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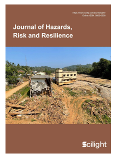

*Article*

# Building Safety and Resilience in Mountain Communities: A Community-Centric Risk Mitigation Planning, Design, and Implementation in Afghanistan

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**Abstract:** Afghanistan's mountain communities are increasingly exposed to floods, landslides, avalanches and rockfalls as a result of climate change, environmental degradation and socio-economic fragility, while practical and sustainable models for community-centred risk mitigation remain limited. In this study, a comprehensive practice-led framework for building safety and resilience in mountainous Afghanistan is presented based on 22 mitigation projects implemented across five high-risk provinces by the Aga Khan Agency for Habitat (AKAH). The national hazard scape is first characterised using EM-DAT disaster trends, which indicate the dominance of hydro-meteorological hazards in driving human and economic losses. The physical, ecological and socio-institutional constraints shaping mountain hazard mitigation strategies are subsequently outlined, with emphasis placed on terrain instability, climatic extremes, resource limitations and governance challenges. A structured eight-step community-centric methodology anchored in participatory Hazard, Vulnerability and Risk Assessment (HVRA), risk-informed planning, and blended structural and Nature-based Solutions (NbS) is then described. Scientific tools such as GIS-based hazard mapping and numerical modelling are integrated with indigenous knowledge to support site prioritisation, design optimisation, and locally owned implementation, operation and maintenance. Observation and results indicate that approximately 12.5 km$^2$ of land, including 2.95 km$^2$ of agricultural land, more than 550 households, over 4,900 people and 58 critical infrastructure units are safeguarded through these interventions. Scenario-based hazard modelling demonstrates that rockfall impact area is reduced by 47% and population at risk by 92% in Bezokh village, while flood inundation extent is reduced by 55% in Baghlan following construction of a protective river wall. NbS feasibility assessments conducted at 12 sites achieve scores of up to 74% against the IUCN Global Standard, indicating strong ecological suitability, technical performance and community relevance. Recurring implementation challenges are identified, including weak regulatory frameworks, limited availability of risk data, capacity constraints and logistical barriers in remote mountain settings. However, a consistent causal relationship is observed in which evidence-based HVRA, co-designed hybrid mitigation measures, community-led quality assurance and sustained operation and maintenance collectively lead to measurable reductions in hazard exposure and strengthened resilience. It is concluded that this integrated, community-centric and risk-informed model

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provides a scalable and transferable pathway for climate-resilient infrastructure development and disaster risk reduction in fragile mountain environments within Afghanistan and comparable regions worldwide.

**Keywords:** hazard vulnerability and risk assessment (HVRA); community-based planning & design; nature-based solutions (NbS); structural and non-structural measures; project impact assessment

## 1. Introduction

Natural hazards are extreme events that often transition into disaster causing severe harm to life, and damage to infrastructure and ecosystems. Among the different risk management practices, hazard mitigation is one that controls or contains propagation. Hazard mitigation is defined as "any cost-effective measure which will reduce the potential for damage to a facility from a disaster event." [1]. It has proven to be largely successful but sustainability of many mitigation projects beyond certain period is not guaranteed, particularly in challenging and remote mountain locations where regular maintenance is often not possible. In addition to lack of skilled technical personnel, remote mountain regions are often marginalized and do not have access to regular funding to maintain and sustain mitigation function of the infrastructure. While resource will always remain constrained, examples of alternative low-cost approach to sustainable mitigation projects are far and few. It requires an innovative and all rounded model of delivery of mitigation projects, where community members are engaged from the start to finish, also engaged during post implementation operation and maintenance (O&M) services. The non-functional mitigation infrastructure is not only a matter of wasted investment, but also a source of risk to communities and infrastructure as it provides false sense of security.

Literature review and case study searches was not helpful as there were no good cases to replicate, indicating no documentation on the topic of community-centric mitigation intervention. There were ample references on community-based early warning system (CBEWS) [2,3], but very limited on community-based disaster mitigation (CBMit). Although, social capital in the form of communities is recognized as an important part of community-based disaster risk management (CBDRM) [4], including in disaster mitigation [5,6]. There are very limited publications outlining what it entails to implement a community centric sustainable mitigation model, main considerations, and key players. The workshop paper on community-based approaches to disaster mitigation [7] presents summary of key learnings from mitigation projects around the globe. There exists a pressing research need to explore contextualized, community-based approaches to disaster risk reduction (DRR) in mountainous and fragile environments, particularly in regions like Afghanistan where hazard exposure, governance fragility, and resource scarcity intersect. Prior research in DRR has often lacked sufficient integration of incremental localized knowledge systems, multi-hazard assessments, and inclusive, participatory design methodologies that are essential for sustaining resilience in high-risk, remote communities.

Additionally, policymakers and practitioners face a significant evidence gap in understanding how hybrid mitigation strategies that blend structural and nature-based solutions perform in conflict-prone, geographically isolated settings. There is also limited operational research that demonstrates the institutional pathways, technical standards, and community co-ownership models necessary for replication and scale-up.

This paper directly addresses these research gaps by presenting a practice-led model of risk-informed planning and implementation, rooted in over two decades of field engagement in Afghanistan. This further demonstrates how participatory Hazard, Vulnerability and Risk Assessment (HVRA) can inform safe site selection and retrofitting. It documents a unique blend of engineering, indigenous knowledge, and socio-political negotiation, which is essential for DRR in fragile states. It offers a replicable planning framework, and critical lessons learned that are applicable to other mountainous, post-conflict regions facing complex hazard scenarios.

## 2. Hazard Scape in Afghanistan

Afghanistan is a landlocked and arid country characterised by harsh terrain and rugged topography [8], which makes it highly susceptible to various natural hazards. More recently, erratic and intense climate events such as rainfall, snowmelt, and glacier melt, has resulted in frequent flash floods. The EM-DAT (Emergency Events Database) is a comprehensive, global database managed by the Centre for Research on the Epidemiology of Disasters (CRED), containing data on natural and technological disasters from 1900 to the present, detailing their occurrence, human impact (deaths, affected people, injuries), economic losses, and aid. It serves as a vital resource for researchers, humanitarian organizations, and policymakers to assess risks, plan disaster response, and support disaster risk reduction (DRR) efforts worldwide. According to the EM-DAT database from 1950 to 2025, Afghanistan witnessed 3264 major disaster events accounting for 27,441 fatalities, 87,192 injuries, and the destruction or damage of 249,375 houses. In total, 36,128,177 individuals were affected, and led to substantial economic losses, estimated at approximately USD 1.63 billion. Earthquake and flood events are top two hazard types in case of impacts: death count (79%), injury count (97%) and damage houses (87%). These figures underscore the severe impact of natural hazards and highlight the urgent need for comprehensive efforts to assess potential disaster impacts and implement effective mitigation measures. The event and impact trend (Figure 1) shows exponential rise in disaster-related casualties over successive decades particularly after 2000.

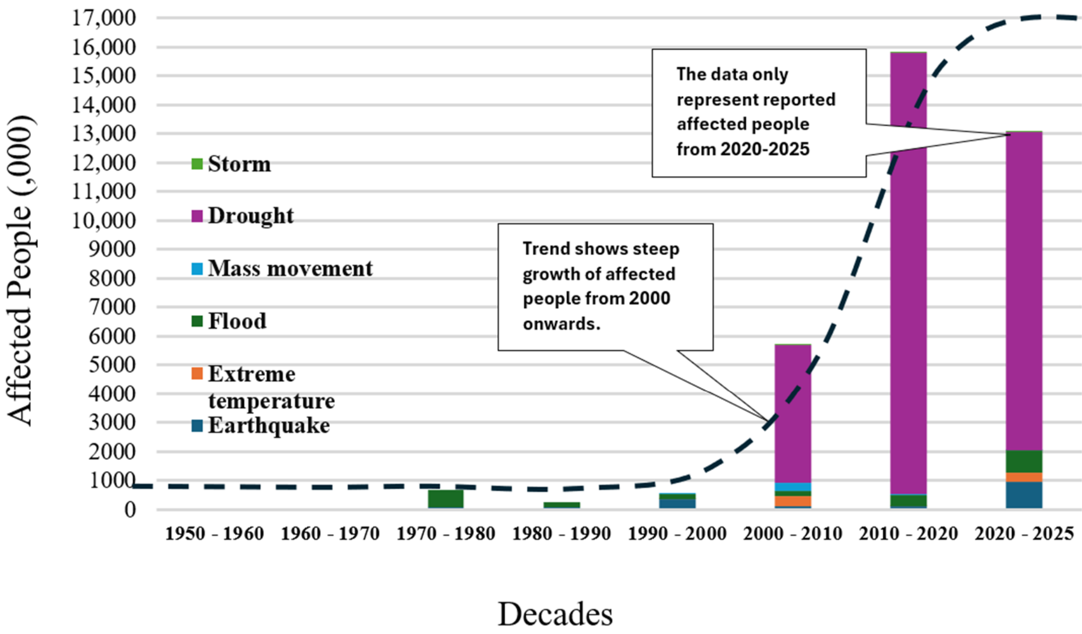



**Figure 1.** Decadal increment of affected people by disaster events (Data: EM-DAT).

### 3. Mitigation Strategy of Mountain Hazard

The formulation of mitigation strategies in mountainous regions, as evidenced by the case studies, largely depends on ten key factors: (1) topography and terrain; (2) geological and geotechnical conditions; (3) climate and weather patterns; (4) hydrology and drainage; (5) ecological sensitivity; (6) human settlements and their exposure & vulnerability; (7) available and feasible technologies and equipment; (8) hazard types and their unique characteristics; (9) cost-benefit considerations; and (10) applicable design standards and regulatory frameworks.

