

Nature-Based Solutions (NbS) for the Ecological Reclamation of Abandoned Volcanic Tuff Quarries and Flood Risk Mitigation: The Case of Artik, Armenia

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Abstract

Background

Abandoned open-cast quarries present severe ecological and hydrological hazards in mountainous ecosystems, accelerating soil degradation and downstream flash floods.

Methods

This study evaluates the efficacy of an integrated Nature-Based Solutions (NbS) framework implemented across 40 hectares of a closed volcanic tuff quarry in Artik, Armenia. The intervention combined macro-topographic re-engineering (60,498.5 m³ of substrate reshaped into stable 15–20° terraces), intense edaphic melioration (two-stage organic-mineral fertilization using N90P90K60 and 25–30 t/ha of composted manure), and the establishment of a mixed-species silvicultural phytocenosis (29,318 saplings across targeted functional clusters). Concurrently, cascading porous gabion check dams were constructed along the main ephemeral gullies to attenuate hydro-turbulent kinetics.

Results

Comprehensive 36-month empirical monitoring demonstrated significant ecological regime shifts: barren substrate soil organic matter (SOM) increased from < 0.1% to 1.8–2.2%, baseline hyper-alkalinity (pH > 8.5) stabilized to near-neutral levels (7.2–7.4), and mean sapling survivability reached 72–82%. Hydrologically, the gully roughness coefficient (Manning's n) optimized to 0.035–0.040, resulting in a 100% reduction in coarse sediment transport into urban drainage infrastructure.

Conclusions

The findings substantiate that transitioning from technogenic baselines to structured ecosystems via NbS enhances structural landscape resilience and successfully mitigates climate-driven hydrologic risks.

1. Introduction

Anthropogenic landscape degradation driven by extractive mining operations constitutes an acute challenge within global environmental management and ecosystem restoration. Open-cast quarrying of volcanic tufa deposits invariably causes total ecosystem decimation, characterized by the stripping of fertile topsoil (O and A horizons), destruction of autochthonous vegetative covers, and the permanent alteration of local geomorphology. In these post-extraction zones, natural ecological succession is strictly arrested for decades. The exposed parent rock lacks essential organic complexes, exhibits extreme compaction, and creates highly hostile microclimatic and edaphic conditions that prevent spontaneous seed germination or seedling establishment.

In the Artik region of the Shirak Marz (Republic of Armenia), unregulated industrial volcanic tuff extraction over several decades has generated a fragmented complex of abandoned quarries covering more than 100 hectares. This degraded zone functioned as a persistent source of environmental disservices. Fine-grained volcanic tuff dust was continuously remobilized by aeolian forces, significantly escalating ambient particulate matter (PM) concentrations in adjacent urban sectors and threatening public health (Environmental 2019).

This baseline vulnerability has been severely amplified by climate change (IPCC 2023). Regional climate projections indicate an increasing frequency of high-intensity, short-duration convective precipitations over the high-altitude catchments of the Artikaget and Gharanghu torrents. Because the barren, highly compacted surfaces of the abandoned quarries exhibit negligible rainwater infiltration capacities, the landscape runoff coefficient (C) spiked to an alarming 0.85–0.88. During extreme rainfall events, surface runoff cascaded through the open quarry pits, picking up loose industrial debris and crushing waste. This process generated hyper-concentrated sediment-laden flash floods and debris flows. These flows repeatedly overwhelmed urban downstream stormwater collectors, inflicting severe structural and socio-economic damages on the Artik municipality.

Conventional civil engineering techniques, such as concrete-lined channels and rigid retaining structures ("grey infrastructure"), provide limited long-term protection in these contexts because they fail to address the root ecological causes of catchment degradation. To mitigate these risks, this study examines an integrated Nature-Based Solutions (NbS) framework (European Commission 2020) designed and supervised using the GIS-based environmental zoning protocols of the Environmental Project Implementation Unit (EPIU). This paper details the long-term structural and functional outcomes of combining macro-topographic re-engineering, chemical edaphic melioration, multi-tier afforestation, and bioengineered gully stabilization. Ultimately, it demonstrates a scalable methodology for converting a hazardous industrial wasteland into a self-sustaining forest park ecosystem capable of regulatory climate and hydrologic control.

