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Review Article

An Integrated Geotechnical Framework for Flood-Induced Ground Failure and Infrastructure Resilience in Charsadda, Khyber Pakhtunkhwa, Pakistan

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Abstract

Introduction: Flood assessment in Pakistan is commonly organized around inundation depth, exposed population, and direct asset loss. These measures are necessary, but they do not explain why bridge approaches settle, riverbanks retreat, earthen bunds pipe, culvert embankments breach, or saturated foundations lose capacity. The limitation is important in Charsadda District, Khyber Pakhtunkhwa, where the Kabul-Swat River system, low-relief alluvial terrain, irrigation infrastructure and dispersed road networks create coupled hydraulic and ground-failure pathways.

Objective: This study develops an integrated, field-calibratable framework that connects flood loading, geotechnical failure mechanisms, infrastructure consequences and intervention priorities for Charsadda.

Methodology: A systematic, PRISMA-informed evidence review was completed to 31 January 2026. Forty-four peer-reviewed studies, engineering standards, government reports and authoritative data products were retained using transparent relevance and quality criteria. We appraised evidence for source authority, methodological transparency, mechanism specificity, spatial transferability, and validation or uncertainty, then synthesized it into a multiscale decision-support architecture.

Results: We identified five recurrent mechanism groups: local and contraction scour; bank and surface erosion; seepage, uplift, and internal erosion; saturation- and drawdown-induced instability; and settlement or bearing-capacity degradation. Existing Charsadda studies provide useful flood-hazard and social-vulnerability mapping but seldom connect hydraulic forcing with soil stratigraphy, erodibility, transient pore-water pressure, foundation geometry or observed asset distress. IGFRF-Charsadda addresses this gap through district screening, corridor diagnosis, asset-level investigation, coupled hydraulic-geotechnical analysis, intervention selection and performance monitoring. It also introduces a transparent Risk Priority Index combining geotechnical hazard, asset-condition deficiency, exposure-consequence and recovery difficulty.

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Conclusion: The proposed framework provides a practical route from flood maps to defensible engineering decisions while maintaining a clear boundary between screening, detailed assessment and design. Its provisional weights and action bands require local calibration, consistency testing and sensitivity analysis before operational adoption.

1. Introduction

Pakistan's 2022 floods converted a climatic and hydrological shock into a national infrastructure and development crisis. The post-disaster needs assessment estimated US$14.9 billion in direct damage, US$15.2 billion in economic losses, and at least US$16.3 billion in resilient recovery needs [1]. These national totals are important, but they compress markedly different physical failure processes into sectoral loss categories. At the scale of a bridge, road embankment, flood-protection bund or irrigation structure, service failure is often controlled by the ground: scour removes support, seepage concentrates through defects, rapid drawdown leaves destabilizing pore pressures, and prolonged saturation reduces stiffness and undrained strength. Pakistan's flood-management literature has long recognized the interaction of river morphology, floodplain occupation, aging protection works and institutional fragmentation [2], yet geotechnical diagnosis remains weakly coupled to operational flood-risk mapping.

Charsadda is an especially instructive setting. The district occupies the Peshawar Basin's alluvial lowlands and is influenced by the Kabul and Swat River systems and smaller drainage channels. The 2010 event demonstrated how flood waves generated across the upper Kabul basin can propagate through densely settled agricultural corridors [3]. Hydraulic modelling of the Kabul River has mapped inundation and floodplain extent [4], while district-focused studies have added remote-sensing hazard zoning [5], social vulnerability [6] and multi-criteria exposure assessments [7,8]. These contributions establish that flood risk is spatially uneven and socially consequential. They do not, however, provide a consistent line of reasoning from flood loading to subsurface response, asset failure mode and intervention priority.

That missing line of reasoning matters because different ground failures demand different evidence. A deep-flow zone near a bridge pier is not equivalent to a high-gradient seepage exit at a bund toe. Bank retreat visible in satellite imagery is not interchangeable with settlement caused by saturation of a loose approach fill. A susceptibility map can identify where attention is warranted, but design decisions require soil layering, hydraulic conductivity, erosion resistance, groundwater response, foundation geometry and condition observations. Recent reviews of flood geotechnics and transportation embankments confirm that flood damage develops through coupled hydraulic, mechanical and geomorphic mechanisms that evolve during rising stage, prolonged submergence and recession [9,10].

This paper therefore asks four questions: (1) which flood-induced ground-failure mechanisms are most relevant to Charsadda's infrastructure systems; (2) what evidence is currently available, and where are the decisive gaps; (3) how can regional hazard information be converted into a defensible, asset-scale decision process; and (4) which implementation arrangements are realistic within Pakistan's present institutions and engineering codes? The answer is an Integrated Geotechnical Flood Resilience Framework for Charsadda (IGFRF-Charsadda). Its contribution is methodological rather than predictive: it organizes what must be observed, tested, modelled and revisited before an authority can move from a flood map to maintenance, investigation, restriction, retrofit or replacement.

2. Study setting and problem definition

2.1 Physical and infrastructure setting

Charsadda District covers approximately 996 km² and, according to Pakistan's 2023 census reporting, supports a population exceeding 1.8 million [11,12]. The district is characterized by intensively cultivated alluvial plains, expanding settlements, irrigation channels and a road network that repeatedly crosses natural and engineered drainage paths. District hydrology is shaped by the Kabul-Swat system, seasonal monsoon rainfall and upstream catchment processes. Flood footprints derived after the 2010 disaster documented extensive inundation in Charsadda and neighbouring Nowshera [13]. The resulting exposure is not confined to river margins: access routes, culvert approaches, canal crossings and floodplain public facilities can fail through indirect hydraulic and geotechnical pathways.

At screening scale, the district may be described as an alluvial floodplain. For engineering purposes, that label is too coarse. Young channel and overbank deposits can vary abruptly between gravelly channel fills, sand lenses, silty overbank strata and locally cohesive fine-grained soils. Man-made fills add another layer of variability because compaction history, borrow source, drainage details and maintenance condition differ between assets. The framework therefore treats mapped soil products and geomorphology as hypotheses to be verified, not as substitutes for ground investigation. Table 1 summarizes the Charsadda system profile and its geotechnical significance, linking each system attribute to the evidence-based interpretation, geotechnical relevance, and required local verification.

Table 1: Charsadda system profile and its geotechnical significance

System attribute	Evidence-based interpretation	Geotechnical relevance	Required local verification
River setting	Kabul-Swat influence, tributary and irrigation interfaces [3-5]	Scour, bank retreat, changing flow alignment and backwater effects	Cross-sections, thalweg change, flood marks, bed-material gradation
Floodplain	Low-relief alluvial terrain with broad agricultural occupation [5-8]	Variable saturation, shallow groundwater and lateral facies changes	Boreholes/CPT, groundwater seasonality, geomorphic mapping
Transport network	Roads and crossings provide essential inter-settlement access	Approach settlement, culvert blockage, toe erosion and foundation scour	Asset register, as-built drawings, condition survey, detour consequence
Flood-protection and irrigation work	Bunds, canals, headworks and transitions influence flood paths	Seepage, piping, uplift, erosion at interfaces and breach propagation	Crest/toe survey, seepage exits, filters, animal burrows, penetrations
Settlement pattern	Dense population and dispersed rural communities [6,12]	Failures can isolate communities even when direct structural loss is limited	Critical-facility inventory, route redundancy and emergency-access time
Data environment	Remote sensing is relatively accessible; subsurface records are fragmented	Regional screening is feasible, but design uncertainty remains high	Shared geodatabase, standardized logs and post-event evidence capture

Source: Author synthesis from cited evidence. District-scale descriptions must be checked against site-specific data before design.

