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Modular Defenses with Tires, Geomesh, and Vetiver for Water Erosion Control in the Cahuachulla Stream – Combapata 2025

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Abstract
This research develops a methodology for the design and construction of modular defenses using recycled tires, geogrids, and Chrysopogon zizanioides (vetiver) to control hydraulic erosion in the Cahuachulla stream basin, Peru. The study evaluates the structural effectiveness of tire-geogrid modules as an eco-friendly alternative to traditional gravity walls. The methodology integrates bioengineering principles to stabilize slopes and reduce sediment transport. Results indicate that the modular system significantly improves soil retention and energy dissipation of water flow. The proposal offers a sustainable, low-cost solution for disaster risk management in Andean basins, demonstrating that recycled materials combined with vegetation effectively mitigate land degradation and prevent landslides.

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1. Introduction

Water erosion affects riparian ecosystems and the communities that live in their vicinity. In the district of Combapata, in the province of Canchis, in the region of Cusco, the Cahuachulla stream is experiencing accelerated erosion on its slopes, causing the loss of farmland, endangering nearby homes, and degrading water quality (Paz, 2024.). River defenses have traditionally been built with concrete, stone, or metal.

Current solutions are economically unviable, unsustainable, and difficult to maintain in rural areas. Therefore, it is necessary to introduce innovative alternatives that use recycled materials, geosynthetics, and plant biotechnology (Firoozi, 2024; (Mayhua Escobar et al., 2023).

The research proposes the design and implementation of modular defenses using recycled tires, geogrids, and vetiver (Chrysopogon zizanioides) as a comprehensive solution for water erosion control. This combination takes advantage of the mechanical strength of tires, the reinforcing capacity of geogrids, and the deep root system of vetiver, creating an economical, sustainable, and replicable defense.

The project aims to demonstrate that the integration of civil engineering and bioengineering can offer superior results to conventional solutions in the search for appropriate technologies for rural communities from an environmental and social perspective (Shamontee et al., 2023.

1.1 Problem Statement

The Cahuachulla riverbed flows through agricultural and densely populated areas in the district of Combapata. During periods of heavy rainfall, the banks of this watercourse suffer erosion, which causes the loss of fertile soil, an increased risk of flooding, damage to essential infrastructure such as roads and real estate, and pollution due to sediment deposits in the riverbed, which are the main cause of pollution. The existing protective structures are inadequate and, in some sections, conspicuous by their absence. The community lacks the financial resources necessary to implement large-scale solutions (Autoridad Nacional del Agua (ANA), 2025).

The main problem is how to reduce water erosion, that is, how to decrease soil loss due to water in the Cahuachulla stream. To this end, sustainable modular defenses will be used, specifically, defenses that are environmentally friendly and can integrate recycled tires, geogrids, and Vetiver.

1.2 Determine the current level of erosion on the stream banks and choose the best way to install them.

A modular design using tires and geogrids is presented as a more efficient way to stabilize slopes. It is also important to analyze the impact of using vetiver in reducing erosion and improving the landscape.

1.3 Justification

In terms of sustainability, this initiative helps reduce pollution by reusing tires. It increases the greenness of vegetation by using vetiver grass. In social terms, it protects infrastructure and farmland, which directly benefits local communities. It is relatively inexpensive because it uses materials that are readily available and do not have a significant cost.

The academic provides a bioengineering model that is replicable and applicable to river management.

1.4 Objectives of the study

The general objective is to design and implement sustainable modular defenses to control water erosion along the Cahuachulla River. For this purpose, the specific objectives are designed: a) to evaluate the morphology of the riverbed using freely available parameters, carrying out a series of standardized procedures for this purpose; b) to propose a modular design composed integrally of tires, geogrids, and the implementation of bioengineering using vetiver; and c) to evaluate the effectiveness of the system in stabilizing slopes and reducing erosion, with consideration for environmental impact and sustainability.

2. Theoretical Framework

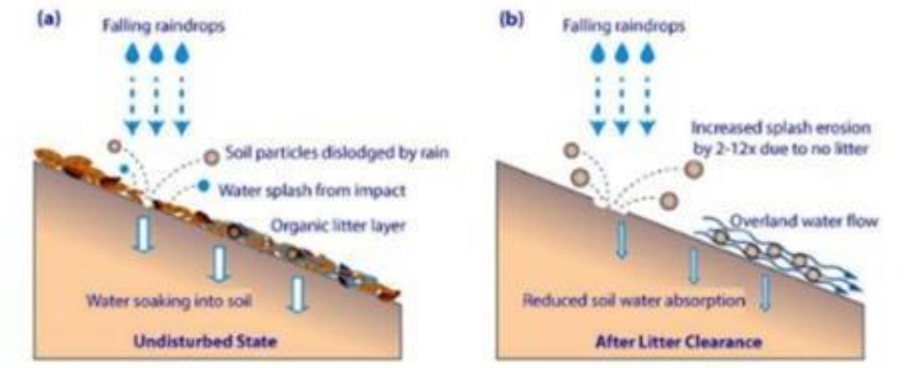
2.1 Water erosion

Water erosion reshapes terrestrial environments and affects soil stability and fertility. This process, which progressively alters the landscape, is driven by hydrological forces that begin when water moves or infiltrates the soil, carrying particles with it and modifying the surrounding topography. The impact of water erosion on global food security is affected by the reduction of arable land. According to certain studies, global agricultural productivity could experience an annual reduction of up to 0.3% (Schlaefer et al., 2021).

Water erosion occurs when climatic and surface factors interact, triggering complex interactions between soil and water that result in various types of erosion. The most persistent form, sheet erosion, is caused by the removal of the topsoil due to the impact of raindrops or runoff. Gully erosion occurs when water accumulates in depressions in the terrain. If not addressed promptly, these can progress to more severe forms of erosion.