To ensure global scalability and systematic alignment, the ecological reclamation design of the Artik project is framed within the IUCN Global Standard for Nature-based Solutions (IUCN, 2020). By addressing societal challenges such as disaster risk reduction and ecosystem degradation, this study evaluates a multi-barrier NbS model. This framework transitions from purely technical quarry stabilization to integrated eco-engineering, aligning localized interventions with international best practices (Cohen-Shacham et al., 2016).

2. Materials and Methods

2.1. Site Description and GIS-Based Spatial Zoning

The pilot research area covers a 40-hectare continuous segment of the closed, abandoned volcanic tuff quarries situated on the north and north-eastern periphery of Artik (40°37' N, 43°58' E; elevation range:

1850–1980 m a.s.l.). Spatial analysis, mapping, and post-intervention monitoring were conducted using a Geographic Information System (GIS) based on the foundational program map generated by the EPIU. The 40 ha restoration zone was partitioned into two strategic functional clusters:

- **Cluster A (30 hectares):** Structured forest protection belt optimized for maximum root anchoring and slope stabilization (represented as the green and dark green broad-leaved and coniferous tree planting zones on the map).
- **Cluster B (10.5 hectares):** Recreational green zone integrated closer to the urban boundary (represented as the shrub planting and grass cover zones adjacent to the community borders).

In-text Integration

As visualized in Fig. 1, the GIS spatial modeling partitioned the 40 ha site into two distinct zones to target both ecological stabilization and public recreational integration.

2.2. Mechanical Reclamation and Topographic Re-engineering

The baseline technogenic landscape was highly unstable, characterized by steep vertical quarry faces (> 45°, up to 85°) left behind by industrial stone-cutting machinery. This topography posed ongoing landslide, collapse, and severe rill erosion risks. Earth-moving machinery (heavy bulldozers and excavators) executed macro-topographic remodeling, redistributing 60,498.5 m³ of loose quarry waste, accumulated industrial overburden, and sub-economic volcanic tuff fragments. High vertical cliffs were cut back and graded to form a sequence of stable, terraced slopes with safe inclines ranging between 15° and 20°, establishing a suitable topographic foundation for subsequent bio-engineering and soil placement.

In-text Integration

The extreme contrast between the baseline degradation and the post-intervention biophysical outcomes is systematically documented in Fig. 2, showing both slope stabilization and drainage clearance.

2.3. Edaphic Melioration Protocols

Because natural soil profiles were absent, a synthetic topsoil layer (20–30 cm thick) was laid down across the graded terraces. This topsoil layer utilized fertile soil material recovered from regional municipal construction excavations. To revitalize biological cycling and correct macronutrient deficits within the raw substrate, an aggressive two-stage melioration protocol was deployed in autumn 2019. Organic amendment consisting of well-composted, dry cattle manure was disked into the topsoil layer at an application rate of 25–30 t/ha. This organic base was supplemented with mineral fertilization supplying N90P90K60 kg of active ingredients per hectare.

Core edaphic parameters (pH, soil organic matter (SOM), available P2O5, and exchangeable K2O) were evaluated at the end of each vegetative period (2019, 2021, and 2022) using standardized laboratory chemical analysis of composite core samples (0–20 cm depth) collected across established monitoring plots according to GOST standardized methodologies.

In-text Integration

The initial mechanical step of reshaping the land using heavy machinery to establish stable terraces for soil placement is captured in Fig. 3.

2.4. Phytocenotic Selection and Afforestation Mechanics

To avoid monoculture vulnerabilities, a multi-tier, mixed-species silvicultural structure was designed. A total of 29,318 nursery-grown saplings (2–3 years old, with hardened root systems) were planted across Clusters A and B. Planting pits measuring 50 x 50 x 50 cm were excavated and backfilled with an enriched humus-soil matrix to prevent initial transplant shock. Species selection was rigorously determined based on ecophysiological traits: high frost resistance, extreme drought tolerance, low nutritional requirements, and rapid root-network development to maximize biophysical anchoring.

