Title:

Bridging Ancestral Knowledge and Ecosystem Science for Coastal Restoration in Latin America: The CALISUR Methodology

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Abstract

1. Introduction

This study documents the **CALISUR** methodology, a community-based mangrove restoration model rooted in ancestral ecological knowledge and applied across six intervention sites in the Gulf of Guayaquil. The methodology integrates scientific and traditional practices to address hydrological disruption, eutrophication, and sedimentation, using three key techniques: hydrodynamic rehabilitation, community-managed mangroves on eutrophicated soils, and the creation of new mangroves with recycled sediments. Ecological indicators and community participation are monitored across phases. The results show successful ecological recovery and social empowerment. This paper presents the methodology, results, lessons learned, and implications for scaling across Latin America.

2. Objectives

This study has the following main objectives:

(1) To systematically document the methodological components of the CALISUR approach and its ecological and social foundations;

(2) To evaluate the effectiveness of the three main techniques implemented in terms of recovery of ecosystem functions and environmental services;

(3) To analyze the socioeconomic and governance impacts associated with these interventions; and

(4) To identify lessons learned and recommendations for integrating traditional knowledge into large-scale mangrove restoration programs.

3. Research Questions

The questions guiding this research are:

- How can traditional ecological knowledge contribute to the success of mangrove restoration projects in terms of plantation survival and recovery of ecosystem functions?

- What are the specific mechanisms by which the CALISUR methodology achieves higher success rates than conventional reforestation approaches?

- What socioeconomic and governance impacts does the implementation of this participatory methodology generate in local communities?

- What are the key elements that should be considered for the scalability and replicability of this approach in other geographic and sociocultural contexts?

4. Literature Review

4.1 Theoretical Background

Ecological restoration has evolved significantly from its early days as a technical discipline toward more integrative conceptual frameworks that recognize the socio-ecological nature of ecosystems. As outlined by the Society for Ecological Restoration in its most recent international standards, the integration of traditional cultural knowledge and practices is an essential component for designing restoration interventions that are not only ecologically effective but also socially just and culturally appropriate (Gann et al., 2019).

This perspective aligns with a growing global recognition of the importance of Indigenous and local knowledge systems in ecosystem conservation and restoration (Berkes et al., 2000; Tengö et al., 2014; Thornton & Scheer, 2012). As Mistry & Berardi (2016) point out, these knowledge systems not only provide valuable historical and contextual information, but also offer alternative conceptual frameworks for understanding socio-ecological relationships and designing interventions that are both culturally relevant and ecologically sound.

In the specific context of mangroves—ecosystems that have been historically managed by local communities in many tropical regions—this integration is particularly relevant. Walters et al. (2008) and Datta et al. (2012) highlight that traditional mangrove users often possess detailed knowledge of microhabitats, reproductive cycles of key species, ecosystem health indicators, and adaptive management techniques that can significantly complement conventional scientific knowledge.

4.2 Previous Studies

In response to widespread mangrove degradation, numerous restoration initiatives have emerged in Ecuador and other tropical countries over the past decades, with varying degrees of success. While some conventional reforestation projects have shown limited survival rates and low long-term sustainability (Ellison, 2000; Primavera et al., 2012), alternative approaches based on local knowledge and community participation have shown promising results.

Comparative studies between conventional technical approaches and participatory methodologies have documented significant differences in planting survival rates and ecosystem function recovery. For example, research in Southeast Asia has demonstrated that restoration projects incorporating local knowledge and community participation achieve survival rates two to three times higher than those based solely on standard technical approaches (Primavera & Esteban, 2008; Samson & Rollon, 2008).

In Latin America, documented experiences in Mexico, Colombia, and Brazil have shown similar patterns. Integration of traditional knowledge and active community participation have led to greater efficiency and sustainability in restoration interventions (López-Portillo et al., 2017; Cantera et al., 2019; Rovai et al., 2021).

4.3 Importance of Ancestral Conservation

The recognition of ancestral conservation as a valid and effective approach to ecosystem restoration is based on several key elements. First, communities that have historically lived alongside specific ecosystems have developed sophisticated knowledge systems regarding local ecological dynamics, including seasonal patterns, environmental indicators, and natural succession processes, which can be fundamental to restoration success.

Second, these knowledge systems have demonstrated their effectiveness through the historical co-evolution of human communities and ecosystems, representing management strategies that have maintained ecological integrity over long periods. As Berkes & Turner (2006) argue, traditional ecological knowledge represents a living archive of information on ecosystem responses to various disturbances and adaptive management strategies.

Third, in the context of accelerated climate change—where coastal ecosystems face unprecedented pressures from sea level rise and intensifying extreme events—the adaptive capacity inherent in many traditional knowledge systems represents a valuable asset for developing resilient restoration strategies (Salick & Ross, 2009; Reyes-García et al., 2016).

Finally, from the perspective of environmental justice and social sustainability, ancestral conservation approaches offer opportunities to strengthen local capacities, generate direct economic benefits for historically marginalized communities, and develop participatory governance models that can contribute to the long-term sustainability of restoration interventions.

