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Restoring Wetland Ecosystems in La Mojana, Colombia

An economic valuation of nature-based interventions for flood protection and sustainable development

NBI REPORT

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Restoring Wetland Ecosystems in La Mojana, Colombia: An economic valuation of nature-based interventions for flood protection and sustainable development

March 2023

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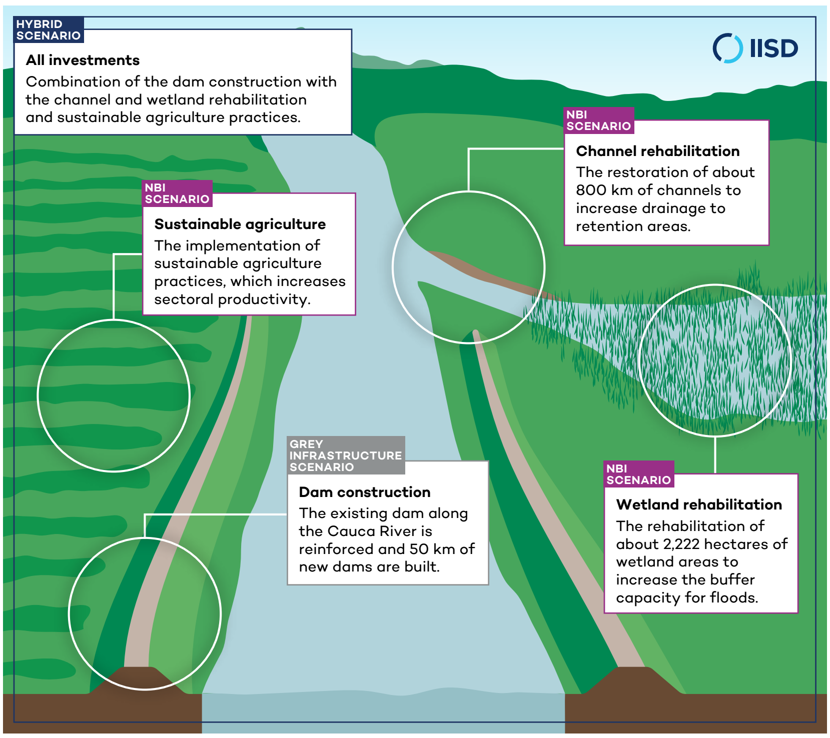
Executive Summary

IISD engaged with experts from the Department of National Planning (DNP) of Colombia to create a cost-benefit assessment of different flood mitigation measures in the La Mojana region. La Mojana is located in northern Colombia in the departments of Bolivar, Sucre, Antioquia, and Cordoba. The complex ecosystem collects water from three main rivers (the Magdalena River, Cauca River, and San Jorge River) and features extended swamps, marshes, forests, and canals. The project's footprint impacts 435,873 people living in 11 municipalities in La Mojana (Achí, Ayapel, Caimito, Guaranda, Magangué, Majagual, Nechí, San Benito Abad, San Jacinto del Cauca, San Marcos, and Sucre). These communities are part of four departments and span about 41,532 ha. Of the affected people, about 213,000 are women. Ongoing restoration activities in La Mojana specifically aim to foster women's empowerment and gender equality.

In contrast to its rich biodiversity, the region is one of the poorest and most vulnerable to climate change in Colombia. La Mojana is regularly affected by intense floods from the rivers and strong rainfall. Most recently, floods in August and September of 2021 affected about 180,000 people, damaged 7,000 ha of crops, and put 300,000 cattle at risk of drowning or starving.

In addition to devastating impacts on agriculture and livestock, the floods damage infrastructure and displace people from their homes. These effects seriously threaten livelihoods and food security in the region and cause health risks from water-borne diseases and disrupted care services. Across the region, about 500,000 people are exposed to flood risks and affected by the economic impacts of the disasters.

Figure ES1. Infrastructure options considered in the integrated assessment.



This assessment analyzes different flood mitigation options in the La Mojana region. It was conducted using scenario analysis, comparing the intervention scenarios against a base case in which no additional flood mitigation measures are considered. The DNP's current plan envisages a combination of interventions, including both built infrastructure (dam extension) and natural infrastructure components (e.g., channel and wetland rehabilitation). In addition to analyzing these combined interventions for flood mitigation, the assessment analyzes the impacts of specific interventions.

Table ES1 presents a summary of the integrated cost-benefit analysis (CBA) for each of the scenarios. The CBA presents cumulative investment, avoided costs, and added benefits relative to the business-as-usual (BAU) scenario in Colombian pesos (COP). The total investment required for implementing the respective scenarios considers the capital investment and operations and maintenance costs related to each of the interventions. Avoided costs consider avoided flood damages to buildings, roads, and agriculture; the cost of synthetic fertilizers; and the social costs of carbon. Total added benefits consider additional value added and labour from agriculture, as well as labour income from channel rehabilitation.

The combined implementation of dam construction and nature-based infrastructure (NBI) show the highest amount of total avoided costs and added benefits between 2022 and 2050. Cumulative avoided costs total COP 6,148 billion, and cumulative added benefits total COP 8,006 billion. In light of the total cost required (COP 2,486 billion) for implementation and maintenance, **this corresponds to avoided costs and added benefits of COP 5.69 per COP$_{invested}$**. It is noteworthy that the combined implementation of conventional and nature-based interventions yields synergies that amplify avoided costs and added benefits beyond those that are achieved at the individual level of each intervention. This is also confirmed by the results of the financial assessment, which indicates a net present value of COP 5,488 billion, with project-related net benefits generating an internal rate of return of 57% at the system level.

For the individual interventions, the **rehabilitation of channels** exhibited the highestratio of avoided costs and added benefits per COP$_{invested}$, with **COP 26.10 per COP$_{invested}$**. Cumulative avoided costs and added benefits between 2022 and 2050 total COP 2,314 billion and COP 1,860 billion, respectively. It should be noted that the effectiveness was calibrated based on a report published by the Instituto Humboldt Colombia (2019), which may have considered additional nature-based interventions.

Between 2022 and 2050, the **construction of the dam** yields cumulative avoided costs of COP 1.11 per COP$_{invested}$ and added benefits of COP 1.30 per COP$_{invested}$. This is equivalent to **total benefits of COP 2.41 per COP$_{invested}$** and corresponds to total avoided costs and added benefits of COP 1,336 billion and COP 1,565 billion, respectively.

The **rehabilitation of the wetland is projected to generate COP 1.42 per COP$_{invested}$ and COP 0.65 per COP$_{invested}$** in avoided costs and added benefits, respectively, between 2022 and 2050. On the other hand, due to the small scale of the wetland restored relative to the total wetland area, the cumulative amount of avoided costs and added benefits totals COP 100 billion and COP 45 billion, respectively.

Table ES1. Summary of the integrated CBA by scenario (values are cumulative COP from 2022–2050)

CBA output table La Mojana 2022–2050 (undiscounted)	Unit	Dam construction	Channel rehabilitation	Sustainable agriculture	Wetland rehabilitation	All investments
Total investments	bn COP	1,201	159.92	931	70	2,486
Total avoided costs	bn COP	1,394	2,314	12	59	6,148
Total added benefits	bn COP	1,506	1,860	2,573	86	8,006
Total benefits	bn COP	2,901	4,174	2,585	145	14,154
Avoided costs per $COP_{invested}$	bn COP	1.11	14.47	0.01	1.42	2.47
Added benefits per $COP_{invested}$	bn COP	1.30	11.63	2.76	0.65	3.23
Total benefits per $COP_{invested}$	bn COP	2.41	26.10	2.78	2.07	5.69

The results suggest that synergies can be realized through the integrated implementation of built infrastructure and NBI. The simultaneous implementation, as planned by the DNP, generates a significant amount of avoided costs and added benefits. While the expansion of the dam leads to the protection of vulnerable areas to flood water, the rehabilitation of channels and wetlands provides additional retention capacity and buffer zones in case of high tides. Both reduce the flood risk and the severity of flooding impacts and hence contribute to protecting the already vulnerable livelihoods in the La Mojana region.

The combined implementation of measures is also an economically sound decision to implement. The benefit-to-cost ratio (BCR) of COP 5.69 per $COP_{invested}$ highlights that the avoided costs and added benefits generated far outweigh the initial investment. In this context, it is noteworthy that the model does not consider extrabudgetary expenditure for emergency relief or health care, which indicates that the total benefits realized are even higher. Although there are no or few additional benefits in the form of direct financial revenues for the government, the internal rate of return of 60% indicated for the net benefits resulting from the implementation highlights that the combined implementation is a financially sustainable decision.

Table ES2. How stakeholders and decision-makers can use the results

Stakeholder	Role in the project	How can the stakeholder use the results of the assessment?
Government	Design and implementation of climate adaptation strategy	Policy-makers can use it to make decisions on climate adaptation planning, biodiversity and forest conservation, sustainable agriculture, and economic development. For example, the resulting BCRs provide information about the respective value for money that each intervention generates. The results suggest that the channel rehabilitation yields the best BCRs ratios, at COP 26.1 per $COP_{invested}$.
Research institutions	Knowledge dissemination	For analysts, this assessment, including the documentation of the model relationships and equations, showcases the use of an integrated approach for analyzing infrastructure solutions. The approach used may provide guidance for policy-makers and professionals in framing assessments and developing fitting methodological tools.

Glossary

Deep uncertainty: "A situation in which analysts do not know or cannot agree on (1) models that relate key forces that shape the future, (2) probability distributions of key variables and parameters in these models, and/or (3) the value of alternative outcomes" (Hallegatte et al., 2012)

Discounting: A finance process to determine the present value of a future cash value.

Indicator: Parameters of interest to one or several stakeholders that provide information about the development of key variables in the system over time and trends that unfold under specific conditions (United Nations Environment Program [UNEP], 2014a).

Internal Rate of Return (IRR): An indicator of the profitability prospects of a potential investment. The IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero. Cash flows net of financing give us the equity IRR.

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST): "A suite of models used to map and value the goods and services from nature that sustain and fulfill human life. It helps explore how changes in ecosystems can lead to changes in the flows of many different benefits to people" (Natural Capital Project, 2019).

Methodology: The theoretical approach(es) used for the development of different types of analysis tools and simulation models. This body of knowledge describes both the underlying assumptions used as well as qualitative and quantitative instruments for data collection and parameter estimation (UNEP, 2014).

Model transparency: The degree to which model structure and equations are accessible and make it possible to directly relate model behaviour (i.e., numerical results) to specific structural components of the model (UNEP, 2014b).

Model validation: The process of assessing the degree to which model behaviour (i.e., numerical results) is consistent with behaviour observed in reality (i.e., national statistics, established databases) and the evaluation of whether the developed model structure (i.e., equations) is acceptable for capturing the mechanisms underlying the system under study (UNEP, 2014b).

Nature-based infrastructure (NBI): Areas or systems that harness nature to provide infrastructure services for people, the economy, and the environment.

Net benefits: The cumulative amount of monetary benefits accrued across all sectors and actors over the lifetime of investments compared to the baseline, as reported by the intervention scenario.

Net present value (NPV): The difference between the present value of cash inflows net of financing costs and the present value of cash outflows. It is used to analyze the profitability of a projected investment or project.

Optimization: A stream of modelling that aims to identify the policy or set of policies that deliver the best possible outcome from a set of alternatives, given a set of criteria (i.e., parameters to optimize) and/or constraints (i.e., available budget) (UNEP, 2014).

Robust decision: A decision that produces favourable outcomes under a range of possible scenarios (Hallegatte et al., 2012)

Scenarios: Expectations about possible future events used to analyze potential responses to these new and upcoming developments. Consequently, scenario analysis is a speculative exercise in which several future development alternatives are identified, explained, and analyzed for discussion on what may cause them and the consequences these future paths may have on our system (e.g., a country or a business).

Simulation model: Models can be regarded as systemic maps in that they are simplifications of reality that help to reduce complexity and describe, at their core, how the system works. Simulation models are quantitative by nature and can be built using one or several methodologies (UNEP, 2014b).

Acronyms and Abbreviations

BAU	business-as-usual
BCR	benefit-to-cost ratio
CBA	cost-benefit analysis
CLD	causal loop diagram
CONPES 4076	Consejo Nacional de Política Económica y Social República de Colombia
DANE	Departamento Administrativo Nacional de Estadística
DNP	Department of National Planning
GIS	Geographic Information Systems
IGAC	Instituto Geográfico Agustín Codazzi
IRR	internal rate of return
O&M	operation and maintenance
NBI	nature-based infrastructure
NPV	net present value
PV	present value
SAVi	Sustainable Asset Valuation
SD	system dynamics

Table of Contents

1.0 Introduction **1**

1.1 About this Assessment 2

2.0 Methodology **4**

2.1 Causal Loop Diagram 5

2.2 System Dynamics Model 7

2.2.1 Reduced Infrastructure Damage From Flooding 7

2.2.2 The Value of Water Provisioning 7

2.2.3 Value Added From Agriculture and Livestock 8

2.2.4 Labour Income 8

2.3 Spatially Explicit Analysis 8

2.4 Financial Model 9

2.5 Main Data Sources 9

3.0 Scenarios and Assumptions **10**

3.1 Data Used to Calculate Specific Indicators 11

4.0 Results **14**

4.1 Overview of Socio-Environmental Indicators 14

4.2 Overview of Socio-Economic Indicators 21

4.3 Integrated Cost-Benefit Analysis 28

4.4 Financial Indicators 32

Conclusions **35**

References **37**

List of Figures

Figure ES1. Infrastructure options considered in the integrated assessment. iv
Figure 1. Infrastructure options considered in the integrated assessment 2
Figure 2. CLD of the main dynamics considered for the La Mojana assessment 6
Figure 3. Land-use projections by land use class 15
Figure 4. Total agriculture land – La Nina sensitivity analysis 17
Figure 5. Cumulative foregone agriculture production and cattle – La Nina sensitivity analysis 17
Figure 6. Cumulative foregone agriculture value added and labor income – La Nina sensitivity analysis 18
Figure 7. Average water retention indicator and water flow in the Cauca River 19
Figure 8. Flood indicator 20
Figure 9. Total value added 21
Figure 10. Total cropland and agriculture production 23
Figure 11. Cattle in the La Mojana region 24
Figure 12. Cumulative total flood damages – Monte Carlo results 26
Figure 13. Cumulative flood damages to buildings and agriculture – Monte Carlo results 26
Figure 14. Flooded cropland – Monte Carlo results 27
Figure 15. Cumulative value added from agriculture and cumulative labour income from agriculture – Monte Carlo results 28

List of Tables

Table ES1. Summary of the integrated CBA by scenario (values are cumulative COP from 2022–2050) vi
Table ES2. How stakeholders and decision-makers can use the results vii
Table 1. Main data sources used for the La Mojana assessment 9
Table 2. Overview of scenarios simulated and overarching assumptions implemented 10
Table 3. Parameters used to implement flood damages into the La Mojana SD model 11
Table 4. Overview of scenario assumptions by scenario simulated 12
Table 5. Average flood indicator for selected periods 20
Table 6. Average share of cropland flooded for selected periods (%/year) 22
Table 7. Flood impacts on roads and buildings for selected periods 25
Table 8. Avoided costs and added benefits analyzed for the La Mojana assessment 28
Table 9. Integrated cost-benefit analysis 30
Table 10. Overview of data used for the financial assessment 32
Table 11. NPV for each scenario 33
Table 12. BCR and IRR of net project benefits 34

1.0 Introduction

La Mojana is located in northern Colombia in the departments of Bolivar, Sucre, Antioquia, and Cordoba. Its complex ecosystem collects water from three main rivers (the Magdalena River, Cauca River, and San Jorge River) and features extended swamps, marshes, forests, and canals.