- *Pinus sylvestris* (Scots Pine): 11,000 saplings (primary evergreen skeletal species).
- *Quercus macranthera* (Caucasian Oak): 9,000 saplings (long-lived deciduous climax species).
- *Fraxinus excelsior* (European Ash): 6,300 saplings (fast-growing deciduous stabilizer).
- *Juniperus spp.* (Juniper) & Indigenous Shrubs: 3,018 units (understory and boundary windbreaks).

To bridge the high summer evapotranspiration deficits during the critical establishment phase (2020–2022), a dedicated localized irrigation pipeline system was constructed and operated, delivering systematic water inputs based on weekly sapling transpirational demands.

In-text Integration

As visualized in Fig. 4, the progression from raw substrate conditioning to early vegetation cover demonstrates the rapid response of the soil-plant system to edaphic melioration.

In-text Integration

The physical layout and operation of the localized watering infrastructure that supported the sapling establishment phase are illustrated in Fig. 5.

2.5. Hydro-Morphological Gully Bio-engineering

The ephemeral gullies cutting through the quarry zone required stabilization to prevent further headward erosion. Channel beds were cleared of blocking industrial stone debris to re-establish uniform cross-sections. Flexible, porous gabion check dams (double-twisted galvanized steel wire mesh boxes filled

with local 100–250 mm graded volcanic tuff stones) were constructed across critical high-gradient sections of the channels. Hydro-dynamic flow routing and capacity parameters were modeled using Manning’s open-channel equations (Manning 1891) to ensure optimal stone-mesh sizing and spacing, focusing on decreasing peak kinetic velocity and capturing coarse bedload sediment fractions before they reach urban conduits.

3. Results and Discussion

3.1. Landscape-Scale Morphological and Hydrological Transformation

Empirical field data collected over 36 months indicated that the 40-hectare pilot zone shifted from an unstable industrial wasteland to a structured, functioning forest park ecosystem. This structural transformation rearranged the biophysical properties of the landscape matrix, as summarized in Table 1.

Table 1
Comparative Matrix of Pre- and Post-Restoration Landscape and Hydro-Physical Metrics

Evaluation Metric	Technogenic Baseline (Pre-2019)	Restored Ecosystem State (2022)	Scientific Mechanism & Ecosystem Dynamics
Landscape Matrix Structure	Fragmented parent rock, vertical cliffs (> 45°), exposed industrial debris.	Geomorphically stable, graded terraces (15–20°) with structured soil mantle.	Mechanical grading eliminated gravitational shear stress and slope failure risks.
Topsoil Horizon Depth	Absolute absence of topsoil (0 cm). Raw lithic sub-stratum.	Continuous 20–30 cm root-penetrable meliorated topsoil layer.	Established a sustainable substrate for root development and edaphic microflora colonization.
Surface Runoff Coefficient (C)	Extreme impermeable behavior (C = 0.85–0.88).	Elevated infiltration and retention capacity (C = 0.42).	Increased surface roughness and macroporosity converted overland sheet flow to subsurface flow.
Projective Vegetative Cover	Total devegetation (Baseline cover < 2%).	Structured multi-tier canopy cover (> 65%).	Successful development of 29,318 trees/shrubs, stabilizing the microclimate.
Soil Erosion Intensity	Severe rill/gully water erosion; extreme aeolian dust generation.	Near-zero surface erosion; complete suppression of fugitive dust.	Vegetative canopies dissipate raindrop kinetic energy; root networks bind surface aggregates.

Under baseline conditions, the kinetic energy of intense rainfall events was transferred directly onto the exposed tufa sub-strata, driving immediate surface runoff generation and aggressive downslope scouring. Topographic remodeling effectively disrupted these hydrological pathways. The introduction of

terraced gradients reduced the hydraulic slope length, preventing the accumulation of sheet flow velocity and significantly decreasing the catchment's flash-flood generation potential at its source.

