

REVIEW

Beyond Closure: Systems-Based Approaches to Long-Term Geological and Ecological Management of Abandoned Mines

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ABSTRACT

Abandoned mines are timeless legacy landscapes in which the interactions of geological instability, hydrogeochemical contamination, ecological degradation, and government failure collide over a long period of time. Traditional mine closure models have enhanced post-operational rehabilitation, but in most cases, they still focus on endpoint compliance and are limited in the case of abandoned/orphaned mines, which grow decades after mining stops. It is a review that can shift towards a systems-based approach to the problem, in which the abandoned mines are not seen as individual technical threats, but as complex socio-ecological-geological systems. It is a synthesis of the long-term legacies of landform instability, subsidence, acid and metalliferous drainage, groundwater rebound, soil degradation, habitat fragmentation, and constrained ecological succession, and gives greater focus to the feedbacks between these processes. The review also discusses conceptual assumptions underlying stewardship-oriented management: systems thinking, resilience, vulnerability, adaptive capacity, and risk-based decision models. It then weighs the major long-term management approaches and tools and includes the site characterization, monitoring networks, remote sensing, predictive modeling, multi-criteria decision support, and threshold-based early warning systems. Based on this synthesis, the article suggests the integrated pathways of management, which integrate the source control, passive and active treatment, geomorphic design, restoration of the ecological, and active climate adjustment, and stable governance mechanisms. The main thesis is that the management of abandoned mines needs a shift in the approach towards closure to the approach towards stewardship that is long-term, adaptive, and interdisciplinary. This is a more realistic approach to mitigating the risks of legacies and is used to steer the

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resilient post-mining landscape futures.

Keywords: Abandoned Mines; Long-Term Stewardship; Socio-Ecological-Geological Systems; Mine Legacy Risk; Adaptive Management

1. Introduction

One of the most tenacious anthropogenic imbalances in the Earth system is abandoned mines^[1]. In both the historically industrialized and the rapidly developing world, tens of thousands of abandoned and orphan mines still have continuing effects on the environment, geomorphology, hydrology, and ecology long after they were abandoned^[2,3]. These effects are far-reaching in their effects on the operation of a mine, and they frequently have an outliving effect on the institutional set-up that is meant to control it. The post-closure anomalies are not isolated, however, as they are all manifestations of the long-term coupled processes that run at geologically, hydrologically, biologically, and socially different times. In this respect, one should not perceive abandoned mines as mere industrial sites, which are closed, but a developing landscape system whose risks and recovery patterns continue to operate for decades or centuries^[4].

The practice of mine closure that has been done traditionally has yielded significant achievements in engineering design, land rehabilitation, and regulatory compliance^[5]. But the majority of closure paradigms stick to the project-based logic of the assumption about a change in active management into the comparative environmental stability after the completion of capping, grading, revegetation, and water control activities. This is typically not a sufficient method on an abandoned mine, where the operator is not present in good faith, records might be fragmentary, and man-made controls are likely to be eroded during the long-term weathering, climate changes, and social decay^[6]. Additionally, closure plans have frequently been formulated in the contexts of disciplinarity: geotechnical stabilization is discussed without reference to hydrogeochemical control, ecological restoration is discussed without reference to contaminant fluxes, and long-term governance is discussed when technical measures have already been determined. This fragmentation restricts our capacity to predict emergent acts, late failures, and cross-system responses that generally predetermine whether post-mining terrains are degraded, stabilized,

or recovered^[7].

This is particularly a sharp dilemma due to the fact that abandoned mines represent coupled socio-ecological-geological systems. Waste landforms are constantly changing physically and chemically; groundwater bounces back and redistributes contaminants; soils are structurally and chemically constrained; ecological communities adjust to toxicity, hydrological stress, and habitat fragmentation; human institutions have to deal with gaps in liability, incompatibilities of land uses, uneven monitoring, and intergenerational stewardship liability^[3,8,9]. An example is a tailings impoundment, which is not just an engineered structure that may either erode or burst open. It is also a geochemical reactor, a source of sediments, a hydrological control point, a barrier or substrate of ecological colonization, and a socially controlled hazard whose management is dependent on financial support, continuity of policy, and trust of the people^[10]. Likewise, the ecological restoration of the former mine areas cannot be minimized to the success of revegetation since the establishment of vegetation is strictly regulated by the geochemistry of the substrate, soil development, the availability of contaminants, drainage characteristics, and the recurrence of disturbances. It is not any single intervention that is going to result in long-term performance, but rather the interplay between different subsystems.

Resilience thinking, nature-based solutions, adaptive management, and climate-informed remediation in contaminated and degraded landscapes have been growing in attention over the past years^[11]. Nevertheless, the state of the literature on the management of abandoned mines is still scattered among mining engineering, hydrogeology, environmental geochemistry, geomorphology, restoration ecology, analysis of risks, and environmental governance. Consequently, review research studies tend to prioritize a particular type of dominant problem area, such as acid mine drainage treatment, tailings stability, revegetation, or policy reform, without paying sufficient attention to the intersection of these areas on long-term time scales^[12,13]. This opens a serious gap in knowledge. The essence is no longer merely how to

close mines in a more successful way, but how to control and administer the abandoned mine landscapes when the closure has failed, changed, or become obsolete or simply inadequate to the environment. To answer this question, it is necessary to move away from systems-based long-term stewardship at the endpoint of remediation.

It is based on that change that inspires this review. It asserts that the management of abandoned mines needs to be re-packaged beyond the limited closure compliance response to an active, systems-oriented process of geological and ecological custodianship^[14]. Beyond closure is here used to encompass a transition, both temporal and conceptual. Time-wise, it understands that risks remain unresolved even after

official milestones of formal closure have been achieved. The conceptual representation of the systems-based framing taken in this review is presented in **Figure 1**. Theoretically, it highlights that mine disturbance does not attain closure, but is just a single stage in the ongoing process of landscape transformation. In this approach, long-term management has to deal with changing landform instability, hydrochemical change, ecological succession, infrastructure decay, and fluctuating climatic and socio-political conditions^[15,16]. This kind of interaction necessitates the incorporation of monitoring, feedback-prone risk evaluation, a flexible intervention pathway, and institutional machinery that is capable of functioning cross-generationally.

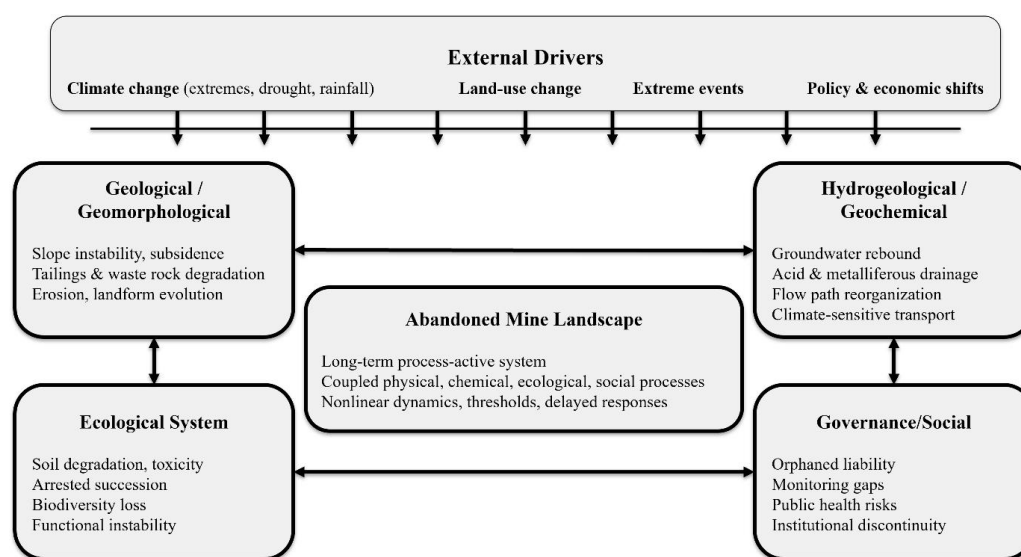


Figure 1. Conceptual framing of abandoned mines as coupled socio-ecological-geological systems influenced by environmental and governance drivers.

This article is innovative in its clear synthesis of abandoned mine management as a geological-ecological system of interactions as opposed to a complex of coexisting technical issues. To begin with, this review unifies geotechnical, hydrogeological, geochemical, and ecological studies in one conceptual model based on coupled processes, feedbacks, thresholds, and path dependency^[17]. Rather than considering slope stability, contaminant release, and ecosystem recovery as some discrete review themes, we consider their co-production of long-term site trajectories. Second, the article does not just focus on environmental processes only, but introduces governance, continuity of monitoring, and capacity of stewardship as inherent performance aspects within systems and not issues of external implementation. The rea-

son is that most of the most dangerous risks occurring at the abandoned mines are not only due to the biophysical hazards, but also due to the deterioration of responsibility, funding, and adaptive response^[18].

Third, the review highlights the timescale mismatch as one of the central issues that is under-examined. Intervention engineering projects can take decades to be planned and financed, as opposed to geochemical weathering, groundwater rebound, geomorphic adjustment, and ecological succession, which may take centuries or more^[12]. Systems of control can also allow the closure to be certified in the context of the short administrative horizon, despite the dynamically unstable or chemically active site. The paper provides a more realistic foundation of post-closure success and failure by pointing

out the mismatch. Fourth, through the review, a facilitated hybrid administration approach of bridging engineered control and ecological process is accelerated. Instead of pitting hard engineering and ecological restoration in opposition to each other as competing strategies, we consider the combination of passive treatment systems, revegetation, redesign of landforms, hydrological reconnection, soil reconstruction, and long-term containment in adaptive forms, which enhance resilience to uncertain future conditions^[19,20].

Another value of this review is that it has narrowed down on abandoned mines in particular, and not mine closure in general. Unoccupied and orphaned sites are a special challenge: incomplete background information, run-down or unaltered infrastructure is present, there lacks any corresponding accountable operator, contaminating sources are diffusely spread, and they are often overlapped with occupied or redeveloped landscapes. These are such that even standard closure models cannot be transferred directly. This paper focuses on a group of sites in which long-term stewardship is hardest, most neglected, and least socially consequential by focusing on abandoned mines. It also presages the relevance of retrospective system reconstruction with the help of historical records, remote sensing, field diagnostics, and proxy indicators, where formal documentation of closure does not exist^[21,22].

This reframing is further added with urgency caused by climate change^[23]. Increased precipitation, drought periods, wildfire, and thawing permafrost in cold areas, as well as changes in vegetation cover, are expected to change the erosion rates, drainage chemistry, containment activity, and ecological recovery processes in the abandoned mine sites. Such pressures may revive features that were initially suppressed but will aggravate latent hazards. The systems-based approach is thus not integrative in an academic sense only, but it is required for the predictive capacities of nonlinear responsiveness and cascading risks, given the changing environmental circumstances. Long-term management should not be strong as per the familiar contamination and stability issues, but also the uncertainty of the future^[24].

It is on this background that the objectives of this review are threefold. The former is to harmonize the major long-term geologic, hydrogeochemical, and ecological inheritances of the deserted mines as interlinked procedures^[25]. The second is to review theoretical and practical models of

the support of systems-based management, such as the idea of resilience and adaptive monitoring, risk-based decision-making, and the design of restoration (integrated restoration)^[26]. The third is to pinpoint significant research and governance gaps that thwart the practicality of long-term stewardship of the future, and to present that which should be a more consistent interdisciplinary agenda^[27]. In this way, this article will not only add to the literature synthesis but also to a conceptual reorientation of the way the abandoned mine landscapes are understood and dealt with.

This review synthesizes peer-reviewed literature on long-term management of abandoned mines, with emphasis on systems-based approaches integrating geological, hydrogeochemical, ecological, and governance dimensions. A systematic literature search was conducted using Web of Science, Scopus, and Google Scholar databases for the period 2000–2025. Search terms included combinations of: “abandoned mines,” “orphan mines,” “mine closure,” “long-term stewardship,” “acid mine drainage,” “post-mining landscape,” “ecological restoration,” “mine legacy,” and “adaptive management.” Additional articles were identified through citation chaining and gray literature from international mine closure conferences (2006–2025). Inclusion criteria were: (1) focus on abandoned/orphaned (not active or recently closed) mines, (2) temporal perspective beyond 10 years post-closure, (3) relevance to coupled physical-chemical-biological-social processes. Exclusion criteria removed studies limited to active mine operations, single-event acute disasters without legacy context, and purely engineering designs without environmental or temporal dimensions. From an initial 847 identified records, 148 sources were selected for full review based on relevance, methodological rigor, and contribution to systems-based frameworks.

Overall, the main idea of this review is that the long-term issues of abandoned mines cannot be resolved by using isolated technical solutions or closure-based regulatory reasoning. They need long-term thinking that treats mines as changing landscape systems where geological processes, pathways of contaminants, ecological recovery, infrastructural deterioration, and institutional capacity are closely interwoven^[7]. The originality of this paper is that it attempts to state that connection as the basis of a systems-based model of post-abandonment management. The review aims to offer a more integrative approach to the identification of risks that

legacy mines present, and, in the design of management approaches, which are scientifically sound, ecologically knowledgeable, and longer lasting than the temporal scales that the abandoned mines require.

