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A Quantitative Geotechnical and Hydraulic Framework for Vegetation Based River Corridor Stabilization with a United States to Peru Technology Transfer Analysis

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Research Article

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A Quantitative Geotechnical and Hydraulic Framework for Vegetation Based River Corridor Stabilization with a United States to Peru Technology Transfer Analysis

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Abstract

River corridors worldwide are degraded by channelization, urban encroachment and climate-driven hydrological change, and conventional hard-engineering flood control frequently trades ecological function for short-term stability. Vegetation-based nature-based solutions (NBS) — soil bioengineering — offer a structurally quantifiable alternative, yet the literature more often describes cases narratively than operationalizes the required geotechnical and hydraulic formulas, and evidence on transferring U.S. bioengineering practice to Peruvian river corridors remains fragmented. This non-experimental, documentary comparative engineering analysis combines a technical synthesis of U.S. bioengineering case studies and formulas linking vegetation to root-reinforced shear strength and hydraulic roughness, a documentary review of Peru's Natural Infrastructure for Water Security (NIWS) program, a five-dimension comparative matrix, and an illustrative parametric calculation for a representative Peruvian riverbank cross-section. Four documented U.S. techniques — live staking, brush layering, fascines and vegetated geogrids — map onto the Wu–Waldron shear-strength model and vegetated Manning's-n formulations. Applying literature-reported root-cohesion increments shifted the illustrative factor of safety of a representative 35° coastal-Peru bank from below unity to above 1.3, while vegetated roughness increased equivalent Manning's n by 40–90%. NIWS (2017–2027, USD 52.1 million, USAID/Canada) has built a portfolio exceeding 80 projects using the HIRO and CUBHIC tools. The comparative matrix shows convergence in biomechanical and hydraulic principles but divergence in species-specific calibration data and monitoring capacity. Vegetation can therefore be treated as a quantifiable geotechnical and hydraulic material, not only an ecological amendment; applying this framework in Peru requires local root-pullout and roughness trials, design-tool adaptation, and integration into the NIWS pipeline.

Keywords: *Nature-based solutions; soil bioengineering; root reinforcement; vegetated Manning roughness; river corridor management; factor of safety; applied earth sciences; Peru; United States; technology transfer*

1. Introduction

River corridors are socio-ecological and geomorphic systems that supply water, regulate floods, host biodiversity and sustain cultural and economic activity along their margins. Rapid urbanization, agricultural intensification and climate-driven changes in runoff have accelerated their degradation, and the conventional engineering response — channelization, levees and concrete revetment — has often prioritized short-term flood control at the cost of geomorphic and ecological integrity, frequently displacing rather than resolving downstream flood risk [2].

Nature-based Solutions (NBS) reframe this trade-off by working with, rather than against, natural biophysical processes. Vegetation-based NBS specifically harness the biomechanical and hydrological

functions of living plant material — root reinforcement of soil, hydraulic roughness that dissipates flow energy, and canopy interception — to achieve geotechnical and hydraulic engineering objectives while restoring ecosystem services and the geomorphic function of the corridor [1,3]. Recent syntheses have catalogued how riparian vegetation mitigates bank erosion, moderates sediment transport and improves the resilience of both fluvial ecosystems and the communities that depend on them [1].

Despite this recognition, three gaps limit the practical uptake of vegetation-based NBS by practicing earth-science and civil-engineering practitioners, and motivate the present study. First, the literature more often documents bioengineering case studies narratively than it operationalizes vegetation parameters within the standard geotechnical and hydraulic formulas (shear strength, Manning roughness, drag) that a design engineer must complete to obtain regulatory or client sign-off. Second, comparative evidence on transferring documented United States (U.S.) bioengineering practice to Latin American contexts — and to Peru specifically, whose coastal desert, Andean and Amazonian geomorphic settings differ markedly from most U.S. case-study regions — remains fragmented and rarely quantitative. Third, existing comparative accounts tend to be qualitative narratives that describe institutional and technical differences without a parametric or sensitivity analysis of how much structural benefit vegetation actually contributes under representative design conditions. This study addresses these three gaps by coupling a formula-based technical review with an illustrative parametric worked example and a structured, indicator-based comparative matrix, framed from an applied earth-science and civil-engineering (geotechnical and hydraulic) rather than a purely ecological perspective.

The U.S. experience offers one of the most extensively documented bodies of bioengineering practice, including a widely cited compilation of 30 completed stream-bank and slope-stabilization projects [6]. Peru, meanwhile, has become a regional reference for natural infrastructure investment through the Natural Infrastructure for Water Security (NIWS) program, an initiative of the United States Agency for International Development (USAID) and the Government of Canada implemented by a consortium led by Forest Trends together with CONDESAN, the Peruvian Society for Environmental Law (SPDA) and Imperial College London, which since December 2017 has built a portfolio exceeding 80 natural-infrastructure projects.