2.2 Why a geotechnical framework is needed

The central problem is a scale mismatch. Hazard studies are usually built from rainfall, discharge, terrain, land cover and remotely sensed water extent. Infrastructure decisions are made at a pier, abutment, embankment reach, culvert or foundation. Between these scales lie the processes that govern ground failure: near-bed velocity and turbulence, hydraulic gradient, pore-pressure lag, soil erodibility, filter compatibility, unsaturated collapse and loss of confinement. If those processes are not represented, a map may correctly locate flood exposure while still misidentifying the dominant failure mechanism or the most effective intervention.

3. Systematic review method

3.1 Review design and search strategy

The review followed PRISMA 2020 principles of transparent identification, eligibility and reporting [14], adapted for a mixed evidence base that includes engineering manuals, codes, government assessments and geospatial data products. Searches were completed to 31 January 2026 using

Google Scholar and Crossref-linked publisher discovery, supplemented by official repositories of the Government of Pakistan, Government of Khyber Pakhtunkhwa, World Bank, UN agencies, the US Federal Highway Administration, the US Army Corps of Engineers and professional standards bodies. The core Boolean structure combined flood terms (flood, inundation, monsoon, river stage) with geotechnical mechanism terms (scour, bank erosion, seepage, piping, internal erosion, rapid drawdown, slope instability, settlement, bearing capacity, embankment) and geographic terms (Pakistan, Khyber Pakhtunkhwa, Kabul River, Swat River, Charsadda).

The principal publication window was 2000-31 January 2026. Older work was retained when it was foundational to the equations, analytical methods or standards used in the framework. Records were eligible if they (i) investigated flood hazard or vulnerability in Charsadda or the Kabul-Swat system; (ii) explained a flood-driven ground-failure mechanism with infrastructure relevance; (iii) established a recognized analysis, design or resilience method; or (iv) provided an authoritative Pakistan policy, code, census or event dataset. Sources were excluded when they lacked retrievable methods, repeated an already captured result without additional evidence, treated flood exposure without decision relevance, or made location-specific claims that could not be transferred to Charsadda.

The source-selection process is summarized in Figure 1. The final evidence base comprised 44 sources, including scholarly studies, engineering standards and manuals, institutional reports, and authoritative data products. The diagram distinguishes the reported source total from the unreported intermediate selection counts; the latter are shown as NR and are not interpreted as zero.

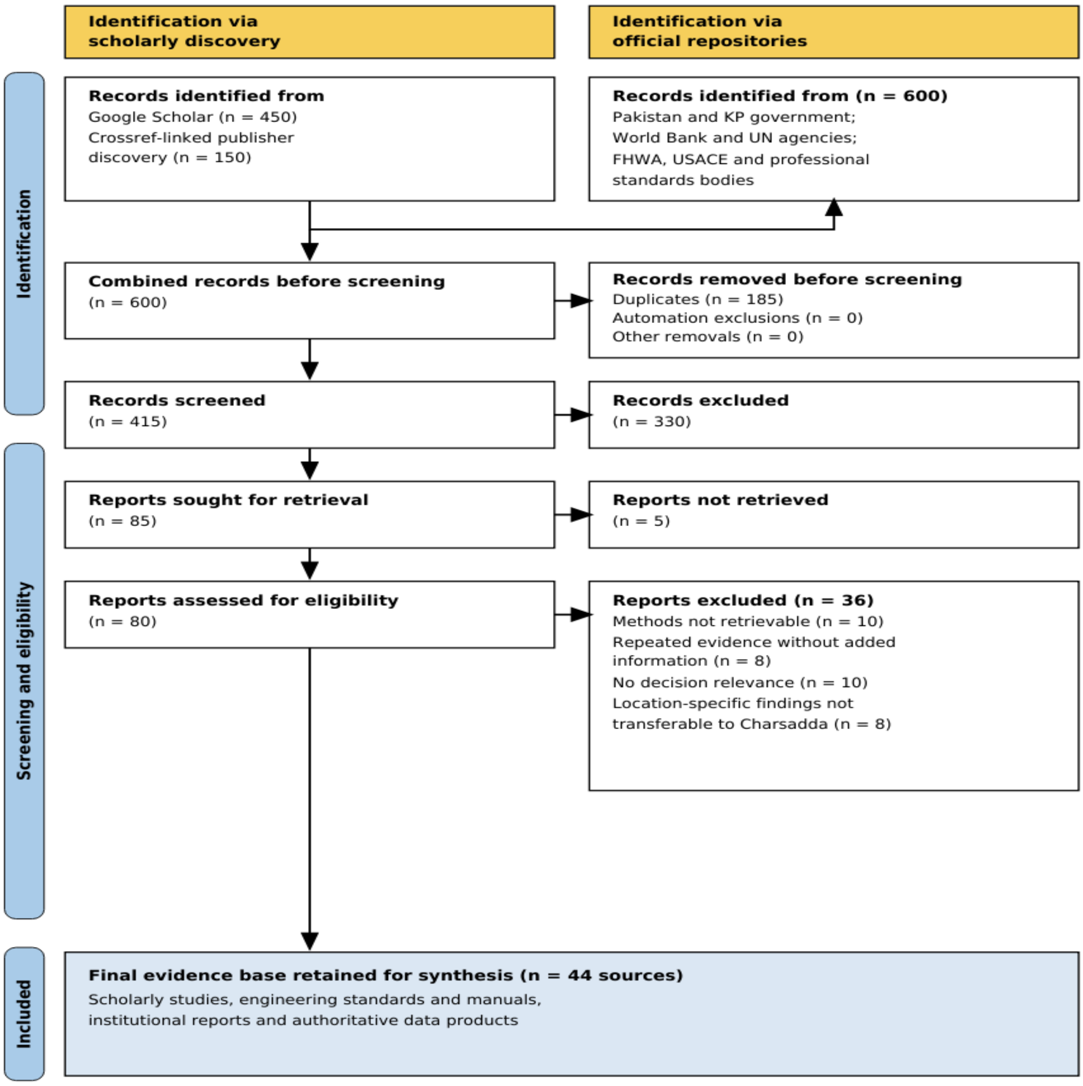

Figure 1: PRISMA 2020-adapted flow diagram of source selection for IGFRF-Charsadda.

Note: Records were excluded if they lacked retrievable methods, duplicated existing evidence, lacked decision relevance, or presented location-specific findings that could not be transferred to Charsadda.

3.2 Appraisal and synthesis

Each retained source was appraised across five domains: authority of the source; transparency of methods and data; specificity of the physical mechanism; spatial transferability to Charsadda; and validation or explicit treatment of uncertainty. Two points were available in each domain. Scores of 8-10 were treated as strong evidence, 5-7 as moderate evidence, and 0-4 as contextual evidence only. The categories were used to govern interpretation rather than to produce a pooled effect size. A formal meta-analysis was inappropriate because the evidence ranges from numerical hydrology and GIS susceptibility mapping to laboratory erosion studies, engineering manuals and policy documents.

The synthesis proceeded in three passes. First, local and basin studies were coded for hazard variables, spatial scale, infrastructure content and stated limitations. Second, geotechnical sources were coded by loading phase, soil response, failure signature and required analysis. Third, the two strands were joined through a transfer test: could a regional indicator be linked to a measurable ground mechanism and a decision at district, corridor or asset scale? Multi-criteria decision analysis was used only as a transparent organizing device; the review of flood applications by de Brito and Evers [15] was used to guard against opaque weighting and double counting. Table 2 presents the review protocol, eligibility rules, and evidence controls that governed the systematic review.