2. Long-Term Legacy Risks of Abandoned Mines as Coupled Socio-Ecological-Geological Systems

Abandoned mines are frequently spoken about in discrete terms of hazard, i.e., acid mine drainage, slope instability, or vegetation failure^[18]. Although these types of categorizations are analytically helpful, they have the potential to obscure the fact that the long-term risk at abandoned mine sites is often caused by a single process working alone. Instead, these landscapes are coupled socio-ecological-geological systems where geomorphic adaptability, hydrogeochemical development, ecological succession, and governance potential interact over long time periods. The mine legacies that have remained are not only due to the magnitude of the disturbance at its inception, but also because the physical, chemical, and biological processes are constantly dynamically interrelated following the end of the operations. In most instances, it is not the acute disaster but long-term instability that defines the nature of abandoned mine risk: a situation where the location appears inert, yet gradually reorganizes during degradation, failures with intermittent outbursts, and delayed contaminant escape^[12].

It is the coupled-systems perspective that is of particular significance since the abandoned mine sites often outlived institutional frameworks that created them, governed them, or even remediated them in part^[28]. After active management finishes, engineered cover, drainage systems, waste repositories and revegetated surfaces become progressively more reliant on environmental variability, as well as self-organizing ecological processes. However, it is these same processes that are limited by substrates that are chemically toxic, hydrologically perturbed and structurally unstable. The outcome is a group of mutually reinforcing legacy risks. Sulfide-rich materials can be subject to oxidation in geological instability; soil formation and plant establishment can be hampered by hydrogeochemical change; underperformance of ecology may result in a decrease of slope protection and erosion; and poor monitoring or fragmented governance may pro-

vide the opportunity for small failures to become long-term landscape-scaled problems. These interacting risks are discussed in more detail below^[29–31].

2.1. Geological and Geomorphological Legacies

Geological heritage of the old mining is not merely kept in excavation holes or the heaps of waste that are deposited on the surface of the land. This radical restructuring of topography, underground structure, drainage connectivity, and sediment supply, as a result of mining, results in post-mining landscapes that are still continually changing long after mining has stopped^[16]. Most open pits, underground workings, spoil heaps, tailings impoundments, and waste-rock dumps are usually in metastable conditions and their long-term behaviour is influenced by weathering processes, settlement, subsidence, erosion and change in hydrology^[32]. The difference between these post-mining landforms and natural geomorphic systems lies not only in the fact that they are man-made, but also the fact that they often combine steep gradients, unconsolidated materials, geochemical reactivity and the lack of internal drainage control. They seem to be stable at the time of abandonment hence this does not give a great prediction of long-term performance.

Abandoned mines have one of the most enduring geomorphological impacts by causing a progressive erosion of engineered or semi-engineered landforms of waste^[33]. Tailings deposits and waste-rock piles are frequently constructed or placed based on short to medium-term operational requirements, and not on the landscape evolution over the century. Fine grained ones could experience surface sealing, gully, desiccation cracking, internal piping or differential settlement over a period of time. Rougher dumps of waste-rock may be subject to ravel, erosion of toes, steepening of the slope, and local collapse, particularly where drainage channels are blocked or diverted^[34]. These processes are not surface manifestations of infrastructural ageing; they are processes by which the contaminants that were stored, are now able to be mobilised, and the exposure pathways are produced. The geomorphic change, in this case, also serves as a hazard by itself, as well as a cause of deterioration of hydrochemical and ecological conditions.

Subsidence is another long-term geological hazard, especially in regions of old underground mines^[35]. The de-

layed failure of pillars, roof spans or shallow voids can cause ground deformation that affects soils, alters the drainage systems, disturbs the infrastructures and causes safety risks to the people living around the areas. Notably, subsidence is usually spatially heterogeneous and temporally lagged and manifests many years after the official termination of mining activity. This delay makes hazard mapping and drawing of the liability difficult. It also brings to the fore a larger issue with post-mining assessment: that only the most serious physical threats are those that can be seen at the time of closure. As a matter of fact, in reality, abandoned mines of geological nature usually suffer a sluggish form of violence, as a result of progressive weakening that goes unnoticed until the encounter of an extreme of rainfall, seismicity, or groundwater rebound, or land-use change^[36].

The most severe concern is that long-term development of mine landforms is often assessed with the help of stable engineering standards, but not with geomorphic arguments^[37]. Stability tests can be used to declare slopes or covers to be satisfactory in their design conditions, but not much care is taken of the behavior of those landforms under a few decades of weather and vegetation succession and altered runoff regimes. This is particularly a problem in abandoned areas where upkeep is not done or is not done consistently. Unless some periodic action is taken, small erosion channels can develop into large gullies, drainage controls can be rendered ineffective and local instability can spread over larger parts of the landscape. Geological legacy risk can thus not be reduced to the issue of whether a structure fails or not, then, in systems terms; it equally exists in whether landforms again reorganize and restructure marginally around and around processes in the environment^[16].

2.2. Hydrogeological and Geochemical Legacies

One of the most long-term and extensively researched effects of mine abandonment is the hydrogeological and geochemical legacy, which is, however, commonly perceived as too limited in scope of water-quality issues^[38]. Actually, post-mining hydrogeochemical transformation can be better conceptualized as a complex of interactive responses and flow-path adaptations that modify the chemistry as well as the geomorphological dynamics of landscapes. Mining changes the connections of the aquifers, pore structures, recharge,

hydraulic gradients and surface-water interactions^[39]. Meanwhile, it opens vulnerable reactive minerals to oxygen and water, creating conditions of acidification, neutralization, release of metal, secondary mineral precipitation, and changes in salinity^[40]. Such processes are not linear. They are seasonally and storm-eventually and decadently saleable, and are heavily dependent on the changing structure of abandoned workings and waste deposits.

The most iconic statement of this legacy is acid mine drainage, though it is not only related to low pH conditions^[41]. The sulfide oxidation causes a series of geochemical reactions that can mobilize iron, aluminum, manganese, arsenic, lead, cadmium, copper, zinc, and other possibly harmful elements^[40]. The resultant pollution may extend to streams, flood plains, wetlands, and the groundwater system way beyond the mine area. Nevertheless, the classical paradigm of acid drainage fails to represent the variability of that of abandoned mine waters. Numerous locations produce circumneutral, yet metal-enriched drainage, salty seepage, or intermittently pulsed loads of contamination that are not so visually noticeable, but equally damaging to the environment. A small concentration of acidity can thus cover up a big chemical danger.

Mine abandonment groundwater recovery is a process that is especially significant but unvalued^[42]. In active operations, natural conditions of hydraulicity are frequently cut off through dewatering. After the cessation of pumping, the water level can come back step by step, rejoining already-isolated mine voids, filling the fractures, and discharging out of new or already-existing openings^[43]. This recovery can mobilize the contaminants that have been stored in underground workings, change redox conditions, and generate delayed pollution pulse in systems downstream. It can also lead to stabilization or destabilization of slopes or foundations due to change in pore pressure. The long-term importance of groundwater rebound is that it has been able to recycle mine landscapes decades or years after being closed, which shows that hydrological recovery does not mean environmental recovery. In deserted environments, rebound often takes place, with no thorough observation, and prediction is hard and early correction is not feasible.

Climate variability and climate change are also important in creating hydrogeological legacies. Intense rainfall may enhance infiltration rates through covers, faster flush-

ing of contaminants, and swamping passive treatment systems^[44]. Drought may lead to concentration of solutes, decrease the treatment capacity of wetlands and destabilize vegetation cover and further rewetting may cause a sudden burst of accumulated contaminants. Thawing of permafrost in cold areas or transport of mostly modified freeze-thaw conditions may lead to disruption of seepage routes and undermining of waste depositories^[45]. These interactions demonstrate that mine water management cannot be treated as a rigid design problem that has stationary boundary conditions. Instead, the abandoned mine hydrogeochemistry is to be perceived as a climate-sensitive system that in the future may behave significantly differently as compared to past monitoring files.

The common weakness of the literature is the disconnection between hydrogeological analysis, geomorphic, and ecological context. Water is commonly observed at the points of discharge, with the changing physical and biological landscape, where water passes through, perceived separately. All, however, are influenced by erosion patterns, substrate development, and vegetation structure in the way flow routing, residence time, attenuation of contaminants, and biological exposures are concerned. A passive treatment wetland, such as that, can be effective, chemically, during a certain period of time and discarded, ecologically, during another period due to changes in its functionality as a result of sediment loading, invasion by invasive species, or short-circuiting of hydrological processes. The critical point is that hydrogeochemical legacies do not just entail the production of contaminants; they entail the reorganization of the connectivity of water across the system of abandoned mines on a long-term basis^[46].

2.3. Ecological Legacies and Constraints on Recovery

Similar to the situation of the old mine sites, ecological degradation is often discussed as an issue of incomplete revegetation or loss of biodiversity, but this overlooks the extent and long-term nature of the effects of the ecological legacy^[7]. Mining disturbs soils, eliminates or transfers levels of seed reserves, divides habitats, disturbs hydrology, causes changes in microclimates, and induces permanent chemical stress^[9]. Such alterations do not merely impact visible vegetation patterns but also affect microbial communities, nutrient cycling, trophic interactions, and successional

dynamics as well. The ecological effects are thus not merely the lack of pre-disturbance ecologies, but rather the result of new and mostly unstable ecological conditions in the face of continuing abiotic limitation.

The soil situations are the key to this problem. A large number of abandoned mine substrates are described as compaction, coarse texture, low organic matter, low water-holding capacity, nutrient deficiency, salinity, or even at toxic levels of harmful elements^[8]. These conditions inhibit the penetration of roots, microorganisms, litterfall, and pedogenesis, therefore, reducing the process of establishing self-sustaining ecological processes. Revegetation can result in a superficial cover of plants with complete functional recovery. A site can be green, and that can be ecologically weak, relying on artificial additions, and be affected by drought, soil erosion, or this contaminant stress. This is a distinction between structural and functional recovery. The continued poor work of an ecosystem can be concealed through visual restoration^[47].

The long-term mine legacies also have an impact on the aquatic and riparian systems^[48]. Metal contamination, changes in the pH, sediment pulse, and modification of the flow may decrease the aquatic biodiversity, simplify the food webs, and interfere with the reproduction or survival of fish, macroinvertebrates, algae, and microbial assemblages. Biological recovery can be slow even in areas where chemical concentrations are declining with time, due to a limited complexity of the habitat, quality of the substrate, or avenues of recolonization^[49]. The recovery patterns due to these types of disturbances are therefore frequently nonlinear and asymmetrical: the effects of pollution may appear quickly, whereas the completion of the ecological reconstruction is slow and disproportionate. This time asymmetry implies that no passive recovery can be presumed even in cases when there is partial success in the contaminant control measures.

The second significant environmental problem is the propensity of the abandoned mine landscapes to take alternative paths of succession^[50]. Natural succession can be frozen, divergent or formulate assemblages of stress-tolerant, invasive or low-diversity communities in highly disturbed or polluted conditions. These communities can offer certain amount of surface stabilization, though they are not always able to recover larger-scale functions of the ecosystem or conservation value. In addition, the desirability of

natural succession as such needs to be subjected to critical analysis. Spontaneous colonization can form potentially beneficial new habitats in a few cases, and it can entrap in some cases the states that continue to bear risks of contamination exposure or are unable to defend themselves against geomorphic instability. Ecology at the mining sites that have been abandoned cannot be based on bare assumptions that disturbance will be corrected over time. Substrate chemistry, hydrological connectivity, landscape position, species pools, disturbance recurrence, and management history are all used as mediators of recovery^[51].

The literature on mine-site restoration has grown considerably, although it still tends to give preference to vegetation establishment as the major indicator of success. It is not surprising that vegetation is visible, measurable, and associated with erosion management. Nevertheless, the assessment of the SCI-level needs to be more critical. Plant cover does not tell us whether or not nutrient cycling is self-sustainable, whether microbial communities are recovering, whether the transfer of contaminants by food webs is decreasing or whether the site is adapting to climatic extremes. Ecological analysis based on systems, however, has to get beyond cover measures to function, connectivity and adaptive capacity measures. Whether an abandoned mine can support plants is not the point of interest, but rather whether it can become an ecologically coherent and dynamically stable landscape under further geological and chemical pressure^[52].

2.4. Human Exposure, Governance Failure, and Socio-Environmental Feedbacks

Human institutions, land use, and social vulnerability cannot be separated from the long-term risks of abandoned mines^[53]. Even though environmental assessments tend to isolate between what could be considered as physical hazards and the social issues, this can be deceptive. The human patterns of exposure dictate the type of mine legacies that become pressing, whereas the quality of governance dictates whether minor issues are being identified at an early stage or letting them snowball. Abandoned mines should thus be viewed not simply as polluted or unstable places, but as socio-environmental systems where the risk is defined by property regimes, regulatory persistence, popular consciousness, technical capacities, and financing schemes^[54].

A clear responsibility breakdown, or lack thereof, is

one of the characteristics of abandoned mines^[14]. The liable operators can be absent from orphaned sites, ownership may be unknown, or jurisdiction may be divided between agencies. It is not a marginal administrative issue that this governance discontinuity takes place; it is a significant force behind environmental persistence. The long-term management needs involve regular check-ups and maintenance of drainage and containment structures, periodical review of site behaviors, and the capacity to take corrective actions before failures have gone out of control. In case of the lack of responsibility or insufficient funding, the management becomes reactive and episodic. Consequently, the abandoned mines are prone to go through a cycle where chronic deterioration occurs until a crisis becomes apparent, and thus, temporary attention is provided, and after which the negligence is reemerged. This trend cannot occur structurally with the slow cumulative post-mining risk.