The barren substrate of the abandoned Artik quarries consists predominantly of volcanic tuff (Karapetian et al., 2001), which presents severe nutrient deficiencies and physical compaction. Relying solely on spontaneous ecological succession in such highly disturbed sites is often insufficient, requiring decades to establish minimal vegetative cover (Prach & Hobbs, 2008). Therefore, active bioengineering interventions—combining organic soil enrichment with native species afforestation—are crucial to accelerate primary soil formation and stabilize the microclimatic conditions of degraded quarry ecosystems (Wong, 2003; Prach et al., 2011).

3.2. Chemical and Physical Evolution of the Edaphic Stratum

The deployment of organic-mineral melioration initiated chemical changes within the previously sterile substrate. Fresh tufa quarry waste typically exhibits strong alkaline properties ($\text{pH} > 8.5$) due to its chemical composition, which immobilizes critical orthophosphate ions (P_{205}) and vital micronutrients. Manure decomposition counteracted this constraint by releasing organic humic and fulvic acids, which buffered the profile down to an optimal, near-neutral pH range of 7.2–7.4 (Table 2).

Table 2
Quantitative Dynamics of Primary Edaphic and Structural Parameters (2019–2022)

Soil Physicochemical Parameter	Pre-Restoration Baseline (2019)	Post-Melioration Phase (2022)	Ecophysiological Interpretation & Effects
Soil Organic Matter (SOM, %)	< 0.1% (Sterile mineral mass)	1.8% – 2.2%	Successful initialization of the humification process via added carbon matrices and root exudates.
Available Phosphorus (P2O5, mg/100g)	0.5–1.2 (Severely deficient)	3.5–4.8 (Moderately sufficient)	Enhanced mineral phosphate availability directly stimulated juvenile root-tip elongation.
Exchangeable Potassium (K2O, mg/100g)	6.0–8.5	18.0–24.5	Reached concentration thresholds required to reinforce sapling drought and frost turgor mechanisms.
Water-Stable Aggregates (> 0.25 mm, %)	< 5% (Unconsolidated powder)	35% – 40%	Tufa dust bound into structural peds, increasing bulk porosity and aerating the root zone.
Active Soil Reaction (pH)	> 8.5 (Highly Alkaline)	7.2–7.4 (Near-Neutral)	Acidic buffering via organic decomposition optimized nutrient bioavailability.
Note: Values represent the mean of composite soil samples (n = 15 per cluster) ± standard deviation (SD). Differences between 2019 baseline and 2022 post-melioration phases are statistically significant at p < 0.05 based on paired t-tests.			

The introduction of the organic matrix established a functional Cation Exchange Capacity (CEC) within the topsoil layer. As water-stable structural aggregates expanded from < 5% to 35–40%, the highly erodible volcanic tuff dust consolidated into micro-peds. This structural transformation prevented wind-driven dust suspension and improved sub-surface hydrologic connectivity.

The integration of gabion check dams with vegetative buffers acts as a highly effective sediment-retention system. As demonstrated by eco-engineering models in alpine environments, the spatial distribution of vegetation directly controls erosion rates and sediment yield (Rey, 2006). By reducing the peak velocity of floodwaters in the Artik riverbeds, these hybrid green-gray structures provide immediate mechanical protection while facilitating the long-term establishment of riparian vegetation (Stokes et al., 2014).

3.3. Silvicultural Stand Dynamics and Ecophysiological Adaptations

The established mixed phytocenotic architecture across Clusters A and B reached high establishment rates. Field surveys from November 2021 and June 2022 track the structural evolution of the forest protection belt. The survival and adaptation rates of the selected species are detailed in Table 3.

