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Integrating Blue-Green Infrastructure strategies to enhance climate resilience in Colombia.

By Laura Medina Rivera[1], Robert Faggian[1]

ABSTRACT:
Colombia is a tropical developing country that faces frequent and unpredictable flood events. Previous efforts to mitigate the impacts of flood have revolved around traditional approaches like the construction of levees. However, as seen in other parts of the world, levees often make flooding worse. Considering the increasing frequency and severity of extreme weather associated with a changing climate, it is clear there is a pressing need for more effective strategies to mitigate the impacts of extreme weather events. However, poor data availability makes understanding flood risk and developing new approaches a difficult task.
This research examines the feasibility of Blue-Green Infrastructure (BGI) as a nature-based methodological approach to deal with flooding focuses, focusing on the Guarapas River and Pitalito town, in regional Colombia. Utilizing PCSWMM as a modelling tool, the study demonstrates the applicability of BGI in reducing peak flow. Validating the model proved difficult given the substantial gaps in official data sources. So, it was necessary to use proxies such as social media posts of flood events, to determine the date and severity of flood events in the town.
The analysis revealed that deploying a limited number of BGI elements can mitigate the adverse effects of floods in a cost-effective manner, and that the underpinning modelling could be carried out using data proxies such as local news reports and social media posts. This research contributes to the growing body of knowledge on BGI as a valuable solution for flood management in a changing climate but does so in a developing country context. By showcasing the feasibility of BGI in reducing peak flow and enhancing resilience in a region with limited data resources, this study shows that it is possible for developing countries to move away from traditional and sometimes increasingly ineffective solution. Barriers to adoption are still significant. But nature-based solutions to flooding represent a new, proactive measure in addressing the challenges posed by climate change, with implications for policymakers and stakeholders involved in sustainable planning.

Keywords: Blue-Green Infrastructure, Climate change, Sustainable development, Developing countries, Water management.

1. Introduction

Developing countries, particularly those in tropical regions, face heightened vulnerability to climate change. These nations often rely heavily on natural ecosystems and agriculture, making them susceptible to unpredictable weather patterns and extreme weather. Traditional approaches to dealing with are becoming less reliable as climatic conditions change.

Flooding has emerged as one of the most predominant issues related to extreme weather events in these countries. Traditional flood mitigation measures, such as levees, remain prevalent due to their historical application. However, recent studies have demonstrated that these measures are frequently ineffective in addressing contemporary flooding challenges (Dufty et al., 2022). In response, numerous innovative solutions

[1]Centre for Regional and Rural Futures (CeRRF), School of Life and Environmental Sciences, Deakin University, 221 Burwood Highway, Burwood VIC 3125, Australia;

tailored to mitigate the effects of flooding and enhance resilience have been developed (Kiribou et al., 2024; Porto de Albuquerque et al., 2023), including nature-based solutions (NBS). Despite their potential, these approaches have seen limited application in developing countries, primarily due to challenges associated with their implementation such as the lack of up-to-date knowledge, skills and data.

This paper discusses the barriers to NBS implementation in Colombia and illustrates how Blue-Green Infrastructure (BGI), a sub-set of NBS, can serve as an effective alternative flood mitigation approach while deals with the barriers.

1.1 The barriers to adoption in developing countries.

NBS is commonplace in developed countries, particularly within Europe, where it forms an integral part of urban planning and development processes. It provides green and open spaces for cities, biodiversity corridors, recreational areas and of course, flood mitigation. But in these locations, expertise is available, financial resources are not limiting, and data is high quality and readily available. The situation is very different in many developing countries, where there are some clear barriers to the adoption of NBS.

1.1.1 Immediate and Tangible Solutions:

Flood threats require immediate action in terms of emergency response. But once the threat has passed, communities look to their governments for evidence of preparedness, hoping to avoid the impacts of the next flood. Levees provide rapid and visible relief that often increases community acceptance (Chambers et al., 2023; Gissing et al., 2018; O'Donnell et al., 2017). In contrast, nature-based solutions (NBS) typically require longer-term establishment and may not visibly look like a protective element to laypeople. NBS could also involve ecosystem restoration and enhancement, which can take years to mature and become fully effective. For instance, wetland restoration may require several years before the area can effectively absorb floodwaters. Consequently, communities may not perceive NBS as an appropriate approach for recurring flood events.