There is also a focus on human health and environmental justice^[55]. A large number of the abandoned mines are found close to the rural, Indigenous, and economically marginalized communities that have limited access to remediation resources and limited say in the land-use decisions^[54]. Exposure can be made by contaminated water, dust, ingestion of soil, crop absorption, fisheries, or other direct physical risks like open shafts and unstable ground. These burdens are never evenly distributed and, in most cases, the historical disparities in the governance of resource extraction magnify them. System-based analysis should therefore be able to acknowledge the fact that the legacies of abandoned mines are not solely the technical legacies of any previous industry, but a reenactment of the desire of socio-political relationships that persist. The geography of abandonment is often the same as that of unequal protection.

Another problem that makes the risk landscape more complicated is land reuse^[56]. Others are mine rehabilitation to recreation, settlement redevelopment, renewable energy facilities or farmlands or conservation. This kind of reuse opens up possibilities of economic regeneration and landscape incorporation, but there are also prospects of novel exposure channels in the occurrence of contaminated or subsidence hazards that may be poorly comprehended. Notably, redevelopment can tend to favor the superficial and short-term utility rather than a diagnosis of the underlying system. A location can be found to be fit for a new use due to the

presence of apparent hazards that are already controlled, although the safety of hydrogeochemical or subsurface hazards has not been fully defined. One more time, there is an issue with a temporal mismatch; the social need to recover land within a short period of time can be faster than the scientific process of comprehending how a site will behave over time.

Another revelation is that governance does not have to be considered as purely an outer control of environmental risk. It is also a component of the system that affects environmental paths. Observation of networks, source of funds, legal definitions of closure, community involvement, and institutional memory all play a role in the recognition and resolution of a geological and ecological change^[57]. Governance failure in this sense may be viewed as some form of systemic vulnerability similar to slope instability or treatment failure. In the event that institutions are enduring, nimble, and localized, risks in abandoned mines can be handled in a gradual and efficient manner. In a weak, fragmented, or short-term institution, the same physical location can be much more dangerous. Material conditions and management capacity are the co-producers of the risk.

2.5. Interactions, Thresholds, and Long-Term System Behavior

The categories of legacies given above are analytically independent, yet in practice, interact in feedback mechanisms giving rise to long-term site paths. A sloping waste-rock that is washed away in times of heavy rains can reveal new sulfides, and this enhances the acidic drainage as well as the release of metals. High levels of contamination can reduce vegetation formation, decrease root strength and surface rugae, which consequently increases erosion. The rebound of groundwater can activate underground pollutants and destabilize surface ground, displacing the water quality and the safety of the land. When governance is not effective, then the maintenance of drainage controls may be postponed, and a localized problem may turn into a problem at the catchment level. These examples demonstrate that the concept of abandoned mine risk had a better definition as an exemplary system behavior than an aggregation of individual hazards^[27].

This has significant consequences on management and evaluation. Traditional measures of closure typically assess the achievement of certain goals; e.g., pH levels, slope incli-

nation, or proportion of vegetation cover^[58]. These metrics are helpful yet too few since they do not quantify system resilience or approach to thresholds. A site can be up to date and still susceptible to the sudden change due to climatic stress, hydrological reorganization or institutional neglect. Thresholds are thus a necessary concept. Systems of abandoned mines can take years to absorb incremental change before they reach cross points where recovery becomes significantly harder or the cost of recovery surges dramatically. These could be the beginning of internal erosion in tailings, the failure of passive treatment performance, the death of immature vegetation during drought, or localized to catchment-wide contamination^[59].

Critical analysis implies that the biggest problem about the management of abandoned mines is not merely the uncertainty about certain processes, but rather the uncertainty about the relationships between the scales and the times. The short-term monitoring can only record the average conditions and overlook an episodic event that can bring about long-term transformation. Local-scale research only detects local processes but does not see the effects at the downstream or landscape levels. The engineering designs can take a set of climatic conditions that are at rest, and the ecological recovery pathways are dependent on the directionally changing environment. Consequently, the prediction of abandoned mine systems has to be done in a probabilistic and adaptive way, but not a one-time establishment of the safety of the mine after closure^[60].

In this sense, the so-called legacy risk cannot be viewed as an active legacy of the past. These risks are proactively created and recreated by continuous interactions of geological materials, hydrological flux, ecological constraints, and social institutions^[2]. They are persistent, which means that the abandoned mines are process-active landscapes. The fact that they have been recognized as coupled socio-ecological-geological systems is thus not just a theoretical choice, but an expedient requirement in perceiving why certain sites are still known to produce hazards even after decades of remediation work. **Table 1** summarizes the key legacy risks in the long-term, the prevailing driving processes, and the interactions between them across systems. This system's conception gives the basis to the following section that explores the conceptual foundation for transitioning to long-term adaptive stewardship by stepping out of closure-focused thinking.

Table 1. Major long-term legacy risks at abandoned mine sites are viewed as coupled socio-ecological-geological system components.

Legacy Domain	Main Long-Term Manifestations	Primary Driving Processes	Cross-System Interactions	Management Significance
Geological and geomorphological	Slope instability, subsidence, gully erosion, tailings degradation, waste-rock collapse	Weathering, differential settlement, pore-pressure change, runoff concentration, structural weakening	Physical instability may expose reactive materials, alter drainage, and destroy vegetation cover	Requires long-term stability assessment beyond closure-stage engineering criteria
Hydrogeological	Groundwater rebound, altered flow paths, seepage emergence, changed recharge-discharge regimes	Mine dewatering cessation, aquifer reconnection, fracture flow, hydraulic gradient recovery	Hydrological shifts may mobilize contaminants, trigger slope failure, and affect wetland or riparian recovery	Demands long-duration monitoring of water levels, discharge points, and flow connectivity
Geochemical	Acid mine drainage, neutral metalliferous drainage, salinity increase, metal mobilization, delayed pollutant release	Sulfide oxidation, redox fluctuation, mineral dissolution, secondary precipitation, flushing events	Chemical stress limits revegetation, degrades aquatic ecosystems, and interacts with hydrological variability	Highlights need for source control and adaptive water-quality management
Ecological	Poor soil development, arrested succession, biodiversity loss, habitat fragmentation, low resilience	Toxicity, nutrient limitation, compaction, hydrological alteration, repeated disturbance	Weak ecological recovery can reduce erosion resistance and biogeochemical buffering capacity	Indicates that vegetation cover alone is insufficient as a success metric
Societal and governance	Human exposure, land-use conflict, orphaned liabilities, discontinuous monitoring, underfunded remediation	Institutional fragmentation, uncertain ownership, weak regulatory continuity, limited stewardship finance	Governance failure amplifies all physical and ecological risks by delaying intervention	Long-term stewardship capacity is as important as technical remediation capacity
Climate-related amplification	More intense rainfall, drought stress, wildfire, thaw-related instability, increased contaminant flushing	Climatic nonstationarity, extreme events, vegetation stress, cryospheric change	Climate stress can reactivate previously stabilized features and reduce treatment reliability	Calls for scenario-based, climate-resilient management approaches

3. Conceptual Foundations for Systems-Based Management

The ever-increasing realization that even after the official closure of the mine, its abandoned mines continue to be active in the environmental front has created an additional conceptual issue in the management of post-mining^[27]. To a large degree, the traditional literature still views closure as a final stage in the mining life cycle, which means that, after engineering works have been done and regulatory requirements are met, the site remains in a state of relative stability, interrupted only by some occasional needs to maintain it. It is becoming more challenging to maintain this framing regarding abandoned and orphaned mines, where the containment structures are in a state of degradation, the hydrogeochemical conditions are changing, ecological recovery is incomplete, and institutional responsibility is either fragmented or non-existent. In these circumstances, closure is not the end but a new step of landscape change. The key dilemma is thus both conceptual and technical: the management needs to be reconstructed around the accomplishment

of the remedial works for the long-term care of dynamically coupled systems.

A systems-based approach is not just an interdisciplinary approach. It is important since it admits that a post-mining condition is being influenced by constantly interacting physical, chemical, biological, and social processes that cannot be adequately explained using single-disciplinary models. The section elaborates the conceptual principles of such an approach by considering the change in approach to closure to stewardship, the applicability of systems thinking and the resilience theory, the importance of risk-based and adaptive approaches, and the necessity of integrating engineered and ecological approaches, as opposed to viewing them as antagonistic paradigms^[61].

3.1. From Closure to Long-Term Stewardship

The classical closure concept has been constructed on finality. Regulatory and engineering practice in regulatory and engineering practice, closure usually refers to landform reworking, contamination management, revegetation, infrastructure decommissioning, and site stabilization to a stan-

dard considered appropriate to relinquishment^[12]. This is administratively effective since it enables limits to liabilities, transfer or termination of liabilities, and closure success to be evaluated in terms of predetermined standards. But in the case of deserted mines, such a conclusion can be frequently imagined. The site can still give rise to acidic drainage, subsidence, loss of revegetation cover, or erosion and redistribution of contaminants that may take decades before the site can be reclassified as an inactive or closed site. Where no formal shutdown has taken place, the concepts used to make approaches to the abandoned sites are often based on the same endpoint-oriented framework, resulting in short-term-compliant interventions instead of a long-term system^[62].

The concept of stewardship offers a more realistic conceptual alternative. It means that Stewardship is a continued care with regard to the state, role, and developmental path of a site over long periods of time. It changes the focus from the issue of whether the requirements for closure have been established to whether the landscape is more stable, more resilient, and less hazardous in a changing environmental and social context. This difference is significant in that a location can meet the closure criteria and still be heavily reliant on the maintenance of an infrastructure or an institutional framework, or climatic assumptions that might fail in the future. Continuity, contingency, and depth are thus foreshadowed by stewardship. It acknowledges that the landscape of post-mining is not a fixed product but a dynamic system, the future of which cannot be accurately established at the time of intervention^[63].

Another perspective that opposes the idea that post-mining management aims to recreate an equivalent land use or a site to a pre-disturbance baseline is the stewardship perspective, which questions this notion. In most of the abandoned mines, the disturbance is such that the degree and duration of disturbance would render it impractical or conceptually unsuitable^[64]. The soils can be irreversibly changed, the hydrological routes are changed permanently, and the species communities are restructured into new ecological communities^[7]. In such a situation, stewardship would not imply the maintenance or reconstruction of some conceived original state. Instead, it would be the management of paths towards acceptable, resilient, and socially legitimate future conditions. These states might involve hybrid landscapes in

which residual contamination is not removed but contained, where ecological purpose is re-established without historical reference, and where surveillance is becoming a permanent element of land management.

The originality of this change is that it suggests changes in the definition of success. The achievement of a condition usually serves as the measure of success based on closure. The success of stewardship should be more quantified as the preservation of a course. The first is whether or not a site has attained a target, and the second is whether or not the system is approaching a non-instability regime and entering a stable functional state at realistic future loads. This change can be observed as not very evident, but it changes the logic of design, monitoring, and intervention significantly. It needs management structures that are open to changes as they occur, as opposed to assuming that at the point of completion, technical works could solve all the major risks permanently^[65].

3.2. Systems Thinking, Feedback, and Cross-Scale Interactions

Systems thinking provides a way to think with an analytical language as to why the abandoned mine landscapes cannot be handled effectively using the single-problem approaches. Primarily, within the realm of systems thinking, one should focus on relationships, feedback mechanisms, nonlinear dynamics, and emergent behavior. In regard to abandoned mines, this translates to the understanding that there are interdependencies among landforms, drainage networks, pathways of contaminants, vegetation communities, microbial processes, performance of infrastructure, and institutional arrangements. Alterations in any given subsystem may increase, decrease, or divert alterations in another. As a result, the activities of the management that seem to be effective when measured in a particular domain can lead to unintended effects in a different domain^[2,16].

The significance of the feedback is quite evident in the post-mining surroundings. The establishment of vegetation can minimize erosion, enhance the control of infiltration, and promote the formation of soil, thus helping with geomorphic stabilization^[8]. Concomitantly, the toxicity of contaminants or hydrological stress can prevent plant life, and this is accompanied by a new exposure to reactive substances, as well as runoff^[66]. Passive treatment systems have the potential

to enhance the quality of downstream water; however, when they fill with contaminated sediment or short-circuit hydrologically, their efficiency decreases, and they can become new management burdens in their own right. Likewise, synthetic caps that are developed to minimize the entry of oxygen can be effective at first, but settlement, cracking, or burrowing can destroy their functionality with time, resulting in a slower recovery of geochemical activity. Unstock failures of independent elements are not an isolated phenomenon; they are manifestations of the behavior of interacting systems.

Scale is also attracting attention in a systems perspective^[67]. Numerous site-based closure interventions have been created, whereas the effects of post-abandonment tend to spread across the catchments, aquifers and areas. The contaminant plumes are flowing down, floodplains are hit by the pulses of the sediments, and the land use is transformed at great distances beyond the actual footprints. Time scale is also of importance. Engineering design horizons can be in the range of years to decades, compared to the geochemical weathering, soil development, ecological succession and institutional memory, which work over longer and less synchronized times^[7]. The issue is that when the system evolves on a different temporal scale and management is based on a single scale problems occur. e.g., a treatment system can be subsidized over a period of ten years yet generation of contaminants is expected to continue over a period of 100 years. Even though deeper soil functioning is yet to be developed, a vegetation program can be considered successful after three growing seasons. Systems thinking serves to bring up these disjunctions and reveals the inadequacy of short-term indicators as proxies of long-term stability.