In contrast to its rich biodiversity, the region is one of the poorest and most vulnerable to climate change in Colombia. La Mojana is regularly affected by intense floods from the rivers and strong rainfall. Most recently, floods in August and September of 2021 affected about 180,000 people, damaged 7,000 ha of crops, and put 300,000 cattle at risk of drowning or starving (Department of National Planning [DNP], 2022).

In addition to the devastating impacts on agriculture and livestock, the floods damage infrastructure and displace people from their homes. This seriously threatens livelihoods and food security in the region and causes health risks from water-borne diseases and disrupted care services. Across the region, about 500,000 people are exposed to flood risks and affected by the economic impacts of the disasters (DNP, 2022).

In addition to floods, La Mojana is facing prolonged dry seasons that affect communities' access to water and their livelihoods from fishing and agriculture. The climate impacts are exacerbated by environmental deterioration, watershed degradation, and the physical and social vulnerability of human settlements in the area.

With increasing climate change, floods and droughts in the region are expected to become even more frequent and intense, underlining the urgent need for increased climate resilience. Government stakeholders and international organizations are therefore searching for infrastructure options that mitigate floods and water scarcity while supporting local livelihoods and healthy ecosystems.

Currently, a dam along the Cauca River has proven to be insufficient to protect the surrounding areas from floods. Regional policy-makers are considering reinforcing the dike and extending it by 50 km. Yet, this conventional, grey infrastructure solution raises concerns about its impacts on the sensitive wetland ecosystem.

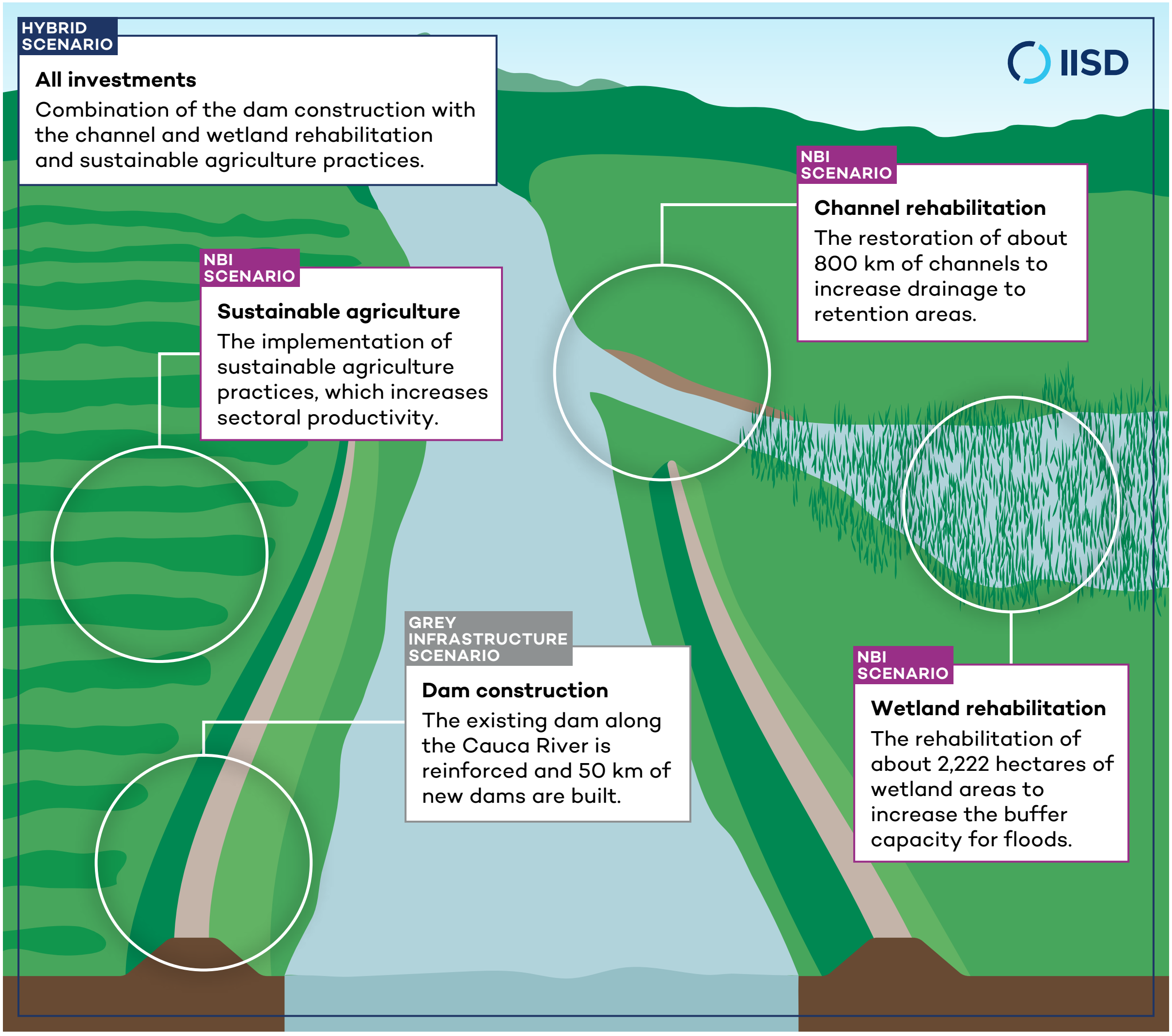
Alternatively, policy-makers, planners, and civil society organizations are exploring the potential of nature-based infrastructure (NBI) for climate adaptation and sustainable development in the region. Over the last few years, they have restored diverse canals between rivers and swamps to support the regulatory function of the wetlands. Further measures included reforestation and improved agricultural practices. The interventions are planned and implemented in a community-based approach and leverage Indigenous Knowledge from communities that have long lived in La Mojana.

1.1 About this Assessment

In this assessment, we analyze the performance of different infrastructure options used for flood mitigation in La Mojana:

- A grey infrastructure scenario in which the existing dam along the Cauca River is reinforced and 50 km of new dam is built.
- Two NBI scenarios that entail the restoration of channels to increase drainage to retention areas and a scenario that considers the rehabilitation of wetland areas to increase the buffer capacity for floods.
- A scenario that considers the implementation of sustainable agriculture practices that increase sectoral productivity but only marginally reduce flood damages.
- A scenario that includes the combination of the dam and NBI interventions. We compare these investments to a business-as-usual (BAU) scenario in which the existing dam remains unchanged, and no additional measures are taken.

Figure 1. Infrastructure options considered in the integrated assessment.



The range of interventions considered is quite diverse, and it should be highlighted that each of the interventions is conceived with a specific purpose in mind. While the analysis directly compares the performance of each intervention, the individual interventions have different but complementary systemic impacts. Moreover, the choice of scenarios for this assessment is consistent with the interventions considered by the DNP, with the aim of supporting their decision-making process. As a result, some of the investments may be small in comparison to others, and not all investments result in the same benefits for climate resilience.

For each option, we quantify the costs of action (investment and maintenance), direct benefits, and avoided costs of implementation. These calculations include a quantification of carbon sequestration benefits, avoided flood damages and health costs, job creation from the investment, and value added from crop and livestock production. The economic valuation is based on system dynamics (SD) and project finance modelling, as well as spatial analysis.

During the assessment, we worked closely with Colombia's DNP to collect data, customize the models, and verify the assumptions and results. Other stakeholders that were consulted in the process include the United Nations Development Programme, Green Climate Fund, Humboldt Institute, Integral SA, and local organizations and policy-makers.

The integrated economic valuation demonstrates the flood protection value and wider environmental and societal impacts of the NBI and dam construction. NBI's track record can help to mobilize investments and scale up such projects in the La Mojana region and beyond. The results can inform Colombia's National Development Plan, as well as policies on infrastructure, water management, and climate adaptation.

On the ground, the project impacts 435,873 people living in 11 municipalities in La Mojana (Achí, Ayapel, Caimito, Guaranda, Magangué, Majagual, Nechí, San Benito Abad, San Jacinto del Cauca, San Marcos, and Sucre). These communities are part of four departments and span about 41,532 ha. Of the affected people, about 213,000 are women (Departamento Administrativo Nacional de Estadística [DANE], 2022). Ongoing restoration activities in La Mojana specifically aim to foster women's empowerment and gender equality.

2.0 Methodology

For this assessment, we used the Sustainable Asset Valuation (SAVi) methodology with a combination of SD and geographic information systems (GIS) as core methodologies. The SD model is used to conduct a systemic assessment and analyze the impacts and resulting value for money generated by different intervention options. It captures cross-sectoral impacts to forecast and assess the impacts of action and inaction over time. Data generated by the SD model includes the quantification and economic valuation of social and environmental indicators. GIS is used to assess the spatial impacts of interventions on ecosystem extent, condition, and ecosystem service indicators. For this purpose, an updated land-cover map is created for each scenario, with and without interventions in place, to analyze how landscape-related impacts affect the future performance of the area.

The analysis compares results under several climate scenarios. However, given that the area defined for the assessment is receiving water flow data from the river, river flow data and flow data projections are used for this assessment. This choice is due to the high uncertainty in linking water flow data directly to precipitation, as upstream land use and use of water for hydropower generation affect river flow data.

For each scenario, we quantify the costs of action (investment and maintenance), direct benefits, and avoided costs. Specific benefits quantified in the assessment include

- Avoided flood damages
- Damages to buildings
- Damages to roads
- Value added from crop production
- Avoided losses due to flooding
- The effects of interventions on cropland and related value added
- Value added from livestock production
- Avoided losses due to flooding
- Job creation
- Carbon sequestration

2.1 Causal Loop Diagram

The analysis of flood mitigation measures using grey infrastructure and NBI in the La Mojana region requires the consideration of multiple dynamics that play out over time. The purpose of this assessment is to assess the effectiveness of different built and nature-based alternatives for flood mitigation. We have developed a causal loop diagram (CLD) in collaboration with project stakeholders at Colombia's DNP. The CLD (Figure 2) presents key indicators and outlines the key interconnections between them. It is an analytical tool that integrates information from sectoral experts and different sources to provide a more comprehensive view. This analysis allows for the exploration of feedback effects that may result from the implementation of interventions and how these effects ripple through the system. A CLD hence aids the identification of potential synergies between policies, as well as trade-offs between policies.

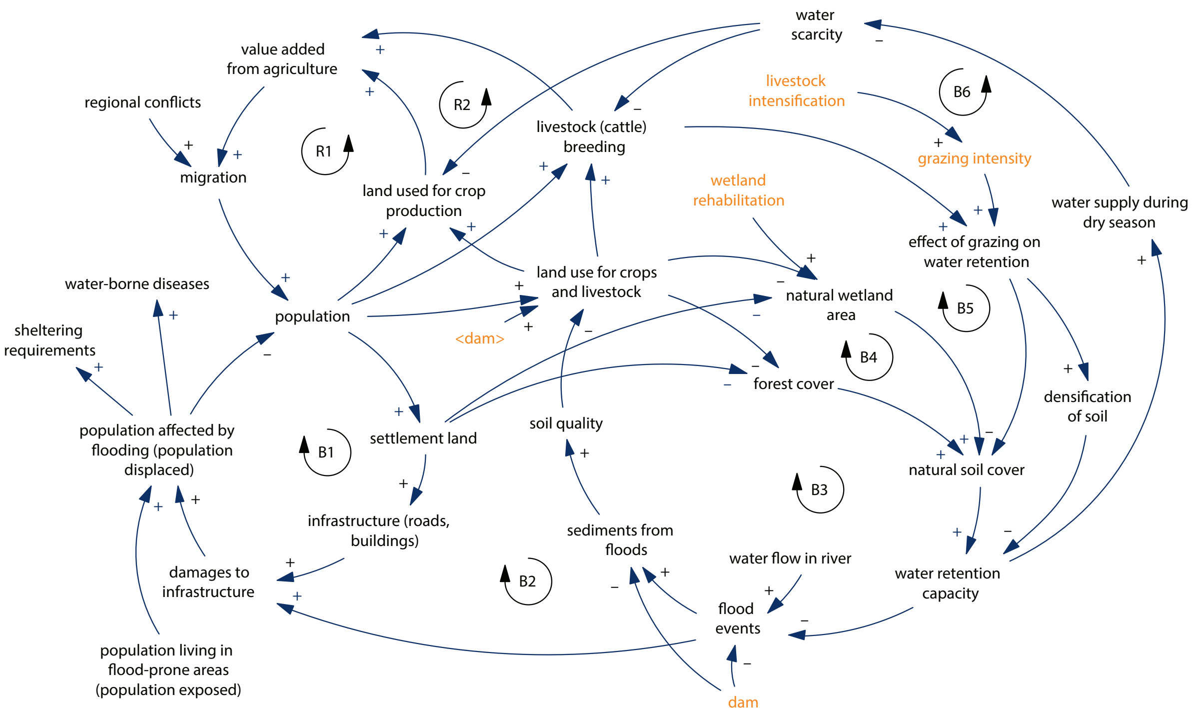
The CLD developed for the La Mojana assessment, as presented in Figure 2, illustrates the main drivers for the system that shall be analyzed in the form of feedback loops. Feedback loops can be reinforcing (R) and balancing (B), and their interactions determine the dynamics that occur in the system over time. To understand the impact of each feedback loop, each loop is analyzed in isolation from the others. Reinforcing feedback loops represent the main drivers of change and typically cause exponential growth or decline while balancing loops constitute the system's self-correcting properties or carrying capacity-induced limits to growth.