1.1.2 Limited Financial Resources:

Financial constraints generally mean the least expensive option is the preferred option. NBS can require higher initial investments (Heidari et al., 2023) than traditional infrastructure. Also, levees and other hard infrastructures are often perceived as more cost-effective in the short term, despite their potential inefficacy or higher maintenance costs in the long run (Schleifstein, 2023; van Rees et al., 2023).

Financial constraints also impact the availability of knowledge and expertise that in other contexts would serve to suggest alternative flood mitigation approaches. A lack of knowledge about alternative approaches leaves developing countries beholden to ineffective traditional approaches, and less able to access to international funds or grants dedicated to sustainable infrastructure. This financial barrier propagates through the entire flood preparedness and response system, with fewer comprehensive flood risk assessments and management strategies, poorer flood prediction and warning systems, and inadequate emergency response systems, all of which require financial and other resources.

1.2.3 Lack of Awareness and Policy Support:

NBS provide multiple co-benefits, including biodiversity enhancement, improved water quality, and recreational spaces. However, these benefits are often undervalued in policy frameworks that focus solely on immediate flood prevention. In developing countries, there is a significant lack of awareness of the additional benefits that NBS bring, both among policymakers and the public. This stems from a limited understanding of how to maximize the multidimensional benefits of Blue-Green Infrastructure (BGI) through effective policies and regulations. Consequently, current policies may not adequately support NBS implementation, resulting in incomplete regulatory frameworks and a lack of comprehensive guidelines for design, application, and integration with existing grey infrastructure (Consumer Scotland, 2022; Croeser et al., 2021; Heidari et al., 2023).

1.2.4 Technological and Research Constraints:

Financial limitations restrict access to new technologies and the application of academic research findings (Price, 2021). This leads to constraints in technological capabilities, particularly in conducting detailed hydrological modelling or environmental impact assessments necessary for effective NBS design. The lack of complete and reliable datasets further complicates research on infrastructure and technology. These issues limit the design, implementation, and maintenance of effective NBS, ultimately complicating the decision-making process.

1.2.5 Governance and Institutional Challenges:

NBS implementation faces various politico-institutional barriers, including internal corruption, fragmented governance structures, and poor decision-making due to lack of coordination among different governmental and non-governmental entities (Consumer Scotland, 2022; Heidari et al., 2023; Henderson et al., 2023). This fragmentation hinders adequate policy enforcement and NBS adoption (Seddon et al., 2020).

Effective NBS implementation requires a holistic approach and coordination between various sectors and government levels. Developed countries like Australia (from which this study was conducted) have compiled their regulations into a cohesive system, creating a regulatory environment that drives better solutions. This approach considers multiple sectors, addressing not only the core issue but also analysing possible additional benefits. In contrast, levees, a common flood mitigation measure, are known to introduce unintended consequences, characteristic of hard engineering solutions (Esteves, 2014). They often fail to address the multifaceted nature of flooding challenges. In countries with fragmented governance structures, adopting a comprehensive approach becomes challenging, a problem frequently faced by developing nations.

This paper presents an analysis of BGI application in a rural area of Colombia. To understand whether any of the listed barriers can be overcome, it was first necessary to understand if NBS and BGI would be effective in the goal of mitigating flood. Therefore, the goal of this research was to show proof-of-concept by modelling flood and designing a BGI system within a data-poor environment, assessing the costs of BGI solutions relative to reduction of flooding, and then socialising the results with researchers and public officials in Colombia. The paper concludes with a suggested framework for evaluating the feasibility and effectiveness of BGI in the context of the identified implementation challenges.

2. Methods

The research framework for this study comprises four main stages: case study selection, flood computer modelling and BGI system design, economic assessment, and community engagement.

2.1 Case study selection.

The study focused on the Guarapas River catchment in the Huila region of Colombia (Figure 1). This site was selected based on several criteria: frequency of flooding events, presence of human settlements affected by floods, and availability of essential data for analysis.

The region is characterized by high rainfall and mountainous terrain, making it susceptible to both riverine floods and landslides. Traditional flood management approaches, predominantly relying on levees, have proven ineffective in mitigating flood risks in this area. This context provides an ideal setting for evaluating the potential of Blue-Green Infrastructure (BGI) as an alternative flood management strategy.