Table 2: Review protocol, eligibility rules and evidence controls

Element	Operational rule	Reason for inclusion
Time window	2000-31 Jan 2026; foundational older sources allowed	Captures modern flood mapping while retaining established mechanics and methods
Geographic scope	Charsadda, Kabul-Swat basin and transferable flood-geotechnical evidence	Balances local specificity with mechanism depth
Source types	Peer-reviewed papers, codes, manuals, government/UN reports and authoritative data products	Engineering decisions rely on more than journal articles
Inclusion	Explicit mechanism, infrastructure relevance, local hazard evidence or authoritative implementation role	Keeps the synthesis decision-focused
Exclusion	Unverifiable claims, duplicate evidence, no methodological detail, or no transfer pathway	Reduces false precision and unsupported localization
Quality domains	Authority, transparency, mechanism specificity, transferability and validation/uncertainty	Separates strong analytical evidence from contextual material
Synthesis form	Narrative, mechanism matrix and framework construction; no pooled effect	Methods, assets and outcome metrics were too heterogeneous for meta-analysis

Source: Author-developed protocol. The review is PRISMA-informed but not registered as a clinical or intervention-review protocol.

4. Results of the evidence synthesis

4.1 Charsadda and Kabul-Swat evidence

The local evidence is strongest at basin and district scales. Rainfall-runoff-inundation analysis has reproduced major features of the 2010 Kabul basin flood and demonstrated the value of coupled hydrologic-inundation simulation [3]. One-dimensional and two-dimensional HEC-RAS studies have mapped Kabul and Swat floodplains [4,16]. District studies have combined GIS, remote sensing and multi-criteria methods to delineate hazard or vulnerability [5-8,17-19]. Together, these studies provide a credible base for district screening: they locate corridors repeatedly exposed to flooding, show where terrain and drainage concentrate hazard, and identify communities for which infrastructure interruption would have high consequences.

The same studies reveal the present boundary of knowledge. DEM resolution and vertical error affect predicted flood pathways; land-cover and population layers date rapidly; weighting schemes are often judgement-dependent; and observed ground failures are rarely inventoried with consistent coordinates and attributes. Most importantly, soils are represented through generalized classes rather than stratigraphic profiles, erodibility tests or transient groundwater measurements. The result is a mature capacity to screen exposure but a limited capacity to explain why a particular asset will fail. Table 3 presents selected local and basin evidence and assesses its transfer to a geotechnical decision framework, identifying both the useful contribution and the geotechnical limitation of each study.

Table 3: Selected local and basin evidence and its transfer to a geotechnical decision framework

Study	Method and scale	Useful contribution	Geotechnical limitation/framework response
Sayama et al. [3]	Rainfall-runoff-inundation model; Kabul basin; 2010 event	Event-scale hydrograph and inundation dynamics	Does not resolve asset subsurface conditions; use as loading evidence
Khattak et al. [4]	HEC-RAS and GIS; Kabul River	Floodplain delineation and hydraulic zoning	Bridge/embankment mechanisms require local geometry and soil data

Bibi et al. [5]	Remote sensing/GIS; Charsadda	District hazard and affected-area screening	No foundation or erodibility characterization; feeds Tier 1 only
Hamidi et al. [6]	Flood exposure and social vulnerability; rural Charsadda	Consequences and social sensitivity	Not a physical failure model; informs exposure-consequence component
Ibrahim et al. [7]	AHP-GIS vulnerability; flood-prone KP/Charsadda setting	Multi-indicator spatial prioritization	Weights and input resolution need sensitivity tests; no design use
Ibrahim et al. [8]	MCDA-GIS; Mirzadhare subarea	Local risk integration and hotspot identification	Subarea results cannot be generalized district-wide without validation
Farooq et al. [16]	2D HEC-RAS and 12 m TanDEM-X; Swat River	Hydraulic detail and high-resolution terrain value	Bed change, scour and asset condition remain separate analyses
Rahman et al. [17]	Bivariate susceptibility model; Swat basin	Statistical susceptibility and validation practice	Susceptibility is not a factor of safety or failure probability
Farish et al. [18]	GIS flood-risk zonation; Charsadda 2010	Historical district context	Limited subsurface and process resolution
Fida et al. [19]	Land-use change analysis; Charsadda/Kabul River	Post-event land-cover evidence	Discussion paper; contextual weight only
Iqbal et al. [20]	Climate/flood frequency analysis; Kabul basin	Future loading context	Scenario uncertainty must be propagated to hydraulic design
Ushiyama et al. [21]	Forecast rainfall ensemble and basin simulation	Lead-time and forecast uncertainty	Forecasting informs preparedness, not asset resistance

Source: Author synthesis of [3-8,16-21].

4.2 Coupled flood-ground failure pathways

Flood-induced infrastructure failure is rarely the product of a single maximum water level. It develops through a sequence. Rising stage applies hydraulic head and increases saturation. Prolonged high water allows seepage fronts and pore pressures to migrate. High velocity mobilizes surface and bed particles, while flow contractions and structural obstructions intensify local turbulence. During recession, external support may fall faster than pore pressure dissipates. The surviving asset can then carry residual deformation, voids or weakened fill into the next event. Reviews across transport embankments and water-driven ground disasters identify this time dependence as a central cause of under-diagnosis [9,10].