Table 3
Biometric Performance and Functional Roles of Selected Silvicultural Species

Species Botanical Name	Total Planted (Saplings)	Mean Survival Rate (%)	Primary Hydro-Mechanical Function	Ecophysiological Adaptation Mechanism
<i>Pinus sylvestris</i>	11,000	72%	Deep geomechanical slope anchoring via vertical taproot elongation.	Sclerophyllous needles limit winter transpiration stresses during prolonged soil freezing.
<i>Quercus macranthera</i>	9,000	75%	Lateral structural root interleaving; generation of dense organic forest litter.	Extreme cold tolerance; organic litter deposition drives autochthonous humification.
<i>Fraxinus excelsior</i>	6,300	78%	High-density superficial root networking to control sheet erosion.	Rapid initial biomass accumulation and Leaf Area Index (LAI) expansion maximizing rainfall interception.
<i>Juniperus spp. & Shrubs</i>	3,018	82%	Low-tier ground binding along exposed terrace boundaries.	Low transpirational coefficients; functions as a multi-tier boundary windbreak.
Note: Mean survival rates were evaluated across 12 permanent monitoring quadrats (50 x 50 m) randomly distributed within Clusters A and B. Differences in survival between species were analyzed using one-way ANOVA ($p < 0.05$).				

The spatial alternation of *Pinus sylvestris* and *Quercus macranthera* avoided the disease and pest vulnerabilities common to industrial monocultures. As the Leaf Area Index (LAI) expanded, the canopy intercepted an estimated 15–20% of gross rainfall, mitigating direct mechanical droplet impacts on the soil surface. Furthermore, the developing forest canopy altered the local albedo, cooling the formerly bare stone surfaces and reducing microclimatic aridity within the park boundaries.

3.4. Hydro-Dynamic Performance of Bioengineered Check Dams

Monitoring along the modified sectors of the Artikaget and Gharanghu torrents showed that the porous gabion check dams successfully transitioned the hydrological regime from destructive torrential flow to controlled energy-dissipating step-pools (Table 4).

Table 4
Hydro-Morphological and Sediment Transport Variations Along Regulated Gullies

Hydraulic Parameter	Pre-Project Technogenic State	Post-Restoration Regulated State	Hydro-Dynamic Assessment & Engineering Rationale
Channel Bed Stability	Unstable, choked with loose mining debris and collapsing banks.	Graded, uniform bed profile secured by flexible step-dam foundations.	Suppressed channel bed degradation and localized bank failure via hydrodynamic shear stress reduction.
Manning's Roughness (n)	Highly irregular, turbulent-inducing (n = 0.065–0.080).	Optimized, controlled resistance (n = 0.035–0.040).	Standardized channel resistance allows predictable flood-routing and crest-level calculations.
Coarse Sediment Load	Unchecked downstream transport of sand, gravel, and stone fragments.	Systematic trapping and filtering behind porous stone structures.	Porous check dams act as mechanical filters, separating heavy bedloads from water flows.
Scouring and Downcutting	Severe vertical downcutting during peak discharge periods.	Attenuated hydraulic energy; stable grade lines.	The gabion steps break the hydraulic jump, forcing energy dissipation within designed pools.

The gabion structures managed peak flow volumes by converting steep longitudinal channel gradients into a sequence of flatter sub-critical slopes. The space behind each check dam functions as a siltation basin, retaining coarse sediments and volcanic tuff fragments. This upstream trapping mechanism prevented the physical blockage of downstream urban collectors within Artik city, addressing the structural cause of historical municipal inundations.

4. Conclusion

The application of an integrated Nature-Based Solutions (NbS) framework across 40 hectares of abandoned volcanic tuff quarries in Artik provides several key insights for regional environmental management:

Resolving the environmental hazards of abandoned open-cast mines requires a coordinated combination of mechanical grading, organic-mineral soil amendment, and multi-tier afforestation.

The deployed edaphic melioration protocol altered the raw substrate, neutralizing hyper-alkalinity (pH stabilized to 7.2–7.4) and increasing soil organic matter to 1.8–2.2%. This established the necessary conditions for a 72–82% mean sapling survival rate across the mixed-species protective stand.

Bioengineered porous gabion check dams effectively reduced peak flow velocities and filtered coarse sediment loads within the ephemeral gullies, safeguarding downstream municipal infrastructure from flash floods.