Steep and unstable slopes, coupled with fragile geological formations and orientations, necessitate extreme caution during mitigation planning and design. In addition, climate variability and shift observed across High Mountains Asia (HMA) results in intense weather events triggering catastrophic hazard events in region underlain by relatively young and fragile geological formations. The steep terrain further contributes to generating high runoff velocities with greater impact potential. In addition, mountain geographies are relatively un-resourced and therefore it is imperative to develop optimised mitigation strategies, leveraging local materials, traditional skills, and using accessible technologies. It is also imperative that mitigation strategy should maximise use of Nature-based Solutions (NbS) either as stand along solution or in conjunction with structural intervention. Prioritising high-risk zones for community protection becomes essential when challenged with resources.

All in all, mitigation strategy in mountainous geographies require a pragmatic approach that best uses limited resources and community capital for best and sustainable outcome. This paper presents AKAH's approach to implementing hazard mitigation that has proven effective protection and has greater chance of sustainability. The unique model is scalable and exemplify a systematic and integrated approach of AKAH.

The Aga Khan Agency for Habitat (AKAH), one of the core agencies of the Aga Khan Development Network (AKDN), operates under an institutional mandate to "improve the quality of life" of vulnerable communities by reducing their exposure to natural hazards and enhancing long-term resilience [9]. Within this mandate, AKAH works across remote mountain geographies to identify, map, and manage disaster risk through an integrated programme of hazard monitoring, safe settlement planning, and climate-resilient infrastructure development. Its operational scope combines community-based hazard, vulnerability, and risk assessments (HVRA) with participatory planning, where scientific tools—such as GIS, numerical hazard modelling, and NbS feasibility assessments—are systematically coupled with indigenous knowledge and local priorities [10]. Methodologically, AKAH emphasises community ownership, multi-hazard analysis, and the blending of structural and Nature-based Solutions, supported by standardised procedures for project design, implementation, and monitoring. Given this long-standing presence in Afghanistan's high-risk mountain regions and its tested HVRA and mitigation frameworks, AKAH provides an appropriate and highly relevant institutional setting for this study, which draws directly on 22 AKAH-implemented mitigation projects (Figure 2) to illustrate how these principles translate into practice in hazard-prone Afghan communities. The Figure 2 graphically presents the geographical distribution of the project provinces, district, their sites, hazard intensity level and salient mitigation features.

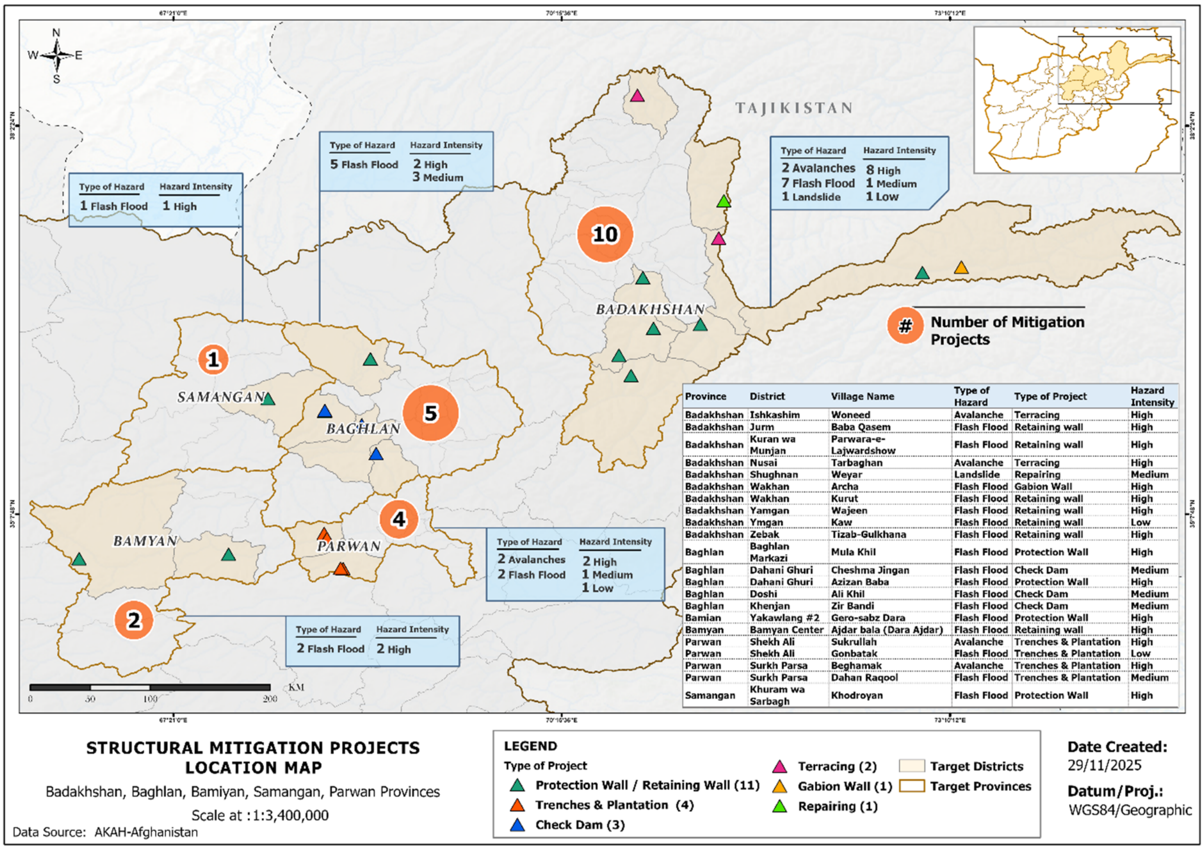



**Figure 2.** The geographical distribution of structural mitigation projects.

## 4. Methodology–AKAH's Community Centric Approach

AKAH's mitigation model constitute 8 step approach (Figure 3), starting with comprehensive risk assessment (HVRA exercise) informing planning and designing before implementation, ending with evaluation. Testing, commissioning and handing over to community happens between implementation and evaluation steps.

Step 1—Project Initiation and Prioritisation

Projects are identified and long-listed based on preliminary hazard information and community demand. High-risk locations with significant exposed assets, strong community interest, lower relative cost, government endorsement and NbS opportunities are prioritised. A rapid feasibility scan and stakeholder analysis (community, local authorities, donors) leads to a preliminary concept and Letters of Agreement outlining roles in implementation, O&M and co-financing.

Step 2—Planning and Scoping

Together with communities and local institutions (Figure 4), the project scope, objectives, and expected risk-reduction outcomes are defined. This phase confirms legal and policy compliance, allocates indicative resources and timelines, and agrees on how community knowledge and participation will shape the process. It sets the basis for a detailed HVRA. The HVRA process and key diagnostic tool is being discussed in the subsequent sections.

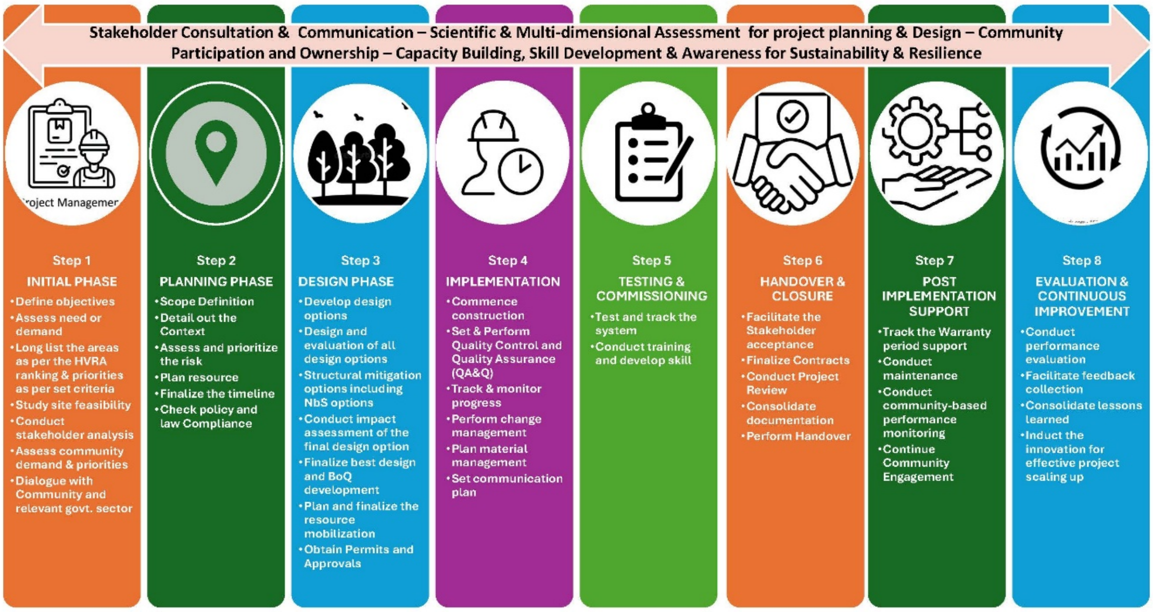



**Figure 3.** Methodology for AKDN community centric disaster mitigation.

**Figure 4.** Community consultations during planning, design work and validation in Nusai of Badakhshan.

Step 3—Data Collection and HVRA

The HVRA is designed as a quick yet comprehensive risk screening tool, institutionalised and mandated within AKAH for last 20 years or so. Over the period, the assessment framework underwent several refinements to reflect the operational realities—field situation, technological advancement and accessibility. Unlike traditional community risk assessment (CRA) framework, AKAH's HVRA framework integrates scientific tools (geospatial technology, satellite imagery, and hazard modelling) with community knowledge [10]. While the integrated approach places communities at the heart of the assessment process, it benefits from advance tools and technologies like GIS and satellite data.

It is a data intensive risk screening process and entails extensive secondary and primary data collection (demographic, hazard and exposure) process, including field work using participatory tools (transect walks, risk mapping, focus groups, household surveys). Field work is also an opportunity to validate and update data collected through secondary sources, which then leads to data analysis and risk map generation. HVRA is discussed in detail in HVRA section.