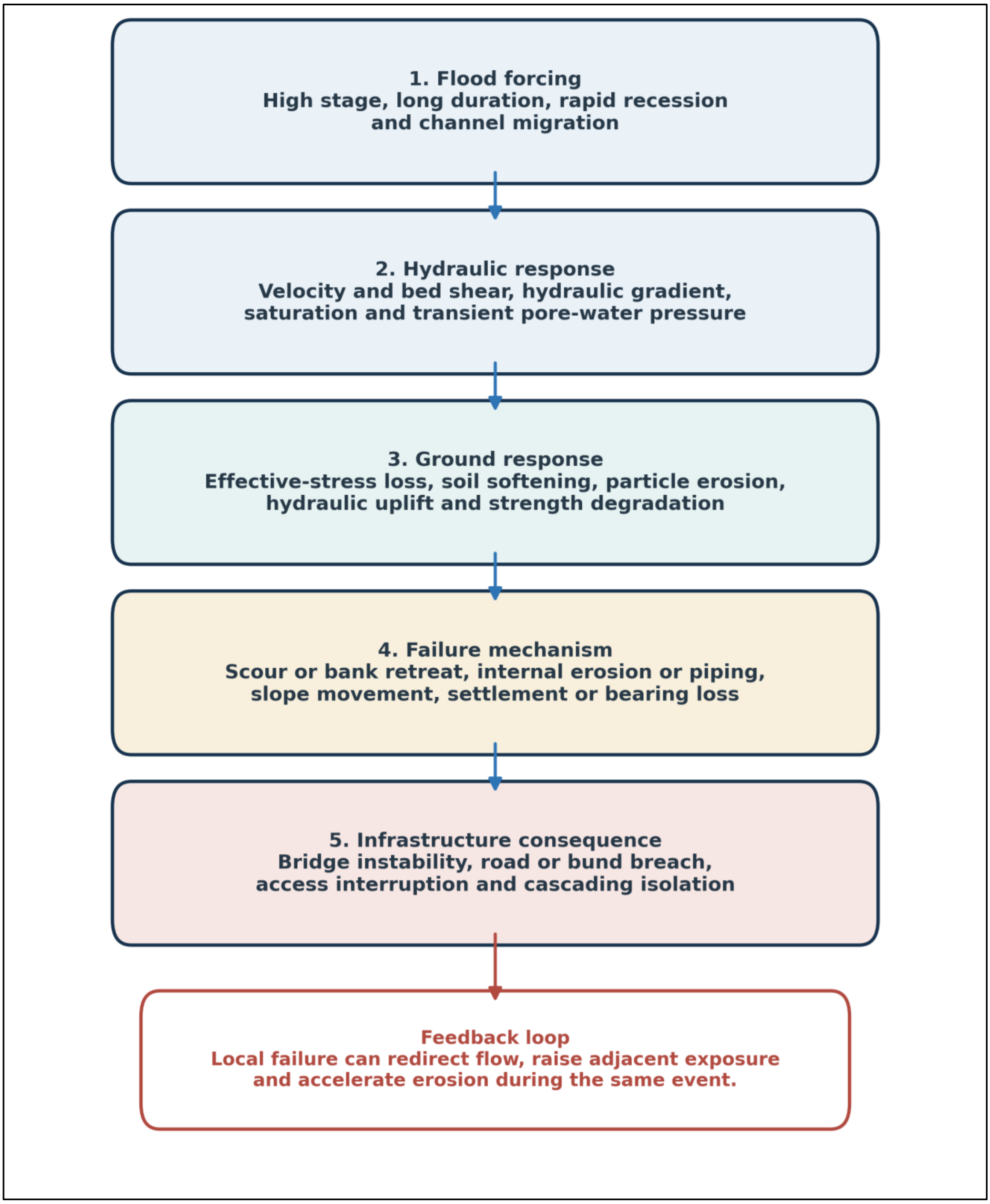

Figure 2: Coupled hydro-geotechnical pathway from flood forcing to infrastructure service consequence. *Source: Author-developed mechanism synthesis based on [9,10,22-29].*

4.3 Mechanism 1: scour, bank erosion and surface erosion

Scour removes soil from around foundations or across the bed and banks when applied hydraulic shear and turbulent vortices exceed the resistance of the material. At bridges, total scour is conventionally separated into long-term bed change, contraction scour and local scour [23]. The distinction is practical: a stable-looking channel cross-section can still conceal a deep local hole near a pier or abutment, while a reach experiencing migration can threaten approach fills without first undermining a structural foundation. Charsadda screening should therefore combine historical channel position, event-scale water extent, crossing geometry, debris potential and post-flood bathymetry.

Erosion resistance cannot be inferred reliably from a broad soil-texture class. Critical shear and erosion rate depend on gradation, plasticity, density, fabric, cementation and stress history. Where consequences are high, erodibility should be measured with a suitable flume, jet erosion or erosion-function test, and its uncertainty should be carried into countermeasure selection [29]. Riprap sizing without filter compatibility, launching allowance, toe keying and inspection access may transfer rather than remove the failure.

4.4 Mechanism 2: seepage, uplift and internal erosion

Earthen bunds, road embankments and canal transitions are vulnerable when floodwater establishes a sustained head difference. Seepage may emerge diffusely, concentrate along poorly compacted lifts or utility penetrations, or erode fine material into a coarse foundation. The effective vertical stress governing heave and many instability problems is reduced by pore-water pressure:

$$sigma' = sigma - u \quad (1)$$

where sigma' is effective stress, sigma is total stress, and u is pore-water pressure. The hydraulic gradient is:

$$i = Delta\ h / L \quad (2)$$

For an idealized granular soil, a first-screen critical gradient may be written as:

$$i\_c = (G\_s - 1) / (1 + e),$$
$$FS\_p = i\_c / i\_exit \quad (3)$$

where G_s is the specific gravity of solids, e is void ratio and i_exit is the computed exit gradient. Equation (3) is a screening expression, not a complete piping assessment. Internal erosion requires an initiation pathway, erodible material, a transport route, and an unfiltered exit. Soil segregation, concentrated leaks, contact erosion and suffusion can violate simple homogeneous assumptions. Seepage analysis should therefore be paired with filter compatibility, crack and penetration inspection, foundation continuity and evidence of turbid discharge or sand boils [24,26-28].

4.5 Mechanism 3: saturation, slope instability and rapid drawdown

Flooded slopes experience two contrasting boundary conditions. During sustained high water, external water can buttress the slope even as saturation raises pore pressure and reduces suction. During rapid recession, buttressing disappears before internal pressures dissipate, producing an adverse transient condition on the waterside face. The controlling case depends on soil permeability, layering, slope geometry, antecedent moisture and recession rate. Limit-equilibrium analysis should be supported by transient seepage when these variables are consequential, with shear-strength parameters selected for the drainage condition and stress path [25]. Cracking, slumping at the toe, tension features near the crest, leaning trees or posts and fresh scarps are field indicators that screening has to escalate.

4.6 Mechanism 4: settlement and bearing-capacity degradation

Approach fills and shallow foundations may remain standing yet lose serviceability through settlement, differential movement or rutting. Saturation can collapse metastable fabric in poorly compacted or partly saturated fill, weaken fine-grained soils, remove capillary suction and promote cyclic softening under repeated traffic. Water flowing through pavement defects can also erode fines and form subsurface voids. These failures are easily mistaken for routine maintenance defects unless elevations, crack patterns, groundwater and material history are documented. For critical approaches, repeated level surveys, density and moisture checks, penetration testing and targeted sampling should be linked to a pre-flood baseline. Table 4 links each flood-induced ground-failure mechanism to its loading phase, diagnostic signature, and required investigation method.

Table 4: Mechanism-to-evidence matrix for Charsadda infrastructure

Flood loading	Ground mechanism	Field signature	Minimum analysis/test	Typical exposed asset
High velocity; contraction; debris	Local/contraction scour and surface erosion	Exposed footing, bed lowering, bank notch, riprap displacement	Repeat cross-section/bathymetry; bed gradation; scour analysis; erodibility test where	Bridge pier/abutment, approach, culvert outlet

			critical	
Sustained head difference	Seepage, uplift, backward erosion or concentrated leak	Wet toe, turbid flow, sand boil, sinkhole, crest crack	Piezometry; seepage model; gradation/filter checks; defect mapping	Bund, road fill, canal bank, headworks transition
Prolonged saturation	Strength/stiffness loss	Rutting, bulging, settlement, lateral spreading	Moisture-density; SPT/CPT; strength and consolidation testing	Road embankment, approach fill, shallow foundation
Fast falling stage	Rapid-drawdown instability	Fresh scarp, tension crack, waterside slump	Transient seepage and limit-equilibrium/finite-element stability	Riverbank, bund, canal bank, approach slope
Channel migration or toe attack	Bank retreat and toe undercutting	Overhang, tension cracks, vegetation tilt, lateral channel shift	Multitemporal imagery; survey; bank-material characterization	River road, settlement edge, protection work
Overtopping and concentrated return flow	Crest erosion and breach initiation	Rills, headcut, crest lowering, downstream fan	Crest survey; overtopping hydraulics; erosion resistance and breach pathway	Earthen bund, rural road acting as barrier

Source: Author synthesis from [9,10,22-29].

4.7 Climatic, land-use and governance context

The framework must operate under non-stationary loading. Basin studies project changes in Kabul River flood frequency and intensity [20], while attribution work on Pakistan's 2022 monsoon shows that climate change increased the likelihood and intensity of extreme rainfall in a highly vulnerable setting [30]. Forecasting studies also show that the spatial and temporal distribution of rainfall matters for the Kabul basin response [21]. Recent work emphasizes that the 2022 disaster emerged from interacting climatic and anthropogenic drivers rather than a single cause [31]. Design and prioritization should consequently test multiple hydrographs and geomorphic states, not merely reproduce one historical water level.