Deterioration on valley slopes is an extreme form, occurring when water erodes the soil and forms large gullies. This often renders the land unsuitable for agricultural use, causing significant changes to the environment and water resources.

Bank erosion is mainly caused by the hydraulic action of moving water, which reshapes riverbanks and affects adjacent land, impacting terrestrial and aquatic ecosystems (Shamontee et al., 2023).



(a) Raindrop impact on bare soil (b) Soil particle displacement resulting from the impact

Figure 1 - Dynamics of erosion due to the effect of rain. Adapted from (Firoozi, 2024).

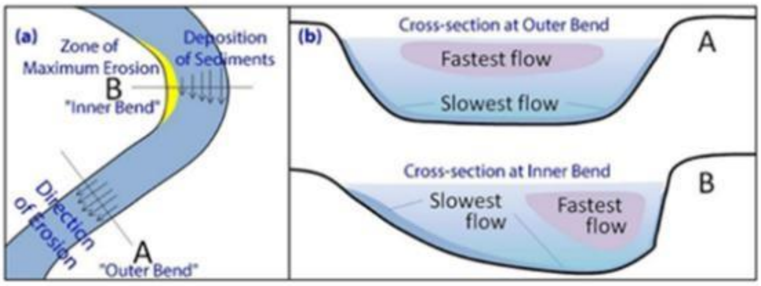
2.2 Weathering processes caused by water

Splash erosion: causes and consequences. Splash erosion occurs when rainfall impacts the earth's surface, creating small cavities and projecting soil particles up to 60 centimeters away. This phenomenon is particularly relevant in arid regions, where research has revealed that it plays a significant role in soil loss over time.

Surface runoff is explained as the mechanics and progression of erosion. Surface runoff quickly gains speed and energy, which increases the potential for soil erosion. As water accumulates more volume, it gains enough force to detach and transport soil particles, causing erosive impacts.

Underground flow: movement and impact on the soil. Groundwater flow, although less visible, influences soil erosion. This movement involves water seeping into deep layers and flowing through the soil, which can weaken the soil structure and increase erosion. This section analyzes groundwater flow and its impact on land stability, emphasizing the impact of management on maintaining the landscape. Soil degradation is due to water flow velocity.

High-velocity and high-volume water flows can cause damage to the soil due to their erosive capacity, resulting in soil loss and compromising its stability. This section examines the impact of variations in flow velocity and evacuation on erosion rates, facilitating understanding of the interaction between flow properties and soil wear processes. Here it is analyzed how water velocity and volume affect soil erosion. Understanding these relationships is essential for controlling erosion and managing soil (De Sousa Barbosa et al., 2024).



(a) Early-stage runoff on a slight slope, (b) Advanced soil erosion due to runoff on a steep slope

Figure 2 - Water flow dynamics. Adapted from (FIROOZI, 2024).

2.3 Riverbank Defenses

Conventional riverbank defenses consist of structural elements such as concrete walls, metal gabions, and rockfill. Although they are highly resistant and stable, they face limitations such as high construction and maintenance costs, negative environmental impact due to the alteration of the natural dynamics of the riverbed, and limited adaptability in rural communities with scarce resources. This has led to the search for sustainable alternatives based on bioengineering and recycled materials.

2.3.1 Conceptual Rationale

Geotechnical engineering contribute significantly to the field of construction and urban development, playing a crucial role in the implementation of large-scale projects. Significant population growth has been observed, as the implementation of mitigation strategies has been effective in resolving natural disasters.

As an integral part of the research process, studies and practical applications of bioengineering techniques in control strategies applied in various parts of the world have been explored.

2.4 Global Context Background

The study carried out in Brazil, entitled "Modeling soil erosion using the revised universal soil loss equation and a geographic information system in a watershed in the northeastern Brazilian Cerrado," was conducted by Wellynne Carla de Sousa Barbosa, Antonio José Teixeira Guerra, and Gustavo Souza Valladares in 2024.

Soil is indispensable to society, but its rapid erosion linked to population growth is an environmental problem. The objective of this study was to assess soil erosion in the lower Parnaíba River basin in northwestern Brazil. In the Cerrado region, the objective was to understand soil loss and map erosion, using qualitative and quantitative results together with geotechnical products and tools to support basin management and planning. In the field of modeling, the Revised Universal Soil Loss Equation (RUSLE) was used in this study.

The range of erosion variation spans from minimum to maximum values, i.e., from very low to extremely high. The integration of natural physical factors with land use (human activities) resulted in a classification of soil loss from mild to extremely high.

The greatest soil losses were observed in grasslands, exposed soils, and cultivated land. Signs of erosion were also observed, underscoring the importance of implementing conservation measures (De Sousa Barbosa et al., 2024).

Also, consideration should be given to the study conducted by Sestras et al. in Romania in 2023 entitled “GIS-based soil erosion assessment using the USLE model for efficient land management: a case study in an area with diverse pedogeomorphological and bioclimatic characteristics”.

Soil erosion is a complex environmental process of utmost importance for land management and conservation. This research used the Universal Soil Loss Equation (USLE) model to understand the interactions that promote soil erosion in Cluj County (Romania).

This analysis explains erosion patterns from critical points to stable areas, providing valuable information. Gradient maps are an essential tool for identifying erosion risk and determining vulnerable areas, enabling preventive and appropriate measures to be taken to protect soils and the environment. Time series analysis illustrates how environmental disturbances affect soil erosion, providing fundamental data for preservation.

An analysis of the USLE model reveals its impact on soil erosion. Erosion rates were classified into five sensitivity levels according to the model's standard methodology. Although most of the county's area is at low or very low risk, several critical sites undergoing severe erosion processes were identified (Sestras et al., 2023).