Step 4—Risk-Informed Mitigation Design

HVRA map of the prioritized villages are used to identify sites affected by different hazard types, helping understand the need for context-specific mitigation solutions. AKAH's engineering team in consultation with community leaders come up with multiple mitigation options, integrating structural and NbS interventions. These options are further evaluated for technical performance, feasibility, cost, social acceptability and environmental impact. Refinements were made to the design options through community consultations before finalizing the mitigation design. Final designs follow appropriate engineering codes and safety checks, and where relevant are benchmarked against the IUCN Global Standard for NbS. Bills of quantities, value-engineering, procurement and implementation plans are then prepared and submitted to government for approval. Comprehensive suitability and feasibility of NbS interventions using International Union for Conservation of Nature (IUCN) Global Standard (IUCN, 2020) framework is discussed in NbS section.

Step 5—Implementation

Project implementation focused on maximum local engagement, prioritise use of local skills, materials, and resources. Community teams, led by selected focal persons, execute labour-intensive works (e.g., terracing, trenching, planting, masonry) while engineers and social mobilisers provide on-site guidance and oversight. A quality assurance & quality control (QAQC) plan governs material testing, workmanship checks, financial tracking and documentation, ensuring works are completed to agreed standards, on time and within budget. A dedicated field team, including both engineering staff and social mobilisers in addition to providing oversight maintained ongoing dialogue with the community. This ensures effective and efficient participation.

Step 6—Testing, Commissioning and Capacity Building

Upon completion of the project, the testing and commissioning phase verified the functionality of all systems through comprehensive inspection which included but not limited to inspection of beneficiary satisfaction, functionality of the intervention, site layout, changes in design and locations, material, workmanship, and safety. The inspection is conducted by QAQC teams, field staff, local leaders, and community representatives to ensure that the project meet the standards outlined in the Quality Management Plan (QMP). In preparation to handing over of the project to community, training of responsible personnels or committees on O&M is done. These committees, often comprising local volunteers including women and youth, are equipped to manage infrastructure. They receive maintenance manuals, tools, and routine schedules. For complex systems, committees are connected to local government technical departments to access support for significant repairs or technical issues. All through the testing and commissioning phase, community members remained engaged and provided inputs all along. Prior to handover, any discrepancies identified through monitoring are addressed, documented, and resolved, ensuring the delivery of only fully functional, and quality-assured structures.

Step 7—Handover and Post-Implementation Support

After the joint final inspection by project management team (PMT), community and government confirm compliance with the QMP, responsibility for day-to-day O&M is transferred to community committees and relevant government departments formalized by a formal handover ceremony and signing of a Letters of Agreement (LOA). The handover phase marks a critical milestone, signifying both the formal completion of the project and the transition to community-led operation and management. During a defined warranty/support period, the project team provides technical backstopping, periodic QAQC visits and troubleshooting to stabilise performance. The LOA is also helpful to delineating post-handover responsibilities, particularly in operation, maintenance, and oversight. These handover ceremonies served not only as a formal closure but also fostered trust, promote transparency, and reinforce collective ownership.

Step 8—Monitoring and Impact Evaluation

Monitoring is critical to ensure infrastructure projects are serviced and maintained timely, prerequisite to make it sustainable. Phase progress was monitored through the proportion of completed activities, milestone achievement, and timely implementation of corrective actions, while performance across key activities was assessed by tracking delays and associated resolutions. Quality control was monitored through compliance with standards, occurrence of non-conformities, and required rework. Readiness for upcoming milestones was assessed based on prerequisite completion and dependency-related risks. The community representatives are trained in monitoring process using simple and context-specific matrices.

Impact evaluation is an important post-implementation process to demonstrate benefits of the mitigation project in minimizing risk to the communities and infrastructure, by stopping or containing hazard propagation. We adopted mixed approach for impact assessment as using scenario modelling and qualitative feedback. Scenario modelling entailed modelling hazard footprints and population/asset exposure, with and without mitigation intervention. The qualitative feedback used feedback from community members and stakeholders on risk perception, livelihood benefits and ecosystem effects. The impact assessment is further discussed in appropriate section while presentation a case.

### *4.1. Hazard, Vulnerability and Risk Assessment*

As illustrated in Figure 5, the AKAH's HVRA framework is a four-step process starting with desktop assessment using secondary data and available report, followed by onsite assessment including field visit and community consultation (Figure 6). Using high resolution print out maps of the locality, a multi-disciplinary team comprising of geologist, GIS specialist, and social mobilizers, collects both hazard and vulnerability data from the field. Each hazard present in the locality is mapped and classified into three categories based on intensity and frequency (low, medium and high) using simplified classification scheme (Table 1), in consultation with community feedback. Similarly, vulnerability data reflecting susceptibility, coping capacity and adaptive capacity, of the communities were collected through focus groups discussion (FGD), and included demographic, access to facilities, access to early warning system (EWS), state of emergency preparedness (stockpile, safe location, safe route), school enrolment, insurance coverage, livelihood options, and more (Figure 7). Upon completion of data collection, hazard and risk analysis is performed, leading to development of risk maps (Figure 8) and a report, which is then disseminated to relevant stakeholders.

**Table 1.** Scheme for intensity classification for different hazard types in HVRA exercise.

| Hazard | Scale | Low | Medium | High |
|---|---|---|---|---|
| **Avalanche** | European Scale | 1—Sluff: (Runout: Small snow slide that cannot bury a person, though there is a danger of falling. Potential Damage: Unlikely, but possible risk of injury or death to people. Physical Size: length < 50 m, volume < 100 m$^3$)<br><br>2—Small: (Runout: Stops within the slope.<br><br>Potential Damage: Could bury, injure or kill a person. Physical Size: length <100 m volume <1000 m$^3$) | 3—Medium: (Runout: Runs to the bottom of the slope.<br><br>Potential Damage: Could bury and destroy a car, damage a truck, destroy small buildings or break trees. Physical Size: length < 1000 m volume < 10,000 m$^3$) | 4—Large: (Runout: Runs over flat areas (significantly less than 30°) of at least 50 m in length, may reach the valley bottom.<br><br>Potential Damage: Could bury and destroy large trucks and trains, large buildings and forested areas. Physical Size: length > 1000 m, volume > 10,000 m$^3$) |
| | Canadian Classification | 1—Relatively harmless to people.<br><br>2—Could bury, injure or kill a person. | 3—Could bury and destroy a car, damage a truck, destroy a small building or break a few trees. | 4—Could destroy a railway car, large truck, several buildings or a forest area up to 4 hectares.<br><br>5—Largest snow avalanche known. Could destroy a village or a forest of 40 hectares. |
| | United States Classification | 1—Sluff or snow that slides less than 50 m (150′) of slope distance.<br>2—Small, relative to path. | 3—Medium, relative to path. | 4—Large, relative to path<br><br>5—Major or maximum, relative to path. |
| **Cyclone** | Beaufort Scale | 0–7 | 8–11 | 12 |
| | 10-min sustained winds | <28–33 knots<br>(32–38 mph; 52–61 km/h) | 34–63 knots<br>(39–72 mph; 63–117 km/h) | 64–>136 knots<br>(74–157 mph; 119–252 km/h) |
| | India Meteorological Department | Depression and Deep Depression | Cyclonic Storm and Severe Cyclonic Storm | Very Severe Cyclonic Storm and Super Cyclonic Storm |
| | National Hurricane Center | Tropical Depression | Tropical Storm | Hurricane (1–5) |
| **Flood** | Water Depth | < 0.3 m | 0.3–1 m | 1+ m |

The HVRA map also shows hazard and exposure distribution in addition to safe open places and access routes. While the hazard and exposure distribution is helpful to prioritize site for mitigation projects, safe open areas and access routes helps in designating safe place and evacuation routes. Engineering teams use detailed hazard and risk maps to identify sites and plan appropriate hazard specific (rockfall, flood, landslide) mitigation measures. While emergency management team uses the map to select site for establishing stockpiles, safe sites and evacuation routes.

The final phase is presenting data into meaningful outputs (maps and reports) and along with actionable strategies in the form of Village Disaster Management Plan (VDMP), which is disseminate to stakeholders including local level government institutions, community leaders, and community members, through local level workshops. Engineering teams use detailed hazard and risk maps to identify sites and plan appropriate hazard specific (rockfall, flood, landslide) mitigation measures.