Pakistan's National Flood Protection Plan IV and National Adaptation Plan already support integrated, risk-based and climate-aware investment [32,33]. Khyber Pakhtunkhwa's flood-response planning establishes a provincial coordination pathway [34]. The Building Code of Pakistan 2021 includes flood-resistant construction provisions [35], and the province's 2025 Highway Bridge Design Code provides a contemporary route for climate-informed bridge decisions [22]. IGFRF-Charsadda complements these instruments by specifying the geotechnical evidence needed between basin planning and asset design. It also reflects the Sendai Framework's emphasis on understanding disaster risk, strengthening governance and investing in resilience [36].

5. IGFRF-Charsadda: the integrated decision-support framework

5.1 Design principles

IGFRF-Charsadda is organized around six principles. First, mechanism precedes intervention: the same visible damage may have different causes. Second, evidence resolution must match the decision. Third, uncertainty is recorded rather than hidden inside a composite score. Fourth, asset condition and network consequence are assessed alongside hazard. Fifth, post-flood observations are treated as calibration data. Sixth, screening never substitutes for the code-based design of a life-safety or high-consequence structure.

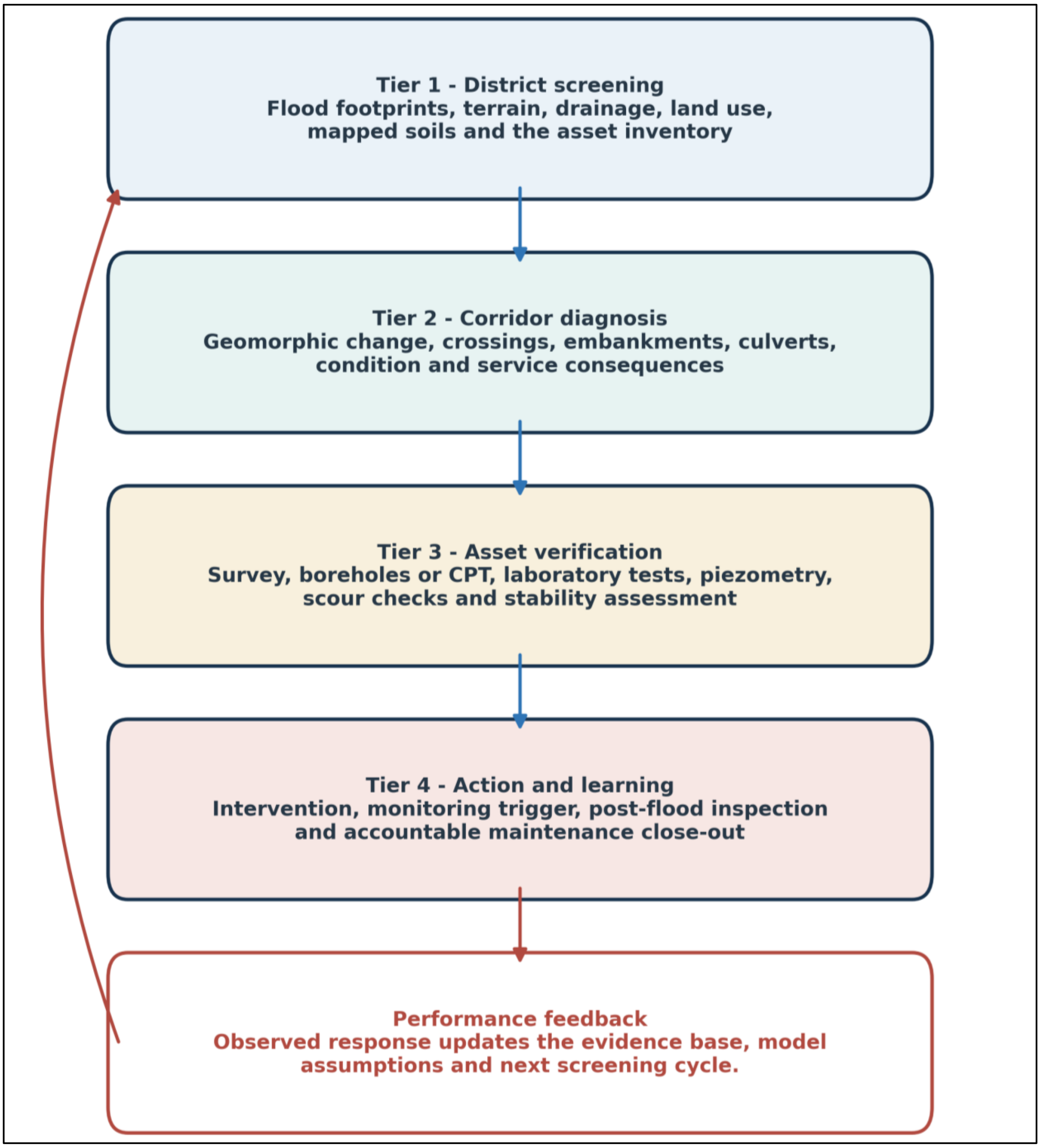

Figure 3: Four-tier architecture of IGFRF-Charsadda.
Source: Author-developed framework.

5.2 Tier 1 - district screening

Tier 1 constructs a district geodatabase with one purpose: to decide where corridor and asset evidence should be collected first. It combines multitemporal flood footprints, terrain derivatives, drainage and channel migration, land use, mapped soils, asset locations and consequence indicators. Satellite-derived terrain and surface-water products can provide an auditable base [37-39], while cloud geospatial platforms support repeatable processing [40]. Nevertheless, SRTM-scale elevation and SoilGrids-scale soil predictions are insufficient for bridge or embankment design. Each layer must carry metadata describing date, resolution, vertical datum, source and confidence. Table 5 specifies the minimum data architecture for district-to-asset assessment, listing each layer, candidate source, framework use, and critical limitation or local check.

Table 5: Minimum data architecture for district-to-asset assessment

Layer	Candidate source	Framework use	Critical limitation / local check
Flood extent and recurrence	Sentinel-1 SAR; UNOSAT event maps [13]	Historical exposure, persistence and calibration	Cloud/radar interpretation; distinguish standing water from permanent channels
Terrain	SRTM [37], TanDEM-X where licensed, local survey	Flow paths, relative elevation, corridor screening	Vertical error and vegetation/building bias; survey high-consequence assets
Hydrology/hydraulics	PMD/FFD gauges, discharge records, HEC-RAS studies [3,4,16]	Water levels, velocities, durations and recession rates	Rating curves, missing records, cross-section age and boundary uncertainty
Channel change	Multitemporal optical/SAR imagery; survey	Migration, bank retreat and scour-prone bends	Image date and planform change do not reveal buried scour
Soils/geology	GSP mapping; SoilGrids [38]; project records	Initial stratigraphic hypotheses and test planning	Coarse predictions cannot replace boreholes, CPT or laboratory tests
Surface water	Global Surface Water [39]; local irrigation mapping	Persistent/wet-season water and drainage connectivity	Engineering channels and seasonal maintenance need local updating
Assets	C&W/PKHA, Irrigation, local government, field GPS	Crossings, approaches, bunds, culverts, public facilities	Incomplete IDs/as-builts; establish a unique asset key
Population and critical services	PBS census [12], health/education and emergency records	Exposure, isolation and recovery consequence	Aggregation and temporal mismatch; validate routes and operating status

Source: Author framework using authoritative data products [12,13,37-40].