The La Mojana region was traditionally a floodplain that accumulated flood waters during the rainy season. However, over the last decades, the population in the floodplain has grown, which led to additional land conversion and economic activity. Additional land was converted for agriculture and livestock production, which generated income for the population and made the area attractive for migration. Further exacerbated by conflicts in other regions of Colombia, migration to the La Mojana region has increased, in turn leading to more demand for land for crop and livestock production (R1 + R2).

The population growth—along with the growth of urban areas and infrastructure, such as roads—has increased the potential for damage in case of flooding. As more roads and buildings were built, the probability and extent of damage during floods increased, and so did the number of people that were affected. As a result, the government needs to both act—to make the flood-prone areas less attractive for people to migrate to—and react, as people flood-affected people require shelter (B1).

Total population, population growth, and the regional dynamics caused by land conversion processes have also exacerbated the problem of flooding. The expansion of urban areas has come at the expense of natural soil cover that previously served as buffer areas for flood waters, such as forests and wetlands. This change has reduced the natural water retention capacity of the area and replaced it with densified, less permeable land cover, which increases runoff and hence the risk of flooding. As a result, in combination with higher population and infrastructure density, both flood risk and the severity of floods have increased (B2).

Figure 2. CLD of the main dynamics considered for the La Mojana assessment



The dynamics described as B1 and B2 have led to the implementation of built infrastructure for flood protection, in particular, a dam built to protect infrastructure and productive land. The construction of the dam, along with flood impacts and the loss of livelihoods, means that more land was converted for agricultural purposes. Agriculture is an important contributor to livelihoods in the La Mojana region, and cattle breeding has strong cultural roots in the flood plains. This additional increase in land used for agriculture exacerbated the problems described for (B2) and made even more land vulnerable to floods. Furthermore, by reducing flooding of the area, the dam also reduced fertile sediments that flood waters used to carry onto productive lands, which has increased the demand for land to maintain the same level of production due to reduced fertility (B3 + B4).

An additional effect of using the floodplain for economic production is the impact on cattle breeding. Cattle require pasture areas for feeding, which have grown over time to maintain and expand the herds. Cattle grazing causes soil densification over time due to the heavy weight of the animals and the removal of root biomass during the grazing process. This densification and reduction in root biomass cause more water to run off from pastureland than before, which in turn reduces the total water retention capacity of the area, increasing flood risk (B5) and leading to water scarcity impacts during the dry months of the year (B6).

2.2 System Dynamics Model

Given the spatial-temporal dynamics involved in the La Mojana region, an SD model was developed for this assessment. The SD model was used to forecast specific indicators required for the quantification of the direct and indirect costs and benefits of action and inaction, which were used to create an integrated cost-benefit analysis (CBA). The assessment emphasized the estimation of the cost of interventions relative to the cost of inaction to analyze the net additional investment required, the resulting avoided cost and added benefits that accrue for grey infrastructure (scenario 2), the use of nature-based alternatives (scenarios 3 through 5), and a combined scenario implementing all interventions at the same time (scenario 6). Furthermore, a simplified financial assessment was conducted to calculate the internal rate of return (IRR) and net present value (NPV) of the investments, both with and without social and environmental externalities. Selected indicators included in the SD model are presented next to provide more detail on the main model outputs presented in this study.

2.2.1 Reduced Infrastructure Damage From Flooding

Infrastructure damage was calculated for each scenario using historical flood damages and projections on expected damages generated by Integral SA (2018b). Infrastructure that can be affected by floods includes buildings, roads, bridges and dam(s). Damages to cropland and livestock are captured under the respective categories below. The change in flood (and drought) risk under the intervention scenarios leads to a change in related damages, indicating that a reduction in flood risk, and the actual number and severity of floods, will lead to a reduction in flood damages to infrastructure.

2.2.2 The Value of Water Provisioning

In addition to flood impacts and related damages, the La Mojana region has been experiencing more frequent droughts over the last decades. While there is an abundance of water during the flooding season, if water levels lower, water scarcity occurs. The interventions are assumed to have an impact on land use and land cover, which in turn affects the capacity of the wetland to store water that could potentially be used for productive purposes. For example, higher water availability during the dry season would prevent crop production losses due to water scarcity or increase the carrying capacity of the area for cattle production. The value of water provisioning will be calculated based on the change in water available for economic production and the average value added per litre of water, depending on the activity for which water will be made available.

2.2.3 Value Added From Agriculture and Livestock

Changing the way in which water flow—and hence flood risk—is managed affects how the area of interest can be used for productive purposes. Both crop and livestock production require suitable land for either farming or grazing. This implies that a change in total usable area induced by interventions envisaged translates into an increase or decrease in the suitable production area and hence total output. For crop production, there may be a reduction in total suitable area, however, with a lower risk of flood-related losses. The net benefit then depends on the reduction in production resulting from the loss of suitable land and the avoided production losses due to flood damages. For livestock production, the amount of pasture available and the livestock management practices used (conventional versus intensified) determine the total herd size and resulting environmental impacts. The total herd size, together with an average value-added multiplier per head of cattle, is used to determine the net change in value added from livestock production.

2.2.4 Labour Income

Total employment from both economic activity and the installation and maintenance of interventions depends on the changes induced by the interventions. This change in employment translates into changes in labour income—and, hence, discretionary income that would be spent in the economy. The change in labour income is assessed by comparing the change in employment and related income (e.g., from crop production, livestock production, forestry, etc.) in the intervention scenarios against the labour income generated in the BAU (no-action) scenario.

2.3 Spatially Explicit Analysis

In addition to the above, several analyses concerning the provisioning of ecosystem services and habitat quality were conducted (e.g., using the InVEST model). The results can primarily be used to inform potential impacts outside of the wetland boundary. The indicators assessed with InVEST were estimated based on the availability of GIS data (maps). The list of indicators assessed using spatial models includes

- Carbon storage
- Habitat quality
- Soil erosion (affects agriculture productivity)
- Sediment transport (potentially sediments leaving the wetland)
- Water retention
- Nutrient export (potentially water purification)

2.4 Financial Model

The objective of the financial analysis is to provide an estimate of the profitability of individual and combined infrastructure solutions when environmental, social, and economic externalities are considered. Thus, our financial modelling allows us to determine whether the four interventions are financially viable for generating expected returns.

Indicators such as NPV and IRR traditionally consider only investment and maintenance costs. Therefore, we depart from the classical modelling of these indicators by including additional factors, such as avoided costs and added benefits, in the calculation. Therefore, NPV and IRR reported in this assessment estimate the profitability of the projects in relation to their sustainability aspects.

NBI projects, such as wetlands, generally might not generate financial returns. However, as we observe in the CBA, additional positive externalities from wetland rehabilitation are delivered for the local community in the form of avoided damages to infrastructure, crop production, etc. Consequently, it can be extremely important to consider avoided costs and benefits in the financial assessment of the interventions.

We also analyze a fifth scenario in which the four interventions are all implemented simultaneously. This scenario provides an overview of the synergies created across the four projects in terms of financial viability and expected returns.

Finally, a benefit-to-cost ratio (BCR) analysis is also included in the assessment in order to show a large number of benefits compared to the associated costs of the interventions.

2.5 Main Data Sources

The main data sources used for the assessment are listed in Table 1.

Table 1. Main data sources used for the La Mojana assessment

Indicator(s)	Type of data	Reference
Total population	Time series/projection	DANE, 2022
Value added, total and by sector	GIS; 2000/2010/2018	Provided by DNP
Distribution of value added within agriculture	Time series	DANE, 2022
Water flow data	Time series	Based on FAOSTAT, 2022
Agriculture production	Time series	Obtained from DNP, based on Instituto Geográfico Agustín Codazzi, 2022
Water flow data	Time series	Institute of Hydrology, Meteorology and Environmental Studies (IDEAM)

3.0 Scenarios and Assumptions

Scenario analysis is used to compare different scenarios in which additional flood mitigation measures are assumed against a BAU scenario in which no additional flood mitigation measures are implemented. The BAU scenario hereby constitutes the scenario of inaction in which historical trends continue in the future, meaning that no additional mitigation measures are assumed and land-use change continues as it did historically. The BAU scenario represents the baseline scenario against which alternative scenarios in which flood mitigation measures are implemented are compared. Table 1 presents an overview of the scenarios simulated for this assessment; additional information about more specific assumptions implemented in each of the scenarios is presented in Table 2.

Table 2. Overview of scenarios simulated and overarching assumptions implemented

Scenario	Description
BAU	The BAU scenario is the baseline scenario in which no additional flood mitigation measures are implemented. This scenario constitutes the baseline scenario for an assessment of the costs and benefits resulting from the implementation of one or several interventions.
Dam construction	The construction (or expansion) of the dam increases the amount of land available for agricultural production. The dam is assumed to make 5,000 ha of land available for productive purposes. On the other hand, the dam is assumed to cause congestion in multiple channels that drain the wetland, reducing the potential for self-regulation and leading to a loss in water retention.
Channel restoration	Long before the construction of the dam, the population indigenous to the La Mojana floodplain had implemented a complex network of channels. These channels connected various areas and were used for flood water management; however, they have deteriorated over time. The channel rehabilitation scenario assumes that around 800 km of existing channels will be rehabilitated. This increases water exchange between flooded areas and buffer zones and contributes to reducing flood impacts on cropland, livestock, and infrastructure.
Sustainable agriculture	The implementation of sustainable agriculture practices increases the productivity of cropland and is assumed to be more labour intensive than conventional production practices. Further, sustainable cropland is assumed to have twice the water retention capacity of conventional land, contributing to a reduction in flood impacts on crop production.
Wetland restoration	The wetland restoration scenario assumes the rehabilitation of around 2,222 ha of encroached wetland. Rehabilitation of the encroached wetland area is assumed to increase the natural water retention capacity and reduce both flood risk and the impact of floods on crop production.
All-investments scenario	The all-investments scenario combines the dam construction, wetland restoration, sustainable agriculture, and channel restoration scenarios. This scenario is used to indicate the maximum potential impact resulting from the simultaneous implementation of interventions, including the dam. In summary, this scenario assumes: • The construction of the new dam • The rehabilitation of 800 km of channels • The restoration of 2,222 ha of wetland • The implementation of sustainable agriculture

3.1 Data Used to Calculate Specific Indicators

Flood risk and damages are calibrated using the information on the last flood reported in the Consejo Nacional de Política Económica y Social República de Colombia (CONPES 4076) report published by the DNP (2022). The information from this report was used in combination with national and sectoral statistics to estimate parameters used in the SD model for an estimate of flood damages, flood impacts on agriculture and infrastructure, and population affected (DANE, 2022; Instituto Geográfico Agustín Codazzi, 2022). The data used for generating flood-related impacts and their economic valuation are presented in Table 3.

Table 3. Parameters used to implement flood damages into the La Mojana SD model

Summary of parameters used to estimate damages and disaster risk	
Agricultural land*	
Cropland 2018, according to GIS	131,200 ha
Share of cropland flooded	26.5%
Land affected	34,721 ha
Summary from COPNES 4076	
Population of La Mojana 2021	450,461
People affected	126,800
Share of people affected	28.1%
Average # of people per household	3.451
Families affected (assumed homes)	36,747
Number of homes	36,747
Homes affected	2,969
Homes damaged	3,291
Homes destroyed	500
Share of homes affected	9.0%
Livestock affected*	
Cattle	6,757
Pigs	6,803
Horses	675
Poultry	40,287
Flood indicator	
Assumed water flow threshold for flood risk	3,000 m^3/s

Summary of parameters used to estimate damages and disaster risk

Cost parameter assumption	
Cost per km of road	10,000 USD
Average damage per building damaged	40,000,000 COP

*Crop and livestock are used to estimate foregone profits.

Table 4 summarizes information on assumptions concerning the costs and impacts of interventions implemented in each of the scenarios described in Table 2. The simulation of these assumptions leads to differences emerging between the scenarios presented in this report. Furthermore, the financial indicators presented in Table 4 are used as inputs to the financial assessment.