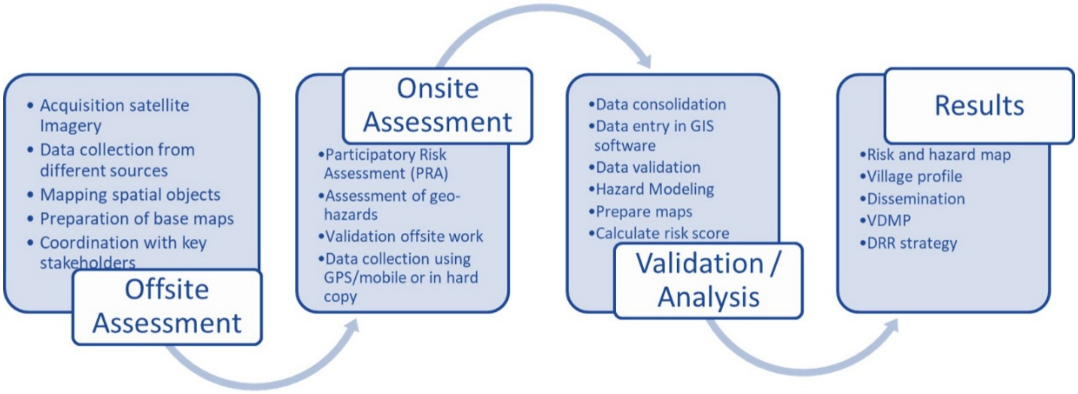



**Figure 5.** AKDN HVRA—4 Step Process.

**Figure 6.** Field data collection (**left**) and participatory risk mapping with communities (**right**).

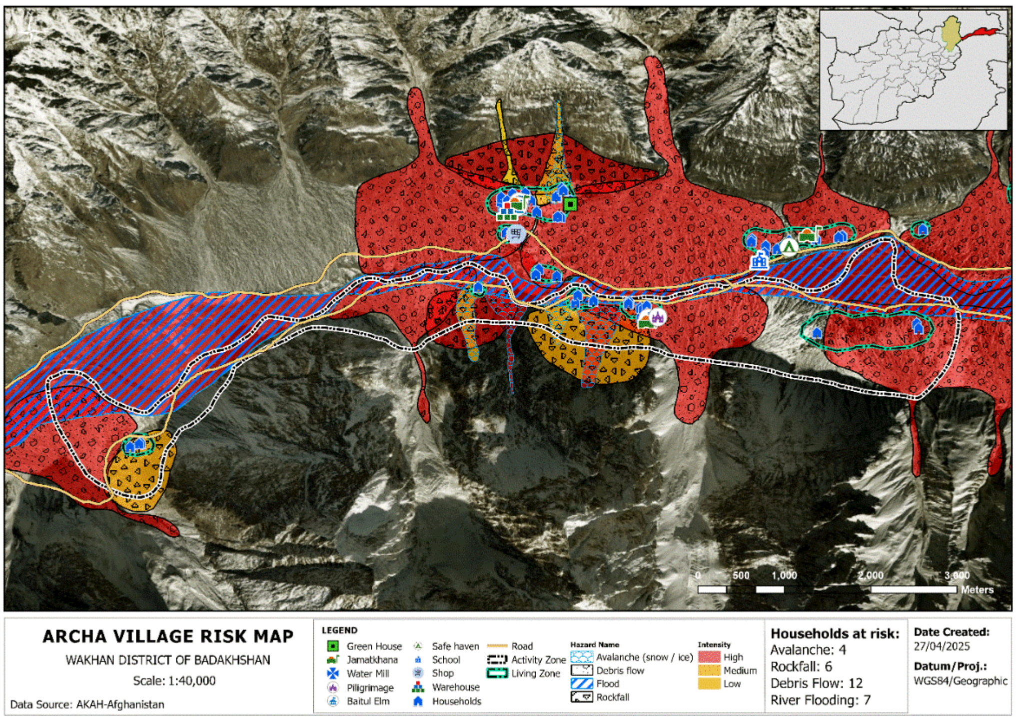



**Figure 7.** HVRA map showing hazard distribution and exposure of social and economic infrastructure of the project site.

This collaborative, data-rich process laid the foundation for locally owned and context-specific disaster risk reduction strategies.

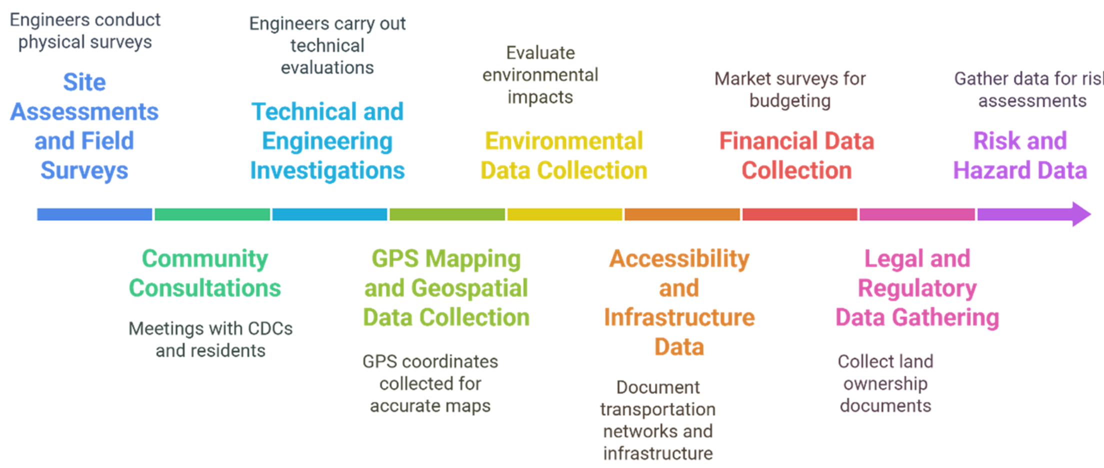



**Figure 8.** Details of data collected for hazard exposure and vulnerability assessment.

Figure 9 illustrates the data collection steps from inception to the data readiness for HVRA. In addition to site specific topographic and engineering data, legal data on ownership is also considered to ensure all legal compliance to facilitate smooth project implementation. Additional data analysed pertains to material access and market, labour rates, and transportation expenses which goes into assessing financial feasibility of the project. In order that mitigation intervention do not create environmental damage, environmental impact assessment (EIA) is done. To incorporate threat analysis to the mitigation infrastructure from hazard, particularly cascading hazard, historical events are mapped and impact assessed. This systematic data collection and consideration during the site selection avoided obvious threats to mitigation infrastructure, aligned with community needs, environmentally sustainable, hazard specific and financially feasible mitigation projects.

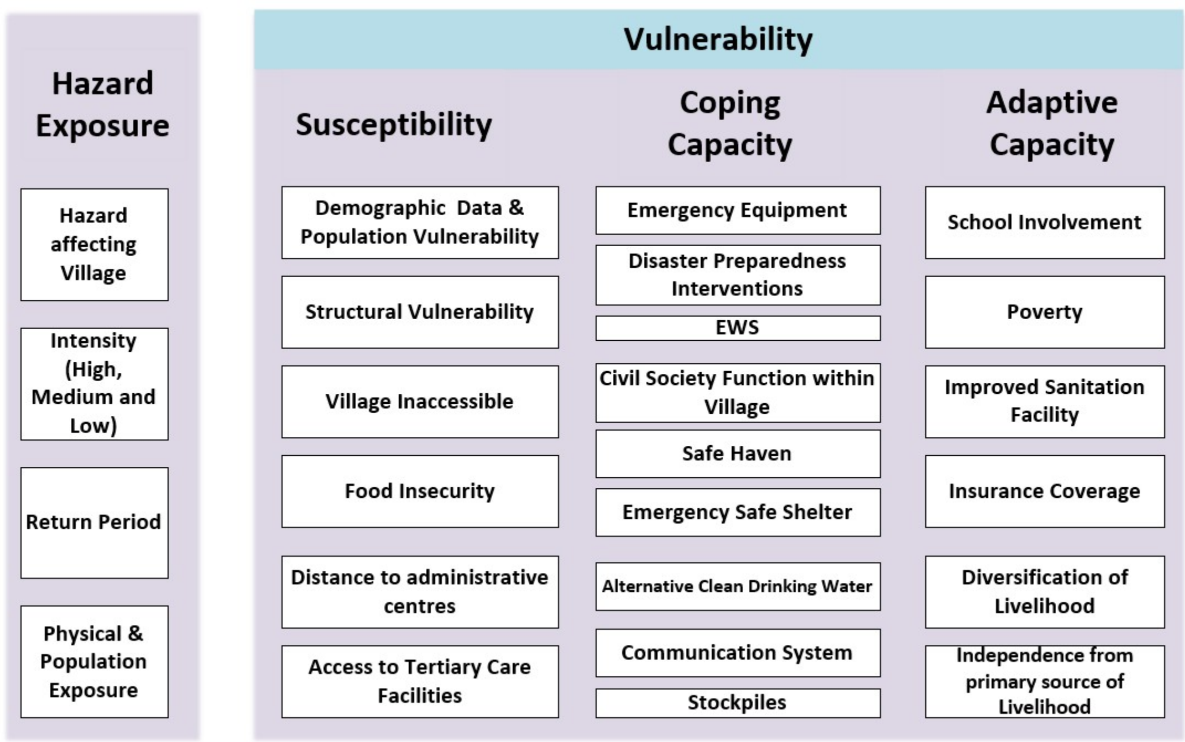



**Figure 9.** Data collection, collation for the mitigation planning.

A sound engineering design was developed using appropriate engineering and construction codes with their safety checks. Figure 10 illustrate examples of engineering designs developed for implementation specific to floods, avalanche and rockfall. Upon finalisation, a bill of quantities was prepared, employing value engineering principles to optimise costs without compromising quality. Efforts are made to restrict the scope of work within the allocated budget. A procurement and financial plans were then developed in alignment with the budget and schedule, followed by a detailed work plan for implementation. In accordance with federal and local legal procedures, the final design document, accompanied by community agreements—was submitted to the relevant government authority for approval. The technical and management teams maintained close coordination with government counterparts to address queries and comply with any feedback. Once approved, the revised documentation proceeded to the implementation phase.

