant exposure risk to humans, including children,[40,41] and has led to international calls for reductions in Pb use.[39] In contrast, industrial and household uses of Hg have declined in part because of the success of the United Nations Environment Program (UNEP) Minamata Convention (adopted in 2013[42]) and related international agreements. However, artisanal and illegal gold mining and coal combustion remain significant global Hg sources, and legacy Hg contamination and biogeochemical cycling persist.[43] Arsenic continues to be a concern, particularly in low- and middle-income countries that rely on groundwater for drinking water[44] and in urban and agricultural soils.[45] Arsenic is still used in pesticides and herbicides, for wood preservation, and in batteries and semiconductors, and mining and fossil fuel combustion continue to release As to the environment.[39] More broadly, climate change adds another dimension to the long-term efficacy of remediation. Practices must increasingly consider resilience to flooding, storm surge, wildfire, sea-level rise, drought, and other extreme events.[33,46] Climate-driven changes can affect metal mobility by altering water levels, pH, salinity, redox conditions, erosion, sediment transport, and organic matter cycling. They can also alter exposure pathways and ecological sensitivity or disrupt engineered controls, treatment systems, and long-term stewardship.[33,47] Remedies that depend on permanent containment or stable geochemical conditions will therefore require resilience to uncertain and potentially extreme climate events.

Growing demand for elements classified as "critical minerals and materials" introduces a new generation of potential metal contamination. These elements are used in batteries, renewable energy, electronics, defense technologies, and other advanced applications, and are driving expansion of mining, processing, recovery, and manufacturing. Among the metals identified as critical for the US[48] and EU,[49] Sb, Co, Li, Mo, W, and Tl warrant particular attention because of their toxicity, environmental persistence, or increasing production. Of this list, Sb and Tl are regulated in US drinking water, whereas the others are not.[50] For rare earth elements (REEs) and other prominent but less toxic critical metals, environmental and health impacts stem from extraction and recovery involving large-scale releases of acids and solvents, waste generation, and landscape disruption. These impacts are particularly acute where extraction occurs illegally or with limited environmental oversight, as reported in Myanmar and parts of Southeast Asia.[51,52]

Experience with legacy metal contaminants and knowledge of their biogeochemical behavior can help anticipate and prevent new problems. Antimony, for example, is used in flame retardants, plastics manufacturing, pigments, glass, ceramics, and metal alloys.[53,54] It has similar chemical behavior to As but may be more toxic depending on its chemical speciation.[53,54] However, the crustal abundance of Sb (~0.2−0.5 ppm) is roughly an order of magnitude lower than that of As,[55] making it unlikely to accumulate in groundwater from natural sources like As. New Sb pollution may result from industrial releases, leaching from waste plastics, or or as a byproduct of mining and separation.[56] Knowledge developed for As speciation, sorption, redox transformation, and treatment can help inform management of Sb-containing materials and wastes.

Similar analogies apply to other emerging metals. The oxyanion chemistry of Mo[57] and W[58] shares characteristics with Cr, while Co[59] resembles Ni in many sorption and mineral partitioning reactions. However, Li presents a more distinctive challenge. It generally occurs as the highly soluble Li^+ ion, which does not undergo environmentally important

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Environ. Sci. Technol. 2026, 60, 31252−31262

redox reactions and has relatively limited precipitation or strong sorption mechanisms under common groundwater conditions.[60,61] As Li extraction, processing, battery manufacturing, and recycling expand, contamination in relatively mobile aqueous plumes may occur, for which conventional immobilization approaches are less effective. In addition to the better design of pollution prevention, recycling, and waste management systems, chemical similarities can also be exploited in the development of sustainable practices for extraction, recovery, and use of critical metals. International sustainable-mineral standards and initiatives emphasize innovation, supply chain transparency, environmental performance, market competitiveness, and stronger regulation of informal or illegal activities.[62] Such measures are protective of human and environmental health and likely to be more economical than cleanup of new metal contamination.