The other important lesson is that most of the abandoned mine systems are nonlinear. The environmental change is not always a gradual process that is proportional to the pressure. Periods of seeming stability might be separated by sudden changes, e.g., cover failure in extreme rainfall, acidification following exposure of sulfides, or sudden collapse of vegetation during drought stress^[68]. Such threshold behaviors make it difficult to predict, as average conditions can mask susceptible status to episodic disturbance. In real life, this implies that system knowledge should not merely be limited to central tendencies only, but also to the sensitivity to extremes, cumulative stress, and cascading interactions. A site that seems stable and stable when assessed in normal

circumstances may prove to be very delicate when examined through the perspective of threshold dynamics.

In the case of SCI level analysis, systems thinking is not valuable in rhetorical holism, but in the operational consequences. It transforms what is monitored, the interpretation of uncertainty, and the prioritization of response to the interventions. It promotes the management to look beyond the existence of hazards, but the form of interactions that result from it. This is especially so about the abandoned mines, where there is usually a scarcity of resources, compelling the adoption of selective intervention. It is possible to determine leverage points, i.e., processes or components that, when stabilized, can bring more extensive benefits to more areas by a systems-based framework. Examples of such leverage points are drainage control nodes, erosion hotspots, important revegetation zones, or governance systems that enhance the continuity of monitoring^[69].

3.3. Resilience, Vulnerability, and Adaptive Capacity

This is partly why resilience thinking offers a complementary conceptual basis of systems-based management since it is concerned with how systems can take in disturbances, restructure, and go on with operations without entering the undesired states^[70]. As applied to abandoned mines, resilience does not mean that everything goes back to a clean state, and all change is achievable and harmless. Rather, it provides a means of assessing the ability of post-mining landscapes to maintain acceptable levels of geological stability, control of contaminants, ecological functioning, and social safety under the continued load^[71].

A strong point of resilience as an interpretive framework is that it has left binary categories like stable/unstable or restored/degraded behind. Abandoned mine sites tend to lie in mid-grounds where they can survive in a normal situation, but are extremely vulnerable to disturbance^[72]. A revegetated waste-rock slope, as an example, might still seem stable in a matter of years but may have low resilience when the vegetation on it is shallow-rooted, when erosion channels are still latent, or where the underlying material is still oxidizing. Equally, a passive treatment wetland can also sustain a satisfactory quality of effluent when operating at an average flow, but might be unable to withstand storm-induced sediment loads or seasonal drying. This conditional

stability and the ability of systems to endure disturbance in the future without disproportionate degradation are the subjects of the field of resilience thinking^[73].

The vulnerability concept is also significant. Vulnerability is not merely exposure to dangers, but the vulnerability of elements of the system to damage and its low responsiveness^[74]. The vulnerability in the abandoned mine environment is spread unevenly both in the environmental and social domains. Some of the landforms could be particularly vulnerable to failure due to geotechnical inefficiency or concentration of drainage. Some ecosystems can be quite delicate due to low diversity, stress of contaminants, or hydrological isolation. Some communities can be more vulnerable due to the use of polluted water sources, the absence of institutional assistance, or high-density populations near hazards that are not cleaned up. The management of systems-based systems should therefore take into consideration the differentiated vulnerability and not consider the site as a homogeneous unit of risk.

Adaptive capacity is the connection between resilience and vulnerability, which focuses on the system or management regime's capability to change in response to change, uncertainty, or disturbance^[75]. As a matter of fact, adaptive capacity entails access to monitoring information, technical expertise, financial support for maintenance, institutional integration, and social groups. Even physically similar mine sites can be characterized by vastly different long-term perspectives based on the ability of the managers to adjust interventions, react to early warning signals, and acquire experience through watching how the system behaves. That is why resilience in abandoned mines cannot be explained as an ecological or geotechnical characteristic. Material conditions and the ability to govern co-produce it.

The most important observation in this regard is that resilience is not something that needs to be romanticized. There are also some unwanted conditions that may be resilient. Waste systems that produce acids can end up being chemically resistant^[76]. The ecologically impoverished but stable simplified communities of plants are dominated by tolerant species^[77]. Institutional neglect may turn into a strong pattern of governance. As a result, it is not resilience that is aimed at but rather desirable functions and pathways of resilience. This involves making clear normative judgments regarding the acceptability of future, to whom, and

on what trade-offs. The desired resilience in the case of abandoned mines can be long-term contaminant mitigation, erosion reduction, better ecological connectivity, less human contact, and monitoring systems that can react to changes. The concept is as such, most useful when conceived in relation to specific functional objectives as opposed to being a universally positive property.

3.4. Risk-Based and Adaptive Management under Uncertainty

The systems perspective of abandoned mines organically guides to risk-based and adaptive strategies, as the future action of such landscapes remains unpredictable and path-dependent, and is also susceptible to variations in boundary conditions^[78]. The traditional methods of closure commonly believe that reasonable characterization and design can significantly reduce uncertainty before intervention. Conversely, abandoned mine management is often faced with incompleteness of records, poor documentation of waste structures, little baseline data, and vague inventories of contaminants. It is often impossible to clear up everything beforehand. A better approach is to deal with uncertainties explicitly by making a series of evaluations, tracking, and decision modification.

The risk-based management process starts by acknowledging the fact that not every hazard is just as likely to happen, as serious, or as some others that are manageable. It tries to rank actions based on the potential likelihood of bad consequences, the severity of the consequences, and the possibility of alleviating them. In the case of abandoned mines, however, risk cannot be brought to a level of a steady ranking exercise. Risk is dynamic since the conditions of the site vary. Drainage chemistry can be aggravated or mitigated, slopes can be undermined, an ecological community can develop or disintegrate, and surrounding land use can expose humans^[2,79]. Risk framework based on systems must therefore be time-specific. It must take into consideration delayed onset, cumulative change, and compound events as opposed to considering hazards at the time of assessment.

Adaptive management builds on this reasoning by viewing interventions as a learning process^[80]. Monitoring of an organization under adaptive management is not merely a compliance effort but a way of testing assumptions, discovering new feedback, and improving future behaviors. This

particularly applies where responses of the system are unpredictable or where interventions are likely to interact. To illustrate, a revegetation program may need to be redefined when it is observed that the presence of contaminants is limiting plant survival, rather than nutrient limitation^[8]. A passive treatment system can be redesigned in case the observed patterns of flows vary from the model expectation. Drainage controls can be changed due to the redistribution of runoffs caused by erosion. The success of management is therefore evaluated not only in terms of the actual performance of actions, but also in terms of the ability to identify discrepancies between anticipation and reality and act on them.

The key strong point with adaptive approaches is the ability to accept the fact that it is sometimes impossible to avoid partial failure. Within the systems of abandoned mines, the performance of some of the interventions will be inferior, and the appearance of some of the hazards will not disappear as expected, and external conditions like climate or land use will vary. The actual question is not whether failure can be avoided at all, but whether management systems can fail safely, identify issues at the right time, and re-arrange before it is too late. This is a more practical criterion of long-term stewardship than the traditional prospect of an enduring technical solution^[81].

Simultaneously, adaptive management is not a panacea in every situation. It needs to observe continuity, institutional memory, and funding structures that tend to be poor at abandoned sites. It may also be used rhetorically in a bad way, where adaptation is a pretext to under-design first interventions or put off tough decisions. There must be a critical outlook then. Adaptive management can only have a certain sense in the context of clear thresholds, decision rules, and action accountability mechanisms. In the absence of these, it will be a hollow language of malleability that covers the ongoing governance failures. In the case of abandoned mines, the issue is to create adaptive systems that are not only conceptually sustainable but also sustainable under severe institutional instabilities in the long run^[82].

3.5. Integrating Engineered and Nature-Based Solutions

The commonest conceptual fault line in the post-mining management is the difference between engineered remedia-

tion and ecological restoration^[7]. Control, containment, predictability, and reduction of risk as soon as possible have been linked with engineered strategies, whereas self-organization, long-term recovery, and reduced maintenance are linked with ecological strategies. In the real world, this difference is often exaggerated. The vast majority of the abandoned mine sites need both types of intervention, and the question of which of the two paradigms is better is not an important issue, but rather how both can be combined to make the entire system more resilient.

Measures that are engineered are still necessary in the case of acute hazards. Unstable slopes, open shafts, contaminated seepage, and reactive waste materials are usually dealt with by direct physical action, either by regrading, capping, drainage diversion, sealing, reinforcement, or active treatment^[83]. Nevertheless, engineered systems are not only expensive but also prone to decay over time, particularly when located in locations that do not have regular monitoring. It can increase buffering capacity, enhance habitat functionality, and diminish the need to use ongoing mechanical management by nature-based or ecologically-informed practices, which include rehabilitative construction of wetlands, revegetation, soil-building, and geomorphic landforms^[84]. However, not all such ways are benign and self-sustaining. They can collapse in the event of excessive contamination, poor understanding of water balance, or ecological processes that are supposed to balance the unresolved geotechnical weaknesses.

The theoretical breakthrough is in perceiving these interventions as part of the hybrid systems. Not only an engineering barrier, but also a substrate, the ecological development of which adds to its long-term performance. Not only is a treatment wetland a biogeochemical reactor, but also a hydrological and ecological system that evolves in terms of succession and sedimentation. A regraded slope is not merely a form of the structure, but also a topography, the stability of which is partially imposed by the vegetation cover, roughness of the surface, and the distribution of the runoffs. Integration then implies designing engineering measures considering ecology, and ecological measures considering engineering limitations^[85]. It also implies that the effectiveness of interventions will rely on the interactions between these components and will not be determined by the theoretical effectiveness of one of the elements.

It is especially this integrated view that is significant in times of climate uncertainty. Models that were developed under station conditions are likely to become unreliable with alterations in the intensity of rainfall, frequency of droughts, or freezing-thaw cycle patterns^[86]. Adaptive buffering can be provided by ecological systems, where there are underlying loads of contaminants and physical constraints permit it. Hybrid designs have the ability to apportion risks more effectively through immediate control and long-term ecological stabilization. On the other hand, initial slope armoring can be combined with revegetation approaches that will ultimately decrease erosion exposures, or passive treatment systems can be enhanced with upstream source-control mechanisms that will decrease contaminant loading over the years^[87]. These combinations cannot be added in a one-dimensional way; they signify a conceptual change towards the design of changing performance other than a fixed end-state.

3.6. Toward a Framework for Long-Term Systems-Based Stewardship

Combined, these conceptual grounds would imply that successful management of abandoned mines would demand more than just technical advancement within the existing closure logic. It necessitates a redefinition of the management problem as such. The deserted mine is not just a troubled place to be made stable, a pollution source to be segregated, and an ecosystem to be replanted^[88]. It is a changing socio-ecological-geological system filled with feedbacks, thresholds, uncertain trends, and long time periods. The framework of stewardship based on systems needs to incorporate four

fundamental paths, namely, temporal realism, interaction-based analysis, adaptive governance, and hybrid intervention design.

Temporal realism implies taking the reality that numerous post-mining processes will not disappear over decades or even longer, and management systems should be designed to deal with it. Interaction-based analysis demands more than consideration of individual hazards, but an attentive consideration of the relationships in which they enhance or restrict each other. Adaptive governance acknowledges that the system has monitoring, funding, legal responsibility, and community engagement, and is not supported by them^[89]. The design of a hybrid intervention recognizes that, unless a long-lasting management will likely rely on a mix of engineering and ecological processes and not use only one sphere^[90].

This framework has more than just conceptual value. **Table 2** is a synthesis of these key conceptual approaches and their associated strengths and weaknesses in the management of abandoned mines. It gives a foundation on which the concept of what is considered as evidence, success, and responsibility in the management of abandoned mines may be reconsidered. It implies that long-term stewardship ought to be assessed in terms of trajectory-based indicators, cross-domain performance metrics, and sensitivity to future disturbance as opposed to assessing it by simply closing it. It further highlights the fact that uncertainty is not a temporary inconvenience that should be eradicated prior to action-taking, but one that must be dealt with to be learned, redundant, and institutionalized^[91].

Table 2. Main conceptual frameworks that support a systems-based transition from closure-oriented remediation to long-term stewardship of abandoned mines.

Conceptual Framework	Core Idea	Relevance to Abandoned Mines	Main Strength	Main Limitation If Used Alone
Closure-based management	Site rehabilitation is evaluated against predefined completion criteria	Useful for defining minimum technical and regulatory targets	Provides administrative clarity and measurable benchmarks	Often assumes stability too early and underestimates long-term evolution
Long-term stewardship	Management continues beyond formal closure and focuses on site trajectory	Better reflects persistent risks at abandoned and orphaned mines	Aligns with intergenerational monitoring and adaptive intervention	Can remain vague unless linked to indicators, responsibilities, and finance
Systems thinking	Mine sites are interacting physical, chemical, biological, and social systems	Helps explain feedbacks among instability, contamination, ecology, and governance	Reveals cross-domain drivers and leverage points	May remain descriptive unless operationalized through tools and decisions

Table 2. *Cont.*

Conceptual Framework	Core Idea	Relevance to Abandoned Mines	Main Strength	Main Limitation If Used Alone
Resilience perspective	Focuses on the ability of a system to absorb disturbance and maintain function	Useful for evaluating recovery under climate stress and uncertainty	Shifts attention from static condition to dynamic performance	“Resilience” may be misleading if undesirable states are also persistent
Vulnerability and adaptive capacity	Risk depends on exposure, sensitivity, and ability to respond	Clarifies why similar hazards produce different outcomes across sites or communities	Integrates environmental and institutional dimensions	Requires context-specific interpretation and cannot substitute for process analysis
Risk-based management	Interventions are prioritized according to likelihood and consequence	Supports prioritization where resources are limited and liabilities are extensive	Enables strategic allocation of effort	Can oversimplify interacting and delayed risks if treated as static
Adaptive management	Management is iterative and revised through monitoring and learning	Particularly relevant where data are incomplete and site behavior is uncertain	Well suited to dynamic, long-term systems	Fails if there is no durable monitoring, funding, or institutional memory
Hybrid engineering-ecological approach	Technical controls and ecological processes are combined in integrated designs	Matches the mixed hazard profile of most abandoned mine landscapes	Supports more durable and less maintenance-intensive outcomes	Integration is difficult where severe contamination or instability remains unresolved

In that regard, systems-based management is not merely a larger lexicon of the description of abandoned mines^[92]. It is an alternative means of structuring knowledge and intervention in terms of the fact that these landscapes are process-active and socially consequential, many years after the process of extraction is over. In the following section, this conceptual basis is followed by the approaches and instruments according to which long-term geological and ecological management may be transformed into practice.