In addition, there is the work carried out on the African continent by Ali Akbar Firoozi and Ali Asghar Firoozi entitled "Water erosion processes: mechanisms, impact, and management strategies."

This analysis examines water erosion, which threatens soil productivity and ecosystem stability. Addressing gaps in region-specific erosion assessments, this study proposes a strategy that combines traditional methods with modern techniques. It assesses the interaction between wind erosion, surface runoff, and groundwater flow. These factors cause significant changes to the landscape and reduce soil fertility. Therefore, key factors such as rainfall intensity, soil type, topography, and vegetation have been analyzed. The analysis was carried out on the Loess Plateau, the Mississippi River Basin, and the Ethiopian Highlands. The research has revealed various erosion dynamics. In addition, this study evaluates the introduction of advances in nanotechnology and biotechnology for soil stabilization. As mentioned above, it is very important to look at the rules and show that these technologies can be used in specific locations. This guarantees the relevance of the erosion processes observed and ensures the effectiveness of the procedures. This article advocates adaptive and inclusive strategies to effectively manage water erosion, with the aim of strengthening sustainability and environmental resilience globally.

Another study mentioned is the one carried out in Costa Rica by Alexander Molina Villalobos, Yuval Greismann Vivas, and Josselyn Guevara Ibarra, entitled Proposal for the Improvement of the Design of a Geocell Wall Made with Tires, in 2024.

This initiative focused on optimizing the configuration of tire walls by additionally using geocells.

Although tires of various sizes were considered, a standard size was ultimately adopted. An effective methodology was established to ensure a uniform aesthetic appearance and adequate structural strength. This process required extremely robust fastening between the tires.

Guidelines were formulated regarding the minimum maintenance required, such as periodic inspections and cleaning of drainage systems, based on the standards of the Costa Rican Geotechnical Society and the Costa Rican Foundation Engineering Society Committee.

Tests on the design wall with recycled tires confirmed its structural stability. The construction method developed proved to be effective and safe, allowing the retaining wall structure to be built quickly with satisfactory results. Soil compaction improved the fixation of the tire fill material. The safety factor analysis concludes that the constructed structure is safe and can be installed near populated areas without posing a hazard (Molina Villalobos et al., 2024).

2.5 Local Context Background

Like the rest of the world, the implementation of strategies to mitigate natural disasters caused by climate variations and greenhouse effects associated with climate change is also being analyzed and studied. In this regard, the studies carried out in Lima by Flores Merino, Robert Edú, and Ríos Garcia, Alexander Rodrigo, entitled Comparative Technical - Economic Analysis of Gabions and Vetiver Barriers to Stabilize and Protect Slopes in the Malecón Checa Sector, Río Rímac, in 2023

This analysis examines slope stabilization techniques in contrast to conventional gabion methods. Despite their functionality, gabions have a significant environmental impact, lack self-repairing properties, and affect the aesthetics of the landscape.

Vetiver barriers represent a novel technique that uses plants such as vetiver and bamboo, which is an innovation in the field of construction and civil engineering. In this case, vetiver was selected due to its root intertwining properties.

It provides soil stability, resists erosion, and does not affect the geometric parameters of the riverbank, which is beneficial to the natural environment. It is tolerant to chemicals, drought, flooding, submersion, and temperatures from -14°F to 133°F. This vegetation has a certain degree of shade intolerance, which is ideal for the study area, as it lacks trees or buildings that generate shade. It can grow in sandy soils and rocky areas, from sea level to 2000 meters. In unprotected areas, it retains silt transported by river erosion, reducing suspended particles (Flores Merino et al., 2023).

Also mentioned is the study carried out in Huancayo, Peru, by Rocio del Pilar Ruiz Davila, "Design of Riverbank Protection on the Left Bank of the Chillón River - Comas District, Zone 14 - Lima," in 2020. The main objective of the study was to design a structure to protect the riverbanks, allowing the river to be restored to its original course and preventing flooding that could damage nearby towns.

The general problem addressed in this study concerns the most appropriate type of protective structure to be implemented on the left bank of the Chillón River in the district of Comas (zone 14, Lima).

The objective of this project is to design the riverbank protection structure to be adopted on the left bank of the Chillón River. The hypothesis evaluated was that the adoption of riprap revetments on the left bank of the Chillón River is the optimal proposal for the riverbank protection structure in the district of Comas, located in the fourteenth district of Lima.

Therefore, necessary and critical factors such as geology, precipitation, and flow volume and scale were considered, based on the hydrology of the area studied. This study conducted a preliminary hydrological analysis of the potential for high maximum flows, using data going back at least 15 years, which provided information on river flow conditions in the study area.

In order to proceed with the design of the riverbank protection works, a comprehensive assessment of the river flow conditions was carried out. Subsequently, a preliminary hydrological analysis of the maximum flows recorded over a minimum period of the last 15 years was performed. This analysis made it possible to document the flow trends within the study area.

In the process of designing the riverbank protection works, a comprehensive analysis was carried out of the materials to be used, as well as their quantities and quality, considering the resources available at the nearest quarry (Ruiz Davila, 2020).

In addition, mention should be made of the work carried out by Majluf Diaz, María Luzmila De Los Milagros, and Pacheco Loayza, Jesús Manuel, in Lima, entitled Proposed solution for slope instability on the banks of the Chillón in the Brisas del Malecón de Chillón neighborhood in the District of Comas through the design of gabions using Geo5 software in 2023.

The purpose of this analysis is to resolve the problem of slope instability along the banks of the Chillón River, specifically in the Brisas del Malecón residential area of Chillón, located in the district of Comas. The gabion designs generated with GEO5 software will provide a solution for residents of the area.