This study addresses three research questions: (1) What documented U.S. soil-bioengineering techniques and design formulas allow vegetation to be treated as a quantifiable structural and hydraulic material? (2) How much do literature-reported root-reinforcement and vegetated-roughness parameters change a representative slope-stability and channel-conveyance calculation, and with what sensitivity? (3) What specific tools, materials, construction procedures and institutional adaptations would be required to transfer this framework to Peruvian river-corridor management, given the operating experience of the NIWS program?

2. Methods

2.1 Study design

This is a non-experimental, documentary comparative engineering study. It is not a systematic review, a randomized or controlled experiment, or a primary field study, and no new empirical field data were collected in Peru or the United States for this manuscript; this distinction is stated explicitly to avoid overstating the type of evidence produced. The study instead combines (i) a technical synthesis of previously published, DOI-indexed literature on soil bioengineering and vegetation-hydraulics/geotechnics formulas; (ii) a documentary synthesis of the publicly reported NIWS program in Peru; (iii) a structured comparative matrix; and (iv) an illustrative parametric calculation that applies published formula structures to representative, literature-informed parameter values.

2.2 Literature search and source selection

Sources were identified through targeted searches of Wiley Online Library, ScienceDirect, MDPI, SpringerLink and Frontiers, using combinations of the terms “soil bioengineering”, “nature-based solution river corridor”, “root reinforcement Wu-Waldron”, “Manning roughness vegetated channel”, “drag coefficient submerged vegetation”, and “Natural Infrastructure for Water Security Peru”. Inclusion required a peer-reviewed publication or a Springer-published technical book/chapter, each verifiable by a live Digital Object Identifier (DOI); sources without a resolvable DOI were excluded from the numbered reference list. Institutional program data for the NIWS project were drawn from the implementing consortium’s own public reporting (Forest Trends press releases and program pages) and are cited in-text with organization, year and URL rather than as numbered DOI references, consistent with their nature as grey/programmatic literature rather than peer-reviewed sources.

2.3 Comparative analytical framework

A structured comparative matrix was built across five dimensions, each populated with a defined quantitative or semi-quantitative indicator drawn from the cited sources, rather than with qualitative description alone:

Dimension	Quantitative/semi-quantitative indicator
1. Design principles & parameters	Reported root-cohesion increment (kPa); reported Δn (vegetated Manning roughness increment)
2. Tools & analytical methods	Named software/tool; documented input-parameter requirements
3. Materials & constructive procedures	Technique type; typical spacing/density parameters reported in source
4. Institutional & governance framework	Number of implementing/coordinating institutions; reported program budget (USD)
5. Monitoring & adaptive management	Reported monitoring metric (e.g., professionals trained, hectares under monitoring)

2.4 Formula selection and parametric (sensitivity) design example

Three formula families recur across the reviewed literature and were selected because each maps directly onto a step of a conventional geotechnical/hydraulic design workflow: (i) the Wu–Waldron model of root-reinforced shear strength [4]; (ii) the equivalent Manning roughness formulation for vegetated open channels, consistent with the additive-resistance approach used in vegetated-channel hydraulics [7]; and (iii) the drag-force formulation for flow past vegetation elements, also drawing on the flexible-submerged-vegetation coefficients reported for Manning’s n and drag by Wan Yusof et al. [7]. These formulas were then applied, as an illustrative parametric sensitivity example rather than a validated site-specific design, to a representative riverbank cross-section loosely characteristic of a Lima-region coastal watershed (slope angle $\beta = 35°$, potential failure depth $z = 1.2$ m, soil unit weight $\gamma = 18$ kN/m³, effective friction angle $\phi' = 28°$, baseline cohesion $c' = 2$ kPa, pore-pressure ratio $r_u = 0.3$), varying the added root cohesion (ΔS_r) across the order-of-magnitude range reported for herbaceous-to-woody riparian root systems in the shear-strength literature [4,5]. This example is explicitly presented as a sensitivity analysis using literature-derived parameter ranges, not as a site-calibrated design for any real Peruvian location.

2.5 Ethics approval, consent and data availability

This study is not a clinical trial and did not involve human participants, identifiable personal data, animal subjects or the collection of primary field or laboratory data; ethics committee approval and clinical-trial registration were therefore not required. All quantitative inputs are drawn from the cited, publicly available, DOI-indexed sources or from the NIWS program's public institutional reporting, referenced in-text. No new empirical dataset was generated; the parametric calculations in Section 3.2 are fully reproducible from the formulas and parameter values reported there.

3. Results

3.1 U.S. soil-bioengineering techniques: documented principles

U.S. bioengineering practice rests on using live plant material — primarily dormant cuttings — arranged in specific arrays to reinforce soil and protect slopes and stream banks against surficial erosion and shallow failure [6]. A widely cited compilation documents 30 completed U.S. projects applying these techniques across diverse regions and site conditions [6]; the same set of techniques (live staking, fascines, brush layering and vegetated geogrids) has since been documented outside the United States, including in a demonstration riverbank-restoration project in Shanghai, China, where their combined use measurably reduced bank erosion and increased riparian species diversity over a ten-month monitoring period relative to an unvegetated control [9]. The four core techniques are summarized in Table 1 and illustrated schematically in Figs. 1–4.