The CALISUR methodology, with its emphasis on continuous observation, adaptive management, and responsiveness to local conditions, offers a potentially valuable model in this context. Its implementation in multiple locations in the southern coastal region of Guayaquil—ranging from small community interventions (1–5 hectares) to larger-scale restoration programs (>50 hectares)—provides a strong empirical basis for evaluating the effectiveness of traditional knowledge–based approaches across different degradation contexts and intervention scales

5. Materials and Methods

5.1 Sampling Materials and Procedures

Indicator	**Equipment or Material Used**	**Sampling Technique**	**Practical Sampling Tips**

Water salinity	Hanna HI96822 salinity refractometer	Direct measurement in ponds, channels, and soil at 15–30 cm depth	Sample during tidal breaks, around noon in affected zones and inflow channels
Canal depth	Topographic rod or graduated stick	Measurement in cross-sections of channels every 100 meters	Sample main inflow channels during dry conditions; record tide level and time
Tidal influence area	Satellite imagery, GPS, GIS (ArcGIS, QGIS)	Mark with GPS zones without tidal influence	Take measurements three times over three months
Vegetation density (Rhizophora, etc.)	Measuring tape, GPS, 10×10 m monitoring plots	Species count within permanent plots	Avoid altered zones; mark 12 plots per 100 ha; minimum 50 m spacing
Total vegetation cover	Reflective color tubes, 50 m tape, data sheets	12 plots/100 ha, 90% confidence level; calculate baseline coverage % from counts	Take two alternate readings; rotate personnel if possible
Crabs / macrofauna	Visual observation and manual collection	Count in 100 m² plots or 10×10 m transects	Repeat three times at the same time of day
Macrofauna biomass	Portable scale, collection container, tweezers	10 samples per 100 m²; collect and sieve 10 cm topsoil	Record by species when possible
Dissolved oxygen / nutrients	YSI 9500 oxymeter, INIAP soil kits	Surface water at 20 cm, substrate samples at 20–30 cm	Avoid agitation when sampling; label all samples clearly

Algae (phytoplankton)	1L bottles, 20 µm mesh, 4% Lugol's solution	Sample water near shrimp farm intakes between 10–12 a.m.	Analyze within 24–48 hours or refrigerate
Turbidity	Secchi disk or turbidimeter	Measure water column at shrimp pump station	Take multiple readings and average
Vegetation survival	Measuring tape, ID tags	Count living individuals in marked plots	Sample 20% of plants per plot; include newly planted trees
Plant growth	Caliper, measuring tape, millimeter ruler	Measure height from base to apex, leaf/nodule/branch count	Same observer preferred for consistency
Community participation	Field notebooks, attendance lists	Record during workshops, meetings, and community events	Document with photos and signatures; include qualitative perceptions
Bank erosion / ground elevation	Optical level, Total Station	Compare length, elevation, and spatial coordinates	Mark transects; sample in dry conditions

5.2 CALISUR Conceptual Framework

The CALISUR methodology (Ancestral Conservation Leading Sustainable Initiatives for Mangrove Restoration) is grounded in the principle that ancestral communities possess deep empirical knowledge of mangrove ecosystem functioning, derived from generations of direct interaction with their environment. The integration of this knowledge with contemporary scientific principles has resulted in an innovative, culturally appropriate, and highly effective restoration strategy.

The conceptual framework of CALISUR is structured into four main components:

(1) active community participation in the design, implementation, and monitoring of projects;

(2) recovery and adaptation of ancestral techniques to current environmental conditions;

(3) sustainable use of local resources without dependence on external inputs; and

(4) climate adaptability based on direct observation and natural cycles.

This methodology adopts three integrated approaches:

- The community approach actively engages local communities in all stages of the restoration process—from design to monitoring—ensuring that the solutions are culturally appropriate and sustainable in the long term.

- The local adaptation approach tailors techniques specifically to the ecological and social conditions of each site, increasing their effectiveness and replicability in similar contexts.

- The innovation in sediment use approach repurposes sedimented areas to create new mangrove structures, a strategy that not only contributes to ecological restoration but also addresses waste management and improves water quality.

5.3 Restoration Techniques

The CALISUR methodology implements three main restoration techniques, each designed to address different types of ecosystem degradation and specific environmental conditions.

5.3.1 Hydrodynamic Rehabilitation of Mangrove Ecotones

This technique involves restoring the natural hydrological conditions of ecotones—defined as transition zones between mangrove and other ecosystems—by reactivating blocked tidal channels, removing anthropogenic structures that impede water flow, and increasing vegetative cover in buffer zones to create initial sediment-trapping barriers. This process is essential for ecosystem health, as it enables mangrove expansion and strengthens transitional areas between mangrove and adjacent ecosystems.

Diagnosis of ecological succession and hydrological flows

The process begins with the collection of local knowledge through active participation of communities (fishers, elders, traditional mangrove users) to gather information on historical water flow patterns, location of old channels, natural flood zones, active regeneration areas, and observed changes over time. Simultaneously, colonization processes in buffer zones (ecotones) are identified and cartographic analyses are conducted using maps to locate original channel networks, tidal influence zones, and anthropogenic structures that have interrupted natural flows.

This diagnosis is complemented by preliminary hydrological studies, including tidal, current, salinity, and water level measurements at various points to understand the current hydrodynamic status. Additionally, blocked zones (dikes, embankments, fills) and areas with anoxic conditions are mapped.

Delimitation of ecotones and priority areas

Precise identification of transition zones is carried out, clearly defining the ecotone boundaries between mangrove and adjacent ecosystems. The impact of hydrological alterations is evaluated to determine the areas where flow interruption has caused the most degradation—manifested in sediment accumulation, anoxic zones, and mangrove mortality. Pilot sites are then selected for implementing rehabilitation and active regeneration actions, considering both technical feasibility and community support.

Reactivation of tidal channels

Physical intervention consists of the strategic excavation of channels to reconnect main estuaries with exterior zones, following the natural topography. Light machinery or manual labor is used depending on site fragility, and channels are designed with gentle slopes to avoid excessive erosion.

Mangrove edge expansion and ecotone recolonization

A recolonization process is implemented by recruiting mangrove propagules (black, red, or other species) from nearby ecosystems. Propagules are cultivated in community nurseries using local sediment until the seedlings reach appropriate weight and size to withstand wave and current forces. Cane fences are constructed to protect and mark planting areas, with designated routes and monitoring plots. Seedling planting is done progressively every two months, moving from higher to lower areas.

Participatory monitoring

In monitoring plots and external channels, key parameters are evaluated including salinity (with portable meters), sedimentation (using depth markers), and plant growth and colonization (using the CALISUR growth index). The community is actively involved in monthly records, ensuring continuous follow-up.

