Nature-based solutions for mine water challenges: Linking mining reclamation, environmental remediation, ecological restoration, and sustainable resource extraction

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Abstract

In response to the unprecedented environmental challenges of the 21st century, proposed solutions incorporating the terms "nature" and "natural" have become ubiquitous in the scientific literature and the popular press. Some relevant recent terms include nature-based solutions (NBS), natural infrastructure (NI), and natural and nature-based features (NNBF). In the mine water community, passive treatment systems are prime examples of these applications, although not typically referred to in this manner. The role of NBS and related efforts is especially relevant in the mining sector, as the global transition to a renewable energy economy requires continued resource extraction, despite decarbonization efforts. Reclamation of mined lands and waters is particularly difficult at sites requiring remediation of hazardous materials. In addition, successful reclamation often does not lead to acceptable ecological restoration. NBS, which inherently recognizes the interdependencies of humanity and nature, may be key to linking mining reclamation, environmental remediation, ecological restoration, and sustainable resource extraction. Much can be learned from existing NBS applications at derelict mine sites. The Tar Creek (Kansas-Oklahoma, USA) watershed of the abandoned Tri-State Lead-Zinc Mining District is a test bed exploring the links between reclamation, remediation, restoration, and potential future resource extraction. Remediation of source materials has increased dramatically in the past decade and has resulted in the reclamation of previously derelict lands to agricultural uses. Two full-scale mine water passive treatment systems have been installed to address some source waters, producing circumneutral pH, net alkaline effluents containing ecotoxic metals concentrations meeting in-stream water quality criteria. The receiving stream has demonstrated substantial water quality improvement and ecological recovery, with documented increases in both fish species richness and abundance, as well as the return of North American beaver and river otter. The potential for resource recovery from both passive treatment residual solids and the remaining abandoned mining wastes is being explored. By taking a nature-based solutions approach, legacy mine sites may be able to be restored to functioning ecological systems while closing the resource recovery loop by informing future resource extraction via waste recycling or sustainable mining efforts. The mine water community is well-served by understanding and incorporating NBS, NI, NNBF and related ideas into life of mine planning.

Keywords: Ecological engineering, natural infrastructure, passive treatment, ecosystem services

Introduction

Although often used interchangeably, the terms reclamation, remediation, and restoration have quite distinct definitions, especially in the mine water community. Reclamation simply describes the recovery of mined lands and waters to a regulatorily approved post-mining use, which may or may not be similar to the original pre-mining landscape (e.g. OSMRE 2024). Environmental remediation specifically refers to actions taken to address the release of hazardous materials likely affecting human health and the environment (e.g. USEPA 2024) and often includes removal and/or containment of contaminants from soil, sediment, ground water and surface water. Ecological restoration was quite generally defined by the Society for Ecological Restoration (2004) as the process of assisting recovery of ecosystems that had been degraded, damaged, or destroyed. However, Martin (2017) amended this definition to include a reflection of "values regarded as inherent in the ecosystem and to provide goods and services that people value". The United Nations Environment Programme (UNEP 2021) defines ecosystem restoration as assisting in recovery of degraded or destroyed ecosystems as well as conserving intact ecosystems. UNEP declared 2021–2030 as the UN Decade on Ecosystem Restoration, the end of which coincides with the deadline for the UN Sustainable Development Goals.

While interrelated, reclamation, remediation and restoration do not refer to identical actions nor do they imply identical objectives on a site- or project-specific basis. In addition, none of these terms explicitly includes a forward-looking approach to examine resource recovery and sustainable resource extraction, an area of special interest to the mining and mine water communities. The purpose of this paper is to examine the potential benefits of recognizing a holistic and flexible nature-based approach to mine water and waste management. An umbrella approach incorporating aspects of mining reclamation, environmental remediation, ecological restoration, and sustainable resource extraction (withdrawal of materials from the environment for human use) is proposed and a site-specific case study is provided.

Proposed Approach

The unparalleled environmental challenges of the 21st century, including complex and interrelated issues like human overpopulation, climate change, resource scarcity, energy supply and consumption, social equity, and waste generation, require innovative and sustainable solutions. Proposed solutions incorporating terms like "nature" and "natural" have become ubiquitous in both the scientific literature (e.g. Quintero-Angel 2023) and in the popular press (e.g. GMR 2023) in recent years.