5.3 Tier 2 - corridor diagnosis

Tier 2 converts district hotspots into corridor hypotheses. A corridor is not just a road centreline; it includes the channel reach, floodplain flow path, drainage crossings, approach embankments, adjacent bunds and the communities that depend on the route. Teams should walk or drive each priority corridor before and after the flood season, record condition against a common vocabulary, photograph fixed viewpoints and survey any rapidly changing bank or bed. Historical imagery should be used to identify channel migration and informal modifications such as borrow pits, blocked openings and unrecorded fill.

5.4 Tier 3 - asset verification and coupled analysis

Asset verification begins with a conceptual ground model. The model should show units, interfaces, groundwater, fill limits, foundation type, seepage paths and plausible failure surfaces. Investigation then targets the uncertainties that could reverse a decision. Boreholes and SPT provide samples and stratigraphy; CPT/CPTu improves continuous profiling and pore-pressure interpretation; trial pits expose shallow fill and drainage details; geophysics can extend coverage between intrusive points; and laboratory work should address gradation, plasticity, density, compaction, permeability, shear strength, consolidation and erodibility as relevant. Unsaturated hydraulic parameters may be modelled with established relationships [41], but fitted values require local water-retention evidence when transient suction controls stability. Table 6 outlines the tiered ground-investigation programmed, specifying the decision tier, typical methods, primary output, and escalation trigger for each level of investigation.

Table 6: Tiered ground-investigation programme

Decision tier	Typical methods	Primary output	Escalation trigger
District screening	Desktop GIS, event imagery, records review, rapid reconnaissance	Hotspot and uncertainty map	Critical asset within recurrent flood, migration or isolation zone

Corridor diagnosis	Geomorphic walkover, drone/total-station survey where permitted, fixed photographs, drainage inventory	Failure hypotheses and prioritized asset list	Observed change, high consequence, conflicting or low-confidence data
Asset preliminary	Targeted boreholes/SPT or CPTu, trial pits, groundwater standpipes, bed/bank sampling	Conceptual ground model and parameter ranges	Potential life-safety failure, unfavorable mechanism check, poor parameter confidence
Asset detailed	Supplementary investigation, piezometers, cross-hole/geophysics, lab strength/permeability/erosion, repeat bathymetry	Calibrated hydraulic-geotechnical model and design basis	Mandatory for major retrofit/replacement or unresolved failure mode
Performance monitoring	Survey monuments, piezometers, scour sensors where justified, inspection triggers	Observed response and threshold record	Threshold exceedance, trend acceleration or post-event damage

Source: Author-developed minimum programmed; final scope must be set by the responsible geotechnical and hydraulic engineers

Hydraulic and geotechnical models should exchange variables explicitly. The hydraulic model supplies stage hydrographs, duration, depth-averaged or local velocity, bed shear, recession rate and plausible geomorphic change. The seepage/stability model supplies pore pressure, gradient, deformation and factor of safety under the relevant drainage condition. Bridge scour evaluation should follow recognized practice [23] and the applicable Pakistan/Khyber Pakhtunkhwa bridge code [22]. Flood-resistant building decisions should be checked against the Building Code of Pakistan [35] and, were useful for comparison, ASCE/SEI 24-24 [42].

5.5 Risk Priority Index for transparent triage

A Risk Priority Index (RPI) is proposed to rank where additional evidence or intervention is most urgent. It is not a probability of failure. Four normalized components are used: mechanism-specific geotechnical hazard (H_G), asset-condition deficiency (C_A), exposure-consequence (E_C), and recovery difficulty (R_D). Each is scored from 0 to 1 using documented evidence. The provisional screening relationship is:

$$RPI = 100\,[0.45\,H\_G + 0.20\,C\_A + 0.20\,E\_C + 0.15\,R\_D] \quad (4)$$

The geotechnical hazard component is itself a weighted synthesis:

$$H\_G = 0.25\,H\_hyd + 0.25\,H\_sco + 0.20\,H\_seep + 0.15\,H\_slope + 0.15\,H\_set \quad (5)$$

where H_hyd represents flood loading, H_sco scour and erosion susceptibility, H_seep seepage and internal-erosion susceptibility, H_slope instability susceptibility, and H_set settlement or bearing degradation. The coefficients in Equations (4) and (5) are starting weights for stakeholder calibration, not empirical constants. A local AHP or Delphi exercise should involve hydraulic, geotechnical, bridge, irrigation, disaster-management and local-government specialists. The AHP consistency ratio should be below 0.10 [43], and one-at-a-time plus global sensitivity tests should report whether asset rankings change under reasonable weights. Correlated indicators, such as flood depth and hydraulic forcing, must not be counted twice. Table 7 defines the RPI components and their scoring anchors, providing the evidence notes for each component across low, moderate, and high scores. Table 8 proposes suggested RPI action bands, linking each screening interpretation to a minimum required action.

Table 7: RPI components and scoring anchors

Component	0.0-0.2 (low)	0.4-0.6 (moderate)	0.8-1.0 (high)	Evidence notes
H_G: geotechnical hazard	Weak loading and resistant ground; no change evidence	One credible mechanism under design-relevant loading	Multiple active mechanisms or great observed change	Record subcomponent values and uncertainty separately
C_A: condition deficiency	Good condition; drainage/protection functioning	Localized defects or incomplete maintenance	Movement, active erosion/seepage, exposed foundation or repeated repair	Red flags bypass the score and trigger immediate review
E_C: exposure-consequence	Low use; redundant route; limited receptors	Important local access or moderate damage consequence	Life-safety role, critical facility, major crossing or large isolation potential	Use service and network consequence, not replacement cost alone
R_D: recovery difficulty	Materials, plant and detour readily available	Seasonal or logistical constraint	Long detour, scarce specialist work, access likely lost during repair	Validate with district emergency and works teams

Source: Author-developed screening anchors. Intermediate scores require a written rationale; blank or uncertain evidence must not be treated as zero risk.

Table 8: Suggested RPI action bands

RPI band	Screening interpretation	Minimum action
<20	Routine priority	Maintain records and inspect after threshold events
20-39	Watch	Close obvious data gaps and add targeted monitoring
40-59	Detailed assessment	Undertake corridor/asset survey and mechanism-specific checks
60-79	Mitigation priority	Engineer interim controls and develop funded permanent work
>=80	Urgent escalation	Immediate competent-person review; consider access/load restriction under authority procedures

Source: Author proposal for calibration. The bands are governance triggers, not safety thresholds or code acceptance criteria.

5.6 Tier 4 - intervention, monitoring and learning

Interventions should interrupt the diagnosed pathway. Surface armoring addresses hydraulic erosion only when the toe, filter and transitions are stable. A downstream drain may lower pore pressure but can be dangerous if it lacks filter compatibility. Flattening a slope may improve stability yet increase the footprint exposed to flow. Raising a road without added openings can protect the carriageway while increasing upstream head and community inundation. The preferred measure therefore follows a coupled check of the structure, ground, water and network. Resilience should also be measured by the speed and completeness of service recovery, consistent with the broader resilience framework of robustness, redundancy, resourcefulness and rapidity [44]. Table 9 provides a mechanism-linked intervention library, pairing each mechanism with near-term risk reduction, engineered intervention, and inspection/maintenance controls.