4. Methods and Tools for Long-Term Geological and Ecological Management

The methodological basis of management also needs to change in case abandoned mines are to be treated as evolving socio-ecological-geological systems, and not as fixed residual hazards^[67]. The traditional practice of post-closure has been mostly based on disaggregated datasets, limited monitoring horizons, and discipline-oriented assessment instruments, which are ill-adapted to long-term, interacting processes. In most sites that have been abandoned, the issue is even deeper: there might not be enough reliable base data, and history is not recorded fully, and engineered constructions are not fully recorded. Consequently, management does not start with complete knowledge of the system, but with an incomplete reconstruction of the manner in which

the site was developed, how it has developed, and how its current behavior is expected to develop. The problem is thus conceptual in addition to being methodological. Good long-term stewardship requires instruments that can help capture the slow change, identify emergent instability, synthesize heterogeneous evidence, and make decisions in the presence of persistent uncertainty^[93].

A methodological framework of the systems approach should not merely measure individual variables^[94]. It should expose the interconnection between landforms, water routes, ecological activities, and governmental limitations. It should also span retrospective to prospective analysis: to rebuild the legacies of past disturbance, and to predict the future courses under climatic, hydrological, and institutional change. In this way, the strategies of the management of abandoned mines are not objective technical tools. They define what is risky, the kinds of degradation that are perceived, and those that are deemed acceptable. The respective subsections discuss the key areas of methodology needed in the long-term geological and ecological management and focus on their usefulness as well as their limitations^[95].

4.1. Site Characterization and Baseline Reconstruction

The site characterization is the start of long-term management, but in the case of abandoned mines, this is not always an easy task. In contrast to operating mines or those

that have just been closed, an abandoned one is likely to have incomplete engineering documentation, sound waste catalogues, hydrogeological base, or pre-disturbance ecological records. The historical functionality can be badly mapped, the ownership can have changed multiple times, and the legacy infrastructure can have been eroded, informally reused, or simply not documented^[96]. Therefore, characterization is not merely an inventory practice; it is a practice of re-creation. It is not only to write about the site as it appears at the moment, but to make inferences about the way in which the current risks were created during the previous mining processes, post-mining changes, and improvised interventions.

Historical sources are consequently, methodologically significant. In the lower underground mines, the site of underground openings, tailings disposal, drainage, and waste entanglement activities, which can no longer be detected on the surface, can be disclosed by archival mine plans, production records, aerial photographs, geological surveys, and regulatory files^[96]. The historical documents, however, are usually incomplete and should be critically interpreted. There may be differences in informal waste disposal sites that are not included in maps, operational shifts that have never been documented, and location boundaries that have been changed over time. Historical reconstruction does not need to restore an ideal past, but has the beneficial result of minimizing uncertainty about obscured structures, sources of contaminants, and pathways of processes over time. The incomplete history is a risk factor in itself in the area of abandoned mine management, as the unknown legacies often result in delayed failures^[97].

The use of field-based characterization is also critical since most of the most significant controls of long-term behavior cannot be deduced from documentation^[98]. The empirical information on how the current site is performing is obtained by geological mapping, geotechnical inspection, hydrochemical sampling, geophysical survey, sediment tracing, soil analysis, and ecological assessment. However, characterizing fields should go beyond description per se. It must define areas of active erosion, sulfide exposure, where seepage forms, where groundwater discharges, failed revegetation, or steep geomorphological adaptation. Such a process-based approach becomes especially significant since the hazards of abandoned mines are likely to be spatially heterogeneous. It

can also be found that there can be relatively stable areas on a site that are close to highly reactive or unstable areas, and failure by management can be common when site groupings are too broad to see local complexity.

One of the most important challenges is to establish a meaningful baseline. In most of the mines that were abandoned, it is found that there is no uncontaminated or pre-mining reference condition within the site itself, and past ecosystems may be neither recoverable nor worthy of management^[7]. Rebuilding of the baseline should thus be taken in a pragmatic manner. Instead of trying to reproduce an ideal state of a character, characterization must provide a practical starting point upon which change may be evaluated in the future. This can be the existing amounts of contaminants, slope retreat rates, groundwater table, vegetation cover, soil characteristics, or ecological connectivity. It is not a fixed historical standard, therefore, that the ground is, but rather an active standard of movement to identify. This difference is significant as long-term stewardship relies less on the knowledge of what the site used to be but on the knowledge of whether it is becoming more stable, more connected, and less dangerous^[99].

Critically speaking, the tendency to divide characterization into the compartments of disciplines is one of the greatest methodological shortcomings in the literature. The geological survey is based on an inadequate ecological context, ecological analysis is carried out on an inadequate substrate or hydrological diagnosis, and hydrochemical analysis is usually concentrated on the discharge points without the incorporation of catchment geomorphology. In systems with abandoned mines, this sort of compartmentalization restricts the power of explanation. Most helpful characterization techniques are those that are illuminating interactions: in which landform instability is motivating release of contaminants, in which hydrology is limiting revegetation, or in which underperforming ecology is revealing geotechnical vulnerability^[100]. In other words, site characterization should not be used merely to record conditions, but to display system coupling.

4.2. Monitoring Technologies and Long-Term Observation Systems

Due to changes in the risks of abandoned mines over the years and decades, it is not possible to simply characterize

them at one time^[101]. The methodological basis of stewardship is long-term monitoring, which gives the evidence to identify change, performance of intervention, and thresholds beyond which irreversible degradation takes place. However, the limitations on monitoring at abandoned mines due to limited funding year cycles, sparse instrumentation, and a very narrow focus on regulatory compliance variables, such as a few water-quality parameters, have often been a constraint. Systems-based approach entails the wider and more strategically combined observation systems that can monitor the geological, hydrochemical, ecological, and climatic processes in a simultaneous fashion^[102].

Geotechnical observation is essential where an unstable slope, tailings' structure, waste-rock pile, or underground workings, which are liable to subsidence, are present. Traditional methods, including inclinometers, piezometers, settlement markers, crack gauges, and survey benchmarks, are still useful, particularly where deformation rates or graphical changes in pore pressures must be measured directly. Nonetheless, they are effective with regard to spatial placement, maintenance, and continuity. Instrumentation networks are sparse at most abandoned sites, and are also terminated as soon as stabilization work is done on immediate local mechanistic failures. It indicates an issue on a larger scale: geotechnical monitoring is frequently tailored in such a way that it is used to verify acute hazard conditions, instead of learning about long-term landscape motion. Systems-based programs must regard deformation surveillance as a component of a dynamic evaluation of the route that hydrology, erosion, vegetation, and weather extremes are all jointly impacting the stability^[103].

Hydrological and hydrochemical surveillance is retained with a focus on the fact that water is the key driver in mobilizing and spreading mine legacies^[104]. Surface-water stations, seepage sampling points, groundwater wells, flow measurements, together with chemical analyses of pH, redox potential, sulfate, alkalinity, major ions, and dissolved metals (typically some combination of these) are usually monitored. Such data are very important, yet their interpretation is often compromised by poor resolution in time. Episodic spikes of contaminants due to storms, groundwater rebound, or bypass of treatment systems may be overlooked in monthly or quarterly sampling. Event-driven hydrology can be extremely important where average chemistry is not, particu-

larly in the abandoned mine catchments. Correspondingly, high-frequency sensors, automated samplers, and continuous level loggers are becoming more and more significant not due to increased data volume, but to the fact that they provide insight into the behavior of the system that periodic sampling tends to smooth out^[105].

The ecological monitoring has long been the least considered part of long-term mine control, although the ecological processes are both the indicator and the determinant of the stability of the site^[106]. The ecological recovery process can be observed by the use of vegetation surveys, species richness measurements, soil biological examination, aquatic bioassessment, habitat mapping, and remote detection of plant stress as well. Ecological monitoring is, however, commonly reduced to either visual cover estimations or short-term post-revegetation survival estimates. These measures are effective but partial. They are indicative of superficial occupation, and do not necessarily capture any underlying functional change. The ability of the ecosystem to observe soil development, nutrient cycling, microbial activity, reproductive success, trophic complexity, and drought or contaminant stress resilience should be incorporated into a stronger ecological observation system. The most important methodological point is that ecological recovery is to be monitored as a functional integration process, but not an aesthetic one^[107].

The latest developments in remote sensing have broadened the scope of observation of abandoned mines and that too to a considerable extent^[108]. All of them can offer repeated and spatially explicit land deformation, erosion, vegetation dynamics, surface moisture, thermal anomalies, and water-body evolution data collected by satellite, UAV-based surveys, LiDAR, hyperspectral sensing, thermal imaging, and InSAR^[109]. These technologies are mostly useful in big or inaccessible locations where ground-based coverage is limited. They are also useful in showing patterns and trends that might otherwise not be apparent when only point measurements are used. Remote sensing is not to be considered, however, as an alternative to field study. It is strong in terms of synoptic detection and interpretation, but it still remains a subject of ground truthing and process knowledge. A shrinking zone that is observed through imagery could be an indication of hydrological concentration, failure of covers, grazing pressure, or a sign of incipient subsidence; the implications for management without knowledge of the

field are not clear. The best monitoring systems are thus those that integrate remote sensing with some special in situ measurements by informing each other.

Another important question on monitoring design is not what is measured, but how measurements combine over time. Most of the abandoned mine programs end up building data counts without learning, as datasets are usually discipline-based, not well standardized, or not linked to explicit management questions^[110]. The difficulty lies in overcoming the passive surveillance of monitoring to the system diagnosis of monitoring. This will necessitate the clear connection between indicators, thresholds, and decisions. In the absence of such a connection, even advanced surveillance technology will be prone to generating descriptive richness without being strategic.

4.3. Modeling and Predictive Tools for Coupled System Analysis

The activity of a site can be monitored; the activity of a site can be explained by modeling. Predictive tools in the management of abandoned mines are unavoidable since, in stewardship decision-making, making a decision before the failure is evident can be a necessity^[111]. The challenge is that any one modeling approach is incapable of describing the complexity of coupled geologic, hydrologic, geochemical, ecological, and social processes. Models are thus not to be described as a representation of reality in its entirety, but as organized simplifications that shed light on certain dynamics and inevitably leave others out of the picture. Their worth is determined by the fact that they must fit the management question well and the sensitivity with which their uncertainties are interpreted.

One of the most commonly used predictive tools used in the assessment of mine legacy is hydrogeological and geochemical models^[112]. Rebound groundwater flow models are able to simulate rebound, workings-aquifer connectivity, contaminant transport mechanisms, and the location of discharge. Reactive transport models introduce chemical process representation, which allows the study of sulfide oxidation, metal mobilization, its precipitation, adsorption, and neutralization. Such tools may be very informative, particularly in cases where the future water quality trends or treatment-system requirements are to be estimated. Their usefulness is, however, limited in most cases by a decided

source terms, subsurface architecture not well characterized, and calibration over long periods. The uncertainties that can appear in abandoned locations include the unknown geometry of underground workings or unrecorded waste piles that can cause a change in the conclusions made by the management. This does not negate modeling, only that it is necessary to take predictions as probabilistic and iterative as opposed to deterministic predictions.

Another important critical area of prediction is that of geotechnical and geomorphic models^[113]. Slope stability studies, erosion and sediment transport simulations and landform development models can be used to determine areas of susceptible slopes, test the stability of regraded slopes and can determine how the garbage can be reshaped due to runoff or weathering processes over time. Their significance is their use to change focus from the current geometry to the future response of a process. What seems to be a stable slope in the current conditions of the moisture may prove susceptible when there is a groundwater rebound or an increase in the intensity of rain. Similarly, a tailings surface can be left in place until it begins to be incised progressively by a localized flow of water. Still, numerous such models are utilized in a quasi-static form, focusing on design compliance and not dynamic evolution. In the case of abandoned mines, it is more useful to use scenarios in application: to test how landforms will respond to disturbance sequences, maintenance failures, or to climate extremes, than to test whether they meet these current factors of stability^[114].

Ecological modelling has not had as much historical development in mine management as hydrochemical or geotechnical modelling, but modelling has an increasing role to play in long-term stewardship. Suitedness models, HS models, SDMs, succession models, and ecosystem frameworks may be useful in determining whether the restored or spontaneously colonized communities are likely to persist, diversify, or be arrested under prevailing substrate and hydrological limitations. These kinds of models come in handy, especially to assess alternative restoration pathways and where ecological breakdown can be reinforcing of physical instability. Nevertheless, ecological assemblages in those mining sites that have been abandoned are quite frequently heavily affected by local contingencies, such as microsite variation, toxicological limits, invasive species, and disturbance restoration. As a result, ecological models cannot be

applied to predict precise outcomes but can be applied to find possible pathways and management sensitivities^[115].