The main objective of this project is to provide a comprehensive solution for the Brisas del Malecón neighborhood, which will be achieved through the implementation of various strategies and the collaboration of all parties involved. Residents in this area experience damage due to landslides caused by recurrent flooding of the river. In the most extreme cases, this situation can have devastating consequences, even leading to the loss of their homes.

The problem is to resolve the instability of the slopes in the Brisas del Malecón district of Chillón, located on the banks of the Chillón River in Comas, which is a situation that requires an urgent solution. To this end, a 4 m gabion was designed using GEO5 software. The design complies with regulations and meets stability verification requirements. It was adopted as an effective measure to address the instability affecting the slopes in the area of the Chillón riverbank, within the Metropolitan Area (Majluf Diaz et al., 2023).

3. Materials and methods

3.1 Recycled Tires

An interesting application of recycled tires is their use in the construction of retaining walls. Their main purpose is to contain earth fill with structures built from waste tires. A retaining wall is a structure that retains natural terrain or supports artificial fill (Jaramillo-Véliz, 2021).

Over time, retaining barriers have been erected using various materials. There are various techniques and materials for their development, each with different characteristics and costs. The retaining wall transmits the loads it generates to the foundation to achieve stabilization and balance of the earth mass. Its application is intended for land containment when conditions are not favorable for the natural slope. Among the most notable advantages are:

- High mechanical strength.
- Easy stacking in modules.
- Reuse of solid waste (Alva Hurtado, 2025).

Figure 3 - Graphic representation of walls with tires. Own photograph, 2025.

3.1.1 Geomants or Geogrids

Currently, there are practices and products available that serve as solutions to mitigate erosion caused by precipitation, water currents, wind force, and gravitational forces. Representative examples include rollable erosion control products, known as PECE (Rollable Erosion Control Products), such as erosion control blankets. Geogrids are flat fabrics used to cover land exposed to environmental degradation. Their function is to protect the land from surface runoff and prevent soil loss and the deformation of slopes and hillsides. These are blankets manufactured for use on the ground, either temporarily or permanently (Vargas Jiménez et al., 2017).

Biodegradable Geomants: This is a mulching material consisting of a structure of natural filaments, commonly covered between two artificial fabrics with large openings. It has excellent resistance to erosive agents and is also biodegradable, which means that it eventually integrates into the soil. This element has a unique characteristic that allows moderate penetration of sunlight, which effectively promotes plant germination and development. In addition, it has the ability to store and release moisture, creating a microclimate between the soil and the geogrid. These are geosynthetic materials used to strengthen soils and structures (Castro, 2025).

Figure 4 - Biodegradable Geomants. Adapted from Castro (2025).

Photodegradable or Synthetic Geomants: The soil surface is protected from erosion caused by natural events, such as rain and wind, by a natural-looking green synthetic mesh. Vegetation growth is encouraged by the partial shade and heat storage provided by the mesh. This geomant is designed to keep organic soil in place until vegetation is established (Parraga, 2023).

Figure 5 - Photodegradable or Synthetic Geomants. Adapted from Castro (2025).

3.1.2 Vetiver (Chrysopogon zizanioides)

Vetiver is a plant of the grass family, with an herbaceous appearance and persistent throughout the year. Its stem is apparently non-existent, and it develops very dense clumps that grow continuously without becoming invasive. This plant does not develop underground roots or stems, but rather its leaves, which can reach up to 80 centimeters in length and less than one centimeter in width, are what give it its name. These leaves are very resistant and have a rough edge. In addition, it grows very quickly, reaching two to three meters in height in six months. The roots exhibit accelerated growth, extending to a depth of three to four meters during the first year (Mejía, 2021).

The main roots are very strong, growing upwards and clinging to the ground, reaching depths of more than five meters. The roots have a rigid structure, are very long, vertically oriented, and of equal thickness throughout their length. They are able to acclimatize to a variety of terrains and even penetrate the hardest formations (Truong, 1999), demonstrating their ability to overcome different obstacles and terrain conditions. These are very strong roots that protect the soil and hold it in place thanks to a spongy and highly branched structure formed by secondary and tertiary root systems.

Studies have been conducted on the tensile strength of the root system, which depends on the diameter and composition of cellulose, protein, and pectin. The tensile strength of the root has been determined to be 75 MPa, although higher values have been reported. This value corresponds to the strength of the average diameter.

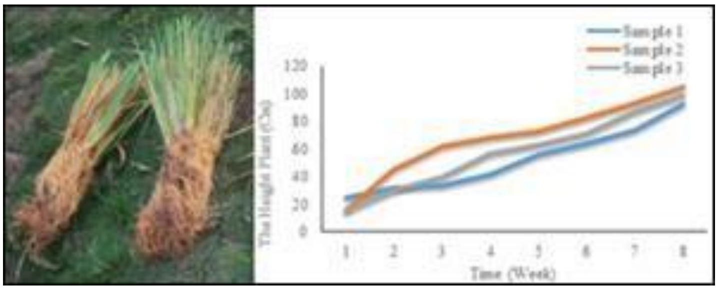


Figure 6 - Extraction and growth of vetiver. Adapted from Flores Merino & Rios García (2024).

3.1.3 Type and level of research

This article is an applied research study that investigates the relationships between variables related to slope stability using bioengineering techniques that utilize the cultivation of vetiver in tropical regions, as well as the environmental, physical, and mechanical properties of soils. The explanatory analytical level and methods used combine qualitative and quantitative considerations to demonstrate why phenomena occur, under what conditions they appear, or why two or more variables are related (Marcano, 2023).