Table 4. Overview of scenario assumptions by scenario simulated

Scenario/assumption	Description/value	Source
Dam construction scenario		
Km of dam constructed	50 km	First team call on the project, 50 km of additional dam will be built
Cost of dam construction	COP 728.34 billion	Based on Integral SA, 2018a; Integral SA, 2018b
Dam maintenance cost	2.5% of capital investment per year	Assumption
Reduction in flood risk from dam	9.47%	Based on Integral SA, 2018a
Additional area unlocked for agriculture production	5,000 ha	Assumption
Km of channels blocked from building dam	1,000 km	Assumption; was discussed during one of the first meetings
Channel rehabilitation scenario		
Total km of channels in the area of analysis	4,500 km	Assumption
Average channel deterioration per year	1% of total km	Assumption
Cleanup of annual channels deteriorated	50% of deterioration rate	Assumption, leads to more and more congested channels over time
Km of channels rehabilitated	800 km	M. A. B. Paniagua, personal communication, June 2, 2022

Scenario/assumption	Description/value	Source
Total cost of channel rehabilitation	160 billion	M. A. B. Paniagua, personal communication, June 2, 2022
Average employment per km of channel restored	4.4 jobs/km	J. Bedoya, personal communication, September 24, 2021
Reduction in flood risk from the rehabilitation of channels	9%	Assumption, based on Instituto Humboldt Colombia, 2019
Sustainable agriculture		
Additional productivity	75%	Assumption, based on U.S. Agency for International Development, 2017
Reduction in fertilizer use	50%	Assumption
Water retention relative to conventional land	+25%	Assumption
Wetland rehabilitation		
Total wetland area rehabilitated	2,222 ha	M. A. B. Paniagua, personal communication, June 2, 2022
Cost per ha of wetland rehabilitated	18,001,800 COP/ha	M. A. B. Paniagua, personal communication, June 2, 2022

4.0 Results

The following key findings were obtained from the assessment:

- The combined implementation of dam construction and NBI showed the highest amount of total avoided costs and added benefits between 2022 and 2050. Cumulative avoided costs total COP 6,129 billion, and cumulative added benefits total COP 8,025 billion. In light of the total cost required (COP 2,486 billion) for implementation and maintenance, this corresponds to avoided costs and added benefits of COP 5.69 per $COP_{invested}$. It is noteworthy that the combined implementation of conventional and nature-based interventions yields synergies that amplify avoided costs and added benefits beyond those that are achieved at the individual level of each intervention.
- For the individual interventions, the rehabilitation of channels exhibited the highest ratio of avoided costs and added benefits per $COP_{invested}$, with 26.10 COP per $COP_{invested}$. Cumulative avoided costs and added benefits between 2022 and 2050 total COP 2,314 billion and COP 1,860 billion, respectively. It should be noted that the effectiveness was calibrated based on a report published by the Instituto Humboldt Colombia (2019), which may have considered additional NBIs. The results for channel rehabilitation should hence be regarded with care.
- Between 2022 and 2050, the construction of the dam yields cumulative avoided costs of COP 1.11 per $COP_{invested}$ and added benefits of COP 1.30 per $COP_{invested}$. This is equivalent to total benefits of COP 2.41 per $COP_{invested}$ and corresponds to total avoided costs and added benefits of COP 1,336 billion and COP 1,565 billion, respectively.
- The rehabilitation of the wetland is projected to generate COP 1.42 per $COP_{invested}$ and COP 0.65 per $COP_{invested}$ in avoided costs and added benefits, respectively, between 2022 and 2050. On the other hand, due to the small scale of the wetland restored relative to the total wetland area, the cumulative amount of avoided costs and added benefits totals COP 100 billion and COP 45 billion, respectively.

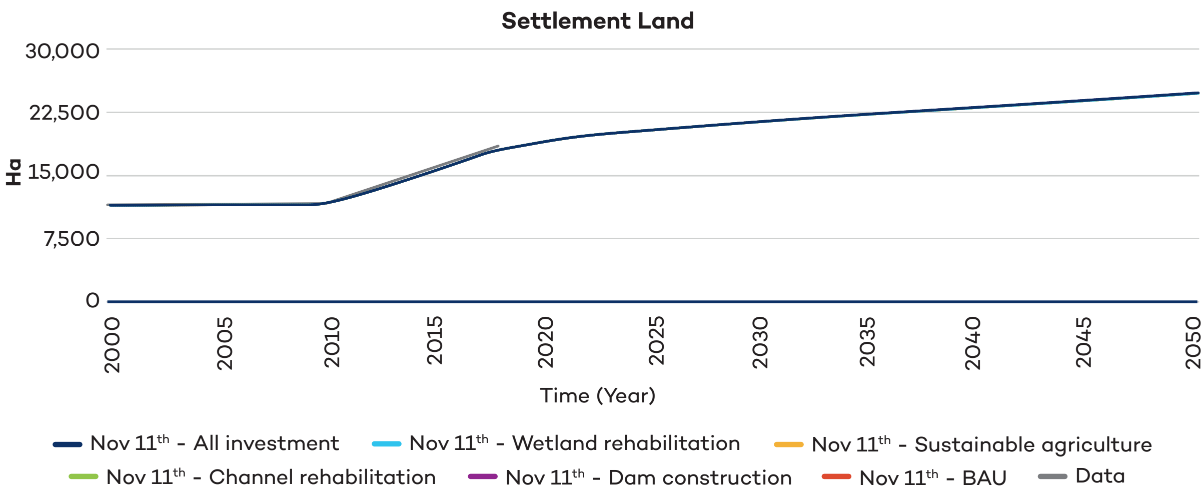
4.1 Overview of Socio-Environmental Indicators

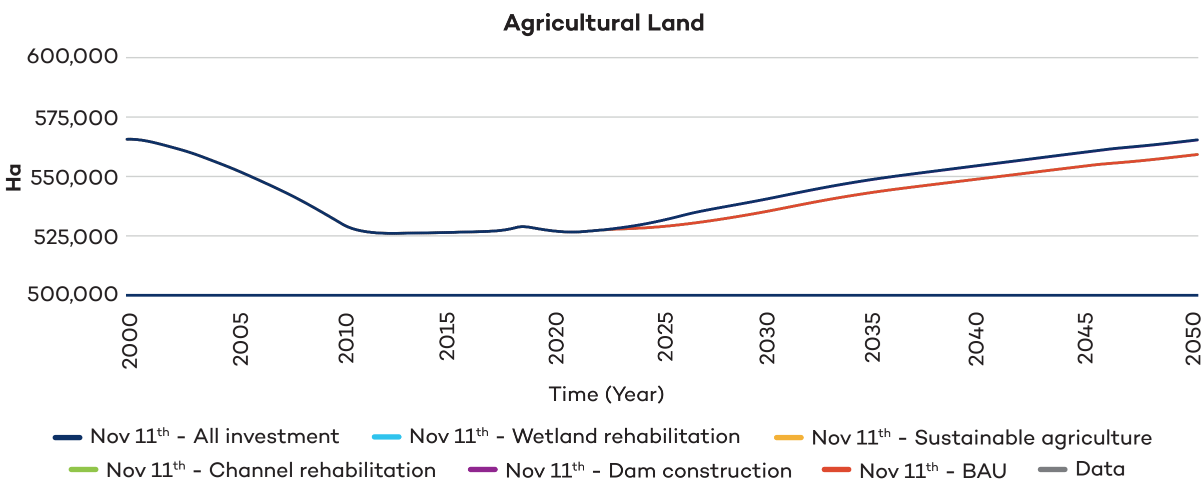
Population growth in the La Mojana model is calibrated to match the official government forecasts for Colombia until the year 2030 (DANE, 2022), and the average birth rate is kept constant at 1.7% per year after 2035. The total population of the departments analyzed for this study is projected to increase from around 447,800 people in 2020 to 568,750 people in 2050 in all scenarios. By 2050, this corresponds to a 27% increase compared to the year 2020.

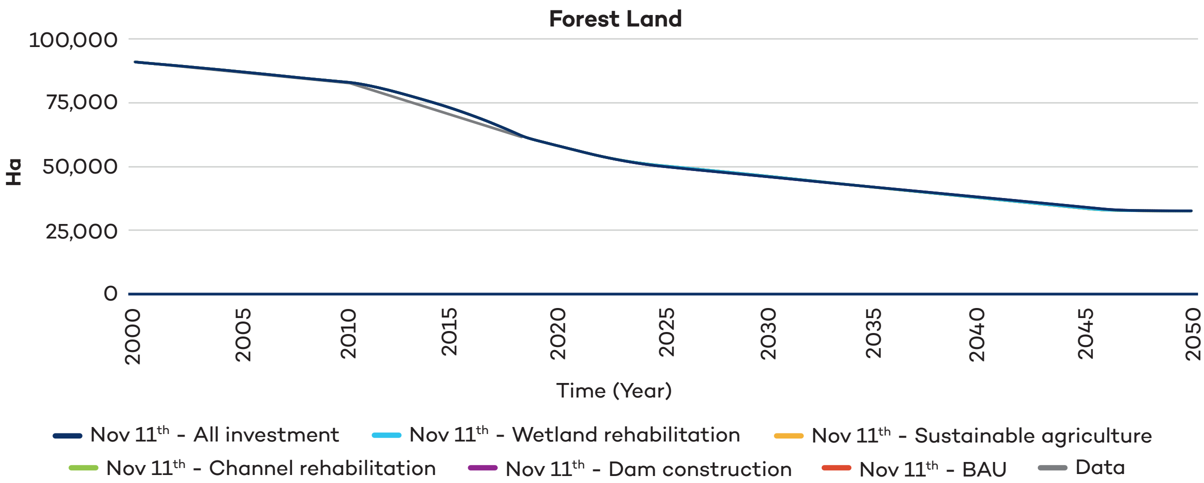
The change in population leads to an increase in total settlement and agricultural land in all scenarios. The projected land use, by land-use category, is presented in Figure 3. The results indicate that, across all scenarios, settlement land will increase by around 29% between 2020 and 2050, from 19,300 ha in 2020 to 24,900 ha in 2050. Agricultural land is projected to increase to 559,200 ha in all scenarios without dam construction (+6.2% versus 2020) from 527,700 ha in 2020. In the dam construction scenario and the all-investment scenario, additional agricultural land is unlocked through the implementation of the dam. In these two scenarios, total agricultural land is projected to reach 565,400 ha by 2050, which is 7.3% higher compared to 2020 and 1.1% higher compared to the BAU scenario.

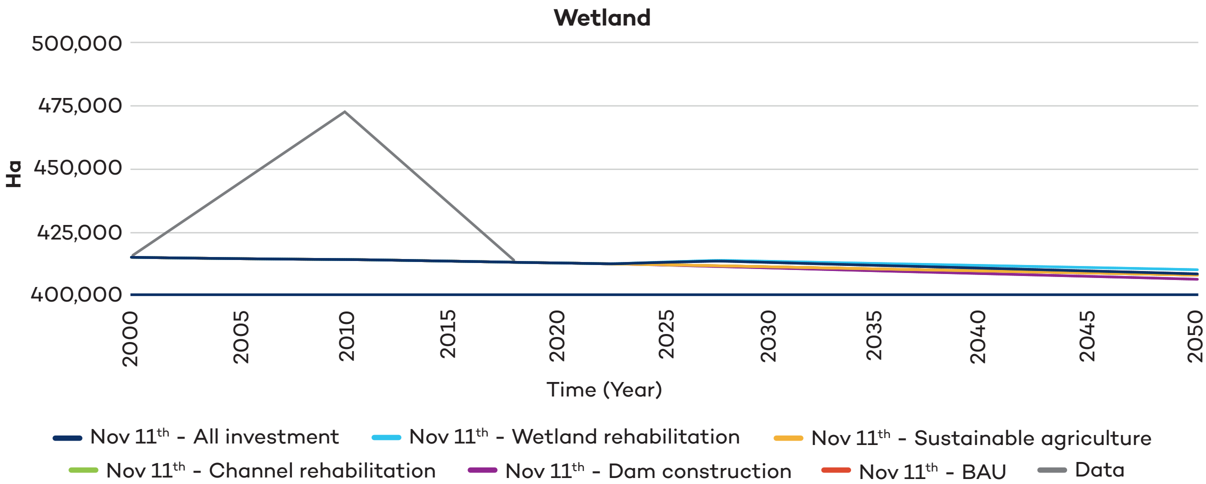
The expansion of urban areas and agricultural land comes at the expense of forest land and, to a lesser extent, fallow land and wetlands. Between 2020 and 2050, land conversion is projected to lead to a reduction of 25,400 ha in total forest land, around 4,900 ha of wetland and between 70 ha (no dam scenarios) and 6,750 ha (all-investment scenario) of fallow land.

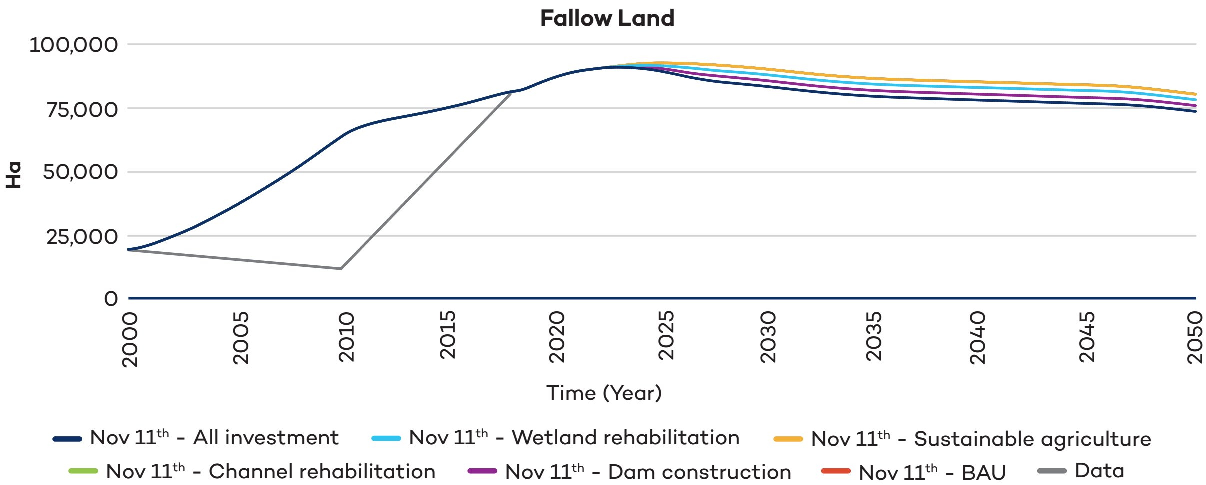
Figure 3. Land-use projections by land-use class






Forest Land
100,000
75,000
50,000
25,000
0
Ha
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Time (Year)
Nov 11th - All investment
Nov 11th - Wetland rehabilitation
Nov 11th - Sustainable agriculture
Nov 11th - Channel rehabilitation
Nov 11th - Dam construction
Nov 11th - BAU
Data