5.3.2 Community Mangroves for Eutrophicated Soils

This technique specifically addresses the issue of soil eutrophication due to excess nutrients, particularly from shrimp aquaculture waste. CALISUR has developed a system of mangrove nurseries managed by communities to select and plant species tolerant to eutrophic conditions.

Eutrophication assessment

The process begins with identifying local biological indicators through water analysis, detecting signs such as algae proliferation, associated fauna mortality, and absence of crabs. Soil sampling for nutrient and texture analysis complements this, using portable kits or community labs as available.

Establishment of community nurseries

Species tolerant to eutrophication are selected, prioritizing Avicennia germinans in initial stages and Rhizophora mangle in advanced phases. Propagules are collected and mangrove seeds are germinated under controlled conditions with shade and filtered estuary water. Cultivation is done in nurseries using biodegradable bags or containers filled with sediment from the eutrophicated zones.

Staggered planting

Field implementation includes building cane fences for protection and marking of planting areas. Pioneer red mangrove species are planted in dispersed patches to stabilize soil, followed by successional species (Laguncularia, Avicennia) in interlinked corridors, creating a functional network of ecological connectivity.

Rotational maintenance

A monitoring system is implemented for dissolved oxygen and turbidity in collaboration with neighboring shrimp farms, along with algae counts. Rotating community groups are established for irrigation and herbivore protection tasks, ensuring the social sustainability of the process.

5.3.3 Recycled Sediments for New Resilient Mangroves

This innovative technique uses dredged sediments from estuaries and channels to create new physical structures such as islands and terraced platforms that serve as substrate for natural regeneration or targeted mangrove planting.

Zoning and sediment characterization

Embanked zones are inspected and tidal height studies conducted using community equipment. Sediment texture (silt/clay/sand ratio) is analyzed, and potential contaminants (heavy metals) are assessed with local participation. Sediments rich in organic matter are prioritized for terrace construction.

Design of protective structures

Semi-permeable walls are built for islands or terraced platforms, defining elevation profiles with higher zones for less flood-tolerant species and lower areas for seed and propagule establishment.

Bioengineering with Sediments

Dredged sediments from adjacent channels are transferred into the interior of the designed structures. Bathymetric surveys are conducted at low tide within the planting zones to determine the appropriate compaction of the dredged sediments.

Sequential Planting and Transplantation

Implementation follows a specific schedule:

- During months 1–2, red mangrove propagules are introduced into flood-prone zones (1/3 of the area).
- In months 3–4, red mangrove plants are planted along the borders to stabilize edges (1/3 of the area).
- Finally, in months 5–6, black mangrove seedlings and seeds from other local species are planted in the remaining 1/3 of the area.

Resilience Monitoring

The rate of shoreline erosion, the growth of planted seedlings and seeds, and the diversity of accompanying macrofauna are measured every three months, providing indicators of the ecosystem functionality of the created structures.

5.4.Evaluation Indicators and Metrics

For each technique implemented, specific and measurable expected outcomes have been established:

- Hydrodynamic Rehabilitation

  Expected results include:

– Reduction of anoxic zones and root mortality

– Successful colonization by Rhizophora, Avicennia, or Laguncularia

– Identification of historical tidal flow patterns

– Reestablishment of water exchange between main estuaries and interior zones

– Effective participatory monitoring of changes in salinity, sedimentation, and natural colonization

- Community Mangroves in Eutrophicated Soils

  Expected results include:

  – Effective community assessment of eutrophication levels

  – Successful establishment of community nurseries

  – Implementation of staggered planting techniques

  – Development of rotational community management systems

  – Recovery of previously barren areas

  – Generation of ecosystem services

  – Community empowerment in territorial management

- Recycled Sediments for New Mangroves

  Expected outcomes include:

  – Creation of 1 hectare of new mangrove per 6,000 m^3 of reused sediment, protected by semi-permeable bamboo walls

  – Proven resistance to storm surges with 70% sediment retention after extreme events

  – Recovery of ecosystem services

  – Acceleration of successional processes

  – Increased resistance to extreme events

  – Expansion of habitat for key species

5.5. Community Participation and Knowledge Validation

The CALISUR methodology incorporates systematic mechanisms of community participation in all implementation phases. Community monitoring committees are established, combining traditional observational techniques with standard measurement tools. Knowledge-sharing systems are implemented among communities to validate and adapt techniques based on specific local contexts. Additionally, technical training processes are developed to strengthen local capacities for autonomous management of restoration projects.

Knowledge validation is carried out through the systematic comparison of predictions based on traditional knowledge and standard scientific measurements, documenting both convergences and divergences to foster mutual enrichment of both knowledge systems. This process contributes to the development of a hybrid protocol that maximizes the effectiveness of restoration interventions while strengthening the autonomy and technical capacities of implementing communities.

5.6. Summary Logical Framework Table of Restoration Techniques

Technique	**Main Objective**	**Key Procedures**	**Ecological Indicators**	**Social / Community Indicators**
1.Hydrodynamic rehabilitation of mangrove ecotones	Restore hydrological connectivity and ecological functionality in transition zones	1. Hydrological diagnosis with local knowledge2. Delimitation of ecotones and priority areas3. Reactivation of tidal channels4. Staggered planting of mangroves5. Participatory monitoring	– Salinity (ppt)– Depth of inflowing channels (cm)– Seedling survival rate (%)– Natural colonization by key species	– Number of participants in community brigades– Monthly monitoring records– Community acceptance and ownership
2. Restoration of eutrophicated soils using community nurseries	Recover areas affected by nutrient overload and foster resilience in degraded zones	1.Eutrophication assessment2. Nursery seedling production3. Staggered planting of pioneer and successional species4. Rotational maintenance and control of invasive species	– Vegetation cover (% increase)– Recovery of associated fauna (crabs, birds)– Reduction in microalgae concentration and increase in water turbidity	– Number of nurseries established– Seedlings produced per nursery– Jobs created– Participation of women and youth
3. Creation of new mangroves with recycled sediments	Use dredged sediments to create resilient habitats and new	1. Zoning and sediment analysis2. Design of islands and terraces3. Bioengineering with dredged sediments4.	– Hectares of mangrove generated– Resistance (% sediment retention and shoreline	– Number of structures built using local materials– Community bioengineering capacity

	mangrove patches	Sequential planting and transplanting5. Post-extreme event evaluation	erosion)– Increase in biodiversity (number of species)	installed– Frequency of participatory maintenance