3.1.4 Methodological process

Public institutions and official bodies in the district of Combapatra, in the province of Canchis, in the Cusco region, within the Cahuachulla river basin, will provide the technical information necessary for the study. The study will be carried out in several stages, with the aim of identifying and locating critical sections that require urgent measures, subsequently evaluating and analyzing the documentation, and proposing solutions or modular defenses using tires, geogrids, and Vetiver.

Stage 1: Evaluation and analysis of the bibliographic documentation.

Qualitative analysis and review of existing and publicly available literature related to the elements involved in the proposal.

Evaluation and analysis of existing official technical documentation.

- On-site visualization and inspection.
- Soil mechanics of the area.
- Regional topography (watershed area).
- Topography of the study area (topographic surveys, topographic profiles, and cross-sections of the sectors involved).
- Climatic conditions and climate change factors within the river basin (Márquez Subieta, 2025).

Stage 2: Selection and quantitative definition of design parameters for wall and slope stabilization (Martinez Chalco et al., 2022).

- On-site visual inspection and survey. Critical sections at risk of landslides are defined and documented, along with their physical and geometric characteristics, as well as photographic documentation. (Length, deterioration, photographic documentation, etc.)
- Topography: With regard to topography, it is necessary to carry out topographic surveys of the longitudinal profiles and cross sections of each selected section.
- Hydrology: Information will be collected from the observation stations that have been established in the relevant area, and historical records of flows in the region will also be analyzed to obtain more relevant data. The design flow will be estimated using a reference recurrence interval, which will be taken as a reference for the calculation.
- The analysis and study of the terrain, which is carried out through a detailed analysis, allows for the identification of the classification of primary geological materials, as well as the regional stratigraphic structure, providing a comprehensive understanding of the geological environment. As indicated in the technical report, these data are verified by exploratory drilling recorded in situ (test wells).
- Geotechnical techniques: The technical report provides geotechnical parameters. These are calculated through the theoretical application of geotechnical engineering concepts. The parameters obtained include, for example,

cohesion, friction angle, unit weight, granulometric analysis, and soil classification. This provides information on these aspects of the terrain.

Stage 2 (Design and construction phase): Design of modular defenses (tires + geogrids + vetiver) (Carranza Aguilar, 2025).

- Clean and excavate the surface where the modular sections will be placed for foundation, excavating to a considerable depth of 20 to 30 cm, improve the foundation base if necessary, and consider changing or varying the material, ensuring the foundation depth as initially planned (20 to 30 cm).
- Modular placement and stacking of tires. Place the first row or level of tires across the entire surface (the tires must maintain uniform geometric characteristics). Along the perimeter line, reinforce the fastening between them and interlock them with the nearest internal line. Then, after filling and compacting inside the tires and the gaps between pieces, place the next level.
- Compaction and filling. The interior of the tire is filled using materials in situ with the optimum moisture content (according to laboratory data). Compaction with manual equipment is carried out until sufficient compaction is achieved. The same procedure is followed to compact the gaps between the tires, resulting in a uniformly compacted surface.
- Placement and installation of the geotextile. It is installed along the slope or at the rear of the tire to improve contact with the ground and blend in with the surrounding vegetation. It is secured with metal anchors and compacted fill material.
- Vertical and horizontal stacking of tires. The tires are stacked in such a way as to maintain the slope in the vertical perimeter of the wall or barrier. With respect to the previous row or first level, the process of compaction and placement of the geotextile mesh is carried out. The procedure is repeated until the height estimated according to the design calculations (maximum flood height) is achieved.
- Sowing and planting vetiver. Vetiver is sown and planted in strips parallel to the water channels, with a separation of 15-20 cm between plants, and also in the spaces where rubber has not been planted. This is done at the different levels of the modular defense constructed and on the slope above the final module (PÉREZ et al., 2020).

3.1.5 Population and sampling

The population under study is located in the area surrounding the Cahuachulla River basin, located in the district of Combapata, in the province of Canchis, within the Cusco region, in the South American country of Peru. The samples obtained correspond to sections that have been meticulously selected to carry out the reconstruction of the Cahuachulla Riverbed.

3.1.6 Theories and considerations on slope and retaining wall stability

Design flow: The design flow covers the preliminary design, evaluation, and design documentation phases, as well as the construction period and the service life of the embankment. Using this procedure, it is possible to estimate future flows using the topography of the area in question (cross sections and slopes) and data from neighboring observation stations, thus calculating the maximum water level for the section studied where Eq. (1) will be used for this purpose (Castañeda Morey, 2024).

$$Q = A \cdot V \tag{1}$$

Where:
Q = flow rate (m^3/s)
A= cross-sectional area considered (m^2)
V= average velocity
Hydraulic level of flood water (Manning coefficient)
Flow-head ratio (trapezoidal section):

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

Where:

$A(h)$: wet area as a function of head h.
$R(h) = \frac{A(h)}{P(h)}$: hydraulic radius.
n: roughness (gravel/stones: 0.030–0.045).
S: energy slope
Análisis de suelos y Característica de los suelos en consideración:
Soil analysis and characteristics of soils under consideration:
Grain size analysis, cohesion coefficient (c), angle of internal friction or shear strength (ϕ).

Slope stability: limit equilibrium method (Fellenius).

Safety Factor (S.F.). In geotechnical terms, it is the relationship between the actual conditions of the current slope and its potential failure. Slope stability is calculated as the safety factor. The relationship between the soil's resistance to sliding and the forces acting on potential failure zones is a research topic that requires in-depth knowledge and detailed understanding to comprehend the interaction between these concepts and their application in various conditions. The safety factor is related to stability (PÉREZ SILVA, 2022) (Campos Ojeda et al., 2024).