This successful reclamation framework offers a standardized, empirical protocol for executing ecosystem restoration and climate risk mitigation projects across degraded mountainous mining catchments globally.

Declarations

Ethical Approval

This study involved ecological restoration on public municipal land in Artik, Armenia. All necessary permissions for land access and implementation were obtained from the Artik Municipality and the Ministry of Environment of the Republic of Armenia. No human or animal subjects were used in this research.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

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Competing Interests

The author declares that she has no competing financial or personal interests that could have appeared to influence the work reported in this paper.

Availability of Data and Materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Authors' Contributions

Aida Sargsyan: Conceptualization, Methodology, Software (GIS mapping), Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Project administration.

References

1. Cohen-Shacham E, Walters G, Janzen C, Maginnis S (2016) Nature-based solutions to address global societal challenges. IUCN, Gland, Switzerland
2. Environmental PIU (2019) Pilot project report: Management of closed volcanic tuff quarry wastes and flood risk mitigation in Artik City. Ministry of Environment, Yerevan, pp 45–62
3. European Commission (2020) Evaluating the impacts of Nature-Based Solutions: A handbook for practitioners. Directorate-General for Research and Innovation, Brussels
4. IPCC (2023) Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva
5. IUCN (2020) Global standard for Nature-based Solutions. A first edition for the design and verification of solutions to societal challenges. IUCN, Gland, Switzerland
6. Karapetian SG, Jrbashian RT, Mnatsakanian AH (2001) Late collision rhyolitic volcanism in the Republic of Armenia. *J Volcanol Geotherm Res* 112(1–4):189–220
7. Manning R (1891) On the flow of water in open channels and pipes. *Trans Inst Civ Eng Irel* 20:161–207
8. Prach K, Rehounková K, Řehounková K, Schnablová R, Vítovcová K, Tropek R, Marhoul P, Jongepierová I (2011) Ecological restoration of central European mining sites: a summary of a multi-site study. *Restor Ecol* 19:201–209
9. Prach K, Hobbs RJ (2008) Spontaneous succession versus technical reclamation in the restoration of disturbed sites. *Restor Ecol* 16(3):363–366
10. Rey F (2006) Influence of vegetation distribution on sediment yield in gully catchment areas. *CATENA* 65:218–225
11. Stokes A, Douglas GB, Fourcaud T, Giadrossich F, Gillies C, Gruber F, Irons T, Mickovski SB, Mitchell KL, Norris JE, Palazzolo N, Petrone RV, Schwarz M, Sloboda B (2014) Bioengineering and eco-engineering design for slope stabilization and soil erosion control. *Ecol Eng* 65:1–10
12. Wong MH (2003) Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. *Chemosphere* 50:775–780
13. Prach K, Hobbs RJ (2008) Spontaneous succession versus technical reclamation in the restoration of disturbed sites. *Restor Ecol* 16(3):363–366
14. Rey F (2006) Influence of vegetation distribution on sediment yield in gully catchment areas. *CATENA* 65:218–225
15. Stokes A et al (2014) Bioengineering and eco-engineering design for slope stabilization and soil erosion control. *Ecol Eng* 65:1–10