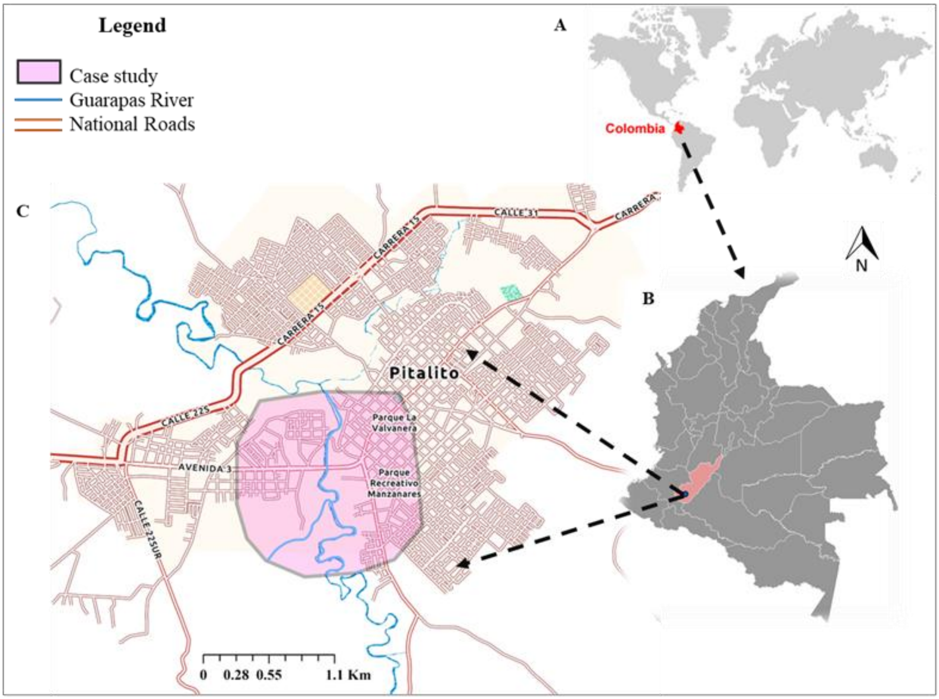

Figure 1. Location of case study selected. A) Colombia located in Latin America. B) Huila region in southwest Colombia, C) inner centre of Pitalito town crossed in the middle by main Guarapas river, the case study chosen is in the centre of town compound by two main roads and three suburbs.

The selected case study presents significant challenges for hydrological modelling due to limited data availability. However, it represents one of the best-case scenarios for data collection in the region, second only to the capital city, Neiva. The study aims to apply the approach in a decentralized area, contrasting with most other projects, which focus on Neiva.

Data scarcity in the case study was significant but representative of similar locations all over Colombia; that is, sporadic data across very few geographic points, and of varying quality. Generally, this means hydrological modelling is difficult or even impossible for these locations, which in turn limits the possibility of creating locally specific flood management solutions. This study's approach to overcoming such data limitations was multifaceted. First, any available open-source data was acquired (for example, data from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) for rainfall data). Additional data from non-public sources were also acquired, such as geographic information system (GIS) layers, digital elevation model (DEM), land cover, soil type, and water resources. These layers were compiled from the Regional Autonomous Corporation upper Magdalena institution (CAM). The datasets provided essential information on the catchment's physical characteristics and meteorological conditions, enabling a comprehensive representation of the study area in the hydrological models. The integration of both public and private data sources enhanced the overall quality and resolution of the input data, potentially improving the accuracy of the model simulations.

2.2 Flood modelling and BGI system design

The Personal Computer Storm-Water Management Model (PCSWMM) was chosen for its user-friendly interface and advanced visualization capabilities. The software facilitates a comprehensive understanding of complex hydrological systems. Crucially, it also enables the design and testing of BGI elements. The modelling process involved delineating sub-catchment boundaries, identifying outfalls, junctions, and conduits using GIS layers. The model was validated using periods of time characterised by the presence of floods and the existence of corresponding historical rainfall times series data.

This software provides a range of tools enabling the creation and execution of models under various scenarios. It also incorporates the primary focus of the study – BGI elements. Within the software, these elements are categorized as Low Impact Development (LID) elements, offering seven distinct options for BGI implementation.

To effectively demonstrate BGI's role in floodwater management following heavy rainfall, four specific BGI elements were selected after careful consideration of the geographical features of the case study area, their appropriateness for the regional context, and their documented effectiveness (Adaptation Solution, 2017; Ghofrani et al., 2019): bioretention cell (BRC), infiltration trench (IT), permeable pavement (PP), and Rain Garden (RG), as detailed in table 1. BRCs are engineered to store and infiltrate stormwater, significantly reducing runoff from sub-catchments. Their design can be customized to maximize storage capacity and infiltration efficiency based on the intended use (Lisenbee et al., 2021). ITs, similar to BRCs, are permeable structures designed to accumulate runoff water. However, they differ in terms of soil storage requirements and size variations (Urban Water, 2023). PP refers to a porous surface that permits water percolation, simultaneously maintaining functionality for pedestrian and vehicle traffic (Madrazo-Uribeetxebarria et al., 2021). Lastly, RG, also known as a stormwater garden, is a landscaped area that stores and filters runoff (Bai et al., 2019).