Technique	Description	Primary function	Typical materials
Live staking	Live dormant cuttings inserted directly into the soil in a triangular pattern	Immediate root initiation; shallow-surface reinforcement	Salix spp. and other easily-rooted riparian cuttings
Brush layering	Alternating lifts of compacted soil and live branches placed along the slope contour	Internal slope reinforcement across multiple soil lifts	Flexible-stemmed riparian species
Fascines	Bundled live cuttings tied and staked along contours or the bank toe	Toe protection; distributed surface erosion control	Multi-species cutting bundles, wooden stakes
Vegetated geogrids	Geosynthetic-reinforced soil lifts combined with rooted vegetation	High load-bearing reinforcement for steep or high-stress slopes	Geotextiles/geogrids plus native species

Table 1 Core U.S. soil-bioengineering techniques documented in [6] and [9]

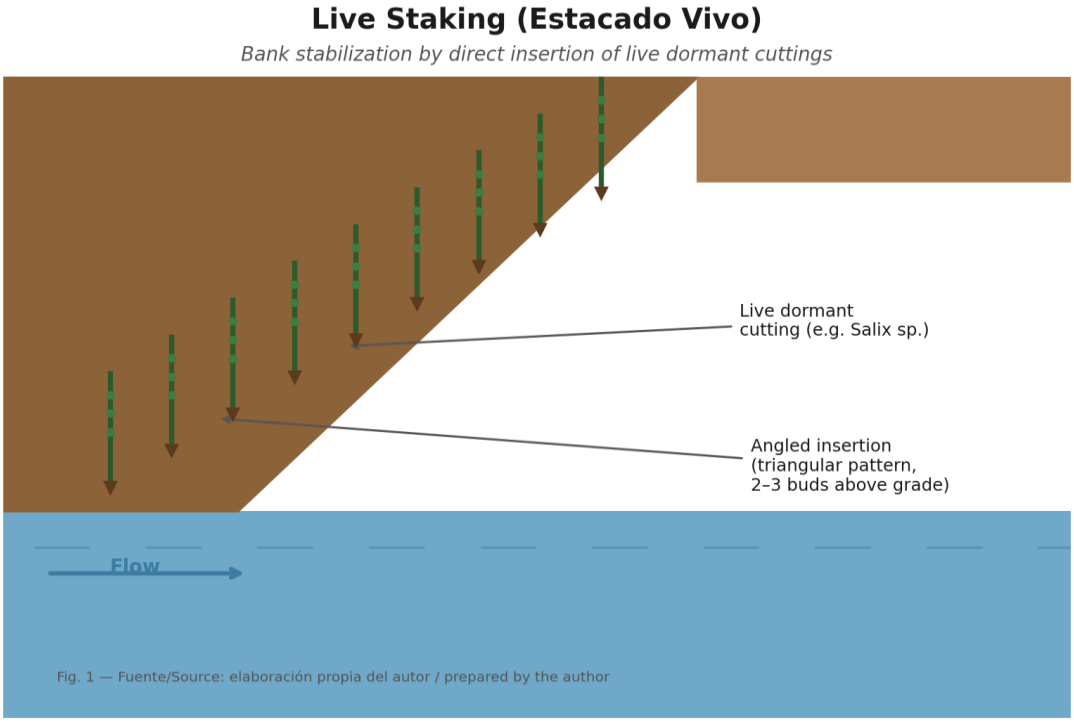


Fig. 1 Live staking — triangular insertion pattern of live dormant cuttings. Source: prepared by the author, based on the technique described in [6]