Probably the most promising methodological frontier is integrated and systems-dynamics models, which seek to capture interactions between environmental and management variables, and not to isolate them. An example of such a systems-dynamics framework is where erosion, contaminant exposure, performance of treatment, establishment of vegetation, frequency of maintenance, and availability of funding are interrelated on a shared causal framework. These tools are useful in the exploration of feedback, delays, and leverage points, especially in areas that cannot be predicted directly. They are weak in that they tend to be simplified at a high level of abstraction and are thus out of touch with the particulars of the site. However, they come in handy with the fact that the management of abandoned mines is not just a question of modeling physical processes, but the interactions between environmental and governance processes that produce results together^[116].

An important critical methodological aspect is that technical sophistication should not be used to assess models. Practically, it means that very complicated models may be brittle in situations in which parameter uncertainty is acute, calibration data is weak, or the outputs of the result are too opaque to be interpreted by decision-makers. Necessarily fewer complex models, openly associated with monitoring data and decision requirements, can have more practical value. This is not aimed at maximizing the complexity, but to be able to reason well in the face of uncertainty. To that extent, modeling must be integrated into the adaptive management process instead of being placed as a predictive solution. It is most useful when determining the range of uncertainty, uncovering the controls, and where further monitoring would bring the most advantage to future decision-making^[117].

4.4. Decision-Support Frameworks and Multi-Criteria Evaluation

Long-term geological and ecological management refers to the decisions between competing interventions, constrained funds, uncertain results, and varying priorities of the stakeholders^[118]. Decision support methods are thus needed, not so much to prioritize risks but to organize a complex judgment clearly and justifiably. In the case of abandoned mines, a single variable is hardly ever optimized. An intervention

that has better containment of contaminants can create more of a maintenance burden, a revegetation plan that would provide better habitat would offer less geotechnical protection, and a cheaper intervention would be more socially acceptable in the short run but less resistant in the face of future climatic extremes. Such trade-offs can be made explicit with the help of decision-support tools.

The use of multi-criteria decision analysis is especially relevant as it makes it possible to take into account such criteria as the environmental, technical, ecological, economic, and social ones at the same time^[119]. This particularly comes in handy where there is no single indicator that can depict success. In the case of abandoned mines, requirements can consist of the reduction of contaminants, enhancement of slope stability, potential to recover ecological conditions, viability in terms of monitoring, cost, institutional competence, and community acceptance. The advantage of this method is that the plural goals have been considered instead of simplifying the decision-making process to a small-scale engineering performance. Nonetheless, the tools of multi-criteria are as credible as the assumptions regarding weighting criteria and scoring alternatives. When such assumptions are not explicit or when one disciplinary approach prevails, objectivity can be a deception. The transparent stakeholder engagement and sensitivity analysis are thus necessary in case multi-criteria approaches are going to bolster as opposed to mask major judgments^[120].

Risk matrices and prioritization systems are also popular, especially where there are numerous abandoned sites vying for the scarce remediation funds^[121]. Such techniques may prove useful in focusing concentration on those locations with large consequences and a large likelihood of failure or exposure. However, they may tend to make dynamic risks appear to be simple risks, thus undervaluing delayed risks or interactive hazards. A site that has low instant visibility and a high threshold transition potential can be given a low priority as compared to a site with more apparent but constant contamination. Decision support systems based on systems-based need to be able to include trajectory and uncertainty (not merely present condition). This can involve scenario planning or trigger-based ranking systems which determine how the priority of the sites varies in case of different climatic, hydrological, or land-use futures.

The scenario analysis is specifically valuable to the

stewardship that takes into consideration long-term due to the high sensitivity of the mines to the uncertain exogenous forces, particularly, climate change, pressure of redevelopment, and institutional persistence^[122]. Scenarios are not predictions of the future that will happen, but they help to understand the performance of interventions in a variety of plausible futures. This methodological value lies in the fact that it changes the focus of evaluation from apparent optimality based on one set of assumed futures to that of robustness in a variety of futures. An intervention that works sufficiently under a variety of scenarios could be better than an intervention that works exceptionally under one set of assumptions but fails under slight change. Put differently, the approaches to decision-support ought to be more biased towards resilience and flexibility rather than limited short-term optimization.

Another methodology issue is participation. Making decisions concerning the management of abandoned mines can be handled as a technical issue, but the outcomes are social and political in addition to being environmental. Participatory approaches like stakeholder workshops, community mapping, and participative monitoring design would enhance the relevance and legitimacy of decision support by including local knowledge, exposure experience, and judgments of values that may not be identified in technical assessments^[123]. This is especially vital in situations where communities have a long-time mine legacy, and they can become aware of the emerging risks before they reflect in official datasets. The role of participation does not exclude that of technical analysis, but can demonstrate aspects of feasibility and vulnerability that are not reflected in expert-oriented models.

4.5. Indicators, Thresholds, and Early Warning Systems

Measuring performance is the key to the operational efficiency of the long-term management^[124]. Indicators put complex system behavior into signals that can be used to lead to interpretation and action. However, in abandoned mines, indicator design has been too limited by focusing on variables that are easily measured or directly controllable and ignoring those that are more indicative of system resilience and trajectory. Systems-based method demands indicators that are scientifically sound as well as functional

to the decision-making process.

Geological signs can be sloping movement rates, crack expansion, settlement, gully development, erosion depth, landform roughness, and drainage density variation^[125]. Indicators of hydrogeochemical conditions can be the level of contaminants, load estimates, redox conditions, variability of the flow, rate of rebound of groundwater, or retention of performance of treatment systems. Some examples of ecological indicators are vegetation survival, species turnover, depth of root penetration, soil organic matter or microbial activity, aquatic community composition, or habitat connectivity. The methodological difficulty does not merely lie in gathering numerous indicators, but in utilizing combinations that demonstrate interaction and direction of change. A parameter of water quality, such as a decreasing one, is more informative when interpreted with the rates of erosion, vegetation stress, and hydrologic changes than when viewed alone.

The thresholds provide a practical meaning to the indicators as they define values or rates of change by which reassessment or intervention can be initiated^[126]. However, threshold design in abandoned mine management is yet to be developed. Most programs are based on regulatory overshoots, which are significant but, in most cases, not adequate since they determine failure when much of it has already taken place. To have sustainable stewardship in the long run, more process-sensitive thresholds are required and earlier. They can be a faster rate of deformation, storm-induced turbidity bursts, and a decreasing vegetation strength across drought cycles, or more variability in the passive treatment effectiveness. These thresholds are used as early indicators and the intervention is done before systems slide into more destructive or expensive modes.

The early warning concept is particularly beneficial in systems that are nonlinear and slow to respond. Before catastrophic failure in abandoned mines, there are frequently subtle indicators of increased seepage, local erosion, vegetation dieback, redox oscillation, or deterioration of infrastructure^[127]. Early warning systems aim to identify such precursors. Their approach has the potential to link high-frequency tracking, in-built indicators, and pre-programmed decision rules. Nevertheless, early warning is not just a technical issue. It is also subject to the ability to govern: the information needs to be analyzed, processed, and responded

to promptly. An elaborate warning system that lacks the capability of institutional response is of minimal practical protection.

More importantly, indicator frameworks must not be subject to the fallacy of false precision. Since the topic of abandoned mine systems is a heterogeneous and uncertain one, not all these thresholds can be provided with clear universal values^[126]. Others have to be site-specific and adaptive, and they can be developed by observation and experience. This does not undermine their utility; on the contrary, this is an indication of the truth that stewardship is a learning process. Indicators and thresholds have been found to work best as dynamic parts of management and not immutable ones at the start of a project.

4.6. Toward Integrated Digital Platforms and Knowledge Infrastructures

With larger and more varied data volumes in abandoned mine management, there is a final frontier of methodology dealing with integration. Records on site characterization, records on monitoring, remote sensing, model results, maintenance records, and community observations are usually stored in different databases that use different formats and time scales. This fragmentation diminishes the ability to detect cross-domain associations and demeans continuity among members of personnel or institutions. Prolonged stewardship thus does not only need improved tools in each field, but also improved infrastructure to bridge them^[65].

Geographic information systems are already at the centre of spatial integration, where it is possible to overlay geological hazards, drainage networks, contamination hotspots, vegetation patterns, and land-use characteristics^[128]. More sophisticated digital solutions, such as relational databases, cloud proprietorship control panels, and the idea of digital twins, are starting to be examined to mine legacy management. These systems are capable of facilitating close-to-real-time visualization, trend analysis, comparison of scenarios,

and interdisciplinary communication. It is not technological novelty in itself that gives them their greatest potential, but the ability to preserve institutional memory and facilitate adaptive learning over long time periods. Knowledge infrastructures can be as significant as physical infrastructure at a deserted mine, where turnover of staff and lack of continuity in governance are the order of the day.

Meanwhile, the digital integration is to be approached with criticism^[129]. Data-intensive platforms have the potential to give an illusion of control when the measurements underlying them are thin, biased, or misinterpreted. They are also able to make quantitative variables superior to historical, local, and qualitative information, which might be essential in comprehending site action. A methodological approach that is systems-based in its approach must therefore regard the digital tools as facilitators of synthesis and not a subject of expert judgment or stakeholder participation. They are to aid coherent interpretation across domains in assisting managers to shift from fragmented observations to integrated stewardship.

To conclude, long-term geological and ecological management of abandoned mines needs to be done with methods and tools that are capable of reliving incomplete legacies, tracking slow and episodic change, searching for uncertain futures, and helping open decisions under complex trade-offs^[130]. Their strength is not only in their technical perfection, but in the fact that they turn system interactions to the surface and put them into practice. **Table 3** outlines the major methodological domains, their uses, and the key limitations of the domains when used in long-term stewardship. There is no successfully managed site because it is carefully gauged or modeled; a successfully managed site is one in which the characterization, monitoring, prediction, and decision support evidence is built up into an adaptive perception of the path. This is a critical methodological change that stewardship requires to go beyond the linear compliance of the question and into the radical sustainability of operating the abandoned mines as dynamic socio-ecological-geological systems.

Table 3. Principal methods and tools for the long-term geological and ecological management of abandoned mines, with their stewardship value and limitations.

Method/Tool Category	Typical Applications	Main Data/Output	Contribution to Long-Term Stewardship	Limitation
Historical reconstruction and archival analysis	Reconstructing mine layout, waste emplacement, drainage history, and undocumented workings	Historical maps, aerial images, production records, closure files	Reduces uncertainty about hidden legacies and source areas	Records are often incomplete or inconsistent

Table 3. *Cont.*

Method/Tool Category	Typical Applications	Main Data/Output	Contribution to Long-Term Stewardship	Limitation
Field geological and geotechnical surveys	Assessing landform condition, instability zones, subsidence risk, cover degradation	Structural observations, deformation evidence, material properties	Identifies process-active instability areas and maintenance priorities	Often spatially limited and episodic
Hydrochemical and hydrological monitoring	Tracking seepage, discharge, groundwater rebound, contaminant loads, seasonal variability	Water levels, flow rates, pH, sulfate, metal concentrations	Essential for detecting delayed and climate-sensitive pollution dynamics	Low-frequency sampling may miss episodic events
Ecological monitoring	Evaluating vegetation establishment, soil recovery, aquatic ecosystem response, habitat condition	Species composition, cover, biomass, soil properties, biotic indices	Reveals whether restoration is functionally progressing or stalled	Commonly reduced to superficial cover metrics
Remote sensing and UAV surveys	Mapping erosion, subsidence, vegetation stress, moisture patterns, landform change	Spatially explicit imagery, elevation models, deformation signals	Allows repeated, site-wide observation over large or inaccessible areas	Requires field validation for interpretation
Geophysical investigation	Detecting subsurface voids, seepage pathways, buried waste, internal heterogeneity	Resistivity, seismic, radar, magnetic or electromagnetic data	Improves understanding of hidden structures and subsurface risk	Interpretation may be ambiguous without complementary data
Predictive modeling	Forecasting water quality, slope evolution, contaminant transport, restoration trajectories	Scenario outputs, sensitivity analysis, future risk estimates	Supports proactive planning and intervention prioritization	Strongly influenced by uncertainty in site parameters
Multi-criteria decision analysis	Comparing intervention options across technical, ecological, social, and economic criteria	Ranked alternatives, trade-off structure	Helps make complex decisions more transparent	Weighting schemes may introduce subjectivity
Threshold and early warning systems	Triggering reassessment or intervention before major failure	Action thresholds, trend deviations, alarm signals	Enables shift from reactive crisis response to preventive stewardship	Requires long-term data continuity and institutional response capacity
Digital integration platforms	Linking monitoring, modeling, mapping, and maintenance records	Integrated dashboards, geodatabases, digital twins	Preserves institutional memory and supports cross-domain synthesis	Data-rich platforms can mask weak underlying evidence

5. Integrated Management Strategies and Future Directions

When the idea of abandoned mines is perceived as developing socio-ecological-geological systems, then one cannot arrange management strategy around individual hazards, limited time perspectives, or close-out interventions^[52]. It is not merely the problem of remediation of discrete contaminants or stabilization of discrete landforms as a practical challenge, but the problem of long-term site trajectories in the circumstances of an ongoing uncertainty, climate change, partial continuity of institutions, and uneven distribution of resources. This involves a multimedia approach to geological risk mitigation, hydrochemical containment, ecological restoration, enduring governance, and social authenticity in a united custodianship dimension^[131]. Integration is not as easy as abandoned mine sites are heterogeneous in terms of their disturbance history, hazard profiles, and post-abandonment context. However, it is the complexity where the need to integrate management is most needed. The aspect

of fragmented measures can be applied to achieve short-term benefits, but the problem lies in the fact that these practices rarely address the systemic relationships that propagate the legacy risk.