Table 1: LIDs parameters used in PCSWMM. Four specifications were taken into consideration. Soil parameter does not apply for IT, and pavement feature only apply for PP

Features		BGI type			
		BRC	IT	PP	RG
Surface	Berm Height (mm)	150000	2000	150	1000
	Vegetation volume (fraction)	0.1	0	0.2	0.1
	Surface roughness (Manning's n)	0.03	0.2	0.025	0.04
	Surface slope (%)	1	2	1	1
Storage	Thickness (mm)	400	100	100	0
	Void ratio (voids/solid)	0.95	0.8	0.25	0.75
	Seepage rate (mm/hr)	6	0	0.2	6
	Clogging factor	60	0	60	0
Soil	Thickness (mm)	100	/	100	150
	Porosity (volume fraction)	0.98	/	0.8	0.7
	Field capacity (volume fraction)	0.9	/	0.49	0.6
	Wilting point (volume fraction)	0.02	/	0.1	0.02
	Conductivity (mm/hr)	40	/	0.5	40
	Conductivity slope	7	/	10	10
	Suction head (mm)	48.26	/	45	50
Pavement	Thickness (mm)	/	/	150	/
	Void ratio (voids/solid)	/	/	0.25	/
	Impervious surface (fraction)	/	/	0	/
	Permeability (mm/hr)	/	/	1000	/
	Clogging factor	/	/	60	/
	Regeneration interval (days)	/	/	1	/
	Regeneration fraction	/	/	1	/

Four BGI scenarios (Sc) were designed using these elements, to reduce runoff and slow water flow:

- Sc 1: Bioretention Cell – BRC
- Sc 2: Bioretention Cell + Rain Garden - BRC + RG
- Sc 3: Bioretention Cell + Rain Garden + Permeable Pavement - BRC + RG + PP

- Sc 4: Bioretention Cell + Rain Garden + Permeable Pavement + Infiltration trench - BRC + RG + PP + IT or Best-case scenario (BGI_BSc).

2.3 Economic assessment

An estimation of the initial implementation costs of BGI systems under different scenarios related to runoff reduction was developed. The cost efficiency of individual BGI elements and their combined scenarios was evaluated in terms of the cost per cubic meter (m^3) of rainfall runoff reduction. Due to the absence of a comprehensive guide for BGI system implementation, cost data for each BGI element were compiled from several sources. Through an extensive literature review, all costs were initially calculated in Colombian currency, adjusted for inflation, and then converted to US dollars for broader comprehension.

The cost estimation methodology for each BGI element was as follows:

- Bioretention Cells (BRC): The cost was based on a 2020 Colombian document detailing the design costs (Jimenez Pava, 2020). This value was adjusted for inflation from 2020 to 2024 and converted to USD using the May 2024 exchange rate.
- Rain Gardens (RG): The cost was determined by comparing the salary of an expert needed to construct an RG per square meter in Colombia to that in the United States. This value was current and required no inflation adjustment.
- Permeable Pavement (PP): Due to the lack of Colombian-specific data, costs for different PP classes were sourced from US data. To estimate the implementation cost in Colombia, a comparative analysis of standard paving installation costs between Colombia and the US was performed. The percentage difference was then applied to the US PP costs to approximate Colombian PP implementation costs in USD.
- Infiltration Trenches (IT): The cost per square meter was estimated by analysing excavation and main fill values. The volume-based cost was converted to area-based cost using the model's implementation parameters (height: 0.6m, width: 0.4m). This value was then converted to USD using the exchange rate.

2.4 Stakeholder engagement

To socialise the concept of NBS as a viable alternative flood mitigation approach, a range of meetings with stakeholders were conducted from January 2023 to the current time. Most of the meetings were held face-to-face, and with various entities, ranging from environmental agencies to academic institutions.