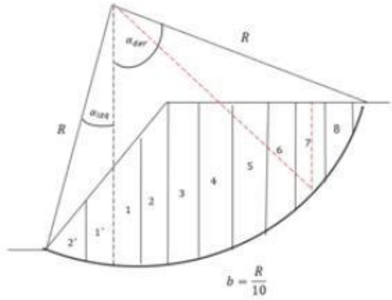


Figure 7- Slope stabilization using the Fellenius method. Taken from Campos Ojeda (2024).

Fellenius (1922) defined the safety factor as the ratio between the actual shear strength of the slope material and the critical shear stress required to cause failure across the entire assumed failure surface, which allows the behavior of the material under extreme conditions to be determined:

$$F.S. = \frac{\textbf{Resistencia al cortante disponible}}{\textbf{Esfuerzo al cortante actuante}} \tag{3}$$

In addition, the ratio between F.S. and the (circular) failure plane generates a resistant moment and an acting moment. These moments originate at the center of rotation:

$$F.S. = \frac{\textbf{Momento resistente disponible}}{\textbf{Momento actuante}} \tag{4}$$

Equation: limit equilibrium method (Fellenius).

$$FS = \frac{\sum (c' \cdot L + (W \cdot \cos\theta - U) \cdot \tan\phi')}{\sum (W \cdot \sin\theta)} \tag{5}$$

F_s = Safety factor.
c'= effective cohesion.
L = length of the base of the wedge.
W= weight of the soil block.
Θ = angle of inclination.
U = pore pressure.
Φ' = angle of internal friction.
Fs ≥1.5 to ensure stability.

Design/Calculation (wall stability).

Active thrust (Rankine/Coulomb)

$$K_a = \tan^2(45° - \frac{\phi}{2}); \sigma_h(z) = K_a \cdot \gamma \cdot z \tag{6}$$

$$P_a = \frac{1}{2} \cdot K_a \cdot \gamma \cdot H^2 \textbf{(}\text{without overload}\textbf{)} \tag{7}$$

$$P_q = K_a \cdot q \cdot H. \tag{8}$$

(With uniform overload q)

Hydrostatic pressure on wet face:

$$p_w(z) = \gamma_w \cdot z; P_w = \frac{1}{2} \cdot \gamma_w \cdot H^2 \tag{9}$$

Sliding (base):

Action: $T = P_{\text{total}}$horizontal at the base.

$$R = N \cdot \tan\ \delta + c' \cdot BFS_{\text{desl}} = \frac{R}{T} \geq 1{,}5(\text{Static}); \geq 1{,}1 - 1{,}2(\text{seism}) \tag{10}$$

Where: N= total normal load (self-weight + vertical loads), δ= friction base–foundation, c'= effective cohesion of the stratum, B= effective width.

Overturning (front edge point):

$$FS_{\text{vuelco}} = \frac{M_{\text{resistente}}}{M_{\text{volcante}}} \geq 2{,}0(\text{static}); \geq 1{,}5(\text{seism}) \tag{11}$$

Sum of moments relative to the heel; resistance due to own weight and geometry (tires + fill).
Bearing capacity and contact stresses:
Eccentricity: $e = \frac{M_{\text{volcante}} - M_{\text{resistente}}}{W}$
"No traction" criterion: $e \leq \frac{B}{6}\, q_{\max,\min} = \frac{W}{B}\left(1 \pm \frac{6e}{B}\right)$ (12)

Verify $q_{\max} \leq q_{\text{adm}}$ of the foundation soil (adjust for water table).
Overall slope stability (deep failure):
Evaluate circular/non-circular surfaces with limit equilibrium. Objectives:
Overall FS ≥ 1.3–1.5 (static).
Reinforce with geogrids if FS < target.
Lifting due to underpressure:

$$u = \gamma_w \cdot h_{\text{piez}};\ N_{\text{ef}} = N - U \quad (13)$$

Ensure drainage to reduce u and maintain FS_{desl} and safe stresses.

4. Results

4.1 Location of the study area

The Cahuachulla River, a tributary of the Vilcanota River system, has an altitude of 3716 meters above sea level. It is a study site located on the riverbed, which is part of the Vilcanota River basin. It is a seasonal study site, with heavy rains between December and March that cause sudden flooding sudden flooding. Erosion and gully formation processes. The riverbanks are used for subsistence farming, although they are vulnerable to erosion and water sedimentation on the slopes and margins, which affects water quality and hydraulic capacity. There is a risk of overflowing in the event of heavy rains (Miguel Mendoza et al., 2024).