Table 9: Mechanism-linked intervention library

Mechanism	Near-term risk reduction	Engineered intervention	Inspection/maintenance control
Scour/bank erosion	Debris removal under approved procedure; protect exposed	Foundation strengthening; guide bank; engineered	Post-peak and post-recession bed survey; displaced stone and

	approach temporarily	armoring with toe and filter; opening modification	bank-retreat markers
Seepage / piping	Control access; manage head only under engineering direction; contain and observe turbid exits	Graded filter/drain, seepage berm, cutoff or rebuild of defective zone	Piezometer/flow trends; filter outlet clarity; burrow, crack and penetration checks
Rapid drawdown / slope instability	Load restriction; drainage clearance; emergency surface protection	Geometry change, internal drainage, toe berm, reinforcement or retaining solution	Crack pins, survey targets, pore pressure and recession trigger
Settlement / bearing loss	Traffic control; seal water entry; temporary leveling only after void check	Excavate/recompact, ground improvement, drainage, foundation retrofit	Repeated levels, rut/crack map and drainage inspection
Overtopping / breach	Protect critical low points if feasible; emergency warning and route control	Crest rehabilitation, erosion-resistant surface, spillway/relief opening or setback	Crest profile, animal damage, vegetation and transition inspection

Source: Author synthesis based on [9,10,22-29]. Measures require site-specific design and environmental/social review.

6. Charsadda implementation pathway

6.1 Priority asset classes

Initial deployment should prioritize asset classes where ground failure can produce disproportionate service loss: river bridges and their approaches; rural road culverts that cross broad floodplain flow paths; earthen bunds and road embankments that act as unintended barriers; canal and headworks transitions; riverbank roads; and public facilities whose only access depends on a single crossing. This is a class-based starting point, not a claim that every asset in those classes is deficient. A verified inventory is the first implementation deliverable.

6.2 Institutional arrangement

A district steering group should be chaired through the deputy commissioner's disaster-management structure and include PDMA Khyber Pakhtunkhwa, the Irrigation Department, Communication and Works/Provincial Highways, local government/TMAs, PMD/FFD, emergency services and utility representatives. Bacha Khan University and UET Peshawar can support method development, field training and independent review, subject to formal agreements and competence requirements. Communities should contribute event timing, inaccessible-route records and observations of new seepage, bank retreat and culvert blockage; such reports become engineering evidence only after verification. Table 10 identifies these priority asset classes, the dominant geotechnical mechanisms affecting them, and the initial actions required.

Table 10: Phased implementation plan for Charsadda

Phase and indicative period	Lead and support	Core activities	Auditable output
0. Mobilize (0-3 months)	Deputy Commissioner/PDMA; all asset owners	Agree governance, unique asset IDs, data schema, safety rules and sharing protocol	Signed protocol; accountable asset register; review calendar
1. Screen (3-9 months)	PDMA/GIS cell; universities; Irrigation/C&W	Compile event footprints, terrain, channels, assets, condition and consequences	District hotspot map with confidence and data-age fields
2. Diagnose (6-15	Asset owners with	Corridor surveys, fixed	Mechanism register;

months)	geotechnical/hydraulic teams	photos, cross-sections and preliminary investigations	conceptual ground models; ranked investigation plan
3. Verify/design (12-30 months)	Responsible design authority	Detailed investigation, coupled models, option appraisal and code checks	Design basis report; drawings/specifications ; environmental/social approvals
4. Monitor/learn (continuous)	Asset owner; district control room; PDMA	Threshold monitoring, post-event triage, maintenance close-out and annual review	Condition trend, intervention performance and updated RPI/model

Source: Author-developed implementation pathway aligned conceptually with [22,32-36]. Timings are indicative and depend on procurement, access and monsoon windows.

6.3 Post-flood triage

Immediately after a flood, the first task is not to calculate a composite score; it is to identify conditions that may require restriction or emergency engineering review. Exposed or undermined foundations, sudden movement, active piping, sinkholes, a breach, large fresh cracks or rapid bank retreat are red flags. The responsible authority must apply its closure and traffic-management procedures. Only after immediate safety has been addressed should the team update the RPI, plan tests and select repair options.

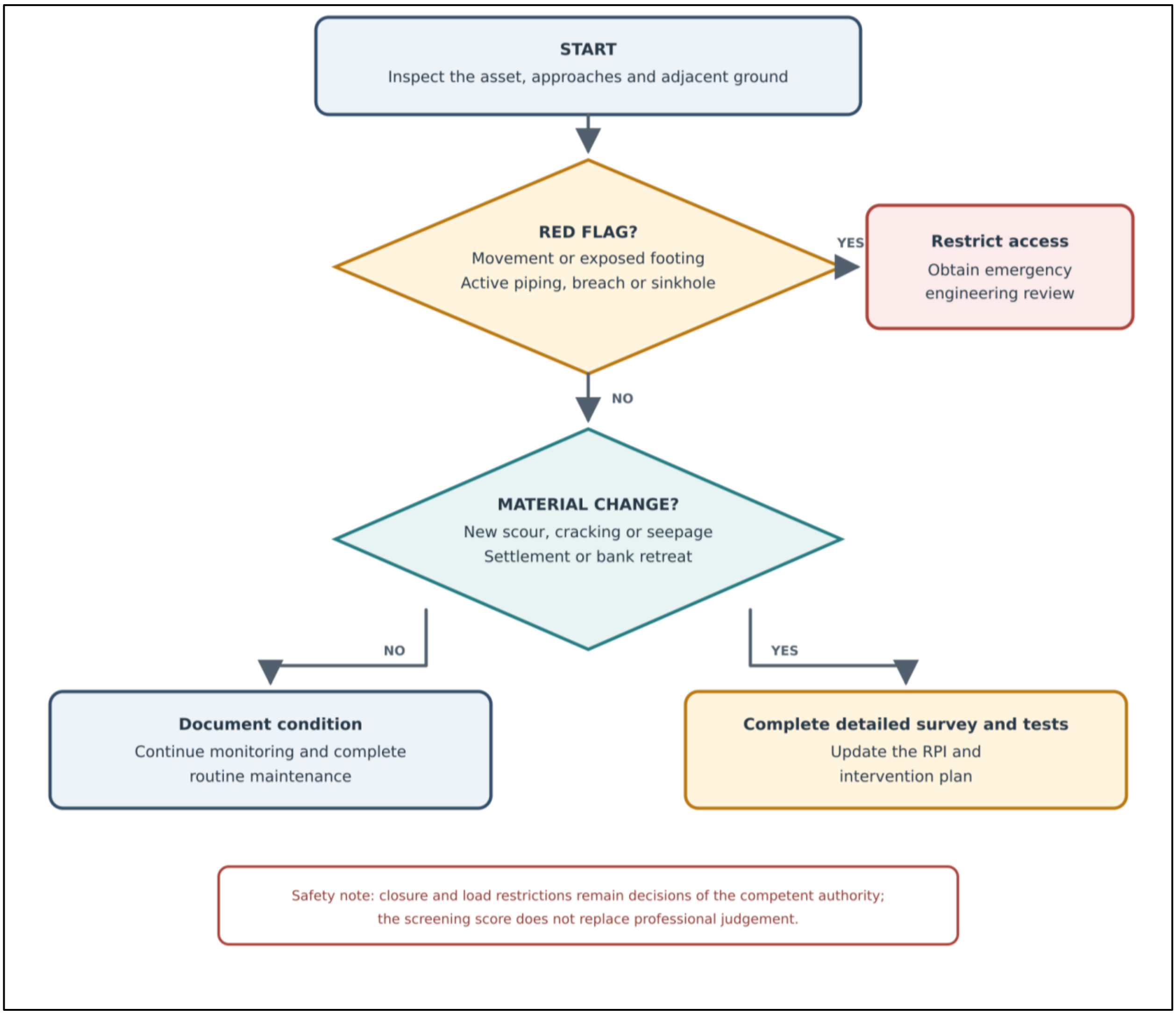

Figure 4: Post-flood asset triage and escalation decision tree.