For both legacy and emerging hazardous metals, new sites of large-scale metal pollution will be discouraged in many countries by the combination of environmental regulations and enforcement, public demand for green and sustainable practices, and more favorable economics for recycling and reprocessing. New metal pollution is more likely to be dispersed and sourced from the informal economy, especially from unregulated or illegal activities. At large, expensive legacy sites, government intervention and funding are vital for cleanup to achieve site closure or appropriate land reuse, but remediation and redevelopment goals will not be successful without strong stakeholder engagement and a knowledgeable local public. Under-resourced governments will need assistance from wealthy nations to implement sustainable practices that are resilient to climate change and can effectively curb metal pollution and exposure risk. The polluter-pays laws that followed the environmental crisis of the 1970s were considered a bold rebuke to uncontrolled industrial pollution and attempted to hold polluters accountable.[3] While not entirely successful, they were a key provision in establishing a strict, transparent framework for environmental regulations in many nations and for setting public expectations and trust in environmental quality standards and remediation actions.

The challenges posed by persistent metals have therefore evolved rather than disappeared. Five decades of research and practice have greatly improved our understanding of contaminant behavior and advanced the development of treatment technologies and risk management. However, national and international funding, initiatives, and enforcement remain essential for addressing legacy contamination and preventing new metal pollution. Combining remediation technologies, meaningful stakeholder engagement, economic incentives, climate-resilient design, and sustainable practices offers a path toward limiting new metal contamination and reducing long-term human and ecological risks.

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Author Contributions

All authors contributed to the writing of the manuscript and approved the final version.

Notes

The authors declare no competing financial interest.

Biographies



Peggy A. O'Day is a Professor in the Department of Life and Environmental Sciences at the University of California, Merced. She joined the new Merced campus as a Founding Faculty member in 2003 from Arizona State University, where she was an Assistant and Associate Professor in the Departments of Geology and Chemistry and Biochemistry. She is an environmental geochemist who studies the chemistry, reactivity, transport, and biogeochemical cycling of metals and inorganic species. Over her career, she has pioneered the development and application of synchrotron X-ray spectroscopic techniques to study element speciation and molecular-scale bonding and transformations in complex environmental media. Her work spans from basic to applied and integrates laboratory experiments, field studies, and geochemical modeling. Her collaborative research projects have included studies of metal sorption and coprecipitation on mineral surfaces, environmental speciation and cycling of contaminant metals and metalloids, mechanisms and rates of uranium oxidation and mineral dissolution, metal speciation and availability in airborne particles, and novel remediation approaches and amendments for arsenic and mercury in soil and sediment. During her time at UC Merced, she has been a leader and contributor in academic and institutional program-building through many department, university, and academic senate roles.



Marc Beutel is a Professor of Environmental Engineering at the University of California, Merced, and a licensed professional engineer in California. Dr. Beutel studies how chemical and biological processes affect water quality in lakes, reservoirs, wetlands, and

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other managed surface waters. His research focuses on practical ways to control dilute pollutants, including nutrients, metals, pesticides, and pathogens. His research also focuses on how redox conditions govern contaminant cycling in sediments and overlying water. His work has examined reservoir oxygenation to limit internal nutrient loading and mercury bioaccumulation, constructed wetlands for removing pollutants from urban and agricultural runoff, and the use of activated carbon to remediate mercury-contaminated soils. By connecting field measurements, experiments, and engineering interventions, his research aims to help water managers protect aquatic ecosystems and drinking water supplies.



Dimitri Vlassopoulos, Ph.D., is a Principal Scientist and Project Director at Anchor QEA specializing in environmental geochemistry, contaminant fate and transport, reactive transport modeling, and *in situ* remediation of contaminated groundwater, soil, and sediment. He integrates aqueous and mineral geochemistry, laboratory experimentation, mineralogical and spectroscopic characterization, and numerical modeling to understand contaminant mobility, evaluate natural attenuation, and assess long-term remedy performance. He has particular expertise in metals and metalloids, and in the coupled effects of mineral reactions, sorption, redox processes, and microbial activity on chemical behavior. As a leader in Anchor QEA's Environmental Geochemistry Laboratory, he has developed geochemically engineered remedies that deliberately manipulate subsurface mineralogy and biogeochemistry to achieve durable contaminant attenuation. This research includes redox-active mineral amendments for mitigating sulfide production and mercury methylation in sediments, mineral systems for long-term pH buffering, stimulation of in situ biogenic sulfide formation for contaminant immobilization, and layered double hydroxides for treatment of mixtures of inorganic pollutants. His work bridges fundamental geochemistry and hydrology with practical remediation by translating laboratory-derived mechanisms into predictive models and field-scale remedy designs that leverage natural processes to optimize effectiveness and sustainability.

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■ ADDITIONAL NOTE

[1]Herein referred to as "metals"; discussion of radioactive metals is beyond the scope of this article and not included.

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