Nature-based solutions (NBS or NbS) are "actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature" (IUCN 2023). Natural infrastructure (NI) refers to "the use of preserved, restored or enhanced elements or combinations of vegetation and associated biology, land, water and naturally occurring ecological processes to meet targeted infrastructure outcomes" (CCME 2018). Natural and nature-based features (NNBF) use "landscape features to produce flood risk management benefits; these landscape feature may be natural (produced purely by natural processes) or nature-based (produced by a combination of natural processes and human engineering)" (Bridges et al. 2021). Although characterisations vary somewhat by application, these widely accepted definitions share a common focus on fostering natural processes to benefit human society.

However, the idea of working with as opposed to against natural phenomena is neither new nor a response solely to current environmental challenges. Since the 1960s, Odum postulated that sustainable environmental solutions required a thorough understanding, appreciation, and managed use of ecosystem biogeochemical mechanisms (e.g. Odum 1962, 1963, 1971) that could provide substantial human benefits with relatively modest external energy inputs (Odum 1988). Eventually, the academic discipline of ecological engineering, formally defined by Mitsch and Jørgensen (2004) as "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both was developed and is now well-established at several universities around the world."

This general approach is not unfamiliar to the mine water community, although perhaps using different terminology. Early passive treatment work, as cited by Kleinmann et al. (2021) demonstrates mine water-specific applications of ecological engineering. The mine water community was designing, building, and evaluating NBS decades before the term became commonplace. Although this statement is justifiably valid, one may argue that the mine water community would be well-served by further understanding and clearly incorporating current terminology (NBS, NI, NNBF, and related ideas) into mine planning and reclamation. The NBS approach comprehensively incorporates established practices to reach multiple objectives in an effective manner (Fig. 1). Several reasons for this postulation are provided.

First, successful reclamation (and remediation and restoration) planning must strive to achieve holistic and sustainable goals, while achieving cost-effectiveness. However, at many US EPA mining waste Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) sites, contaminant remediation activities (Remedial Actions focused on current and prospective risk to human health and the environment) are wholly separate from attempts at ecosystem restoration (Natural Resource Damage Assessment and Restoration), requiring lengthy, costly, and duplicative efforts. An inclusive NBS approach could be effective.

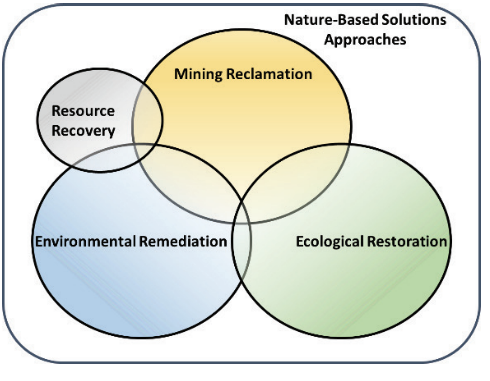

Figure 1 Conceptual Venn diagram demonstrating how the nature-based solutions approach can holistically incorporate reclamation, remediation, restoration, and resource recovery for mining applications. The relative magnitude of the individual overlapping areas reflects the current state of practice, which is hypothesized to collapse into the single outer box as these approaches evolve

Second, existing mining related NBS, like passive treatment systems, produce multiple, yet often unquantified, co-benefits (e.g. Sobolewski and Sobolewski 2022). In addition to the water quality improvement function for which they were designed, these systems provide regulating, provisioning, supporting, and cultural ecosystem services which are increasingly recognized and valued (Costanza et al. 2017). Quantification of ecosystem services through an NBS approach incentivizes widespread application and produces multiple and varied benefits.

Third, NBS approaches can assist in closing the resource recovery loop. The accumulation of relatively dense mine drainage residual solids from mine waters (e.g. iron oxyhydroxides and metal sulfide precipitates) in specific passive treatment process units provides potential source material for sustainable reuse or resource extraction (Tang and Nairn 2021, Dorman and Nairn 2023). In addition, the renewable energy economy requires substantial quantities of several critical minerals, a need that is likely unreachable solely via commercial recycling (NRC 2008). In addition to new sustainable mining, recovery of minerals in existing and derelict mine wastes may provide an alternative approach which could be combined with needed remediation and restoration efforts, thus co-producing an economically viable NBS approach.