3. Results

3.1 Case study: Pitalito town and available data.

Like many other regional Colombian towns, Pitalito town is characterized by sparse meteorological monitoring, with only two weather stations capturing rainfall data:

- Marengo Station: This is the sole automatic station in the vicinity, providing high-resolution rainfall data at 10-minute intervals. However, the dataset is incomplete, with some months offering comprehensive records while others have significant gaps, ranging from several days to entire months.

- Insfopal Station: This conventional pluviometric station offers a broader range of rainfall data. However, it only records daily measurements, limiting the temporal resolution of the data.

For the purposes of the modelling outlined in this paper, data from marengo station was gathered. Rainfall intensity data measured in mm/10 min was sourced for November 2021 (figure 2) based on an exhaustive search to secure data of high quality, prioritizing minimal data gaps and coinciding with known flooding events, for model validation purposes.

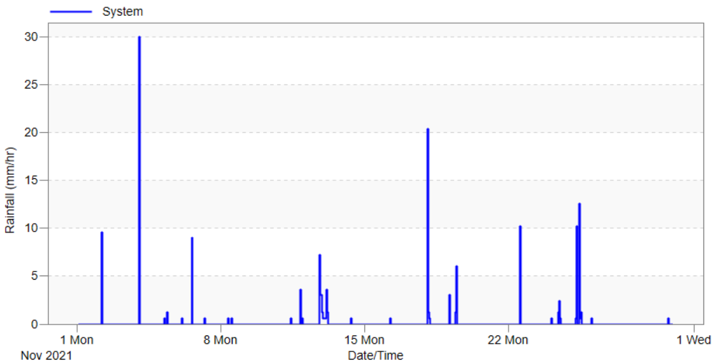

Figure 2. Rainfall data for November 2021, Marengo station in mm/10 min, Pitalito town, Huila, Colombia.

3.2 Modelling results

Using GIS layers, thirty junctions and thirty-one conduits were manually added to reflect the natural flow patterns of the Guarapas river and small tributary creek in the case study area. An outfall was placed at the termination point of the Guarapas River within the study area. Then the watershed delineation tool was employed in conjunction with DEM data to establish thirteen sub-catchments with a total area of 130.71 ha (refer to figure 3).

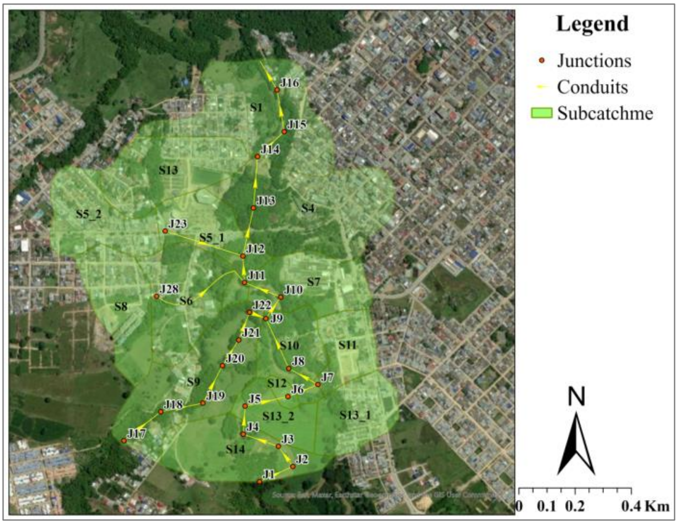

Figure 3. PCSWMM model configuration of the study area in Pitalito, Huila, Colombia. This figure illustrates the hydrological model configuration of the study area in Pitalito town using PCSWMM. The model represents the urban drainage system and includes the following key components: Sub-catchments (green): delineated areas within the study site that contribute runoff to the drainage system; Junctions (orange): nodes in the drainage network where channels or pipes intersect, and Conduits (yellow): channels to simulated Guarapas river and small creek within the case study.

For the November 2021 flood event, the implementation of the four BGI elements and the four scenarios, resulted in reduced peak flow and flood volumes in the Guarapas River catchment (refer to figure 4).