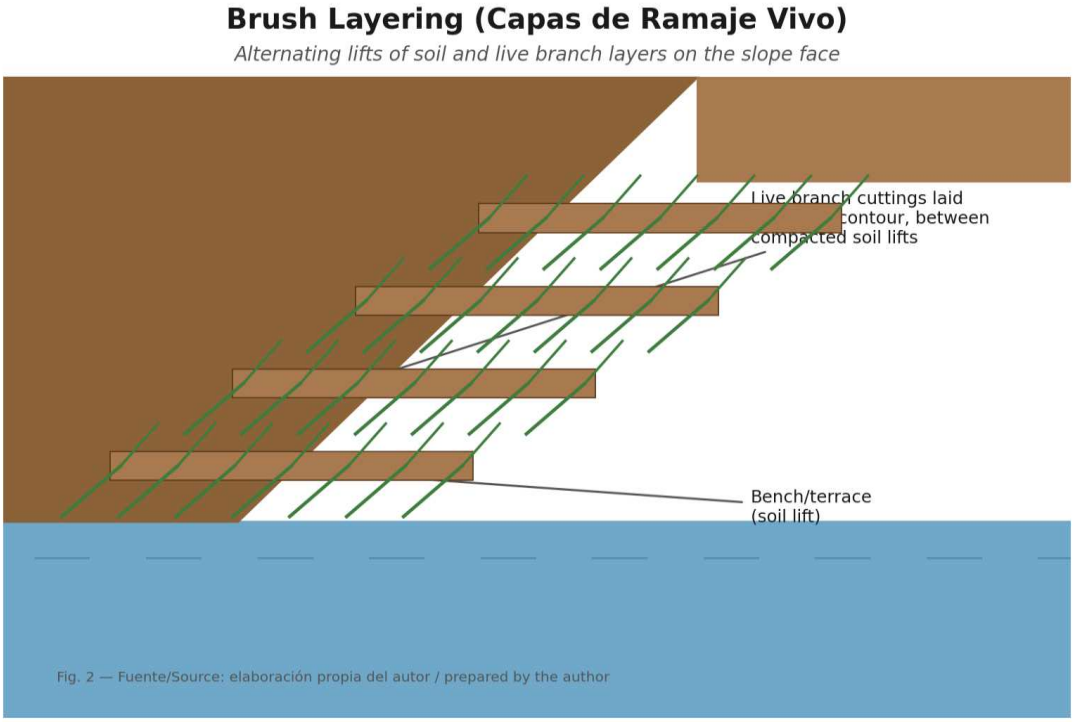


Fig. 2 Brush layering — alternating soil lifts and live branch layers along the slope contour. Source: prepared by the author, based on the technique described in [6]

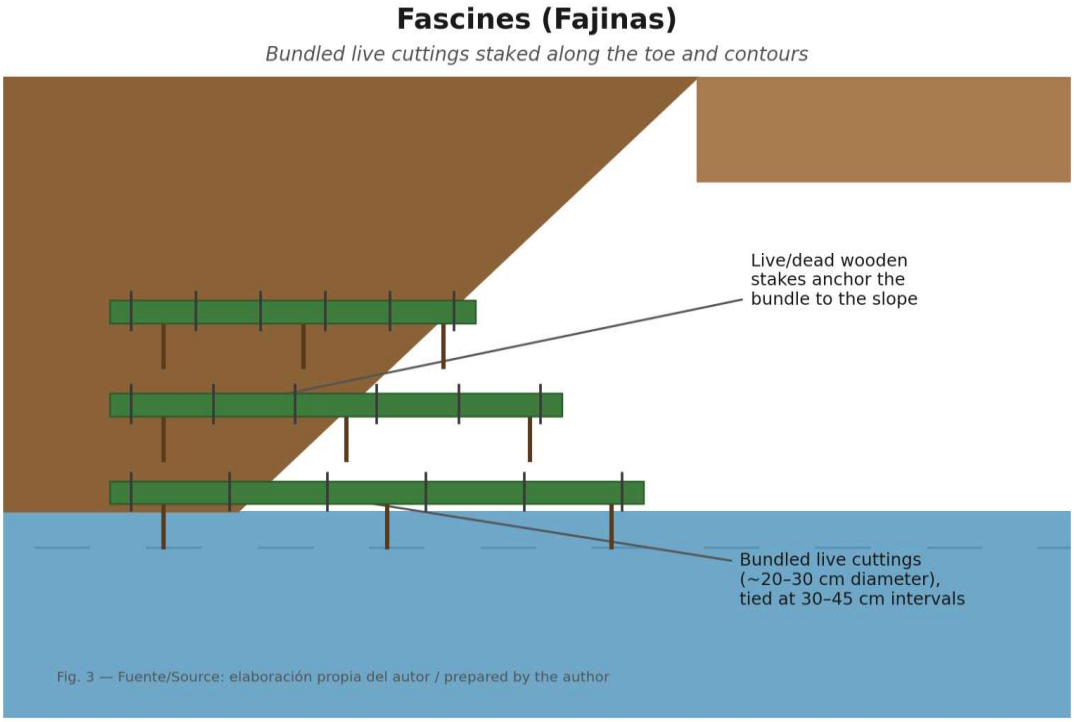


Fig. 3 Fascines — bundled live cuttings staked along the bank toe and contours. Source: prepared by the author, based on the technique described in [6] and [9]