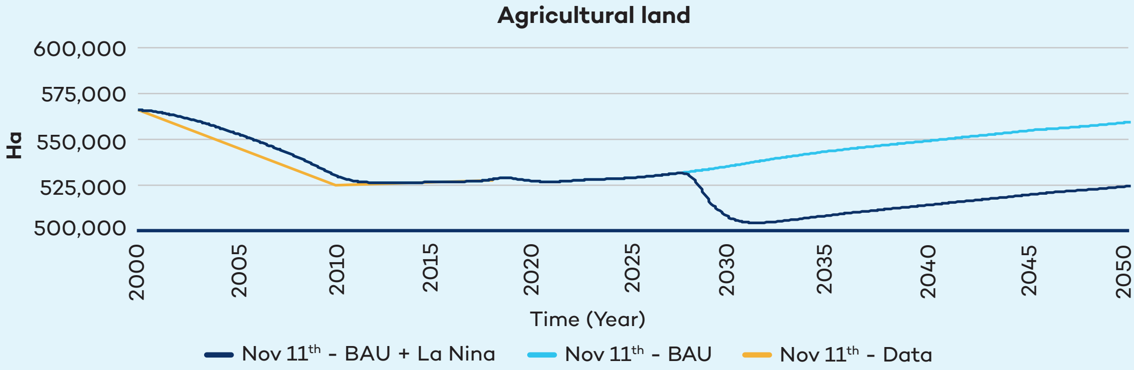

Wetland
500,000
475,000
450,000
425,000
400,000
Ha
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Time (Year)
Nov 11th - All investment
Nov 11th - Wetland rehabilitation
Nov 11th - Sustainable agriculture
Nov 11th - Channel rehabilitation
Nov 11th - Dam construction
Nov 11th - BAU
Data


Fallow Land
100,000
75,000
50,000
25,000
0
Ha
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Time (Year)
Nov 11th - All investment
Nov 11th - Wetland rehabilitation
Nov 11th - Sustainable agriculture
Nov 11th - Channel rehabilitation
Nov 11th - Dam construction
Nov 11th - BAU
Data

Box 1. Assessing the systemic impacts of La Niña climate dynamics

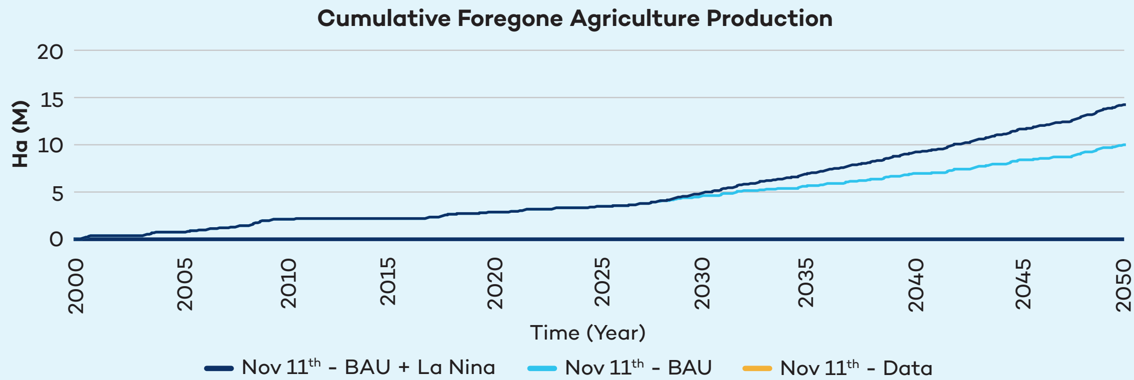
A sensitivity scenario was simulated that assumes that another La Niña impact will occur in the year 2028. This scenario assumes that the event in 2028 will lead to a reduction of 35,000 ha of agricultural land with corresponding impacts on agriculture production and employment. As a result, cropland and pastureland will decline proportionally, as presented in Figure 4.

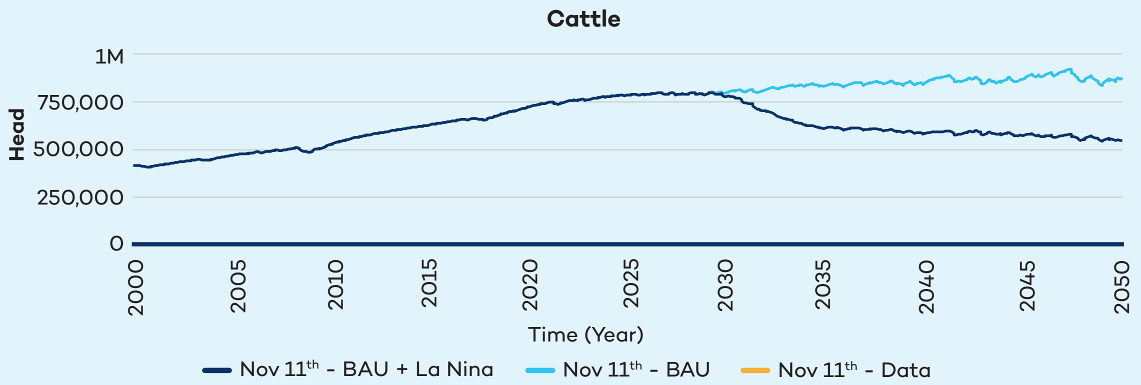
Figure 4. Total agriculture land – La Nina sensitivity analysis



The cumulative foregone agriculture production and the total amount of cattle projected for the baseline scenario and the BAU + La Niña scenario are presented below. The reduction of agricultural land occurring in 2028 leads to a bifurcation between the cumulative foregone production in the BAU and the La Niña scenario. By 2050, the loss of land through La Niña increases the cumulative foregone production from around 10 million tonnes in the BAU scenario to 14.2 million tonnes in the BAU + La Niña scenario. At the same time, the loss of pastureland leads to a reduced carrying capacity for livestock production, leading to a total reduction of 37.6% in herd size in 2050 relative to the BAU scenario.

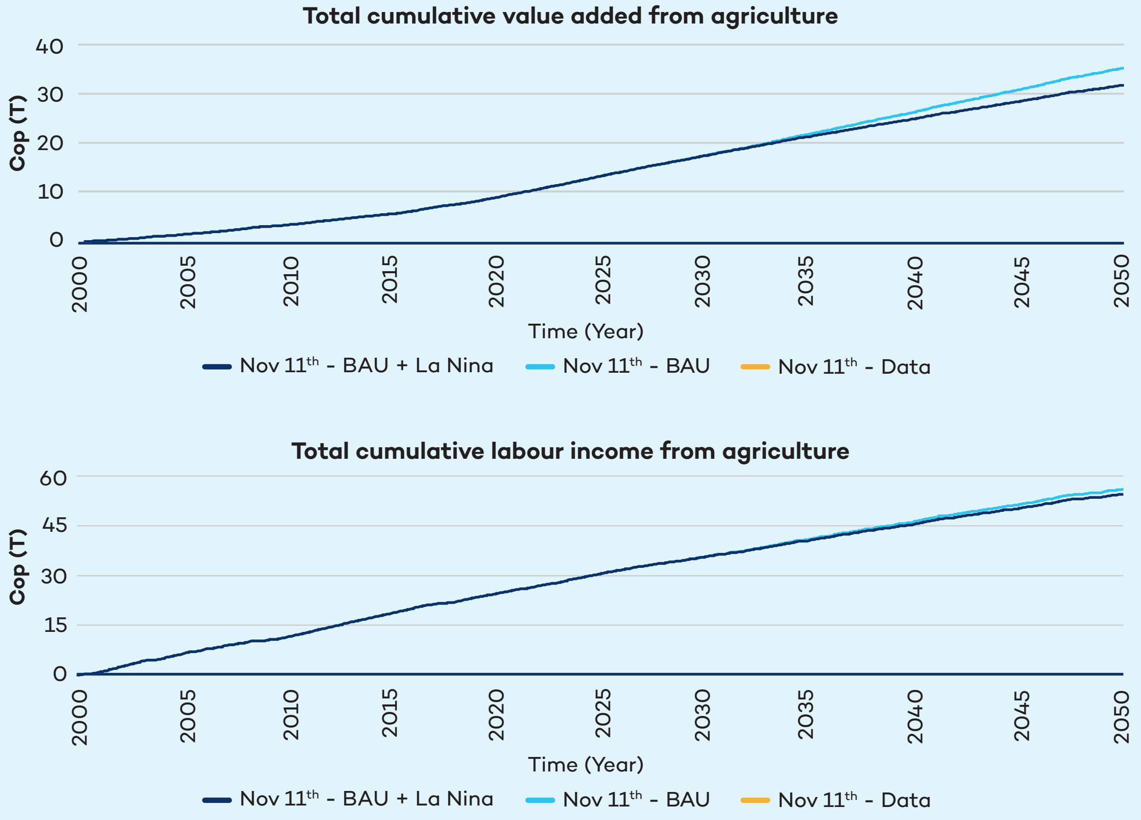
Figure 5. Cumulative foregone agriculture production and cattle – La Nina sensitivity analysis





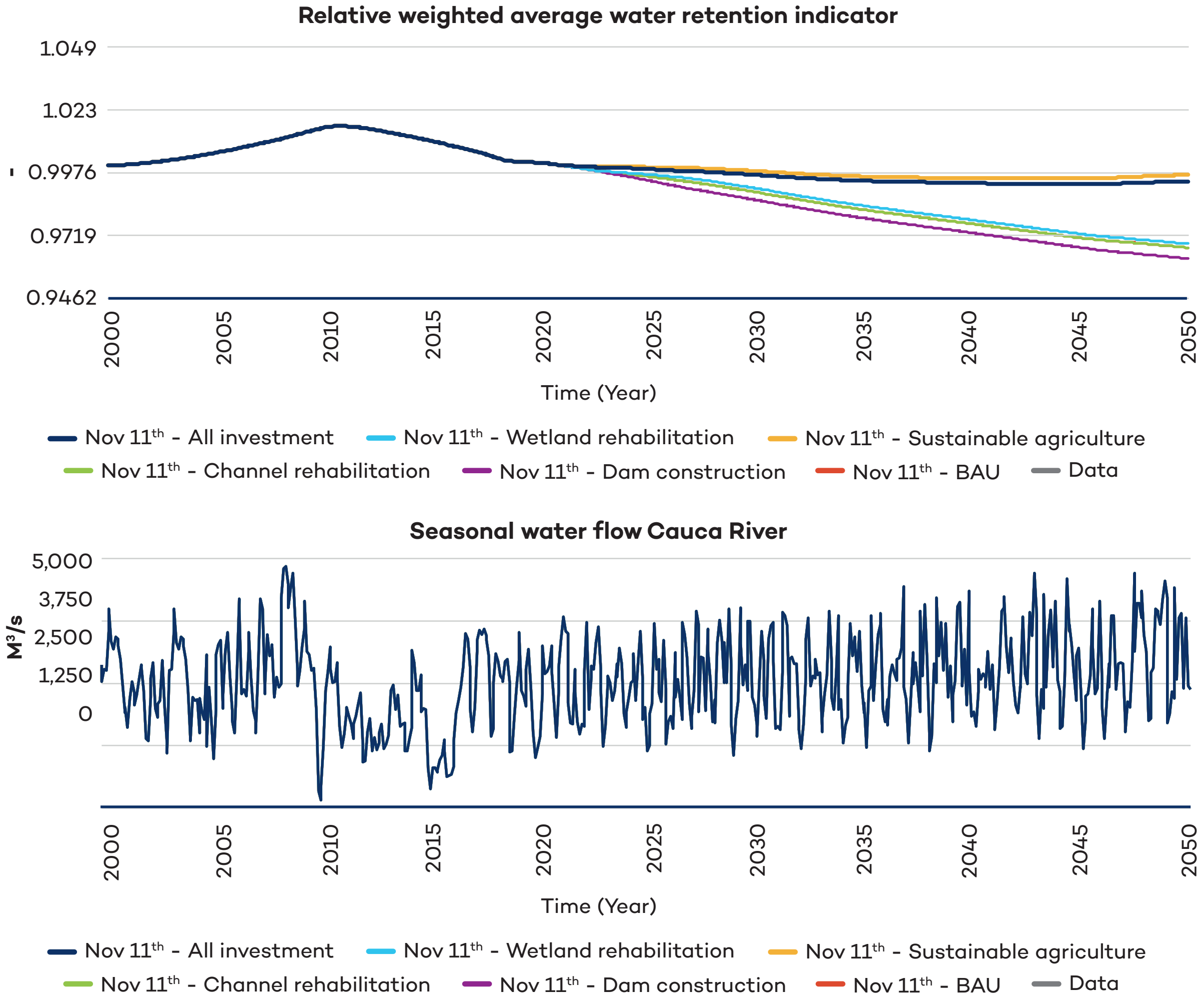
The reduction in land and production leads to a reduction in the cumulative agriculture value added and agriculture-related labour income. Cumulatively, between 2022 and 2050, the impact of La Niña reduces agriculture's real GDP and labour income by around COP 3.5 trillion and COP 1.5 trillion, respectively.

Figure 6. Cumulative foregone agriculture value added and labor income – La Nina sensitivity analysis



The change in land use to productive uses leads to an overall reduction in the area's ability to retain water, which is reflected in the decrease of the relative water retention indicator in the BAU, the dam construction, and the channel restoration scenario. In the sustainable agriculture and the wetland restoration scenario, the average water retention indicator is kept stable during the implementation phase from 2022 and 2030, after which it slightly declines. The resulting behaviour for the relative weighted average water retention indicator is presented in Figure 7 on the top.

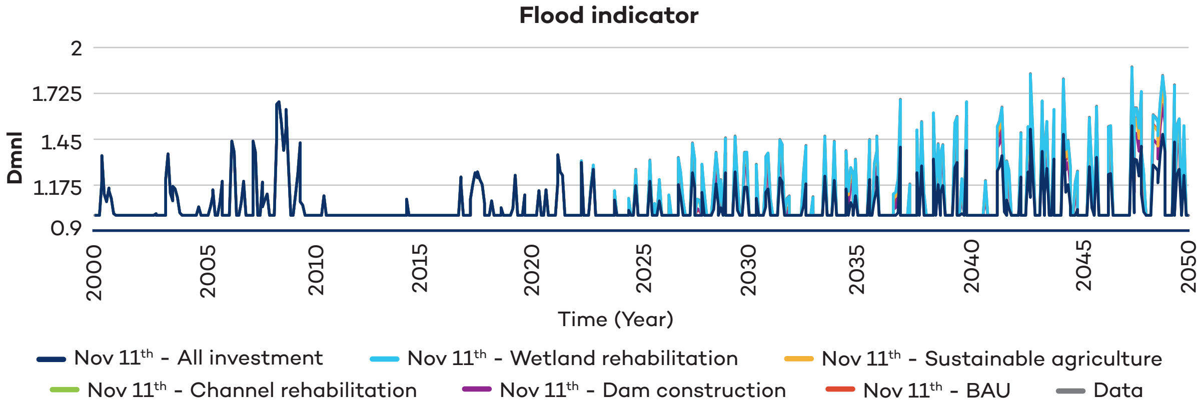
Figure 7. Average water retention indicator and water flow in the Cauca River



The seasonal water flow projected in all scenarios is presented in Figure 7 on the right. Historical measurement data is used for the period until the year 2019, after which the model generates the water flow projections endogenously. The simulations assume a 12.5% increase in average water flow for the decade between 2040 to 2050 relative to the decade from 2020 to 2030. In absolute terms, this means that the average water flow of the Cauca River will increase from 2,550 m^3/s (on a monthly basis) for the decade 2020–2030 to 2,870 m^3/s for the decade between 2040 and 2050.