The main problem is that most of the abandoned mine programs still are intervention-based but not trajectory-based^[132]. They are concerned with whether there is a treatment system in place, whether there is a slope regraded, or whether there is a seeded vegetation, without much consideration of the interaction of these processes over time, and whether they will be effective as the pressure mounts. There is another logic that is needed in integrated management. It has started with the realization that not every place can be completely rehabilitated, not every pollutant can be taken away, and not every danger can be eradicated. This is not the ultimate closure in a technical sense, but the strategic lessening of the threat of hazard in the long term by combinations of containment, attenuation, adaptation, and ecological reorganization. The subsections below analyze the major aspects of this strategy and present the ways of further development.

5.1. Long-Term Remediation and Restoration Pathways

The long-term management of abandoned mines is frequently represented as a decision between remediation and restoration, where remediation is linked with technical risk management and restoration is linked with ecological revival^[49]. This distinction is, in an actual sense, false. An efficient stewardship needs the combination of both, since most of the time the same site needs the control of sources of contamination, hydrological intervention, geomorphic stabilization, and ecological reconstruction. The real question is not which between remediation and restoration should prevail, but how these two processes can be sequenced and combined in a manner that will not foster dependency on continuous high-intensity intervention and will not create the illusion of self-recovery in a situation where the constraints of the systems are acute.

The most basic approach in any site where reactive waste, exposed sulfides, unstable tailings, or contaminated seepage persist in fueling site degradation is the source control approach^[133]. Downstream restoration and ecological recuperation are expected to be partial and intensive without decreasing the creation or mobilization of contaminants. The control of sources can include capping, regrading, water diversion, oxygen restriction, encasement of reactive material, or removal of the most dangerous wastes selectively^[133]. However, source control is not an easy concept. The covers can crack, drainage systems can malfunction, and buried material cannot remain inactive in changing moisture regimes. The concept of source control, therefore, cannot be taken as an end but as a step in a more extensive system of risk minimization. Its success relies on its persistence of geomorphic evolution, hydrologic behavior, and ecological development.

Passive attenuation and containment are the strategies that frequently need to be implemented in those cases when it is not possible to eliminate the source^[134]. They are passive treatment wetlands, permeable reactive barriers, alkaline drains, settling ponds, sediment traps, and landscape designs that enhance the residence time and immobilization of contaminants. They are also attractive because their operation may be at lower costs compared to full active treatment system, particularly in remote sites or orphaned sites. Neverthe-

less, passive systems are occasionally simplified to the ideal of being low-maintenance systems when in practice, they are process-sensitive, and may fail slowly by being clogged up, overloaded with sediments, bypassed hydrologically or vegetatively, or unstable in redox conditions. One of the important lessons obtained in the course of long-term practice is that passive treatment must not be compared to passive governance. Even systems that run on a low level need to be observed, to be periodically adjusted, and expectations need to be set as to lifespan and seasonal influence.

Restoration of the ecology is also not simple as revegetation alone. In deserted mine environments, restoration may have to start on a substrate level through rebuilding of soils, checking soil erosion, hydrology, and re-establishing plant communities^[135]. Even at this stage, it might not be the reconstruction of pre-mining ecosystems, which are often irreversible because of irreversible topographical, geochemical, and drainage changes. A more justifiable aim is the construction of functionally resilient ecosystems with the ability to stabilize surfaces, facilitate biogeochemical cycles, limit exposure routes, and offer habitat as abiotic constriction continues. This strategy suggests that more liberalism is given to new ecosystems and novel ways of succession, as long as they do not embed toxicity or geomorphologic vulnerability.

The intervention sequence is therefore important. On certain sites, ecological restoration projects are unsuccessful on repeated occasions due to the failure to establish geotechnical and hydrochemical controls beforehand. In others, overvaluing engineering creates sterile landscapes that need constant maintenance. The integrated pathways should be able to negotiate between these extremes. Interventions at an early stage can focus on acute reduction of hazards and containment of contaminants, and also on the later stages, which increasingly aim to provide ecological buffering, soil formation, and landscape connectivity^[84]. This is not that sites are traversing the boundary between engineering and ecology, but that the management should be gradually overtaken by the externally imposed control to be more dependent on the ecological stability of a situation, in which the conditions of a site allow. This is the direction that long-term stewardship uses as its main tool since it is the only way of reducing continuous reliance on intensive technical maintenance.

5.2. Designing for Self-Sustaining but Monitored Post-Mining Landscapes

Among the main conflicts in the management of abandoned mines is the wish to have self-sustainable landscapes and the fact that most of them are still reliant on human involvement^[7]. The notion of self-sustainability is appealing due to the fact that it suggests less cost, less maintenance load, and increased ecological validity. But the word is usually employed in an inaccurate way. A landscape can support vegetation and, at the same time, emit contaminants. It might seem that on the geomorphic level, it may be silent, but internal drainage systems may be corrupted. It can operate satisfactorily with average climatic conditions, and it is very susceptible to extreme conditions. Self-sustainability should thus be more strictly defined as the ability of a post-mining system to tolerate satisfactory degrees of stability, controlling the contaminants and ecological integrity without major interventions regularly, yet still be prone to strategic surveillance and periodic regulation.

When it comes to designing such landscapes, it is necessary to move out of end-state thinking as well as what may be thought of as performance under disturbance. Landforms are not only supposed to be designed or retrofitted to suit current engineering requirements, but they are also expected to change predictably over a period of time due to weathering, runoff, and vegetation cover. It is the reason why the design of geomorphic landforms has gained greater interest: such a way of matching engineered surfaces more strongly with the natural drainage organization and erosional processes would possibly decrease the risk of concentrated failure and decrease the maintenance costs in the long run. Nonetheless, geomorphic mimicry ought not to be romanticized. The techniques that are produced due to anthropogenic waste materials tend to vary radically from the natural substrates regarding their texture, chemistry, and behavioral structure. An already geomorphically formed landform can be left chemically unstable or hydrologically unsound. Long-term design, therefore, should synthesize geomorphic principles with geochemical and ecological facts and not place any belief in the presumed naturalness of forms that are likely to be resilient^[136].

The same applies to the ecological design. The restoration, which requires repeated fertilization, irrigation, or re-planting, cannot be considered truly self-sustaining despite

its visual success. In contrast, the early-stage support can be explained in case it contributes to the subsequent development of the soil-forming processes, nutrient circulation, and species recruitment that decrease the intervention requirements in the long term. The pertinent issue is thus whether management activity is causing dependency or capacity. One of the design principles to be applied is to prefer interventions that create reinforcing feedback, e.g., vegetation to enhance soil retention and moisture control, or hydrological structures to limit erosion and to encourage wetland-based attenuation. Conversely, solutions to one issue but susceptibility to greater system weakness should be approached with care, even though they might lead to short-term benefits^[137].

Meanwhile, the process of designing under self-sustaining conditions does not exclude the necessity of monitoring^[4]. The concept of a walk-away landscape can be especially troublesome in the setting of abandoned mines due to the long-term hazards, which are, in many instances, nonlinear, delayed, and climatic. A more justifiable model is the monitored self-sustaining landscape: the one where intervention is less common, though long-term monitoring is present to signal an approach to the threshold, treatment failure, vegetation stress or subsidence. These landscapes are not left alone in a management regard; they are transferred to less intensive stewardship. This difference is conceptually significant in the sense that it balances the desire for less intervention with the fact that process-active landscapes still need long-lasting institutional concern.

5.3. Governance, Finance, and the Institutional Durability of Stewardship

The ability to achieve the long-term stability of abandoned mine landscapes cannot be achieved only through technical means. The efficiency of this is pegged on the reliance on the strength of the governance arrangements that facilitate monitoring, maintenance, decision-making, and accountability. In most instances, institutional continuity collapses following formal closure or disappearance of operators is the largest cause of failure, rather than engineering lack of knowledge. The issue of governance should therefore be viewed as an internal management tool, not as an administrative issue^[132].

The orphaned liability problem is considered to be one of the most enduring governance issues. In the absence of

responsible companies or diffuse legal responsibility, long-term management is left to the public agencies, which might not be well-funded, staffed, or authorized to operate^[138]. This makes an imbalance between environmental timescales and governance timescales. Geological processes and geochemical processes can be generational, whereas budgets, regulatory priorities, and administrative mandates are short-lived. Consequently, the management of abandoned mines is usually intermittent, accompanied by crisis continuity. Then a tailings erosion issue can be addressed following a storm, only to be neglected once the monitoring is ignored after the initial repairing. These forms of government are structurally inconsistent with governments that need decades to learn.

Environmental performance cannot, therefore, be separated from financial design. Stewardship may also be a result of trust funds, long-term maintenance bonds, such as public reclamation programs, and even liability transfer mechanisms, although their effectiveness varies depending on whether they are sized and designed to handle actual long-term risk. One weakness widespread in mine closure finance is the failure to estimate the future costs of adapting to climate change, the deterioration of treatment systems, or the recurring ecological intervention. When a site gets under communal care, it frequently turns into reactionary and politically determined. This compromises continuity itself, which adaptive management demands. A better solution would consider long-term stewardship funding as infrastructure finance and not residual cleanup financing, considering that in legacy mining areas, monitoring, data systems, and periodic intervention are long-term public goods^[139].

Sectoral coordination is also important in institutional durability. The usual areas of concern covered by abandoned mine risks are environmental regulation, water management, land-use planning, public health, disaster preparedness, and conservation of biodiversity^[140]. Nonetheless, administrative systems tend to be subdivided in a disciplinary manner that resembles the scientific literature. This may result in the partial management where water agencies manage the chemistry of drains, land agencies manage the access of the site, and conservation agencies manage the habitat, but no institution handles the overall system trajectory. The needs of integrated stewardship are governance arrangements that can span these areas, whether in formal mechanisms of coordination, shared databases, regional governments, or site-based

management agencies.

The involvement of stakeholders is also significant^[141]. Settlement near mines, which are frequently abandoned, requires specific practical expertise in seepage development, seasonal water variations, local erosion, dust issues, or deterioration of infrastructure. Monitoring sensitivity and social legitimacy can be enhanced by including them. Additionally, the concept of long-term stewardship is always accompanied by normative decisions on the tolerable risk, land use in the future, and restoration goals. These decisions cannot be solved only by technical specialists since they are related to who is left with residual burdens and who benefited from the redevelopment or conservation. By engaging, no consensus is guaranteed, though concealed vulnerabilities can be uncovered, realistic success stories challenged, and trustworthiness developed to act as a long-term steward through intergenerational eras.

5.4. Climate Change and Emerging Stressors in Abandoned Mine Landscapes

Climate change is not merely another factor that influences abandoned mines; it completely changes the environment within which all management strategies should be considered^[142]. Most remediation and stabilization designs were based on assumptions of relative climatic stationarity, with little regard to the impact of increasingly intense rainfall, extended drought, rising temperatures, vegetation changes, wildfire, or cryosphere change on long-term performance. In sites that have fallen out of use, with maintenance that is usually inadequate, climate change can turn long-term instability into short-term danger.

One of the most immediate issues is hydrological intensification. Extreme precipitation may promote infiltration debate through covers, create huge contaminant pulses, initiate gully erosion on waste deposits, and overtax passive treatment systems^[143]. The effects are not limited to extraordinary disasters, but could be caused by repeated moderate phenomena that would build up to diminish resilience. On the other hand, drought will be able to inhibit the performance of the wetland treatment, concentrate dissolved contaminants, emphasize revegetation, and enhance dust generation on the open tailing or waste-rock surfaces. The successive droughts and heavy precipitation can be particularly destructive since they alternate the structural deterioration, plant stress, and

contaminant flushing in that order. Conventional design standards that rely on average weather conditions are thus becoming incompetent.

The changes are also caused by warming in vegetation and disturbance regimes, which make managing them even more difficult. The chosen plant species during the restoration process can prove to be less viable in a different temperature and moisture regime, and invasive species can outcompete the stressed substrates^[144]. Another uncertainty that may take away surface cover, enhance erosion, and expose contaminated soils to atmospheric dispersion is the wildfire threat in vegetated reclamation areas. The permafrost in cold areas begins to warm up, and the freeze-thaw processes can lead to partial destabilization of frozen waste facilities and a shift in the direction of seepage^[45]. They are not mere regional environmental impacts, but they change the suppositions of slope stability, cover functionality, water treatment effectiveness, and ecological succession.

One significant implication is that stewardship strategy should be founded on climate adaptation as opposed to being an ex-post modification^[23]. This is the need to have scenario-based planning, robust, as opposed to narrowly optimized design and monitoring systems, which can spot climate-sensitive changes before it is too late. It also demands conceptual humility: certain interventions that seemed to have been lasting might not be fitting in the climate regimes in the future. It is not simply a matter of how to ensure that abandoned mines are not affected by climatic factors, but a matter of re-architecting management systems in such a way that they can continue functioning when the very basis conditions are changing.

5.5. Research Gaps and Priorities for a Next-Generation Stewardship Agenda

Although significant progress has been made in the science of mine closure, the field of abandoned mine management continues to encounter several knowledge voids that preclude the formulation of real solutions that can be considered highly integrated. Lack of long-term datasets relating to geological, hydrochemical, ecological, and governance variables at the same sites is one of the gravest ones. Most of the studies are short-term, intervention-based, or punitive^[131]. This complicates the realization of whether observed improvements are long-term transitions or short-

term stabilization with the assistance of positive conditions. Devoid of long-period, cross-domain datasets, the notion of stewardship is strong enough as opposed to entirely justified.