Fourth, as NBS have gained global acceptability, the mine water community must recognize the resulting availability of dedicated resources. In the United States, the current Presidential administration has provided NBS-specific guidance and associated funding for multiple federal agencies and programs, including the Department of the Interior (The White House 2023). In addition, the U.S. Army Corps of Engineers "Engineering With Nature"

(EWN) initiative, begun over a decade ago to promote the "intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration" (Bridges et al. 2018), has resulted in the Network for EWN, an active and diverse consortium of researchers and practitioners. The European Union, United Kingdom, Australia, and other nations have made similar commitments to NBS (EC 2024, STSC 2022, DFAT 2024).

By taking a nature-based solutions approach, active and legacy mine sites may be able to be restored to functioning ecological systems while closing the resource recovery loop, which informs future resource extraction, whether it be via waste recycling or sustainable mining efforts. The mine water community is well-served by understanding and incorporating these ideas into life of mine planning.

Case Study

The Tar Creek (Kansas-Oklahoma, USA) watershed of the derelict Tri-State Lead-Zinc Mining District may be considered a test bed to explore links between mining reclamation, environmental remediation, ecological restoration, and sustainable resource extraction (Fig. 2). It must first be noted that the NBS approach has not been holistically implemented in this watershed. Administratively, efforts since the early 1980s have focused on traditional approaches to reclamation and remediation. However, several innovative research efforts provide insight into the potential of the NBS approach. Both the Tar Creek Superfund Site (Oklahoma) and the adjacent Cherokee County Superfund Site (Kansas) have been on the National Priorities List since 1983.

At this time, large piles of processing and beneficiation waste materials, contaminated by elevated concentrations of zinc, lead, and cadmium, are considered potential sources of construction aggregate, mainly for asphalt production (Wasiuddin et al. 2010). This approach has proven to be a safe and effective recycling of mining waste materials and has been incorporated into CERCLA Records of Decision (USEPA 2008). However, these materials must be size separated, and substantial quantities remain unusable for this purpose. The remaining smaller size fractions typically contain greater trace metals concentrations (Datin and Cates 2002). In addition to lead and zinc, Andrews et al. (2013) found that concentrations of aluminium and titanium were sufficiently elevated to be economically recoverable. In recent years, exploration for recovery of rare earth elements and other critical minerals in these wastes has accelerated (White et al. 2022). If resource recovery and extraction were to be proven sustainable, concurrent or subsequent land reclamation is still necessary. An NBS approach holds promise for provision of multiple benefits.

The pace of land reclamation activities in the Tar Creek and adjacent watersheds accelerated greatly after 2013 when the U.S. Environmental Protection Agency issued the first ever tribally- led remedial response cooperative agreement to the Quapaw Nation (USEPA 2015), a sovereign Indigenous tribe removed to Oklahoma in the 1830s. Since 2013, the Quapaw Nation, through the subsidiary Quapaw Services Authority, has removed more than 7 million t of source material and reclaimed more than 250 ha, much to agricultural land use. These amounts represent nearly 90% of all source material remediation since 1983. Prior to 2013, remedial action agreements were issued to private sector firms. Although specific activities are constrained by traditional CERCLA agreements, the role of the NBS approach is recognized by the Quapaw Nation who have expressed interest in incorporating traditional ecological knowledge into future restoration activities. Although land reclamation is critical to eventual ecological restoration, the relatively massive (100 million m^3) contaminated mine pool continues to contribute to surface water quality degradation, as it has for decades.

Water quality in Tar Creek and its tributaries is influenced by artesian discharges of mine water from underground mine workings, runoff and leachate are from mine wastes in large piles on the surface, and mine wastes washed into stream channels. Two full-scale mine water passive treatment systems were installed in 2008 (UT1) and 2017 (UT2) to address artesian discharges in a small unnamed tributary watershed. Both systems effectively and consistently produce circumneutral pH, net alkaline effluents containing ecotoxic metals concentrations meeting in-stream water quality criteria (Nairn et al. 2023). Conceptual designs have been completed for a third passive treatment system (Shepherd 2022) to address the greatest volume discharges in the watershed. If implemented, the resulting passive treatment system, receiving up to 200,000 m^3/d, would arguably represent the largest such system on Earth.