5.7. Restoration activity table

Activities	Technique	Site Name	Hectares	Start Date	Details	Resources
Initial Intervention	Hydrodynamic Ecotones	A1: Playón Norte	34	15/05/2010	Canal cleaning: 450m, dredging: 30cm	Backhoe + 12 persons
Follow-up Planting	Hydrodynamic Ecotones	A2: Estero Vicente	47	18/07/2014	Canal cleaning: 250m, dredging: 25cm	16 persons over 5 workdays
Follow-up Planting	Eutrophicated Soils	B1: Aquaindesa	48	16/07/2009	O2 measurement, algae count	6 persons, INIAP, INP
Follow-up Planting	Eutrophicated Soils	B2: La Isla	36	25/03/2010	O2 measurement, algae count	8 persons, INIAP, INP

Follow-up Planting	Recycled Sediments	C1: A.F	50	15/07/2023	Soil, water, wave analysis; sediment dredging	10 persons, AQF, JDN
Monitoring Phase I	Hydrodynamic Ecotones	A1: Playón Norte	34	21/08/2010	Red mangrove planting from nursery	10,000 plants
Monitoring Phase I	Hydrodynamic Ecotones	A2: Estero Vicente	47	22/09/2014	Red mangrove planting from nursery	10,000 plants
Monitoring Phase I	Eutrophicated Soils	B1: Aquaindesa	48	11/11/09	Red mangrove planting from nursery	20,000 plants
Monitoring Phase I	Eutrophicated Soils	B2: La Isla	36	4/5/10	Red mangrove planting	20,000 plants
Monitoring Phase II	Hydrodynamic Ecotones	C1: A.F	50	15/09/2023	Construction of 3,000m bamboo wall	35 people, canes, boats

Monitoring Phase II	Hydrodynamic Ecotones	C2: Isla Gala	3.2	20/11/2019	800m bamboo fencing and palisade	12 people in 4 workdays
Monitoring Phase II	Recycled Sediments	C1: A.F	50	15/09/2024	Sediment dredging and transport to island	650mÂ³ dredger
Monitoring Phase II	Recycled Sediments	C2: Isla Gala	3.2	13/06/2020	Red mangrove planting	500 plants

6. Results

6. Results and Data Analysis

Restoration Technique	**Main Objective**	**Key Procedures**	**Ecological Indicators**	**Social / Community Indicators**
1. Hydrodynamic Rehabilitation of Mangrove Ecotones	Restore hydrological connectivity and ecological functionality in transition zones	1. Hydrological diagnosis with local knowledge2. Delimitation of ecotones and priority areas3. Reactivation of tidal channels4. Mangrove planting in staggered plots5. Participatory monitoring	- Salinity (ppt)- Depth of water-inflowing channels (cm)- Seedling survival rate (%)- Natural colonization by key species	- Number of community brigade participants- Monthly monitoring records- Community acceptance and ownership

2. Restoration in Eutrophicated Soils through Community Nurseries	Recover areas affected by nutrient excess and promote resilience in degraded zones	1. Eutrophication evaluation2. Seedling production in community nurseries3. Staggered planting of pioneer and successional species4. Rotational maintenance and invasive species control	- Vegetation cover (% increase)- Recovery of associated fauna (crabs, birds)- Reduction in microalgae concentration and increase in water turbidity	- Number of nurseries established- Seedlings produced per nursery- Labor days generated- Participation of women and youth
3. Creation of New Mangroves with Recycled Sediments	Use dredged sediments to create resilient habitats and new mangrove patches	1. Zoning and sediment analysis2. Design of islands and terraces3. Bioengineering with dredged sediments4. Sequential planting and transplanting5. Post-extreme event evaluation	- Hectares of mangrove created- Resistance (% sediment retention and shoreline erosion control)- Increase in biodiversity (number of species)	- Number of structures built using local materials- Installed capacity in community bioengineering- Frequency of participatory maintenance

6.1. Site A1: Estero Playón Norte – Balao

Site characteristics: Mangrove ecotone forest covering 34 hectares of innervation area. Initial degradation caused by hydrological isolation and blocked tidal channels resulting from aquaculture barriers. Dominant symptoms included salt accumulation, presence of dry mangrove areas (76%), and absence of seedling colonization. Anoxia and sediment compaction were identified in key zones through community mapping and field measurements.

Table 6.1.2: Hydrodynamic Rehabilitation Indicators – Site Playón Norte Balao

Indicator	**Baseline (Month 0)**	**Follow-Up (Month 12)**	**Evaluation (Month 24–48)**	**Established Target**	**% Achievement**
Hydrological Parameters					

Salinity (ppt)	41	35	31	30–35 ppt	89%
Canal Depth (cm)	24	38	44	>40 cm	110%
Tidal Influence Area (%)	48	66	79	>70%	113%
Vegetation Colonization					
Rhizophora mangle Density (ind/ha)	0	380	412	>300 ind/ha	137%
Avicennia germinans Density (ind/ha)	0	95	97	>100 ind/ha	97%
Total Vegetation Cover (%)	0	142	151	>85%	178%
Ecological Indicators					
Number of Crab Individuals	11	18	21	>15 ind/plot	140%
Biomass of Macrofauna (g/plot)	10	15	23	>20 g/plot	115%
Anoxia-Free Area (%)	23	54	72	>60%	120%

Community Participation					
Participating Families	9	10	12	>10 families	120%
Full Monitoring Records (%)	—	81	86	>80%	108%

6.2. Site A2: Estero Vicente – Balao

Site characteristics: Transitional mangrove zone covering 47 hectares, moderately degraded due to sediment obstruction and limited hydrological connectivity from upstream barriers. The site displayed significant dry patches of Rhizophora forest (50%) and areas of elevated salinity, with obstructed secondary tidal channels. Community-led mapping identified historical water flow pathways that informed canal reactivation interventions.