16. Wong MH (2003) Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. Chemosphere 50:775–780

Figures

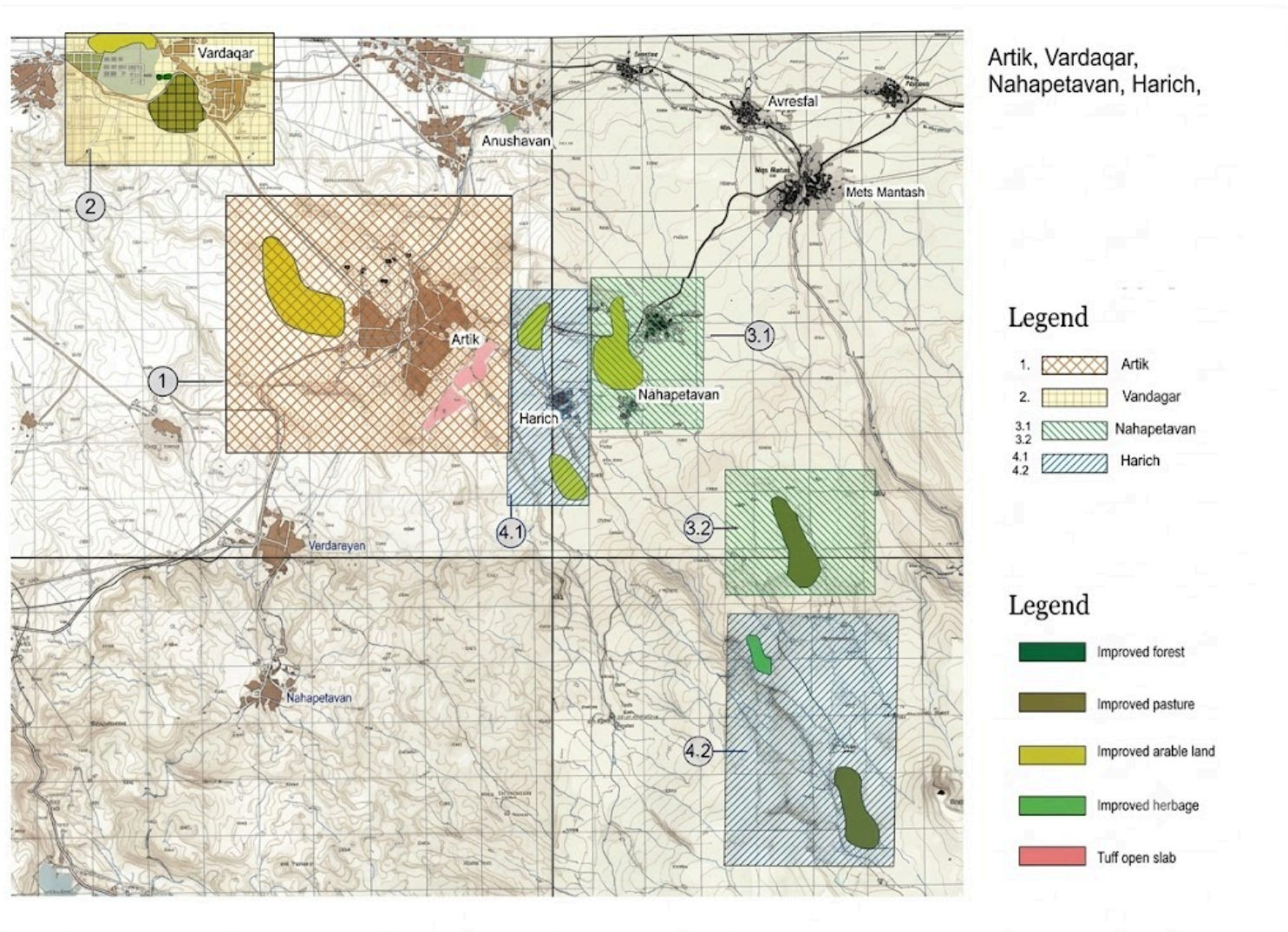


Figure 1

GIS-based zoning, mapping, and spatial planning of the 40-hectare pilot restoration zone, illustrating Cluster A (protection belt) and Cluster B (recreational green zone).



Figure 2

Biophysical transformations of the quarry landscape: (a) pre-restoration unstable vertical cliffs, (b) post-restoration terraced and stabilized slopes, (c) blocked concrete drainage channels with volcanic tuff debris, and (d) fully cleared and operational drainage channels.



Figure 3

Macro-topographic modeling and terrace grading operations utilizing heavy machinery to reduce high vertical quarry cliffs into stable slopes.



Figure 4

Chronological substrate engineering, showing soil placement, organic-mineral conditioning, and early-stage 2020 vegetative expansion on the terraces.



Figure 5

Implementation of the high-efficiency localized drip and sprinkler irrigation system designed to mitigate extreme summer evapotranspiration deficits.