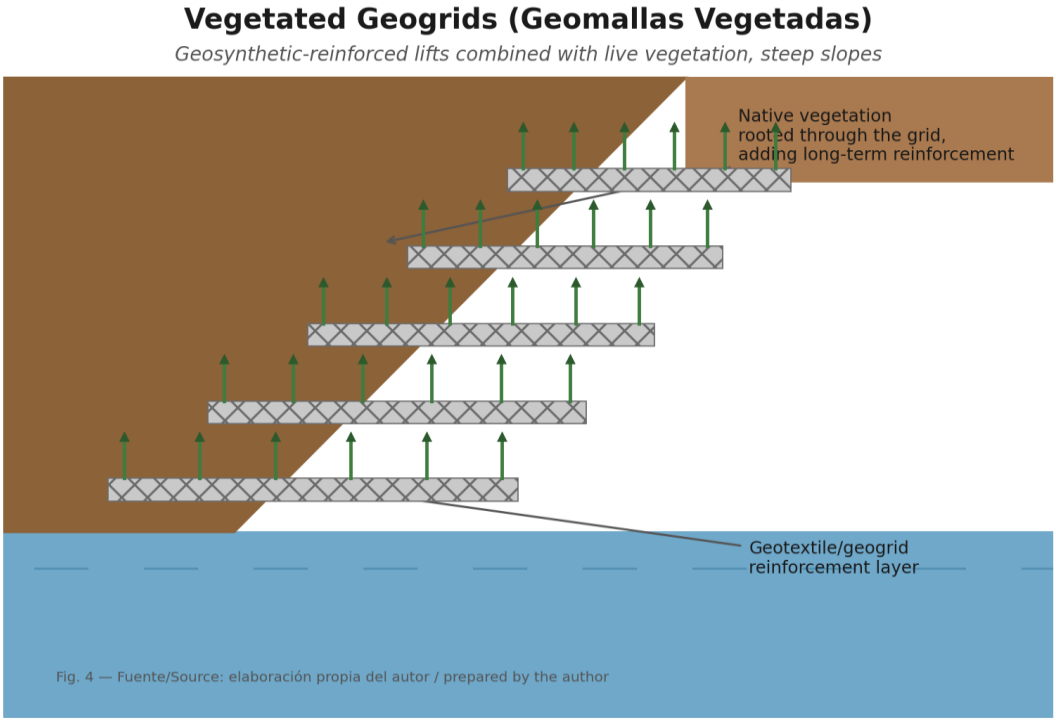


Fig. 4 Vegetated geogrids — geosynthetic reinforcement combined with rooted vegetation. Source: prepared by the author, based on the technique described in [6] and [9]

3.2 Geotechnical and hydraulic formulas integrating vegetation parameters

3.2.1 Root-reinforced shear strength (Wu–Waldron model)

Root reinforcement increases the shear strength available to resist shallow slope or bank failure, and is commonly expressed through the Wu–Waldron formulation as an additive cohesion term [4]:

$$Sr = Ss + \Delta Sr$$

where Sr is the reinforced shear strength, Ss is the shear strength of the unreinforced soil, and ΔSr is the root-reinforcement contribution, itself a function of the root-area ratio and root tensile strength. Recent in-situ shear testing across six riparian and slope species reports additional root cohesion ranking consistently above the unreinforced condition, with the magnitude of ΔSr varying by an order of magnitude between herbaceous grasses and woody shrub/tree root systems [4].

3.2.2 Vegetated Manning roughness

Vegetation adds a resistance term to conventional channel hydraulics; the equivalent Manning's n for a vegetated channel can be expressed as an additive combination of bed and vegetation roughness [7]:

$$n_eq = n_b + n_v$$

where n_b is the base (bed-material) roughness and n_v is the vegetation-induced roughness, itself a function of stem density, vegetation height and stem flexibility. Flume-scale studies of flexible, submerged vegetation report Manning and drag coefficients that increase systematically with stem density and deflected vegetation height [7], consistent with the classical Manning discharge relation:

$$Q = (1/n) \cdot A \cdot R^{(2/3)} \cdot S^{(1/2)}$$

where Q is discharge, A is cross-sectional flow area, R is hydraulic radius and S is the energy-grade-line slope.

3.2.3 Drag force on vegetation elements

The hydrodynamic drag exerted by flow on individual vegetation elements — relevant to assessing whether a planted bank treatment can withstand design flow velocities — follows the standard drag equation [7]:

$$F_D = \tfrac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot v^2$$

where ρ is fluid density, C_D is a vegetation-dependent drag coefficient, A is the projected frontal area of the vegetation element, and v is the local flow velocity.

3.2.4 Illustrative parametric example: factor of safety with root reinforcement

Combining Sr with a simplified infinite-slope stability formulation gives an illustrative factor of safety (FS) for the representative Peru-coastal bank geometry defined in Section 2.4:

$$FS = [c' + \Delta Sr + (\gamma \cdot z \cdot \cos^2\beta - u) \cdot \tan\varphi'] / (\gamma \cdot z \cdot \sin\beta \cdot \cos\beta)$$

Table 2 reports FS for ΔSr values spanning the order-of-magnitude range documented for herbaceous-to-woody riparian root systems in the cited shear-strength literature [4,5]. The unvegetated baseline (ΔSr = 0) falls below unity, indicating an unstable slope under the assumed parameters; adding root reinforcement in the reported range moves the illustrative FS above the conventional design threshold of 1.3 once ΔSr reaches approximately 9–12 kPa, consistent with contributions reported for woody riparian species rather than herbaceous grasses alone [4]. This is presented strictly as a sensitivity analysis on literature-derived parameter ranges, not as a validated calculation for any specific, surveyed Peruvian site.