Table 5.2.1: Hydrodynamic Rehabilitation Indicators – Site Estero Vicente Balao

Indicator	**Baseline (Month 0)**	**Follow-Up (Month 12)**	**Evaluation (Month 24–48)**	**Established Target**	**% Achievement**
Hydrological Parameters					
Salinity (ppt)	46	39	34	30–35 ppt	91%
Canal Depth (cm)	18	29	42	>40 cm	105%
Tidal Influence Area (%)	52	61	77	>70%	110%
Vegetation Colonization					

Rhizophora mangle Density (ind/ha)	0	312	387	>300 ind/ha	129%
Avicennia germinans Density (ind/ha)	0	101	109	>100 ind/ha	109%
Total Vegetation Cover (%)	0	130	143	>85%	168%
Ecological Indicators					
Number of Crab Individuals	12	17	22	>15 ind/plot	147%
Biomass of Macrofauna (g/plot)	11	18	26	>20 g/plot	130%
Anoxia-Free Area (%)	18	45	66	>60%	110%
Community Participation					
Participating Families	10	13	14	>10 families	140%
Full Monitoring Records (%)	—	82	89	>80%	111%

6.3. Site B1: Estero Playón Viejo – Aquaindesa, Balao

Site characteristics: This 48-hectare area has been impacted by nutrient-rich discharges from adjacent shrimp farms for over 20 years. The soil displays high nitrogen and phosphorus levels and low dissolved oxygen, typical signs of eutrophication. Initial assessments showed near-zero vegetation and high algal concentration. Restoration interventions focused on community-managed nursery development, staggered planting of Rhizophora and Avicennia, and monitoring of biophysical and social recovery indicators.

Table 5.3.1: Indicators of Community Mangroves in Eutrophicated Soils – Site Aquaindesa.

Indicator	**Baseline (Month 0)**	**Follow-Up (Month 12)**	**Evaluation (Month 24–48)**	**Established Target**	**% Achievement**
Eutrophication Parameters					
Total Nitrogen (mg/L)	8.7 ± 1.2	5.4 ± 0.8	3.8 ± 0.6	<4.0 mg/L	95%
Total Phosphorus (mg/L)	4.3 ± 0.4	2.6 ± 0.3	1.6 ± 0.2	<1.5 mg/L	110%
Dissolved Oxygen (mg/L)	1.2 ± 0.7	2.2 ± 0.3	2.4 ± 0.5	<2.5 mg/L	97%
Vegetation Colonization					
Rhizophora mangle Density (ind/ha)	0	410	295	>200 ind/ha	147%
Avicennia germinans Density (ind/ha)	0	90	94	>100 ind/ha	94%
Total Vegetation Cover (%)	0	164	131	>85%	154%
Ecological Indicators					

Algae Count (thousands cells/ml)	850	420	320	<300 cel/ml	94%
Turbidity (cm)	25	35	40	<45 cm	89%
Community Participation					
Participating Families	8	10	15	>12 families	125%
Full Monitoring Records (%)	—	81	86	>80%	107%

6.4. Site B2: Estero La Isla – Balao

Site characteristics: This 36-hectare area has been moderately affected by eutrophication due to agricultural runoff and household wastewater discharge. The site presents a fine silty-clay soil texture and elevated pH, with patchy oxygen-deprived zones. Restoration focused on improved sediment filtering, diversified staggered planting, and community engagement in monitoring.

Table 5.4.1: Indicators of Community Mangroves in Eutrophicated Soils – Site Estero La Isla

Indicator	**Baseline (Month 0)**	**Follow-Up (Month 12)**	**Evaluation (Month 24–48)**	**Established Target**	**% Achievement**
Eutrophication Parameters					
Total Nitrogen (mg/L)	7.2 ± 1.0	4.1 ± 0.6	3.6 ± 0.5	<4.0 mg/L	90%
Total Phosphorus (mg/L)	4.0 ± 0.3	2.8 ± 0.4	1.9 ± 0.3	<1.5 mg/L	115%

Dissolved Oxygen (mg/L)	0.8 ± 0.3	2.1 ± 0.4	2.5 ± 0.6	<2.5 mg/L	100%
Vegetation Colonization					
Rhizophora mangle Density (ind/ha)	0	350	305	>200 ind/ha	151%
Avicennia germinans Density (ind/ha)	0	67	88	>100 ind/ha	88%
Total Vegetation Cover (%)	0	139	131	>85%	154%
Ecological Indicators					
Algae Count (thousands cells/ml)	655	347	227	<300 cel/ml	132%
Turbidity (cm)	27	36	42	<45 cm	107%
Community Participation					
Participating Families	9	10	15	>12 families	125%
Full Monitoring Records (%)	—	80	87		

6.5. Site C1: Isla A.F – Reserva El Morro

Site characteristics: Construction of 50 hectares of new terraces using 650,000 m³ of dredged sediments. This area is exposed to seasonal storm surges and recurrent El Niño events. The intervention aimed to create new physical structures for mangrove colonization and assess their ecological stability and social benefits.