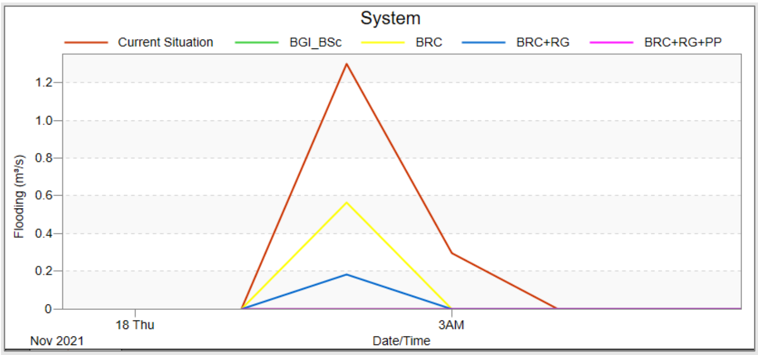

Figure 4. Flooding reduction by BGI scenarios in Pitalito, Huila, Colombia. This figure compares the flooding values of different BGI systems using four scenarios to the current situation (CS – shown in red) in Pitalito, Huila, Colombia. Scenario (Sc) 1: BRC, Sc 2: BRC+RG, Sc 3: BRC+RG+PP, and Sc 4: BGI_BSc. Note that Sc 3 and Sc 4 overlap on the graph and are not distinguishable from each other, but both reduced flooding to zero.

Comparable results were observed for Sc 3 and 4, effectively reducing the flooding value to zero. Sc 1 and 2 did also reduced flooding, but not to the same extent. These findings demonstrate that each BGI unit can mitigate flood conditions more effectively than the current situation (i.e. without any BGI elements in place).

Flood control is primarily achieved by reducing water runoff, which was also estimated for each scenario (Figure 5). The results show varying levels of total runoff reduction across all scenarios, consistent with flood reduction (Figure 4).

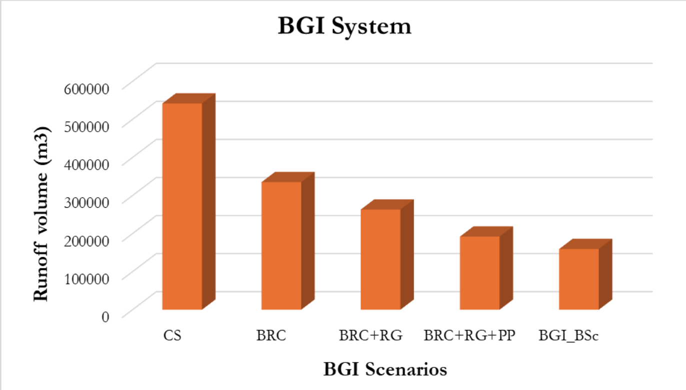

Figure 5. Runoff Volume (m³) for current situation and four BGI Scenarios. This figure presents the runoff volume by the current situation (ground-truth data) and the four BGI scenarios. The reduction values are based on the total runoff discharge per second during a 48-hour storm event in November 2021. The scenarios demonstrate a total stormwater storage capacity that results in a 72% reduction in runoff volume compared to the current situation.

3.2.1 Validation with Proxies

The scarcity of high-quality data necessitated the use of grey literature and social media reports for model validation. The model's predictions were cross-referenced with real-world flood events, ensuring accuracy and reliability. Local news confirmed the November 2021 floods, providing valuable data for verifying the model.

Rainfall data with a 10-minute interval for November 2021 and two other sources with 24-hour intervals for the months of October 2022 and June 2023 were selected. In fact, these were the only periods for which good quality data was available. Running the model with these data sets, the results coincided with flood observations in social media reports, evidencing flooding in junctions 10, 11, and 15 for specific months. Table 3 presents the compiled information, including the event date, observed data referring to the specific flooded location, photographic evidence of the event, cross-checking with modelling results translated into overflowed junctions, and finally, the social media source.

This approach demonstrates the potential of leveraging social media reports as a complementary source for model validation in the absence of official data, particularly in cases where flooding events are not formally documented by government agencies.

Table 3. Model validation using literature and social media data for Pitalito, Huila, Colombia. The validation process incorporates two key components: Literature-based validation: Comparison of model outputs with published data from relevant literature, and social media cross-checking sources for three specific flood events

Events	November 2021, 10 min rainfall data	October 2022, 24 hrs rainfall data	June 2023, 24 hrs rainfall data
Observed data	Libertador suburb (photo below)	Street in from of 'Drogas la rebaja' (image below). Also, evidence of 'ESE Manuel Castro, and San Antonio Hospital	Libertador suburb and bridge in 'carrera 6th' (evidence in photo)
Evidence from social media			
Modelling results	J15 and S1	• Street: J15 and S1 • ESE: J11 and S6 • Hospital: J10 and S7	J15 and S1
Source	(SVC, 2021)	(Villarreal Ruiz, 2022)	(Neiva Stereo, 2023)

3.3 Economic Assessment

The cost efficiency of BGI elements in different scenarios was evaluated based on the implementation cost per m³ of runoff volume reduction, as illustrated in table 4 and figure 6.