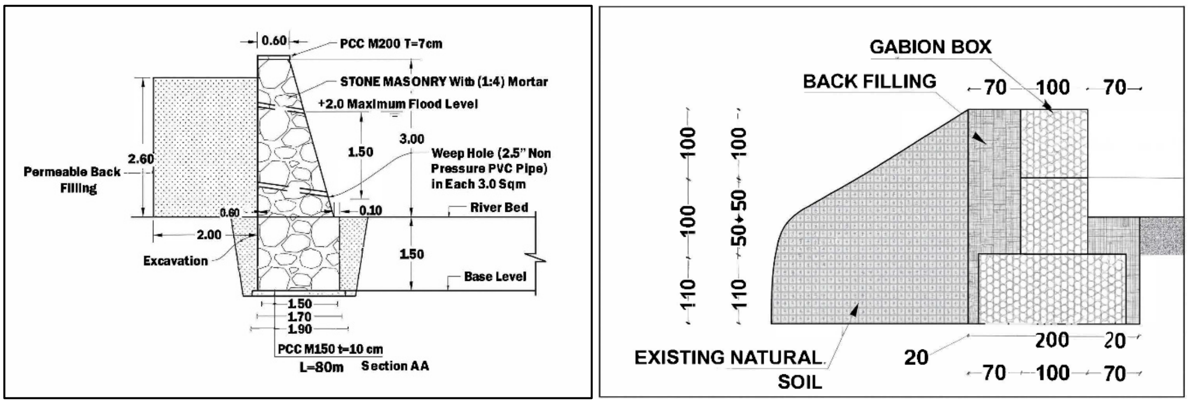



**Figure 10.** Engineering design of mitigation project for floods (**right**) and rockfall (**left**).

*4.2. Nature-Based Solutions*

At every possible opportunity, integration of NbS alongside traditional engineering interventions was explored, for holistic risk mitigation. NbS are increasingly acknowledged as essential components of risk mitigation, providing low cost, sustainable and resilient alternatives to conventional engineered interventions. A field teams is deployed to conduct comprehensive suitability and feasibility of NbS interventions, using IUCN Global Standard framework [11]. The NbS suitability and feasibility assessment was conducted using the IUCN Global Standard framework, applying its eight core parameters and 28 associated indicators at selected project sites. Multidisciplinary field teams carried out site inspections, ecological screening, community consultations, and hazard-context verification to populate each indicator. Each criterion was scored using a standardized rating scale, reflecting technical feasibility, social acceptance, ecological integrity, and governance alignment. The individual indicator scores were then aggregated into criterion-level scores, which were subsequently normalized to generate overall NbS feasibility percentages for each site. These results were finally interpreted through cross-site comparison to identify strengths, limitations, and suitability of NbS across different hazard environments. The evaluation is based on eight NbS parameters as illustrated in Figure 11 (left), using 28 specific indicators to ensure effectiveness, equity, and long-term sustainability. Figure 11 (right) presents the feasibility scores for the 12 pilot project sites based on the 8 parameters, illustrating the feasibility of each project and its adherence with NbS Global Standard. Sites such as Weyar, Woneed, and Tarbaghan achieved high feasibility scores-up to 74%-driven by strong community relevance, robust technical design, and alignment with biodiversity objectives. Conversely, sites such as Gonbatak, Sukrullah, Beghamak and Dahan Raqool recorded lower feasibility scores, averaging around 54%. In total, NbS interventions were done on 12 hazard-prone locations–flash flood (7), avalanche (4), and landslide (1).

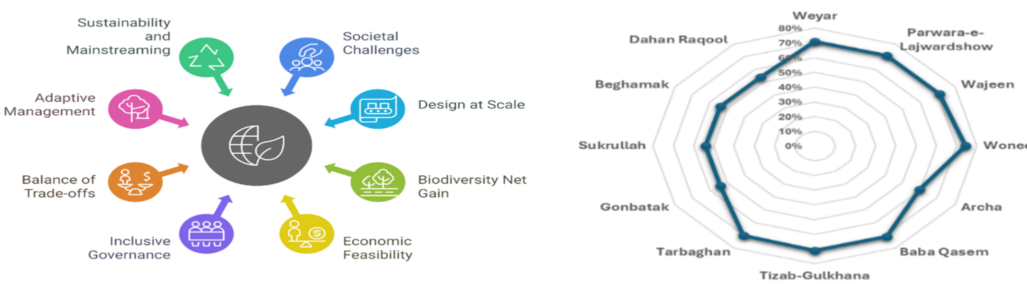



**Figure 11.** NbS assessment parameters (**left**) and scores for pilot project sites (**right**).

A participatory approach was adopted from the outset, including early involvement in planning, consultation meetings, and feedback loops, which contributed to securing local ownership and support for the NbS interventions. Engaging communities ensured equitable decision-making, enhanced ownership, reduces financial risks, and strengthens the long-term viability of the NbS [11]. One of the mitigation project sites (Figure 12) illustrates the design and implementation of avalanche and mud flows applying NbS concept.

**Figure 12.** Design of NbS solutions for avalanche and mudflow.

### *4.3. Rockfall Mitigation Project*

The case used to showcase impact of the mitigation intervention is from Bezokh village of Shughnan District (Figure 13), where scaling (removing of large boulders) along with terracing was used. The rockfall mitigation project used as a case in this paper was implemented in 2023. Two rockfall scenarios (with and without mitigation interventions) were modelled using the Rockyfor3D software solution, a widely used numerical model for mass movement modelling [12,13]. The Rockyfor3D simulates runout trajectory of boulders during the rockfall and quantify velocity and energy distribution along the propagation path. This enables mapping of interaction between hazard (boulders) and exposures (houses, infrastructure), which forms the basis for accounting how much risk has been reduced.

The Rockyfor3D model was implemented using a 5m digital elevation model (DEM) as representation of terrain along with boulder size measured during the field visit. DEM of resolution less than 5m is considered suitable for local scale occurrence simulation [14]. A rockfall event was simulated using a defined release area (Figure 13 (bottom)) representing potential source of boulders, and accounted for different modes of travel: falling, bouncing, rolling, and sliding processes. The model was trained using the location (distance travelled) of existing boulders on the site as reference, and involved iterative simulations, till 90% of the existing boulders were adequately simulated. The trained model was then run considering mitigation interventions by adjusting boulder size (scaling) and cell-level modification of raster values (terracing). The model generated layers for kinetic energy, propagation probability, boulder distribution, velocity and bounce height. By cumulating four parameters (except bounce height) a unitless layer was generated and classified into 4 levels using a defined classification scheme (Table 2). This was further overlaid with exposure data (house) to compare how many houses were out of impact zone due to mitigation intervention. The map (Figure 13) presents visual impression of impact zone of different rockfall hazard levels, showing obvious difference in hazard distribution, minimizing impact area by 47% and bringing down at risk houses by 94% (Table 3). The mitigation interventions are successful in bringing down population at risk by 92%, proving successful in minimizing risk. Validation of post mitigation simulation is not possible till an event unfolds, therefore comparing observed boulders in the field and pre-mitigation intervention simulation is one way to evaluate model performance [15]. As mentioned above, the model was able to simulate 90% of the boulders in pre-intervention simulation, suggests acceptable model accuracy.

**Table 2.** Rockfall hazard classification scheme based on combination of kinetic energy, propagation probability, boulder distribution, and velocity parameters.

| Hazard Level | Value |
| --- | --- |
| Very High | 50,442–100,089 |
| High | 19,791–50,441 |
| Medium | 9861–19,790 |
| Low | −9998–9860 |

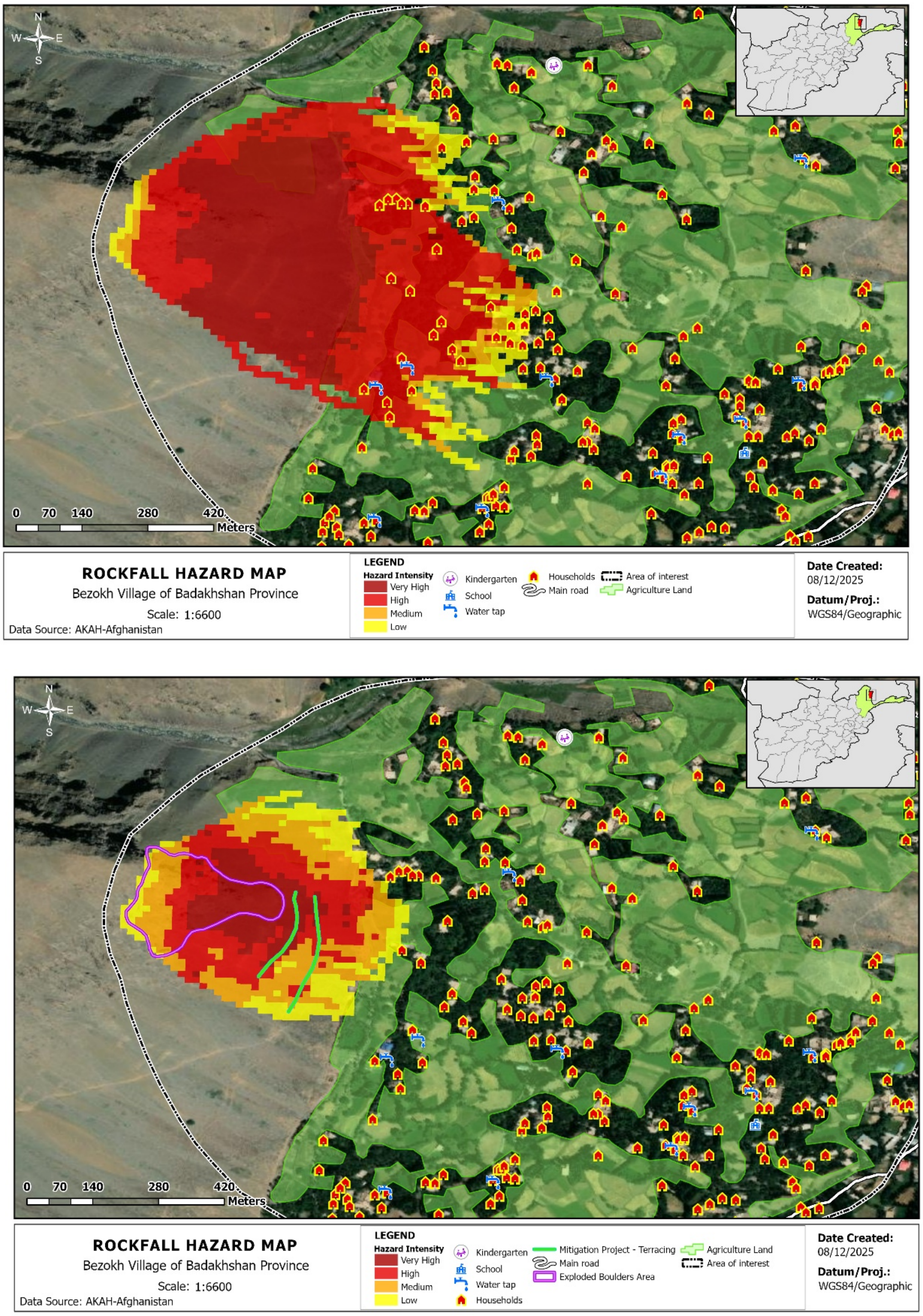



**Figure 13.** Rockfall simulation showing impact zones with (bottom) and without (top) mitigation intervention in Bezokh village.