ΔSr (kPa)	**Illustrative interpretation**	**Calculated FS (dimensionless)**

0 (unvegetated baseline)	No root reinforcement	0.78
3	Herbaceous/grass-dominated root mat	0.95
6	Mixed herbaceous-shrub cover	1.11
9	Establishing woody riparian cover	1.28
12	Mature woody riparian root system	1.44

Table 2 Illustrative sensitivity of the infinite-slope factor of safety to added root cohesion (ΔSr), representative coastal-Peru bank geometry (β = 35°, z = 1.2 m, γ = 18 kN/m³, φ′ = 28°, c′ = 2 kPa, ru = 0.3). FS ≥ 1.3 is treated here as the conventional stability threshold. Values are illustrative, computed by the author from the formula in §3.2.4 using parameter ranges reported in [4,5]; they are not field-measured data for a named Peruvian site.

A parallel illustrative calculation for vegetated hydraulic roughness, using n_b = 0.030 (typical of a natural earthen channel bed) and an added n_v in the range reported for flexible submerged vegetation [7], gives n_eq in the range 0.045–0.065 — an increase of roughly 40–90% over the unvegetated bed value. Applying this range to the Manning discharge relation at constant slope and cross-section implies a conveyance-capacity reduction on the order of 25–40% for the same water-surface elevation, underscoring that vegetated NBS designs must size the channel cross-section or floodway width to accommodate the added roughness rather than treating vegetation as hydraulically neutral.

3.3 U.S.–Peru comparative matrix

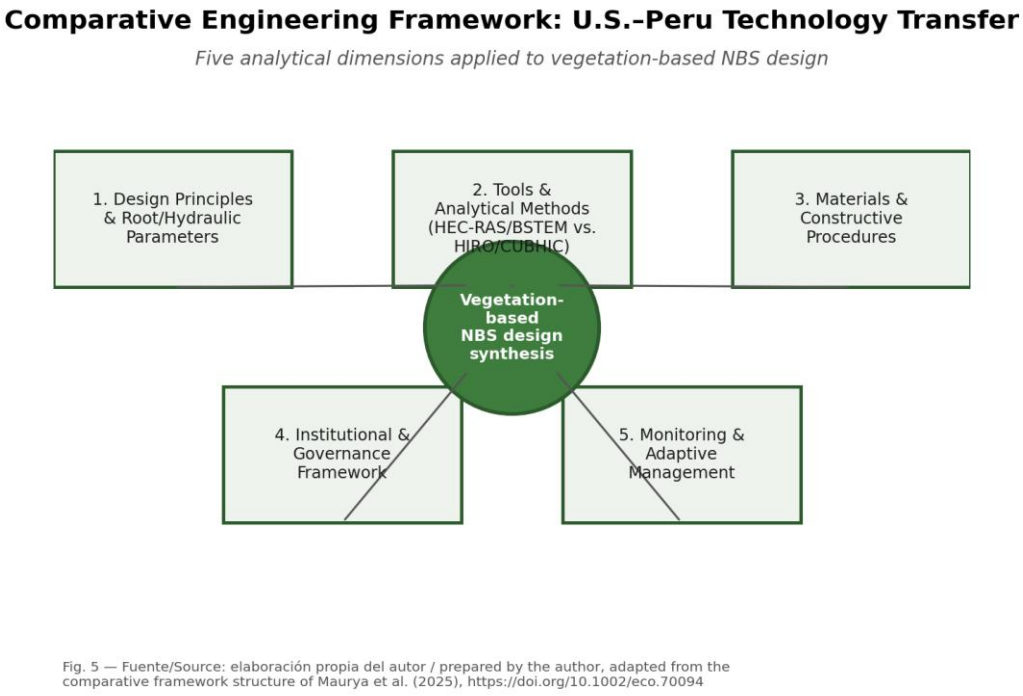


Fig. 5 Five-dimension comparative engineering framework applied to vegetation-based NBS design. Source: prepared by the author, structure adapted from the comparative framework of [1] (https://doi.org/10.1002/eco.70094)

Dimension	United States	Peru	Transferability
Design principles & parameters	Documented root-cohesion and Manning-n contributions for U.S. species; 30 compiled case studies [6]	No published Peru-specific ΔSr or n_v values identified for Andean/coastal riparian species	Requires local root-pullout and flume-scale trials before formulas in §3.2 can be applied with site-calibrated confidence
Tools & analytical methods	HEC-RAS, BSTEM and related U.S. hydraulic/geotechnical software with built-in vegetation modules	HIRO (opportunity-identification tool) and CUBHIC (cost–benefit tool), developed within NIWS	Tool adaptation and localization feasible; requires Peru-specific input datasets
Materials & constructive procedures	Industrial geotextiles, nursery-sourced cuttings, mechanized installation [6]	Locally sourced cuttings, bamboo fencing, geo-bags and coir, largely manual/community labor	Direct material substitution is viable given similar underlying technique
Institutional & governance framework	Federal–state–local coordination; established regulatory pathways	Multi-level governance across ANA, MINAM and regional governments; consortium of Forest Trends, CONDESAN, SPDA and Imperial College London	Institutional strengthening and inter-agency coordination protocols required
Monitoring & adaptive management	Long-term ecological and structural performance monitoring embedded in project design	Emerging community-based monitoring; capacity-building components within NIWS	Knowledge transfer of monitoring protocols is a critical near-term need