Despite the highest absolute cost corresponding to the final scenario, which incorporates all four elements, a more nuanced picture emerges when considering the cost relative to runoff reduction. Scenario three, which omits one element, proves more cost-effective. Similarly, the second scenario demonstrates greater cost efficiency than the final scenario when comparing implementation costs against volume reduction.

The analysis reveals that the final scenario, incorporating all four elements, has the second highest total cost but does not yield the best cost-efficiency. In contrast, scenario three, which utilizes only three elements, shows superior cost-effectiveness compared to the final scenario. Furthermore, the second scenario also exhibits better cost efficiency than the final scenario when evaluating the relationship between implementation costs and volume reduction.

Table 4. Cost estimates and runoff volume reduction for BGI scenarios.

Scenario	Runoff Reduction (m3)	$ in millions USD
BRC	206668.8	18
BRC+RG	278726.4	20
BRC+RG+PP	349747.2	24
BGI_BSc	382406.4	30

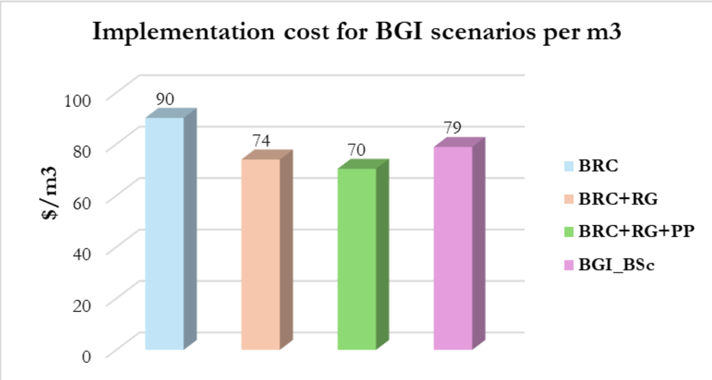

Figure 6. Cost-Effectiveness of runoff reduction across four BGI scenarios. This figure presents a comparison of the cost per unit volume of runoff reduction for BGI scenarios. The cost-effectiveness values were determined by dividing the total implementation cost of each scenario by its corresponding runoff reduction volume. This metric allows for a standardized comparison of the economic efficiency of different BGI configurations in managing stormwater runoff.

3.4 Towards implementation

Meetings with the main local environmental institution, to acquire data, were not fruitful. Despite consistent feedback indicating the appeal of, and interest in, the project, moving forward to data exchange or collaboration proved difficult. This was primarily due to the methodology not yet being codified into existing policies and therefore providing no incentive for cooperation or collaboration.

Meetings with local researchers also yielded little. Three universities were selected based on their satellite campuses in the rural town of Pitalito, the case study area. While the project and methodology were acknowledged as innovative and well-suited to address the region's flood situation, again the response to data sharing or collaboration was lukewarm at best. The primary reason cited was the lack of economic incentives for individuals or the universities to participate in the project.

In conclusion, both governmental and academic entities demonstrated reluctance to engage with the project without direct financial benefits being offered, citing concerns about increased workload without corresponding compensation. This situation clearly illustrates a significant challenge prevalent in developing countries, where systemic issues such as corruption creates the expectation of financial gain for cooperation.

4. Discussion

This study demonstrated that NBS offer a more sustainable and resilient flood mitigation approach compared to traditional approaches like levees, despite potentially having higher establishment costs and/or requiring longer establishment periods. The case study illustrated that BGI can be effectively implemented in regions facing immediate flood threats by integrating interim measures together with long-term NBS, providing multiple benefits beyond those offered by conventional flood management strategies.

The successful application of PCSWMM, together with validation via social media posts, showcases how advanced hydrological modelling can be utilized in developing countries, even with limited data availability. Data scarcity forced validation of the model against a single time-period (Nov 2021) where high resolution, government-curated rainfall data was available that coincided with a significant flood. Ideally, an extended time-period of high-resolution data, covering multiple floods, would be available for model development. However, this is unlikely in a developing country context. Proxy data in the form of social media posts therefore proved crucial to test the accuracy of the model. This situation points to the possible utility of citizen science as a data collection tool, although there are challenges with this approach that would require standardisation and oversight (Assumpção et al., 2018). Another approach could involve the deployment of low-cost hydrological monitoring equipment (Segovia Cardozo et al., 2021). In both cases, collaboration with local researchers would be mutually advantageous; studies like this one would benefit from improved data availability, and local researchers would benefit from knowledge sharing and skill acquisition.