**Table 3.** Pre and post mitigation exposure details in case of rockfall mitigation.

| Hazard Level | Exposed Houses | | Exposed Population | |
|---|---|---|---|---|
| | Pre-Project | Post-Project | Pre-Project | Post-Project |
| Very high | 0 | 0 | 0 | 0 |
| High | 18 | 0 | 170 | 0 |
| Medium | 4 | 0 | 27 | 0 |
| Low | 6 | 1 | 48 | 11 |
| Total | 26 | 1 | 245 | 11 |

*4.4 Flood Mitigation Project*

Many of the AKDN programme areas are prone to flooding, witnessing flood event of different magnitudes and scales every year. The case presented here pertains to Mullah Khil village of Baghlan Markazi District, which witnessed a major flood event on 10 and 11 May 2024. The 2024 flood event impacted some houses and damaged large portion of agriculture land and road network. To address high flood risk to the community due to breaching and overtopping of riverbank during high flow season, PMT designed and implemented 233 m long and 3.1 m high wall of stone masonry with mortar (Figure 14 (left)).

**Figure 14.** Structural mitigation projects, flood protection wall along Mullah Khil in Baghlan Markazi (**left**) and gabion wall as rock fall mitigation (**right**).

For impact evaluation, 2D flood inundation simulation representing pre and post intervention scenarios were done using HEC-RAS. In absence of river discharge data, the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) rainfall data of 10th and 11th May 2025 was used in HEC-HMS to simulate high flow discharge that resulted in flooding of targeted areas. The flood event inflicted heavy damage to properties, particularly agriculture land. The modelled hydrograph from HEC-HMS was used as input to HEC-RAS to simulate flood inundation, modelled using 5m DEM, for high flow level. The modelled flood layer included flood depth and flow velocity in addition to inundation extent, and former (depth) was used to develop flood severity map (Figure 15) using depth-severity matrix (Table 4). The flood hazard layer was overlaid with exposure data (agriculture land) and land area exposed to different flood severity classes was calculated. Through the modelling exercise, flood protection wall resulted in reduction in the area exposed to inundation by 55% and thereby significantly minimizing exposure to flood hazard.

The model validation for post mitigation was not possible as there is no case to compare. However, modelled and actual (mapped using Sentinel 2A image) areas of pre mitigation situation of the flood in May (Figure 15), indicated overestimation by model. Therefore, mitigation intervention as illustrated in Figure 16 ss(bottom) provides protection even in case of overestimated (extreme) flood situation. Intercomparison of mapped and modelled flood extent has become standard evaluation framework for flood extent [16]. Flood severity classification matrix is developed for the basin (Table 4).

**Table 4.** Flood severity classification matrix.

| Intensity Level | Flood Depth in Meters |
|---|---|
| Very High | 2.064–3.703 |
| High | 1.309–2.063 |
| Medium | 0.742–1.308 |
| Low | 0.321–0.741 |
| Very Low | 0.001–0.32 |

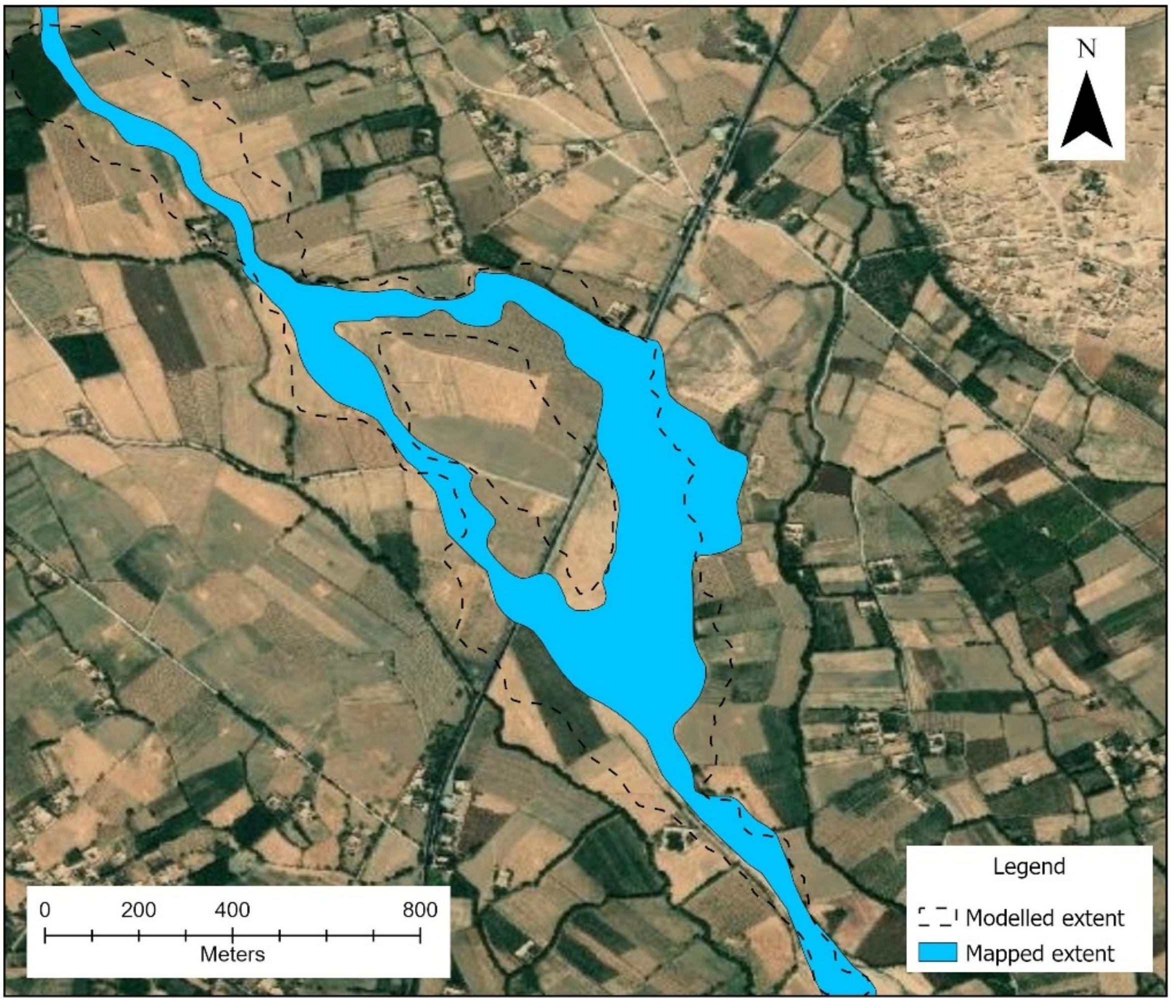
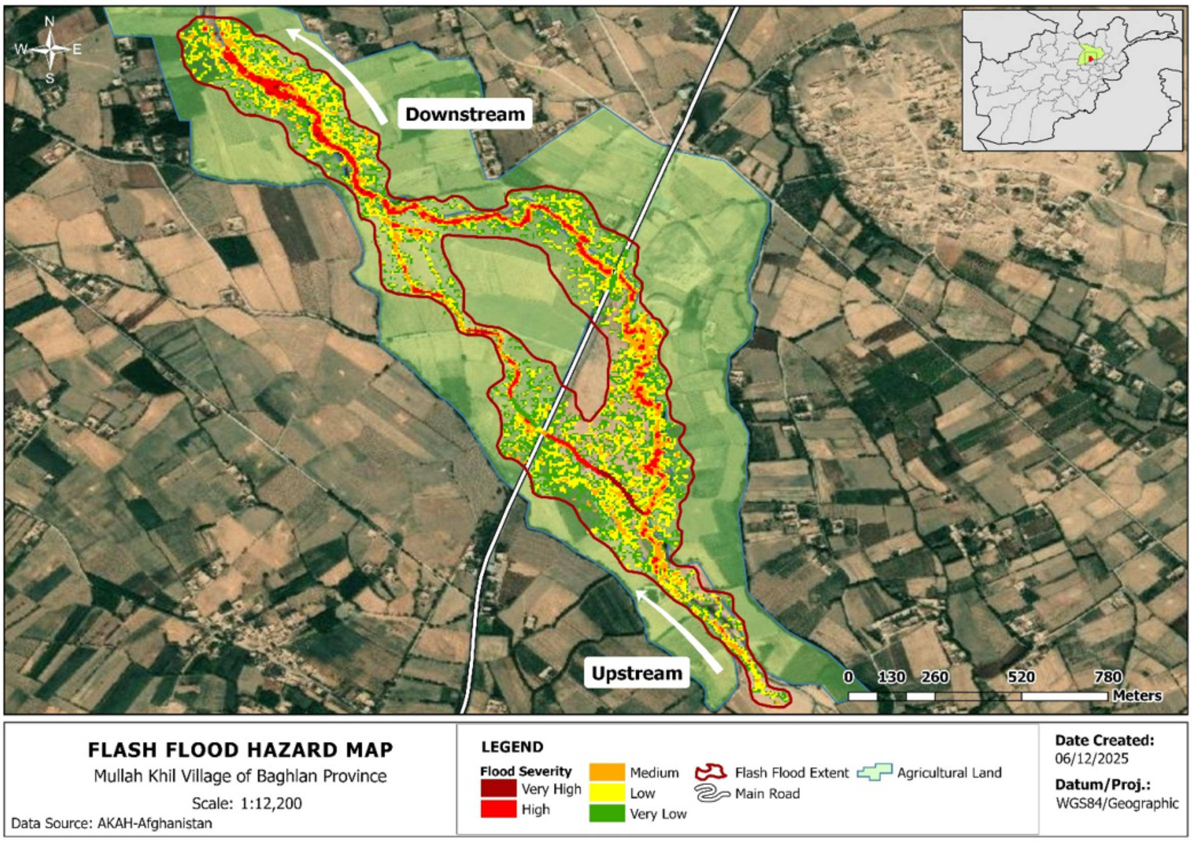