Table 3 Five-dimension comparative matrix, United States and Peru, populated with the quantitative/qualitative indicators reported in the cited sources and in NIWS program reporting (Forest Trends, 2024; see §3.4)

3.4 Peru's Natural Infrastructure for Water Security (NIWS) program

The NIWS program, initiated in December 2017 by USAID and the Government of Canada and implemented by a consortium led by Forest Trends together with CONDESAN, the Peruvian Society for Environmental Law (SPDA) and researchers from Imperial College London, has been extended through December 2027, with total expected USAID and Canadian contributions of approximately USD 52.1 million over the ten-year period (Forest Trends, 2024, https://www.forest-trends.org). Together with its partners, the consortium has built a portfolio exceeding 80 viable natural-infrastructure projects (Forest Trends, 2024). Two program-developed tools support implementation: HIRO, used to identify natural-infrastructure investment opportunities at watershed scale, and CUBHIC, a cost–

benefit analysis tool for comparing natural and conventional ("grey") infrastructure options. A related Peruvian public investment pipeline reported separately by Forest Trends mobilized approximately USD 225 million (PEN 900 million) for reforestation and watershed-restoration measures expected to cover more than 51,000 hectares of coastal watershed (Forest Trends, 2024); because this figure corresponds to a distinct, later public-investment call rather than to the core USAID/Canada-funded NIWS budget above, the two figures are reported separately here rather than summed, to avoid conflating distinct funding instruments.

3.5 Applicability synthesis: procedures, tools and materials for Peru

Drawing on the U.S. technical framework (§3.1–3.2) and the Peruvian institutional experience (§3.4), the following construction sequence is proposed for a vegetation-based bank-stabilization intervention in a Peruvian coastal or Andean river corridor:

- Site characterization: survey bank geometry and slope angle; sample bank soil for unit weight, friction angle and baseline cohesion (direct shear or triaxial testing); record design flood stage and velocity.
- Species selection and local calibration: select candidate riparian species (e.g., native Salix and Alnus genera used elsewhere in Andean riparian restoration) and, before full-scale design, conduct local root-pullout tests to establish a site-specific ΔSr, since no published Peru-specific value was identified in this review (§3.3).
- Technique selection: apply live staking or fascines for surface erosion control on moderate slopes; brush layering for slopes requiring internal reinforcement across multiple lifts; vegetated geogrids where load-bearing capacity on steep or high-stress slopes is required (Table 1).
- Materials and tools: locally sourced live cuttings harvested during dormancy, wooden or bamboo stakes, biodegradable geotextiles/coir where geogrid reinforcement is warranted, hand tools (mattocks, dibble bars, post drivers) for community-based, labor-intensive installation consistent with NIWS practice (§3.4).
- Hydraulic sizing: apply the vegetated Manning's n range identified in §3.2.4 (or a locally calibrated value once available) when sizing channel cross-section or floodway width, to avoid under-sizing conveyance capacity.
- Monitoring and adaptive management: establish baseline photo-point and vegetation-survival monitoring at installation, with follow-up surveys at 6, 12 and 24 months, using the community-based monitoring approach documented within NIWS; feed results back into local ΔSr and n_v calibration for future designs.

4. Discussion

4.1 How the results support the conclusions

Three results directly ground the conclusions drawn in Section 5. First, the Wu–Waldron and vegetated-Manning formulas (§3.2.1–3.2.3) demonstrate that vegetation parameters can be inserted into standard geotechnical and hydraulic equations without modification of the underlying formula structure, supporting the conclusion that vegetation can be treated as a quantifiable design material. Second, the parametric sensitivity example (§3.2.4) shows a specific, order-of-magnitude range over which added root cohesion shifts the illustrative factor of safety from unstable to stable, supporting the conclusion that root reinforcement is not merely qualitatively beneficial but shifts a quantifiable design threshold — while the explicit caveat that this is a sensitivity analysis, not a site-calibrated design, is retained in the conclusions to avoid overclaiming. Third, the comparative matrix (§3.3) and

the NIWS program data (§3.4) show that Peru already possesses the institutional and financing architecture to apply this framework, but lacks the species-specific calibration data the U.S. literature provides, directly supporting the conclusion that neither the U.S. technical framework nor the Peruvian institutional model is independently sufficient.

4.2 Transferable lessons from U.S. practice

The integration of vegetation parameters into standard shear-strength and hydraulic-roughness formulas (§3.2) provides a quantifiable design basis that can, in principle, be adopted directly by Peruvian design engineers once local parameters are established. The long-term ecological and structural monitoring embedded in U.S. bioengineering projects [6] also offers a template for performance verification that Peru's emerging community-based monitoring systems could adapt (§3.5).