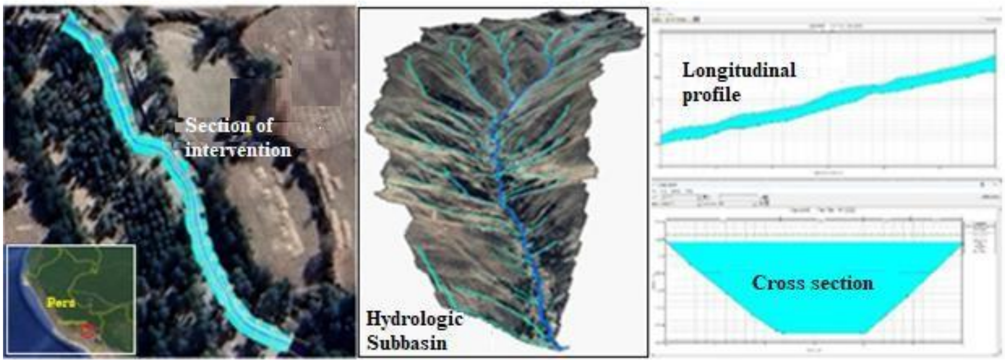


Figure 8 - Location and Characteristics of the Intervention Section

4.2 General calculation data

4.2.1 Sub-basin data

Basin area (A) 18.94 km².
Perimeter (P) 22.03 km.
Length of the basin (Lb) 8.05 km.
Basin width (B) 2.35 km.
Elevation (E) 1196.26 m.
Average altitude 4150.55 m above sea level.
Minimum altitude 3483.5 m above sea level.
Maximum elevation 4,679.77 m above sea level. Initial elevation (main channel) 4,255.90 m above sea level.
Final elevation (main channel) 3,487.27
m above sea level
Average slope of the basin 23.04 °C.
Average slope of the basin 42.52%.
Slope of the main channel (ends) 11.22%.
Compensated channel slope 0.097 m/m.
Compensated slope of the channel (%) 9.774%.
Drainage density (D_d) 2.73 km/km².
Stream frequency (F_s) 7.17 streams/km².
Elongation index (R_e) 0.6102
Circularity index (R_c) 0.4906.
Compactness coefficient/Gravelius (K_c) 1.4278.
Shape factor (F_f) 0.2924.
Horton shape factor 0.2924.

Schumm elongation ratio 0.6102 (SENAMHI. PHISIS, 2025).

4.2.2 Analysis section data

Approximate design parameter period
100-year return period.
Design flow Q100 = 2.4 m^3/s.
Total slope height H = 4.0 m.
Average velocity V = 0.54 m/s.
Channel section Type of section Trapezoidal
Bottom width b = 2.0 m .
Channel slopes 1V:2.4H z = 2.4 m.
Flow depth design y100 = 1.0 m.
Hydraulic area A = 4.4 m^2.
Channel material, Gravel.Manning's roughness coefficient n = 0.030 m.
Average channel slope S = (0.05%).
Tire height 2.4 m (8 rows).
Embedment in the bed 0.20 m.
Saturated unit weight: γ sat = 20 kN/m^3.
Dry unit weight: γs = 18 kN/m3.
Effective cohesion: c′ = 8Kpa.
Effective friction angle: ϕ' = 27°C (sandy loam mixture with gravel).
Unit weight of water: γw=9.81 kN/m (SENAMHI. PHISIS, 2025).

4.3 Slope stability verification: limit equilibrium method (Fellenius)

The embankment stability test was performed using the Fanelli method, which assumes a feasible circular failure. The surface was subdivided into ten vertical sections and two scenarios were examined: the current state, without protection, and the installation of modular protection. The modular tire-based protection was considered equivalent to a 2.4-meter-high (8 tires) gravity retaining wall with a base width of 1.8 meters (6 tires), with the same slope and weight as saturated soil. Table 1 shows the safety factors for different scenarios.

Table 1 - Calculation of SF, different scenarios, Own elaboration 2025.

Scenario	Slope conditions	Calculated FS	Analysis
Current	Slope 4 m, 1V:2.4H, no water table, no defenses	1.55	Stability at the threshold of the limit.
Proposed	Slope 4 m, 1V:2.4H, no water table, with defenses	1.90	The scenario is optimal. It meets safety criteria above the limit values.

4.4 Verification of the design and calculation of wall stability

Active earth pressure (Rankine):

K_a= tang^2(45 - ϕ/2) = tang^2(31.50) = 0.376.
P_a= 1/2* γ_S *Ka*H^2.
P_a= 1/2*18*0.376*(2.4)^2 kN/m.
P_a= 19.49 KN/m, Acts at H/3=0.80 m above the base.

Hydrostatic thrust

P_h= 1/2 * γw h^2= 4.91 kN/m.
Acts at h/3=0.33 m.

Equivalent gravity wall weight (for 1 m length)

V = B·Hm·1.0 = 1.8·2.4 = 4.32 m^3
P = V* γh = 4.32*20 kN/m^3 = 86.40 kN/m.

4.4.1 Sliding verification

R_{des} = N·tan (δ) = 86.40* tan (22) = 34.91 kN/m.

Shear stress

S_{des} = 19.49 KN/m + 4.91 kN/m = 24.40 KN/m

Sliding safety factor

$FS_{des} = R_{des} / S_{des} = 34.91 /24.40 = 1.44$

Sliding was verified with a friction angle of 22° between the ground and the composite wall, a value consistent with the friction between the filled tire, geogrid, and vetiver with the granular soil (gravel).

4.4.2 Overturning verification

Overturning moment:

$M_v = Pa*Hm/3 + Ph*Hm/3 = 19.49*0.8 + 4.91*0.33 = 17.21$ kN.

Stabilizing moment:

Centro de gravedad del muro, para bloque rectangular, a $B/2$=0.9 m

$M_e = Wm*0.9 =86.40 *0.9 = 77.76$ kN

Overturning safety factor:

$FS_{volc} = Me / Mv = 77.76/17.21 = 4.52$

The safety factor indicates stable conditions.

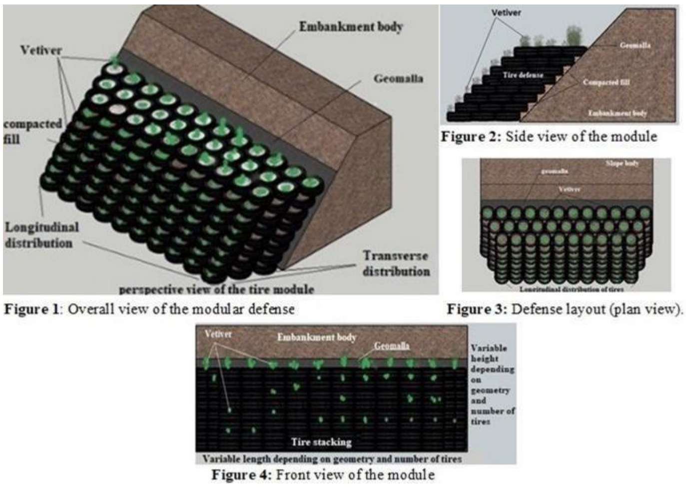


Figure 1: Overall view of the modular defense

Figure 2: Side view of the module

Figure 3: Defense layout (plan view).