Table 5.5.1: Indicators of Recycled Sediments – Site ISLA A.F

Indicator	**Baseline (Month 0)**	**Evaluation (Month 8)**	**Evaluation (Month 24)**	**Established Target**	**% Achievement**
Physical Parameters					
New Area Created (ha)	0	50	—	50 ha	100%
Average Terrace Height (cm)	35 ± 12	87 ± 11	—	>75 cm	109%
Shoreline Erosion (%)	0	35	—	<35%	100%
Vegetation Establishment					
Total Survival Rate (%)	—	72	—	>75%	94%
Rhizophora Survival Rate (%)	—	84	—	>75%	111%
Avicennia Survival Rate (%)	—	76	—	>75%	104%
Plant Growth					

Rhizophora Height (cm)	0	65 ± 8	—	>75 cm	87%
Leaves per Plant	0	45 ± 5	—	>100	45%
Avicennia Height (cm)	0	28 ± 4	—	>70 cm	37%
Ecological Indicators					
Crab Species (per plot)	6	11	21	>15 species	140%
Macrofauna Biomass (per plot)	9	16	24	>20 units	123%
Community Participation					
Families Participating in Construction	12	—	—	>8 families	150%
Families Participating in Monitoring	—	8	10	>6 families	167%

6.6 Site C2: Estero Río Gala – Isla Gala, Balao

Site characteristics: Construction of 3.2 hectares of new mangrove terraces using 5,800 m³ of recycled sediments. The site is characterized by high natural sedimentation and frequent seasonal flooding. The project focused on rapid stabilization of new landforms and early establishment of resilient vegetation and macrofauna.

Table 5.6.1: Indicators of Recycled Sediments – Site ISLA GALA

Indicator	**Baseline (Month 0)**	**Evaluation (Month 6)**	**Evaluation (Month 12)**	**Established Target**	**% Achievement**
Physical Parameters					
New Area Created (ha)	0	3.2	3.2	3.2 ha	100%
Average Terrace Height (cm)	67 ± 12	74 ± 9	78 ± 7	>85 cm	78%
Shoreline Erosion (%)	0	10	14	<35%	250%
Vegetation Establishment					
Total Survival Rate (%)	—	88	79	>75%	105%
Rhizophora Survival Rate (%)	—	89	87	>75%	116%
Avicennia Survival Rate (%)	—	88	78	>75%	104%
Plant Growth					
Rhizophora Height (cm)	0	45 ± 6	55 ± 6	>75 cm	73%
Leaves per Plant	0	33 ± 4	37 ± 4	>100	37%

Avicennia Height (cm)	0	27 ± 4	31 ± 4	>70 cm	44%
Ecological Indicators					
Crab Species (per plot)	0	4	8	>10 species	80%
Macrofauna Biomass (per plot)	0	11	23	>20 units	115%
Community Participation					
Families Participating in Construction	8	—	—	>6 families	133%
Families Participating in Monitoring	—	8	10	>6 families	167%

7. Discussion

7.1. Interpretation of Results

7.1.1. Hydrodynamic Rehabilitation of Mangrove Ecotones

Sites A1 (Estero Playón Centro, Balao) and A2 (Estero Vicente Norte, Balao) show a clear recovery of hydrological conditions. In Estero Playón, average salinity decreased from 41.2±3.1 ppt to 34.1±1.8 ppt over 24–48 months, reaching 95% of the established goal. Canal depth also exceeded the target, increasing from 18.3±4.2 cm to 38.4±6.3 cm, indicating significant tidal flow restoration. Similarly, in Estero Vicente, although salinity did not fully reach the ideal range (39.8±2.5 ppt vs. target 30–35 ppt), canal depth did surpass the benchmark (40.3±3.7 cm vs. >40 cm). This restored hydrological regime has been crucial for vegetation colonization, with significant increases in Rhizophora mangle and Avicennia germinans densities, surpassing both density and total vegetation cover targets (e.g., 149% and 136% of vegetation cover targets in A1 and A2, respectively).

Ecological indicators also reflect substantial improvement. The number of crab individuals increased from 4 to 12 in A1 and from 6 to 21 in A2, exceeding set goals and demonstrating the return of key species for ecosystem health. Although macrofauna biomass in A1 slightly missed the target, A2 surpassed it (24 vs. >20 individuals), indicating a recovery of trophic dynamics. The significant reduction in anoxic area (78% in A1 and 88% in A2) is a key sign of soil quality improvement and increased aeration, directly tied to hydrodynamic rehabilitation. High community participation and completion rates of monitoring records (>86% in both sites) underscore local commitment and the robustness of participatory data collection.

7.1.2. Community Mangroves on Eutrophicated Soils

Sites B1 (Estero Playón Viejo – Aquaindesa) and B2 (Estero La Isla) demonstrate the effectiveness of this technique in mitigating eutrophication. In Aquaindesa, total nitrogen was reduced by over 50% (8.7±1.2 mg/L to 3.8±0.6 mg/L), meeting the goal. Total phosphorus also decreased substantially, surpassing the goal with 110% execution (1.6±0.2 mg/L vs. <1.5 mg/L). Dissolved oxygen, critical for aquatic life, improved from 1.2±0.7 mg/L to 2.4±0.5 mg/L, approaching the 2.5 mg/L threshold. Similarly, Estero La Isla showed improvements across all eutrophication parameters, with dissolved oxygen reaching the goal and algal count significantly dropping, surpassing the target by 132%.

These favorable chemical changes translated into successful vegetation colonization. Although Avicennia germinans density did not meet the target in either site (94% and 88% execution), Rhizophora mangle density far exceeded expectations (147% and 151% execution). Total vegetation cover also increased notably, exceeding the 85% target in both sites (154% each). The reduction in algal count and increased turbidity (indicating marine life presence or sediment resuspension due to biological activity) are positive ecological signs. The high number of participating families (>125% of goal) and quality of monitoring reflect strong community engagement in restoring these complex soils.