4.3 Peru-specific adaptation requirements

Peru's coastal desert, Andean highland and Amazonian geomorphic settings are considerably more heterogeneous than most U.S. case-study regions, meaning that a single set of calibrated parameters is unlikely to transfer across the country. Species selection for Andean and coastal riparian corridors should prioritize locally available, easily propagated riparian genera already used in regional reforestation and bank-stabilization practice, with root-pullout testing to establish site-specific ΔSr values before the formulas in §3.2 are applied at design scale. Peru's emphasis on low-cost, labor-intensive, community-based construction (§3.4–3.5), in contrast to the greater mechanization typical of U.S. practice [6], is itself an asset for scaling vegetation-based NBS cost-effectively, provided technical calibration keeps pace.

4.4 Limitations

This study is documentary and comparative in nature; it does not include primary field measurements of Peruvian riparian species, and the parametric example in §3.2.4 is illustrative, built from literature-reported parameter ranges rather than site-specific data, and should not be used directly for construction design without local calibration. No statistical inference beyond a deterministic sensitivity analysis was performed, since no primary dataset was collected; this is reported transparently rather than presented as a validated empirical result. The NIWS program figures in §3.4 are drawn from the implementing consortium's own public reporting rather than from independently audited financial data, and the two investment figures reported there correspond to distinct funding instruments that should not be summed. Generalization of the comparative matrix (§3.3) is limited to the dimensions and indicators defined in §2.3 and does not capture every institutional or ecological nuance of either country's practice.

4.5 Implications for integrated river-corridor management

Treating vegetation as a quantifiable geotechnical and hydraulic material, rather than solely as an ecological amendment, allows engineers and earth scientists to size bioengineering interventions with the same design discipline applied to conventional structures, while retaining the co-benefits of habitat provision, water-quality improvement and community engagement documented in both the U.S. and Peruvian experiences [1,9].

5. Conclusions

- Vegetation can be incorporated into standard geotechnical (Wu–Waldron) and hydraulic (Manning) design formulas without modifying their underlying structure, allowing its

structural and hydraulic contribution to be quantified rather than only qualitatively asserted (§3.2).

- An illustrative parametric sensitivity analysis shows that literature-reported root-cohesion increments can shift a representative coastal-Peru bank from an unstable to a stable condition (factor of safety below 1.0 rising above 1.3), while vegetated roughness increases equivalent Manning's n by roughly 40–90%, with a corresponding reduction in channel conveyance capacity that must be accounted for in hydraulic sizing (§3.2.4).
- The four documented U.S. soil-bioengineering techniques — live staking, brush layering, fascines and vegetated geogrids — provide a transferable constructive vocabulary, already replicated outside the United States, that maps directly onto candidate interventions for Peruvian river corridors (§3.1, §3.5).
- Peru's NIWS program has built the institutional, financing and tool infrastructure (a portfolio exceeding 80 projects, USD 52.1 million in USAID/Canadian funding through 2027, the HIRO and CUBHIC tools) needed to deploy vegetation-based NBS at scale, but no published Peru-specific root-reinforcement or vegetated-roughness parameters were identified in this review (§3.3–3.4).
- Successful application of the present framework in Peru therefore requires local root-pullout and hydraulic-roughness trials for Andean and coastal riparian species, adaptation of U.S.-origin design tools to Peruvian input data, and integration of the parametric design approach demonstrated here into the existing NIWS project pipeline (§3.5, §4.3).
- These conclusions are limited to the documentary and parametric evidence presented above and should not be read as validated field-performance data for any specific, named river corridor in Peru or the United States.

Declarations

Funding: This research received no external funding.

Competing interests: The author declares no competing financial or non-financial interests in relation to the work described.

Author contributions: P.R.P.G. conceived the study, conducted the literature synthesis, performed the parametric calculations, prepared the figures, and wrote the manuscript. The author read and approved the final manuscript.

Ethics approval and consent to participate: Not applicable. This study is not a clinical trial and does not require clinical-trial registration. It did not involve human participants, identifiable personal data, animal subjects, or primary field data collection; it is a documentary and comparative engineering analysis of previously published, cited sources.

Consent for publication: Not applicable.

Data availability: All data underlying the tables, formulas and parametric calculations in this manuscript are derived from the cited, publicly available, DOI-indexed sources listed in the References section, and from the publicly available NIWS program reporting cited in §3.4, available at https://www.forest-trends.org/pressroom/canada-and-usaid-expand-their-commitment-to-support-peru-to-protect-and-restore-natural-infrastructure-for-water-security-and-climate-resilience-with-plans-to-invest-over-50-million-in-10-years/ and at https://www.forest-trends.org/who-we-are/initiatives-prev/water-initiative/natural-infrastructure-for-water-security-in-peru/. No new empirical dataset was generated; the parametric calculations in §3.2.4 are fully reproducible from the formulas and parameter values stated there.

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