Figure 4: Front view of the module

Figure 9 - Views of the defense module.

5. Discussion of Results

The combination of these three elements is effective in stabilizing slopes, preventing landslides, and controlling erosion. The control blanket protects the soil from rain. The blanket, together with the modular tire defenses, creates optimal conditions for the growth and deep development of vetiver roots, improving long-term soil stability. Therefore, compared to conventional solutions, it achieves rapid recovery, greater sustainability, and significant cost reduction, which translates into greater savings and improved process efficiency.

The fundamental purpose of this system is to preserve soil integrity, ensuring its stability and preventing surface erosion. This feature allows vetiver to establish itself more effectively, using its deep root system, which grows naturally, to create a natural reinforcement effect. The retaining walls formed by stacking tires in modules or sectors improve mechanical resistance and facilitate the reuse of solid waste.

Without the protection provided by early mulching, seedlings can be washed away by heavy rains or runoff and lost before they can establish themselves. Mulching acts as a protective cover that promotes vetiver growth by slowing water flow, retaining moisture, and trapping sediment.

Following the completion of land and slope stabilization works and the planting of vetiver, it can be said that the process of vegetation regeneration has accelerated considerably. These measures promote landscape integration and restore the surrounding ecosystem, thus contributing to environmental sustainability and improved quality of life, which is essential for community development.

This comprehensive feature makes the solution a self-sustaining system, in which the topsoil provides initial protection, while vetiver ensures long-term stability. As vetiver grows, its deep root system expands, functioning as a living mesh that compresses, strengthens, and stabilizes the soil, contributing to its structuring and consolidation.

The combined use of tire walls and blankets provides a protected and stabilized environment for the development of other plant species alongside vetiver, contributing to ecosystem restoration and improved environmental resilience.

6. Conclusions and Recommendations

The installation of modular protective walls using recycled tires, geogrids, and vetiver represents a technically and environmentally viable alternative for controlling water erosion along the Cahuachulla River. This approach allows for the conversion of difficult-to-dispose-of solid waste into a useful resource for slope stabilization, while geogrids provide essential structural strength and improve the stability of the modules against hydraulic forces by optimizing stress distribution. Furthermore, the deep root system of vetiver contributes significantly to soil stabilization and the restoration of riparian landscapes. Ultimately, the fusion of civil engineering and plant biotechnology generates results that surpass conventional protection measures in terms of sustainability, cost, and reproducibility. However, active community participation in the implementation and maintenance of the system remains essential to ensure its long-term success and the endurance of its environmental benefits.

Based on the findings of this research, it is recommended to replicate the modular protective barrier model in other streams and creeks within the region that face similar erosion challenges. To support this expansion, training programs should be promoted to educate local communities on bioengineering techniques and river protection maintenance. Additionally, establishing agreements with local authorities and environmental organizations is crucial to institutionalizing the collection and reuse of tires. Future work should prioritize long-term hydrological monitoring to assess the system's effectiveness under diverse climatic conditions and integrate these modular defenses with soil conservation measures in neighboring agricultural areas. Finally, the dissemination of these results in scientific journals and engineering conferences is encouraged to promote the adoption of sustainable bioengineering solutions globally.

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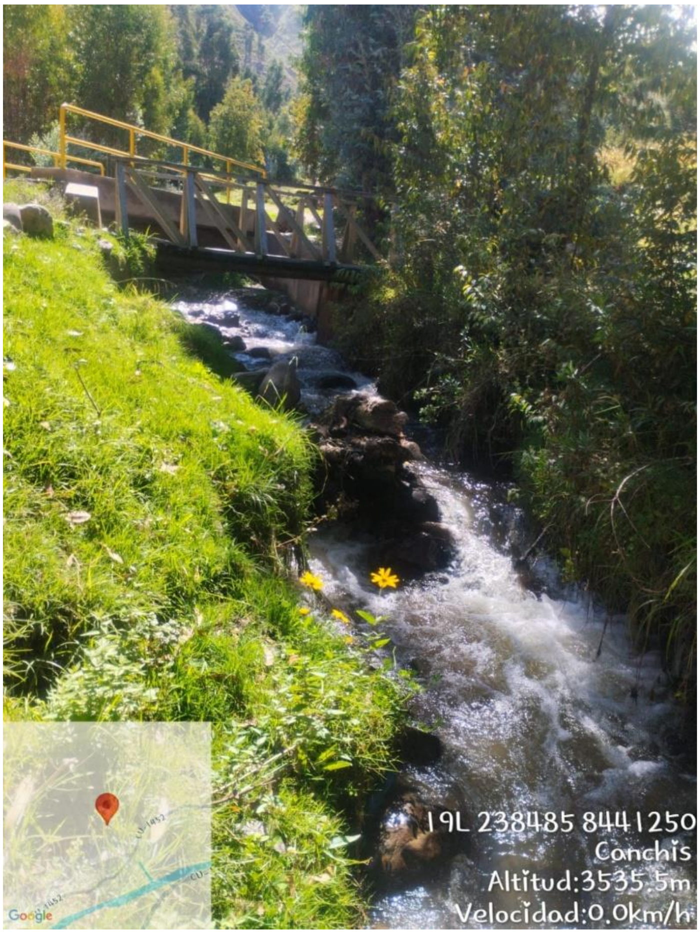
Annex


Google
19L 238493 8441240
Conchis
Altitud:3557.7m
Velocidad:0.0km/h


Google
19L 238485 8441250
Conchis
Altitud:3535.5m
Velocidad:0.0km/h

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