Source: Author-developed triage logic. Closure and load restrictions remain decisions of the competent authority.

6.4 Validation and assurance

Validation must be planned before a district map or asset score is accepted. Flood extent should be compared with independent SAR interpretation, surveyed high-water marks and community time-location evidence. Hydraulic models should report calibration and validation events separately, with sensitivity to terrain, roughness, boundary conditions and blocked openings. Susceptibility layers should use spatially independent failure inventories where possible and report discrimination and reliability metrics; a high area-under-curve value does not validate a geotechnical mechanism. Asset models should compare predicted pore pressure, deformation or scour with monitoring or repeat survey.

Quality assurance should include independent review of high-consequence assets, version control for datasets and models, a parameter register distinguishing measured from assumed values, and a decision log recording why an intervention was selected. AHP weights should be published with the pairwise matrix, consistency ratio, and ranking sensitivity. Missing data must be scored as uncertainty, not as a benign condition. Table 11 presents the minimum validation and reporting checklist, specifying the minimum evidence and reporting requirements across each validation domain.

Table 11: Minimum validation and reporting checklist

Domain	Minimum evidence	Reporting requirement
Flood mapping	Independent footprint or surveyed flood marks	Event date, sensor/model, vertical datum, accuracy and mismatch map
Failure inventory	Georeferenced observed distress with date and photographs	Mechanism confidence, asset ID, observer and repair history
Ground model	Logs/tests appropriate to the decision	Measured versus inferred units and parameter ranges
Hydraulic model	Calibration/validation or explicit no-data limitation	Geometry date, roughness, boundaries, blockage assumptions and sensitivity
Geotechnical model	Relevant loading phases and groundwater conditions	Constitutive/strength assumptions, drainage case, uncertainty and governing mechanism
RPI/MCDA	Traceable indicator evidence and stakeholder weights	Normalization, pairwise matrix, CR, sensitivity and rank stability
Intervention	Mechanism-to-measure rationale	Design standard, residual risk, inspection access and maintenance owner

Source: Author-developed assurance checklist informed by [14,15,23-26].

7. Discussion

7.1 What the framework adds

IGFRF-Charsadda changes the unit of analysis from a flooded pixel to a coupled ground-asset system. Existing hazard and vulnerability studies remain essential: they identify loading corridors and social consequences [5-8]. The framework adds the intermediate mechanisms needed for engineering action. It asks whether the critical variable is local bed lowering, a seepage exit gradient, delayed pore-pressure dissipation, erodible approach fill or loss of route redundancy. That shift improves both efficiency and accountability. Investigation funds can target uncertainties that affect a decision, while a visible evidence trail shows why one asset was escalated ahead of another.

The tiered architecture is also suited to uneven data availability. Charsadda does not need a dense borehole grid across the entire district before it can act. It needs honest screening, followed by progressively more discriminating evidence at corridors and assets with high consequence or strong failure signals. Conversely, data abundance should not create false confidence. High-resolution imagery may improve channel mapping but cannot measure a buried filter defect; a calibrated inundation model cannot establish the shear strength of an undocumented fill.

7.2 Practical and policy implications

The framework can be embedded in existing project cycles. Pre-monsoon maintenance can use the Tier 2 checklist; emergency teams can use the red-flag triage logic; rehabilitation projects can use the conceptual ground model and investigation schedule; and provincial investment planning can use transparent RPI bands. Compliance should be tied to the Building Code of Pakistan, applicable bridge code and asset-owner specifications [22,35]. International manuals provide useful analytical reference [23-26,42], but they should not displace local law, material experience or competent professional judgement.

A shared evidence system may deliver an immediate institutional benefit. Flood marks, scour surveys and seepage observations are often lost after emergency repairs. Assigning a permanent asset ID, fixed photo points and a minimum post-event record turns each flood into a calibration opportunity. This is especially valuable under non-stationary climate and land-use conditions, where yesterday's frequency curve or channel alignment cannot be assumed to remain stable [20,30,31].

7.3 Limitations

This paper has four main limitations. First, the review used open scholarly discovery and authoritative repositories rather than a reproducible export from every subscription bibliographic database; overlapping interfaces did not provide stable identification counts. The final 44-source evidence base and eligibility logic are transparent, but the review should be updated with Scopus and Web of Science exports before submission to a journal that requires database-complete systematic-search reporting. Second, no primary subsurface, hydraulic or condition data were collected in Charsadda. The paper therefore proposes a framework and parameter architecture, not a calibrated district risk map. Third, the provisional RPI weights and bands have not been elicited from local decision-makers or validated against a georeferenced failure inventory. Fourth, channel change, sediment supply, informal construction and maintenance practices may vary at scales finer than available datasets.

These limitations are deliberate boundaries on inference. They indicate the next research steps: compile a district asset and failure inventory; instrument representative bund, approach and bank sections; compare laboratory erodibility with observed retreat; calibrate coupled hydraulic-seepage-stability models to the 2010 and 2022 events where records permit; and test whether RPI rankings predict observed damage and service interruption.

8. Conclusions

Flood resilience in Charsadda cannot be secured by mapping water alone. Infrastructure fails through identifiable ground processes that begin with hydraulic forcing and evolve through scour, erosion, seepage, pore-pressure change, instability and loss of support. The reviewed literature provides a strong district and basin hazard base but only limited asset-scale geotechnical evidence. IGFRF-Charsadda closes the methodological gap by linking four decision tiers: district screening, corridor diagnosis, asset verification and monitored action.

The proposed RPI makes prioritization explicit while preserving a strict boundary between triage and design. Its value lies less in a particular weight than in requiring every score to be supported by a mechanism, observation, uncertainty statement and accountable action. Local calibration, independent validation and sensitivity analysis are mandatory. Red-flag conditions bypass the index and trigger competent engineering review.

For Charsadda, the immediate priorities are practical: establish a unique asset register, preserve post-flood evidence, map corridor-scale geomorphic change, investigate representative ground conditions and connect provincial flood planning to mechanism-specific maintenance and design. Implemented in that sequence, the framework can turn scattered hazard studies and emergency observations into a cumulative engineering record - one capable of supporting safer crossings, more reliable access and better-targeted resilience investment.

Table 12: Abbreviations used in the manuscript

Abbreviation	Meaning
AHP	Analytic hierarchy process
CPT/CPTu	Cone penetration test / piezocone
DEM	Digital elevation model
FFD	Flood Forecasting Division
GIS	Geographic information system
GSP	Geological Survey of Pakistan
IGFRF	Integrated Geotechnical Flood Resilience Framework
PDMA	Provincial Disaster Management Authority
RPI	Risk Priority Index

SAR	Synthetic aperture radar
SPT	Standard penetration test
TMA	Tehsil municipal administration

Declarations

Ethical approval: Not applicable. The study used published and institutional sources and collected no primary human or animal data.

Funding: No external funding is declared for this manuscript draft.

Data availability: The evidence base consists of the publications, standards, and public institutional sources listed in the references. No new field dataset was generated.

Use of this framework: The framework supports screening and investigation planning. Site-specific work must be completed by competent professionals under applicable Pakistani law, codes, and asset-owner procedures.

Conflict of Interest
The authors declare no conflict of interest.

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