The results for the flood indicator, which is estimated based on the water flow data in the Cauca River, are presented in Figure 8 and Table 5 below. The flood indicator is used to determine the impacts of flooding on agriculture production, livestock as well as infrastructure damages. The results show that all intervention scenarios lead to a reduction in the strength of floods, whereby the highest average reduction between 2022 and 2050 is observed for the all-investment scenario (-6.0% vs BAU).

Figure 8. Flood indicator



The strongest reduction in the flood indicator for any individual intervention scenario is indicated for the channel rehabilitation scenario, with a reduction of 2.9% relative to the BAU scenario, followed by the dam construction scenario with a reduction of 1.8%. This reduction in the flood indicator is reflected in reductions in flood-related productivity impacts and damages relative to the baseline scenario.

Table 5. Average flood indicator for selected periods

Average flood indicator	Unit	2020 –2030	2030 –2040	2040 –2050	2020 –2050
All investments	%/Year	1.039	1.042	1.084	1.057
% vs BAU	%	-3.3%	-5.9%	-8.3%	-6.0%
Wetland rehabilitation	%/Year	1.073	1.107	1.180	1.124
% vs BAU	%	-0.1%	-0.1%	-0.1%	-0.1%
Sustainable agriculture	%/Year	1.072	1.099	1.162	1.114
% vs BAU	%	-0.2%	-0.8%	-1.6%	-0.9%
Channel rehabilitation	%/Year	1.058	1.073	1.133	1.092
% vs BAU	%	-1.4%	-3.1%	-4.0%	-2.9%
Dam construction	%/Year	1.057	1.085	1.159	1.104
% vs BAU	%	-1.5%	-2.0%	-1.9%	-1.8%
BAU	%/Year	1.074	1.108	1.181	1.124

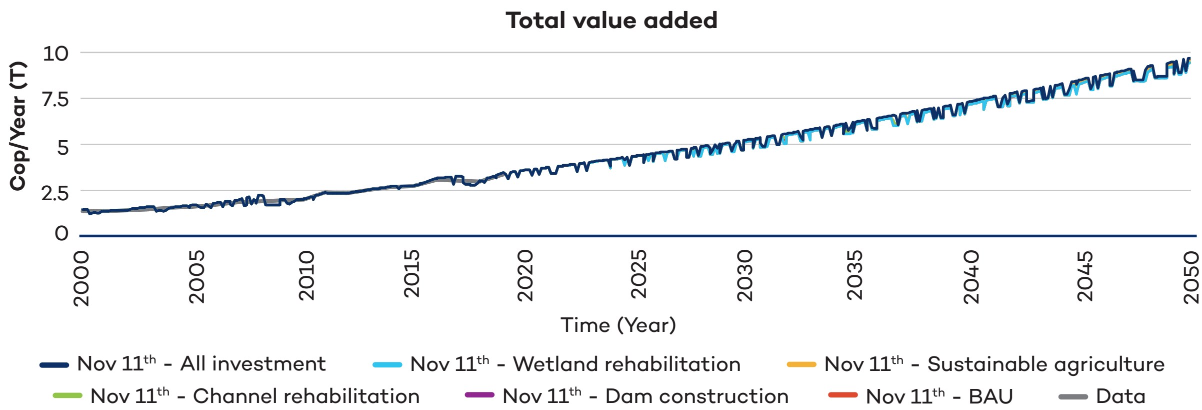
In summary, the implementation of interventions reduces projected flood damages. The dam, the rehabilitation of channels, and wetlands reduce the exposure and vulnerability to floods by (i) serving as a flood wall that diverts water, as is the case with the dam; (ii) increasing connectivity, which ensures that water can reach dedicated retention areas; and (iii) increasing the retention capacity of the area, induced by sustainable agriculture and the rehabilitation of wetland area.

4.2 Overview of Socio-Economic Indicators

The projections for total real GDP from agriculture, industry, and services of the departments in the La Mojana region are presented in Figure 9. For the productivity impacts of floods, only the agricultural production sector was assessed, as information on flood impacts was available from the DNP (2022). Between 2020 and 2050, the annual total real GDP in the BAU scenario averages COP 6.22 trillion per year. The implementation of interventions for flood mitigation reduces the volatility of growth and leads, on average, to a higher average GDP per year relative to the BAU scenario. In the absence of damages to capital and related impacts on total productivity, the implementation of sustainable agriculture practices has the biggest impact on total value added.

The largest gain is observed in the all-investment scenario, where the average real GDP between 2020 and 2050 is 2.2% higher compared to the BAU, which corresponds to an average of COP 136.65 billion in additional real GDP per year on average. The additional value added in the all-investment scenario is hence caused by a combination of reduced flood impacts on production and increased production from sustainable practices. The sustainable agriculture scenario is projected to increase the average value added per year by 0.96%, corresponding to an additional COP 59.82 billion in annual real GDP per year between 2020 and 2050. The channel construction scenario, the dam construction scenario, and the wetland rehabilitation scenario, on the other hand, are projected to increase average annual real GDP between 2020 and 2050 by 0.48% (COP 29.7 billion per year), 0.35% (COP 21.9 billion per year), and 0.02% (COP 0.96 billion per year) relative to the BAU scenario, respectively.

Figure 9. Total value added



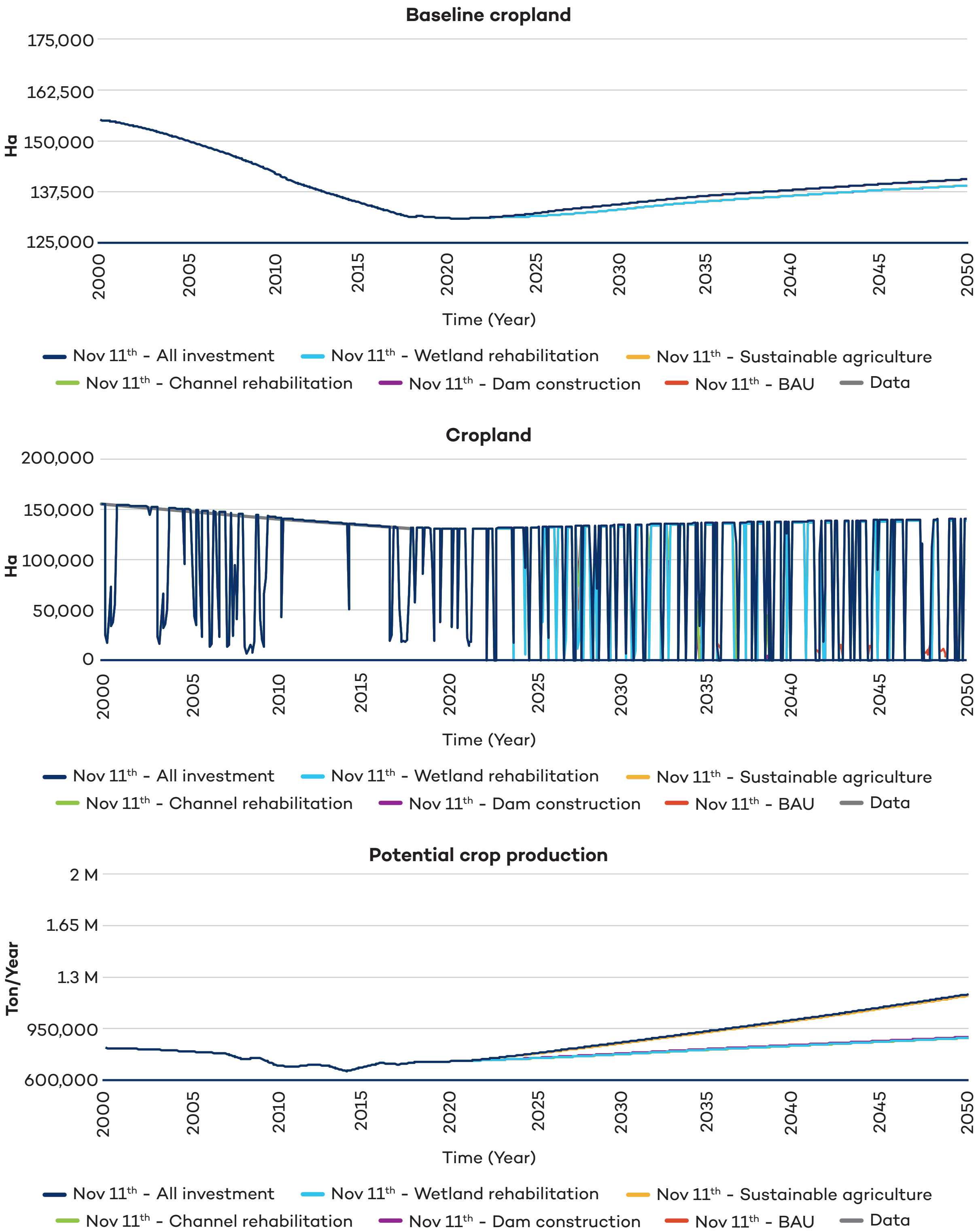
The main driver for the increase in total real GDP is the reduction of flood-related impacts on total agriculture production. Results for the average share of cropland that is flooded and the share of cattle herds lost due to floods are presented in Table 6. The results show that the reduction in the average share of cropland flooded between 2020 and 2050 ranges from 0.1% in the wetland rehabilitation scenario to 8.2% in the all-investment scenario. At the same time, the average annual share of cattle that is lost to floods is reduced by between 0.03% (wetland rehabilitation) and 2.3% (all-investment scenario).

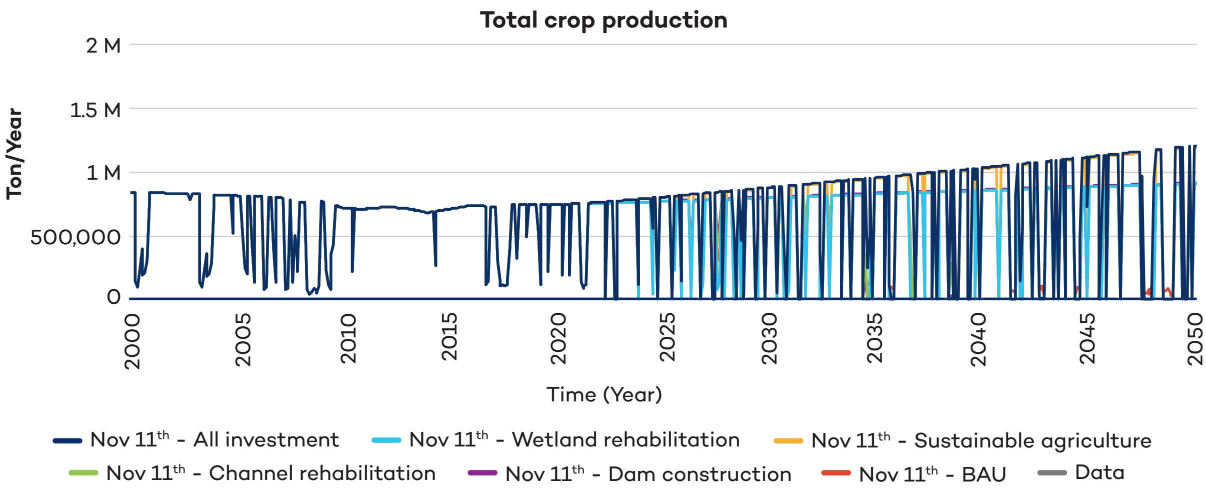
Table 6. Average share of cropland flooded for selected periods (%/year)

Flood impacts on agriculture	2020–2030	2030–2040	2040–2050	2020–2050
Average % of cropland flooded				
All investments	16.7%	16.4%	25.1%	20.0%
Wetland rehabilitation	23.9%	26.9%	32.1%	28.1%
Sustainable agriculture	23.7%	26.3%	31.6%	27.7%
Channel rehabilitation	21.6%	22.6%	30.4%	25.4%
Dam construction	21.1%	24.4%	31.5%	26.2%
BAU	24.0%	27.0%	32.1%	28.2%
Average % of cattle lost				
All investments	1.3%	1.4%	2.8%	1.9%
Wetland rehabilitation	2.5%	3.6%	6.1%	4.2%
Sustainable agriculture	2.4%	3.3%	5.5%	3.9%
Channel rehabilitation	2.0%	2.5%	4.5%	3.1%
Dam construction	1.9%	2.8%	5.4%	3.5%
BAU	2.5%	3.6%	6.2%	4.2%

Figure 10 shows total cropland and total crop production, with and without flood impacts. Flood impacts are estimated at a monthly level and subsequently averaged across the year. The resulting percentages are presented in Table 6. The graphs on the left in Figure 10 illustrate total cropland and total crop production without flood impacts, which are used to calculate the average productivity impacts presented in Table 7.