Substantial mass retention of targeted constituents (Table 1) provides an opportunity for either direct resource recovery or beneficial reuse. One promising approach for accumulated iron oxyhydroxide residuals is potential reuse as anionic sorbents, especially phosphate (Tang and Nairn 2021, Dorman and Nairn 2023). Tang (2020) found that Tar Creek mine drainage derived iron oxyhydroxide residual solids retained nearly 35,000 mg P/kg, compared to 7,000 mg P/kg for a local lake sediment. As an example of closing the resource recovery loop, solids obtained from passively treated mine waters may be reused to treat nutrient-rich waters from agricultural or municipal wastewater sources.

From an ecological restoration perspective, installation and operation of passive treatment systems in the unnamed tributary watershed resulted in substantial water quality improvement and ecological recovery. In-stream metal concentrations regularly meet hardness-adjusted acute and chronic aquatic life criteria. Depending upon sampling site, fish species richness has increased from as low as 3 to as high as 20 species, and the dimensionless Shannon Diversity Index for fish has increased from 0.2 to nearly 2. In addition, North American beaver and river otter communities have repopulated the watershed.

Conclusions

New paradigms are essential for sustainably addressing the complex and interrelated challenges of 21st century mining and mine water management. A holistic and flexible nature-based approach potentially

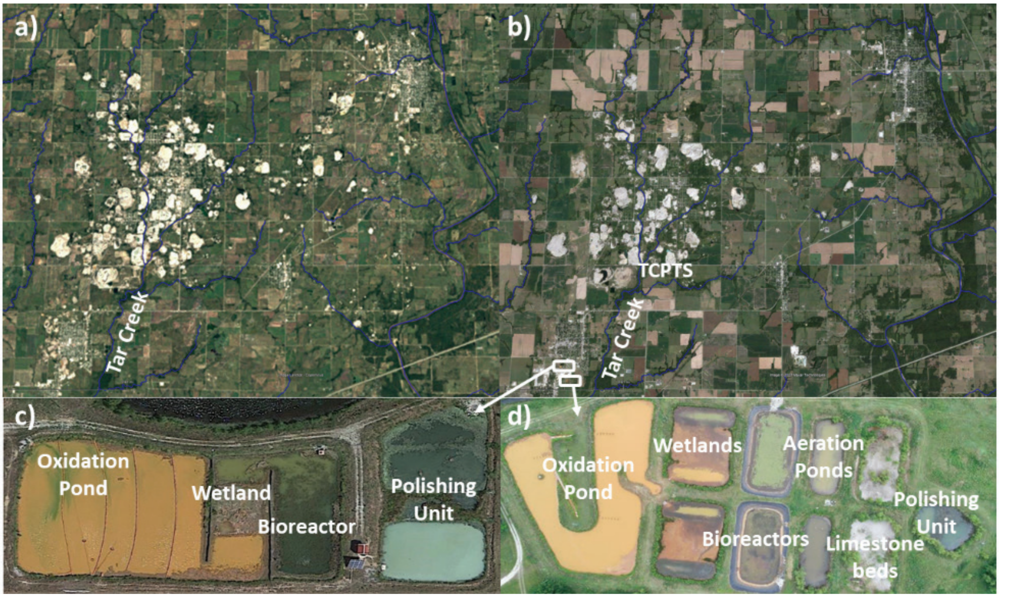

Figure 2 a) 2003 aerial photo of Tar Creek watershed showing extensive surface waste materials, b) 2023 aerial photo of Tar Creek watershed showing progress in distal clean-ups and remaining core waste material, c) UT2 passive treatment systems process units and d) UT1 passive treatment systems process units. Location of additional proposed passive treatment system is shown as TCPTS provides an efficient model to attain multiple reclamation, remediation, restoration, and resource extraction objectives. Much can be learned from existing NBS applications at derelict mine sites, like the Tri-State Mining District of the central United States where environmental remediation and ecological restoration have been successfully coupled. Nature-based solutions, based on a thorough systems-based comprehension of interrelated hydrological, biogeochemical, ecological, and related processes, are key to sustainable management of mining landscapes.

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Table 1 *Estimated mass retention (kg/yr) of selected trace metal contaminants for existing (UT1 and UT2) and planned (TC1) passive treatment systems (year of implementation) in the Tar Creek watershed*

	UT1 (2008)	UT2 (2017)	TC1 (planned)
Fe (kg/a)	37000	35000	59000
Zn (kg/a)	1550	1580	13000
Pb (kg/a)	20	64	122
Cd (kg/a)	3.3	5.0	43

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