**Figure 15.** Map showing comparison of actual (mapped) and modelled of May 2025 flooding.



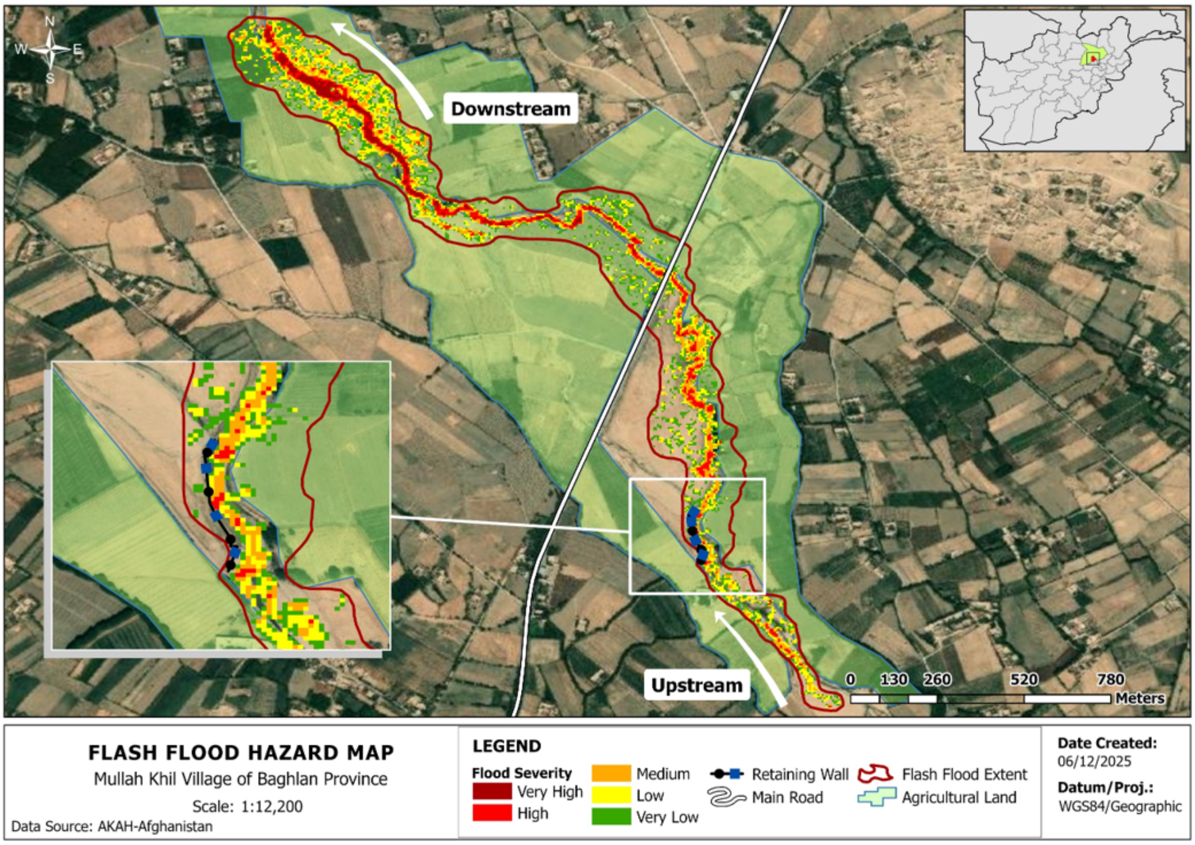



**Figure 16.** Flood propagation simulated with (**bottom**) and without (**top**) mitigation intervention in Mullah Khil village, Baghlan Markazi District.

### *4.5. Community-Centric Implementation*

The implementation phase adopted a participatory and inclusive approach that leveraged local capacities, indigenous knowledge, and labour to deliver development interventions that were both cost-effective and sustainable. In this model, the community were not merely a beneficiary but assumes a central role in both planning and implementation. The construction of the structure was coordinated by a locally selected team, led by a community-appointed team leader responsible for supervising and managing daily project activities. This strategy was particularly suitable for projects involving labour-intensive activities such as trenching, terracing, tree or seed planting, channel cleaning, and similar tasks. These initiatives typically require limited use of advanced machinery and specialised expertise, making them well-suited for direct community execution.

PMT provided continued technical and managerial support such as establishing of technical standards, training, backstopping, and resolving technical issues, ensuring that community teams achieve the desired outcomes.

### *4.6. Quality Assurance and Quality Control*

To ensure quality and alignment with the objectives and scope outlined in the project documents, PMT engineers developed and implemented a rigorous QAQC plan (Figure 17). This plan involved regular field visits, and had provision for providing technical instructions, verification processes, and progress monitoring. It also included financial oversight to ensure expenditures remain within budget and deliverables were completed on time. Robust documentation and reporting systems supported transparency and accountability, strengthened community trust and promoted responsible engagement.

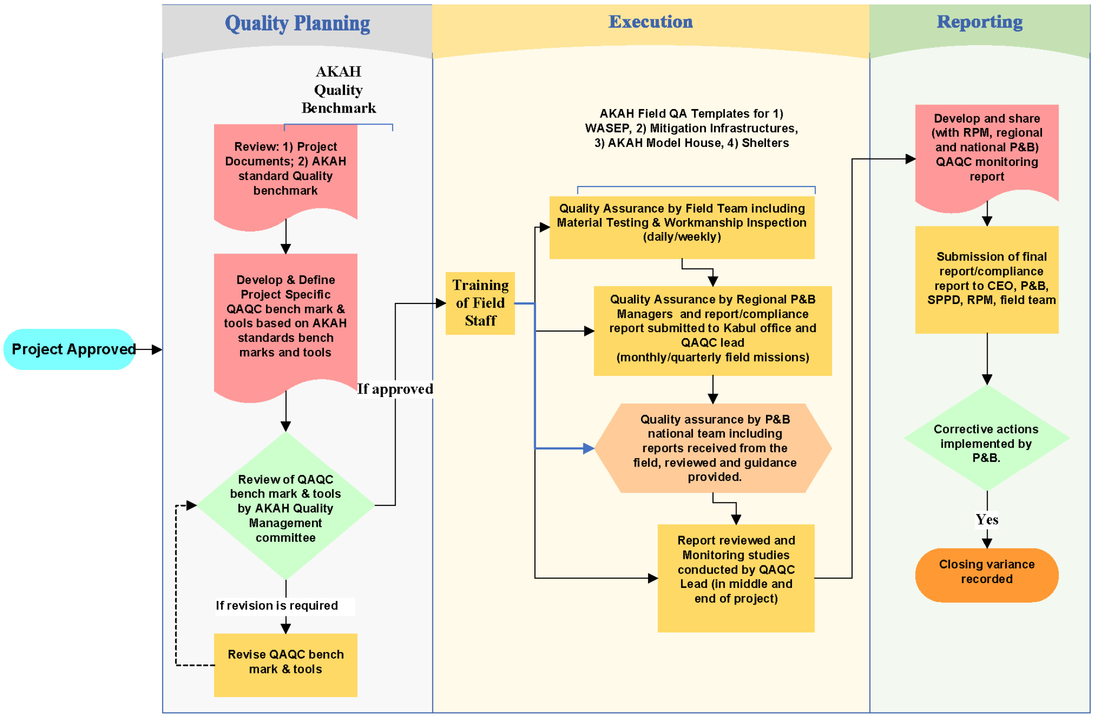



**Figure 17.** QAQC plan workflow.

### *4.7. Testing and Commissioning*

Upon completion of the project, the testing and commissioning phase verified the functionality of all systems through comprehensive inspection which included but not limited to inspection of beneficiary satisfaction, functionality of the intervention, site layout, changes in design and locations, material, workmanship, and safety. The inspection is conducted by QAQC teams, field staff, local leaders, and community representatives. This inspection verified that project outputs meet the standards outlined in the QMP. Training of responsible personnels or committees on O&M was part of this phase, preparing for final project handover. These committees, often comprising local volunteers including women and youth, are equipped to manage infrastructure. They receive maintenance manuals, tools, and routine schedules. For complex systems, committees are connected to local government technical departments to access support for significant repairs or technical issues. All through the testing and commissioning phase, community members remained engaged and provided inputs all along. Prior to handover, any discrepancies identified through monitoring are addressed, documented, and resolved, ensuring the delivery of only fully functional, and quality-assured structures.

### *4.8. Project Handover*

The handover phase marks a critical milestone, signifying both the formal completion of the project and the transition to community-led operation and management. The community members were actively involved in the project handover process, ensuring local ownership and project sustainability. The project handover is formalized through a public ceremony organized by PMT and documented through photographs and attendance records. During the event, LOAs was signed by the PMT, community leaders, and relevant government departments, clearly delineating post-handover responsibilities, particularly in operation, maintenance, and oversight. These ceremonies served not only a formal closure but also fostered trust, promote transparency, and reinforce collective ownership.

### *4.9. Project Handover Support*

Post-handover support forms an integral part of the process. The PMT maintain engagement during a defined warranty period, monitoring the intervention's performance and addressing any emerging issues, in collaboration with the community. This included periodic QAQC visits and technical backstopping. Community feedback was actively solicited and incorporated into future programme improvements, fostering continuous learning and adaptive management.

This comprehensive post-handover mechanism not only reinforced sustainability of the intervention but also empowered communities to take ownership of their development. The integration of training, formal agreements, and participatory governance established a resilient model of post-project accountability and stewardship, critical to ensure sustainability of the interventions.

### *4.10. Monitoring and Evaluation*

In Afghanistan's complex operational context, community-based performance evaluation and monitoring has become a critical for ensuring both the success and sustainability of projects. The PMT enhanced local knowledge, trust, and ownership by involving communities in every stage of the project cycle, from planning through to post-implementation. This participatory approach strengthened accountability and responsiveness, particularly in rural and hazard-prone areas where community involvement is vital for long-term resilience.

Monitoring framework was designed, and indicators are developed with inputs from locals. Structured consultations ensured that monitoring indicators are aligned with local needs and capacities. The community representatives are trained in monitoring process using simple and context-specific matrices.