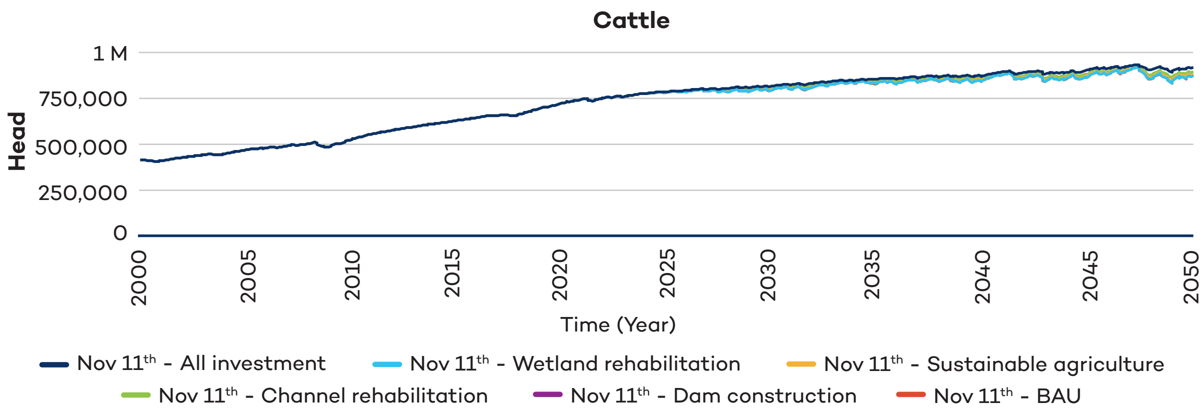
Figure 10. Total cropland and agriculture production





Similar to the impacts on crop production, the flood indicator is used to estimate the impacts on cattle, which is used as a proxy for total livestock in this assessment. In the BAU scenario, the average share of livestock lost due to flooding increases from around 2.5% per year for the period between 2020 and 2030 to 3.6% for the period between 2030 and 2040 and 6.2% for the period between 2040 and 2050. This increase in livestock lost due to flooding is driven by the increase in water flow assumed for the Cauca River and the resulting flood impacts on agriculture.

Figure 11. Cattle in the La Mojana region



The results obtained for flood impacts on roads and buildings are presented in Table 7 for all scenarios and selected time periods. For buildings, the projections indicate that the number of buildings affected by flooding will almost triple over the next 30 years, driven by the severity of floods and an increase in population. The average number of buildings affected in the BAU scenario increases from around 2,051 buildings per year during the period from 2020 to 2030 to an average of around 5,805 buildings per year for the period from 2040 to 2050. During the same period, the average number of kilometres of roads affected and damaged by flooding increases from around 6,613 km per year (2020–2030) to 9,597 km per year (2040–2050), which is an increase of around 45.1% per year.

Given the growth trajectory of population and the total number of buildings, the implementation of flood mitigation measures has the potential to reduce the average number of buildings affected by flooding between 2020 and 2050 by between 2.3% (wetland rehabilitation) and 54.2% (all-investment), depending on the scenario considered. At the same time, the total kilometres of roads affected by floods would be reduced by between 0.3% (wetland rehabilitation) and around 20% (all-investment scenario).

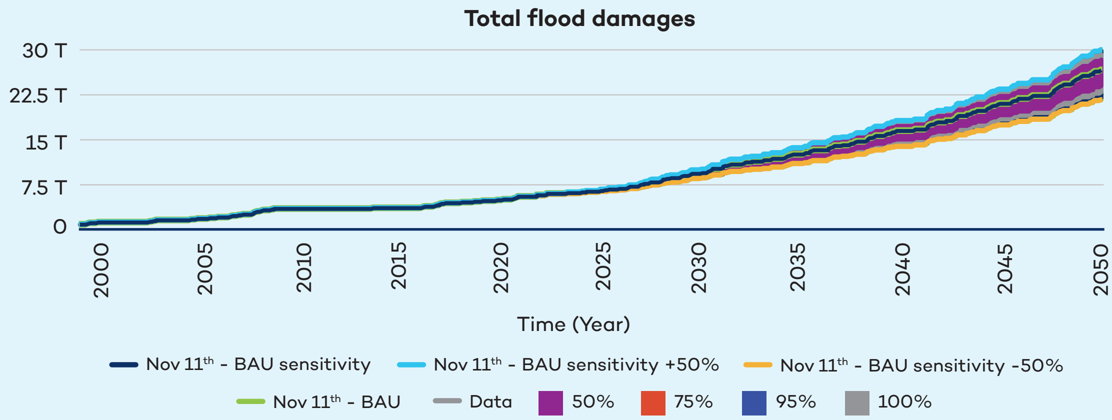
Table 7. Flood impacts on roads and buildings for selected periods

Climate damage to infrastructure	2020–2030	2030–2040	2040–2050	2020–2050
Buildings affected (buildings per year)				
All investments	1,069	1,246	2,689	1,742
Wetland rehabilitation	2,034	3,177	5,764	3,773
Sustainable agriculture	1,981	2,959	5,193	3,482
Channel rehabilitation	1,613	2,193	4,278	2,791
Dam construction	1,588	2,539	5,114	3,189
BAU	2,051	3,208	5,805	3,803
Amount of roads affected (km/year)				
All investments	5,189	5,463	8,354	6,506
Wetland rehabilitation	6,606	8,008	9,590	8,179
Sustainable agriculture	6,587	7,940	9,485	8,115
Channel rehabilitation	6,413	7,584	9,274	7,874
Dam construction	6,377	7,766	9,471	7,986
BAU	6,613	8,017	9,597	8,187

Box 2. Sensitivity analysis of damages

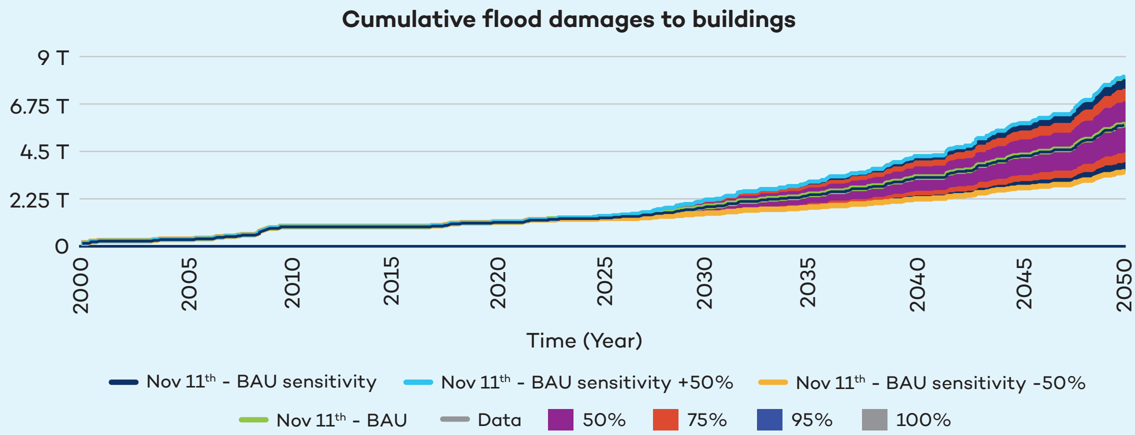
A sensitivity scenario was simulated to assess how damages and related costs would change if the parameters used were 50% higher or lower. A Monte Carlo simulation with 500 runs is used to perform this sensitivity analysis. The results show that cumulative flood damages between 2022 and 2050 resulting from the sensitivity analysis range from around COP 20.9 trillion and COP 29.4 trillion.

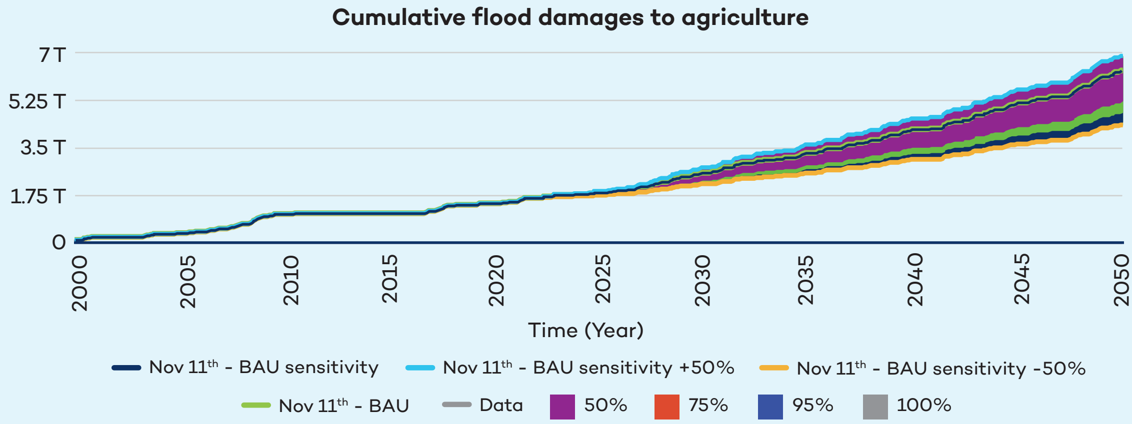
Figure 12. Cumulative total flood damages – Monte Carlo results



Over the same period (2022–2050), the cumulative damages to buildings range from COP 3.4 trillion to COP 8 trillion, while cumulative damages to agriculture range from around COP 4.2 trillion if flood damages are 50% reduced to COP 6.8 trillion of damages are 50% higher compared to the baseline calibration of the model. At the same time, cumulative flood damages to roads are indicated to range from COP 13.3 trillion to COP 14.6 trillion over the period 2022–2050.

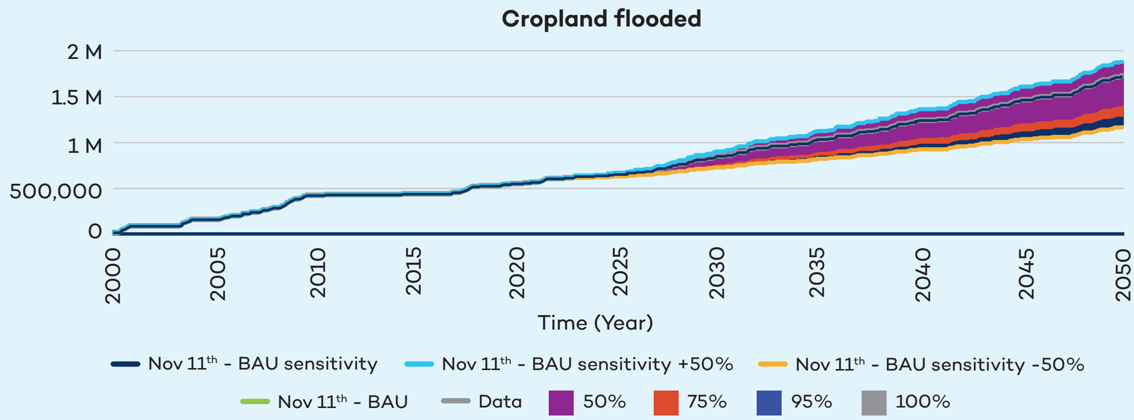
Figure 13. Cumulative flood damages to buildings and agriculture – Monte Carlo results





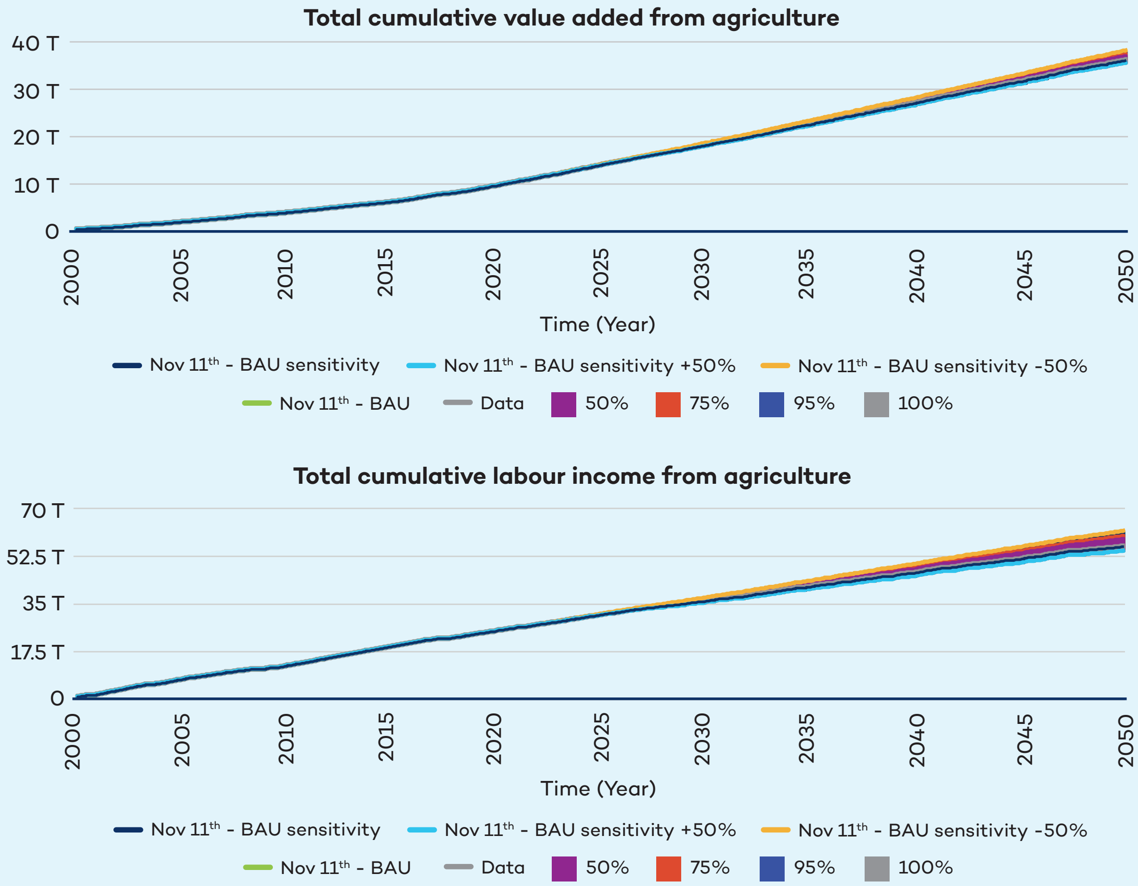
The sensitivity results indicate that the cumulative amount of cropland affected by floods between 2022 and 2050 ranges from around 0.99 million ha (-50% flood impact) to 1.57 million ha (+50% flood impact). This implies that the difference in the average annual amount of cropland flooded is around 20,700 ha per year.