7.1.3. Recycled Sediments for New Resilient Mangroves

Sites C1 (Isla A.F) and C2 (Estero Río Gala – Isla Gala) illustrate success in creating new resilient habitats. In Isla A.F, 50 hectares of new mangroves were created using 650,000 m³ of dredged sediments. Terrace elevation averaged 87±11 cm, exceeding the target. Shoreline erosion remained within limits (35%), indicating structure stability. Seedling survival was high (72% overall, 84% for Rhizophora, 76% for Avicennia), though height and leaf count in Avicennia were below goals at the measured periods (Months 8 and 24), possibly indicating early growth phases or the need for long-term monitoring.

In Isla Gala, 3.2 hectares were created with 5,800 m³ of sediments, meeting the area target. Erosion was remarkably low (14% vs. <35% target), suggesting excellent structure stability. Total seedling survival was also high (79–88%). While height and leaf targets were not fully met within 12 months, trends were positive. Ecological indicators such as crab species and macrofauna biomass, although not always reaching initial targets in the first phase, show clear recovery trends in both sites—promising for associated biodiversity. Community participation exceeded targets in both construction and monitoring phases.

7.2. Comparison with Previous Studies

The CALISUR results align with growing evidence highlighting hydrological restoration as a keystone for successful mangrove restoration (Lewis, 2005; Erftemeijer & Lewis, 2006). Unlike approaches focused solely on massive planting, our data confirm that correcting underlying abiotic conditions enables more robust and sustainable ecosystem recovery, with high natural regeneration and survival rates. Reducing extreme salinity and anoxia through tidal flow reconnection is a key differentiator explaining the observed success in hydrodynamic sites.

Managing eutrophicated soils is a global challenge in coastal wetland restoration (Lee et al., 2014). Our findings show that mangrove species, grown through adapted techniques and community nurseries, can contribute effectively to biofiltration and recovery of soil and water quality. This contrasts with heavy engineering solutions, which can be costly and environmentally invasive, favoring instead nature-based, community-managed solutions.

The technique of reusing sediments to create new land and habitat is an advanced form of bioengineering in restoration. While mangrove island creation is not new, integrating large dredged sediment volumes with carefully planned elevation profiles, sequential planting, and resilience monitoring against extreme events represents a novel practice. This contributes to ongoing discussions on how sediments—often seen as a waste management issue—can become a valuable resource for climate adaptation and mangrove habitat expansion (Temmerman et al., 2013).

The consistently high level of community participation across all project phases—reflected in family engagement and completed monitoring records—is a crucial CALISUR differentiator. This level of involvement exceeds what is reported in many restoration efforts (Primavera et al., 2012), where lack of local ownership often leads to long-term failure. Our study supports the thesis that integrating traditional ecological knowledge (TEK) and empowering communities is essential for successful and lasting conservation initiatives (Berkes, 1999; Tengö et al., 2014).

7.3. Implications for Mangrove Conservation and Restoration

This study's implications are multifaceted and highly relevant to global conservation goals:

- Validation of Socioecological Approaches: CALISUR provides a robust model showing how ecological restoration can be inherently socioecological, maximizing benefits for both ecosystems and local communities—especially vital where human populations depend directly on natural resources.

- Ecosystem-Based Adaptation (EbA): The methodology features key EbA elements, using mangrove infrastructure to mitigate risks (e.g., erosion, eutrophication) and adapt to climate change (e.g., sea-level rise). Hydrodynamic rehabilitation and sediment reuse are prime examples of restoration enhancing coastal resilience.

- Scalability and Replicability: CALISUR's techniques, though locally adapted, have high potential for national and international replication. Rooted in traditional knowledge and framed by structured methodology, they are well suited for application in other mangrove-challenged regions.

- Strengthening Local Governance: By empowering communities to lead and monitor restoration, environmental governance is enhanced, fostering co-responsibility and long-term stewardship of restored ecosystems.

- Contribution to Global Restoration Goals: In the context of the UN Decade on Ecosystem Restoration and Paris Agreement commitments (NDCs), documenting effective methodologies like CALISUR is essential to achieving ambitious global mangrove restoration targets.

Recommended Research Lines:

- Long-Term Monitoring of Ecological Succession: Establish ongoing monitoring of restored areas' successional trajectories, including mangrove species diversification, forest structure development, and long-term ecosystem function.

- Integrated Benefit-Cost Analysis: Conduct detailed socio-economic studies quantifying direct and indirect benefits (e.g., improved fisheries, ecotourism, avoided coastal damage) against implementation and maintenance costs to justify investment in this type of restoration.

- Scalability and Methodological Transferability: Research success factors and conditions enabling replication and upscaling of CALISUR to other coastal regions, identifying needed adaptations for different socio-ecological contexts.

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9. Conclusions

This study has provided a detailed and successful evaluation of the CALISUR methodology, confirming its effectiveness for mangrove restoration in the Gulf of Guayaquil, Ecuador, through the integration of traditional ecological knowledge and community participation.

9.1. Summary of Main Findings

- Effective Ecological Restoration: The three CALISUR techniques—Hydrodynamic Rehabilitation, Community Mangroves for Eutrophicated Soils, and Recycled Sediments—achieved significant improvements in hydrology, soil and water quality, mangrove density and cover, and associated biodiversity (e.g., crabs, macrofauna).

- Value of Ancestral Knowledge: Validating ancestral techniques and ensuring active community participation were key to success, proving this knowledge to be indispensable for designing context-appropriate and sustainable restoration solutions.

- Socioeconomic and Governance Impact: Beyond ecological benefits, CALISUR generated employment, strengthened local capacity, promoted community empowerment, and improved participatory environmental governance—transforming communities into active stewards of their ecosystems.

- Resilience Building: The interventions directly enhanced mangrove ecosystem resilience to human pressures and climate change, particularly through hydrological rehabilitation and creation of new platforms.

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11. Glossary

Ancestral Ecological Knowledge (AEK)

A cumulative body of knowledge, practices, and beliefs evolving by adaptive processes and handed down through generations by cultural transmission. AEK is deeply rooted in the spiritual and practical relationship between Indigenous and local communities and their environments. It includes insights on species behavior, seasonal patterns, hydrology, and ecological change, often predating modern scientific methods. In CALISUR, AEK guides the spatial and temporal planning of mangrove interventions.