The second gap is related to thresholds and precursors of failures. Much effort has been put into the characterization of contamination or measurement of the intervention outcomes, but little attention has been given to the identification of the early warning signs of system transition. This is especially significant in the landscapes where hazards are gradually formed and then increase at a fast pace. A better combination of high-frequency monitoring, remote sensing, process modeling, and ecological indicators might be useful to detect thresholds, but such integration would need convergence in methodology that has not been very commonplace yet^[145].

The third priority is to establish a connection between restoration ecology and mine geochemistry and geotechnics^[146]. Although the practice is too common, ecological restoration is often envisioned as a downstream component of engineers, as opposed to coequal to the design of the system. On the other hand, ecological ambitions can be promoted without sufficient knowledge of the behavior of the substrates, bioavailability of contaminants, or hydrological limitations. Further development of the research agenda is thus to be devoted to the hybrid design principles, where not only how engineering can facilitate ecological recovery, but also how ecological processes can facilitate geological and hydrochemical control durability is to be explored.

There is also a need for comparative and regional research^[147]. A large portion of the existing literature is place-specific, which is certainly appropriate due to the personal character of my legacies. However, over-site specificity may inhibit transferability. An older science of stewardship would pursue patterns between mine types, climatic regions, governance situations, and approaches to remediation, where general principles are not applicable and where local deviation is inevitable. These comparative studies would also be useful in trying to explain what management strategies work well when resources are limited, a major concern given the number of abandoned mines found in areas with poor technical or financial capability.

Lastly, stewardship as a socio-technical system, and not an environmental system, needs to be tackled in future research. Not secondary concerns in implementation are in-

stitutional memory, funding persistence, legal responsibility, involvement of the public, and continuity of data, which are variables that determine the successes or failures of environmental strategies^[63]. The combination of these variables into the empirical data and theory is one of the most evident areas where the field is going. So, unless this is integrated, the science of abandoned mine management risks becoming technically advanced but institutionally unsophisticated.

5.6. Toward a Practical Model of Post-Closure Stewardship

The above discussion implies that the future of the management of abandoned mines is not in a quest to achieve a universally stable end-state, but in the development of viable stewardship models that can be used to handle the

changing risk over a long period of time^[132]. In this type of model, source control, passive and active treatment where it makes sense, geomorphologically informed landform planning, ecological restoration of functions, climate adaptation, participatory governance, and long-term monitoring would be integrated into a single adaptive model. An integrated stewardship roadmap of these pathways is provided in **Figure 2**. It would not be supposed that everything could be put back to historical standards and would not see containment as a one-liner. **Table 4** describes these integrated domains of management, their long-term goals, and the research and policy priorities. Rather, it would determine success based on the minimization of hazards, enhancement of resilience, transparency in governance, and the ability to adapt to new changes.

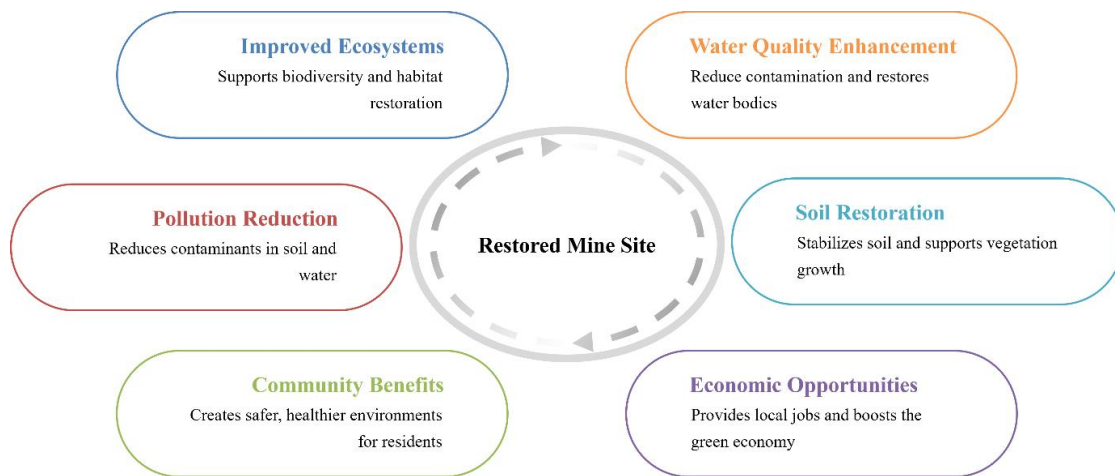


Figure 2. Systems-based management pathways and future priorities for long-term stewardship of abandoned mines.

Table 4. Integrated management strategies, expected benefits, and future priorities for long-term stewardship of abandoned mines.

Strategic Area	Main Management Objective	Representative Measures	Expected Long-Term Benefit	Research/Policy Need
Source control	Reduce the generation and release of contaminants at origin	Capping, encapsulation, selective waste removal, and diversion of clean water	Lower contaminant loading and reduced downstream treatment burden	Better long-term evaluation of cover durability under climate stress
Landform stabilization	Minimize erosion, subsidence impacts, and structural failure	Regrading, drainage control, slope reinforcement, and geomorphic design	Improved physical stability and reduced exposure of reactive materials	Need for dynamic rather than static stability criteria
Water management and treatment	Control contaminated flows and improve water quality	Passive wetlands, alkaline drains, reactive barriers, settling systems, and active treatment where necessary	Reduced pollutant transport and improved aquatic conditions	Long-term performance data for passive systems under variable climate
Soil reconstruction and ecological restoration	Establish functionally resilient ecosystems and support attenuation processes	Soil amendment, assisted succession, native species introduction, habitat reconnection	Better surface protection, nutrient cycling, and ecological recovery	Stronger integration of ecology with geochemistry and hydrology
Monitoring and adaptive intervention	Detect early change and revise management before major deterioration	Long-term monitoring networks, remote sensing, trigger thresholds, iterative review	Greater resilience to uncertainty and reduced risk of delayed failure	Development of standardized cross-disciplinary indicators

Table 4. *Cont.*

Strategic Area	Main Management Objective	Representative Measures	Expected Long-Term Benefit	Research/Policy Need
Governance and finance	Ensure durable responsibility, coordination, and maintenance capacity	Stewardship funds, liability frameworks, interagency coordination, community participation	Improved continuity of action across long timescales	Institutional models for orphaned and underfunded sites remain weak
Climate adaptation	Increase robustness of remediation and restoration under changing conditions	Scenario planning, design for extremes, drought-resilient revegetation, retrofit of drainage and covers	Reduced vulnerability to nonstationary environmental stress	Need for site-specific climate risk integration into closure retrofits
Knowledge integration	Improve evidence continuity and transferability across sites	Shared databases, GIS platforms, digital twins, comparative case synthesis	Better decision support and stronger institutional memory	More long-term, coupled datasets are urgently needed

There is also the implication of professional culture change with this model. The management of abandoned mines has frequently been structured in terms of the completion of the project, the transfer of liabilities, and the technical deliverables. Stewardship, on the other hand, is focused on continuity, revision, and shared responsibility. It raises the question as to whether systems can be directed rather than whether interventions can be installed. That transition is hard due to the fact that it undermines regulatory cultures, budgeting culture, and disciplinary practices. Nevertheless, it is more and more inevitable. The timeless lesson of the forgotten mines is that the landscapes still react even after the official closure, and the management system should be adapted to it^[148].

In this regard, integrated management strategies are not simply more expansive forms of available remediation practice. They are an alternative form of controlling disturbance of legacy: one that appreciates uncertainty, operates with processes of changing ecological and geologic form, and makes institutional permanence a component of environmental design. The last part summarizes these arguments and reflects on the consequences of the arguments to the conceptualization and management of abandoned mines over the decades to come^[14].

6. Conclusion

Abandoned mines are some of the most obvious manifestations of how industrial disturbance continues to exist beyond both the time frame and the conceptual parameters of traditional closure. They do not just have legacies of contamination left behind or local geotechnical risks, but also through long-term relationships between unstable landforms,

changing hydrogeochemical routes, limited ecological recovery, and disproportionate institutional competency. This review has claimed that they should not be considered as rigid relics of the past extraction, or as technical issues that can be solved with the help of interventions of a particular discipline. Instead, they have to be perceived as more interdependent socio-ecological-geological systems with their paths continuing to play out over decades to centuries.

One of the main contributions of this article is the redefinition of management not as closure, but stewardship. The conventional meaning of closure is geared towards end-point compliance, regulatory release, and the supposition of a relative post-intervention steadiness. Physical structures deteriorate, contaminant politics change, and ecological and governance processes are not yet finished in abandoned and orphaned mines, which is why framing is becoming insufficient. This is due to the fact that Stewardship has a more realistic and analytically sound framework since it acknowledges persistence, uncertainty, and the necessity of further institutional engagement. The success of management in this view is not determined by the fact that a site has attained a final condition, but rather by the fact that its path is becoming safer, stronger, and more controllable as new environmental and social forces act on it.

It has also been demonstrated in the review that mine legacies are basically interactive in the long term. Reactive materials can be revealed, and the release of contaminants can increase due to geological instability. Hydrochemical alteration is able to inhibit soil development and biological colonization. Ecological failure may decrease surface stability and decrease attenuation capacity. Governance discontinuity may permit long-term deterioration to take place before threshold failures occur. This feedback describes

why the dangers of abandoned mines are often intractable, even in the case of individual remediation measures that may seem technically viable. They further demonstrate why fragmented management is such a poor performer in most cases. The key to effective long-term intervention should thus be on the hazards and not just the individual hazards, but on the couplings between the hazards to produce, transfer, and enhance.

In this systems-based approach, tools and methods acquire a different role. Site characterization is no longer an easy list of disturbance in residue; it is a recreation of process-active legacies. Surveillance is not just a compliance measure, which is the basis of any long-term diagnosis and adaptive response. One of the benefits of modeling is that it makes it clear how to intervene by clarifying the trajectories, sensitivities, and leverage points of the model. The trend of decision support should be shifting away towards the focus on the narrow optimization to embrace trade-offs of the geotechnical security, hydrochemical control, ecological functionality, cost, governance feasibility, and community priorities. The indicators and thresholds are most effective when they become instruments of identification, and not of ex post breach of failure, in an adaptive management cycle.

Another finding is that hybrid strategies are necessary in long-lasting management. The complexity of abandoned mine landscapes requires neither engineering nor restoration to address. The combination of the source control, containment, passive and active treatment, geomorphic redesign, substrate reconstruction, assisted succession, and ecological buffering should be in such a manner that it represents site-specific interactions and the uncertainty in the long-term. It is not aimed at getting rid of intervention, but at developing landscapes where the risk, to a greater extent, is minimized and the reliance on high-intensity management will be minimized without neglecting observation and accountability. Here, the most realistic goal is not an alternate reality of a walk-away closure state, but a monitored and progressively self-regulating/self-defeating post-mining system.

The urgency of this change is increased by climate change. The increased rainfall, drought, wildfire, warming, and cryospheric change are expected to change the covers, drainage systems, treatment wetlands, revegetation plan, and waste landforms performance. Most of the interventions that were developed by abandoned mines assume premises that

are no longer true. Consequently, climate-aware, scenario-based, and nonstationary-strong stewardship in the future must be developed. This difficulty makes the point of the article bigger: the mine managerial practice over the long term cannot be founded on stable suppositions about the underlying environment, since even the environment governing it is shifting.

Another point that has been noted in the article is that governance does not exist outside of environmental performance. These aspects of abandoned mine management are long-term funding, liability structure, institutional memory, continuity of data, and stakeholder participation. Sites do not stay dangerous merely because they are hard geology and hard geochemistry; they stay dangerous because accountability is often decentralized to many, funding is often disjointed, and stewardship structures are not intergenerational in nature. The reason behind this is that a scientifically advanced but institutionally weak management strategy is not likely to be effective over the time that it needs. Therefore, the prospects of abandoned mine stewardship lie as much in sustainable governance architectures as in technical innovation.

There are some general implications of this review. In the first place, abandoned mine studies are to shift to longer-term and cross-disciplinary datasets, which connect ecological, physical, and institutional change. Second, the management structures are to focus on trajectory, resilience, and threshold behavior, instead of focusing on the use of the fixed indicators of closure. Third, the disciplines of restoration ecology, mine geochemistry, hydrogeology, geomorphology, and governance studies should be better interconnected in order to have the post-mining landscapes managed as whole systems instead of being treated as parallel realms. Lastly, policy and practice should embrace the fact that not all mine legacies can be remedied once, and that, as such, regulatory design, funding arrangements, and expectations of the public should be made to be attuned to this fact.

To conclude, the long-term impact of the abandoned mines is that mining is not finished with closure, and its history on the environment continues. These landscapes keep on changing both materially, ecologically, and institutionally, even after extraction is no longer taking place in them. To cope with them effectively, it is necessary to shift the closure-based mode of thinking towards a systems-based model of stewardship that is adaptive, interdisciplinary, and

explicitly long-term. Framing abandoned mines as systemic socio-ecological-geological systems, this review provides a more consistent platform through which one can comprehend the ongoing dangers of those systems and in designing management approaches that can mitigate those dangers over the decades and centuries that the historic mining landscapes will insist on.

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Conflicts of Interest

The author declares no conflict of interest.

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