Figure 14. Flooded cropland – Monte Carlo results



The change in agricultural land affected by floods also leads to higher value added and labour income from agriculture. The less cropland is flooded, the higher sectoral output and employment rates will be. While cumulative agriculture value added between 2022 and 2050 is indicated at COP 35.3 trillion, the sensitivity results indicate a range from COP 34.7 trillion (+50% flood impacts) to COP 37.3 trillion (-50% flood impacts). Cumulative labour income from agriculture follows the same trend, indicating a range from COP 53.8 trillion (+50% flood impacts) to COP 61 trillion (-50% damages).

Figure 15. Cumulative value added from agriculture and cumulative labour income from agriculture – Monte Carlo results



4.3 Integrated Cost-Benefit Analysis

The results of flood impacts presented in this report are used to estimate the total amount of flood damages in the BAU and investment scenarios for the purpose of estimating avoided costs and added benefits for each of the scenarios. The results for the flood mitigation scenarios are compared to the BAU scenario to estimate the net additional investment required for the implementation of interventions as well as net avoided costs and added benefits. Table 8 summarizes the parameters that are considered avoided costs and added benefits.

Table 8. Avoided costs and added benefits analyzed for the La Mojana assessment

Avoided costs	Added benefits
Damages to buildings	Value-added crop production
Damages to roads	Value-added livestock production
Damages to agriculture	Labour income livestock farming
Cost of fertilizers	Labour income crop production
Social cost of carbon	Labour income channel rehabilitation

Each of the intervention scenarios is compared against the BAU scenario to calculate the net avoided costs and added benefits, and the results are summarized in Table 9 (in billion COP, undiscounted). The total investment and operation and maintenance (O&M) costs required for the induvial interventions ranges from COP 70 billion for the rehabilitation of 2,222 ha of wetland to COP 1,201 billion in the dam construction scenario, making the dam by far the most expensive intervention in the mix. In the all-investment scenario, the cumulative investment required for implementing all ambitions totals COP 2,486 billion between 2022 and 2050.

The results indicate that, for individual interventions, the highest amount of avoided costs relative to the baseline are obtained in the channel rehabilitation scenario (COP 2,314 billion), followed by the dam (COP 1,336 billion), the wetland rehabilitation (COP 100 billion), and the sustainable agriculture scenarios (COP 12 billion), respectively. In the all-investment scenario, the total amount of avoided costs is indicated at COP 6,148 billion between 2022 and 2050, which indicates that the combination of grey and NBI yields synergies in preventing damages beyond the impacts of individual interventions. These synergies are realized by increasing flood protection through the dam on the one hand and increasing connectivity with buffer zones so that flood waters can be diverted on the other.

Finally, the total added benefits resulting from the implementation of interventions are the highest in the all-investment scenario (COP 6,148 billion). The second-highest benefits are realized in the sustainable agriculture scenario (COP 2,573 billion), driven by yield increases realized from the implementation of sustainable practices. On the other hand, thanks to improved connectivity and flood protection, the channel rehabilitation, dam construction, and wetland rehabilitation scenarios exhibit added benefits of COP 1,860 billion, COP 1,506 billion, and COP 86 billion, respectively.

The ratios for avoided costs per $COP_{invested}$, added benefits per $COP_{invested}$, and the avoided costs and added benefits per $COP_{invested}$ are presented at the bottom of Table 9. The avoided costs per $COP_{invested}$ range from 1.11 COP/$COP_{invested}$ in the dam construction scenario to 14.47 COP/$COP_{invested}$ in the channel rehabilitation scenario. The sustainable agriculture scenario indicates a ratio of 0.01 COP/$COP_{invested}$, as these practices boost productivity while increasing potential losses. At the same time, the added benefits per $COP_{invested}$ are indicated at between 1.30 COP/$COP_{invested}$ (dam construction) and 11.63 COP/$COP_{invested}$ (channel rehabilitation). The ratio of added benefits and avoided costs per $COP_{invested}$ ranges from 2.07 COP/$COP_{invested}$ in the wetland rehabilitation scenario to 26.10 COP/$COP_{invested}$ in the channel rehabilitation scenario. The all-investment scenario exhibits a ratio of avoided costs and added benefits of 5.69 COP/$COP_{invested}$. [1]

[1] It should be noted that the effectiveness was calibrated based on a report published by the Instituto Humboldt Colombia (2019), which may have considered additional NBIs. The results for channel rehabilitation should hence be regarded with care.

Table 9. Integrated cost-benefit analysis

CBA output table La Mojana 2022–2050 *(undiscounted COP billion)*	**Dam construction**	**Channel rehabilitation**	**Sustainable agriculture**	**Wetland rehabilitation**	**All investments**
Investment and cost					
Dam construction	**1,201**	**0**	**0**	**0**	**1,201**
Investment in dam construction	728	0	0	0	728
O&M cost of new dam	473	0	0	0	473
Channel rehabilitation	**0**	**160**	**0**	**0**	**160**
Investment channel rehabilitation	0	160	0	0	160
Wetland rehabilitation	**0**	**0**	**0**	**70**	**70**
Investment wetland rehabilitation	0	0	0	40	40
O&M cost of wetland rehabilitation	0	0	0	30	30
Sustainable agriculture	**0**	**0**	**931**	**0**	**1,055**
Investment in sust. agriculture	0	0	109	0	113
O&M of sust. agriculture	0	0	823	0	942
Total investments	**1,201**	**160**	**931**	**70**	**2,486**
Avoided costs					
Damages to buildings	763	1,257	399	37	2,562.7
Damages to roads	288	489	112	12	2,553.8

CBA output table La Mojana 2022–2050 *(undiscounted COP billion)*	**Dam construction**	**Channel rehabilitation**	**Sustainable agriculture**	**Wetland rehabilitation**	**All investments**
Damages to agriculture	369	596	-588	11	1,013.6
Cost of fertilizers	-26	-28	90	-1	17.6
Total avoided costs	**1,394**	**2,314**	**12**	**59**	**6,148**
Added benefits					
Value-added crop production	351	405	1,527	15	2,930
Value-added livestock production	125	178	56	5	378
Labour income livestock farming	19	27	8	1	58
Labour income crop production	1,069	1,171	982	24	4,580
Labour income channel rehabilitation	0	80	0	0	80
Social cost of carbon	-59	0	0	40	-19
Total added benefits	**1,506**	**1,860**	**2,573**	**86**	**8,006**
Total avoided costs and added benefits	**2,901**	**4,174**	**2,585**	**145**	**14,154**
Avoided costs per COP invested	1.16	14.47	0.01	0.85	2.47
Added benefits per COP invested	1.25	11.63	2.76	1.23	3.22
Avoided costs and added benefits per COP invested	2.41	26.10	2.78	2.07	5.69

4.4 Financial Indicators

The main purpose of the financial analysis is to assess the investment worthiness of a project when all the environmental, social, and economic benefits are counted. We demonstrate the investment worthiness of the four interventions through the calculation of the traditional NPV and IRR.

These externalities are accounted as revenue streams of the project by including avoided costs, indirect monetary benefits, and non-monetary benefits (see Table 10). This extension of traditional "direct cost only" investment analysis makes sense for decision-makers who want to take a more holistic approach when assessing whether the project would deliver value for money to society over its life cycle.

These results are presented in Table 10. Adding the avoided costs and other benefits to the calculation of the NPV improves results relative to the conventional approach across all four alternatives. The financial analysis also provides the results for a scenario in which all four interventions are implemented.

Table 10. Overview of data used for the financial assessment

Overview of data used *(Undiscounted COP billion)*	**Dam construction**	**Channel rehabilitation**	**Sustainable agriculture**	**Wetland rehabilitation**	**All interventions**
Direct project costs	-1,201.31	- 159.92	- 931.45	- 69.89	-2,485.80
"Avoided costs" benefits[2]	1,394.44	2,314.11	12.33	59.25	6,147.96
Indirect monetary benefits[3]	1,564.91	1,860.46	2,573.35	45.36	8,025.50
Non-monetary benefits[4]	-58.55	-0.03	-0.42	40.27	-19.07
Net project benefits	1,699.50	4,014.63	1,653.81	74.99	11,668.59

The analysis has been done on an uninflated 2001 prices basis. Furthermore, our financial analysis assumes a discount rate, excluding inflation, of 5% per year to determine the present value of costs and benefits at the time of intervention. Our calculations are based on a 30-year lifetime of the intervention.

[2] Includes avoided flood damages to buildings, avoided flood damages to roads, avoided flood damages to agriculture, avoided cost of synthetic fertilizers, and avoided cost of shelter for displaced population.

[3] Includes labour income from channel rehabilitation, added crop production value, added livestock production value, labour income from livestock farming, and labour income from crop production.

[4] Includes value of carbon emissions.

Table 11. NPV for each scenario

Indicator	Dam construction	Channel rehabilitation	Sustainable agriculture	Wetland rehabilitation	All interventions
Present value (PV) of direct project costs	-886.60	- 128.80	- 414.90	- 49.40	- 1,536.40
PV of "avoided costs" benefits	750.60	1,074.30	12.70	28.70	3,044.20
PV of indirect monetary benefits	923.30	1,014.70	1,137.80	25.30	3,985.40
PV of non-monetary benefits	- 39.30	- 0.10	- 0.30	34.40	- 5.40
PV of NET project benefits (NPV)	747.90	1,960.10	735.30	39.00	5,487.80

Looking at Table 11, NPV that takes into account only investment and maintenance costs (PV of net direct project benefits) is negative for all four types of interventions. However, NPVs for each intervention that integrate avoided costs and other added benefits show positive results—thus confirming that the four interventions are economically viable if non-tangible benefits are considered. The NPVs range from COP 39 billion for wetland rehabilitation to COP 1,960.10 billion for channel rehabilitation.

Looking at each individual intervention, channel rehabilitation performs better than the other three—although the most profitable scenario is observed when the four interventions are implemented together with an NPV of COP 5,487.80 billion (all interventions). It is also interesting to note that if each separated NPV intervention is summed together (last line in Table 11), the final value is lower than the NPV for *all interventions*. This means that if all four interventions were implemented together, they would generate positive synergies and, therefore, higher profitability.

In terms of IRR, based on all avoided costs and other added benefits, we obtained an IRR of 19% for the dam construction, 57% for the all-investments scenario, and 54% for wetland rehabilitation.

In order to provide a better picture of the value for money of the five options, a BCR was calculated and is represented in Table 12. The table shows that the benefits largely outweigh the costs for each type of intervention, with the highest benefit ratio delivered by the channel rehabilitation scenario (26.10).[5]

[5] If a project has a BCR larger than 1.0, then it is expected to be profitable. On the contrary, if the BCR lower than 1.0, the project is expected to be not profitable.

Table 12. BCR and IRR of net project benefits

Indicator	Dam construction	Channel rehabilitation	Sustainable agriculture	Wetland rehabilitation	All interventions
BCR	2.41	26.10	2.78	2.07	5.69
IRR of net project benefits	19%	*N/A	*N/A	54 %	57 %

**Due to the cumulative effects of the massive benefits and almost no net costs over the considered time frame, the IRR calculation for the channel rehabilitation and sustainable agriculture scenarios generated extremely high values that cannot be considered for this analysis. Values will need to be assessed for further validation.*

Conclusions

For this project, we engaged with experts from Colombia's DNP to assess different flood mitigation measures envisaged for the La Mojana region, with the aim of quantifying avoided costs and added benefits. A CLD outlining the main dynamics was developed in collaboration with the DNP and served as a blueprint for the development of the SAVi La Mojana model. The results show the BCRs for the individual interventions and the combined implementation of the measures envisaged. According to the results, the combined implementation of interventions yields a BCR of COP 5.69 per $COP_{invested}$, indicating that each COP invested yields 5.69 COP in system-wide avoided costs and added benefits. The spatial assessment conducted indicates that the exports of sediments and nutrients continue to increase, driven by the expansion of agricultural land in all scenarios. The change in land use induced by the expansion of agricultural land further leads to slightly lower carbon sequestration and water retention in both the BAU and dam construction scenarios.

The integration of Indigenous and conventional knowledge in this assessment deepens the thinking and analysis surrounding infrastructure planning and implementation and raises the bar for future assessments. This study provides an overview of the BCR of a hybrid solution combining built and indigenous (nature-based) infrastructure and quantifies the avoided costs and added benefits resulting from its implementation. The combined implementation of dam construction and NBI resulted in the highest amount of total avoided costs and added benefits between 2022 and 2050. This highlights the synergies between built and natural infrastructure, which amplify both avoided costs and added benefits relative to the individual implementation of interventions. The results warrant additional research into hybrid solutions to explore potential synergies and trade-offs between solutions as well as their respective impacts on the performance of the investment. While the "channel rehabilitation" scenario yields the highest BCR of all scenarios, additional research into the actual effectiveness of this intervention is required to ensure that the envisaged ambition, in fact, yields the outcomes resulting from this assessment—in other words, that the effectiveness of this intervention is not overestimated and the BCR presented is likely too high.

It is clear, however, that both the protection from high water levels using grey infrastructure and the expansion of buffer zones and their connectivity to the river are required to mitigate flood risk in the La Mojana region. During the planning and implementation process, the design of the individual measures must not inadvertently undermine the effectiveness of the other measures, and if they do, the benefits must still be greater than the trade-offs (e.g., while the implementation of the dam will block some existing channels, the rehabilitation of channel infrastructure and the outlets of the dam are assumed to compensate for this impact).

To further deepen future analysis, the spatial analysis already performed by the DNP could be refined by exchanging water flow data from the SD model to use in flood models analyzing future flood risk. Once updated land-use and land-cover maps become available, this data can be used in combination with the 2000 and 2012 maps to create a more consistent time series of land cover and to create more detailed future land-cover maps. This would also benefit the ecosystem service projections for the different scenarios. Likewise, the SD model developed can be used to generate future water flow projections, which in turn can inform the development of more nuanced flood risk projections. Multiple water flow projections can be generated to assess the change in future flood risk (considering different measures) and to determine critical thresholds.

The results from this assessment can be used to communicate the value of combining conventional solutions with nature-based approaches based on Indigenous Knowledge and to highlight the need to customize the analysis to the project context. The DNP can use these results to inform flood management decision making in future projects. For analysts, this assessment, including the documentation of the model relationships and equations below, showcases the use of an integrated approach for analyzing infrastructure solutions. The approach used may provide guidance for policy-makers and professionals in framing assessments and developing fitting methodological tools.

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