## **5. Observation and Result Analysis**

### *5.1. Key Outcomes*

The community-centric hazard mitigation programme implemented across 22 sites in five provinces of Afghanistan ensures reduced multi-hazard risks through the integration of Hazard, Vulnerability and Risk Assessment (HVRA), participatory design, structural measures, and NbS. Collectively, the interventions will safeguard approximately 12.5 $km^2$ of land, including 2.95 $km^2$ of agricultural land, while directly protecting over 550 households, 4,900 individuals, and 58 critical infrastructure units. The dominant hazard addressed was flash flooding (77%), followed by avalanches (18%) and rockfalls and landslides (5%), confirming the hydro-meteorological dominance of disaster risk in mountainous Afghanistan.

Impact modelling demonstrated substantial quantitative risk reduction, with the Bezokh rockfall project potentially reducing total hazard impact area by 47%, exposed houses by 96%, and population at risk by 92%, while the Mullah Khil flood protection wall will reduce flood inundation extent by 55% under extreme simulated flow conditions. NbS feasibility assessments conducted at 12 sites showed that several projects achieved high compliance with IUCN Global Standards, with peak feasibility scores of up to 74%, reflecting strong ecological integration, community relevance, and technical suitability. The community-led implementation and post-handover maintenance frameworks will measurably strengthen ownership, functionality, and sustainability of mitigation infrastructure.

### *5.2. Cross-Site Patterns*

Across all sites, a consistent pattern emerged in which communities exposed to recurrent flash floods exhibited the highest concentration of structural investments, primarily through masonry flood protection walls, river training, and drainage systems. Sites exposed to avalanches and rockfalls showed a stronger reliance on hybrid solutions, combining terracing, slope stabilization, scaling, and vegetation-based NbS.

A uniform cross-site trend was the high effectiveness of participatory HVRA in accurately prioritising sites, aligning scientific modelling outputs with indigenous risk knowledge. Communities with higher levels of participation during planning and implementation consistently demonstrated better operation and maintenance performance post-handover, indicating a direct relationship between early engagement and long-term infrastructure functionality.

NbS-integrated sites consistently exhibited higher environmental co-benefits and community acceptance than purely structural sites, particularly where vegetation, terracing, and natural drainage control were combined with engineered works. Conversely, sites with lower NbS feasibility scores were typically those constrained by limited land availability, steep geomorphology, and high immediate life-safety threats, necessitating heavier reliance on engineered structures.

Across provinces, similar implementation constraints were observed, including weak regulatory frameworks, limited access to modern construction technologies, logistical isolation, and gaps in risk-informed engineering capacity, yet the standardized 8-step AKAH methodology ensured uniform delivery quality despite contextual variability.

### *5.3. Statistical Aggregations*

Of the 22 total mitigation projects, approximately 17 projects targeted flash flood risk, 4 projects addressed avalanche hazards, and 1 project focused on rockfall and landslide hazards. NbS feasibility assessments were applied at 12 sites, representing about 55% of all projects, with feasibility scores ranging from approximately 54% to 74% across the eight IUCN NbS performance parameters.

Pre-mitigation rockfall modelling at Bezokh village identified 26 exposed houses and 245 at-risk residents, whereas post-mitigation conditions reduced exposure to only 1 house and 11 residents, corresponding to a 96% reduction in exposed housing and a 95% reduction in population exposure. Flood modelling in Baghlan Markazi demonstrated that flood-exposed agricultural land was reduced by more than half (55%) following construction of the 233 m long and 3.1 m high flood protection wall.

Across all sites, the interventions cumulatively protected over 4,900 people, equivalent to an average of approximately 223 people protected per site and safeguarded over 26 households per project on average. Critical infrastructure protection averaged 2–3 facilities per site, indicating strong alignment of mitigation targeting with essential service assets.

## 6. Implementation Challenges and Limitations

Field practitioners encounter several challenges during the planning, design, and implementation of mitigation programmes. These challenges broadly fall into five thematic categories: (1) policy and legislative frameworks, (2) appropriate technology and risk knowledge, (3) social and economic fragility, (4) logistics and programme operations, and (5) relevant skills and awareness.

Policy and legislative frameworks play a pivotal role in ensuring the effective and timely implementation of large-scale mitigation initiatives, particularly in high-risk areas. However, weak institutional commitment across federal to local administrative levels cause delays in approval process of non-government-led mitigation projects. Lack of appropriate construction policy and legislative framework in Afghanistan results in below par engineering design and construction quality. Risk informed design and implementation of mitigation projects are significantly challenged by limited risk-related knowledge, particularly in remote regions. Lack of detailed information on hazards, vulnerabilities, and risks, undermines the accuracy of risk assessments. Currently, hazard and risk assessment methodology is not well developed and tested to assess the impacts of cascading hazards, a phenomenon predominant in mountain geographies. This has direct implications on the design of mitigation structures, which, in the absence of sound risk data, frequently fail during hazard events, leaving human settlements vulnerable. Low education levels within communities add to the challenge, as engaging them meaningfully in planning requires extraordinary effort-often constrained by the rigid timelines imposed by donors and funding agencies. Although the mitigation options are evaluated using realistic scenario modelling, limited data availability results in lower model confidence until validation against actual hazard events is possible.

Furthermore, short-sighted planning often overlooks the integration of safety and resilience into broader development perspective. There is also a pressing need to educate social mobilisers, engineers, and field staff about innovative approaches to large-scale mitigation and the long-term benefits of such interventions. Many design and planning engineers rely on empirical methods (‘thumb rule’), which may not meet established safety standards.

## 7. Causal Relationship Identified in the Mitigation Design Process

The project’s causal logic is that risk-informed, community-centred planning, design and implementation lead to measurable reductions in mass movement and flood risk and stronger resilience of communities with their ownership and assets protection. Overall, the causal chain is sequenced by evidence-based, participatory planning, robust, context-appropriate design, community-led, quality-controlled implementation and maintenance leading to reduced hazard impacts and increased resilience of vulnerable mountain communities. The causal chain is further elaborated in the following section.

In the planning phase, HVRA are combined with participatory methods (surveys, focus groups, mapping) to identify where people, infrastructure and livelihoods are most exposed. This evidence base allows the project to prioritise critical sites and select appropriate measures, such as drainage trenching, terracing, flood protection and vegetation, while LoA clarify roles in construction, operation and maintenance. Better information and clear responsibilities lead to better targeted investments and stronger ownership.

In the design phase, technical surveys and feasibility analyses are translated into solutions that directly interrupt hazard processes. Properly designed trenching and terracing, especially when combined with vegetation, improve drainage, reduce pore-water pressures and increase slope stability; flood walls and channel works reduce water depth and velocity near settlements. This ensures that planned interventions have a demonstrable risk-reduction effect, not just a visible construction footprint.

In the implementation phase, community participation and QAQC link construction outputs to real risk reduction. Mobilising local labour builds skills and ownership, while technical supervision ensures that structures perform as intended. Parallel training and awareness-raising (e.g., on keeping trenches clear and protecting vegetation on slopes) foster behaviours that preserve and enhance the effectiveness of interventions. Post-implementation monitoring by communities and technical staff provides feedback to adjust designs and practices over time.

## 8. Conclusions & Recommendations

In view of increasing frequency and intensity of climate induced hazard, it is imperative that government agencies adopt standardised HVRA methodology across all hazard-prone regions of Afghanistan. Implementing risk-informed land use planning and infrastructure design needs strong policy and legal backing, a framework that helps translate risk knowledge into practice. It is evident from projects in Afghanistan that community has an important role to play in resilient development, and indeed are indispensable player, particularly in remote mountain setting. It is therefore important to have communities involved in every step and decision-making process, giving them a reason to own and be part of the upkeep of the intervention. Post implementation O&M is as important as design and implementation, to sustain the functions of the intervention. Communities should be trained on O&M practices, so that community volunteers can take on themselves the role of undertaking periodic assessment and simple repairs. Capacity building of engineers, planners, and community volunteers is also essential in regions like Afghanistan where skilled manpower is an issue.

Availability and accessibility of materials and technologies are an important consideration while designing and implementing mitigation projects. It is therefore important to integrate NbS in conjunction with civil engineering interventions in the mitigation projects. NbS unlike the engineering interventions, also provides eco-system services (food, improve water quality and quantity) if appropriately thought through. The challenge during design also came from non-availability of context-specific engineering codes tailored to multi-hazard environment and cascading hazard.

Finally, promoting flexible design approaches that accommodate iterative improvements based on feedback and evolving risk profiles, provides opportunity to scale up and replication.

## Author Contributions

A.K.: Conceptualization; Methodology; Data curation; Formal analysis; Investigation; Validation; Supervision; Project administration; Writing—original draft, review & editing. N.A.: Conceptualization; Methodology; Data curation; Formal analysis; Validation; Investigation; Visualization; Supervision; Writing—original draft, review & editing. D.R.G.: Conceptualization; Methodology; Data curation; Formal analysis; Validation; Writing—review, editing and proof reading. M.E.H.: Data curation; Formal analysis; Validation; Investigation; Visualization. K.M.W.: Writing—original draft, review & editing. R.D.: Writing – original draft, review & editing. D.K.: Data curation; Formal analysis; Validation. All authors have read and agreed to the published version of the manuscript.

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## Institutional Review Board Statement

Not Applicable.

## Informed Consent Statement

Not Applicable.

## Data Availability Statement

The research datasets that have been generated through this study will not be shared publicly or published online due to strict ethical standards and confidentiality commitments. The information comprises sensitive, community-level demographic data, which is acquired under formal agreements requiring its use solely for official and humanitarian purposes. In accordance with organizational policies and ethical regulations, all data are kept confidential and are protected from unauthorized access or disclosure. Only aggregated findings and non-identifiable results are presented in the published journal, and no raw datasets will be made available to third parties, ensuring that full compliance with applicable rules and regulations, and data protection principles.

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**Conflicts of Interest**

The authors declare no conflict of interest.

**Use of AI and AI-Assisted Technologies**

Artificial intelligence tools were used solely for language editing and proofreading to improve clarity, grammar, and readability of the manuscript. No AI tools were used in the generation of scientific content, data analysis, interpretation of results, or conclusions. The authors take full responsibility for the content of this manuscript.

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