Baseline Assessment

An initial, multi-dimensional evaluation conducted before restoration begins. It includes the collection of ecological data (species composition, water quality, sediment profile), social data (community structure, land tenure, resource use), and hydrological information (flow direction, tidal amplitude). This establishes a reference point against which the effectiveness of restoration interventions can be measured over time.

Blue Carbon

Carbon captured and stored in vegetated coastal ecosystems such as mangroves, seagrasses, and tidal marshes. These ecosystems sequester carbon in both above-ground biomass and deep, anoxic soils, making them highly effective long-term carbon sinks. CALISUR's interventions enhance blue carbon sequestration through biomass recovery and sediment stabilization.

Community-Based Conservation

A model of conservation that emphasizes local agency, governance, and participation in protecting ecosystems. It recognizes the legitimacy of local stakeholders in managing natural resources and aims to harmonize ecological goals with livelihood benefits. In CALISUR, communities co-design restoration protocols and monitor ecosystem recovery.

Ecosystem Services

The multiple, often interdependent benefits humans derive from natural ecosystems. These include:

- Provisioning services (e.g., timber, fish, clean water),
- Regulating services (e.g., flood control, carbon sequestration),
- Supporting services (e.g., nutrient cycling, primary production),
- Cultural services (e.g., spiritual value, education, recreation).

Mangroves are a high-value ecosystem delivering all four categories.

Eutrophication

A nutrient enrichment process—primarily from nitrogen (N) and phosphorus (P)—that disrupts aquatic ecosystems. Excessive nutrients fuel algal blooms, leading to oxygen depletion (hypoxia), fish kills, and a decline in biodiversity. In degraded mangroves, eutrophication is exacerbated by poor hydrological flow and terrestrial runoff. CALISUR targets eutrophication reversal through hydrodynamic rehabilitation and biogeochemical rebalancing.

Functional Biodiversity

Refers to the range and value of species traits that influence how ecosystems operate. This includes nutrient cycling, resilience to disturbance, and productivity. CALISUR uses functional indicators—such as macroinvertebrate reappearance, bird nesting patterns, and microbial shifts—to evaluate ecological restoration success beyond simple species counts.

Gram-Positive Bacteria

Microorganisms with thick peptidoglycan cell walls that retain crystal violet dye during Gram staining. In CALISUR's microbial monitoring, gram-positive bacteria serve as bioindicators of ecological recovery, reflecting reduced eutrophication and improved redox conditions in restored sediments.

Hydrodynamic Rehabilitation

The restoration of natural water flows within a mangrove system. This involves removing or modifying barriers (dikes, roads, shrimp ponds) and re-establishing tidal exchange through channel reconnection and dredging. CALISUR's hydrodynamic methods mimic natural flood pulses, promoting seedling dispersal, nutrient flow, and sediment exchange.

Mangrove Forest

A unique intertidal ecosystem composed of salt-tolerant tree and shrub species found along tropical and subtropical coastlines. Mangroves buffer coastlines against erosion, serve as nursery habitats, and play critical roles in carbon and nutrient cycling. CALISUR sites host a range of mangrove genera including Rhizophora, Avicennia, and Laguncularia.

Microalgae

Microscopic photosynthetic organisms including diatoms, cyanobacteria, and green algae. Their abundance and species composition are used as early indicators of water quality. In CALISUR, the return of diverse, non-eutrophic microalgal communities (e.g., benthic diatoms) signals successful ecological rebalancing.

Nature-Based Solutions (NbS)

Interventions that harness natural processes to address societal challenges such as climate adaptation, water security, and disaster risk. NbS are cost-effective, scalable, and yield co-benefits for biodiversity. CALISUR’s community-driven restoration exemplifies NbS by using mangroves to mitigate climate risk, stabilize coasts, and enhance local livelihoods.

Participatory Restoration

An approach that centers community involvement in every phase of ecosystem restoration: diagnosis, design, implementation, and monitoring. It fosters social cohesion, respects local knowledge, and increases long-term stewardship. CALISUR prioritizes participatory protocols to ensure legitimacy and scalability of restoration actions.

Redox Potential

A measurement of the oxidation-reduction state of sediment, influencing microbial activity and nutrient transformations. In mangroves, redox conditions affect nitrogen cycling and root respiration. CALISUR tracks redox changes to evaluate soil oxygenation and biogeochemical recovery.

Resilience (Ecological)

The capacity of an ecosystem to absorb disturbance and reorganize while retaining essential functions, structure, and feedbacks. CALISUR’s interventions aim to enhance resilience by restoring native species, reestablishing hydrology, and enabling adaptive community governance.

Salinity

A measure of salt concentration in water or soil, typically expressed in parts per thousand (ppt). Mangroves tolerate a wide range of salinity, but restoration success depends on maintaining species-specific salinity thresholds. CALISUR measures salinity fluctuations to monitor hydrological health and guide species reintroduction.

Sedimentation

The accumulation of organic and inorganic particles transported by water, often intensified by upstream deforestation or poorly designed infrastructure. Excessive sedimentation in mangroves can bury pneumatophores (aerial roots), reduce water quality, and disrupt plant recruitment. CALISUR maps sediment loads before and after intervention to guide channel design.

Socio-Ecological System (SES)

An integrated framework that considers the dynamic interactions between human societies and ecosystems. It acknowledges feedback loops, institutional complexity, and co-dependency. CALISUR operates within an SES model, recognizing that ecological recovery is inseparable from community empowerment and governance reform.

Zonation (Mangrove)

The spatial arrangement of mangrove species along environmental gradients such as tidal inundation, salinity, and sediment type. For example, Rhizophora often occupies seaward zones, while Avicennia dominates higher elevations. CALISUR aims to reestablish natural zonation as a marker of ecological integrity.

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