By examining the cost-effectiveness of various BGI scenarios, this study sought to inform decision-makers regarding alternative flood mitigation solutions. Most perceive new solutions to be more expensive. However, the research highlights the economic viability of BGI by demonstrating the long-term cost savings from reduced flood damage. Importantly, the findings reveal a non-linear relationship between BGI implementation costs and runoff reduction, emphasizing the need for careful consideration when combining elements to optimize cost-effectiveness in BGI projects. This insight is particularly valuable for urban planners and policymakers, as it demonstrates that more extensive BGI implementation does not necessarily yield proportionally greater benefits in terms of cost-efficient runoff reduction. It also potentially demonstrates to local authorities the value of investing in local data collection – more data allows the testing of more BGI scenarios, which could identify a less expensive option.

To support initial investments in NBS, funding mechanisms such as public-private partnerships and international green grants could be an option. Studies like this one could make bids for international grant schemes stronger; by demonstrating the effectiveness and cost-efficiency of BGI, the research provides a compelling case for allocating financial resources towards NBS in developing countries.

The study also tried to address the challenge of enhancing awareness and policy support through its detailed case study approach and stakeholder engagement processes. By raising awareness about the multifaceted benefits of NBS among policymakers and stakeholders, the research opens the possibility that policy frameworks might one day integrate NBS into flood management and urban planning strategies. Clearly though, the obstacle of stakeholders seeking financial compensation for participation needs to be overcome. Similar problems have been encountered in other developing-country contexts, with complex local politicisation interfering in flood management (Desportes et al., 2016). There, academia played an important role in creating a neutral environment by which diverse stakeholders could engage with each other. In the case of this study, building trust with local stakeholders is an ongoing process.

Lastly, the study underscores the importance of coordinated efforts among various government agencies and sectors for effective NBS implementation. It calls for institutional reforms aimed at integrating NBS into existing planning processes. By highlighting governance challenges, the research paves the way for future studies to address the current situation and propose methods to work with institutions, preparing them before project socialization. This contribution aids in developing more effective and streamlined institutional frameworks for NBS adoption.

However, the study acknowledges that institutional reluctance and scepticism remain the most significant challenges for NBS implementation in developing countries. This raises an important question for the scientific community: How can they help bridge the gap and address the scepticism of institutions to promote the adoption of more feasible approaches like NBS in dealing with extreme weather conditions?

5. Conclusions

In conclusion, this study demonstrated that NBS, particularly BGI, offer a sustainable and cost-effective alternative to traditional flood mitigation measures in developing countries. The case study of the Guarapas River provides compelling evidence of BGI's potential to significantly reduce flood impacts while delivering multiple co-benefits. This contrasts with levees, that are already failing to deliver flood mitigation; the situation will only get worse in a changing climate.

The success of the PCSWMM modelling in this study, despite data limitations, demonstrates the feasibility of advanced hydrological modelling in developing countries. This opens avenues for more sophisticated planning and implementation of NBS in similar contexts. Moving forward, the focus should be on overcoming the policy barrier through targeted efforts to raise awareness, build capacity, and reform institutional frameworks. Future research focused on developing data collection methodologies tailored for regions with data challenges, such as developing countries, will be crucial for strengthening planning and decision-making processes. By doing so, developing countries can create an enabling environment for the widespread adoption of NBS in flood management strategies.

This research makes a substantial contribution to the growing body of evidence that supports Nature-Based Solutions (NBS) as a viable and preferable approach for enhancing urban resilience and sustainability in the face of climate change. The methodology presented can be seamlessly integrated with existing grey infrastructure, demonstrating its potential to significantly improve current urban planning processes. This integration not only enhances traditional benefits such as flood control but also provides additional co-benefits, including increased biodiversity, improved water quality, and better water management for future uses such as agriculture, drought mitigation, and potable water supply. By enhancing these co-benefits alongside flood control, the methodology offers economic advantages by reducing damage costs and increasing the value of urban areas. Of course, validating these benefits would require a robust monitoring and evaluation step, to justify the investment in this new approach. However, the methodology can be adapted to other contexts where similar challenges exist, and the need is evident. This study and others like it provide a solid foundation for policymakers, urban planners, and water management professionals to advocate for and implement NBS in developing countries, fostering more resilient, sustainable, and liveable urban environments.

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